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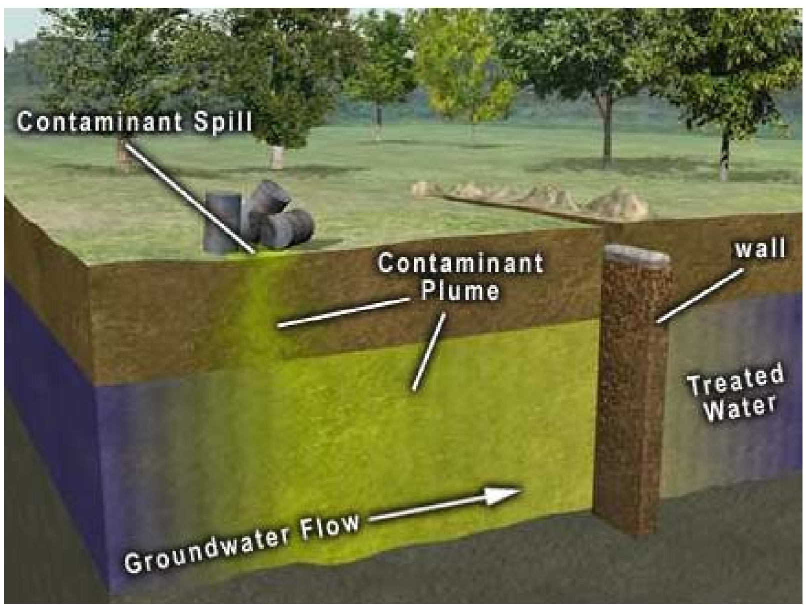
PERMEABLE REACTIVE BARRIER COST AND PERFORMANCE REPORT



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14. ABSTRACT
An evaluation of cost and performance was conducted for three full-scale permeable reactive barriers (PRBs) representing a range of installation technologies, reactive media, and targeted contaminants. Injection media used ranged from zero-valent iron (ZVI) that stimulates abiotic transformation of chlorinated solvents, to organic materials (e.g., mulch; vegetable oil) that treat perchlorate and enhance reductive dechlorination of chlorinated solvents.

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EXECUTIVE SUMMARY

Permeable reactive barriers (PRBs) have been in use for over 15 years as a means to treat contaminated groundwater plumes. More recently, various innovative injection techniques and reactive media have been demonstrated, expanding the types of sites and list of chemicals successfully targeted by PRB technology. PRB treatment technology has moved beyond field demonstrations to full-scale applications, and the cost and performance of PRBs have been documented in multiple publications.

However, never has the sustainability of PRBs been considered as a performance metric and systematically evaluated in light of the broad range of PRB technologies available. Sustainability as a metric has recently been developed by the Naval Facilities Engineering Command (NAVFAC) in its green and sustainable remediation (GSR) fact sheet [1] and guidance document [2] and calculated using SiteWise™.

To conduct this comparison, the Navy selected three sites with full-scale PRBs representing a range of installation technologies, reactive media, and targeted contaminants. Injection media used ranged from zero-valent iron (ZVI) that stimulates abiotic transformation of chlorinated solvents, to organic materials (e.g., mulch; vegetable oil) that treat perchlorate and enhance reductive dechlorination of chlorinated solvents. Injection methods used included a one-pass trench system, pneumatic fracturing, and trench excavation and placement. Targeted contaminants included chlorinated solvents, chromium, and perchlorate. The three selected sites consisted of:

- Granular-scale ZVI trench placement at Naval Weapons Industrial Reserve Plant (NWIRP) Dallas, TX to reduce trichloroethene (TCE) and hexavalent chromium
- Micro-scale ZVI pneumatic fracturing injection at Hunters Point Naval Shipyard (HPNS), CA to target chloroform and TCE concentrations
- Mulch/vegetable oil biowall installation at NWIRP McGregor, TX to treat perchlorate and TCE.

In general, the following are the key observations made in this comparative study:

- At NWIRP Dallas, TX, over 630 tons of granular ZVI was placed in 2008 in two PRBs to prevent impact of chlorinated solvents to surface water. The ZVI PRBs are providing adequate reduction of hexavalent chromium and chlorinated solvents to meet the site-specific remedial goals. To fully evaluate hydraulic and contaminant reduction performance, additional groundwater monitoring wells would need to be installed upgradient, cross-gradient, and within the PRBs. This would provide data on groundwater flow patterns through the wall, along with contaminant reductions and changes in pH and oxidation-reduction potential (ORP) within the PRB.

  The activities most impacting the sustainability of the remedy were production and transportation of the ZVI, together accounting for more than 95% of both the carbon footprint as total greenhouse gas (GHG) emissions (carbon dioxide equivalents [CO_2e]) and energy consumption and approximately 80% of the release of priority pollutants. The transportation of waste soils accounted for the majority of the remaining 20% of priority pollutant release. These activities were offset, at least in part, by the short duration of PRB installation (6 days) and negligible PRB maintenance over time.

- At HPNS, 68 tons of micro-scale ZVI was injected in 2008 within Parcels D1 and G at Installation Restoration (IR)-71 to form multiple barrier rows across a groundwater plume containing low concentrations of chloroform. A series of seven ZVI barriers was injected using pneumatic fracturing with nitrogen as the carrier gas. Based on earlier work at HPNS, the design targeted an iron-to-soil ratio of 0.004. The pneumatic fracturing and ZVI injection showed significant (>99%), rapid (<12 weeks), and sustained (multiple years) reductions in chloroform concentrations within a dilute chlorinated plume. This full-scale application also demonstrated the use of multiple monitoring techniques to estimate the effective radius of influence (ROI) during injection, including biaxial tiltmeter readings, which provided a more accurate record of surface deformation than traditional surface heave measurements. The application highlighted the risks of increasing soil vapor and dissolved metal concentrations. Degradation of chlorinated solvents proceeded even though strongly reducing conditions were not achieved throughout the plume.

  Consumables (ZVI and nitrogen) production and transportation were the largest contributors to the carbon and energy footprints, which together accounted for more than 85% of the carbon footprint as total GHG emissions and 70% of the energy consumption. The pneumatic fracturing processes and extended time on site (several months versus one week at NWIRP Dallas) also contributed to energy consumption, water consumption, generation of criteria pollutants, and accident risk during construction activities. On the other hand, the direct push drilling eliminated soil residual generation.

- At NWIRP McGregor, TX, 34 biowalls totaling 10,162 linear feet, were constructed using a rock trencher, imbedded with diffuser pipes to allow for future injections of carbon substrates, and backfilled using 40% recycled material (e.g., mushroom compost, three-quarter inch pine wood chips) soaked in soybean oil and 60% gravel. The biowalls are achieving between 34% and 97% reduction of perchlorate concentrations. Concentrations of total organic carbon (TOC), ORP, nitrate, and methane are tracked to identify when supplemental carbon addition is needed. During the five to seven years since biowall installation, 13 of the 34 biowalls have required supplemental carbon at least once, generally four to five years after initial installation. Emulsified vegetable oil has proved effective, yet four biowalls required replenishment again within a year. No other maintenance has been required and only minimal settlement has been noted at land surface.

As with NWIRP Dallas, material production and transportation (soybean and vegetable oils) constituted more than 90% of the carbon footprint as GHG emissions and energy consumption, with construction of the biowalls responsible for less than 5% of the carbon footprint and energy consumption.

The primary lessons learned from the PRB application at these three Navy sites are as follows:

- A ZVI design iron-to-soil mass ratio of 0.004 proved adequate to produce sufficient reducing conditions (e.g., ORP less than -150 mV) to degrade chlorinated compounds at the ZVI injection site.
- Monitoring remains key to evaluating system performance. The monitoring plan should include a monitoring network with wells located upgradient, cross-gradient, downgradient, and within the plume. Advanced field tools, including biaxial tiltmeter monitoring and down-hole pressure transducers, should be used to monitor injection of reactive material when fracturing and injecting.
- When fracturing and injecting at shallow depths, be aware of the risks of increasing soil vapor concentrations. Also note that pressurized injection may lead to "daylighting," when reactive media reaches the surface.
- The use of ZVI material may increase dissolved metal concentrations. This impact on secondary water quality should be carefully monitored and mitigated when necessary.
- Using recycled materials and minimizing the quantity and distance materials are transported make a large impact on reducing the carbon footprint and energy usage at a site.
- Rejuvenation of biowalls can be performed sustainably and cost-effectively to provide sufficient bioavailable carbon for perchlorate treatment. Key parameters include monitoring perchlorate, TOC, ORP, nitrate, and methane. For the majority of the wells, no carbon supplementation has yet been needed. The rejuvenation, when needed, may start as early as four to five years after biowall installation. However, the vegetable oil may be rapidly consumed, requiring subsequent additions of supplemental carbon as frequently as annually.

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ACRONYMS AND ABBREVIATIONS

AAL	attenuation action level
ARS	ARS Technologies, Inc.
bgs	below ground surface
BLS	Bureau of Labor Statistics
cfm	cubic feet per minute
CH_4	methane
CO_2	carbon dioxide
COC	contaminant of concern
DCE	dichloroethene
DO	dissolved oxygen
FBR	fluidized bed reactor
GHG	greenhouse gas
gpm	gallons per minute
GSR	green and sustainable remediation
GWP	global warming potential
HPNS	Hunters Point Naval Shipyard
IR	Installation Restoration
LCA	lifecycle analysis
LNAPL	light nonaqueous phase liquid
MMBTU	million metric British Thermal Unit
N_2O	nitrous oxide
NAVFAC	Naval Facilities Engineering Command
NOx	nitrogen oxide
NWIRP	Naval Weapons Industrial Reserve Plant
O&M	operation and maintenance
ORP	oxidation reduction potential
PCB	polychlorinated biphenyl
PCL	protective concentration level
PFI	Pneumatic Fracturing, Inc.
PM	particulate matter
PMZ	Plume Management Zone
PRB	permeable reactive barrier

psi	pounds per square inch
PVC	polyvinyl chloride
RAO	remedial action operation
ROI	radius of influence
SOx	sulfur oxide
SVOC	semi-volatile organic compound
TCE	trichloroethylene
TOC	total organic carbon
U.S. EPA	U.S. Environmental Protection Agency
VOC	volatile organic compound
ZVI	zero-valent iron

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1.0 INTRODUCTION

This cost and performance report is a critical review of technical and performance data from three recent Navy projects involving the use of permeable reactive barriers (PRBs) for treatment of several different contaminants. The review focuses on sustainability as a new performance metric.

A PRB is an in situ permeable treatment zone designed to intercept and remediate a groundwater contaminant plume [3]. The technology has proven useful in remediating contaminants such as volatile and semi-volatile organic compounds (VOCs and SVOCs), inorganic compounds (e.g., metals, nitrate), energetic compounds, radionuclides, and emerging contaminants such as perchlorate. There are many types of PRBs, including barriers that contain reactive media which promote abiotic and/or biotic reactions, or aeration walls that promote either physical or biological reactions [3]. The focus of this report is on those PRBs containing liquid or solid reactive media placed within the subsurface.

The Navy has conducted multiple full-scale projects using PRB technologies. This report evaluates the results of PRB projects that were conducted at the following three sites:

- Two zero-valent iron (ZVI) PRBs installed in 2008 using a rock trencher at Naval Weapons Industrial Reserve Plant (NWIRP) Dallas, Texas [4-6].
- Seven ZVI PRBs placed in 2008 using pneumatic fracturing and injection in Parcels D1 and G in Installation Restoration (IR)-71 at Hunters Point Naval Shipyard (HPNS), San Francisco, California [7].
- Multiple mulch biowalls installed between 2002 and 2005 using a one-pass trencher at NWIRP McGregor, Texas [8, 9].

This document is intended to be a synopsis of the results of these technology applications, an evaluation of the sustainability of the technology, and a consolidation of the lessons learned for future applications.

1.1 Report Organization

This report is organized into the following sections:

Section 1.0: Introduction. This section provides the report framework, an introduction to PRBs, and the variations of this technology currently being demonstrated.

Section 2.0: PRB Installation at NWIRP Dallas.

Section 3.0: ZVI Injection at HPNS.

Section 4.0: PRB Installation at NWIRP McGregor.

Section 5.0: Summary, Discussion, and Lessons Learned. This section compares the three sites in terms of cost, performance, and sustainability. The section also provides a discussion of the results and lessons learned from the PRB applications.

1.2 Technology Description and Performance Metrics

Typically during PRB construction, the reactive zone is installed as a trench in locations intended to intercept and remediate contaminated groundwater. As water passes through the PRB, usually under natural groundwater flow, conditions developed within the reactive medium remediate contaminants either through biological and/or chemical reactions or sorption. Placement of the PRB is vital to the overall functionality of the PRB; while a PRB may be used in source zone remediation (when placed close to the source zone), it is most commonly placed downgradient of the source zone to provide plume treatment and protection of potential receptors.

Traditionally, the most common type of installation design of PRBs is a continuous trench wall filled with reactive medium in the path of a contaminant plume, as illustrated by Figure 1-1 [3]. The PRB is usually keyed into the impermeable layer to capture the entire contaminated groundwater plume, although "hanging walls" may be installed in some situations.

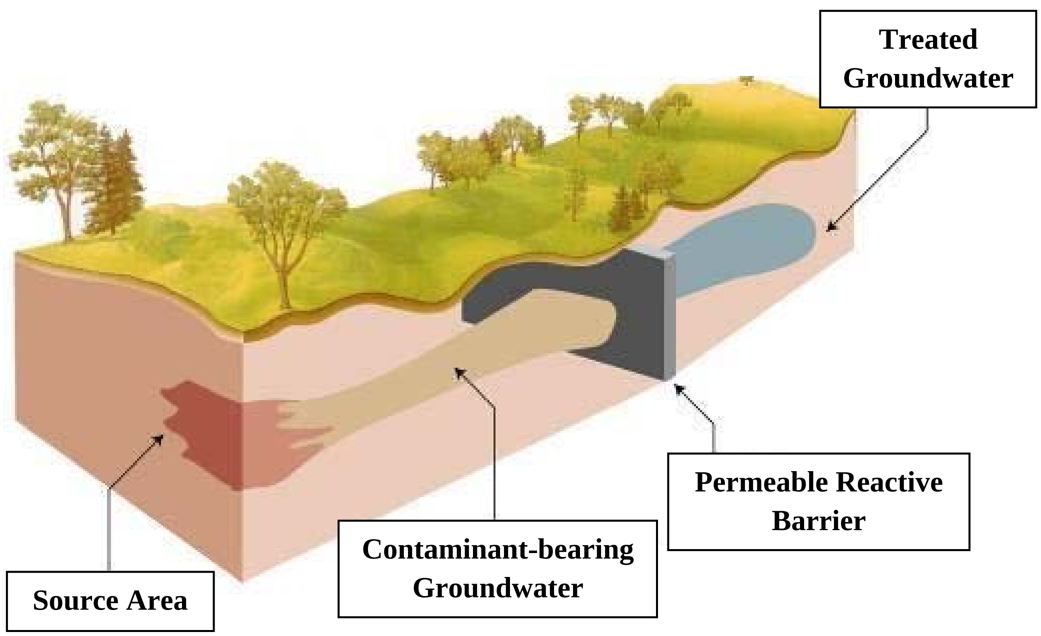

Figure 1-1. PRB Conceptual Design

More recently, PRB design technology has been advanced using single pass trenching, direct injection, hydraulic or pneumatic fracturing injection technology, or large diameter borehole-filled completions.

Apart from the installation design, the other crucial aspect of the proper functioning of a PRB is the reactive media. The PRB should have optimal amount of reactive media and should be able to provide required residence time for the media to react with the contaminants for remediation to occur. Some of the reactive media used to date include:

- A commonly applied reactive media is ZVI, which treats organic contaminants primarily through abiotic pathways, including beta elimination.

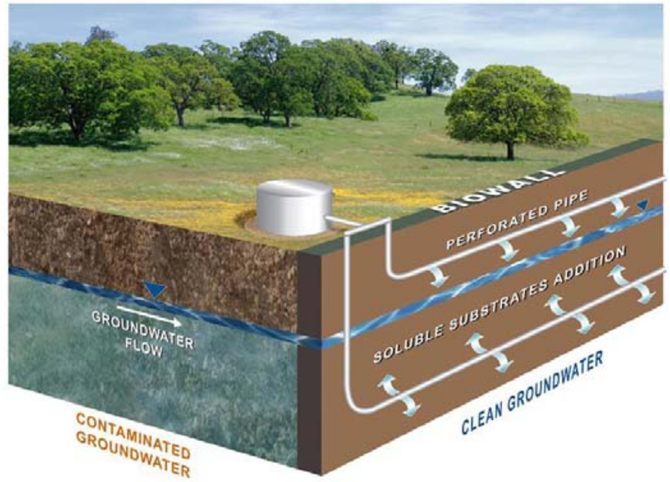

Figure 1-2. Schematic of Biowall with Perforated Pipe for Rejuvenation

- Recycled material, including mulch or compost, is increasingly being placed to treat chlorinated organic compounds and metals, forming a permeable "biowall" (see Figure 1-2).
- Injection of organic substrates such as vegetable oil and nutrients are increasingly being used to enhance the performance of existing PRBs, forming another type of "biobarrier."
- Zeolites are used to treat radionuclide plumes.
- Other new media, including EHC® and sulfate compounds, may simultaneously enhance both abiotic and biotic processes.

Longevity is another crucial aspect of PRBs. Longevity refers to the ability of a PRB to sustain hydraulic capture, residence time, and reactivity in the years and decades following installation [3].

- The primary factors limiting longevity of ZVI barriers are corrosion of iron and precipitation of native inorganic constituents from groundwater onto iron surfaces. When excessive, these factors have led to reduction in reactivity of the ZVI, loss of porosity and permeability, hydraulic mounding, and plume bypass around the PRB [3].
- The longevity of biowall PRBs primarily depends on (1) sustaining appropriate levels of bioavailable organic substrate in the biowall reactive zone and (2) maintaining the permeability of the biowall trench to prevent bypass of contaminated groundwater. In mulch biowalls, the primary factor limiting longevity has been depletion of the more easily biodegradable portion of the organic substrate in approximately four to five years after installation. Injection of a slow-release biodegradable substrate, such as vegetable oil, has been effective in extending the life of a biowall, although this periodic enhancement increases the lifecycle cost of the PRB and makes it more of a semi-passive system [3].
- The longevity characteristics of other PRB media, such as ZVI-carbon substrates and mineral media, are being studied [3].

The design objectives for a PRB are the functional requirements that include both remedial and project objectives [3]. As shown in Figure 1-3, the components of the functional requirements are the hydraulic performance, chemical treatment performance, and sustainability performance of the PRB. The design objectives therefore govern the overall installation, cost, and eventually the capability of a PRB to meet the functional requirements. However, in certain cases, even after considering all of the hydrogeochemical parameters in the installation design, the groundwater geochemistry, lithology, and geochemical parameters of the aquifer can sometimes alter the PRB performance.

1.3 Sustainability Metrics

One of the objectives of this report is to compare several Naval sites to identify the highest cost and largest remedy footprint elements of the overall PRB installation at a site. The term "remedy footprint" is defined as the overall environmental, social, and economic impact of a remedial technology. The remedy footprint of installing PRBs at the different Naval sites considered in this report was calculated using the metrics developed by the Naval Facilities Engineering Command (NAVFAC) in its green and sustainable remediation (GSR) fact sheet [1], and calculated using SiteWise™. These quantifiable sustainability metrics include:

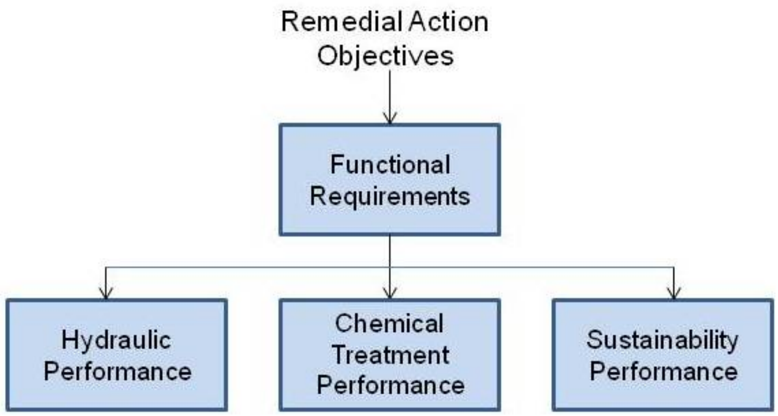

Figure 1-3. Functional Requirement of a PRB [3]

1) **Greenhouse Gas (GHG) Emissions**: Regulation and inclusion of activities that reduce GHG emissions during remedial actions are one of the most important features of sustainable practices in the wake of growing concerns over climate change. The internationally accepted norm is to consider major GHGs that include carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) to develop GHG emission inventories. Emission factors for GHGs (such as N_2O and CH_4) are multiplied by their unitless global warming potential (GWP) to obtain a CO_2 equivalent. The United States Environmental Protection Agency (U.S. EPA) [10] defines GWP as the cumulative radiative forcing (measure of changes in the energy available to the earth-atmosphere system) over a period of time from the emission of a unit mass of gas relative to a reference gas that is CO_2. The GWPs of N_2O and CH_4 are 310 and 21, respectively. A GHG footprint is generally reported in CO_2e, where "e" stands for equivalents. This review considers direct emissions that would be emitted at the site due to transportation and the use of remedial equipment, as well as indirect emissions from electricity that would be used to operate equipment, and indirect emissions from the production of consumables used during the remedial process. The term "carbon footprint" as presented in this document refers to these total GHG emissions as carbon dioxide equivalents (CO_2e).

2) **Energy Usage**: Consumption of non-renewable energy (i.e., fossil fuels) is an important sustainability metric because of the need to conserve the U.S. energy supply and reduce dependence on foreign energy sources. Energy-consuming activities that have been considered during this review include electricity used onsite, fuel consumed for on-site equipment, transportation associated with the remedy, and energy used for the production of consumables associated with the remedy.

3) **Air Emissions**: The air emissions of criteria pollutants such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) due to transportation activities,

electrical usage, and heavy machinery and equipment use during a remedial action is an important metric. Inclusion of a priority pollutant emission inventory in evaluating the sustainability of a remedial effort is important because these air pollutants cause problems such as smog and even health hazards such as asthma, bronchitis, lung cancer, and eye irritation. Each of these pollutants has been evaluated quantitatively in this review using the U.S. EPA emission inventory and factors for criteria pollutants for various industries and activities [11].

4) **Accident Risk**: A measure of a system's sustainability cannot be completely determined without understanding the direct risk to human well-being in conducting the activities in the system's boundary. Impact on human health is an important metric because eventually all of the metrics lead to an effect on human health and existence. Accident risk is a direct calculation of the risk (fatality and injury) attached to carrying out a specific task of a remedial activity. This metric has been included in the evaluation by using fatality and injury risk data for activities such as transportation, construction, heavy equipment handling and operation, and production of material used in remedial efforts. Data have been obtained from various sources, including the Bureau of Labor Statistics (BLS), the Innovative Technology Administration - Bureau of Transportation Statistics, and the National Highway Traffic Safety Administration.

5) **Water Usage:** This metric is a consideration of water that would be consumed during remedy implementation. Water usage considered under this metric includes water consumed during production of consumables, at the power plant, during production of electricity used, and lost due to remedy implementation in certain cases such as pump and treat systems in which treated groundwater is delivered to a surface water body instead of reinjecting it into the aquifer.

6) **Resource Consumption:** This metric is a consideration of resources other than those already quantified that would be consumed during remedy implementation. This typically can include various resources, such as landfill space, topsoil, water, and ecological impacts.

7) **Ecological Impacts:** Ecological impacts include adverse effects such as: introduction of invasive species, changes in ecosystem structure or shifts in the geographic distribution and extent of major ecosystem types, disturbance to soil and surface water bodies, and destruction of habitats. These impacts are generally evaluated along with the positive ecological effects of site remediation.

8) **Community Impacts:** This metric is a qualitative evaluation of local disturbances caused due to remedy implementation. The disturbances can include noise, traffic issues, and odor due to remedial alternatives.

The GSR analysis for the PRBs located at NWIRP Dallas, HPNS, and NWIRP McGregor constituted quantification of the following metrics:

1) GHG Emissions
2) Energy Consumption
3) Criteria Air Pollutants
4) Accident Risk

5) Water Usage

The information sources for these metrics are discussed in Appendix A. The metrics that were not included in the analysis were ecological impacts, community impacts, and resource consumption. Because the study included comparable PRBs at Navy locations, community impacts and ecological impacts were assumed to be similar for all of the sites or not being distinguishable enough for comparison between the different sites.

2.0 NWIRP DALLAS

2.1 Introduction

NWIRP Dallas is located in the city of Grand Prairie, between Dallas and Fort Worth, Texas. The facility was constructed in 1940 to manufacture military aircraft. Manufacturing operations began in 1941 and continued through World War II. After World War II, in 1947, ownership of NWIRP Dallas was transferred to the Navy. Since then, the Navy leased NWIRP Dallas to several aviation companies at different times. Currently, the Navy leases the property for manufacturing military and commercial aircraft components and various weapons systems [5].

2.2 Contaminant Distribution and Groundwater Response Action

Since the late 1990s, a Resource Conservation and Recovery Act facility investigation and other investigations have demonstrated the presence of site-wide plumes of VOCs, SVOCs, polychlorinated biphenyls (PCBs), and light nonaqueous phase liquid (LNAPL) in the groundwater. The groundwater monitoring at the site has demonstrated that the plume is stable and not expanding [6].

Two PRBs were constructed at the site as a preventive measure to preclude potential migration of contaminants of concern (COCs) beyond the Plume Management Zone (PMZ) along the southwest fence line adjacent to private properties. The West PRB was installed to treat groundwater at the southwest boundary to prevent potential off-site migration of VOCs at concentrations above the critical protective concentration levels (PCLs), which are the default cleanup standards for the Texas Risk Reduction Program (Rule 30 TAC 350). The East PRB was installed in the East Lagoon area to manage and control total chromium and hexavalent chromium migration toward the south, to nearby Cottonwood Bay, at levels above the groundwater discharge to surface water PCL. The locations of these two PRBs are illustrated on Figure 2-1.

2.3 Lithology/Hydrogeology

2.3.1 <u>West PRB</u>

The lithology at the West PRB mainly consists of clayey soil, classified as Class II soil. The PRB was anchored into the hard clay found at approximately 35 to 40 ft below ground surface (bgs). This layer is overlain by a gravely clayey soil, which lies beneath a soil consisting of dark grey to yellowish brown clay. The groundwater table in this part of the site is approximately 10 ft bgs.

2.3.2 <u>East PRB</u>

The lithology at the East PRB also consists of clayey soils underlain by a confining shale layer into which the PRB is anchored. The yellow-brown clay is underlain by a gravely sandy clay soil, which overlies the confining shale layer around 15 to 22 ft bgs. Depth of groundwater in this part of the site is approximately 5 ft bgs [5].

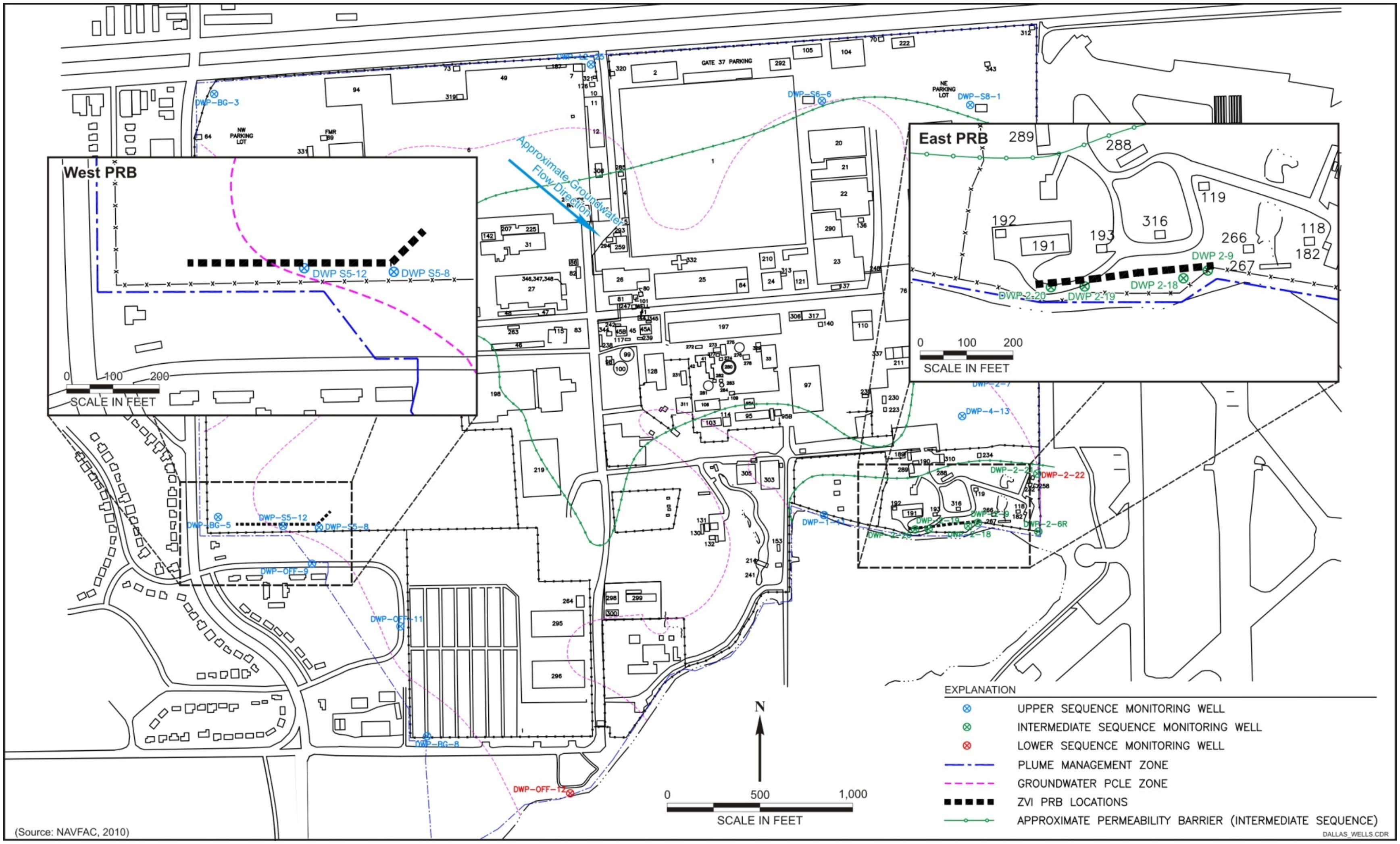

Figure 2-1. Layout of the Monitoring Wells and Two Biowalls at NWIRP Dallas, TX

2.4 PRB Construction

The design required the construction of two PRB trenches, totaling approximately 920 linear feet. The PRBs were installed in September and October 2008. The one-pass trencher equipment, used to complete the installation, is illustrated in Figure 2-2. The iron and sand materials were mixed in a cement mixer truck, conveyed to a hopper, and then injected continuously during trenching [5]. In total, 920 total ft of trenching was installed over six working days, indicating the PRB was installed at a rate of over 153 ft per day.

Figure 2-2. Rock Trencher Used to Install PRBs at NWIRP Dallas, TX

The ZVI, which consisted of -8 to +50 US standard mesh size, was provided by Peerless Metal Powders & Abrasives of Detroit, Michigan, and transported in 3,000 lb "Super Sacks" with 42,000 lb per truck load [5]. The total mass of ZVI delivered to the site and installed in the PRBs was 630 tons. Specific construction details for each of the two barriers are described below.

2.4.1 West PRB

The West PRB was constructed in the southwest parking lot at NWIRP Dallas, anchored in the impermeable clay layer in the subsurface to a depth that ranged from 34 to 43.5 ft bgs. Therefore, the average reactive zone spanned from 10 to 40 ft bgs. The east-west segment of the barrier was approximately 420 feet long. However, to account for the direction of groundwater flow in this area, an additional 100 ft of trench was excavated perpendicular to the groundwater gradient, resulting in a design total length of approximately 520 ft. The design width of this PRB was 18 inches; however, the trencher cutting boom cut a 20-inch-wide trench.

Prior to beginning trenching, the segment of the PRB where the confining layer was deeper than 34 feet bgs was benched to allow the 35-foot cutting boom to reach the confining layer. A ZVI mixture consisting of 15% sand and 85% ZVI by volume,[1] was then placed from the bottom of the excavation to the approximate depth of the highest recorded groundwater level. A layer of filter fabric was placed on top of the ZVI/sand mixture. Clean backfill was placed on top of the fabric and was compacted.

[1]The ZVI to sand ratio specified in the design for the West PRB was 20:80 by volume and that of the East PRB was 30:70 by volume. However, these ratios were modified in the field to account for the additional trench width created by the trencher cutting boom.

2.4.2 East PRB

The East PRB was constructed in the East Lagoon area. The East PRB was anchored into the confining shale layer at a depth that ranged from 15 to 22 ft bgs, which is the top of the impermeable shale layer. The completed length of the East PRB was 400 ft. Depth to groundwater in this area is approximately 5 ft bgs. Therefore, the average reactive zone spanned from 5 to 16 ft bgs.

The East PRB was constructed using a ZVI mixture consisting of 26% ZVI and 74% sand, by volume. Similar to construction of the West PRB, the mixture was placed from the bottom of the excavation to the approximate depth of the highest recorded groundwater level. A layer of filter fabric was placed on top of the ZVI/sand mixture. Clean backfill was placed on top of the fabric and was compacted.

2.5 Performance Evaluation Approach

Verification of the iron quantities injected was performed by collecting samples of the iron-sand mixture directly from the mixer truck.

Six monitoring wells located just downgradient of the PRBs are currently used to monitor performance. Two wells, DWP S5-12 and S5-8, are associated with the West PRB and four wells, DWP 2-9, 2-18, 2-19, and 2-20, are associated with the East PRB. The locations of these monitoring wells are depicted on Figure 2-1, in the two boxes depicting each of the barriers. The remedial objective of the PRBs is not to meet critical PCLs at the PRBs, but to reduce groundwater concentrations sufficiently such that the critical PCLs are met at the downgradient point of exposures as explained above. No monitoring wells were located upgradient or within the PRB.

2.6 Technology Performance Results

To fully evaluate hydraulic and contaminant reduction performance, additional groundwater monitoring wells would need to be installed upgradient, cross-gradient, and within the PRBs. However, data collected from the six available downgradient monitoring wells during the two years following PRB installation indicate decreases in concentrations of chromium and trichloroethylene (TCE) [6].

2.6.1 West PRB

Based on the monitoring results in the two wells located just downgradient of the West PRB, TCE concentrations decreased after PRB installation between 84% and 93% (see Figure 2-3). Concentrations remained above the PCL for TCE; however, they remained below the attenuation action level (AAL).[2]

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[2] The attenuation action level is the value established within a PMZ that is protective of applicable groundwater PCLs at a location outside and downgradient of the PMZ. AALs are determined for each well and may differ in value. The AALs for TCE in wells DWP S5-12 and S5-8, located at the West PRB, are 50 and 270 μg/L, respectively. All four performance wells located at the East PRB have an AAL for TCE of 4,080 μg/L,

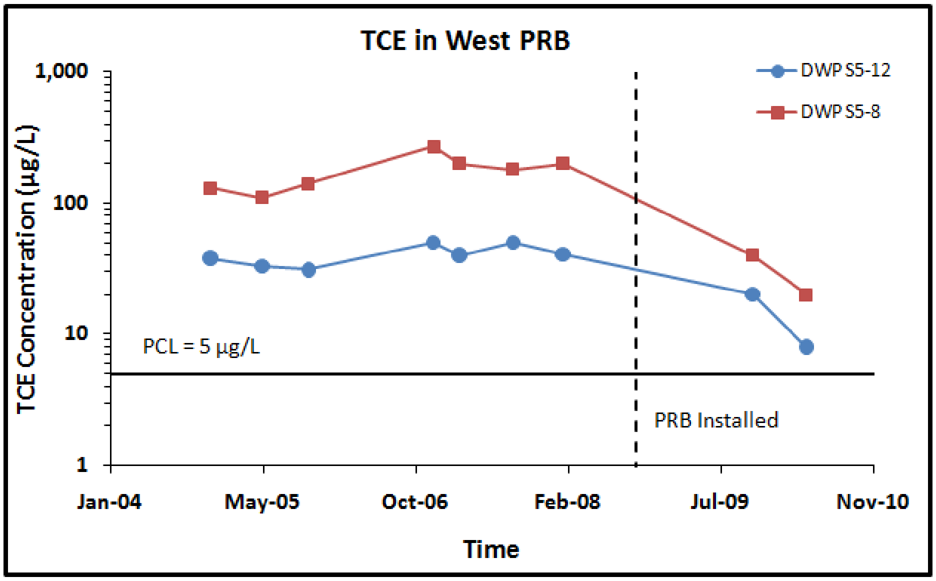


Figure 2-3. TCE Reductions in West PRB, NWIRP Dallas

2.6.2 East PRB

In the four monitoring wells located just downgradient from the East PRB, hexavalent chromium concentrations decreased over 99% from pre-installation concentrations (Figure 2-4). TCE concentrations decreased between 83% and 96% (Figure 2-5). Though not shown, total chromium concentrations also showed decreases between 91% and 99.6%, likely precipitating as low solubility $Cr(OH)_3$ or in association with iron oxyhydroxides [6]. Also, cis-1,2-dichloroethene (DCE) concentrations decreased an average of 80% in the October 2009 event, but subsequently increased, as illustrated in Figure 2-6.

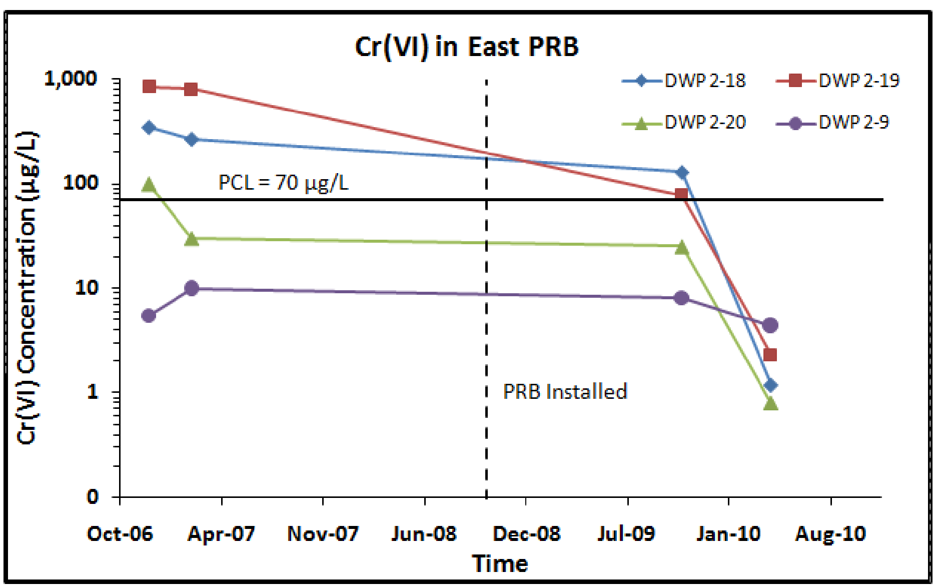


Figure 2-4. Hexavalent Chromium Reductions in East PRB, NWIRP Dallas

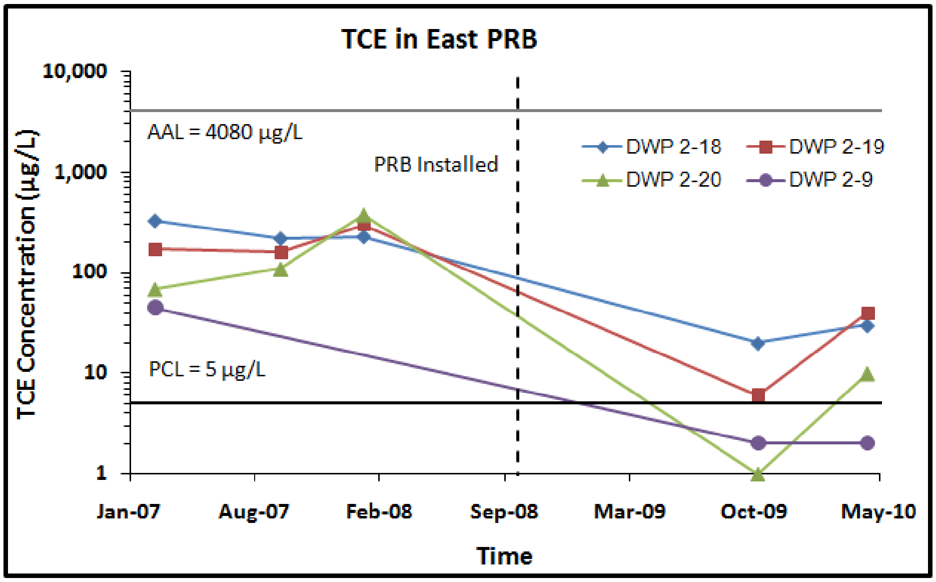


Figure 2-5. TCE Reductions in East PRB, NWIRP Dallas

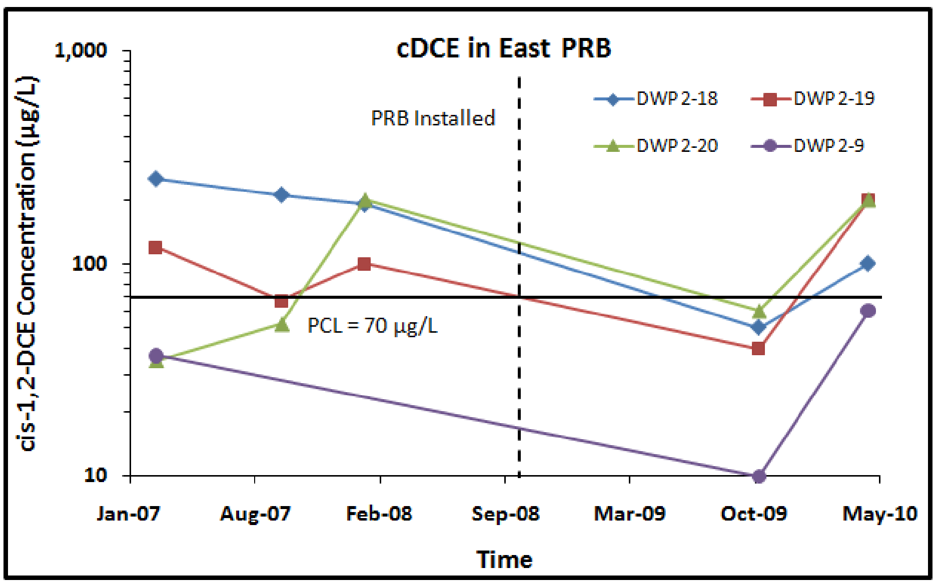


Figure 2-6. cDCE Reductions in East PRB, NWIRP Dallas

Data for selected groundwater geochemical parameters (e.g., dissolved oxygen [DO], pH, oxidation reduction potential [ORP]) were reviewed. Little difference was observed in pH and ORP comparing the six monitoring wells located downgradient of the PRBs to those located in other portions of the site. For example, all monitoring wells averaged a pH of 7, while ORP ranged from -153 mV to 113 mV. However, the six monitoring wells located downgradient of the PRBs showed reduced DO concentrations (average of 2 mg/L in the East PRB and 6 mg/L in the West PRB) compared to background wells (average of 9 mg/L). Data for iron, sulfate, and nitrate were not available. Based on only moderate reduction of TCE and DCE, little change in pH and ORP, and only minor reductions in DO, it appears that strongly reducing conditions were not achieved or maintained in groundwater downgradient of the ZVI PRB.

2.7 Cost

Installation costs of the PRBs installed at NWIRP Dallas are listed in Table 2-1. The costs do not include design, construction oversight, and reporting. The high cost to mobilize and demobilize the specialty one-pass trencher was compensated by the short construction time (less than two weeks). Therefore, the “installation/material” line item consists of only minimal labor and the cost to procure and transport the materials of iron (630 tons) and sand (1,239 tons). Transportation and disposal of soil and liquid wastes contributed a significant percentage (12%) of the overall installation cost because soils were excavated from the PRB wall in order to place the sand and iron.

Table 2-1. Installation Cost of NWIRP Dallas PRBs

Category	Unit Price	Quantity	Unit	Cost	Percent of Total Cost
Construction submittals and bond	$ 38,935	1	LS	$ 38,935	4%
Mobilization/demobilization	$ 161,760	1	LS	$ 161,760	16%
Installation/materials	$ 524,827	1	LS	$ 524,827	52%
Disposal	$ 124,360	1	LS	$ 124,360	12%
Site work/restoration	$ 151,970	1	LS	$ 151,970	15%
Total cost				**$ 1,002,000**	**100%**

LS – Lump Sum

2.8 Sustainability

The impacts of the PRB installation at NWIRP Dallas were calculated using SiteWise™ based on the following activities: material production (“Consumables”), equipment and material transportation (“Transportation—Equipment”), workers commuting to the site (“Transportation—Personnel”), PRB construction activities (“Equipment Use and Misc.”), and waste disposal (“Residual Handling”). Site-specific input assumptions are included in Appendix B. Table 2-2 and Figure 2-7 illustrate the calculated impact of the different remedial activities.

Table 2-2. Relative Impact of Materials and Construction for NWIRP Dallas

	GHG Emissions	Energy Consumption	NO_X Emissions	SO_X Emissions	PM_{10} Emissions
Materials[1]	97%	95%	80%	79%	80%
Construction[2]	3%	5%	20%	21%	20%

[1]Includes material production and transportation.
[2]Includes equipment use, personnel transportation, and residual handling.

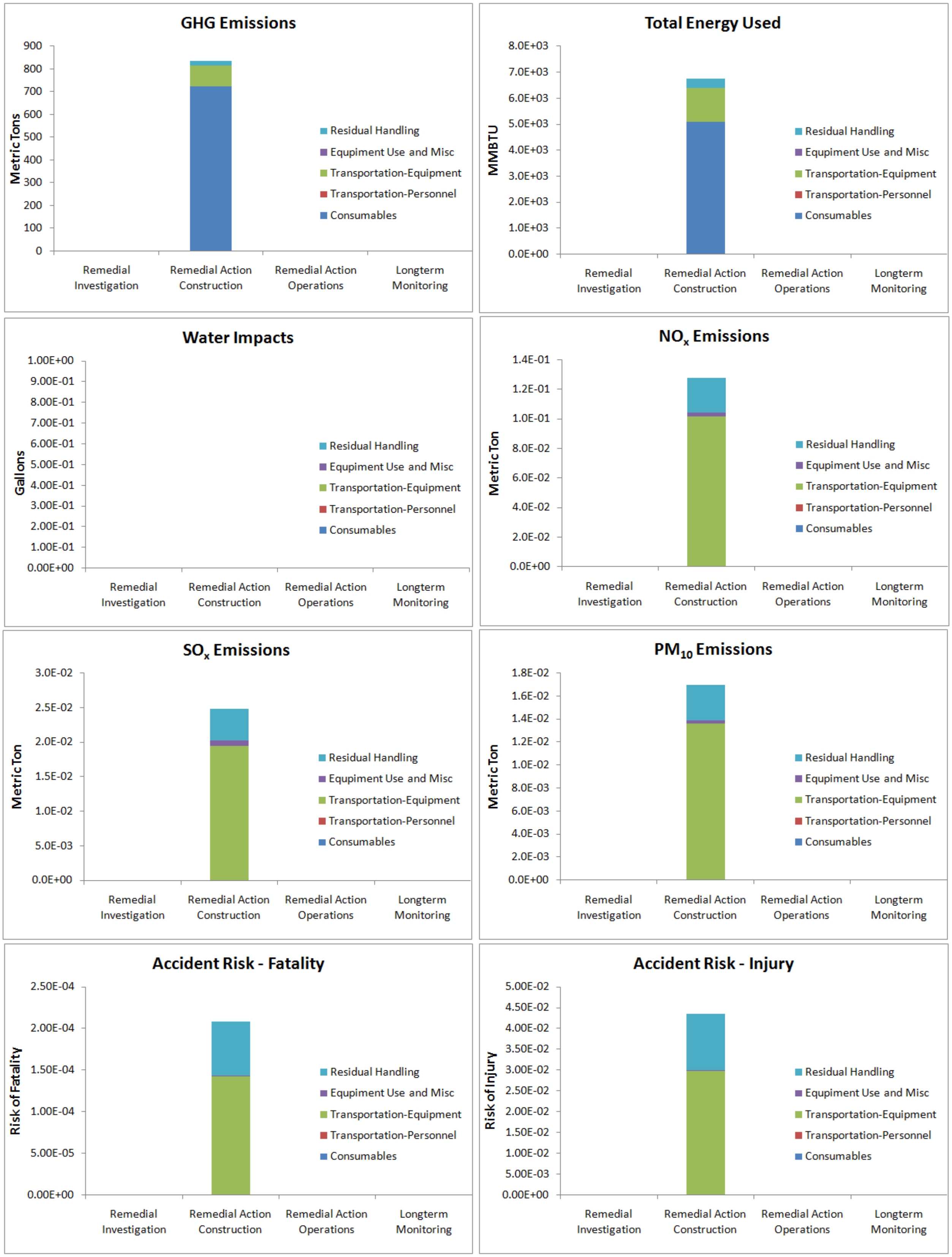


Figure 2-7. Sustainability Metrics for ZVI PRB Installation at NWIRP Dallas

For the PRBs constructed at NWIRP Dallas, the following observations were made:

- Combined, material production and transportation ("Consumables" and "Transportation—Equipment") dominated the remedy footprint for all of the sustainability metrics. Together, the production and transportation of the ZVI and sand materials constituted more than 95% of both the carbon footprint as total GHG emissions and energy consumption.
- The construction of the PRBs, completed within six working days, and waste disposal were responsible for less than 5% of the carbon footprint and energy consumption due to the short time that remedial activities occurred on site. However, these activities were responsible for approximately 20% of the release of criteria air pollutants (NOx, SOx, and PM) due to the volume of wastes transported from the site.
- The transportation of the material used for the PRB construction led to higher emissions of criteria air pollutants than all of the other site activities.
- There are no water impacts associated with this remedy since this remedy does not involve significant use of water resources at or near the site.
- Transportation of materials and waste contributed to the accident risk metrics.

The total carbon footprint for the PRB installation was determined to be 834 metric tons of CO_2e, the majority of which (about 95%) is associated with the production and transportation of the ZVI and sand materials. The footprint for operating and monitoring activities associated with a ZVI PRB is estimated at zero because no replenishment of the ZVI is anticipated. The footprint for routine annual groundwater monitoring was not included, assuming this activity will be similar for all sites.

2.9 Site Discussion

Based on the data provided, the ZVI PRB is providing adequate reduction of chromium, hexavalent chromium, and chlorinated solvents to meet the site-specific remedial goals. To fully evaluate hydraulic and contaminant reduction performance, additional groundwater monitoring wells would need to be installed upgradient, cross-gradient, and within the PRBs. This would provide data on groundwater flow patterns through the wall, along with contaminant reductions and changes in pH and ORP within the PRB.

Regarding the performance metric of sustainability, the production and transportation of the ZVI, followed by the transportation of waste soils were the activities most impacting the sustainability of the remedy. Together, the production and transportation of the ZVI and sand materials constituted more than 95% of both the carbon footprint and energy consumption and approximately 80% of the release of priority pollutants. The transportation of waste soils accounted for the majority of the remaining 20% of priority pollutant release. These activities were offset, at least in part, by the short duration of PRB installation (6 days) and negligible PRB maintenance over time.

3.0 HUNTERS POINT NAVAL SHIPYARD

3.1 Introduction

HPNS is a 936-acre site located in San Francisco, California, situated on a long promontory extending eastward into San Francisco Bay (Figure 3-1). The site was divided into six parcels, A through G, to facilitate environmental investigation and cleanup activities. HPNS operated as a Naval shipyard from approximately 1940 to 1974, a private shipyard from 1976 to 1986, followed by Navy ownership and subsequent subleases for commercial activities through the present. Because past shipyard operations left hazardous materials onsite, HPNS property was placed on the National Priorities List in 1989 as a Superfund Amendments and Reauthorization Act site pursuant to the Comprehensive Environmental Response, Compensation and Liability Act. In 1991, HPNS was designated for closure pursuant to the Defense Base Closure and Realignment Act of 1990.

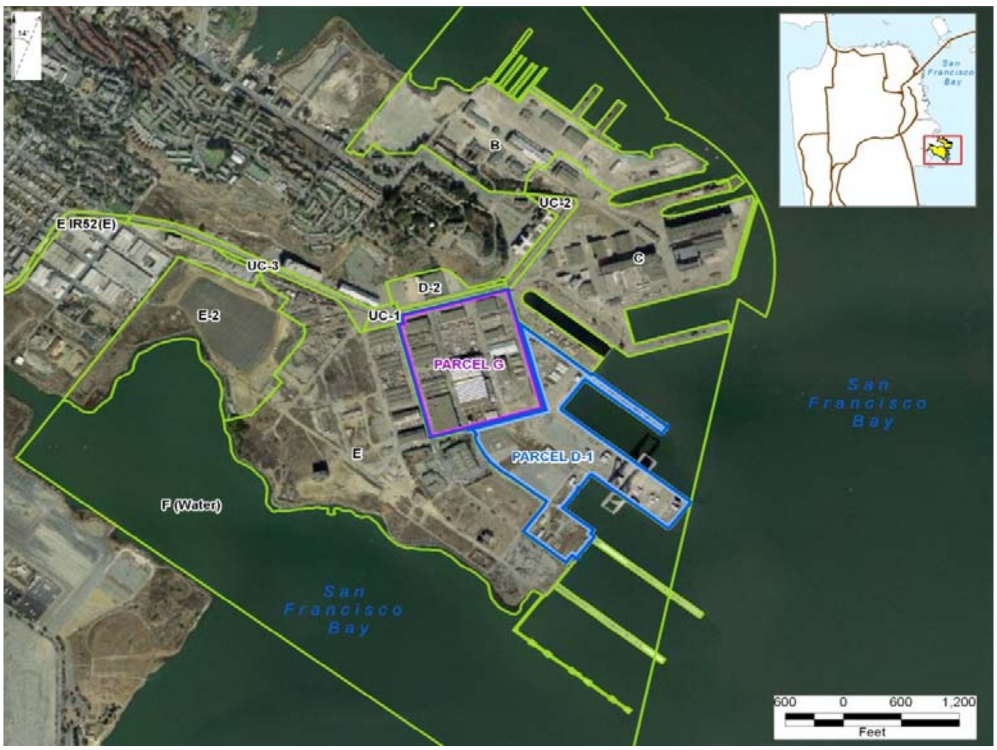


Figure 3-1. Location of Former Hunters Point Naval Shipyard, San Francisco, CA

3.2 Geology and Hydrogeology

Two aquifers and one water-bearing zone have been identified at HPNS: the A aquifer, the B aquifer, and the bedrock water-bearing zone. Groundwater flow patterns are complex due to heterogeneous hydraulic properties of the fill materials and weathered bedrock, tidal influences, effects of storm drains and sanitary sewers, and variations in topography and drainage. Hydrogeology for Parcels D and G is characterized by an uneven surface of the Bay Mud formation overlain predominantly by artificial fill material of variable hydraulic conductivity. The A aquifer is unconfined and directly overlies the Bay Mud formation. The A aquifer consists mostly of sandy gravel and gravelly sand, with limited zones of low permeability sandy clay. Significant portions of the A aquifer are also made up of less permeable fill and Bay Mud clayey sands. The A aquifer typically ranges from 10 to 40 ft thick, with an average thickness of approximately 25 ft. Groundwater flow is generally to the southeast towards San Francisco Bay [7].

3.3 Contaminant Distribution

The focus of this remedial action occurred within IR-71, located within portions of Parcels G and D-1. During baseline characterization in 2008, it was determined that chloroform exceeded its remedial goal of 1.2 µg/L. It was agreed to target active remediation in areas where chloroform groundwater and soil vapor concentrations exceeded 10 times their remedial goals. The estimated groundwater-impacted area was over 45,000 square ft [7].

3.4 PRB Installation

Seven PRBs were constructed in a general east-west direction roughly perpendicular to groundwater flow (primarily southwest) within Parcels G and D-1. Each PRB averaged 190 ft in length, totaling 1,335 linear feet. Each PRB was located approximately 50 ft from the next PRB (see Figure 3-2), allowing groundwater to be treated within a three-year period based on an average groundwater flow velocity of approximately 16.2 feet per year [7].

The ZVI mass injection design was based on the prior groundwater treatability studies performed at HPNS Parcels B and C in 2002-2003 and discussed in a previous cost and performance report [12]. These studies used a range of 0.003 to 0.005 pounds of ZVI per pound of soil. The injection points were to be spaced approximately 10 feet apart assuming a 7.5-foot injection radius based on the coarse-grained lithology of IR-71. In-field monitoring determined a radius of influence (ROI) greater than 12 ft, so some borings were spaced 20 feet apart with increased volume of ZVI injected to maintain the desired design iron-to-soil mass ratio of 0.004. A total of 93 distinct injection points was completed. Approximately 3.3 million cubic feet of compressed nitrogen was used to emplace over 45 tons of granular ZVI and 23 tons of micro-scale ZVI [7].

The depth of each PRB varied, depending on the depth of the confining Bay Mud formation, which ranged from 12 ft bgs to greater than 35 ft bgs. Between the Bay Mud confining layer and the groundwater surface, ZVI was injected into vertical intervals spaced approximately 3 ft apart, with up to seven injection intervals within each borehole to span between the depths of 7 and 35 ft bgs. The average injection depth was 21 feet.

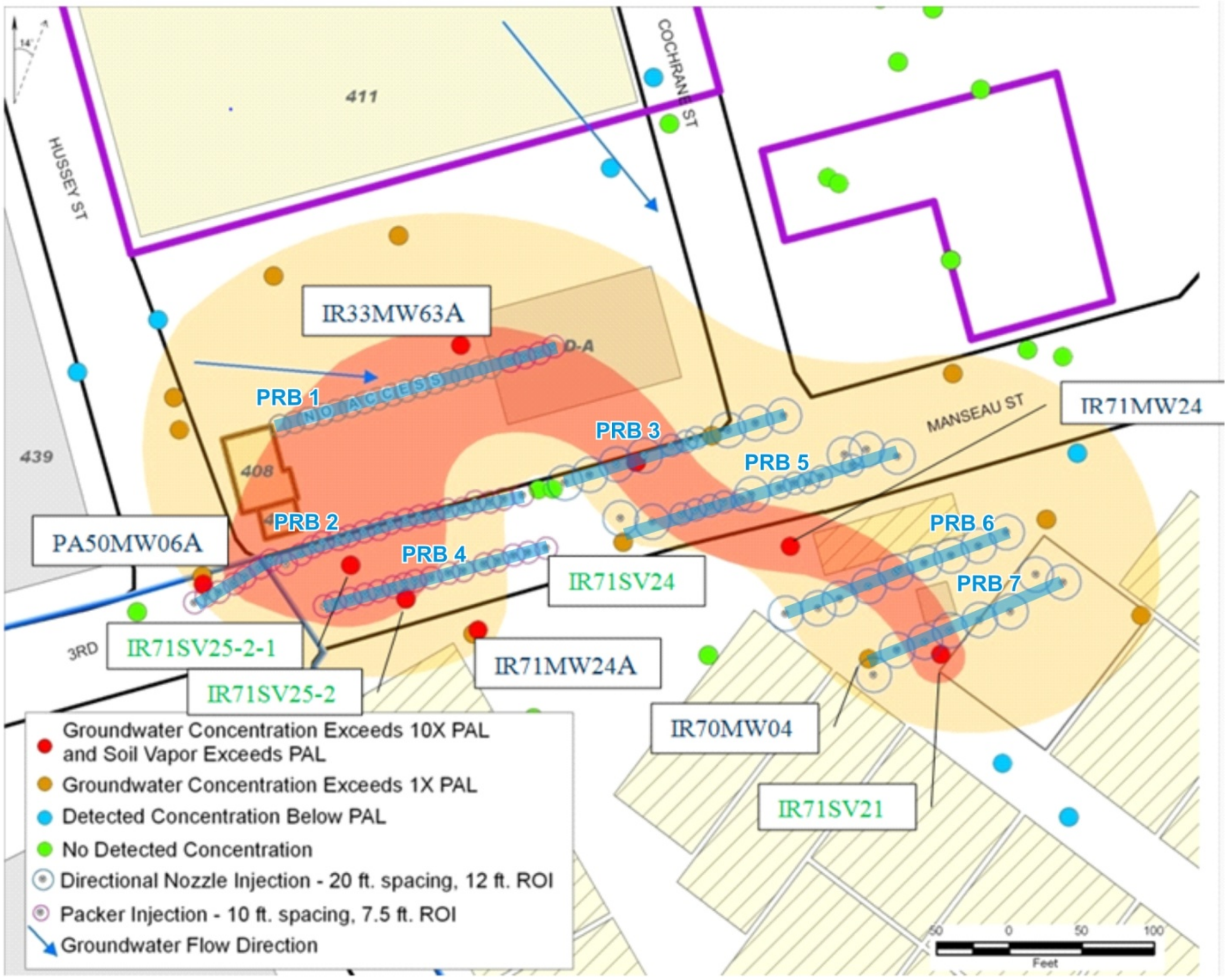


Figure 3-2. Layout of the Seven ZVI Injection Barriers within IR-71 Superimposed on Pre-Injection Chloroform Groundwater Plume, Hunters Point Naval Shipyard, CA

PRB installation consisted of two crews working concurrently to meet a tight project schedule: Pneumatic Fracturing, Inc. (PFI) worked at the site between October 23 and December 22, 2008; ARS Technologies, Inc. (ARS) was active at the site from November 10 through December 18, 2008. The two crews used slightly different injection approaches, as described below. Figure 3-3 depicts the site setup for one of these crews.

Figure 3-3. PFI Pneumatic Injection Equipment Layout

PFI injected 45 tons of granular ZVI (cast iron aggregate Size 14D), which combined coarse ZVI for longevity and finer ZVI for higher reactivity, purchased from Peerless Metal Powders & Abrasives of Detroit, Michigan. Injection points were installed via one of two methods: direct push or sonic drilling. PFI utilized a 90 degree directional injection nozzle for ZVI distribution within the PRBs. The formation was initially fractured or fluidized using nitrogen gas, which temporarily suspends or fluidizes the zone of injection. Once this pathway was established, the ZVI was injected “dry” using the nitrogen as the carrier. The nozzle was then rotated to the next direction and the process was repeated until the ZVI was distributed 360 degrees. The nozzle was retracted to the next target depth, generally 3 ft, and the process resumed until all target depths were completed to the groundwater/vadose interface.

PFI injections utilized a total of 2.7 million cubic feet of compressed nitrogen gas for four PRB barriers. In general, initial nitrogen pressures ranged between 105 and 280 pounds per square inch (psi) for an average of 20 seconds. Actual initiation pressures ranged between 50 and 236 psi, depending on the PRB location and depth. The maintenance pressures ranged between 80 and 155 psi with the injection pressures ranging between 30 and 100 psi, depending on the volume of nitrogen remaining in the tube trailer. Total injection times ranged between 1 and 8 minutes. The average flow rate of nitrogen gas ranged from 680 cubic feet per minute (cfm) to 820 cfm during injection, and from 6,730 cfm to 9,070 cfm during initiation, indicating the permeable natures of the soils.

ARS injected 23 tons of micro-scale ZVI consisting of a 60/40 blend of a fine cast iron (Peerless 50DSP4) and specialty high-carbon atomized iron (Hepure HC-15) to form three PRB barriers. The ZVI was mixed aboveground with water in a mobile mixing/injection plant to form a slurry (see Figure 3-4). The injection involved bulk nitrogen gas as a carrier fluid for the ZVI slurry which was pumped into the gas stream. Injections were completed via a proprietary nozzle and high-pressure packer assembly designed to maximize the distribution of the ZVI slurry throughout the treatment zone.

Figure 3-4. ARS Pneumatic Injection Mixing Equipment

The nitrogen pneumatic fracturing initiation pressures ranged from 95 to 225 psi, and the maintenance pressures ranged from 70 to 160 psi. Slurry injection pressure ranged from 12 to 113 psi and the flow rate from 30 to 60 gallons per minute (gpm) [7].

3.5 Performance Evaluation Approach

ARS measured the quantity of ZVI in pounds injected per interval using load-cells on the mixing/injection plant on a per-batch basis. The quantity of water used per batch was also measured in pounds. PFI verified the volume of ZVI injected by monitoring the decreasing weight registered by a platform scale supporting the vessels housing the ZVI. The injection was terminated when the required volume of ZVI was attained.

Performance monitoring during pneumatic injection was conducted with two objectives: (1) confirm nitrogen influence and (2) confirm injected ZVI radius. Typically, the ROI for each is substantially different, where the gas travels farther than that of the injected media. These objectives were accomplished via:

1) Measuring pressure influence at surrounding monitoring wells, both using gauges at the surface and downhole pressure transducers;
2) Conducting surface monitoring near the active injection well to record surface deflection from fracturing and injection activities, using:
   a. Heave rods and transits
   b. Biaxial tiltmeter monitoring;
3) Individually capturing each injection by a pressure-time history curve indicating initiation pressures, backpressure (if any), maintenance pressures, and injection pressures. All measurements pertaining to fracture initiation and maintenance pressures were collected and logged utilizing pressure transducers.
4) Observing at nearby monitoring wells or injection points looking for evidence of nitrogen off-gassing or ZVI accumulation.

Figure 3-2 illustrates the existing groundwater monitoring wells (names in blue text) and soil vapor monitoring wells (names in green text) used to monitor compliance with remedial goals. A groundwater remedial goal of 1.2 µg/L was established for chloroform. Soil vapor sampling was implemented to evaluate performance and reduce indoor air hazards with a chloroform project action limit of 704 micrograms per cubic meter (µg/m^3).

3.6 Technology Performance Results

The challenges encountered at the site were primarily drilling related, such as presence of cobbles, boulders and even wood debris in the upper 10 to 15 ft in IR-71. The fill layer was very loose in places and included voids, especially at depths of approximately 4 to 5 ft bgs, likely as a result of material consolidation or settlement. The presence of the voids may have impacted the effective ROI of the ZVI placement at shallow depths due to potential short-circuiting.

The seven injection points monitored using biaxial tiltmeters exhibited a consistent minimum radius of ZVI injection of 10 to 15 ft with a maximum radius of 20 ft or greater at deeper depths. Downhole monitoring in nearby monitoring wells using pressure transducers was conducted during injection activities at 10 injection points. This evaluation confirmed that all monitoring locations were influenced by injection activities in direct response to the initiation of the injection event. The results of this biaxial tiltmeter monitoring concluded the effective ROI was larger than the conservative 7.5 ft estimated during design. This allowed the in-field injection locations to be increased from 10 to 20 feet simply by removing every other injection point within the injection rows. The total ZVI injected per point was doubled to account for the larger volume needed, which was more than sufficient to achieve the minimum ZVI to soil injection ratio. Together, these changes provided sufficient overlap to produce a continuous injection barrier between the injection points [7].

The injected ZVI treated an estimated soil volume totaling 13,500 yd^3. The average mass of ZVI applied was 10.1 lb/yd^3 (an iron-to-soil mass ratio of 0.004 lb/lb), which met the design criteria [7].

After PRB injection, groundwater and soil vapor concentrations were monitored at approximately 2-, 6-, and 12-week intervals. Chloroform decreased within weeks to below remediation goals in both groundwater and soil vapor (see Figures 3-5 and 3-6). Within two weeks, chloroform concentrations had decreased between 57% and 97%. Within 12 weeks, all monitoring wells had decreased to greater than 99% pre-injection chloroform concentrations and below the site remedial goals. One exception was noted in soil vapor monitoring well IR71SV25-2-1, where chloroform concentrations increased from 420 µg/m^3 to 940 µg/m^3 after injection, above the soil vapor risk screening criterion of 704 µg/m^3. However, chloroform concentrations gradually decreased (800 µg/m^3 at Week 6 and 630 µg/m^3 at Week 12) [7]. This observation suggests that soil vapors initially increased due to ZVI injection activities pushing contaminated vapors away from the injection point.

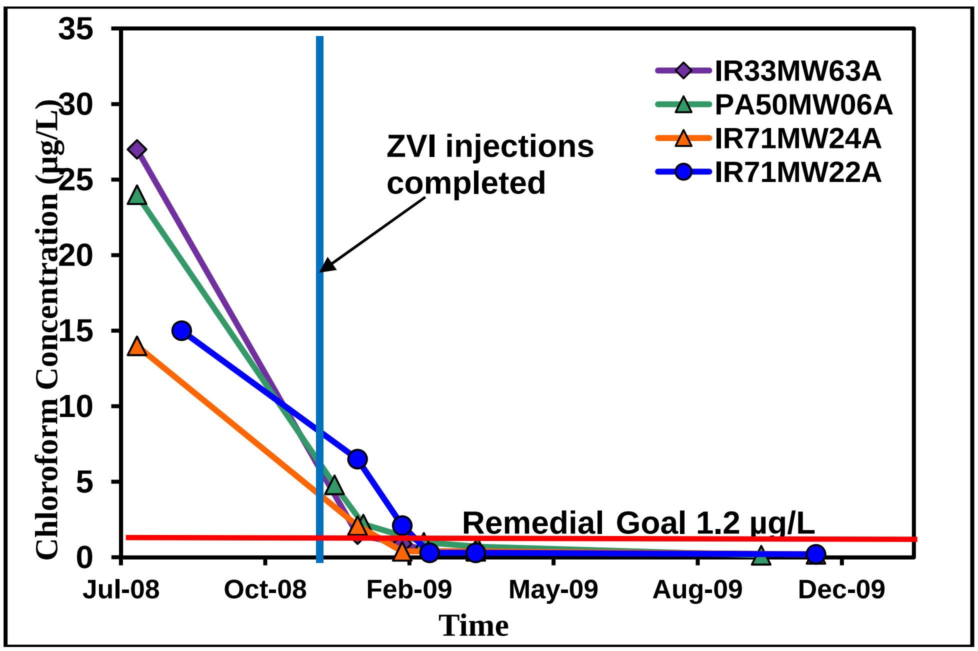


Figure 3-5. Groundwater Concentration Reductions at Hunters Point Naval Shipyard IR-71

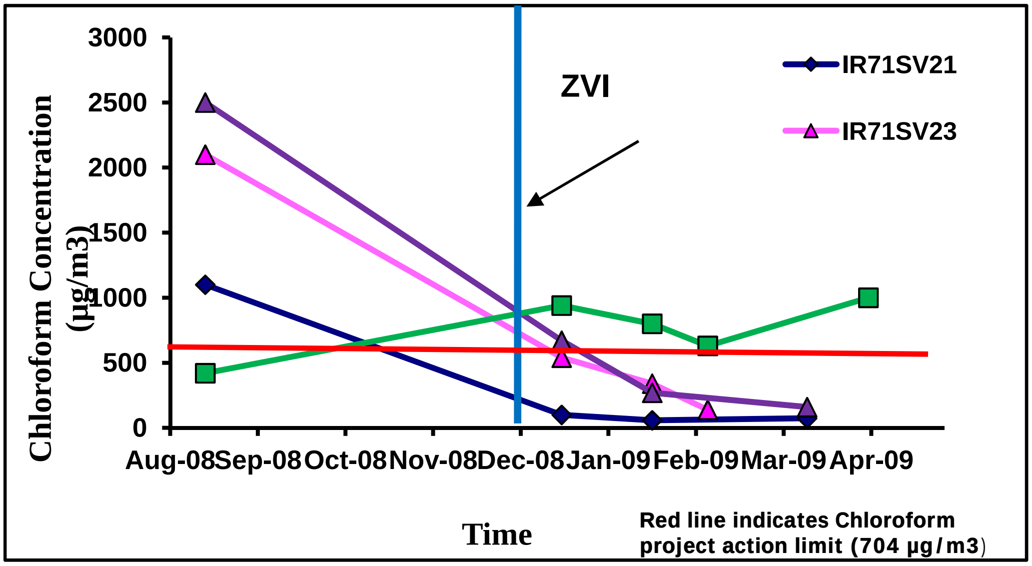


Figure 3-6. Soil Vapor Reductions at Hunters Point Naval Shipyard IR-71

Changes in groundwater geochemistry were also observed in post-injection groundwater samples collected within the projected ROI. Based on the maximum values observed in each treatment area, the ZVI ROIs likely ranged from 10 to 15 feet, confirming the results of the tiltmeter monitoring discussed earlier. Geochemical changes were assessed in multiple site wells, including IR71MW27A, located 3 feet from an injection point, and IR71MW32A, located approximately 15 feet from the injection point. Each well showed declines in ORP and DO levels and increases in pH after ZVI injection, which indicates that ZVI reactions occurred near the wells. In contrast, wells outside the projected ZVI ROIs showed relatively similar pre- and post-injection geochemical conditions. This is summarized in Table 3-1, where post-injection ORP levels in wells within the ROI were between -334 to +60 mV, which is lower than the -119 to +209 mV range before injection or the -1.4 to +242 mV range for wells outside the ROI [7].

Table 3-1. Comparison of Geochemical Parameters Pre- and Post-ZVI Injection

Interval	Dissolved Oxygen (mg/L)	pH	ORP (mV)
Pre-PRB Injection	0.16 to 6.10	6.15 to 8.53	-119.1 to 209.4
Post PRB Injection (outside ROI)	0.08 to 9.49	6.75 to 8.67	-1.4 to 242.3
Post PRB Injection (within ROI)	0.21 to 0.89	6.58 to 8.96	-334.4 to 60.2

Groundwater monitoring also included analysis for a variety of metals to assess the potential for the reducing environment created by the ZVI injections to increase dissolved metals concentrations, especially for metals such as arsenic, iron, and manganese. These metals tend to become more soluble under reducing conditions. Wells monitored within the projected ZVI ROIs (IR71MW27A and IR71MW32A) did show increases in arsenic (from a pre-injection maximum concentration of 5.9 µg/L to the post-injection maximum concentration of 15 µg/L), manganese (from a pre-injection maximum concentration of 8.9 µg/L to a post-injection maximum concentration of 150 µg/L), and dissolved iron (from of 190 to 1,200 µg/L). None of these metals exceeded the groundwater screening criteria for San Francisco Bay protection or for construction worker health and safety [7].

Subsequent long-term monitoring has not seen sustained changes in groundwater geochemistry. No measurable change was detected in DO, pH, or ORP parameters, comparing before and after ZVI injection and measured during semiannual monitoring events. Table 3-2 provides the measurement results for monitoring well IR70MW04A, located within 15 feet of the southern PRB, for which sufficient data (at least three measurements each) were available to compare the average long-term pre- and post-ZVI injection concentrations of chloroform and geochemical parameters.

Table 3-2. Long-term Comparison of Average Chloroform Concentrations and Geochemical Parameters Pre- and Post-ZVI Injection in IR70MW04A

Time Period	Avg. Chloroform Concentration (µg/L)	Avg. Dissolved Oxygen (mg/L)	Avg. pH	Avg. ORP (mV)
Pre-PRB (2007-2008)	7.2	0.5	7.5	-120
Post PRB (2009-2010)	0.1	0.6	7.4	-146
Percent Reduction	99%	-20%	1%	22%

3.7 Cost

Costs for development of a remedial action work plan, design, implementation including oversight and meetings, and reporting are summarized in Table 3-3. The costs for just the installation, excluding the design/planning and reporting activities, was approximately $1,880,000.

Table 3-3. Project Costs for ZVI Injection at IR-71, Parcel G, Hunters Point Naval Shipyard, CA

Category	Unit Price	Estimated Quantity	Unit	Cost	Percent of Total Cost
Design/Planning	$ 303,000	1	LS	$ 303,000	13%
Mobilization	$ 24,000	1	LS	$ 24,000	1%
Injection	$ 14,622	119	points	$ 1,740,000	72%
Verification Monitoring	$ 917	12	points	$ 11,000	0%
Other—Royalties Construction		12	%	$ 96,000	4%
Reporting	$ 240,000	1	LS	$ 240,000	10%
Total Cost				**$ 2,414,000**	**100%**

LS- Lump Sum

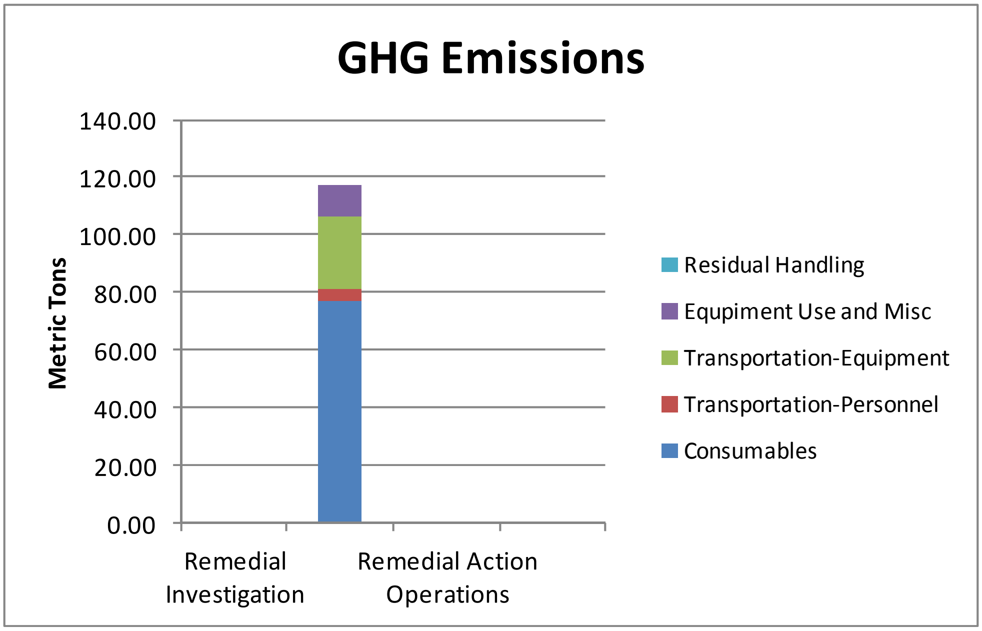
3.8 Sustainability

Assumptions made during the sustainability analysis include:

1) The amount of energy required to generate the nitrogen gas is 86 million metric British Thermal Units (MMBTUs). This energy is equivalent to that required to compress 2.7 million cubic feet of nitrogen in a 70 horsepower pressure swing adsorption unit running for 60 days (8 hours every day).
2) Injected ZVI will effectively reduce the low concentrations of residual chloroform for up to 20 years.

The validity of the second assumption can be verified through continued monitoring over time.

The carbon footprint for the installation of the PRBs at HPNS was determined to be 117 metric tons CO_2e. Similar to NWIRP Dallas, consumables (ZVI and nitrogen) production and transportation are the largest contributors to the carbon and energy footprints (Figure 3-7), which together accounted for more than 85% of the CO_2e footprint and 70% of the energy consumption (Table 3-4). HPNS exceeds NWIRP Dallas in only two metrics, water and accident risk (fatalities). No water was used at NWIRP Dallas during injection activities; however at HPNS, the pneumatic fracturing processes included one that used a water slurry. Longer time on site at HPNS (several months versus one week at NWIRP Dallas) also contributed to energy consumption, water consumption, generation of criteria pollutants, and accident risk during construction activities. For example, construction activities were responsible for almost 40% of the smog producing NOx emissions. On the other hand, the direct push drilling eliminated generation of soil residuals.



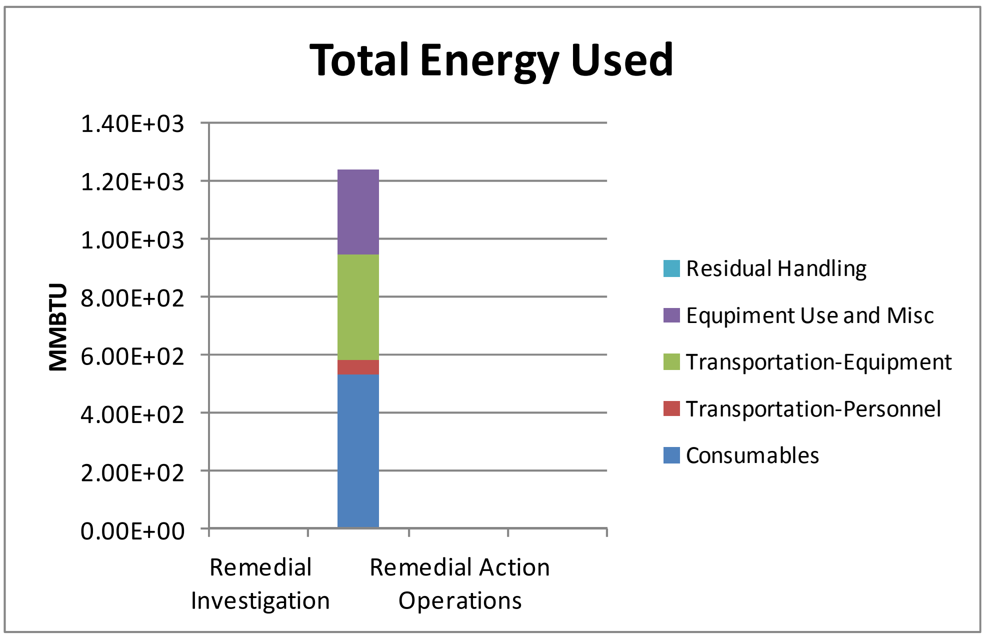
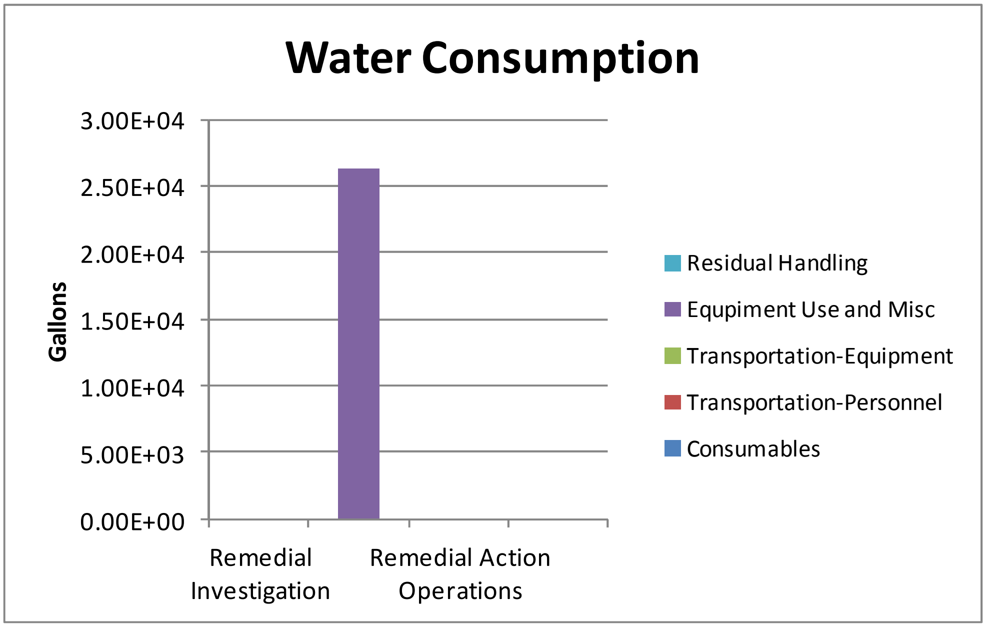


Figure 3-7. Sustainability Metrics for ZVI PRB Pneumatic Injection at HPNS



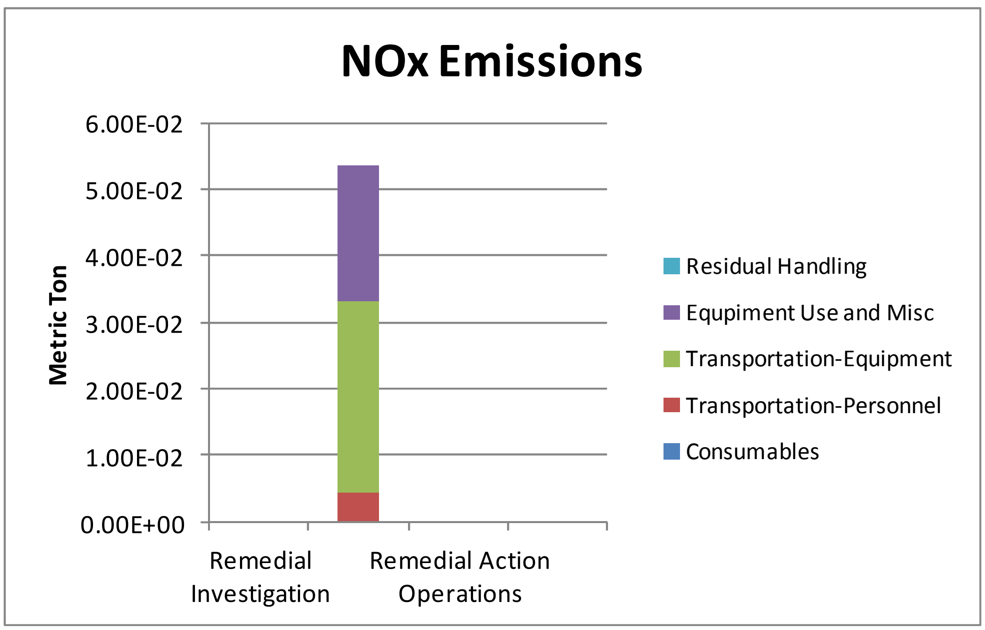
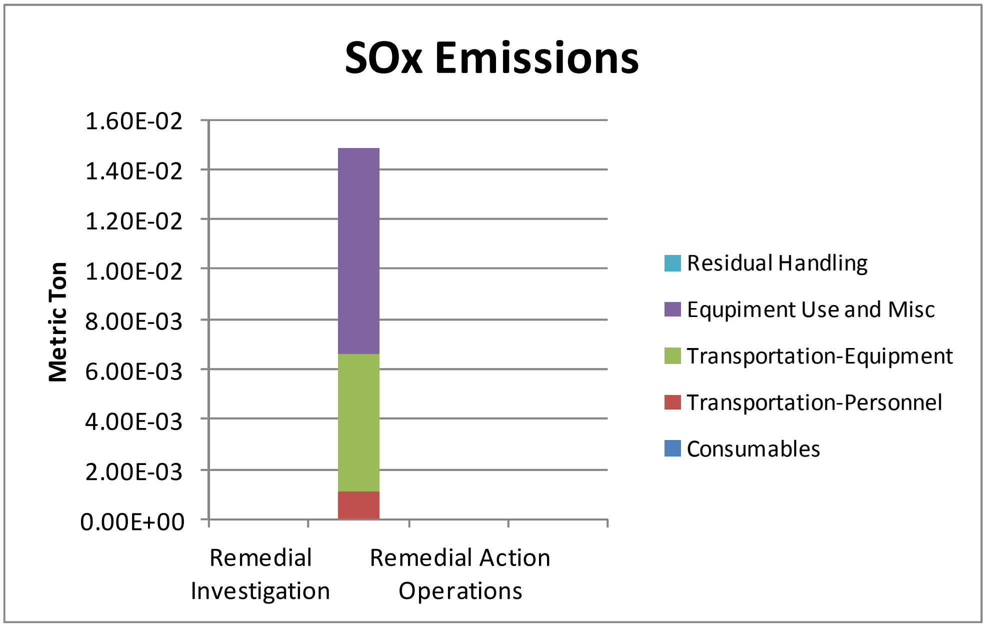


Figure 3-7. Sustainability Metrics for ZVI PRB Pneumatic Injection at HPNS (Continued)



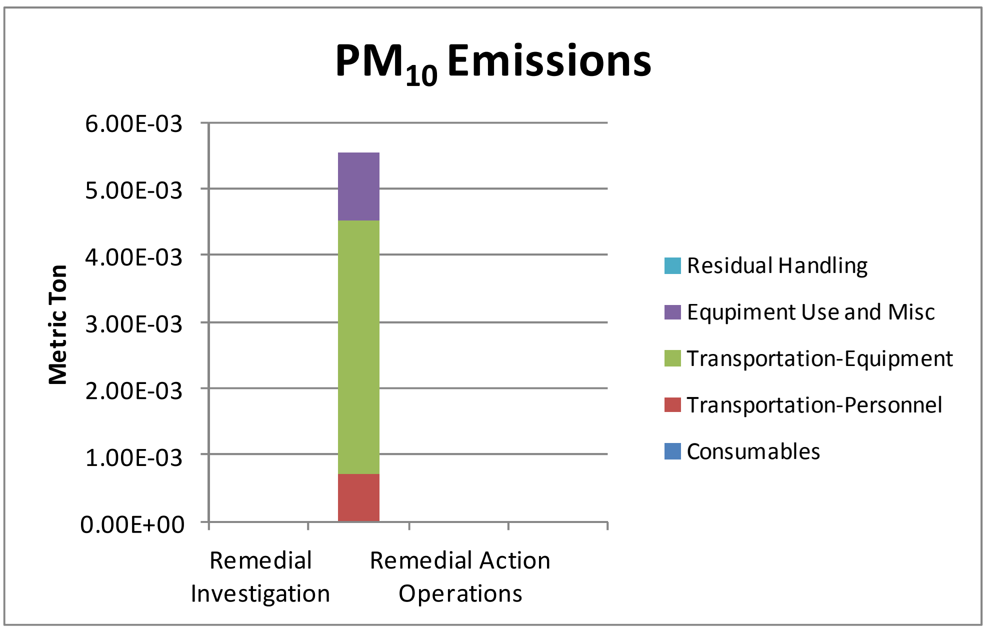
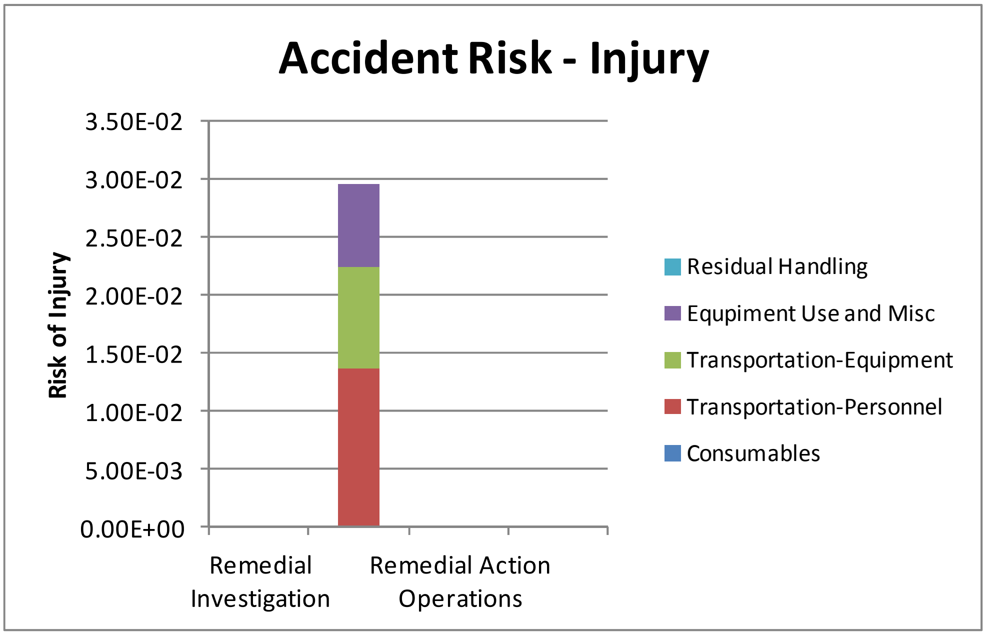


Figure 3-7. Sustainability Metrics for ZVI PRB Pneumatic Injection at HPNS (Continued)



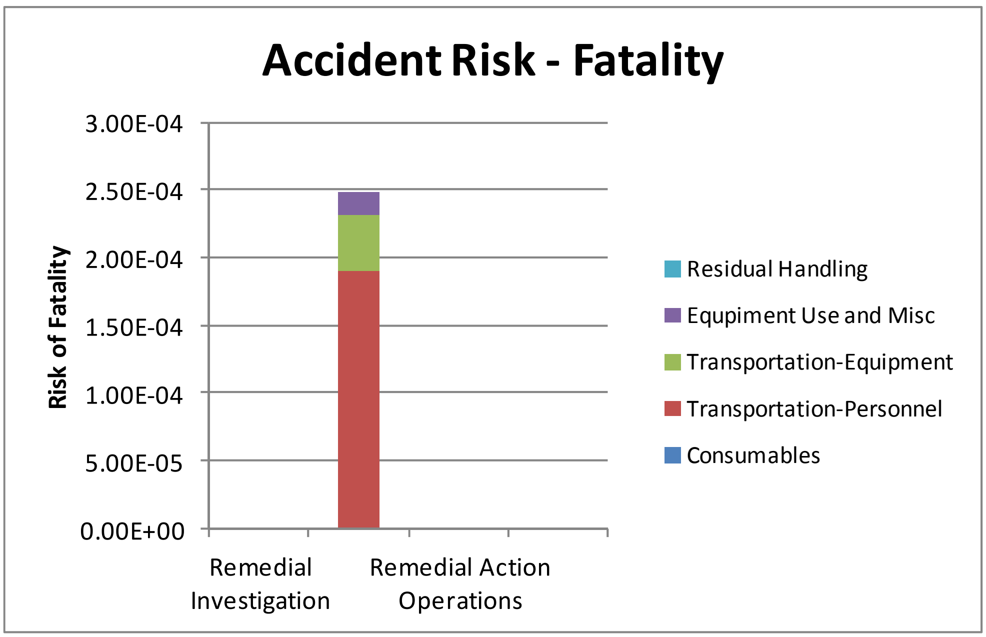


Figure 3-7. Sustainability Metrics for ZVI PRB Pneumatic Injection at HPNS (Continued)

Table 3-4. Relative Impact of Materials and Construction for Hunters Point Naval Shipyard

	GHG Emissions	Energy Consumption	NO_X Emissions	SO_X Emissions	PM_{10} Emissions
Materials[1]	87%	73%	53%	37%	69%
Construction[2]	13%	27%	47%	63%	31%

[1]Includes material production and transportation.
[2]Includes equipment use, personnel transportation, and residual handling.

3.9 Discussion

The pneumatic fracturing and ZVI injection at HPNS demonstrate an alternative injection technique compared to direct ZVI placement. Multiple barriers provided groundwater treatment throughout the plume. The application showed significant (>99%), rapid (<12 weeks), and sustained reductions in chloroform concentrations within a dilute plume. After two years of operation, it continues to achieve the desired reductions in chlorinated solvent concentrations.

This full-scale application also demonstrated the use of multiple monitoring techniques to estimate the effective ROI during injection, consisting of (1) pressure readings using gauges on surrounding groundwater monitoring wells and monitoring the change in pressure during injection, (2) observations at nearby monitoring wells or injection points looking for evidence of nitrogen off-gassing or ZVI accumulation, (3) downhole pressure transducer readings using nearby groundwater monitoring wells, (4) tiltmeter readings to record surface deflection from fracturing and injection activities, and (5) measurements of ground surface deformation (surface heave). It was noted that measurement of surface heave using heave rods was labor intensive and not particularly accurate. The biaxial tiltmeter equipment provided a more accurate record of surface deformation and ROI than surface heave measurements.

The application highlighted the risk of pushing soil vapors during injection activities. This could be a concern if there are nearby occupied buildings. Fortunately for this site application, no occupied buildings were within the injection zone of influence, and soil vapors subsequently reduced below the soil vapor risk screening criterion.

The application also highlighted the risk of increasing dissolved metals concentrations resulting from groundwater reducing conditions. Concentrations of arsenic, manganese, and dissolved iron increased in selected monitoring wells located within the projected ZVI ROI. However, the metals remained below groundwater screening criteria.

A previous cost and performance report evaluating a ZVI pneumatic injection pilot-scale demonstration at HPNS Parcel C Site RU-C4 in 2002-2003 recommended injecting at least enough ZVI mass to achieve an iron-to-soil ratio of 0.004 and an ORP below -400 mV indicative of strongly reducing conditions. The report noted that injection of excess iron might be required to achieve this design ratio, considering subsurface heterogeneities and potential migration of iron outside the target region [12]. A recent review of HPNS data from this site indicates sustained reductions of TCE through 2010 in site wells downgradient of the 2002-2003 ZVI injection. These monitoring wells continue to maintain an ORP in the neighborhood of -150 mV. Therefore, targeting an iron-to-soil mass ratio of 0.004 may not produce optimum groundwater reducing conditions, but it will likely be sufficient to produce sustained degradation of chlorinated solvents using ZVI.

In the 2008 groundwater treatability study at HPNS Parcels G and D-1, the subject of this evaluation, a design ratio of 0.004 was again targeted. ORP concentrations ranged between 60 to-334 mV. While this may suggest insufficient iron to produce the strongly reducing conditions recommended in the 2005 Cost and Performance Report [12], the iron injected was sufficient to reduce chloroform concentrations throughout the plume.

Consumables (ZVI and nitrogen) production and transportation were the largest contributors to the carbon and energy footprints, which together accounted for more than 85% of the carbon footprint as total GHG emissions and 70% of the energy consumption. The pneumatic fracturing processes and extended time on site (several months versus one week) also contributed to energy consumption, water consumption, generation of criteria pollutants, and accident risk during construction activities. On the other hand, the direct push drilling eliminated generation of soil residuals.

4.0 NWIRP MCGREGOR

4.1 Introduction

NWIRP McGregor is a former government-owned, contractor-operated facility that was in operation until 1995. The facility is located in McLennan County, with a small portion in Coryell County, Texas. The site consists of isolated industrial centers separated by large agricultural tracks of land used for farming and cattle grazing (Figure 4-1). In August 1994, NWIRP McGregor was determined to be "excess" to the mission of the Department of Defense and, as a result, the base underwent closure. At the time of its initial closure, NWIRP McGregor consisted of 9,700 acres of land. Through a series of transfers that began in 1999 and concluded in 2006, all of the facility was turned over to the city of McGregor for economic redevelopment [9].

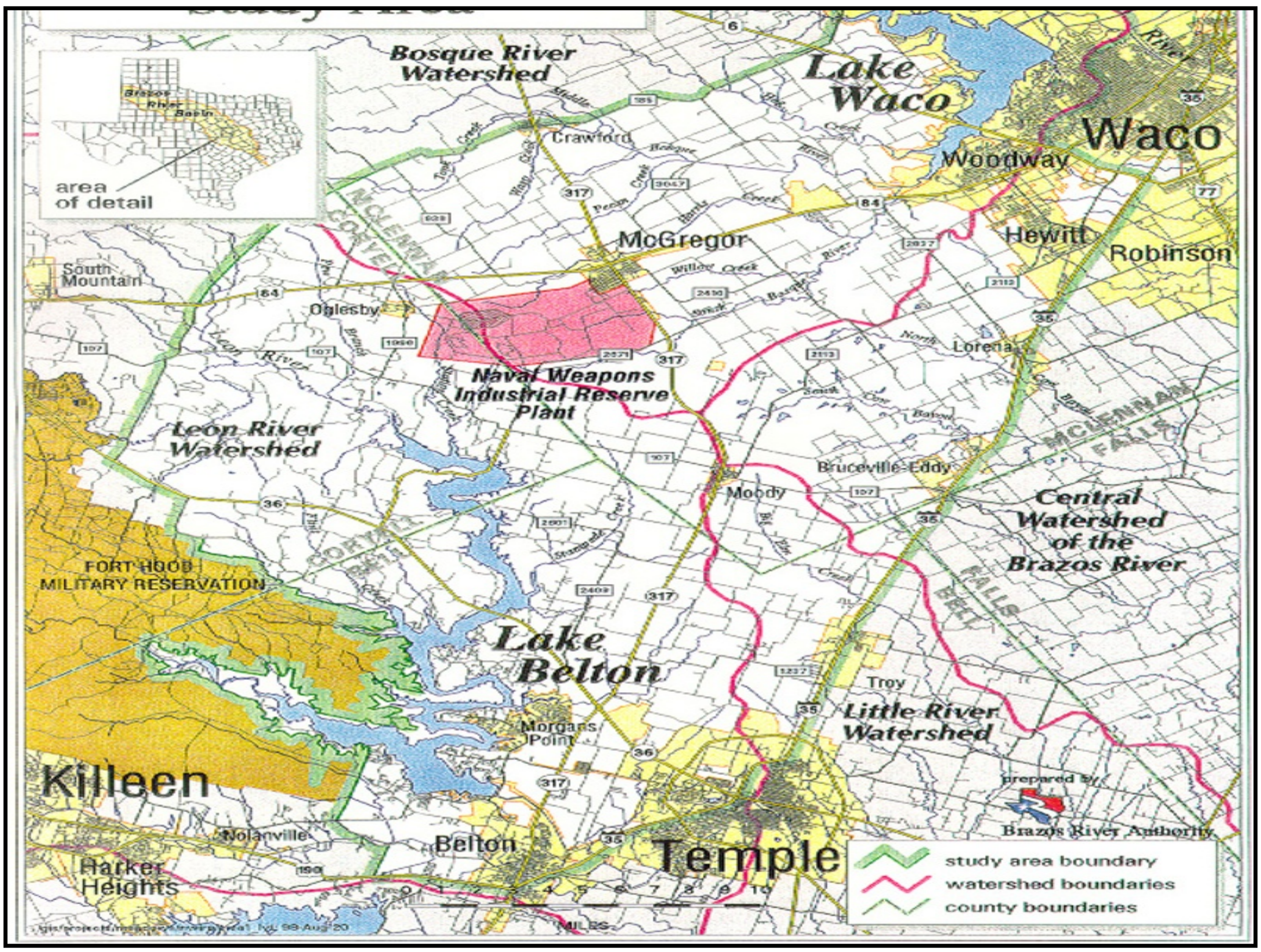


Figure 4-1. Site Location NWIRP McGregor, Texas

4.2 Contaminant Distribution

Site characterization activities at McGregor were undertaken from 1992 to 2005. Due to the past operations and activities performed to support the mission of the NWIRP, the groundwater at the facility has been contaminated with perchlorate, pesticides, SVOCs, and VOCs. The COCs in groundwater were identified as perchlorate and VOCs, specifically TCE and 1,2-DCE.

4.3 Geology/Hydrogeology

The subsurface at NWIRP McGregor mainly consists of water-bearing, weathered, and fractured limestone. Six feet of soil layer sits above the water-bearing limestone layer, which is almost 10 to 25 ft deep. The saturated zone is underlain by a confining shale layer. Groundwater is highly dependent on season and rainfall at the site. Over the course of a year the average groundwater velocity is 100 to 150 ft/year. Following wet periods, the groundwater velocity can increase significantly (3x) and will generally return to average conditions as the rainfall dissipates.

4.4 PRB Installation

Since 2002, 34 biowalls, often referred to as "biotrenches," have been installed in various areas of the NWIRP to reduce the source area, intercept off-site migration of COCs, and expedite the property cleanup (Figure 4-2). These 2.5 to 3 ft wide biowalls, totaling 10,162 linear feet, were constructed using a rock trencher (see Figure 4-3) and were anchored into the non-water bearing zone (10 to 30 ft bgs). The biowalls were backfilled using 40% recycled material (e.g., mushroom compost, three-quarter inch pine wood chips) soaked in soybean oil, and 60% gravel (e.g., 1-inch washed, crushed limestone aggregate). Two-inch diameter polyvinyl chloride (PVC) diffuser pipes were installed on the bottom of each trench to allow for future injections of carbon substrates as needed. The trenches were capped with a compacted clay layer to limit seeps and surface infiltration. Table 4-1 lists the biowalls installed at the site, their dimensions, and the media used for the wall construction.

Rows of bioborings, which comprise 12-inch diameter soil borings backfilled with the biowall media, were installed where biowall construction was difficult. The bioborings were typically drilled using an air rotary drill rig and were installed with 5-ft spacing (10-ft centers) within three offset rows spaced 100-ft apart. Since 2002, 1,077 bioborings have been installed.

4.5 Performance Evaluation Approach

Groundwater monitoring is conducted in monitoring wells either semi-annually or annually, depending on the current sampling requirements for each well. The frequency is adjusted based on the sampling results and criteria.

Each site uses a scoring system to evaluate biowall performance and determine when carbon should be replenished. Metrics include concentrations of perchlorate, nitrate, ORP, total organic carbon (TOC), and CH_4 [8]. When the scoring results indicate that carbon addition is needed, carbon replenishment is typically made by injecting EOS™, which consists primarily of vegetable oil, using the installed diffuser pipe system.

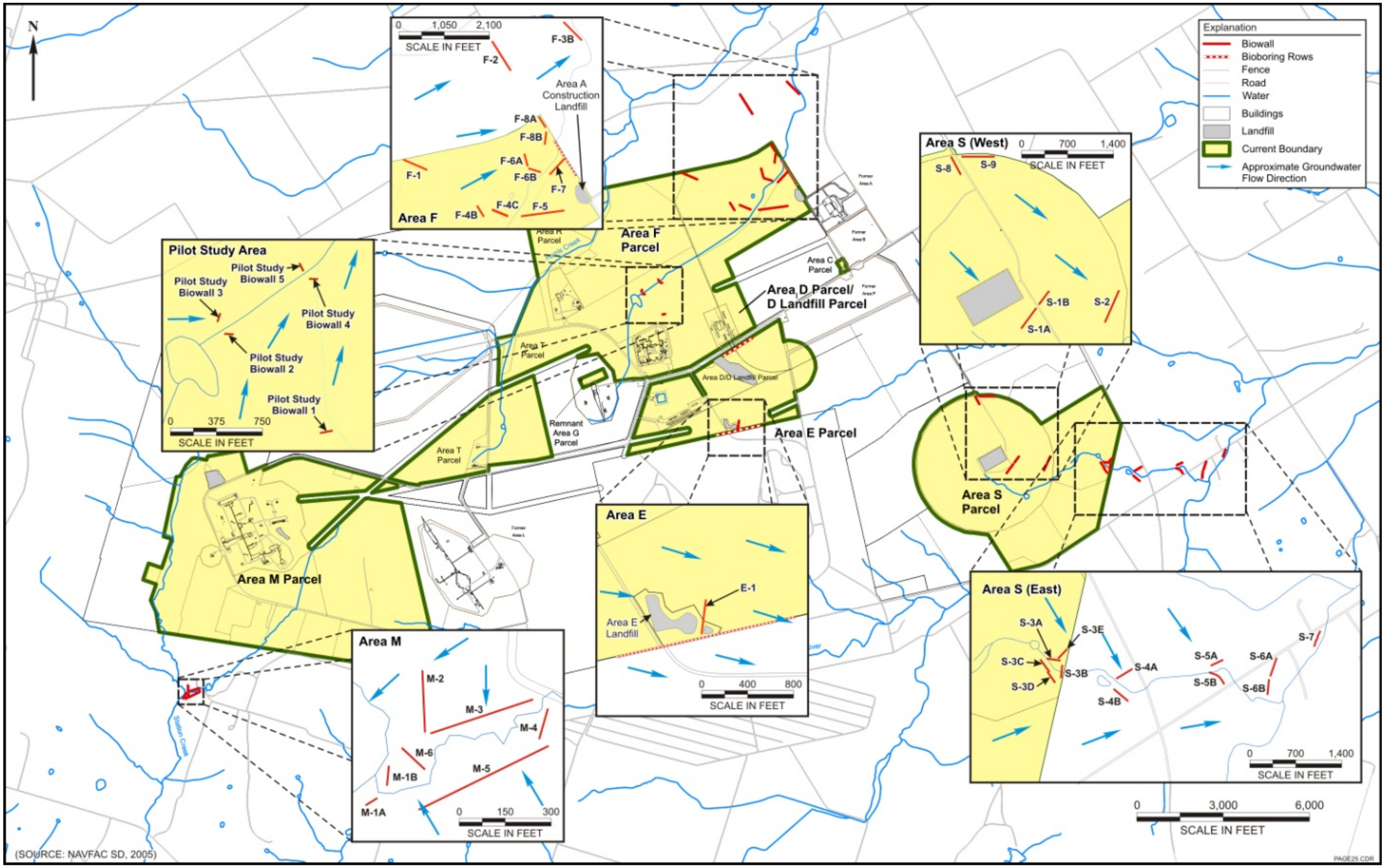


Figure 4-2. Layout of the 34 Biowalls at NWIRP McGregor, TX

Figure 4-3. Rock Trencher Used for Biowall Installation at McGregor, TX

Table 4-1. Summary of Biowalls Installed at NWIRP McGregor

<table>
<tr><th>Area</th><th>Contaminants</th><th>Year Installed</th><th>Dimensions of Biowall</th><th>Material of Biowall</th></tr>
<tr><td rowspan="2">Area E</td><td rowspan="2">TCE, DCE, and cis-1,2-DCE</td><td rowspan="2">2005</td><td>Biowall: 3.5 ft wide, 300 ft in length, 12-19 ft deep</td><td>Gravel, wood chips, and compost saturated with vegetable oil</td></tr>
<tr><td>Two rows of bioborings, each row 1,200 ft long</td><td rowspan="6">Drainage aggregate, compost, and vegetable oil-saturated wood chips</td></tr>
<tr><td rowspan="2">Area F</td><td rowspan="2">Perchlorate, VOCs, Benzene, TCE, DCE, TCA</td><td rowspan="2">2005</td><td>Nine biowalls (7 onsite, 2 offsite), total 3,800 ft long; 16-18 ft bgs</td></tr>
<tr><td>Three rows of bioborings (330 total), each row 1,100 ft long, 16-18 ft bgs</td></tr>
<tr><td>Area M</td><td>Perchlorate and TCE</td><td>2005</td><td>Seven biowalls, total 1,277 ft long</td></tr>
<tr><td rowspan="2">Area S</td><td rowspan="2">Perchlorate, TCE, and DCE</td><td rowspan="2">2002, 2003, 2005</td><td>17 biowalls (10 onsite and 7 offsite), total 4,785 ft long</td></tr>
<tr><td>Supplemental bioborings</td></tr>
<tr><td colspan="3" align="right">Total</td><td colspan="2">34 biowalls totaling 10,162 ft</td></tr>
</table>

Previous optimization studies conducted at NWIRP McGregor identified metrics important to evaluate conditions conducive for perchlorate degradation or biowall breakthrough [8]. These metrics include:

- TOC is an effective indicator of biowall performance. Perchlorate breakthrough occurs when TOC drops below 5 mg/L.
- Humic and fulvic acids are complex carbon substrates produced very quickly from the mushroom compost and wood chips installed within the biowalls. These acids induce and sustain reducing conditions for considerable periods of time both in the biowall vicinity and downgradient as they flow with the groundwater [8].
- Volatile fatty acids are breakdown products of vegetable oils, and play a direct role in perchlorate biodegradation.
- ORP appears to be useful as a long-term tool for biowall operation. ORP values less than - 100 mV are commonly observed soon after biowall installation.
- Nitrate competes with perchlorate for carbon resources in the aquifer. When the carbon substrate becomes depleted, even low concentrations of nitrate (e.g., <0.5 mg/L) may inhibit complete perchlorate biodegradation.
- Methane is often produced in aquifers where biowalls with mixed carbon substrates have been used. Methane concentrations tend to remain high even in moderately reducing conditions. At locations where concentrations of methane have dropped below 2,000 μg/L in the biowalls, perchlorate biodegradation appears hindered [8].

4.6 Technology Performance Results

At Area E, bioborings were installed along 1,200 ft of the southern property line to intercept and remediate contaminated groundwater (TCE and 1,1-DCE) before it exits the property. In addition, a biowall (E-1) was installed in July 2005 on the eastern end of the Area E Landfill as part of active remediation to remediate groundwater contaminated with TCE and 1,1-DCE. With the exception of three wells, groundwater collected from monitoring locations downgradient of the bioborings and the biowall show aqueous contaminant concentrations of TCE and 1,1- DCE below critical PCLs. In recent monitoring, ORP concentrations ranged from -131 mV to -293, along with elevated TOC and methane concentrations present within the biowall. These lines of evidence indicate that additional amendments of a carbon source was not yet required. For those three wells exceeding critical PCLs, one is located downgradient of the biowall and two downgradient of the bioborings. Monitoring well AELMW05, located downgradient of the biowall, showed only a 46% decrease in TCE and a 37% decrease in 1,1-DCE after biowall installation. To understand why these wells are not achieving the anticipated degradation of chlorinated solvents, TOC will be monitored within these monitoring wells to evaluate whether additional carbon should be added to the biowall or whether an additional bioboring should be added [9].

At Area F, seven biowalls and 330 bioborings were constructed in July 2005 in the enclosed area to contain the off-site migration of COCs (especially perchlorate and TCE). In addition, two biowalls (F-2 and F-3B) were constructed offsite to remediate groundwater. Off-site wells that are located downgradient of Biowalls F-2 and F-3B are demonstrating a downward trend in perchlorate concentration. The groundwater wells located offsite do not exhibit any TCE contamination, although groundwater within the Area F boundary remains contaminated with TCE. Perchlorate concentrations in Area F upgradient of the biowalls is lower than the industrial PCL, but in the same general range that has been seen for this area over the past decade of monitoring, demonstrating that no actual reduction of contamination is occurring within Area F. The wells downgradient of the biowalls have shown a reduction in perchlorate concentrations in the groundwater. For example, well AFTMW05, located just downgradient of Biowall F-3, indicated a perchlorate reduction of 97%, allowing groundwater to reach below critical PCLs [9].

At Area M, seven biowalls were installed along the southern boundary of the Texas A&M property (located immediately south of NWIRP McGregor). The biowalls were designed to prevent perchlorate-contaminated groundwater exceeding the residential PCL (17.1 μg/L) from migrating beyond the established PMZ. The biowalls were constructed perpendicular to the hydraulic gradient and keyed into non-water bearing rock. The southernmost downgradient well (OFFWS-11), exhibiting a downward trend of perchlorate concentration, demonstrates a retreating plume. For example, GAM-3 observed decreases in perchlorate from 730 μg/L to 230 μg/L after biowall installation, a 68% reduction and meeting the groundwater performance monitoring target of 400 μg/L. However, perchlorate concentrations in other monitoring wells are still above the residential PCL, demonstrating a need for further evaluation of the biowalls constructed upgradient of the biowall. Concentration maps also show the presence of a TCE plume northwest of the biowalls. The current trend charts show a decreasing TCE concentration in the groundwater collected from these wells [9].

At Area S, 16 biowalls were constructed, primarily to contain the perchlorate-contaminated groundwater from migrating beyond the boundaries of the plume management zone. Most of the trenches were installed in the fall of 2002, except for S-5 (installed in the fall of 2003) and S-8 and S-9 (installed in July 2005). The following observations were made:

- Many of the biowall sampling ports have been dry during the last few sampling events.
- Some biowalls in the area (especially S-3B) were suspected of not being keyed into the impermeable layer, leading to later bioborings being constructed downgradient of this biowall. Since the bioboring construction, groundwater collected from the downgradient GAS-10, TSTMW24, and TSTMW25 wells has shown almost non-detect concentrations of perchlorate.
- Groundwater collected from most wells downgradient of the biowalls exhibits a downward trend in perchlorate concentrations. However, groundwater collected from the northeast well (TSTMW02) is showing a rising trend in perchlorate concentration.
- The biowalls in Area S have been successful in remediating perchlorate to a certain extent and in preventing perchlorate-contaminated groundwater from migrating beyond the boundaries of the plume management zone. Perchlorate removal, based on well pairs, ranged from 31% to 92%. However, groundwater monitoring shows a large perchlorate plume over the entire area that is still persistent and requires continued remediation [9].

Some biowalls have required periodic carbon replenishment, as shown in Table 4-2. In general, biowalls did not need replenishment until four to five years after installation (2002-2005 for Area S biowalls; 2005 for Area F and M biowalls). Only certain biowalls required replenishment, but in several cases these replenishments were required in consecutive years.

Table 4-2. Summary of Carbon Supplements in NWIRP McGregor Biowalls

Year	EOS Added (gallons)	Total Number Biowalls	Area F Biowalls	Area M Biowalls	Area S Biowalls
2006	2,622	15	None	None	Data not located
2008	1,100	5	None	None	S-1A, S-2, S-5A, S-6, S-7
2009	880	6	None	M-2, M-3, M-5	S-3B, S-3E, **S-7**
2010	Not available	11	F-4B	**M-2, M-3**	S-1A, S-2, **S-3B**, S-4A, S-5A, S-5B, S-6A, **S-7**
Total EOS Added		37	1	3	9

Note: Bolded biowalls indicate carbon replenishment repeated in consecutive years.
Source: Ensafe and Dougherty Sprague Environmental, 2010

4.7 Cost

Unit price project costs for biowall installation were provided by the contractor and are summarized in Table 4-3. As reported, the biowall installation cost averages between \$150 and \$200 per linear foot, and \$15 per vertical square foot, for a total of \$1,520,000. Adding design and implementation costs, the total cost is \$1,800,000. These costs do not include reporting. Approximate biowall operation project costs are summarized in Table 4-4, along with annual groundwater monitoring costs and a cost comparison to a pump and treat system that is active in another area of the site.

Table 4-3. Biowall Installation Costs, NWIRP McGregor

Category	Unit Price	Estimated Quantity	Unit	Cost	% of Total Cost
Design	\$ 50,000	5	phases	\$ 250,000	15%
Installation	\$ 150	10,162	linear ft	\$ 1,524,300	85%
Total Cost				**\$ 1,800,000**	**100%**

Table 4-4. Operation Costs, NWIRP McGregor

Category	Number of Units	Annual Cost
Biowall Operation	30 trenches	\$250,000
Fluidized Bed Reactor	89 gpm average flow; acetic acid treatment	\$400,000
Long-term Monitoring Wells	158 wells	\$150,000

4.8 Sustainability Evaluation

The carbon footprint for the installation of the biowalls at NWIRP McGregor was determined to be 1,339 metric tons CO_2e. The footprint was found to be much greater than the footprints at the other two facilities; however, these results are not unexpected considering that the NWIRP McGregor barriers were greater than 10,000 feet long, which is about an order of magnitude greater than the lengths of the barriers installed at NWIRP Dallas or HPNS. Similar to the other two sites evaluated, material production and transportation, in this case soybean and vegetable oils, constituted more than 90% of the carbon footprint as total GHG emissions and energy consumption (see Table 4-5). The construction of the biowalls was responsible for less than 5% of the carbon footprint and energy consumption. The construction activities, including installation and residuals transportation, were responsible for less than half of the criteria pollutant emissions.

Operation and maintenance (O&M) activities at McGregor constitute regular monitoring and periodic vegetable oil injection to enhance the biodegradation of perchlorate and VOCs. The impacts of these efforts were calculated and are illustrated as remedial action operation (RAO) activities in Figure 4-4. In the RAO phase, transportation of the vegetable oil is the largest contributor to the sustainability metrics.

Table 4-5. Relative Impact of Materials and Construction for NWIRP McGregor

	GHG Emissions	Energy Consumption	NO_X Emissions	SO_X Emissions	PM_{10} Emissions
Materials[1]	97%	97%	72%	57%	69%
Construction[2]	3%	3%	28%	43%	31%

[1] Includes material production and transportation.
[2]Includes equipment use, personnel transportation, and residual handling.

4.9 Discussion

Assumptions made during the analysis include:

1) Future EOS injection frequency and quantities will be similar to the last four years
2) The mulch will not need replacement for 20 years.

The validity of these assumptions can only be verified through continued monitoring over time.

Part of the challenge with remediation at NWIRP McGregor is the large size of the property at 9,700 acres. Biowalls are proving to be one of the more economical options to treat large perchlorate and chlorinated solvent plumes.
The following performance observations have been made:

- The biowalls are achieving between 34 and 97% reduction of perchlorate concentrations.
- Concentrations of TOC, ORP, nitrate, and methane are being used effectively as indicators when supplemental carbon addition is needed to provide continued perchlorate treatment.

- To date, 13 of the 34 biowalls have required supplemental carbon at least once. For these wells, the first injection was typically required four to five years after initial biowall installation. Emulsified vegetable oil was effectively added using distribution pipes placed within the original trench. However, in select wells, the vegetable oil was rapidly consumed, and subsequent additions of supplemental carbon were needed as quickly as within one year, as observed in Biowalls M-2, M-3, S-3B, and S-7. It is unclear if the rapid consumption of the vegetable oil is a result of non-uniform distribution of the oil during placement, hydraulic dispersion of the oil outside of the treatment zone, an underestimate of the mass required, or some combination of all three possible factors.
- No other maintenance has been required and only minimal settlement has been noted at land surface.

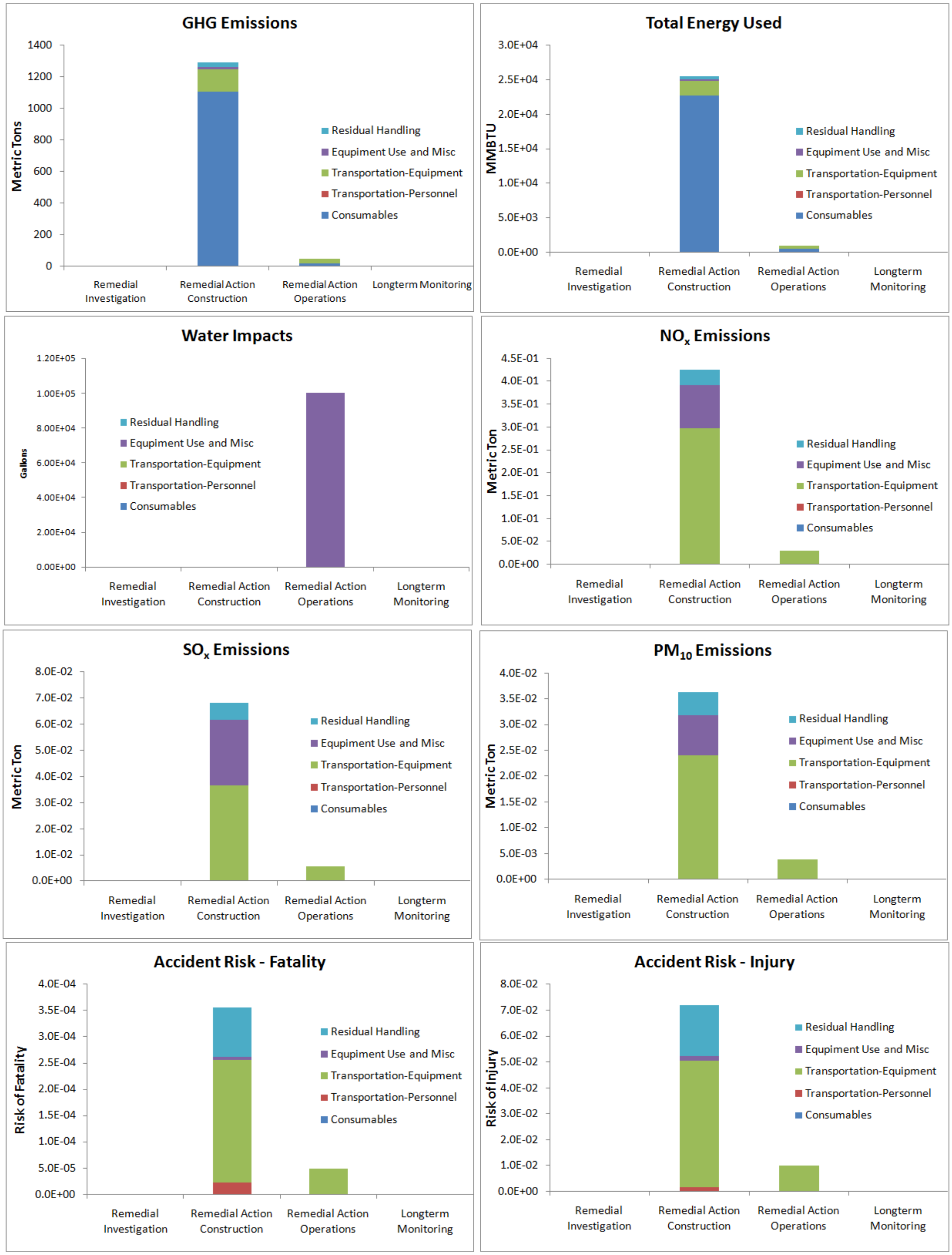


Figure 4-4. Sustainability Metrics for Installation and Operation of Biowalls at NWIRP McGregor

5.0 SUMMARY, DISCUSSION, AND LESSONS LEARNED

This cost and performance report evaluated PRBs installed at three Navy sites, representing a range of geographical locations, targeted contaminants, reactive media, and installation techniques. Site and PRB characteristics are summarized in Table 5-1.

Table 5-1. Comparison of PRBs at Three Navy Sites

Site	COCs	Reactive Media	Injection Method	Equipment	Total Length (LF) and Width	Average Depth/ Thickness (ft)	Quantity Media Used
NWIRP Dallas, TX	VOCs, Cr(6+)	Granular ZVI	One-pass trencher	Mixer and trencher	920 ft; 1.75 ft wide	35/25	• 630 tons ZVI • 1,960 tons sand
Hunters Point Naval Shipyard, CA	TCE, chloroform	Micro-scale ZVI	Pneumatic fracturing	DP/sonic rigs; nitrogen tanker	1,335 ft; width > 20 feet[1]	24/14	• 68 tons ZVI • 2.7M cf nitrogen
NWIRP McGregor, TX	VOCs and perchlorate	Mulch/ vegetable oil	Rock trencher	Trencher	10,162 ft; Avg. 3 ft wide	35/13	• 83,063 cf compost • 41,532 cf wood chips • 1.25M lb soybean oil

[1]The design ROI was 7.5; however, field data indicated that a ROI of 10 feet or greater was consistently achieved at locations monitored.

5.1 Performance

Observations of technical performance differ for each site because the selected case studies represent a variety of design objectives, contaminants, reactive media, and installation techniques. This section highlights some of the key observations related to these diverse PRB applications.

This evaluation indicated remedial goals were being met at all three sites using PRB technologies. ZVI proved effective in reducing chlorinated hydrocarbons (TCE; chloroform) and hexavalent chromium to site remedial goals at NWIRP Dallas and HPNS. Mulch and vegetable oils proved effective in reducing TCE and perchlorate at NWIRP McGregor, though periodic rejuvenation has been necessary at almost half of the biowalls in order to maintain desired performance.

Contaminant reductions and site-specific goals were achieved without reaching strongly reducing conditions of -400 mV recommended by previous reports [12]. Monitoring wells located downgradient of the PRBs resulted in ORP concentrations ranging between -334 mV and 113 mV. Note that the majority of these monitoring wells were located downgradient of the PRBs, not within the PRBs; therefore, it is possible that strongly reducing conditions were achieved within the PRB, but then subsequently the plume became less reducing father downgradient. A related concern noted in the previous *Cost and Performance Report, Nanoscale Zero-Valent Iron Technologies for Source Remediation* is potential loss of reactivity over time [12]. That report evaluated a ZVI injection pilot study conducted at another HPNS site within Parcel C in 2002-

2003. The long-term monitoring data from this older Parcel C site indicates continued reductions in TCE concentrations in groundwater at ORP concentrations ranging from -130 mV to -254 mV, eight years after ZVI injection. This is an important observation regarding the longevity of ZVI injected pneumatically with an iron-to-soil mass ratio of 0.004.

The evaluation of the PRBs at NWIRP Dallas highlights the need for an adequate monitoring network. To fully evaluate hydraulic and contaminant reduction performance, additional groundwater monitoring wells would need to be installed upgradient, cross-gradient, and within the PRBs. This would provide data on groundwater flow patterns, contaminant reductions, and geochemical parameters with respect to the PRB.

The recent HPNS project in Parcels G and D-1 illustrates a number of PRB successes, summarized as follows:

- Successful use of ZVI to reduce concentrations of chloroform, a chlorinated solvent not widely encountered at federal installations.
- Ability to remediate dilute plumes.
- Ability of ZVI to achieve effective and lasting reductions of chlorinated solvents, even within plumes that did not achieve highly reducing conditions (e.g., -400 mV). HPNS documented greater than 99% reductions in chloroform throughout the plume with ORP concentrations ranging from 60 to -334 mV.
- Changes in geochemical parameters served to help confirm the ROI by observing increases in pH and decreases in DO and ORP in monitoring wells located within 15 feet of injection intervals.

Also, the HPNS project demonstrated the use of multiple monitoring techniques to estimate effective ROI during injection. Two of these methods are not yet widely used during injections: (1) downhole pressure transducer readings in nearby groundwater monitoring wells; and (2) biaxial tiltmeter readings to record surface deflection from fracturing and injection activities. These monitoring techniques increase the ability to measure the vertical and horizontal influence of the phased nitrogen fracturing and iron injection.

The HPNS project also illustrates potential issues with pneumatic injection:

- Risk of pushing soil vapors during injection activities, a particular concern if the injection is located near occupied buildings.
- Risk of increasing dissolved metals concentrations resulting from groundwater reducing conditions. Concentrations of arsenic, manganese, and dissolved iron increased in selected monitoring wells located within the projected ZVI ROI. However, the metals remained below groundwater screening criteria.

Interesting observations from NWIRP McGregor include insights into performance monitoring parameters and rejuvenation. Concentrations of TOC, ORP, nitrate, and methane were identified as the key metrics to indicate when supplemental carbon addition is needed for continued perchlorate treatment to meet design objectives. To date, 13 of the 34 biowalls have required supplemental carbon at least once. Those requiring supplemental carbon have generally needed it within four to five years of operation, at which time carbon replenishment began to be required to maintain desired PRB performance. Emulsified vegetable oil has proved effective, yet four biowalls have required replenishment again within a year. It is unclear if the rapid consumption of the vegetable oil is a result of non-uniform distribution of the oil during placement, hydraulic dispersion of the oil outside of the treatment zone, an underestimate of the mass required, or some combination of all three possible factors. No other maintenance has been required and only minimal settlement has been noted at land surface.

5.2 Cost Comparison

PRB installation costs are summarized in Table 5-2. As a comparison, costs to the 89 gpm fluidized bed reactor (FBR) pump and treat system currently operating at NWIRP McGregor at Area M was included in Table 5-2. This is equivalent to treating almost 47 million gallons per year.

Table 5-2. Site Costs for PRB Installation, with Comparison to Pump and Treat

Site	Installation Cost			Annual O&M Cost	Cumulative Present Value[1]
	Materials Cost	Mobilization, Labor, and Equipment	Total Capital Investment		
NWIRP Dallas PRBs	$ 420,000	$ 582,000	$ 1,002,000	$ -	$ 1,002,000
Hunters Point Shipyard Injected PRBs	$ 180,000	$ 1,700,000	$ 1,880,000	$ -	$ 1,880,000
NWIRP McGregor Biowalls	$ 230,000	$ 1,294,000	$ 1,524,000	$ 250,000	$ 4, 600,000
NWIRP McGregor Area M Pump and Treat		$ 1,200,000[2]	$ 1,200,000	$ 400,000	$ 7,300,000

[1]Annual cost in year zero is equal to capital investment; other years is annual O&M at a 5% discount rate over 20 years for PRB sites and 30 years for pump and treat [12].
[2]System installation costs not available; therefore, estimated based on similar sized systems.

Table 5-2 includes estimated annual O&M costs for both the NWIRP McGregor biowall and pump and treat systems. The other systems assume no O&M will be required other than groundwater monitoring, which is not included for any of the technologies. A 20-year period was assumed for estimating cost. The net present value was calculated assuming a 5% discount rate over 20 years using the following equation [12]:

$$PV = \text{Capital Investment} + \Sigma \frac{\text{Annual Cost in Year } t}{(1 + r)^t} \qquad \text{Equation (1)}$$

where
- i = interest rate (0.05)
- r = rate (annual O&M)
- t = anticipated period of operation (20 years for PRB; 30 years for pump and treat)

The range of site characteristics, contaminant concentrations, PRB lengths, and installation techniques makes a direct cost comparison of these three sites challenging. Therefore, to provide a more direct comparison, costs were normalized using (1) cost per PRB cross-sectional area and (2) volume of groundwater treated over a 20-year period. Table 5-3 shows the calculations for the total PRB cross-sectional area and the amount of water treated by each of the three Navy sites.

Table 5-3. Volume of Groundwater Treated for Each Site

Site	Hydraulic Conductivity (ft/day)	Hydraulic Gradient (ft/ft)	Effective Porosity	Effective Groundwater Velocity (ft/day)	PRB Cross-Sectional Area (ft)	Anticipated Longevity (yrs)	Volume Ground-water Treated Over 20 Years (gallons)
NWIRP Dallas	5.9	0.0100	0.3	0.197	23,000	20	2.47×10^{8}
Hunters Point	6.0	0.0025	0.3	0.050	18,690	20	5.10×10^{7}
NWIRP McGregor	12.8	0.0080	0.3	0.342	169,000	20	3.16×10^{9}
NWIRP McGregor Area M Pump and Treat					--	20	9.36×10^{8}

Based on this normalization, the normalized treatment costs are compared in Table 5-4. Looking at these estimated numbers, it is clear that pneumatic fracturing has the highest unit cost, whether normalized by cross-sectional area or the amount of groundwater treated. This is due in part to the labor intensive effort to inject multiple barriers across the site plume. NWIRP McGregor exhibited the lowest unit cost, even considering the annual O&M costs to evaluate the PRBs and to add supplemental carbon.

Table 5-4. Normalized Treatment Costs for PRBs at Three Navy Sites

Site	Cumulative Present Value	PRB Cross-Sectional Area (ft^2)	Volume Groundwater Treated (gallons)	Cost per PRB Cross-Sectional Area ($\$/ft^2$)	Cost per Volume GW Treated ($/1,000 gals)
NWIRP Dallas	$ 1,002,000	23,000	2.47×10^{8}	$ 44	$ 4
Hunters Point	$ 1,880,000	18,690	5.10×10^{7}	$ 101	$ 37
NWIRP McGregor	$ 4,600,000	169,000	3.16×10^{9}	$ 27	$ 1.50
NWIRP McGregor Area M Pump and Treat	$ 7,300,000	--	9.36×10^{8}	--	$ 8

5.3 Sustainability Comparison

The inputs used to calculate the sustainability metrics for each site, along with the outputs, are tabulated in Appendix B. The comparison of the overall "remedy footprint" (as defined in Section 1.3) is discussed in this section. As noted earlier, the footprint for routine annual groundwater monitoring was not included in the sustainability analysis, assuming this activity would be similar for all PRB sites. In reality, more monitoring wells and a higher frequency of groundwater monitoring is required for the biowalls at NWIRP McGregor, given the installation size and need to evaluate the timing for periodic rejuvenation of the biowalls.

Comparing the total carbon footprint of PRB installation activities, HPNS was lowest at 117 metric tons CO_2e, considerably less than the 834 metric tons CO_2e of NWIRP Dallas and the 1,339 metric tons CO_2e of NWIRP McGregor. The total energy used follows a trend similar to carbon footprint, with HPNS site activities consuming less energy than either NWIRP Dallas or NWIRP McGregor. Criteria air pollutants and accident risk (injury) follow a similar trend. HPNS exceeds NWIRP Dallas in only two metrics, water and accident risk (fatalities); no water was used at NWIRP Dallas during injection activities (Figure 5-1).

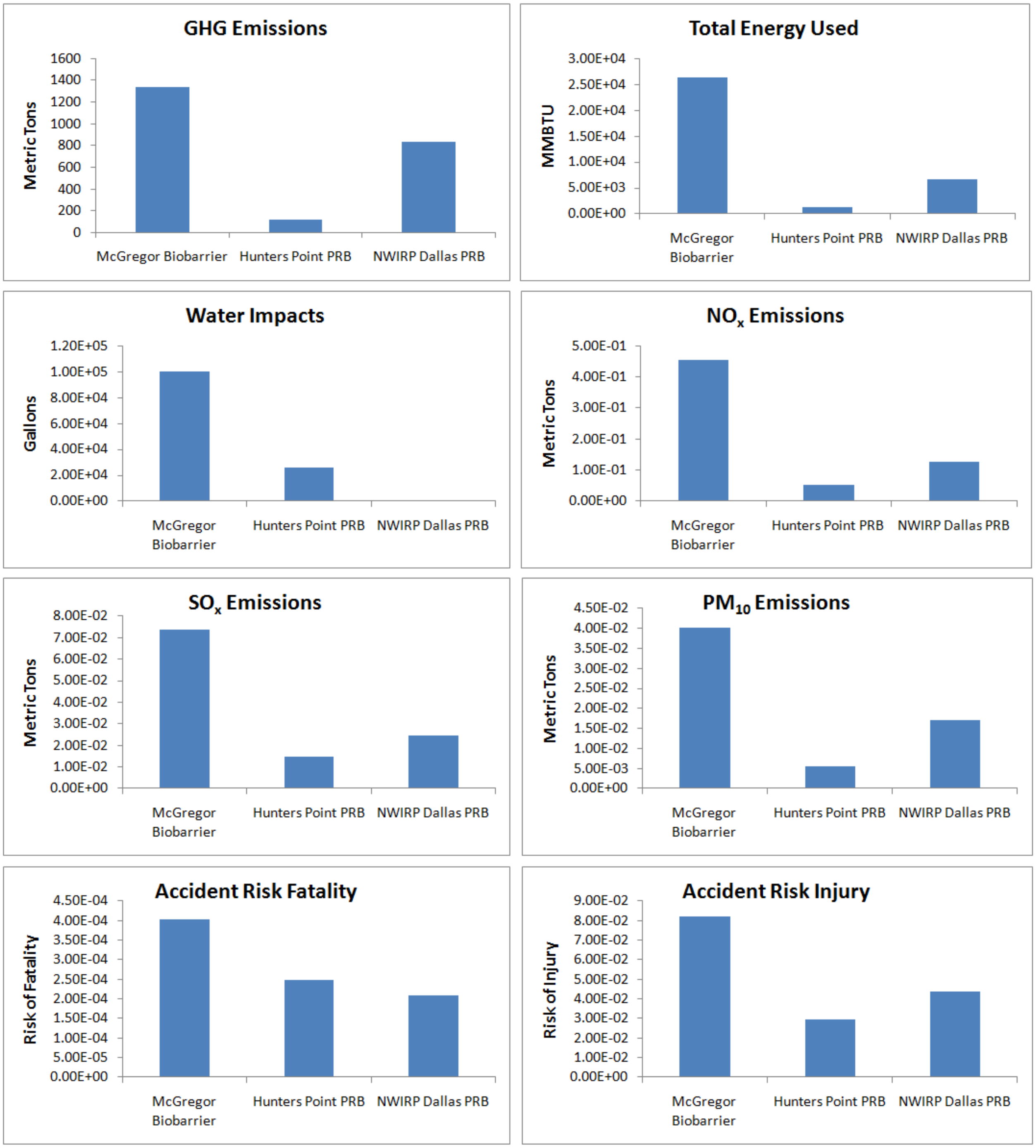


Figure 5-1. Comparisons of Sustainability Metrics

It is reasonable that HPNS demonstrated the lowest overall carbon footprint, energy use, criteria air pollutant emissions, and accident risk (injury), given the small amount of material produced and transported to the site. On the other hand, it also makes sense that NWIRP McGregor generally exhibited the highest remedy footprint because the greatest construction effort took place at that site, with 10,162 linear feet of PRB constructed, which is about 10 times the length installed at HPNS (1,315 linear feet) and over 10 times the length at NWIRP Dallas (620 linear feet).

If a comparison of the remedy footprint is made among the different PRB sites after normalizing all of the sustainability metrics per 1,000 gallons of groundwater treated, then NWIRP McGregor switches from the largest to the smallest in terms of carbon footprint, energy consumption, emission of criteria pollutants, and accident risk (Figure 5-2). This change in comparison is due to the larger size and volume of groundwater treated by the biowalls at the NWIRP McGregor site. NWIRP Dallas exhibits the largest carbon footprint and energy consumption, resulting from the relatively higher quantity of material produced per groundwater treated. HPNS moves from the smallest to the largest emitter of criteria pollutants and accident risk due to the relatively longer amount of time that equipment and workers are on site to install each foot of barrier.

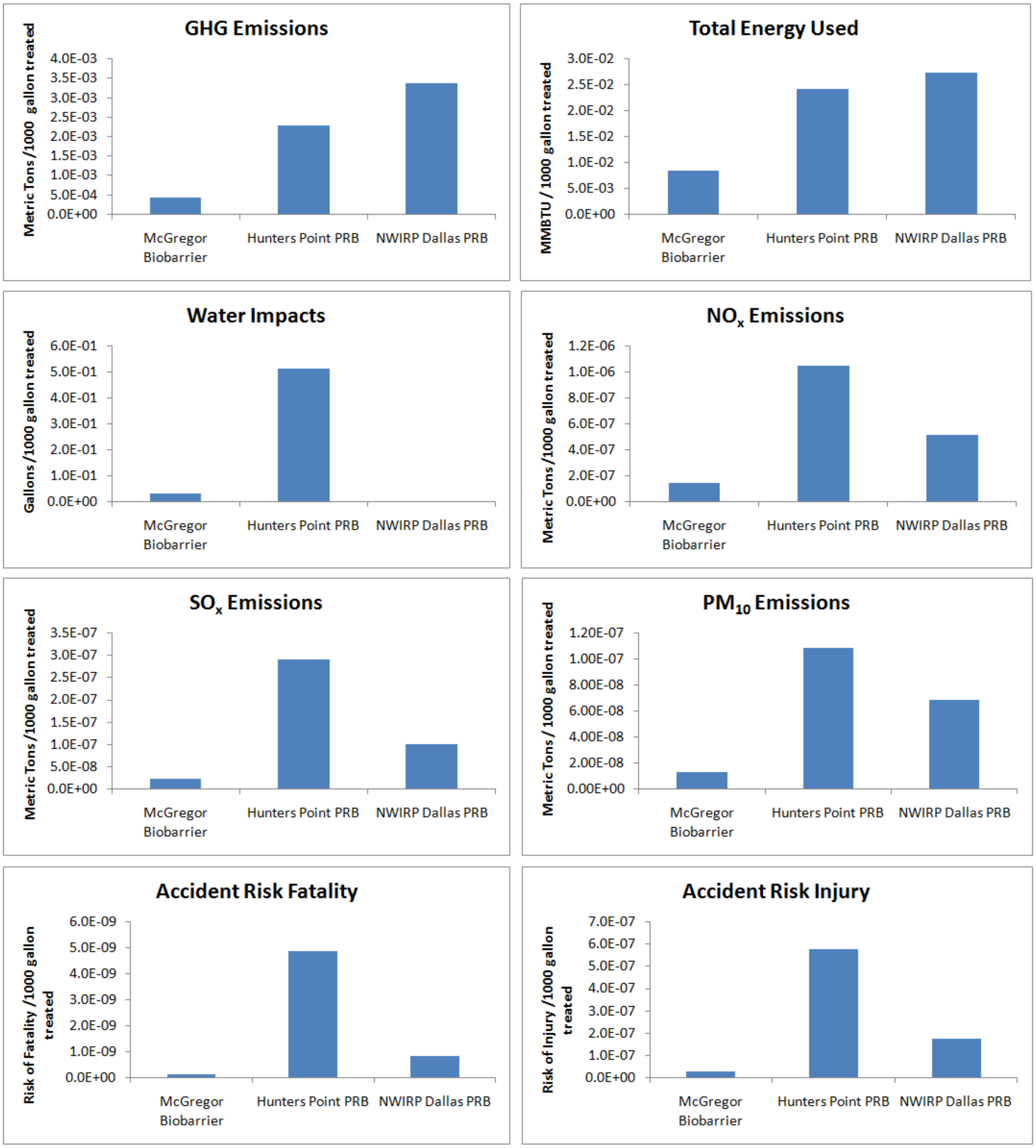


Figure 5-2. Relative Impact Calculated per 1,000 Gallons of Groundwater Treated

Figure 5-3 shows the results of the sites normalized per cross-sectional area. Again, when normalized, NWIRP McGregor exhibits the lowest footprint for criteria pollutants and accident risk, and NWIRP Dallas is the least sustainable with regards to carbon footprint and energy used.

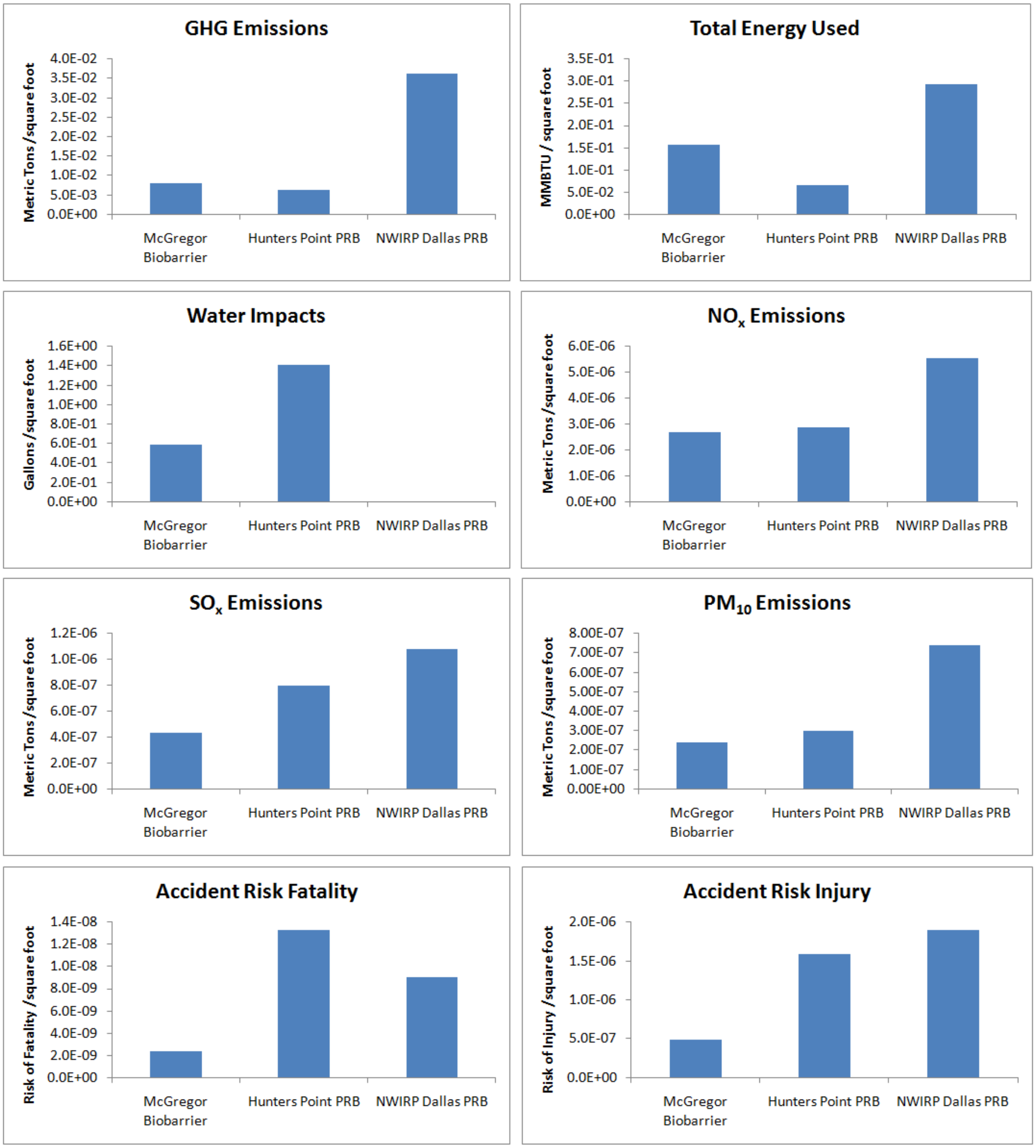


Figure 5-3. Relative Impact Calculated per Square Foot of Biowall Cross-Section

In summary, the volume of groundwater treated or cross-sectional area of the reactive barrier provides equal grounds for the different reactive barriers to be compared. NWIRP McGregor has multiple biowalls that treat the largest amount of water among all of the sites, thereby lowering the overall remedy footprint of the NWIRP McGregor site when the GSR analysis results for this site are normalized. Similarly, HPNS used smaller amounts of injected iron. The normalization exercise demonstrates that the HPNS injected PRB and NWIRP McGregor biowalls are more sustainable because of the lower remedy footprint associated with the material used at the sites for constructing these PRBs.

Recycled materials such as wood chips, compost, mulch and carbon substrates such as vegetable oil and soybean oil have a lower overall lifecycle CO_2e footprint when compared to ZVI. The total materials consumed are detailed in Appendix B. The biowalls at NWIRP McGregor used many more times the amount of material used in the PRBs at NWIRP Dallas, yet this difference is not reflected by the remedy footprint of the material production. This observation demonstrates that the type of material used is a major factor governing the sustainability of a PRB. These results are consistent with those of a recent study by Mak and Lo [13] that determined that the types of materials, quantities of materials, and construction methods were three factors that substantially influenced remedy footprint of a PRB. Using recycled and natural materials such as mulch and vegetable oil has a lower environmental impact than using materials such as ZVI. However, use of recycled material cannot be universal because certain sites require more aggressive materials such as ZVI to attain their remediation goals.

The sustainability evaluations at the PRB sites also provide an insight into the remedial activities that are the largest contributors to the overall remedy footprint of the PRB installation. The highest footprint element is the material used at the site, followed by the transportation activities related to the material mobilization to the site. The construction activities are the next highest footprint element at the site. In an injection site such as HPNS, activities related to injection contributed to the footprint more than traditional shorter-duration trenching activities undertaken for PRB wall construction.

Table 5-5 provides the relative contribution of each activity to the carbon footprint, energy consumption, and criteria air pollutant emissions for each site. These values are also compared with the findings of a study by Higgins and Olson [14] that used a lifecycle analysis (LCA) approach to find the remedial activities that were major contributors to the PRB footprint. The Higgins and Olson [14] study reported that material production and transportation contributed more than 90% of the PRB lifecycle carbon footprint and energy consumption, and more than 80% of the NOx emissions. Their study was based on a funnel-and-gate PRB that used ZVI and sand as material with longevity of 10 years.

The PRB analysis of the three Navy sites conducted using SiteWise™ is consistent with the findings of the Higgins and Olson study [14] as shown in Table 5-5. The PRBs at NWIRP Dallas constructed with ZVI and sand materials compare best with the Higgins study, with more than 95% of the carbon footprint and energy consumption due to the material production, along with 80% of the NOx production mainly due to material transport. The GSR analysis on HPNS is a little different than the other two sites because HPNS is an injection site in comparison to the construction of PRB walls at the other two sites.

Table 5-5. Comparison of Relative Impact of Different Sustainability Metrics for PRB Installations

NWIRP Dallas (Granular Zero Valent Iron)					
	GHG Emissions	Energy Consumption	NO_X Emissions	SO_X Emissions	PM_{10} Emissions
Materials[1]	97%	95%	80%	79%	80%
Construction[2]	3%	5%	20%	21%	20%
Hunters Point Naval Shipyard (Micro-Scale Zero Valent Iron)					
	GHG Emissions	Energy Consumption	NO_X Emissions	SO_X Emissions	PM_{10} Emissions
Materials[1]	87%	73%	53%	37%	69%
Construction[2]	13%	27%	47%	63%	31%
NWIRP McGregor (Mulch & Vegetable Oil)					
	GHG Emissions	Energy Consumption	NO_X Emissions	SO_X Emissions	PM_{10} Emissions
Materials[1]	97%	97%	72%	57%	69%
Construction[2]	3%	3%	28%	43%	31%
Higgins and Olson [14] (Granular Zero-Valent Iron)					
	GHG Emissions	Energy Consumption	NO_X Emissions		
Materials[1]	> 90%	> 90%	80%		
Construction[2]	< 5%	< 5%	20%		

[1]Includes material production and transportation.
[2]Includes equipment use, personnel transportation; and residual handling.

5.4 Overall Comparison

All three applications achieved site-specific objectives. The normalized rankings of the three Navy PRB sites are summarized in terms of cost and sustainability in Table 5-6. For each of the sites, three columns are shown. The first column is the ranking of each factor without performing any type of normalization; the second column normalizes the ranking based on 1,000 gallons of water treated by the barrier; and the third column is normalized based on the cross-sectional area of the barrier perpendicular to groundwater flow. The values (1 through 3) provided in each cell are a score based on the desirability of one application over the other two. The lower the ranking, the more desirable the application with respect to the factor being considered. For example, the non-normalized cost of the NWIRP McGregor application is the greatest of the three applications; hence, it is assigned a value of 3. However, when the cost is normalized with respect to 1,000 gallons of groundwater treated or with respect to the cross-sectional treatment area, the cost of the McGregor application is the least of the three (refer to Table 5-4). A similar comparison was performed using the data provided in the tables and figures in this section for CO_2e footprint, energy and water consumption, criteria pollutants, and accident risk.

Table 5-6. Overall Cost and Sustainability Ranking

	NWIRP McGregor			HPNS			NWIRP Dallas		
Factor	**None**	**GW**	**Sq Ft**	**None**	**GW**	**Sq Ft**	**None**	**GW**	**Sq Ft**
Cost	3	**1**	**1**	2	3	3	1	2	2
Carbon (CO_2e) footprint	3	1	2	1	2	1	2	3	3
Energy used	3	1	2	1	2	1	2	3	3
Water used	3	2	2	2	3	3	**1**	**1**	**1**
Criteria Pollutants	3	**1**	**1**	1	3	2	2	2	3
Accident Risk--Fatality	3	**1**	**1**	2	3	3	1	2	2
Accident Risk—Injury	3	**1**	**1**	1	3	2	2	2	3

Ranking based on 3 being the highest (less desirable) and 1 being the lowest (most desirable). Results are **bolded** when normalized results are both low (1) and red when both are high (3).

The data presented in Table 5-6 indicate the biowalls installed at NWIRP McGregor involve the lowest cost and the most sustainable technology for the majority of the metrics. In terms of carbon footprint and energy used, the pneumatically injected ZVI also reflects a relatively sustainable technology, yet at a higher relative cost.

In addition, the sustainability evaluations at the PRB sites provide insight into the remedial activities that are the biggest contributors to the overall remedy footprint of the PRB installation: material production is the highest footprint element (>80%, except when pneumatically injected), followed by transportation activities (>10%) and construction activities (<10%).

5.4.1 Selection of Material

The GSR analysis and comparison of the three PRB sites demonstrate that judicious use of material at the site is an important factor in governing the environmental impact of installing a PRB. This can also reduce costs, but must be balanced with sufficient reactive media to achieve remedial goals. Noteworthy observations include:

- The amount of material used is calculated based on the residence time required for contaminants to be reduced, design factors of the installed PRB, and the contaminant concentrations in groundwater. If the site remediation goals can be achieved using more sustainable options such as recycled material or vegetable oil, then those options should be given priority.
- The lesson learned from the HPNS site is that injection of ZVI using newer technology such as pneumatic injection can be a more sustainable option. However, attention should be paid to the amount of ZVI that needs to be injected.
- Overly conservative remedial designs can lead to increased usage of materials, equipment, and labor for most sites. To address such a situation, optimal design approaches should be exercised.

The key to optimal design is proper site characterization to delineate plume characteristics, and to ensure a good understanding of site geology, hydrogeology, and any other site-specific factors (i.e., depth of contamination, presence of dense non-aqueous phase liquid, amount of natural organic matter, etc.) that could influence the design. Knowing this information will allow the design practitioner to calculate appropriate dimensions (i.e., length, width and depth for a trench or required ROI for a caisson type barrier), determine the type and composition of amendment required to treat the COCs, the optimum method for placement, the frequency of maintenance, and apply an appropriate safety factor. All of these factors are essential for a PRB to attain remediation goals and be relatively sustainable.

5.4.2 Transportation and Construction

Construction and transportation activities are also critical parameters of overall sustainability of a PRB. Transportation activities can be lowered if the material used at the site is locally sourced. Rail should be considered over truck transport, particularly when ZVI can be sourced only from Chicago or Detroit in the continental United States or from Ontario, Canada, and must be shipped long distances.

Local vendors can be sourced by the contractor for PRB construction and installation, thereby lowering the cost and impact of equipment and personnel mobilization to the site. However, specialty contractors and equipment, though mobilized from a longer distance, may reduce installation time and improve performance, thereby reducing the overall sustainability impact of the installation.

5.5 Lessons Learned and Next Steps

This report helps to expand the definition of PRBs. A PRB is no longer referring simply to a constructed vertical ZVI-filled trench. PRBs can be effectively installed using pneumatic fracturing and injection techniques. PRBs now include biowalls filled with solid reactive media made from recycled material (e.g., mulch and compost) and replenished with liquid carbon substrates (e.g., soybean or vegetable oil). PRBs have proven to be an effective means to treat a variety of dissolved-phase groundwater constituents, including chloroform and perchlorate. This report further demonstrates the applicability of PRBs to address large, dilute plumes in a variety of settings.

It is clear that placing or injecting sufficient quantity of reactive media is key to successful degradation. That said, a design iron-to-soil mass ratio of 0.004 can create sufficiently reducing conditions (e.g., ORP less than -150 mV) to degrade low concentrations of perchlorate and chlorinated compounds.

Before or during PRB construction, one lesson learned is the need to install an adequate monitoring well network to evaluate PRB performance in light of site design objectives. This network should include groundwater monitoring located wells upgradient, cross-gradient, downgradient, and within the plume as well as immediately upgradient of the PRB, immediately downgradient of the PRB and within the PRB itself.

Monitoring also is needed during placement or injection activities. These include:

- Utilize new available techniques to measure the injected zone of influence, particularly biaxial tiltmeter instruments and down-hole pressure transducers.

- When fracturing and injecting at shallow depths, be aware of the risks of increasing soil vapor concentrations. Also note that pressurized injection may lead to "daylighting," when reactive media reaches the surface. Fortunately, reactive media related to PRBs generally poses little health and safety concerns.
- ZVI injection may increase dissolved metal concentrations. This impact on secondary water quality should be carefully monitored.

Another lesson learned is that using recycled materials and minimizing the quantity and distance materials are transported make a large impact on reducing the carbon footprint and energy usage at a site.

The following evaluations should be made in the future to further the understanding of cost, performance, and sustainability of PRBs:

- Evaluation of additional PRB sites to provide a larger statistical basis.
- Expand the comparison to other types of reactive media (e.g., vegetable oil) and injection methods (e.g., hydraulic fracturing).

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ACKNOWLEDGEMENT

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APPENDIX A:
BASELINE SUSTAINABILITY ASSESSMENT METHODOLOGY

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General Approach

This GSR analysis was performed using a tool developed by Battelle, U.S. Navy, and U.S. Army Corps, referred to as SiteWise™. Use of SiteWise is not an endorsement of this tool, nor is it an indication that it is the only method of performing GSR analysis. The SiteWise™ tool uses a compilation of factors that are available from several recognizable sources, such as the U.S. EPA Climate Leaders Program (U.S. EPA, 2009) to perform the analysis. SiteWise™ is available in the public domain for free download from the Navy Web site (https://portal.navfac.navy.mil/portal/page/portal/navfac/navfac_ww_pp/navfac_nfesc_pp/environmental/erb/gsr/gsr-t2tool). The information sources for various metrics are discussed below.

GHG Emission Footprint Calculation. The U.S. EPA Climate Leaders Program and Intergovernmental Panel on Climate Change (IPCC) provide a GHG Inventory Guidance which is used by industry to document emissions of GHGs including CO_2, CH_4, and N_2O. The U.S. EPA Climate Leaders GHG Inventory Guidance is a modification to the GHG protocol developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The emission factor inventories produced by these agencies are widely used to calculate GHG emissions.

GHG emissions are generally a product of an activity and the associated emission factor. Emission factors for vehicular and construction equipment are based on the type of fuel (gasoline or diesel) used and also the type of vehicle (e.g., car, truck, or bulldozer) used. In the case of emission factors due to electrical use, factors are based on the state in which the remedial action would be carried out. Emission factors for GHGs (N_2O and CH_4) are multiplied by their GWP to obtain a CO_2 equivalent (CO_2e) in metric tons.

Energy Usage Calculation Methodology. As part of a site remediation project, energy is consumed in various forms. The SiteWise™ tool calculates the energy consumed due to material production, fuel consumed, and electricity consumed during remedy implementation and reports it in million metric British Thermal Units (MMBTUs). Electricity that would be used on site is calculated for each piece of equipment based on motor nameplate specifications. Fuel used for equipment and transportation requires an estimate of the fuel consumption rate (e.g., miles per gallon for transportation or gallons per hour for equipment) and the quantity of use (e.g., miles for transportation and hours for construction equipment). In addition, electricity used is also reported in megawatt-hours (MWH) of electricity consumed. The fossil fuel resource energy consumed in MMBTUs is calculated based on an efficiency of 40% for sub-critical power plants in the US. This information is available through multiple sources including the Greenhouse Gases and Global Warming Potential Values available in the U.S. EPA inventory of greenhouse gas.

Air Emission Inventories Development. The criteria pollutants, PM, NOx, and SO_2, are estimated using information from "Mobile 6" (http://www.epa.gov/otaq/m6.htm) and "Non-road" (http://www.epa.gov/otaq/nonrdmdl.htm), two programs developed by the U.S. EPA Office of Transportation and Air Quality and AP-42 (U.S. EPA, 1995). These programs provide emission factors for certain activities that are carried out during a remedial action. The Mobile 6 software application calculates air emission factors for 28 vehicle types, including passenger cars, light trucks, and heavy duty trucks in units of grams per mile based on default values for national averages. The Non-road model provides air emission factors for off-road vehicles and equipment such as tractors, backhoes, forklifts, and pumps. The emissions can be calculated based on horsepower, location, equipment type, and fuel consumption. The calculated emission factors are given in units of grams per operating hour, grams per day, or grams per hp-hour. For this analysis, emission factors in grams per operating hour based on the hp of the equipment were used. AP-42 provides air emission factors for various industry processes including the mineral products industry and petroleum industry and solid waste disposal in units of pounds per ton of material processed.

Accident Risk Calculation Methodology. Accident risk is a measure of unintentional injuries and fatalities that could result from remediation efforts. Information is gathered from several organizations that provide statistics on both fatalities and injuries that occur during various activities, including labor and transportation by automobile, airplane, and rail. Labor statistics are available for agriculture, mining, construction, and manufacturing industries, including manufacturing of chemical, wood, metal, plastic/rubber, and machinery products. The organizations from which injury and fatality statistics can be obtained include Automobile Transport Statistics and Bureau of Labor Statistics (BLS, 2007).

To determine the accident risk involved in transportation of personnel, the following equation is used:

Fatality/Injury Risk = (# miles traveled * Fatality/Injury Rate)/100,000,000.

Fatality/injury rate is provided in terms of fatalities or injuries per 100,000,000 passenger miles for different modes of transportations (i.e., automobile, train, and airplane).

To determine the accident risk by labor the following equation is used:

Fatality/Injury Risk = (# hours worked * Fatality/Injury Rate)/200,000,000.

Here, fatality/injury rates are provided in terms of number of fatalities or injuries per 100,000 workers or 200,000,000 hours worked when assuming an average of 2,000 hours worked per year.

Water Consumption. Water consumed is calculated for electric production using an average amount of water consumed (510 gallons) per MWH of electricity produced in the US. For water consumption per MWH, the data are obtained from a study done by Arizona State University (Arizona Water Institute [AWI], 2007).

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APPENDIX B:
SITEWISE™ SUSTAINABILITY CALCULATION INPUT AND RESULTS

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Table B-1. Key SiteWise™ Inputs for Each Site

	Permeable Reactive Barrier Sites		
	McGregor	**Hunters Point**	**Dallas**
Consumables	*Initial Installation:* 2 in. Schedule 40 PVC for a combined total of 20,000 ft for diffuser pipe 1.25M lb of Soybean Oil 4.62M lb of Mulch 283,500 cubic feet of Gravel 108,000 cubic feet of Clay *Supplemental Carbon Added 2006-2009* 144,000 lb Vegetable Oil (EOS) 100,000 gallons of Water	136,000 lb (68 tons) of ZVI 3.3M cubic feet of Nitrogen (~103 MMBTUs to produce) 13,520 gallons of Water	1.26M lb (630 tons) of ZVI 37,465 cubic feet (1,960 tons) of Sand
Transportation Personnel	130 trips of 10 miles with 2 travelers by Car (Gasoline) during RAC	120 trips of 10 miles with 2 travelers by Car (Gasoline) plus 5,000 miles round-trip with 4 travelers by Truck (Gasoline) during installation	
Transportation Equipment and Materials	Combined total of 97,670 miles round-trip by road (Diesel) for Equipment and Biowall Materials (5 to 25 tons/trip) 500 miles by rail with 450 tons for Soybean Oil 10,000 miles one-way by road (Diesel) for EOS (10 tons/trip)	Combined total of 7,200 miles one-way by road (Diesel) from Detroit, MI, for ZVI (23 tons/trip) Combined total of 2,920 miles round-trip by road (Diesel) for Nitrogen (73 trips x 20 miles/trip)	Combined total of 57,600 miles round-trip by road (Diesel) from Detroit, MI, for ZVI (21 tons/trip) Combined total of 1,840 miles round-trip by road (Diesel) for Sand (20 tons/trip)
Equipment Use	17,333 cubic yards removed by Excavator (Diesel)	93 locations using Direct Push Drilling (Diesel), 3 hr per location, 25 ft wells 25,062 kWh electrical use (CAMX California region)	1,178 cubic yards removed by Excavator (Diesel)
Residual Handling	Soil Residue, 5 miles, 2,500 trips full (10 tons) and 2,500 trips empty (0 tons), Heavy Duty (Diesel)		Soil Residue, 55 miles, 158 trips full (19 tons) and 158 trips empty (0 tons), Heavy Duty (Diesel)

Table B-2. SiteWise™ Results Relative Impact (Not-Normalized)

Site	GHG Emissions	Total Energy Used	Water Consumption	NOx emissions	SOx Emissions	PM10 Emissions	Accident Risk Fatality	Accident Risk Injury
	metric ton	MMBTU	gallons	metric ton	metric ton	metric ton		
NWIRP McGregor	1,300	26,000	100,000	0.5	0.07	0.04	4.03E-04	0.08
Hunters Point	117	1,200	26,000	0.05	0.01	0.006	2.49E-04	0.03
NWIRP Dallas	835	6,800	0	0.1	0.02	0.02	2.09E-04	0.04

Table B-3. Relative Impact Calculated per 1,000 Gallons of Water Treated

Remedial Alternatives	GHG Emissions	Total Energy Used	Water Consumption	NOx emissions	SOx Emissions	PM10 Emissions	Accident Risk Fatality /1000 gal	Accident Risk Injury /1000 gal
	metric ton/1000 gal	MMBTU/1000 gal	gallons/1000 gal	metric ton/1000 gal	metric ton/1000 gal	metric ton/1000 gal		
NWIRP McGregor	4.2E-04	0.008	0.30	1.4E-07	2.3E-08	1.3E-08	1.28E-10	2.60E-08
Hunters Point	2.3E-03	0.02	0.5	1.0E-06	2.9E-07	1.0E-07	4.88E-09	5.80E-07
NWIRP Dallas	3.4E-03	0.03	0	5.2E-07	1.0E-07	6.9E-08	8.45E-10	1.76E-07

Table B-4. Relative Impact Calculated per Square Foot Cross-Sectional Area

Remedial Alternatives	GHG Emissions	Total Energy Used	Water Consumption	NOx emissions	SOx Emissions	PM10 Emissions	Accident Risk Fatality /sq foot	Accident Risk Injury /sq foot
	metric ton/sq foot	MMBTU/sq foot	gallons/sq foot	metric ton/sq foot	metric ton/sq foot	metric ton/sq foot		
NWIRP McGregor	7.9E-03	0.2	5.9	2.7E-06	4.36E-07	2.4E-07	2.39E-09	4.86E-07
Hunters Point	6.3E-03	0.006	1.4	2.9E-06	7.96E-07	3.0E-07	1.33E-08	1.58E-06
NWIRP Dallas	3.6E-02	0.3	0	5.6E-06	1.08E-06	7.4E-07	9.07E-09	1.89E-06