



FINAL

20 July 2018

Focused Feasibility Study

Area 6

NAS Whidbey

Oak Harbor, Washington

Department of the Navy

Naval Facilities Engineering Command Northwest

1101 Tautog Circle

Silverdale, WA 98315



**FINAL
FOCUSED FEASIBILITY STUDY
AREA 6, NAVAL AIR STATION WHIDBEY ISLAND
OAK HARBOR, WASHINGTON**

**Prepared for
Naval Facilities Engineering Command Northwest
Silverdale, Washington**

**U.S. Navy Contract No. N44255-09-D-4001
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AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
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Title Page

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Page ii

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Date: 7/20/2018
Page iii

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Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Document ID

Date: 7/20/2018

Page iv

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CONTENTS

ABBREVIATIONS AND ACRONYMS	xi
1.0 INTRODUCTION	1-1
1.1 PURPOSE AND ORGANIZATION	1-2
1.2 BACKGROUND INFORMATION	1-3
1.2.1 Site Description and History	1-3
1.2.2 Nature and Extent of Contamination	1-21
1.2.3 Conceptual Site Model Summary	1-51
1.2.4 Contaminant Fate and Transport	1-55
1.2.5 Groundwater Modeling Summary	1-56
1.2.6 Baseline Risk Assessment	1-56
2.0 REMEDIAL ACTION PERFORMANCE CRITERIA	2-1
2.1 REMEDIAL ACTION GOALS AND OBJECTIVES	2-1
2.1.1 Media and Chemicals of Concern	2-1
2.1.2 Exposure Pathways	2-2
2.1.3 Remedial Action Objectives	2-2
2.1.4 Remediation Goals	2-3
2.1.5 Points of Compliance	2-7
2.1.6 Groundwater Well Installation Restrictions Around Landfills	2-7
2.2 APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS	2-9
2.2.1 Chemical-Specific ARARs	2-10
2.2.2 Location-Specific ARARs	2-10
2.2.3 Action-Specific ARARs	2-10
2.3 GENERAL RESPONSE ACTIONS	2-11
Notes: 2-13	
3.0 IDENTIFICATION AND SCREENING OF TECHNOLOGY TYPES AND PROCESS OPTIONS	3-1
3.1 NATURAL ATTENUATION	3-2
3.2 PUMP AND TREAT	3-3
3.3 PHYTOREMEDIATION SCREENING	3-3
3.4 BIOMATS SCREENING	3-3
3.5 REACTIVE AND IMPERMEABLE BARRIERS SCREENING	3-4
3.6 IN-SITU CHEMICAL OXIDIZATION SCREENING	3-5
3.7 ENHANCED REDUCTIVE DECHLORINATION SCREENING	3-5

CONTENTS (Continued)

3.8	ADVANCED OXIDATION.....	3-5
3.9	DISCHARGE TO THE AULT FIELD WASTEWATER TREATMENT FACILITY	3-6
4.0	ALTERNATIVES.....	4-1
4.1	DEVELOPMENT OF ALTERNATIVES.....	4-1
4.2	ALTERNATIVE 1: CONTINUE WITH CURRENT SYSTEM	4-3
4.3	ALTERNATIVE 2: CONTINUE P&T WITH EX-SITU GROUNDWATER TREATMENT USING ADVANCED OXIDATION PROCESS AND ADDITIONAL EXTRACTION WELLS.....	4-5
4.4	ALTERNATIVE 3: IN-SITU GROUNDWATER TREATMENT WITH ISCO USING BASE-ACTIVATED PERSULFATE.....	4-15
4.5	ALTERNATIVE 4: IN-SITU GROUNDWATER TREATMENT WITH ISCO USING CATALYZED HYDROGEN PEROXIDE	4-23
4.6	ALTERNATIVE 5: EXPANDED GROUNDWATER CAPTURE WITH ALL UNTREATED EFFLUENT DISCHARGED TO NAVY WWTF AT AULT FIELD.....	4-30
4.7	ALTERNATIVE COMBINATIONS	4-41
4.8	GROUNDWATER MODELING SIMULATIONS RESULTS	4-42
4.9	ESTIMATED ALTERNATIVE COSTS.....	4-47
4.10	SUSTAINABILITY.....	4-53
	4.10.1 SiteWise Results	4-54
	4.10.2 Relative Rankings	4-56
5.0	DETAILED ANALYSIS OF ALTERNATIVES.....	5-1
5.1	EVALUATION CRITERIA	5-2
	5.1.1 Threshold Criteria	5-2
	5.1.2 Primary Balancing Criteria	5-2
	5.1.3 Modifying Criteria	5-3
	5.1.4 Alternative Rating Scale	5-3
5.2	INDIVIDUAL ANALYSIS OF ALTERNATIVES.....	5-4
	5.2.1 Alternative 1: Continue with Current System.....	5-4
	5.2.2 Alternative 2: Continue P&T With Ex-Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells.....	5-5
	5.2.3 Alternative 3: In-Situ Groundwater Treatment With ISCO Using Base-Activated Persulfate.....	5-10

CONTENTS (Continued)

5.2.4	Alternative 4: In-Situ Groundwater Treatment With ISCO Using Catalyzed Hydrogen Peroxide	5-14
5.2.5	Alternative 5: Expanded Groundwater Capture With All Untreated Effluent Discharged to Navy WWTF at Ault Field.....	5-15
5.2.6	Combined Alternatives 2 and 4.....	5-18
5.3	COMPARATIVE ANALYSIS.....	5-21
5.3.1	Overall Protection of Human Health and the Environment.....	5-21
5.3.2	Compliance with ARARs	5-23
5.3.3	Long-Term Effectiveness and Permanence	5-23
5.3.4	Reduction of Toxicity, Mobility, and Volume Through Treatment	5-24
5.3.5	Short-Term Effectiveness	5-25
5.3.6	Implementability	5-25
5.3.7	Estimated Cost	5-26
5.4	ALTERNATIVES ASSESSMENT	5-26
6.0	PUBLIC INVOLVEMENT	6-1
7.0	REFERENCES	7-1

APPENDICES (Provided on CD in Hard Copy)

A	Area 6 Groundwater Concentration Trends Evaluation
B	Groundwater Modeling Report
C	Bench Scale Feasibility Tests for 1,4-Dioxane Green Remediation Using Microbial Mats and Enhanced Constructed Treatment Wetlands
D	Removal of 1,4-Dioxane from Groundwater Using Ozone based Advanced Oxidation Process
E	Removal of 1,4-Dioxane and VOCs from Groundwater of Naval Air Station (NAS) Whidbey Island Site using Activated Persulfate
F	APTwater HiPOx Bench-Scale Treatability Report, November 6, 2017
G	Alternatives Cost Estimates

CONTENTS (Continued)

FIGURES

Figure 1-1	Site Location Map.....	1-4
Figure 1-2	Site Aerial Photograph and Features.....	1-5
Figure 1-3	2001 Datum Excavation Limits and Source Area Soil Vapor Monitoring Points and Groundwater Wells	1-8
Figure 1-4	Injection Well Location Map	1-9
Figure 1-5	Area 6 Stratigraphy	1-13
Figure 1-6	February 2014 Groundwater Surface Elevations.....	1-17
Figure 1-7	TCE Concentrations, 1997 and February 2014.....	1-23
Figure 1-8	1,1-DCE Concentrations, 1997 and February 2014.....	1-25
Figure 1-9	1,1-DCE Concentrations, 1997 and February 2014.....	1-27
Figure 1-10	cis-1,2-DCE Concentrations, 1997 and February 2014.....	1-29
Figure 1-11	Vinyl Chloride Concentrations, 1997 and February 2014.....	1-31
Figure 1-12	1,4-Dioxane Concentrations, 2003 and February 2014	1-35
Figure 1-13	TCE Concentration Trends, August 2008 to February 2014	1-41
Figure 1-14	1,4-Dioxane Concentration Trends, August 2008 to February 2014.....	1-43
Figure 1-15	1,1,1-TCA Concentration Trends, August 2008 to February 2014	1-47
Figure 1-16	Vinyl Chloride Concentration Trends, August 2008 to February 2014.....	1-49
Figure 1-17	Conceptual Site Model, OU 1, Area 6	1-53
Figure 2-1	Conditional Points of Compliance (1993 OU 1 ROD) for Groundwater and 1,000-Foot Domestic Well Installation Restriction Zone	2-8
Figure 4-1	Alternative 2 – Continue Pump and Treat With Ex-Situ Treatment Using Advanced Oxidation Process and Additional Extraction Wells	4-11
Figure 4-2	Alternative 3 – In-Situ Groundwater Treatment With ISCO Using Base- Activated Persulfate	4-19
Figure 4-3	Alternative 4 – In-Situ Groundwater Treatment With ISCO Using Catalyzed Hydrogen Peroxide	4-25
Figure 4-4	Alternative 5 – Expanded Groundwater Capture With All Untreated Effluent Discharged to Navy WWTF at Ault Field.....	4-34
Figure 5-1	Comparative Evaluation of Alternatives.....	5-22

CONTENTS (Continued)

TABLES

1-1	Potential Exposure Pathways Evaluated in Baseline Risk Assessment.....	1-58
1-2	1993 Well-by-Well Evaluation of Potential Human Health Risks Associated With Future Residential Use of Groundwater at Area 6.....	1-59
1-3	Chemicals Contributing to Potential Health Risks for Future Residential Users of Groundwater at Area 6.....	1-62
1-4	Potential Human Health Risks Associated with Future Resident Exposure to Soil at Area 6.....	1-62
2-1	1993 ROD Remediation Goals for Chemicals in Groundwater at Area 6.....	2-5
2-2	Recommended ROD Amendment Remedial Goals and COCs for Groundwater at Area 6.....	2-5
2-3	Chemical-Specific ARARs, Area 6	2-12
2-4	Location-Specific ARARs, Area 6	2-15
2-5	Action-Specific ARARs, Area 6.....	2-16
2-6	Remedial Action Objectives and General Response Actions	2-19
4-1	Summary of February and March 2014 Influent Concentrations	4-36
4-2	Summary of Groundwater Modeling Simulations.....	4-42
4-3	Comparison of Alternative Costs	4-50
4-4	Estimated Cost for Combined Alternatives 2 and 4.....	4-52
4-5	Summary of SiteWise Results	4-55
4-6	Alternative SiteWise Rankings	4-57
5-1	Summary of Alternatives Compliance with ARARs	5-6
5-2	Summary of Comparative Numerical Rating for Alternatives	5-28

FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 1

Contents

Date: 7/20/2018

Page x

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ABBREVIATIONS AND ACRONYMS

AOP	advanced oxidization process
ARAR	applicable or relevant and appropriate requirement
bgs	below ground surface
BOD	biochemical oxygen demand
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CHP	catalyzed hydrogen peroxide
COC	chemical of concern
COD	chemical oxygen demand
CSM	conceptual site model
DCA	dichloroethane
DCE	dichloroethene
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
ERD	enhanced reductive dechlorination
ESD	Explanation of Significant Difference
FS	feasibility study
FFS	focused feasibility study
GETR	groundwater extraction, treatment, and recharge
gpm	gallons per minute
GSR	green and sustainable remediation
IC	institutional control
HH	human health
IDW	investigation-derived waste
ISCO	in-situ chemical oxidization
kW	kilowatt
LCL	lower confidence limit
LUC	land use controls
µg/kg	microgram per kilogram
µg/L	microgram per liter
MCL	maximum contaminant level
MGD	million gallons per day
mg/L	milligram per liter
MMBtu	million British thermal units
MNA	monitored natural attenuation
msl	mean sea level
MTCA	Model Toxics Control Act

MWH	megawatt hour
NA	not applicable
N/A	not analyzed
NAPL	non-aqueous phase liquid
NAS	Naval Air Station
NAVFAC NW	Naval Facilities Engineering Command Northwest
Navy	U.S. Navy
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
NPDES	National Pollutant Discharge Elimination System
O&M	operation and maintenance
OSHA	Occupational Safety and Health Administration
OU	operable unit
PID	photoionization detector
PM	particulate matter
PM10	particulate matter of 10 micrometers or less
POTW	publicly owned treatment works
P&T	pump and treat
PW	present worth
RAO	remedial action objective
RCRA	Resource Conservation and Recovery Act
RCW	Revised Code of Washington
RG	remediation goal
RI	remedial investigation
ROD	Record of Decision
SIM	selected ion monitoring
SR	Washington State Route
TCA	trichloroethane
TCE	trichloroethene
TOC	total organic carbon
UCL	upper confidence limit
URS	URS Group, Inc.
VOC	volatile organic compound
WAC	Washington Administrative Code
WWTF	wastewater treatment facility

1.0 INTRODUCTION

This document presents results of a focused feasibility study (FFS) necessary to evaluate an appropriate range of remedial alternatives for addressing 1,4-dioxane at Operable Unit (OU) 1 Area 6, Naval Air Station (NAS) Whidbey Island, Oak Harbor, Washington. A remedial investigation/feasibility study (RI/FS) (U.S. Navy 1993) and Record of Decision (ROD) (U.S. Navy, Ecology, USEPA 1993) have been completed for the OU and site.

In 2002, U.S. Environmental Protection Agency (EPA) asked that the solvent stabilizer 1, 4-dioxane, a common additive to 1, 1, 1-trichloroethane (TCA), one of the volatile organic compound (VOC) contaminants at Area 6, be sampled for at NAS Whidbey Island. 1, 4-Dioxane was first detected in on-site wells in 2003; and in a private off-site well in 2005. According to EPA's Integrated Risk Information System (IRIS), the carcinogenic risk from oral exposure to 1, 4-dioxane is 1.1E-2 milligrams per kilogram per day (mg/kg/day). The maximum contamination limit for drinking water has not been established. However, many state governments have set advisory levels for this compound. The state of California has an action level of 3 micrograms per liter (µg/L). The State of Washington Department of Ecology (Ecology) has set a cleanup level of 0.44 µg/L. The U.S. Navy (Navy) mitigated the potential impact to the public by:

- Replacing the well for a private off-site owner with a deeper well (free of 1,4-dioxane)
- Having the Agency for Toxic Substances and Disease Registry (ATSDR) complete a health consultation for 1,4-dioxane in private drinking water wells near NAS Whidbey Island in 2005
- Educating the public by holding Restoration Advisory Boards and distributing 1,4-dioxane factsheets
- Installation of off-site wells downgradient of landfill to detect leading edge of plume

The existing groundwater extraction, treatment, and recharge (GETR) system uses air-stripping treatment technology which removes trichloroethene (TCE) and other VOCs, but does not remove the low levels of 1, 4-dioxane from extracted groundwater because of the compound's relatively low vapor pressure. 1,4-Dioxane re-enters the shallow aquifer at the site via the treated effluent. Although, the location of the re-entry has changed a few times, it has generally been on site and upgradient of the extraction wells, thus causing 1, 4-dioxane to remain in circulation on-site. However, before the GETR system was installed in 1995, it is possible 1,4-dioxane from the Navy site migrated off site.

Recent remedial action objective (RAO) monitoring has detected levels of 1,4-dioxane that exceed the Ecology Model Toxics Control Act (MTCA) method B cleanup levels of 0.44 µg/L in off-site Navy wells. EPA has informed Ecology that levels were detected above MTCA Method B cleanup levels.

This FFS adds 1,4-dioxane as a chemical of concern (COC). This FFS also recommends removal of 1,1-dichloroethane (DCA), and cis-1,2-dichloroethene (DCE) as chemicals of concern (COCs). Data supporting this recommendation can be found in the Annual Long Term Monitoring Reports for Area 6.

1.1 PURPOSE AND ORGANIZATION

The purpose of this FFS is to present an evaluation of alternatives capable of addressing 1,4-dioxane in groundwater at the site while achieving remediation goals (RGs) that are consistent with risk assumptions and protect potential receptors.

This document is organized as follows:

- Section 1 Introduction
- Section 2 Remedial Action Performance Criteria
- Section 3 Identification and Screening of Technology Types and Process Options
- Section 4 Development of Alternatives
- Section 5 Detailed Analysis of Alternatives
- Section 6 Public Involvement
- Section 7 References

1.2 BACKGROUND INFORMATION

1.2.1 Site Description and History

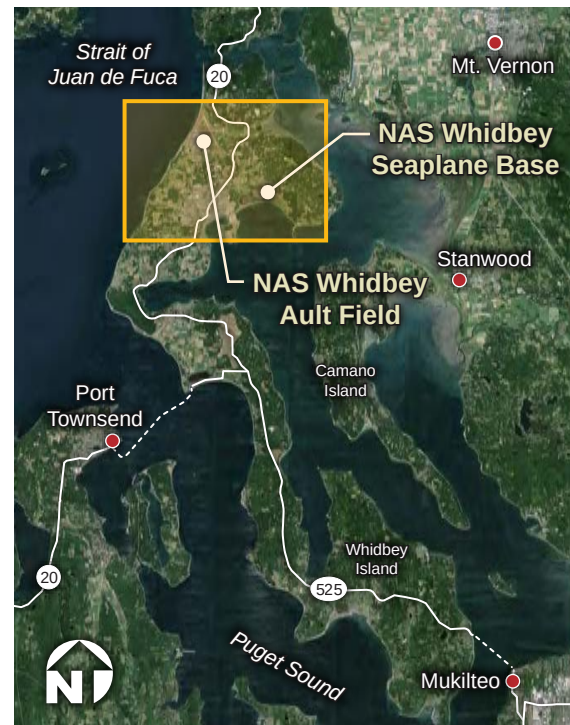
Physical Description and History

NAS Whidbey Island is located at the north end of Whidbey Island along the shoreline of the Strait of Juan de Fuca just north of Oak Harbor, Washington (Figure 1-1). Area 6 is a 260-acre tract in the southeast corner of Ault Field (Figure 1-2).

Within Area 6 are two areas where wastes are known to have been disposed of. Liquid wastes were disposed of at the former industrial waste disposal area at a time when regulatory requirements had not been established (Figure 1-2). These wastes reportedly consisted of solvents, oily sludges, thinners, and other compounds. Waste disposal began in 1969 and ended in the early 1980s. The former industrial waste disposal area is approximately 15 by 40 feet. During operation, it was a pit (also called the former waste oil pit designated as Site 55) approximately 10 feet deep. Prior to remedy implementation, it was filled and covered with natural vegetation.

A separate portion of Area 6 was used for Navy household municipal waste from 1969 to 1992. This landfill operations area was approximately 40 acres and is now covered with a synthetic cap, soil, and natural vegetation, as required by the OU 1 ROD (U.S. Navy, Ecology, and USEPA 1993). The synthetic cap prevents infiltration of rainwater. The presence of vinyl chloride and 1,4-dioxane in groundwater downgradient of the landfill indicates some source materials may have been disposed of in the landfill.

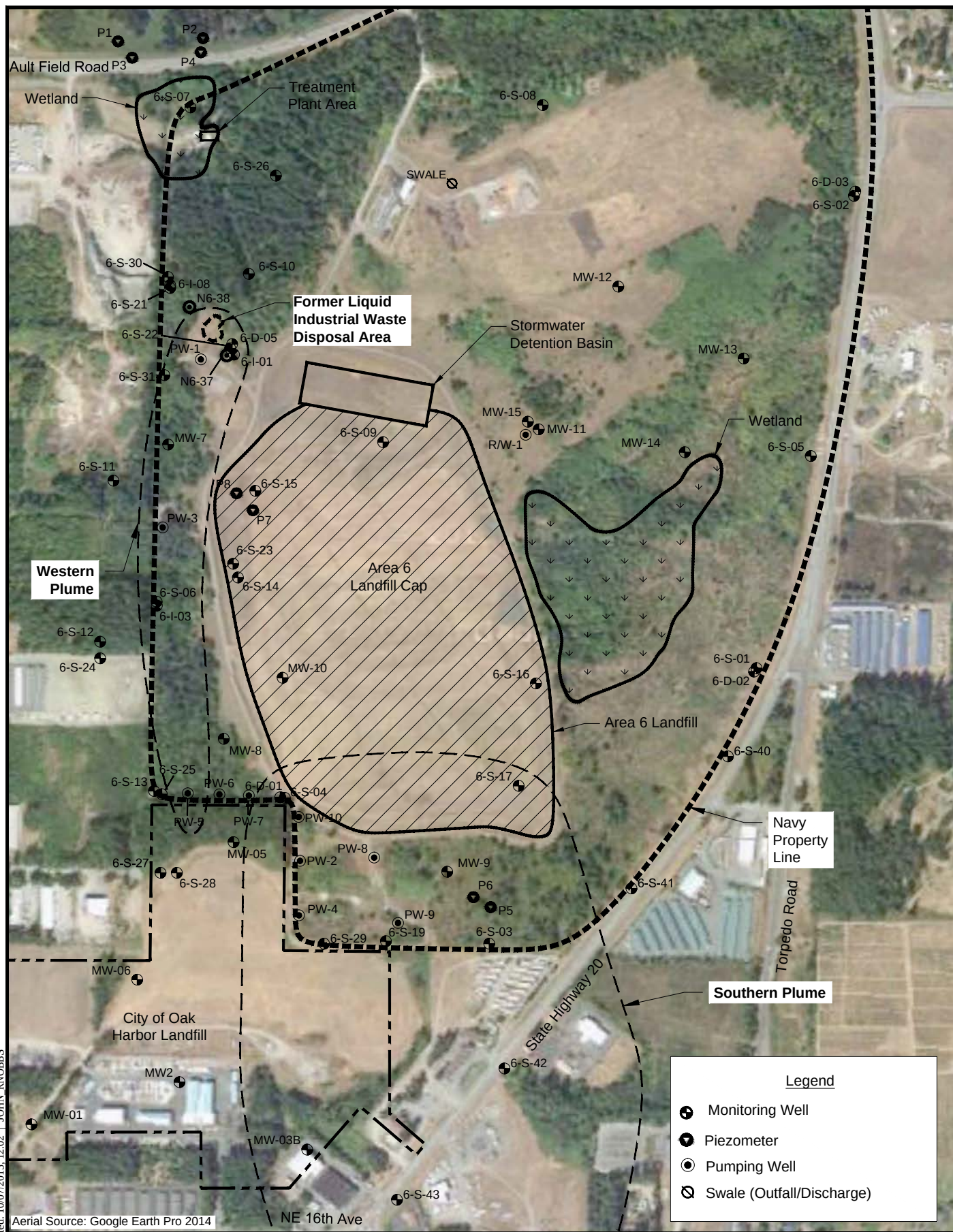
Area 6 is bordered by Ault Field Road to the north, State Highway 20 to the east, and the City of Oak Harbor Landfill on the south and southwest (Figure 1-2). Privately owned forested or logged land and a commercial sand and gravel quarry operation are located immediately west of Area 6. The City of Oak Harbor vehicle maintenance facility, an auto salvage yard, a transmission repair shop, the Auld Holland Inn, and a mobile home park are located on or near the southern boundary of the Oak Harbor landfill property. Private residences are located to the east, west, and south of the Area 6 landfill. A public storage rental facility, business, and private residences are located south of State Route (SR) 20.



U.S. NAVY

**Figure 1-1
Site Location Map**

DO 0055
Area 6
NAS Whidbey Island
FOCUSED FEASIBILITY
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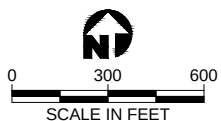


**Figure 1-2
Site Aerial Photograph
and Features**

DO 0055
 Area 6, NAS Whidbey Island
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Investigative History

A chronology of investigations conducted at Area 6 is:

- 1993 - Final RI/FS (U.S. Navy 1993)
- 2001 - Source area characterization (U.S. Navy 2001)
- 2001 and 2003 - Soil vapor sampling (U.S. Navy 2004a)
- 2010 - Evaluation of treatment technologies (U.S. Navy 2011a)
- 2010 and 2011 - Additional vadose zone investigation (U.S. Navy 2013b)
- 2014 - Data gap sampling in source area (U.S. Navy 2015b)
- 2014 - Treatability study (U.S. Navy 2015a)

Geophysical and soil vapor surveys were conducted at Area 6 to evaluate the lateral extent of landfilled material and to choose soil boring and groundwater monitoring well locations for the RI. Five sediment samples and six surface water samples were collected and analyzed during the RI to assess potential impacts to the intermittent stream at the site. Data from 25 groundwater monitoring wells installed at the site were used to assess potential impacts to the shallow, intermediate, and deep aquifers at the site during the RI, and seven soil vapor extraction wells were installed to assess soil vapor. Soil samples from borings installed during the RI suggested that the contaminant mass had migrated to the groundwater and little remained in the vadose zone to serve as a long-term source. An aquifer performance test was performed to estimate hydraulic characteristics of the shallow aquifer (U.S. Navy 1993).

Unacceptable ecological risks were identified based on concentrations of COCs in Area 6 soils and in sediments and surface water from the intermittent stream at Area 6. The precise location for the industrial waste disposal area(s) could not be identified at the time, and it was determined that remedial action could cause more environmental harm than the low levels of existing chemical contaminants. It was also determined that the greatest potential risk to human health at Area 6 was posed by the future movement of organic chemicals in groundwater (U.S. Navy 1993). The location of a disposal pit was later identified and a cleanup action was completed in 2002 (U.S. Navy 2002).

Two distinct groundwater plumes have been identified at Area 6. The first plume is referred to as the western groundwater plume, which originates from the former industrial waste disposal areas (i.e., the former waste oil pit/Site 55). Multiple VOCs were detected at concentrations exceeding risk levels in the western groundwater plume. The second plume is referred to as the southern groundwater plume and is in the southern part of the landfill where contaminants potentially originate from the capped landfill (i.e., landfill leachate) and/or from areas north of

the landfill where a groundwater treatment plant has been discharging since 1995. Vinyl chloride was detected at concentrations exceeding risk-based concentrations in the southern groundwater plume (U.S. Navy 2004). In 2002, the solvent stabilizer 1,4-dioxane was sampled for and identified at concentrations exceeding the MTCA Method B level in both plumes.

An interim action ROD was developed that resulted in the installation of the GETR system in 1995 to prevent the continued spread of contaminants from the former industrial waste disposal area in the shallow aquifer beneath Area 6, and to reduce the risk of impact to existing and future groundwater users (U.S. Navy, Ecology, and USEPA 1992). The system called for in the final ROD (U.S. Navy, Ecology, and USEPA 1993) also addresses the southern groundwater plume. The system consists of 10 groundwater extraction wells with eight currently operating, an equalization tank, particulate filters, packed column air stripper, discharge piping, and miscellaneous pumps, controls, instrumentation, and appurtenances.

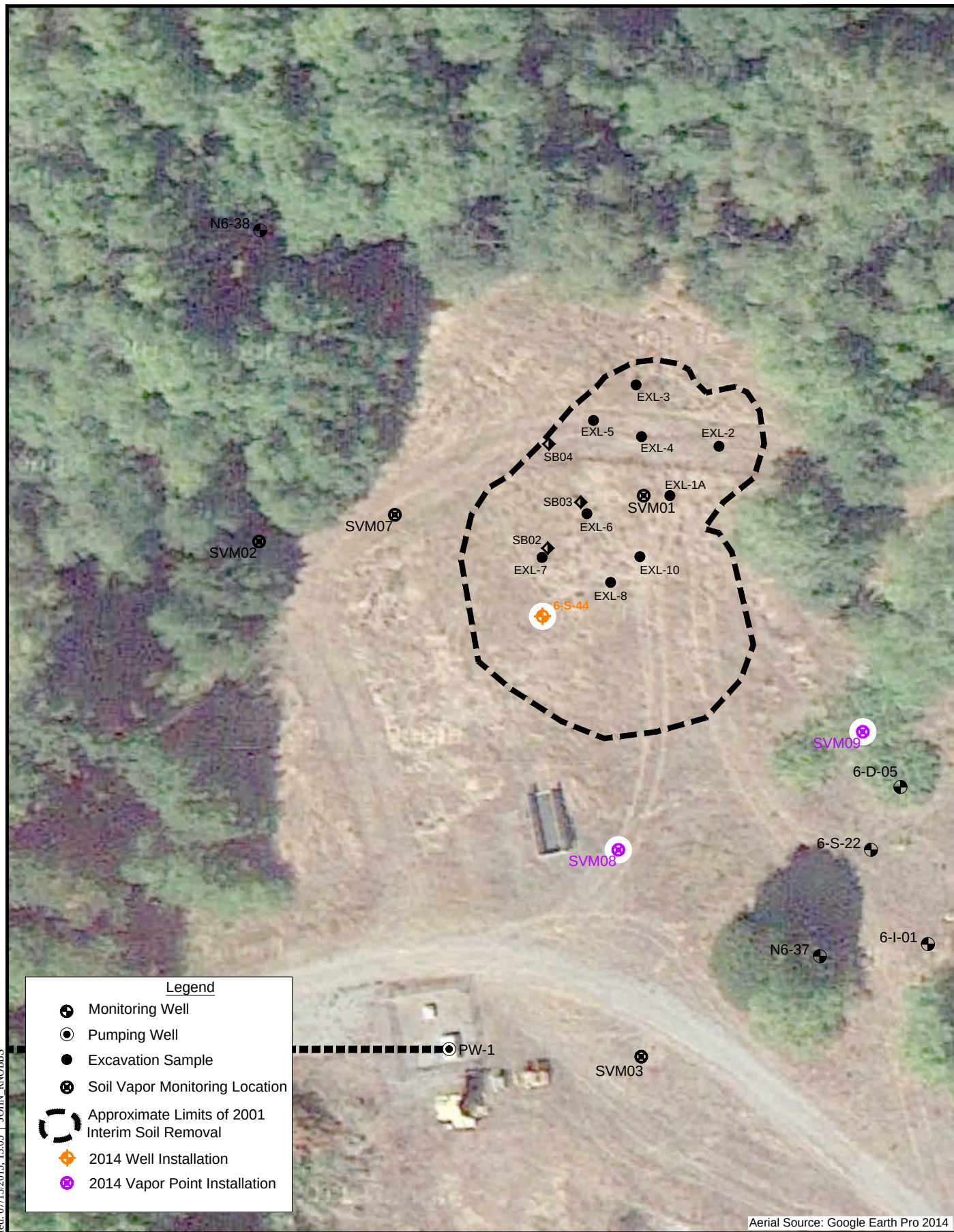
The 1993 OU 1 ROD identified TCE, 1,1,1- TCA, 1,1- DCA, 1,1- DCE, cis-1,2-DCE, and vinyl chloride were identified as COCs in groundwater (U.S. Navy, Ecology, and USEPA 1993).

Soil vapor monitoring points were constructed at nine locations from 2001 through 2014 (U.S. Navy 2015c). These monitoring points were constructed with four depth-specific vapor probes at each point consistent with State of Washington regulations covering vapor soil wells. Soil vapor samples were collected in 2001, 2003, 2010, 2011, and 2014. Results have been used to monitor vadose zone soil impact changes over time (Figure 1-3).

In 2003, 1,4-dioxane was identified in groundwater at the site. Within the limits of the monitoring network at the time, the lateral extent of 1,4-dioxane in groundwater was then approximated. During 2008, four additional groundwater monitoring wells were installed along the northwestern shoulder of SR 20 to further refine the lateral extent of 1,4-dioxane in groundwater (U.S. Navy 2008).

During 2014, a groundwater monitoring well (6-S-44) was installed directly beneath for the former source area where the interim soil removal action was conducted (U.S. Navy 2015c) (Figure 1-3).

Eight multipurpose (oxidant injection and monitoring) wells and three monitoring wells were installed during 2014 to conduct an in-situ chemical oxidization (ISCO) treatability study just south of the former source area (U.S. Navy 2015b) (Figure 1-4).



Legend

Monitoring Well

Pumping Well

Excavation Sample

Soil Vapor Monitoring Location

Approximate Limits of 2001 Interim Soil Removal

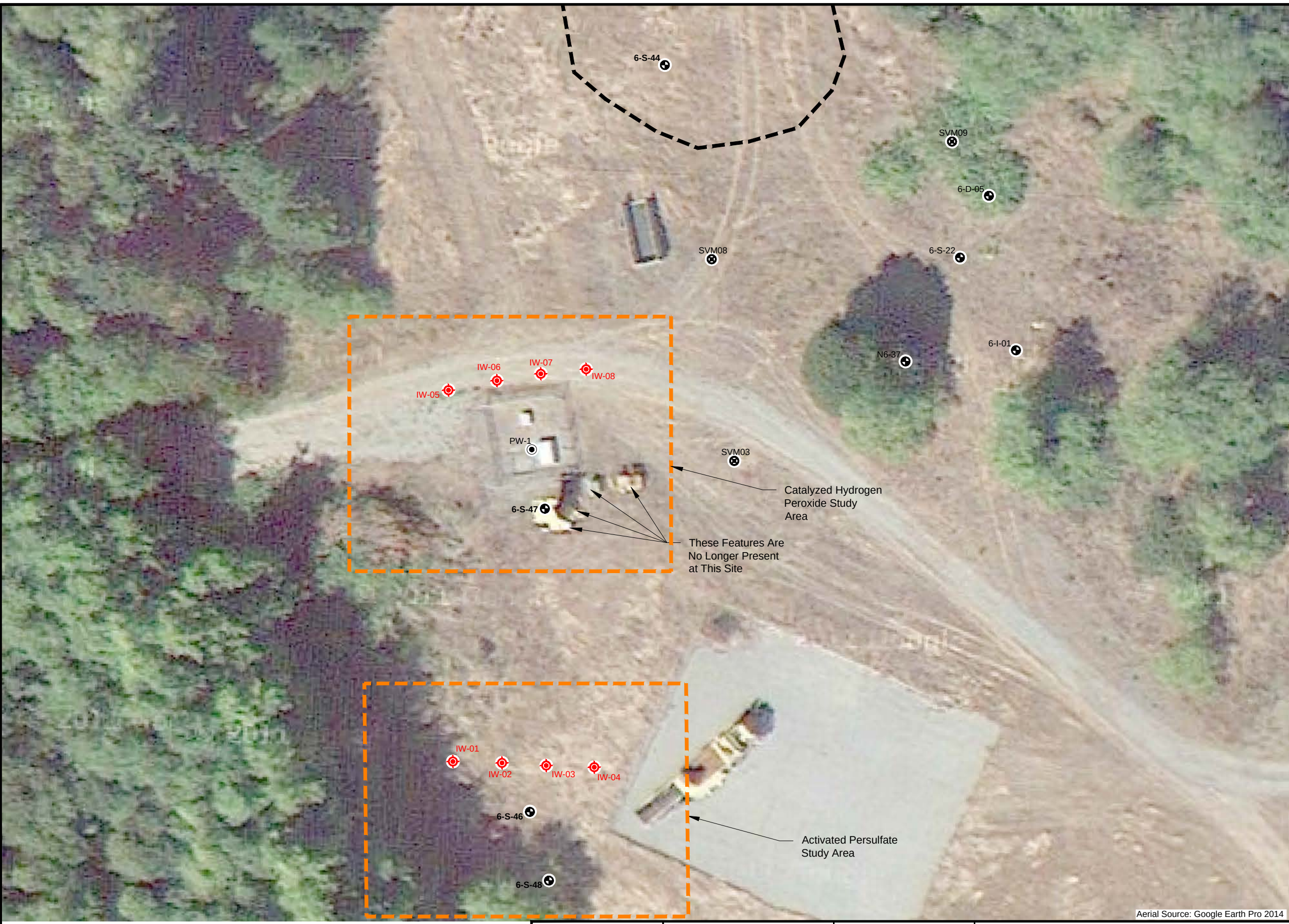
2014 Well Installation

2014 Vapor Point Installation

Aerial Source: Google Earth Pro 2014

J:\GIS\Projects\NAVY\WHIDBEY\DO 55\FFS\Fig 1-3 Soil Vapor_GW\MW.dwg
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J:\GIS\Projects\NAVY\WHIDBEY\DO 55\FPS\Fig 1-4 Inject Well Loc.dwg
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Aerial Source: Google Earth Pro 2014

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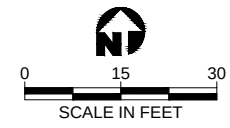


Figure 1-4
Injection Well Location Map

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Delivery Order 0055, Mod 2

Section 1.0

Date: 7/20/2018
Page 1-10

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Hydrogeology

The U.S. Geological Survey has identified up to five major hydrogeologic units (aquifers) above bedrock in Island County (Jones 1985 and Sapik et al. 1988). The existing aquifer units are composed of sand or sand and gravel, while the adjacent confining layers are composed of till, glaciomarine drift, or nonglacial clay and silt. Perched, saturated zones may exist locally above noncontinuous areas of till or other clay-rich units.

Four glacial units were identified at Area 6: the Vashon Recessional Outwash, Vashon Till, Vashon Advance Outwash, and Whidbey Formation. The Vashon Recessional Outwash or the underlying Vashon Till are typically encountered at the ground surface. Where these units are eroded away, sand and gravel of underlying Vashon Advance Outwash is exposed at the surface. Beneath the Vashon Advance Outwash are sand, silt, and clay of the Whidbey Formation (Units 1 through 4). A description of the units can be found in U.S. Navy 2013b. Stratigraphy at the site is shown on the Figure 1-5 south-to-north cross-section.

Three of these five upper aquifers were encountered at Area 6 and are termed the shallow aquifer, the intermediate aquifer, and the deep aquifer. The shallow aquifer is an unconfined groundwater unit located in Vashon Advance Outwash beneath Area 6 and the Oak Harbor Landfill. The former liquid industrial waste disposal pits discharged directly into this unit. The intermediate aquifer is a moderately continuous groundwater body found in the sandy unit that corresponds to the Whidbey Formation Unit 2. Near Area 6 and the Oak Harbor Landfill, this aquifer is confined below the silt and clay of Whidbey Formation Unit 1. The deep aquifer is also a nearly continuous confined groundwater body found in the vicinity of Area 6 and the Oak Harbor Landfill. This aquifer is confined below the silt and clay of Whidbey Formation Unit 3 and occupies a thick sand layer in Whidbey Formation Unit 4. Groundwater data show that the upper aquifer is the only aquifer impacted by former actions at the site.

Groundwater in the upper aquifer at the site is unconfined. The depth to groundwater varies significantly because of an approximate 100-foot difference in the ground surface elevation across the site. Surface elevation is approximately 100 feet above mean sea level (msl) upgradient of the former source area and rises to approximately 200 feet at the source area. Surface elevation remains at around 200 feet msl from the source area to the southern site property line. Surface elevation decreases slightly from this point to around 180 feet msl. Surface elevation also decreases to approximately 175 from the eastern edge of the landfill to the southeast at SR 20.

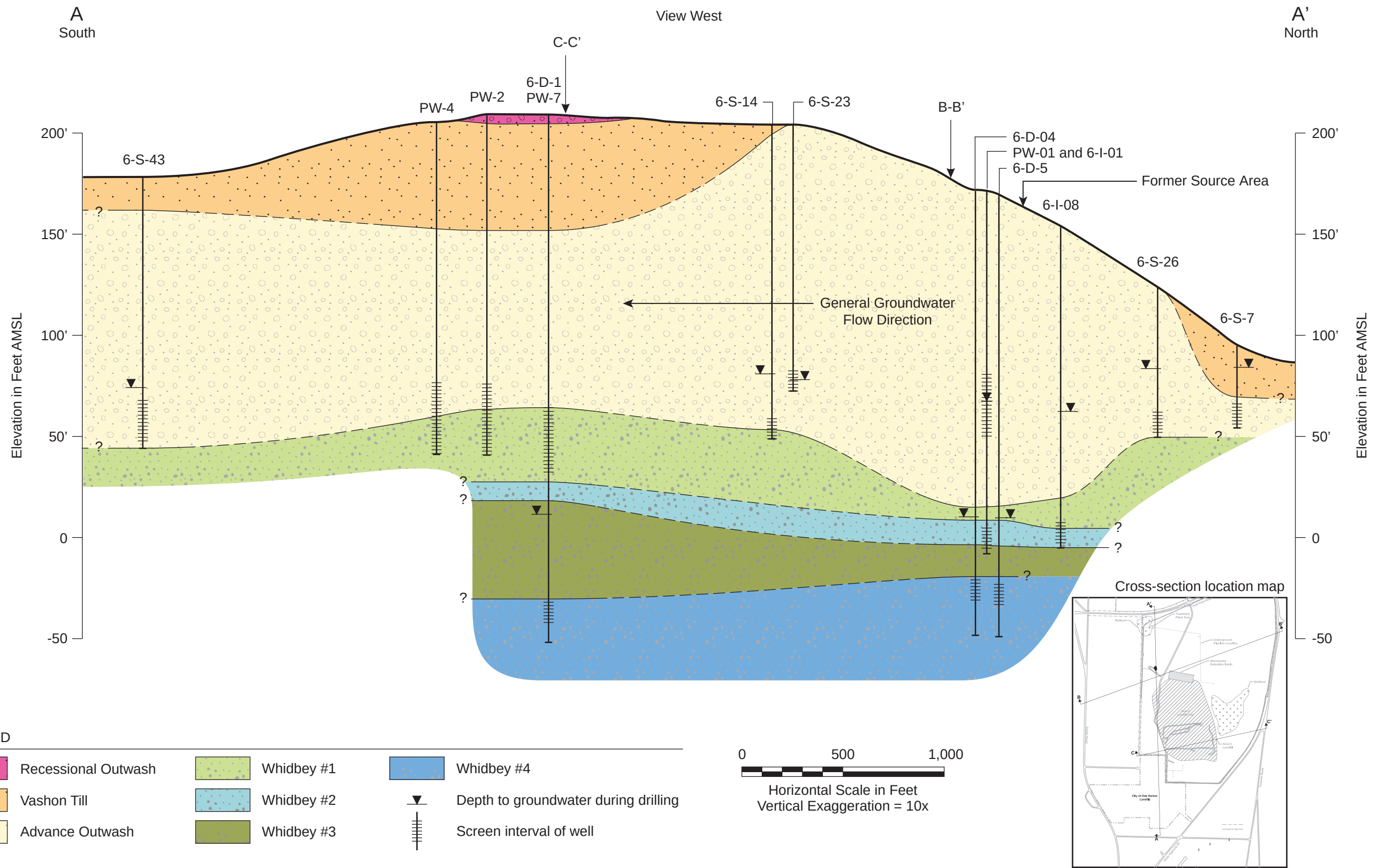
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Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 1.0

Date: 7/20/2018

Page 1-12

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Depth to water was monitored during February 2014 (wet season) in wells shown on Figure 1-6 (U.S. Navy 2014a). At that time, depth to water ranged from 39 feet below ground surface (bgs) in the upgradient portion of the site to 143 feet bgs within the extraction network capture zone along the southern Area 6 boundary. February 2014 depth to water in the source area averaged around 90 feet bgs and increased to an average of around 120 feet bgs in the midplume region along the western landfill edge. February 2014 depth to water ranged from 100 to 120 feet bgs in the downgradient wells.

Groundwater in Area 6 flows generally southward and discharges to Crescent Harbor and Oak Harbor. Figure 1-6 shows the map of groundwater elevations calculated from depth to groundwater water measurements obtained during the February 2014 semiannual monitoring event (U.S. Navy 2014a) under active extraction conditions.

The groundwater velocity within two portions of the site is estimated using the following parameters:

- February 2013 hydraulic gradients across the site:
 - 0.004 in the western plume area based on data for wells 6-S-10 and 6-S-29 (U.S. Navy 2014b)
 - 0.00165 in the southern plume area based on data for wells 6-S-27 and 6-S-43 (U.S. Navy 2014a)
- RI-assumed effective porosity of 0.25 (U.S. Navy 1993)
- An average hydraulic conductivity calculated from the pump test data of 71.67 feet per day (U.S. Navy 1993)

A flattening of the groundwater surface is evident south of the Area 6 property boundary (Figure 1-6). This is reflected in calculated groundwater flow velocities for each area.

Using the above inputs, the average linear groundwater flow in the plume area along the western landfill edge (western plume) is approximately 1.1 feet per day or 400 feet per year, under pumping conditions. The average linear groundwater flow in the southern plume area is approximately 0.5 foot per day or 183 feet per year, under pumping conditions. The slowing in the southern plume region could be a result of a normal gradient change or a reduction in gradient as a result of the upgradient pumping for the extraction and treatment system.

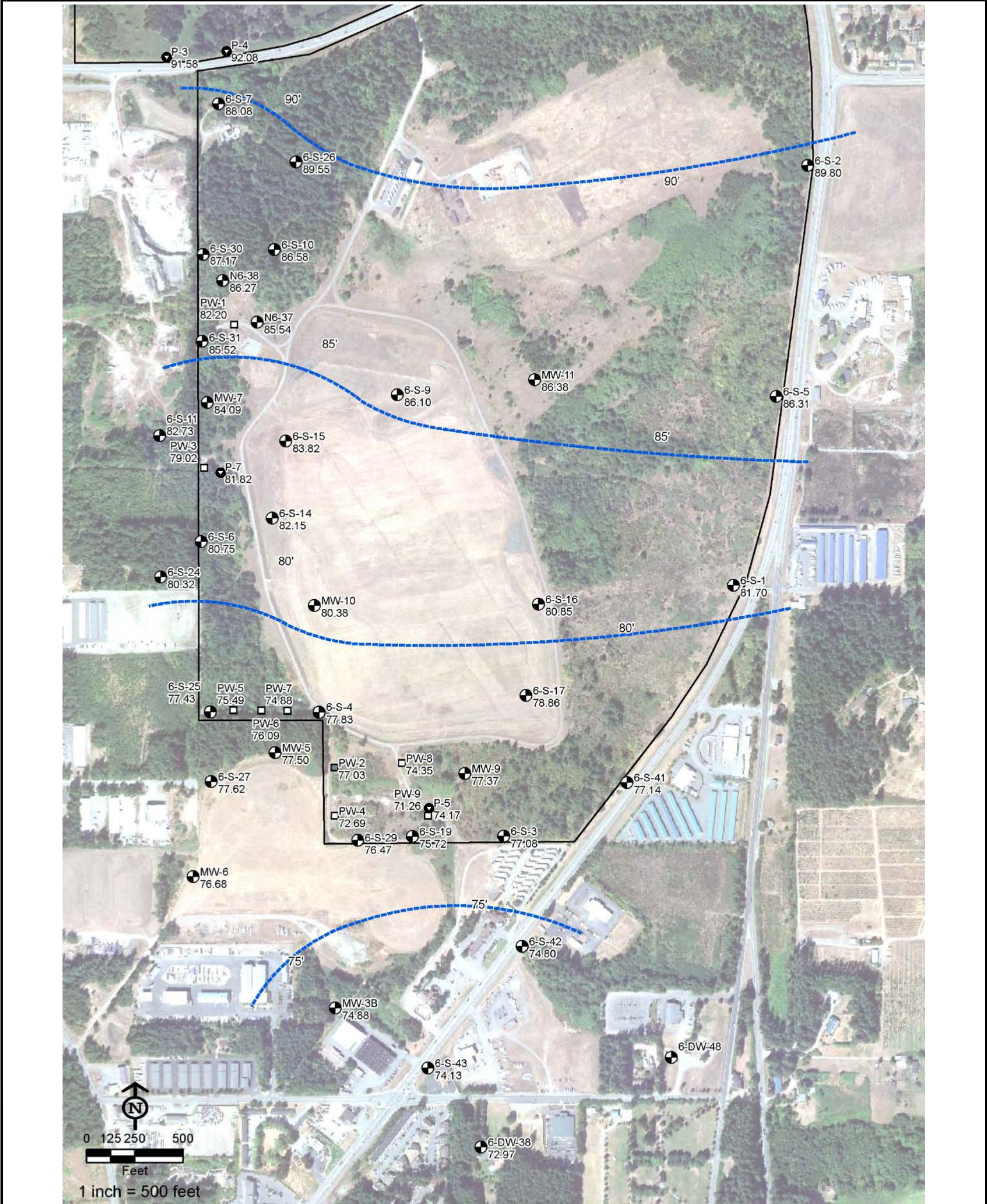
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Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 1.0

Date: 7/20/2018

Page 1-16

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LEGEND

- 75' GROUNDWATER CONTOUR
- NASWI BOUNDARY
- MONITORING WELL

- PIEZOMETER
- PRODUCTION WELL
- PRODUCTION WELL NOT OPERATING

NOTES

- 1) WATER LEVELS WERE MEASURED BETWEEN FEBRUARY 3 AND 19, 2014
- 2) PUMPING LEVELS OF PRODUCTION WELLS WERE NOT CONTOURED

Source: Data and Aerial Photo U.S. Navy 2014a

U.S. NAVY

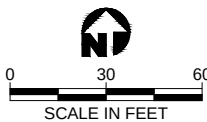


Figure 1-6
February 2014 Groundwater Surface Elevations

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Remedial History

A chronology of remedial actions conducted at Area 6 is:

- 1992 - Interim ROD execution
- 1993 - ROD execution (U.S. Navy, Ecology, and USEPA 1993)
- 1993 to 1994 – GETR system construction
- 1995 to present – GETR system operation and monitoring
- 2001 - Interim soil removal action

The RAOs and groundwater RGs identified in the ROD are based on protection of drinking water criteria in all areas outside of the conditional points of compliance, which are the boundaries of the landfill and an area within the former liquid waste disposal area that is the inferred source of VOCs in groundwater.

The GETR system was installed in 1995 to contain the groundwater plumes and a landfill cap was installed in 1996 to prevent infiltration of precipitation through the landfill. The GETR system has operated continuously since 1995 with minor interruptions. The current air-stripping treatment system does not remove 1,4-dioxane from extracted groundwater. The treatment system effluent discharge point has varied since the initial start. Effluent was first discharged via subsurface injection at wells located east of the northeastern corner of the landfill, in the vicinity of wells MW-11, MW-15, and R/W-1 (Figure 1-2). This setup experienced significant performance issues, primarily biofouling, so a gallery was installed in the same proximity with similar issues. Effluent was then discharged to the stormwater detention pond north of the landfill. Infiltration rates were not sufficient, and discharge was switched to a surface swale north of the stormwater detention pond, which is the current location.

Ten groundwater extraction wells and 67 monitoring wells have been installed to facilitate groundwater extraction and monitor performance. Currently eight production wells, 31 on-site monitoring wells, and 2 private drinking water wells are being sampled. The data used in this evaluation was obtained from the annual 2013 to 2014 groundwater long-term monitoring report (U.S. Navy 2014a). Data continues to be collected in February and August of each year.

To reduce the residual contaminant mass within the former liquid industrial waste disposal area, the Navy conducted an interim soil removal action in 2001. Soil removal occurred to a depth of approximately 20 feet bgs. The approximate limits of this soil removal are shown on Figure 1-3. Pre-soil removal characterization was conducted to refine the Navy's understanding of the lateral and vertical extents of VOCs in soil. The results showed most of the VOC mass resided in the

top 20 feet of soil in the source area. Approximately 2,315 cubic yards of VOC-impacted soil were removed (U.S. Navy 2002).

The Navy began evaluating alternatives to address the wide-spread, diluted 1,4-dioxane plume in 2009. Actions taken by the Navy to address the 1,4-dioxane have included:

- 2009 to 2011 – Conducted bench-scale testing of microbial mats and advanced oxidization for ex-situ treatment of extracted groundwater
- 2010 to 2011 – Updated conceptual site model (CSM) and evaluated residual, vadose zone soil source strength in the hazardous material storage area
- 2011 to 2012 – Performed follow-up advance oxidization bench-scale testing to further evaluate advanced oxidation as an ex-situ treatment technology
- 2012 to 2013 - Developed a comprehensive, 3-dimensional, numeric groundwater model to use as an evaluation and remedy performance assessment tool
- 2013 to 2014 – Continued optimization evaluation and developed plans for conducting field-scale ISCO treatability studies
- 2014 – Conducted field scale ISCO treatability study (eight injection wells and three monitoring wells were installed for this study in the source area)

During 2009, the Navy evaluated the use of microbial mats and advanced oxidation as potential alternatives for treating groundwater containing 1,4-dioxane. Bench-scale tests were performed. Results of the microbial evaluation indicated that the microbial mats would need special microbes (e.g., CB 1190) and regular inoculations arranged in a large constructed wetland to provide the necessary residence time to remove 1,4-dioxane from the treatment system effluent.

Results of the advanced oxidization using ozone and hydrogen peroxide showed a higher degree of viability and additional bench-scale testing was conducted to refine the process, including optimizing dosages and estimating full-scale design parameters.

Additional bench-scale studies were conducted to evaluate sonic technology in combination with persulfate. Sonication applies high energy sound waves to impacted groundwater with causes microbubbles. Collapse of these microbubbles creates hydroxyl compounds that oxidize dissolved organic compounds in groundwater.

The CSM was updated. A comprehensive, 3-dimensional groundwater model was also developed. The 3-dimensional model allows one to simulate site response to various in-situ and

ex-situ technologies. The groundwater model was also used during the optimization study as a tool to evaluate potential outcomes of various remedial alternatives and evaluate more efficient pumping scenarios.

1.2.2 Nature and Extent of Contamination

Source Area Soil

The source area location is identified on Figure 1-2. During the 2001 interim removal action (U.S. Navy 2002), a significant portion of the residual contaminant mass in vadose zone soil was removed. The excavation base soil samples contained TCE at concentrations ranging from 210 to 8,200 micrograms per kilogram ($\mu\text{g/kg}$) and represent soil left in place after the interim removal action (Figure 1-3). The excavation base soil samples did not contain 1,1,1-TCA, 1,1-DCA, 1,2-DCE, cis-1,2-DCE, or vinyl chloride at concentrations greater than their respective reporting limits (U.S. Navy 2002).

Subsequent sampling and investigations were conducted from 2003 to 2011. The *Vadose Zone Investigation and Conceptual Site Model* report (U.S. Navy 2013b) concluded residual TCE in vadose zone soil would not impact groundwater at levels greater than the RG. The data gap analysis (U.S. Navy 2015c) concluded residual TCE has the potential to act as a source to groundwater at concentrations greater than the TCE RG of 5 $\mu\text{g/L}$.

Soil vapor sampling was conducted in the former source area prior to and following the interim removal action (Figure 1-3). Results are summarized in U.S. Navy 2015c. Soil vapor monitoring in 2001, 2003, 2010, 2011, and 2014 show decreasing concentration trends. The rate of decrease is variable between monitoring points and analyte.

Soil samples were collected from a monitoring well (6-S-44) (Figure 1-3) installed in 2014 directly beneath the former excavation area at depths of 25, 40, and 55 feet bgs. Soil contained TCE at concentrations ranging from 72 to 140 $\mu\text{g/kg}$ (U.S. Navy 2015c). These concentrations exceed the calculated MTCA Method B soil cleanup level of 33 $\mu\text{g/kg}$ for protection of groundwater (U.S. Navy 2015c).

Eight injection wells (IW-01 through IW-08) and three monitoring wells (6-S-46, 6-S-47, and 6-S-48) were installed during 2014 for the ISCO treatability study (Figure 1-4). Soil samples were collected from the injection well locations at 5-foot intervals and field screened with a photoionization detector (PID). PID readings from wells IW-01 to IW-04 indicate that vadose zone soil impacts are minimal, limited to the immediate depths near the groundwater surface (approximately 80 feet bgs) in this area south of well PW-1, and could be a result of off-gassing from the groundwater surface. PID results for wells IW-05 through IW-08 line show an area of VOC impacts in the vadose zone above the groundwater surface. This line of wells is

approximately 15 feet upgradient of well PW-1 and relatively close to the former source area. Seventeen samples were submitted for laboratory analysis. TCE concentrations in the submitted samples ranged from 37 to 290 $\mu\text{g}/\text{kg}$, which exceed the MTCA Method B protection of groundwater cleanup level (U.S. Navy 2015b).

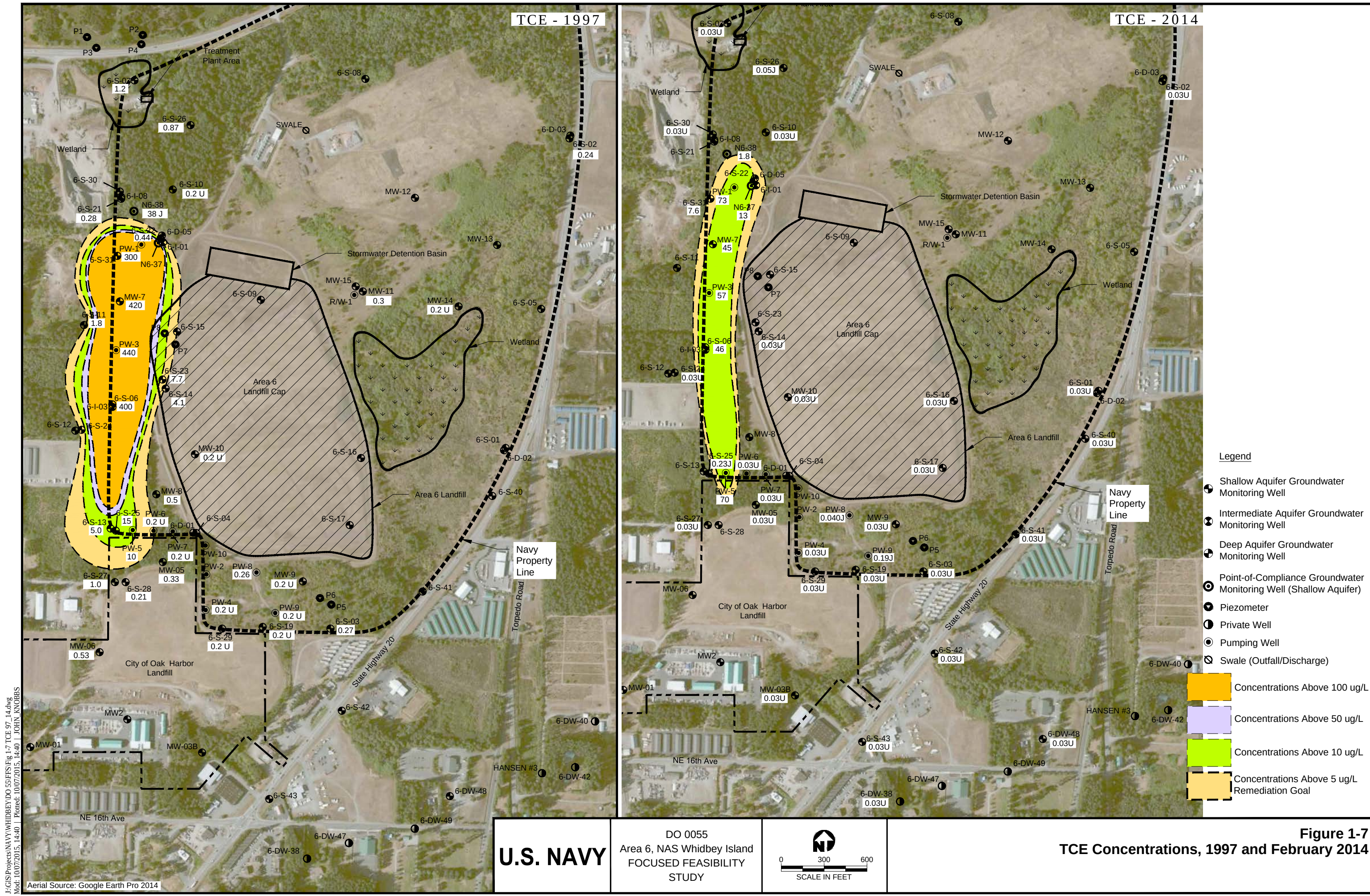
Groundwater

The distribution of VOCs has generally been described as comprising two plumes (Figure 1-2). The western plume, located along the western property boundary, consists of TCE, 1,1,1-TCA, 1,1-DCA, cis-1,2-DCE, 1,1-DCE, and 1,4-dioxane. The southern plume, located in the southern and southeastern portions of the site, consists primarily of vinyl chloride and 1,4-dioxane.

The GETR has been successful at containing and decreasing the areal extent of the VOC plume along the western and southwestern site boundaries and reducing the overall mass of TCE, 1,1,1-TCA, 1,1-DCA, 1,1-DCE, and cis-1,2-DCE in groundwater. The 1997 and 2014 plume areas for TCE, 1,1,1-TCA and 1,1-DCE in groundwater are shown on Figures 1-7, 1-8, and 1-9, respectively. TCE remains in groundwater at concentrations from 5 to 73 $\mu\text{g}/\text{L}$, which are above the RG of 5 $\mu\text{g}/\text{L}$. Figure 1-7 shows one monitoring well (6-S-31) along the western boundary that has a slight elevation of TCE (7.6 $\mu\text{g}/\text{L}$). The 1997 and 2014 plume area for cis-1,2-DCE is shown on Figure 1-10. This shows that the GETR has reduced cis-1,2-DCE to concentrations below the RG of 70 $\mu\text{g}/\text{L}$ for samples from all wells monitored in 2014. 1,1-DCA has not been measured above the RG of 80 $\mu\text{g}/\text{L}$ in samples from wells monitored since at least 2011 (U.S. Navy 2014a). The decreases in TCE and 1,1,1-TCA daughter products suggests sequential degradation is not strong at this site.

The 1997 and 2014 distributions of vinyl chloride are shown on Figure 1-11. Vinyl chloride concentrations have been reduced to levels below the 1993 ROD RG value of 0.1 $\mu\text{g}/\text{L}$ in groundwater along the western site boundary. Although the 2014 data shows that vinyl chloride concentrations in the central portion of the southern plume have declined significantly since 1997, vinyl chloride concentrations exceeding the 1993 ROD RG extend approximately 1,400 feet downgradient of the southern site boundary. The highest vinyl chloride concentrations in groundwater are observed in samples from well 6-S-43, which is immediately downgradient of The City of Oak Harbor Landfill.

Groundwater data for February 2015 samples show similar concentrations.



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Aerial Source: Google Earth Pro 2014

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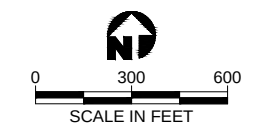
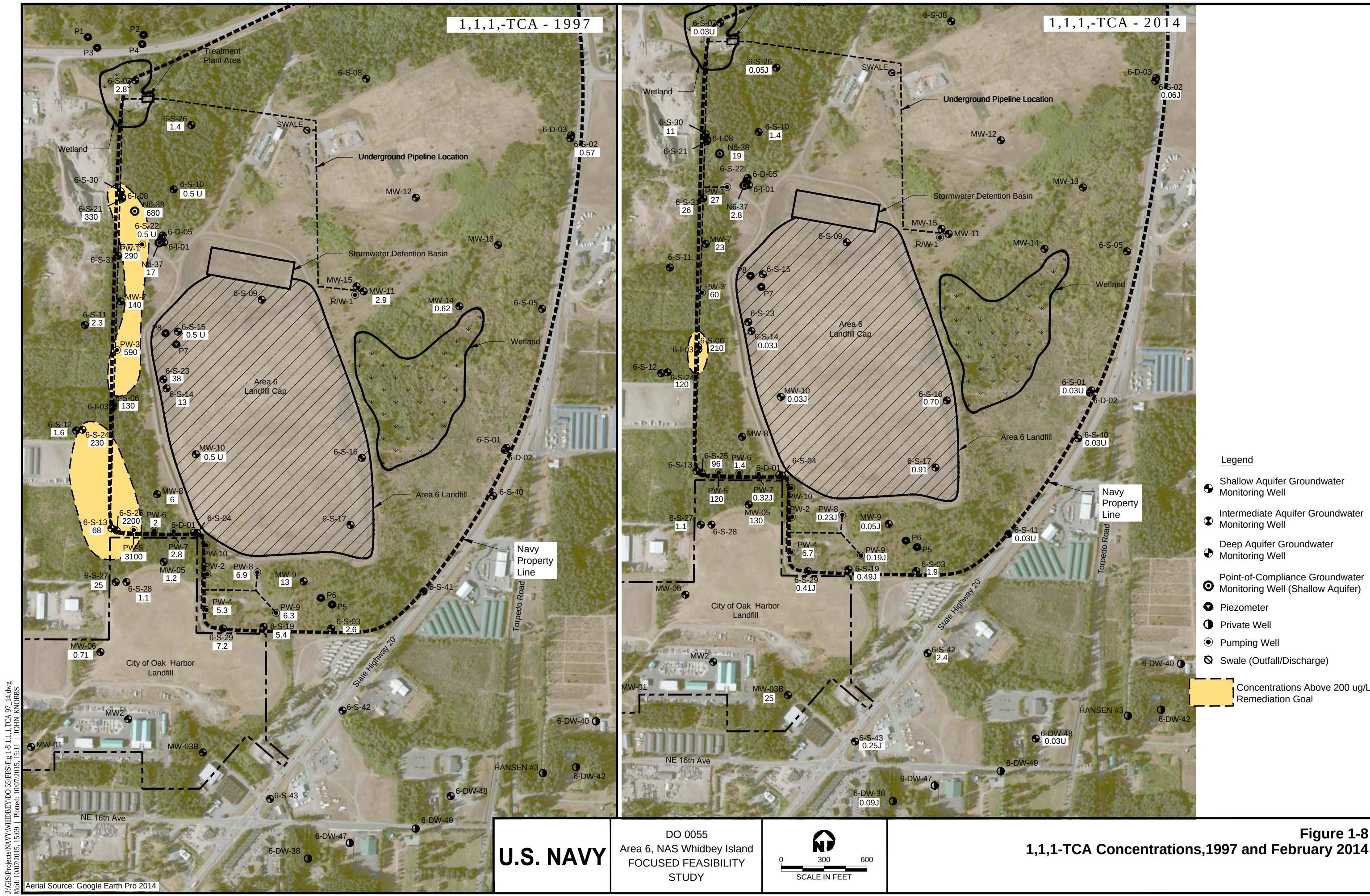


Figure 1-7
TCE Concentrations, 1997 and February 2014

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Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 1.0

Date: 7/20/2018
Page 1-28

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AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 1.0

Date: 7/20/2018

Page 1-30

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The 2003 and 2014 distributions of 1,4-dioxane in groundwater are shown on Figure 1-12. It is believed that 1,4-dioxane has been redistributed at the site by reinjection of treated effluent containing 1,4-dioxane in two different locations as well as subsequent surface infiltration at an additional two different locations. The lateral extent of 1,4-dioxane is far larger, and more dilute, than the VOC plume along the western boundary. The 2014 1,4-dioxane distribution extends at least 2,000 feet downgradient of the southern site boundary. Data through 2015 show that the highest concentrations are observed in groundwater samples from 6-S-43, which is immediately downgradient of The City of Oak Harbor Landfill.

Groundwater modeling (Appendix B) demonstrates that continued pumping from wells along the southern boundary of the site is capturing both 1,4-dioxane and vinyl chloride on site, and is slowing the downgradient migration rate of the portion of the plume that is already off-site and past SR20.

Contaminant Concentration Trends

For discussion purposes, the monitoring well data from February 2008 to February 2014 has been broken into plume segments as follows:

- Six source area wells located within the identified contaminant release area immediately upgradient or downgradient from the release area
- Six midplume wells located along the contaminant plume between the source area and the capture zone, three are situated along the centerline of the plume, one along the western plume margin, and two along the eastern plume margin
- Nine capture zone wells located within the portion of the site where active groundwater pumping occurs at multiple, closely spaced locations, three static monitoring wells, and six active pumping wells
- Seven downgradient wells comprising four monitoring wells located within or downgradient of the capture zone wells and three wells situated off site along SR 20

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Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 1.0

Date: 7/20/2018

Page 1-34

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The methodology used to estimate the concentration trend is summarized as follows:

- Log-transform the concentration data for a designated COC and well.
- Transform time into the decimal equivalent in years, with zero set at the earliest sample date for a given well and 1 equal to one calendar year.
- Plot the log-transformed concentration data against time.
- Compute the concentration decay rate as the slope of the log-transformed concentration data against time.
- Calculate the 95 percent upper confidence limit (UCL) on the concentration decay rate of the log-transformed concentration data as a function of time.
- Calculate the 95 percent lower confidence limit (LCL) on the concentration decay rate of the log-transformed concentration data as a function of time.

These slopes are then used to determine the confidence in the null hypothesis that the log-transformed concentration data possess a negative decay rate (concentrations are decreasing with time). The rationale for this determination is summarized in Appendix A, Table A-1.

VOC concentrations in groundwater have generally decreased between 2008 and 2014, overall VOC concentrations have decreased an order of magnitude since installation of the GETR. VOCs concentrations have decreased significantly between 2008 and 2014 in the source area and western plume. With the exception of vinyl chloride, TCE, 1,1,1-TCA, and identified daughter products are not present beyond the southern extent of extraction system capture zone and do not extend into the southern plume. A comparison of current and historical VOCs and 1,4-dioxane data shows that the extraction system has been successful at mitigating the plume along the western boundary and capturing it in the southwestern extraction wells.

Vinyl chloride and 1,4-dioxane extend downgradient of the extraction system capture zone and appear to continue to migrate. Vinyl chloride concentrations are decreasing and or are stable to decreasing in 12 of the 13 capture zone and downgradient wells. Off-site, there is a decreasing trend in all wells with detectable levels of vinyl chloride.

1,4-Dioxane concentrations are decreasing in 5 of the 9 capture zone wells (PW-6, PW-7, PW-4, and PW-9) monitored between February 2008 and February 2014. In two more wells (6-S-25 and 6-S-27) 1,4-dioxane is below the detection limit. 1,4-Dioxane is stable to increasing at low levels (3.6 to 4.2 µg/L) in two extraction wells (PW-5 and PW-8). These trends indicate that any upgradient source is depleting or contained by upgradient extraction wells. In the monitoring

wells immediately downgradient of the southern boundary extraction wells, 1,4-dioxane levels are stable to decreasing or decreasing (namely, in wells 6-S-29, 6-S-19, 6-S-03, and 6-S-41). Further downgradient, off-site wells 6-S-42 and 6-S-43 showed increasing trends between February 2008 and February 2014, but are less than their peak concentrations of 18 and 8.4 µg/L, measured in 2012 samples.

The data trends of the four study areas are summarized below. Appendix A, Table A-1 shows the decision criteria and interpretation of the statistical analysis. Concentration trend analysis summaries are presented for TCE, 1,1,1-TCA, vinyl chloride, and 1,4-dioxane on Appendix A Tables A-2, A-3, A-4, and A-5, respectively. The trend graphs for these four chemicals are presented on Appendix A Figures A-1 through A-51 for those results between 2008 and 2014 that are above their respective 1993 ROD RGs (1,1,1-TCA, TCE, and vinyl chloride) or MTCA Method B groundwater cleanup level (1,4-dioxane), as appropriate. Vinyl chloride was not measured at concentrations above reporting limits in source area wells during this time frame. Therefore, the vinyl chloride trend discussion is limited to midplume, capture zone, and downgradient wells. Trends were not analyzed for the daughter products 1,1-DCE, cis-1,2-DCE, and 1,1-DCA. Data used in the evaluation were presented in *Annual 2013–2014 Groundwater Long-Term Monitoring Report for Operable Unit 1 Area 6, and Operable 5 Area 31* (U.S. Navy 2014a).

Source Area Trends. Five of the six source area wells show decreasing trends for TCE concentrations (Appendix A Table A-2). The locations and trends are shown on Figure 1-13. As shown in this figure, TCE concentrations are in a declining trend for this entire area. Trend plots for TCE in samples from wells 6-S-31, N6-37, and PW-1, which contained TCE above the RG, are shown on Appendix A Figures A-1, A-2, and A-3, respectively. TCE was not measured above reporting limits for samples from wells 6-S-10 and 6-S-30 between 2008 and 2014. The August 2009 sample was the only sample from well N6-38 that was above the RG. Although these trends are decreasing in the source area, TCE is present at concentrations up to an order of magnitude above the RG of 5 µg/L.

The trends for the six source area wells show that 1,4-dioxane is decreasing (Appendix A Table A-5). The locations and trends are shown on Figure 1-14. Trend plots for 1,4-dioxane in samples from wells 6-S-10, 6-S-30, 6-S-31, N6-37, N6-38, and PW-1, which contained 1,4-dioxane above the RG, are shown in Appendix A Figures A-4 through A-9. Similar to the TCE trend, concentrations of 1,4-dioxane also show a declining trend in the source area. Although these trends are decreasing, 1,4-dioxane is present at concentrations an order of magnitude above the MTCA B level of 0.44 µg/L.

Overall, the data trend for the source area shows that the extraction system continues to reduce TCE concentrations throughout this zone.

None of the groundwater samples collected from source area wells between February 2008 and February 2014 contained 1,1,1-TCA (Appendix A Table A-3) or vinyl chloride at concentrations above their respective 1993 ROD RGs (U.S. Navy 2014a).

Midplume Trends. Five of the six midplume wells show that TCE is decreasing (Appendix A Table A-2). The trend for TCE in samples from well 6-S-14 is stable. The locations and trends are shown on Figure 1-13. The figure shows several locations are below the RG, and the figure also shows decreasing trends at all other locations. Trend plots for TCE in samples from wells 6-S-06, MW-7, and PW-3, which contained TCE above the RG, are shown on Appendix A Figures A-10, A-11, and A-12, respectively. TCE was not measured above reporting limits for samples from wells 6-S-14, 6-S-24, and MW-10 between 2008 and 2014. Although these trends are decreasing in the mid-plume area, TCE is present at concentrations up to an order of magnitude above the RG of 5 µg/L and extends slightly off site to the west.

The trends for five of the six midplume wells show that 1,1,1-TCA is decreasing (Appendix A Table A-3). The trend for 1,1,1-TCA in samples from well 6-S-14 is stable. The locations and trends are shown on Figure 1-15. Only one midplume well (6-S-06) contained 1,1,1-TCA at a concentration above the RG of 200 µg/L. The trend plot for 1,1,1-TCA at well 6-S-06 is shown on Appendix A Figure A-13.

Trends for results from five of the seven sampled midplume wells show that 1,4-dioxane is decreasing (Appendix A Table A-2). The trend for 1,4-dioxane in samples from well 6-S-15 is stable to decreasing and from well 6-S-24 is stable to increasing. The locations and trends are identified on Figure 1-14. Well 6-S-24 is located approximately 200 feet off the property to the west and approximately 800 feet north of the southern site boundary. Concentrations of 1,4-dioxane have ranged from 0.16 to 0.8 µg/L in samples from this well between 2008 and 2014, with the maximum concentration observed in the August 2012 sample. The concentration of 1,4-dioxane has since decreased to 0.2 µg/L in the February 2014 sample (Appendix A Figure A-17). Trend plots for 1,4-dioxane in all midplume wells are shown on Appendix A Figures A-14 through A-20. Although trends are decreasing in the mid-plume, 1,4-dioxane is present at concentrations up to an order of magnitude above the MTCA B level of 0.44 µg/L and extend slightly off site to the west.

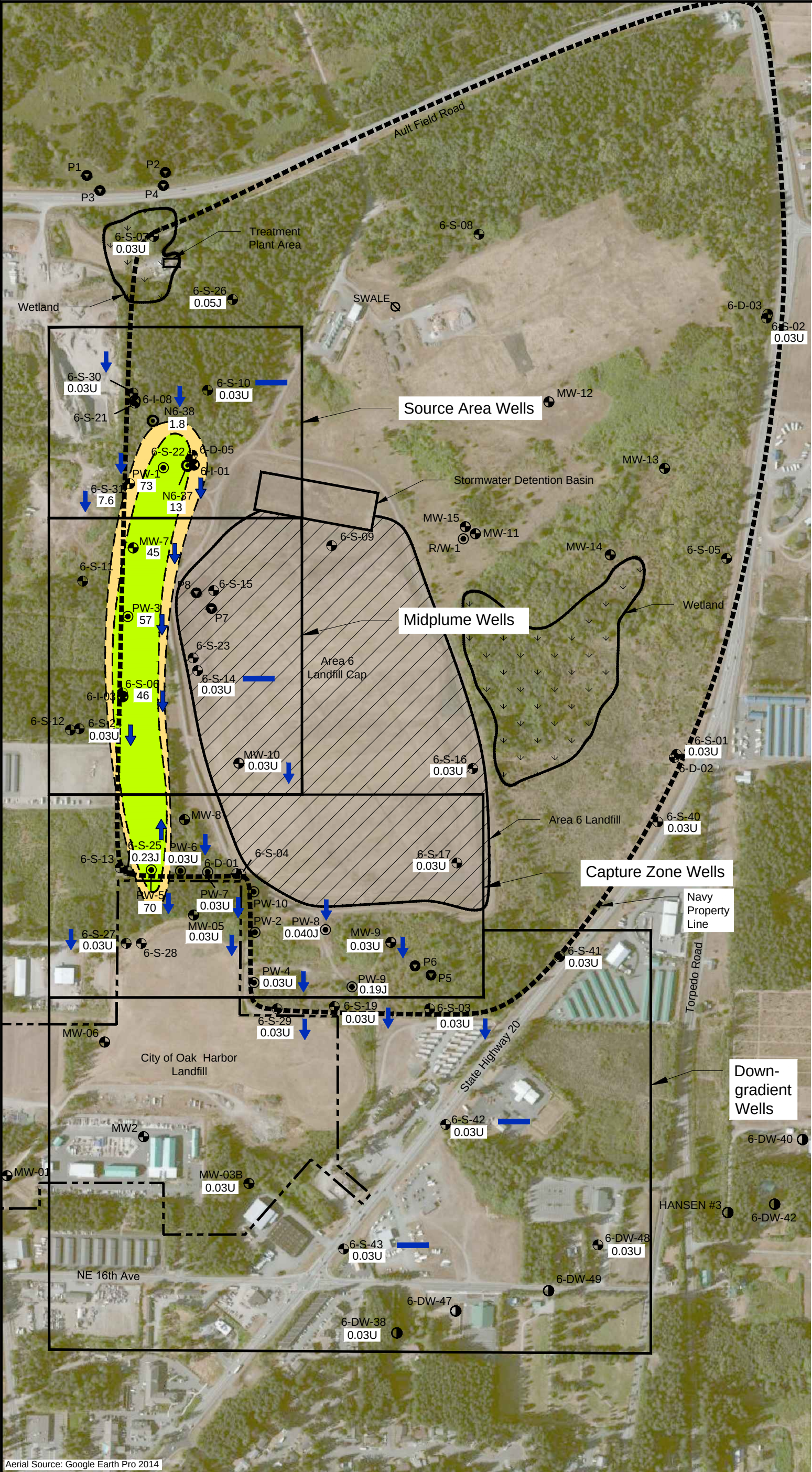
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Section 1.0

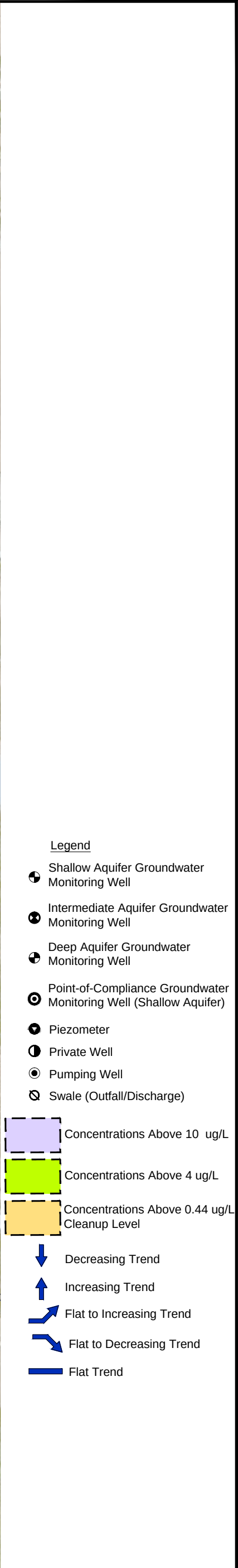
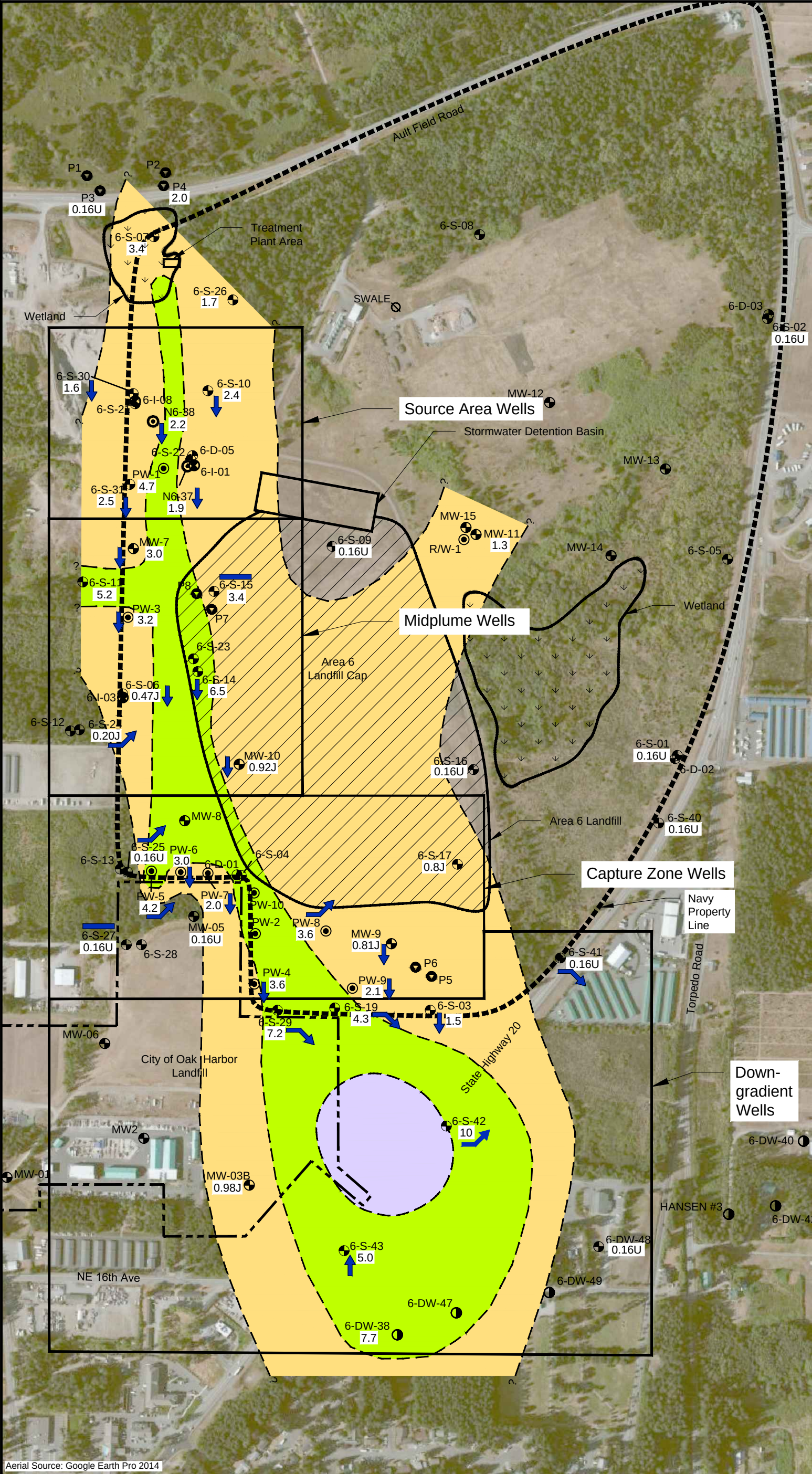
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Page 1-40

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Trends were evaluated for samples from two midplume wells for vinyl chloride (Appendix A Table A-4). An increasing trend was identified for samples from well 6-S-06. The concentrations from 2012 to 2014 ranged from 0.1 to 0.12 µg/L. This location is immediately adjacent to the western site boundary. Vinyl chloride concentrations show a stable to decreasing trend for samples from well MW-10. The locations and trends are shown on Figure 1-16.

Capture Zone Trends. Trends for results from seven of the nine capture zone wells show that TCE is decreasing (Appendix A Table A-2). The trend for TCE in samples from wells 6-S-25 and PW-9 is stable to increasing, with the concentrations ranging from not detected to 0.23J µg/L. The locations and trends are shown on Figure 1-13. Pumping well PW-5 is the only location where samples have detected TCE consistently above the RG. TCE was not measured above the RG in the samples from any of the remaining capture zone wells sampled between February 2008 and February 2014. The trend plot for TCE in samples from well PW-5 is shown on Appendix A Figure A-21. TCE was present in the 2014 groundwater sample from PW-5 at a concentration of 70 µg/L, which is above the 5 µg/L RG.

Six of the nine capture zone wells show decreasing trends for 1,1,1-TCA (Appendix A Table A-3). 1,1,1-TCA was not measured at a concentration above the 200 µg/L RG in 2014 samples from any of the capture zone wells. The trends for 1,1,1-TCA in samples from well MW-5 is increasing, from well PW-4 is stable to increasing, and from well PW-6 is stable to decreasing. The locations and trends are shown on Figure 1-15. Samples from wells 6-S-25, MW-5, and PW-5 are the only samples containing 1,1,1-TCA above the RG during the 2008 to 2014 time frame. Trend plots are shown on Appendix A Figures A-22, A-23, and A-24. At capture zone locations where 1,1,1-TCA was not measured above the RG, the maximum concentrations over this 6-year period were at least an order of magnitude below the 200 µg/L RG (Appendix A Table A-3).

Trends for results from five of the nine capture zone wells show that 1,4-dioxane is decreasing (Appendix A Table A-5). The trend for 1,4-dioxane in samples from wells 6-S-25, PW-5, and PW-8 is stable to increasing. The trend for samples from 6-S-27 is also stable. The locations and trends are shown on Figure 1-14. 1,4-Dioxane was not measured at concentrations above the MTCA Method B cleanup level of 0.44 µg/L in any of the samples collected between February 2008 and February 2014 from wells 6-S-25 and 6-S-27. Trend plots for 1,4-dioxane in samples from wells MW-5, PW-4, PW-5, PW-6, PW-7, PW-8, and PW-9 are shown on Appendix A Figures A-25 through A-31.

Vinyl chloride concentrations in six of the sampled capture zone wells indicate decreasing trends in three of these wells, and a stable to decreasing trend was identified in the remaining three wells (Appendix A Table A-4). Trend plots for these wells are provide on Appendix A Figures A-32 to A-37. The locations and trends are shown on Figure 1-16.

From the data trends observed in the three areas, contaminant concentrations throughout these areas show a predominant trend of decreasing concentrations of chlorinated VOCs and 1,4-dioxane.

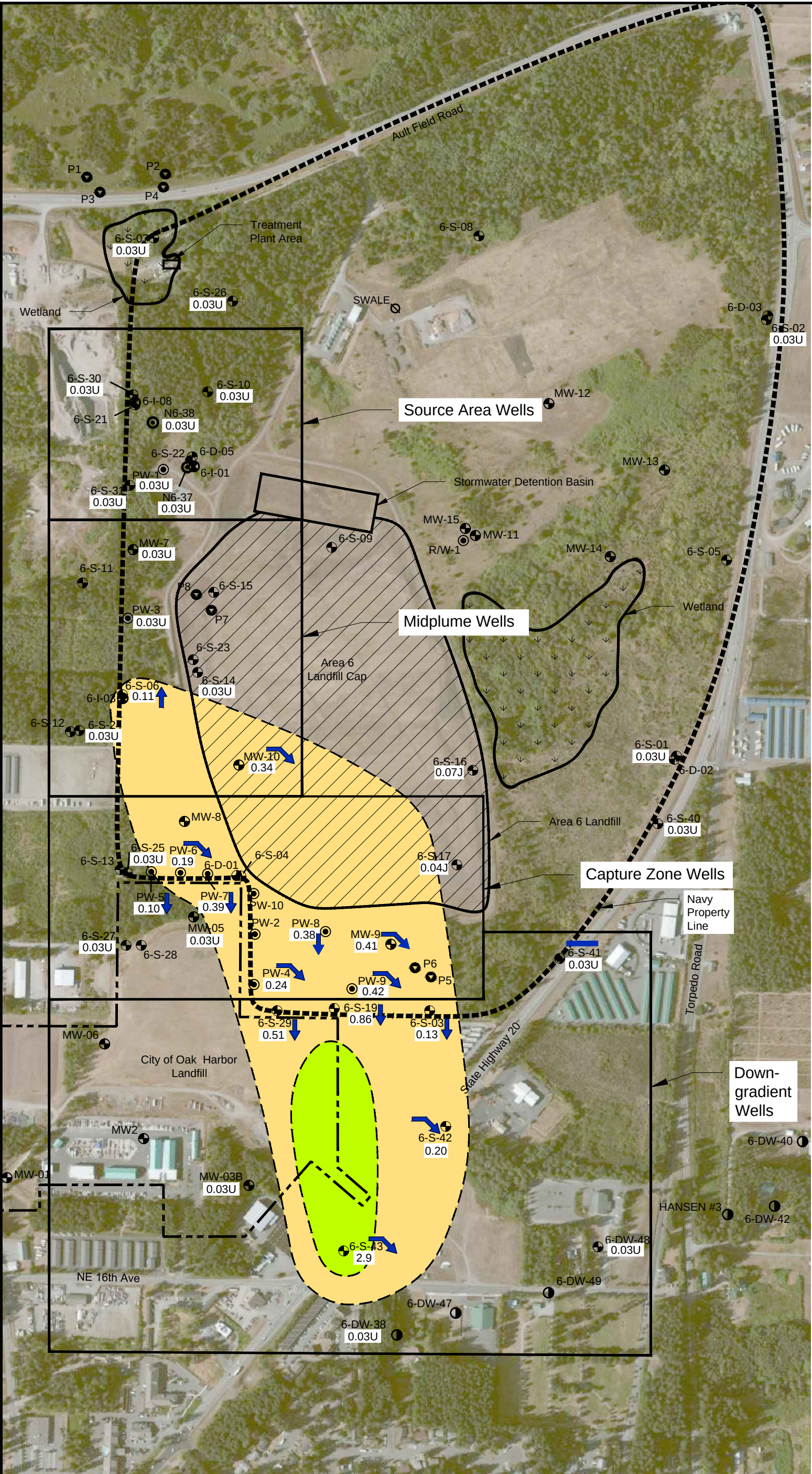
Downgradient Trends. TCE and 1,1,1-TCA have not been measured at a concentration greater than their respective RGs in samples from any of the seven downgradient wells sampled from February 2008 to February 2014 (Appendix A Tables A-2 and A-3).

Groundwater samples were collected from eight downgradient monitoring wells for 1,4-dioxane from February 2008 to February 2014. Trends for two of the eight downgradient wells show that 1,4-dioxane is decreasing (Appendix A Table A-5), and for three downgradient wells, trends are stable to decreasing. The trend for samples from wells 6-S-42 and 6-DW-38 is flat to increasing and increasing in samples from well 6-S-43. The locations and trends are shown on Figure 1-14. Trend plots for these locations are provided on Appendix A Figures A-38 through A-45. Well 6-S-42 is located along the leading edge of the 1,4-dioxane plume. Concentrations of 1,4-dioxane in samples from well 6-S-42 have ranged from 5.3 µg/L in February 2008 to a high of 18 µg/L in February 2012, then decreased to 10 µg/L in February 2014, resulting in a stable to increasing trend. Concentrations of 1,4-dioxane in samples from well 6-S-43 have ranged from 2.9 µg/L in February 2008 to a high of 8.4 µg/L in August 2012, then decreased back to 5 µg/L in 2014, resulting in an increasing trend. Samples from well 6-DW-38 have contained fluctuating concentrations as shown below:

- 3 µg/L in 2008
- 0.16 µg/L in August 2009
- 2.9 µg/L in February 2011
- Less than 0.16 µg/L in August 2011
- 6.4 µg/L in August 2012
- 7.7 µg/L in February 2014

Vinyl chloride shows a decreasing trend in samples from three of seven downgradient wells (6-S-03, 6-S-19, and 6-S-29), a stable to decreasing trend in three wells (6-S-42, 6-S-43, and MW-9), and a stable trend in well 6-S-41. These locations and trends are shown on Figure 1-16. Trend plots are shown on Appendix A Figures A-46 through A-51. Samples from well 6-S-41 did not contain vinyl chloride above the reporting limit, and these data were not plotted.

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Legend

Shallow Aquifer Groundwater Monitoring Well

Intermediate Aquifer Groundwater Monitoring Well

Deep Aquifer Groundwater Monitoring Well

Point-of-Compliance Groundwater Monitoring Well (Shallow Aquifer)

Piezometer

Private Well

Pumping Well

Swale (Outfall/Discharge)

Concentrations Above 1.0 ug/LConcentrations Above 0.1 ug/L Cleanup LevelDecreasing TrendIncreasing TrendFlat to Decreasing TrendFlat Trend

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1.2.3 Conceptual Site Model Summary

The CSM is based on the following:

- Environmental data collected from 1993 to present
- Performance of remedial actions conducted to date
- 3-Dimensional, numeric groundwater modeling

The current CSM is shown graphically on Figure 1-17. The former source area contaminant mass in soil has mostly been depleted through a 2001 interim removal action. Data collected since the 2001 interim removal action has shown that soil contaminant concentrations below the removal action are decreasing due to natural attenuation. The former source area does have residual VOC contaminant mass in the vadose zone, but its contribution to groundwater continues to decrease. Based on the 2010, 2011, and 2014 vadose zone studies, it is believed that source area groundwater concentrations will decrease to levels that would be suitable for monitored natural attenuation (MNA) in the very near future.

Although the areal extent of VOCs in groundwater in the western plume has been reduced by the extraction system, the TCE plume is interpolated to remain slightly off site to the west. Continued operation of the existing GETR system is expected to continue decreasing the areal extent and overall VOC mass. Based on the groundwater concentration trends, it will likely require continued long-term GETR operation to achieve the current RGs. Model predictions support this conclusion. Groundwater model documentation and results are included in Appendix B. The 1,4-dioxane above the MTCA B cleanup level of 0.44 µg/L, which is captured by the GETR system in the western plume, is not treated but recirculated by upgradient surface discharge.

Vinyl chloride and 1,4-dioxane are present downgradient of the site and outside extraction system capture in the southern plume. Data presented in the RI (U.S. Navy 1993) suggest that vinyl chloride had extended beyond the southern site boundary before the extraction system was constructed. The off-site plume extends downgradient of the City of Oak Harbor Landfill. Although no data exist prior to 2003, it is likely that 1,4-dioxane was also present outside of the capture zone prior to the GETR system construction and startup. Vinyl chloride and 1,4-dioxane continue to migrate downgradient. Groundwater modeling predicts the current extraction system operation reduces the downgradient migration rates of off-site vinyl chloride and 1,4-dioxane. The statistical trends discussed above support this prediction.

The present day distribution of 1,4-dioxane is a result of the original disposal operations and redistribution by GETR system effluent reinjection or surface discharge in multiple locations. As previously stated, the treatment system does not remove 1,4-dioxane. Treatment system

effluent containing 1,4-dioxane has been reinjected in two different locations and surface infiltrated in two different locations throughout the site. GETR system effluent containing 1,4-dioxane continues to be surface infiltrated to the swale located north of the stormwater detention pond.

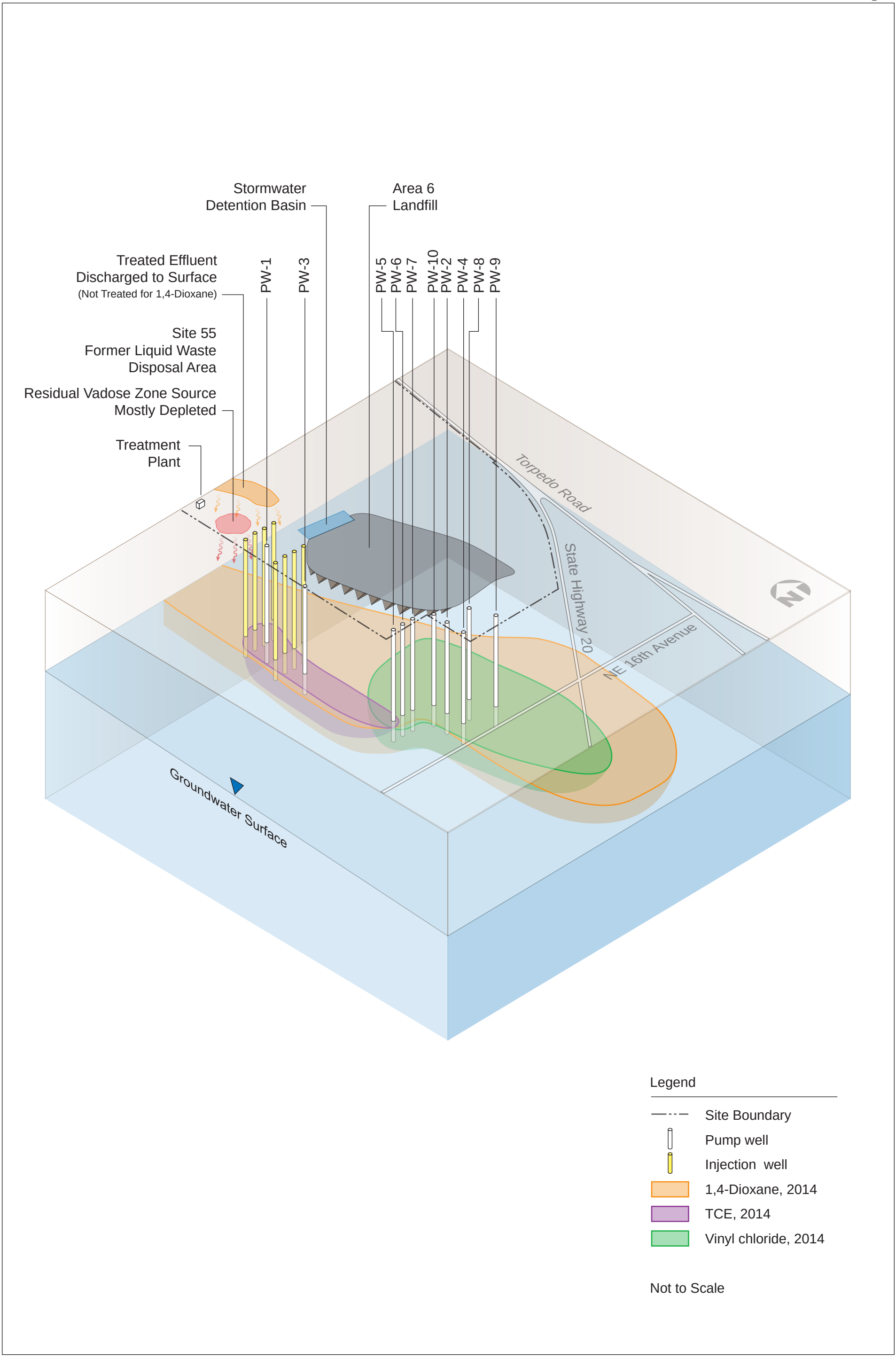
With few exceptions, concentrations of TCE, 1,1,1-TCA, and vinyl chloride in groundwater appear to be decreasing throughout the entire site. Concentrations of 1,4-dioxane are decreasing in western plume and immediately downgradient of the extraction system capture zone along the southern property boundary. 1,4-Dioxane concentrations appear to be increasing in the southern plume at the two most downgradient wells currently being monitored.

With the exception of 1,4-dioxane, groundwater extraction within the western plume is containing VOCs, and contaminant mass continues to be removed. Pumping is also reducing the areal extent. If pumping is terminated, groundwater modeling predicts that the western plume would migrate off site to the south-southwest (Appendix B) where there are potential receptors. A potential exposure pathway would be ingestion or dermal contact by domestic use.

Vinyl chloride and 1,4-dioxane in the southern plume are migrating to the south-southeast. Potential domestic exposure pathways immediately downgradient of this plume have been removed by replacing a well to a deeper, unimpacted aquifer or providing access to the City of Oak Harbor water system. As a result, the shallow aquifer is not currently being used as a drinking water source within the defined plume area (north of 6-DW-38). Continued migration of the southern plume could result in potential exposure via ingestion and dermal contact for property owners downgradient of 6-DW-38, if groundwater is used.

There is also the potential that continued migration could result in surface water exposure along the shores of the Seaplane base. Although the *TSCA Work Plan Chemical Problem Formulation and Initial Assessment 1,4-Dioxane CASRN: 123-91-1* (EPA 2015) states “the hazard of 1,4-dioxane to aquatic organisms is low. The hazard of 1,4-dioxane is expected to be low for soil organisms due to its high potential to volatilize from soil surfaces and low for sediment-dwelling organisms due to its low adsorption potential to sediment.” It also stated that based on carp bioaccumulation testing, 1,4-dioxane bioaccumulation is low.

Area 6 is on an island that is surrounded by salt water. The only drinking water source on the island is groundwater. As a result, the goal for shallow aquifer restoration is to allow maximum beneficial use. A change to the remedy is required to reduce the risk to future potential groundwater domestic users downgradient of the site.



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1.2.4 Contaminant Fate and Transport

Contaminant Persistence

TCE is highly soluble and can persist in groundwater. At high concentrations in confined groundwater aquifers, TCE may form a dense non-aqueous phase liquid (NAPL). In settings where groundwater charges surface water, contaminated groundwater can lead to contaminated surface water and sediment (USEPA Website 1).

TCE transports readily through soil and has a low potential for adsorption to soil and sediments. TCE adhesion to soil is directly proportional to the total organic carbon (TOC) content. The TOC content for this site is very low, 0.003 to 0.014 (U.S. Navy 1993). TCE rapidly evaporates from water with half-lives reported to be on the order of several minutes to hours, depending upon the turbulence. Field studies also support rapid evaporation from water. TCE is not hydrolyzed by water under normal conditions and does not directly photodegrade. Marine monitoring data only suggest moderate bioconcentration (USEPA Website 2).

Based on available environmental fate data, 1,4-dioxane is expected to volatilize readily from dry surfaces, reside in water and soil compartments if released to the environment, and have high persistence and low bioaccumulation potential in the environment. 1,4-Dioxane is not readily biodegradable under normal environmental conditions. However, given sufficient acclimatization, naturally occurring microorganisms can, even at a low rate and over a large plume area such Area 6 could, remove considerable contaminant mass (Li 2015). It is not expected to be susceptible to direct photolysis under environmental conditions, since this compound lacks functional groups that absorb light at visible ultraviolet light wavelengths. It will not hydrolyze in water, because it does not have functional hydrolyzable groups. Once it enters the environment, 1,4-dioxane is expected to have high mobility in soil. 1,4-Dioxane is not expected to significantly sorb to suspended solids and sediment and, therefore, migrates rapidly to surface waters and groundwater. It is not considered to be readily biodegradable (USEPA 2015).

Vinyl chloride released to soil will be subject to rapid volatilization. Vinyl chloride is highly mobile in soil and may leach to the groundwater. It may be subject to biodegradation under anaerobic conditions such as exists in flooded soil and groundwater. If released to water, vinyl chloride will rapidly evaporate. In waters containing photosensitizers such as humic acid, photodegradation will occur fairly rapidly. Limited existing data indicate that vinyl chloride is resistant to biodegradation in aerobic systems and, therefore, may not be subject to biodegradation in aerobic soils and natural waters. It will not be expected to hydrolyze in soils or natural waters under normal environmental conditions (USEPA Website 3).

TCE and 1,1,1-TCA show the highest concentrations of COCs in groundwater at the site. If sequential degradation of the compounds was occurring, it is expected that daughter product concentrations would be increasing or staying relatively stable. Decreasing TCE and 1,1,1-TCA daughter product measurements (1,1-DCA, 1,1-DCE, and cis-1,2-DCE) suggest that naturally occurring sequential degradation is not strong at this site. Therefore, it is expected that TCE would persist in groundwater under nonpumping conditions, with advection, sorption, and dilution being the main naturally occurring concentration reduction processes.

Potential Routes of Migration and Exposure

Since groundwater at the site ranges from 80 to 120 feet bgs, the exposure pathway to VOCs and 1,4-dioxane in groundwater is ingestion or dermal contact via extraction for domestic use. However, land use controls and State of Washington regulations prohibit use of groundwater at Area 6, and 1,000 feet from the Area 6 and City of Oak Harbor landfills for domestic use. Western plume groundwater would migrate to the south-southwest under nonpumping conditions. Southern plume groundwater is migrating to the south-southeast at a rate that is slowed by groundwater extraction along the southern site boundary. Monitoring data shows that 1,4-dioxane has migrated beyond the site boundary, including the 1,000-foot domestic well installation restriction zone (for the Oak Harbor landfill) established by Washington State regulations. However, the domestic well where 1,4-dioxane was detected was taken off-line for production purposes and the well was redrilled to a deeper, unimpacted aquifer.

Surface water exposure of 1,4-dioxane is theoretically possible if it successfully migrates south-southeast to the shoreline of Puget Sound near the Seaplane Base (Figure 1-1).

1.2.5 Groundwater Modeling Summary

A numeric, 3-dimensional groundwater model was developed to predict future fate and transport of the groundwater plumes at the site. A report describing model construction, calibration, and sensitivity analysis of the model is provided as Appendix B of this document. The document also shows how the model predicts the site will react to various potential remedies described in Section 4.0. Results of these simulations are summarized at the end of Section 4.0 and Appendix B.

1.2.6 Baseline Risk Assessment

The ROD (U.S. Navy, Ecology, and USEPA 1993) presents results of the baseline risk assessment using data available at that time. It should be noted that 1,4-dioxane had not been identified at the site during the time of ROD execution. The domestic well where 1,4-dioxane was detected was taken off-line for production purposes and the well redrilled to a deeper aquifer.

by the Navy. Therefore, there are no complete 1,4-dioxane exposure pathways at this time. As a result, an update to the 1993 risk assessment was not necessary and the risk has not changed.

Groundwater and soil were selected for more detailed evaluation in the quantitative risk assessment. Surface water, sediments, and air were eliminated from the risk assessment based on a screening-level risk analysis. VOCs and inorganics in groundwater were identified as the primary COCs at Area 6. However, all chemicals that were detected in soil and groundwater were evaluated in the quantitative risk assessment (U.S. Navy, Ecology, and USEPA 1993).

Summary of 1993 Human Health Risk Evaluation

Three potentially exposed populations were selected for evaluation at Area 6. The exposure scenarios evaluated were the following:

- Future on-site residential scenario
- Future on-site occupational scenario
- On-site trespasser scenario

Off-site resident risks were also evaluated.

For the screening analysis, the future residential scenario evaluated potential exposures and risks from soil, groundwater, surface water, sediment, and air. The future worker scenario evaluated exposures to both soil and groundwater. Exposures of workers to other media were assumed to be insignificant, because the screening-level evaluation for the more conservative residential scenario did not result in unacceptable risks. Screening-level risks for the trespasser scenario were evaluated for soil, sediment, and surface water and found to be insignificant (U.S. Navy, Ecology, and USEPA 1993). Potential exposure pathways that were evaluated are shown in Table 1-1.

Risks for potential residential and worker use of groundwater in the shallow, intermediate, and deep aquifers were evaluated in the quantitative risk assessment. The potential human health risks for both workers and residents from Area 6 groundwater exceeded U.S. Environmental Protection Agency's acceptable risk range for most wells in the three aquifers. Arsenic, primarily present at background levels, was the main risk driver for the intermediate and deep aquifers. In general, VOCs, including carbon tetrachloride, TCE, 1,1-DCE, 1,2-DCE, 1,1,1-TCA, and vinyl chloride, were responsible for the majority of the risks in the shallow aquifer. A summary of the cancer and noncancer risks for future residential use of the groundwater from each monitoring well in Area 6 is shown in Table 1-2 (U.S. Navy, Ecology, and USEPA 1993).

Table 1-1
Potential Exposure Pathways Evaluated in Baseline Risk Assessment

Potentially Exposed Population	Medium of Concern	Exposure Pathway
Future on-site resident	Groundwater	Ingestion
		Inhalation
	Soil	Ingestion
	Sediment	Ingestion ^a
	Surface water	Ingestion ^a
	Particulates in air	Inhalation ^a
	Volatile chemicals in air	Inhalation ^a
Current off-site resident	Volatile chemicals in air	Inhalation ^a
Future on-site worker	Groundwater	Ingestion
		Inhalation
	Soil	Ingestion ^a
On-site trespasser	Soil	Ingestion ^a
	Sediment	Ingestion ^a
	Surface water	Ingestion ^a

^aThese pathways were evaluated only in the screening-level risk assessment, which provided preliminary risk estimates based on the maximum detected concentration of all chemicals in each respective medium.

Table 1-2
1993 Well-by-Well Evaluation of Potential Human Health Risks Associated With
Future Residential Use of Groundwater at Area 6

Aquifer Well Number	Noncancer Hazard Index	Cancer Risk
Shallow		
N6-37	31^a	8 x 10⁻³
N6-38	194^a	3 x 10⁻²
6-S-2	0.6	NA
6-S-3	0.1	2 x 10⁻⁴
6-S-4	0.2	3 x 10⁻⁴
6-S-6	8.2	1 x 10⁻²
6-S-7	0.01	6 x 10 ⁻⁷
6-S-9	0.5	NA
6-S-10	1.3	6 x 10⁻³
6-S-12	1.6	6 x 10⁻⁴
6-S-13	0.8	2 x 10⁻⁴
6-S-14	1.0	2 x 10⁻⁴
6-S-15	0.003	9 x 10 ⁻⁶
6-S-16	0.2	9 x 10⁻⁴
6-S-17	0.1	2 x 10⁻⁴
6-S-19	0.98	4 x 10⁻⁴
6-S-21	10.1	NA
6-S-23	0.1	NA
6-S-24	0.4	2 x 10⁻⁴
6-S-25	3.8	4 x 10⁻³
Intermediate		
6-I-1	0.87	5 x 10^{-1 b}
6-I-2	2 ^b	1 x 10^{-3 b}
6-I-3	4.3^b	2 x 10^{-3 b}
6-I-4	2.4^b	1 x 10^{-3 b}
6-I-6	0.07	3 x 10⁻⁴
6-I-8	1.5	7 x 10^{-4 b}
Deep		
6-D-1	2.5^b	1 x 10^{-3 b}
6-D-2	7.3^b	4 x 10^{-3 b}
6-D-5	4.2^b	2 x 10^{-3 b}

^aThese risks are associated primarily with carbon tetrachloride. Although carbon tetrachloride was detected in the interim sampling, it was not detected in the remedial investigations Phase 2 or 3 sampling. As a result of this sporadic detection, the risks associated with exposure to carbon tetrachloride in groundwater are highly uncertain.

^bThese risks are attributable to background concentrations of arsenic.

(Notes continue on next page)

Table 1-2 (continued)
1993 Well-by-Well Evaluation of Potential Human Health Risks Associated With
Future Residential Use of Groundwater at Area 6

Notes:

Shaded value - cancer risk greater than 1×10^{-4} or noncancer hazard index greater than 1.0

NA - not applicable

The risk assessment evaluated risks on a well-by-well basis. Therefore, a sitewide groundwater risk was not calculated. Although the assessment determined the chemicals that present the highest risk at each well, it did not identify the chemicals that pose the highest risk when combining data from all the wells. Evaluation of the risks for each well in the different aquifers indicated a limited list of chemicals comprised most of the carcinogenic and noncarcinogenic risks. Those chemicals are presented in Table 1-3 (U.S. Navy, Ecology, and USEPA 1993).

Potential human health risks resulting from exposure to other media at Area 6 were also evaluated. Conservative screening-level risks for future residents and trespassers at the site were calculated for soil, sediments, surface water, and ambient air. Screening risks for workers exposed to soil were also evaluated. Although several of these media had screening risk levels that exceeded EPA's acceptable risk levels, site-specific considerations of the chemicals and media indicated significant risks from these media would not occur (U.S. Navy, Ecology, and USEPA 1993).

Potential risks from exposure to soil were evaluated. The results of the screening risk assessment, when combined with site-specific considerations, indicated exposure to soils at Area 6 would not pose an unacceptable risk. The site-specific factors influencing the soil risk at Area 6 included single high detections of certain compounds (e.g., beryllium and silver, though subsequent resampling could not confirm these high levels), contributions to risk from naturally occurring background levels of inorganics (e.g., antimony and arsenic), or a low frequency of detection (e.g., polycyclic aromatic hydrocarbons). VOCs that are COCs in the groundwater do not pose an unacceptable risk in soils, as shown in Table 1-4 (U.S. Navy, Ecology, and USEPA 1993).

Monitoring data shows the vinyl chloride and 1,4-dioxane plume has migrated beyond the 1,000-foot restriction zone. In February 2018, the Navy initiated a voluntary drinking water investigation around Area 6 as a precautionary measure to ensure residents living near Area 6 are not being exposed to 1,4-dioxane and vinyl chloride and to obtain additional information on the distribution of compounds detected in groundwater near Area 6. These data will be used to further delineate the 1,4-dioxane and vinyl chloride plumes for the ROD Amendment.

Ecological Risk Evaluation

To assess the environmental effects of the contaminants present at the site, an evaluation of potentially affected terrestrial species was conducted. A site-specific wildlife survey was not conducted as part of the RI. However, it is known that the Townsend's vole, coyotes and northern harriers inhabit the site. The bald eagle has also been observed in the vicinity of the site (U.S. Navy, Ecology, and USEPA 1993).

Table 1-3
1993 OU 1 ROD Chemicals Contributing to Potential Health Risks for
Future Residential Users of Groundwater at Area 6

Aquifer	Chemicals Posing Significant Noncancer Risks^a	Chemicals Posing Significant Cancer Risks^b
Deep	Antimony Arsenic	Arsenic
Intermediate	Arsenic	Arsenic Vinyl chloride
Shallow	Arsenic Carbon tetrachloride 1,1-Dichloroethene 1,2-Dichloroethene 1,1,1-Trichloroethane Trichloroethene	Arsenic Carbon tetrachloride 1,1-Dichloroethene 1,2-Dichloroethene Trichloroethene

^aA significant noncancer risk corresponds to a hazard quotient of 1.0 or greater for each chemical listed. The concentrations of antimony and arsenic were similar to background levels. Risks were evaluated assuming exposure by both ingestion of groundwater and inhalation of volatile chemicals released from the water during cooking or bathing.

^bA significant cancer risk was assumed to be 10^{-4} , the upper end of U.S. Environmental Protection Agency's acceptable risk range. The concentrations of arsenic in the different aquifers were similar.

Table 1-4
1993 OU 1 ROD Potential Human Health Risks Associated with
Future Resident Exposure to Soil at Area 6

Chemical	Noncancer Hazard Index	Cancer Risk
1,1-Dichloroethane	NA	NA
1,1-Dichloroethene	NA	NA
1,2-Dichloroethene	2×10^{-6}	NA
1,1,1-Trichloroethane	8×10^{-7}	NA
Trichloroethene	1×10^{-5}	5×10^{-10}
Vinyl chloride	NA	NA

Notes:

Risks presented only for chemicals found to be a concern in the shallow aquifer at Area 6

NA - chemical not detected in soil or no toxicity data available in 1993

Area 6 is made up of two distinct habitat types (meadow/grassland and forest transition zone) that were evaluated separately by ecological modeling. The primary concern for this site is terrestrial wildlife exposure to metals through ingestion of soil and food. However, inhalation of volatile vapors by small burrowing rodents was also evaluated. These exposure routes were modeled to estimate reasonable maximum exposures to three receptors with three different foraging patterns: herbivorous small mammal (Townsend's vole), carnivorous mammal (coyote), and carnivorous bird (northern harrier). Exposure modeling indicated potential risks to small herbivorous mammals from chromium, nickel, vanadium, and lead. There was also a potential risk to mammalian carnivores from mercury and lead (U.S. Navy, Ecology, and USEPA 1993). Given completion of the 2001 interim soil removal, installation of the landfill cap, and progress relative to groundwater conditions, ecological risks have been greatly reduced.

Ecological risk was identified for Area 6 soils and for sediments and surface water from the intermittent stream at Area 6. However, no source area was located and remedial action could cause more environmental harm than the low levels of existing chemicals are likely to cause (U.S. Navy, Ecology, and USEPA 1993). Capping of the landfill and the interim soil excavation have mitigated the risk of further sediment and surface water impacts.

FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 1.0

Date: 7/20/2018
Page 1-64

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2.0 REMEDIAL ACTION PERFORMANCE CRITERIA

Alternatives were developed for addressing groundwater at Area 6 by evaluating combinations of technologies capable of addressing VOCs and 1,4-dioxane in groundwater across the site. This evaluation is limited to impacts to groundwater. This process consists of six general steps:

1. Develop RAOs specifying the contaminants and media of interest, exposure pathways, and preliminary RGs that permit a range of treatment and containment alternatives to be developed.
2. Develop general response actions.
3. Identify volumes or areas of media to which general response actions might be applied.
4. Identify and screen the technologies applicable to each general response action to eliminate those that cannot be implemented technically at the site.
5. Identify and evaluate technology process options to select a representative process for each technology type retained for consideration.
6. Assemble the selected representative technologies into alternatives representing a range of treatment and containment combinations, as appropriate.

2.1 REMEDIAL ACTION GOALS AND OBJECTIVES

2.1.1 Media and Chemicals of Concern

Ecological risk was identified for Area 6 soils and for sediments and surface water from the intermittent stream at Area 6. However, the ROD concluded remedial action could cause more environmental harm than the low levels of existing chemicals are likely to cause (U.S. Navy, Ecology, and USEPA 1993).

The ROD concluded exposure to soils at Area 6 would not pose an unacceptable human health risk. It also concluded future movement of organic chemicals in the groundwater at Area 6 posed the most significant human health risk at the site, because it could potentially affect nearby drinking and agricultural water supplies. Future chemical infiltration from landfill leachate into groundwater in Area 6 was also possible, and the potential production of leachate from the landfill posed a potential health risk to future hypothetical groundwater users (U.S. Navy, Ecology, and USEPA 1993). A landfill cover was installed during 1996 to mitigate potential leachate production.

Based on the risk assessment, the ROD concluded groundwater was the media that posed risk to human health. Given there are no complete 1,4-dioxane exposure pathways at this time, an update to the 1993 risk assessment was not necessary and the risk has not changed. The ROD identified the following COCs:

- TCE
- 1,1,1-TCA
- 1,1-DCA
- 1,1-DCE
- cis-1,2-DCE
- Vinyl chloride

Section 2.1.4 identifies the COCs that will be specified in the ROD Amendment.

2.1.2 Exposure Pathways

There is the potential for a future pathway to groundwater via ingestion or dermal contact. This exposure pathway would be complete if impacted groundwater migrates to an active domestic well. In February/March 2018, the Navy initiated a voluntary drinking water investigation around Area 6 as a precautionary measure to ensure residents living near Area 6 are not being exposed to 1,4-dioxane and vinyl chloride. In the event the exposure pathway is complete, the Navy will take an appropriate response action. Monitoring data shows that 1,4-dioxane within the southern plume has likely migrated beyond the 1,000-foot restriction zone and vinyl chloride within the southern plume has migrated but is still within the 1,000-foot restriction zone.

2.1.3 Remedial Action Objectives

The primary RAOs established in the 1993 ROD for OU 1, Area 6 are the following:

- Reduce concentrations of contaminants that have already migrated into the shallow aquifer with the ultimate goal of meeting state and federal drinking water standards at point of compliance locations.
- Prevent the further spread of VOCs in the shallow aquifer and treat extracted water to meet state and federal standards prior to discharge.
- Reduce the potential risk to existing and future groundwater users downgradient of the site.
- Minimize infiltration of rainwater in the Area 6 landfill operations area to prevent leachate generation and migration into groundwater.

- Prevent potential impacts to downgradient surface water bodies and aquatic organisms as a result of stormwater erosion of the surface soils at the Area 6 landfill operations area.
- Prevent exposure to contaminants within subsurface soil and debris in the Area 6 landfill operations area.

Given the refined understanding of the site conditions relative to groundwater and limitations of technologies available to effectively address large, dilute, 1,4-dioxane and TCE plumes, this FFS proposes the following RAOs for an integrated groundwater remedy, which will supersede the 1993 OU 1 ROD RAOs:

- Reduce the potential TCE and 1,4-dioxane risk to current and future groundwater users downgradient of the site.
- Actively remediate TCE and 1,4-dioxane in the western and southern plume to the maximum extent practicable followed by monitored natural attenuation until RGs are met.
- Maximum extent practicable is defined as active treatment completed by meeting the active treatment goal of specified COCs as presented on Table 2-2, or asymptotic conditions for specified COCs, whichever occurs first. These conditions are further discussed in Section 4.0.

Installation of the landfill cap has met the 1993 ROD RAOs relative to the landfill and the landfill operations area. Operation, maintenance, and monitoring of the groundwater extraction and treatment system have been performed since 1995 with the objective of meeting groundwater RAOs.

2.1.4 Remediation Goals

The 1993 ROD identified COCs and established RGs for each. The ROD COCs and RGs in Table 2-1 are based on the protection of human health, assuming Area 6 groundwater is ingested as drinking water. The ROD stipulates that the cumulative excess cancer risk associated with the site will be reduced to, at most, 1×10^{-5} , consistent with MTCA.

1,1-DCA has not been measured at a concentration greater than the RG in any of the groundwater samples collected since 2006. cis-1,2-DCE has not been measured at a concentration greater than the RG in any of the groundwater samples collected since 2008.

1,1,1-TCA was measured at a concentration greater than the RG of 200 µg/L in the groundwater sample from only one well in 2014 and 2015. The 2014 and 2015 samples from 6-S-6 contained

240 and 250 µg/L of 1,1,1-TCA, respectively. Also, the 2008 to 2014 1,1,1-TCA trend in groundwater from well 6-S-6 displays a downward trend. Only 2 other monitoring wells have yielded groundwater samples containing 1,1,1-TCA at a concentration greater than the RG since 2010. The 2010 sample from 6-S-25 contained 290 µg/L 1,1,1-TCA, however the 2015 sample from 6-S-25 contained 99 µg/L, which is below the RG. The 2011 sample from MW-5 contained 600 µg/L 1,1,1-TCA. Subsequent samples from MW-5 showed decreasing concentrations at 310 µg/L in 2012, 170 µg/L in 2013, 130 µg/L in 2014, and 45 µg/L in 2015. The 2013, 2014 and 2015 MW-5 results were below the RG. The 2010 sample from production well PW-5 contained 200 µg/L 1,1,1-TCA, which is equal to the RG. The 2015 PW-5 sample contained 130 µg/L.

Based on the measured concentrations of 1,1-DCA and cis-1,2-DCE throughout the plume since at least 2010, this FFS recommends that 1,1-DCA and cis-1,2-DCE be removed as COCs in the ROD Amendment. Data supporting this recommendation can be found in the Annual Long Term Monitoring Reports for Area 6.

Navy and EPA have agreed that the ROD rationale to assign an RG of 0.07 µg/L in groundwater for 1,1-DCE is no longer appropriate and have been comparing monitoring results to the maximum contaminant level of 7 µg/L.

Based on use of the MCL for TCE (5 µg/L) as the RG and reversion from the ROD-specified RG (0.07 µg/L) for 1,1-DCE to the MCL (7 µg/L), the RGs will be defined as the MCL for all COCs, where an MCL has been established. Therefore, the RG for vinyl chloride is revised to the MCL of 2 µg/L. Since an MCL has not been established for 1,4-dioxane, the RG will be set at the MTCA Method B groundwater cleanup level of 0.44 µg/L.

The recommended ROD Amendment COCs and RGs are shown in Table 2-2.

Table 2-1
1993 ROD Remediation Goals for Chemicals in Groundwater at Area 6

Constituent	EPA Safe Drinking Water Act (40 CFR 141-MCL) (µg/L)	MTCA Method B (WAC 173-340) (µg/L)	Remediation Goals (µg/L)
Trichloroethene	5	4	5
1,1,1-Trichloroethane	200	720	200
1,1-Dichloroethane	*	800	800
1,1-Dichloroethene	7 ^a	400	7
cis-1,2-Dichloroethene	70	16	70
Vinyl chloride	2	0.029	0.1

^aThe EPA and Navy agreed to raise the ROD RG of 0.07 µg/L to the MCL of 7 µg/L in a June 6, 2006 meeting (U.S. Navy 2014a).

Notes:

*No MCL has been established.

CFR - Code of Federal Regulations

EPA - U.S. Environmental Protection Agency

MCL - maximum contaminant level

µg/L - microgram per liter

MTCA - Model Toxics Control Act

WAC - Washington Administrative Code

Table 2-2
Recommended ROD Amendment Remedial Goals and COCs for Groundwater at Area 6

Constituent	EPA Safe Drinking Water Act (40 CFR 141-MCL) (µg/L)	MTCA Method B (WAC 173-340) (µg/L)	Remediation Goals (RG) (µg/L) ^c	Active Treatment Goals (µg/L) ^d
Trichloroethene	5	4	5	15 (3 x RG)
1,1,1-Trichloroethane	200	720	200	600 (3 x RG)
1,1-Dichloroethene	7	400	7	21 (3 x RG)
Vinyl chloride	2	0.029	0.29 ^b	2 (MCL)
1,4-Dioxane ^a	*	0.44	0.44	1.32 (3 x RG)

^aNo 1,4-dioxane cleanup level was established in the ROD. The MTCA Method B groundwater cleanup level is being used as the remediation goal.

^bThe MTCA Method B groundwater cleanup level is based on a 1×10^{-6} risk. The proposed RG is based on a 1×10^{-5} risk which is consistent with the risk magnitude allowed in the 1993 ROD.

^cMonitored natural attenuation will be performed until the Remediation Goals (RGs) are met.

^dActive treatment will be performed until the active treatment goals of specified COCs are met, or asymptotic conditions for specified COCs, whichever occurs first.

Notes:

*No MCL has been established.

CFR - Code of Federal Regulations

EPA - U.S. Environmental Protection Agency

MCL - maximum contaminant level

FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 2.0

Date: 7/20/2018

Page 2-6

µg/L - microgram per liter

MTCA - Model Toxics Control Act

WAC - Washington Administrative Code

2.1.5 Points of Compliance

The 1993 ROD established conditional points of compliance for groundwater in the former source area. It states that “levels of 1,1,1-TCA and TCE in wells N6-37 and N6-38 suggest that NAPL residuals may be present in the aquifer at or near the groundwater surface in the former source area.” The ROD concluded that it may not be practicable to clean up the groundwater directly beneath the former source area, because there is no way to remove NAPL or residual oils if they are present. In addition, the boundary of the former source area is not clearly defined. Therefore, for the shallow aquifer groundwater, the conditional points of compliance for TCE, 1,1,1-TCA, 1,1-DCE, 1,1-DCA, and cis-1,2-DCE will be no greater than the circumference of a circle centered on a point halfway between wells N6-37 and N6-38 and not to exceed the western property boundary. Wells N6-37 and N6-38 were selected, because they were located at the suspected source area and had the highest concentrations of TCE and 1,1,1-TCA, respectively. If TCE or 1,1,1-TCA levels in additional wells installed outside this area during the remedial action indicate the presence of NAPL residuals, these points of compliance would be adjusted at the 5-year review.

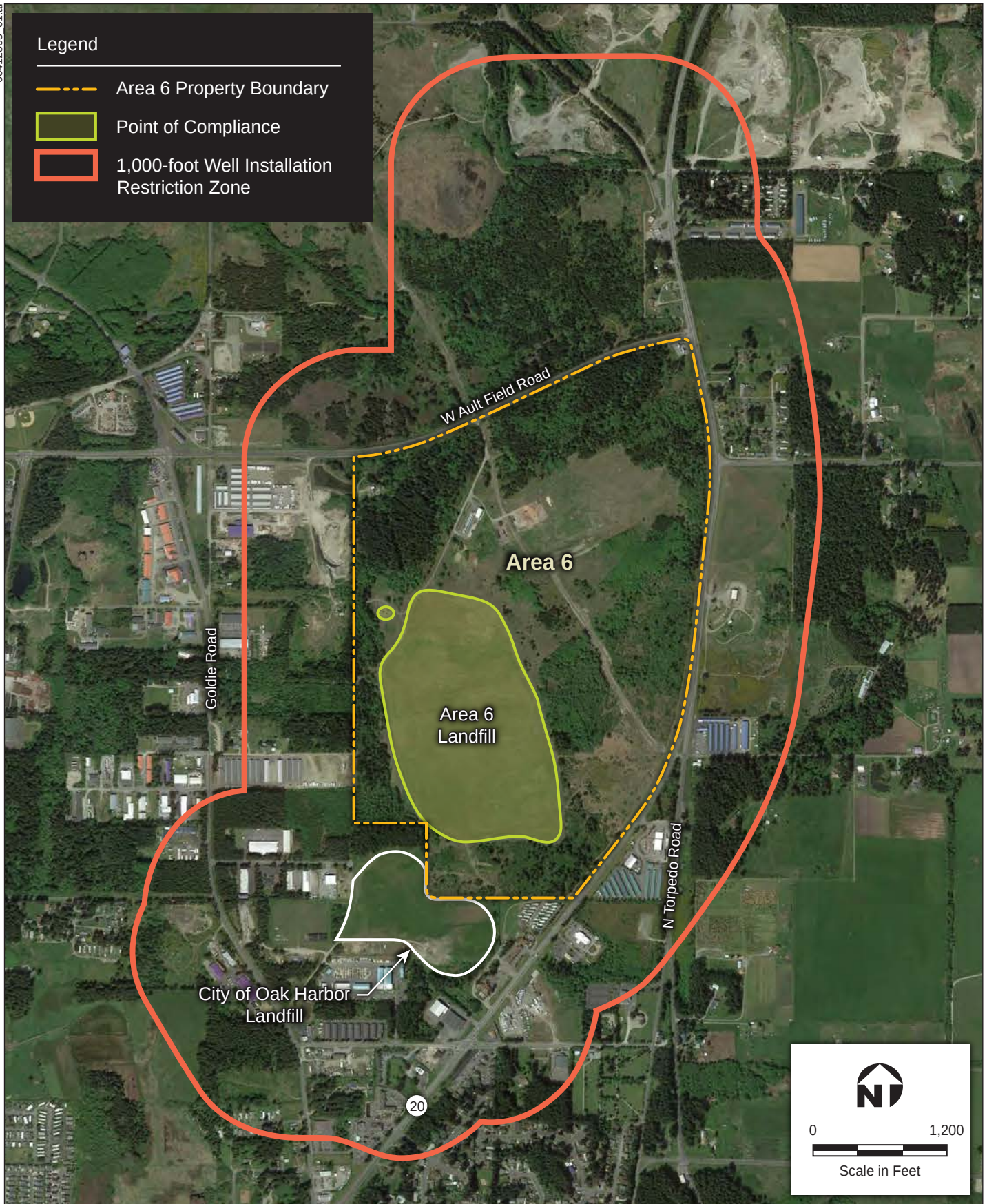
The ROD also identified conditional points of compliance for the vinyl chloride plume within and south of the landfill as the perimeter of the landfill operations area.

These conditional points of compliance from the 1993 ROD are identified on Figure 2-1.

Although the RGs for groundwater have not yet been met, significant progress has been made towards achieving them. Operation of the GETR has significantly reduced contaminant mass and reduced the lateral extent of the western plume.

2.1.6 Groundwater Well Installation Restrictions Around Landfills

Washington Administrative Code (WAC) 173-160-171(3)(b)(vi) establishes a minimum 1,000-foot set-back distance from the boundary of a permitted or previously permitted solid waste landfill, as defined by chapter 173-304, 173-306, 173-351, or 173-350 WAC; or 1,000 feet from the property boundary of other permitted solid waste landfills. This boundary is shown on Figure 2-1.



U.S. NAVY

Figure 2-1
Conditional Points of Compliance (1993 OU 1 ROD)
for Groundwater and 1,000-Foot Domestic Well
Installation Restriction Zone

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 Area 6
 NAS Whidbey Island
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 STUDY

2.2 APPLICABLE OR RELEVANT AND APPROPRIATE REQUIREMENTS

The primary regulatory driver for the NAS Whidbey Island Area 6 FFS is the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Pursuant to CERCLA, the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), and Executive Order 12580, existing cleanup authorities and programs will be used in the risk and hazard reduction actions.

“Applicable” requirements are defined by the NCP (40 Code of Federal Regulations [CFR] 300.5) as those cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal or state environmental and facility siting laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance at a CERCLA site. “Relevant and appropriate” requirements are defined (40 CFR 300.5) as those cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal or state environmental and facility siting laws that, while not applicable to a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance found at a CERCLA site, address problems or situations sufficiently similar to those encountered at CERCLA sites and are well suited to a particular site.

A requirement that is “relevant and appropriate” must be complied with to the same degree as if it were “applicable.” In addition to applicable or relevant and appropriate requirements (ARARs), the lead agency may, as appropriate, identify other advisories, criteria, or guidance as “to be considered.” It is important to note that only those state standards identified by the state in a timely manner are more stringent than federal requirements may be considered ARARs (40 CFR 300.400[g][4]).

ARARs may be categorized as chemical-, location-, or action-specific:

- Chemical-specific ARARs set health or risk-based concentration limits or ranges in various environmental media for specific hazardous substances, pollutants, or contaminants.
- Location-specific ARARs set restrictions on activities within the geographic areas of Area 6, such as wetlands, floodplains, and shorelines and depend on the characteristics of Area 6 and its immediate environment.
- Action-specific ARARs set controls or restrictions on particular kinds of remedial activities that may be selected to accomplish a remedy. These ARARs may specify performance levels, actions, or technologies to be used to manage hazardous substances, pollutants, or contaminants.

Activities conducted entirely on a site need only comply with the substantive aspects of ARARs and not the administrative aspects, such as permitting (specifically exempted under CERCLA Section 121[e]) or administrative reviews. Administrative procedures are not considered ARARs and, therefore, need not be pursued during the planning or implementation of risk reduction actions.

Any off-site activities (e.g., waste transport and disposal) must comply with all necessary federal, state, and local requirements. Occupational Safety and Health Administration (OSHA) requirements are also not considered ARARs, pursuant to EPA's adopted final rule on the NCP. The NCP identified specific OSHA requirements that must be complied with during all CERCLA response actions (i.e., 29 CFR 1910 and 1926).

Potential chemical- and location-specific ARARs are identified on the basis of the compilation and evaluation of existing site data. A preliminary evaluation of potential action-specific ARARs may also be made to assess the feasibility of remedial technologies being considered at this time. In addition to federal ARARs, more stringent state ARARs must also be identified. Other federal and state criteria, advisories, and guidance and local ordinances should also be considered, as appropriate, in the development of RAOs. Site Specific ARARs are discussed below.

2.2.1 Chemical-Specific ARARs

Chemical-specific ARARs set health or risk-based concentrations in environmental media (i.e., soil, sediment, groundwater, and surface water) for specific hazardous substances, pollutants, or contaminants. Potential chemical-specific ARARs are identified in Table 2-3.

2.2.2 Location-Specific ARARs

Location-specific ARARs and to be considered are summarized in Table 2-4. Location-specific ARARs set restrictions on activities within geographic areas, such as wetlands, floodplains, and shorelines, and potential impacts to fish, wildlife, habitat, and cultural resources, depending on the location.

2.2.3 Action-Specific ARARs

Potential action-specific ARARs set controls or restrictions on particular types of activities included in the selected remedial alternative. Table 2-5 identifies potential action-specific ARARs.

2.3 GENERAL RESPONSE ACTIONS

General response actions describe those actions that will satisfy the RAOs described in Section 2.1.3. General response actions for this FFS are identified in Table 2-6 for each of the three RAOs that are applicable to groundwater conditions at the site. The general response actions considered were the following:

- No action
- Containment
- Excavation
- Collection and treatment
- In-situ treatment

No action and excavation would not reduce COC concentrations in groundwater, does not prevent further spread of COCs, and does not reduce potential risk to downgradient receptors.

Containment will prevent further spread and reduce potential risk to downgradient receptors. However, containment alone will not reduce COC concentrations.

Collection and treatment would meet the RAOs. In-situ treatment has the potential to meet RAOs, depending on how aggressive the action is implemented.

Based on this assessment, collection and/or treatment are expected to meet all RAOs.

Table 2-3
Chemical-Specific ARARs, Area 6

Regulation/Requirement	Prerequisite	Citation	ARAR Determination	Comments
RCRA Subpart C, Characteristics of Hazardous Waste – This regulation defines what constitutes a hazardous waste.		40 CFR 261.20	To be considered if hazardous waste identified	A material is a hazardous waste if it is either (1) specifically designated as a hazardous waste, or (2) exhibits any characteristic identified in this subpart, including toxic characteristic leaching potential. If drill cuttings, excavated soil, or other waste generated during construction or operation of the remedy is designated as hazardous waste, these requirements would apply.
Safe Drinking Water Act – These are national primary drinking water standards for public water systems.		40 CFR 141.60 and 141.61	Applicable	It has been determined that groundwater at the site will be treated as if it were a drinking water source for remediation purposes. Therefore, portions of this regulation may be relevant and appropriate. Sampling has identified TCE, 1,1,1-TCA, 1,1-DCA, 1,1-DCE, cis-1,2-DCE, vinyl chloride, and 1,4-dioxane in groundwater. This section establishes MCLs for organics. MCL concentrations for TCE, 1,1,1-TCA, and vinyl chloride are exceeded. Therefore, this is an ARAR
Washington State Model Toxics Control Act (MTCA) – Washington State rules describing the cleanup process at a hazardous waste site. Since this is a federal facility and the Navy is the lead agency, most of the cleanup action is being conducted under federal requirements and U.S. Environmental Protection Agency.	70.105D RCW	173-340 WAC 173-340-360 173-340-700 through 173-340-760 WAC	Applicable	Describes requirements for conducting cleanup at a hazardous waste site. This section describes the minimum requirements and procedures for selecting cleanup actions. This section is intended to be used in conjunction with the administrative principles for the overall cleanup process.

Table 2-3 (Continued)
Chemical-Specific ARARs, Area 6

Regulation/Requirement	Prerequisite	Citation	ARAR Determination	Comments
However, portions of the requirements herein are applicable in the absence of specific federal requirements, which includes the following: Selection of Cleanup Actions Part VII, Cleanup Standards, are applicable if MCLs are not identified, or potentially applicable if levels specified herein are more stringent, and applicable for establishing points of compliance				Provides Washington State cleanup levels by media and analyte based on current and potential land use.
Clean Water Act (Water Quality Standards) – These are the federal water quality standards for waters of the United States. These standards define water quality criteria based on designated water use. Levels are provided for human health for exposure to drinking the water and consuming aquatic organisms. Protection of aquatic life is provided for both marine and freshwater environments and for acute and chronic conditions.		40 CFR 131.1 to 131.15	Applicable	Volatile organic compound and 1,4-dioxane plumes are present at the site. The existing groundwater extraction and treatment system is controlling the western plume and slowing down the southern plume. The southern plume has the potential for exposure to downgradient receptors, including surface water.

Notes:

ARAR – applicable or relevant and appropriate requirements

CFR – Code of Federal Regulations

DCA – dichloroethane

DCE – dichloroethene

MCL – maximum contaminant level

RCW – Revised Code of Washington

TCA – trichloroethane

TCE – trichloroethene

FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 2.0

Date: 7/20/2018
Page 2-14

Table 2-3 (Continued)
Chemical-Specific ARARs, Area 6

WAC – Washington Administrative Code

Table 2-4
Location-Specific ARARs, Area 6

Regulation/Requirements	Prerequisite	Citation	ARAR Determination	Comments
Migratory Bird Treaty Act of 1972 – This act provides protection of most species of native nongame, migratory birds from uncontrolled take, such as poisoning at hazardous waste sites or other environmental degradation.		50 CFR 10.13	Applicable	Migratory and native bird species have been observed at the site.
Bald and Golden Eagle Protection Act – Requires project activities to protect and preserve eagle habitat.		16 USC 668-668d	Applicable	Eagles have been identified at the site.
Archeological Resources Protection Act – This act stipulates that action must be taken to preserve archeological and historic properties and harm to National Historic Landmarks minimized. Activities may not cause irreparable harm, loss, or destruction of significant artifacts.		43 CFR 7	Applicable	No archaeological resource has been identified at the site. Adverse effects from remediation activities on archeological and historic properties are not currently identified. If artifacts are encountered during remedy construction or operation, this requirement would apply.
National Historic Preservation Act National, Historic Landmarks Program, and National Register of Historic Places		36 CFR 800 36 CFR 65 36 CFR 60	Applicable	This is applicable if archeological and historic artifacts are encountered during remedy installation.

Notes:

ARAR – applicable or relevant and appropriate requirements

CFR – Code of Federal Regulations

USC – United States Code

VOC – volatile organic compound

Table 2-5
Action-Specific ARARs, Area 6

Regulation/Requirements	Prerequisite	Citation	ARAR Determination	Comments
Resource Conservation and Recovery Act (RCRA), Subtitle D, Solid Waste Regulations – These are comprehensive cradle-to-grave program requirements for the safe management of solid waste and actions that generate solid waste.		40 CFR 240 through 259	Applicable	These regulations provide for the safe management of solid waste and actions that generate solid waste. In case of remedial activity involving excavation and disposal, solid waste may be generated as part of the remedial action and thereby subject to these requirements.
Standards Applicable to Transporters of Hazardous Waste – These regulations address procedures for the transport of hazardous materials within the United States.	40 CFR 261.20	40 CFR 263	Relevant and appropriate	If drill cuttings, excavated soil, or other waste generated during construction or operation of the remedy is designated as hazardous waste, they would require off-site transport and these requirements would apply. This is a potential ARAR.
Groundwater Monitoring Program – These are applicable to compliance monitoring programs established for landfills and surface impoundments.		40 CFR 264.91 to 264.100	Applicable	These regulations are applicable if hazardous constituents affecting groundwater quality are detected at a predefined compliance point.
RCRA Surface Impoundments and Landfills – These are regulations defining how covers over hazardous waste must be designed and constructed to function with minimal maintenance, provide long-term minimization of fluid migration through the capped area, have a permeability less than or equal to bottom soils or liner, and maintain integrity.	40 CFR 261.20	40 CFR 264.228 and 264.310	Relevant and appropriate	Portions of these regulations may be relevant and appropriate if the remedial activity includes construction of a cover over remediated hazardous waste. These regulations are substantively equivalent to CERCLA regulations and requirements. Since the landfill cover construction is complete, this is not an ARAR.
Clean Water Act (Section 402 – National Pollutant Discharge Elimination System (NPDES) Industrial Wastewater Discharge Permits as implemented by Washington State –		40 CFR 122 And 173-216 WAC	Relevant and appropriate	If a remedial technology application results in an effluent discharge to surface waters or to a publicly owned treatment works (POTW), this would be an ARAR. One of the alternatives to be considered will

Table 2-5 (Continued)
Action-Specific ARARs, Area 6

Regulation/Requirements	Prerequisite	Citation	ARAR Determination	Comments
An NPDES wastewater discharge permit is required for discharge of pollutants into waters of the United States. These regulations define acceptable standards for discharges to receiving waters as well as pretreatment standards for discharge to a POTW.				discharge to a POTW, which discharges to waters of the United States. (Note that the final ARAR determination will be dependent on the selected remedy.)
RCRA, Subtitle C, Regulations for Hazardous Waste – These are comprehensive cradle-to-grave program requirements for the safe management of hazardous waste and actions generating hazardous waste.	40 CFR 261.20	40 CFR 260 through 270	Relevant and appropriate	These regulations are designed to prevent adverse impacts associated with handling of hazardous materials. If drill cuttings, excavated soil, or other waste generated during construction or operation of the remedy is designated as hazardous waste, they would require off-site transport and these requirements would apply.
RCRA, Subtitle D, Regulations for Hazardous Waste – These are requirements for management and disposal of solid wastes that are not RCRA hazardous waste.	40 CFR 261.20	42 USC 6941–6949 and 40 CFR Parts 275 and 258	Applicable	These are applicable to the management of debris and other solid wastes generated during project activities, including recyclable materials.
Air Emission Standards for Process Vents and Equipment Leaks – These regulations define the treatment and control requirements for potential sources of air contamination due to remedial actions that include excavation or pump and treat methods.		40 CFR 264 Parts AA and BB	Applicable	If remedial actions include excavation or pump and treat methods, these would be applicable. (Note that the final ARAR determination will be dependent on the selected remedy.)
State of Washington Hazardous Waste Management Act – This statute and implementing regulations specify the requirements for	70.95 RCW	173-351 WAC	Applicable	Similar to RCRA Subtitle C, if drill cuttings, excavated soil, or other waste generated during construction or operation of the remedy is designated as hazardous

Table 2-5 (Continued)
Action-Specific ARARs, Area 6

Regulation/Requirements	Prerequisite	Citation	ARAR Determination	Comments
identification, accumulation, manifesting, transport, treatment, storage, and disposal of dangerous waste (including state-only dangerous wastes).				waste, they would require off-site transport and these requirements would apply.
State of Washington Solid Waste Management Act – These are requirements for handling, siting, storage, and disposal of solid waste.	70.95 RCW	173-351 WAC	Applicable	Similar to RCRA Subtitle D, this is applicable to the management of debris and other solid wastes generated during project activities, including recyclable materials.
State of Washington Fugitive Dust Control Measures – These are precautions to minimize visible fugitive dust emissions.		Puget Sound Clean Air Agency Regulation I, section 9.15	Applicable	These are applicable to remedial actions that involve soil excavation.
State of Washington Clean Air Act – This act establishes rules generally applicable to the control and/or prevention of emission of air contaminants.	70.94 RCW	173-400 and 173-476 WAC	Applicable	These are applicable to remedial actions that involve soil excavation or other actions that generate fugitive dust.

Notes:

ARAR – applicable or relevant and appropriate requirements

CFR – Code of Federal Regulations

POTW – publicly owned treatment works

RCRA – Resource Conservation and Recovery Act

RCW – Revised Code of Washington

USC – United States Code

WAC – Washington Administrative Code

Table 2-6
Remedial Action Objectives and General Response Actions

Remedial Action Objective	General Response Action	Meets RAO (Yes or No)
Reduce the potential TCE and 1,4-dioxane risk to current and future groundwater users downgradient of the site.	No action	No
	Containment	No
	Collection and treatment	Yes
	Excavation	No
	In-situ treatment	Yes
Actively remediate TCE and 1,4-dioxane in the western and southern plume to the maximum extent practicable followed by monitored natural attenuation until RGs are met.	No action	No
	Containment	No
	Collection and treatment	Yes
	Excavation	No
	In-situ treatment	Yes

Note:

RAO – remedial action objective

See Table 2-2 for Recommended ROD Amendment Remedial Goals and COCs for Groundwater at Area 6

3.0 IDENTIFICATION AND SCREENING OF TECHNOLOGY TYPES AND PROCESS OPTIONS

Following EPA's *Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA* (USEPA 1988), alternatives for remediation were developed by assembling combinations of technologies, and the media to which they would be applied, into alternatives that address contamination on a sitewide basis for Area 6. This process consists of six general steps:

- Develop RAOs. RAOs were developed in the ROD (U.S. Navy, Ecology, and USEPA 1993), which are discussed in Section 2.1.
- Develop general response actions. Potential general responses actions are briefly discussed in Section 2.3. The response action specified in the 1993 ROD was to pump groundwater from the impacted shallow aquifer to contain contaminants in groundwater, prevent further migration, and reduce contaminant concentrations to levels below RGs.
- Identify the areas of groundwater to which the general response actions might be applied (shown on Figures 1-12 through 1-15).
- Identify and screen technologies applicable to the general response actions. Those technologies that could not be technically implemented at the site were screened out.
- Retain technology options that represent the broader range of process options within a general technology type.
- Select technologies to represent a range of treatment and containment combinations as appropriate to continue implementing the general response actions in place at Area 6 and achieve the established RGs.

General process options that were considered for treatment of 1,4-dioxane and VOCs in groundwater, both ex-situ and in-situ, were the following:

- Natural attenuation
- Pump and treat
- Phytoremediation (in-situ)
- Biomats (ex-situ)
- Reactive and impermeable barriers (in-situ)
- ISCO
- Enhanced reductive dechlorination (ERD)

- Advanced oxidization (ex-situ)
- Discharge to the Ault Field wastewater treatment facility (WWTF) (ex-situ)

3.1 NATURAL ATTENUATION

While natural attenuation alone is not expected to be the sole remedy at the current time, it has an important role to play in managing the Area 6 plume.

In a recent study (Li, et al. 2015) showed at three different sites in California that native dioxane degraders were present at each of these sites and were capable of degrading 1,4-dioxane in groundwater. Relatively efficient degradation was observed particularly in upgradient portions of the plume, where microbial communities had acclimatized to the 1,4-dioxane. In the on-site portions of the Area 6 plume, natural degraders, if present, will have experienced an extended period of acclimatization. The majority of the off-site groundwater impacts from 1,4-dioxane occurred before the pump-and-treat system was installed in 1995; 1,4-dioxane degraders, if present, are likely to be active off-site as well. The Navy is currently conducting treatability studies with soil and groundwater from Area 6 to verify the presence of native degraders.

Treated water discharged in the upgradient swale migrates through 80 feet of vadose zone to reach the groundwater surface and then migrates 3,000 feet to the Navy property boundary. In addition to any biodegradation, 1,4-dioxane is expected to attenuate by absorption, advection and dispersion.

The original source of 1,4-dioxane upgradient of PW-1 in the western plume has been depleting rapidly, as evidenced by the progressive decline in 1,4-dioxane concentrations in PW-1 and other Area 6 extraction and monitoring wells. For example, the 1,4-dioxane level in PW-1 peaked at 22 µg/L in 2006 and has progressively declined to the current 7 µg/L. The concentration of 1,4-dioxane in the treated water from the GETR has declined over time to approximately 2 µg/L.

A depleting source, on-site containment and recirculation, and the associated extended acclimatization period for native microbes, biodegradation, absorption, advection, and dispersion are the mechanisms that combine to naturally attenuate 1,4-dioxane on-site, these same mechanisms are active to some extent off-site as well.

For both the on-site and off-site plumes, aerobic conditions are conducive to vinyl chloride degradation, as evidenced by the progressive depletion of vinyl chloride in several on-site and off-site wells. It is believed that vinyl chloride is attenuating through multiple mechanisms, including degradation, adsorption, advection, and dispersion.

3.2 PUMP AND TREAT

Pump and treat has been an important and effective component of the remedy at the Area 6 site since 1995. It has substantially contained the on-site (western) plume and isolated the majority of off-site groundwater impacts that occurred before the GETR system was installed as shown in Figures 1-13 through 1-16.

Although, the western plume has a tendency to expand slightly beyond the western boundary of the site, ultimately it is captured in extraction wells PW-3 and PW-5, as show in Figures 1-13 through 1-16.

Occasional downtime experienced by the GETR due to various reasons could be another factor leading to occasional expansion of the plume beyond the western property boundary. Despite these occasional downtimes, the GETR has effectively contained the western plume at the property boundaries, as evidenced by the sustained decline in COC concentrations.

Pump and treat is also a potentially viable remedy for treatment of the off-site groundwater impacted by 1,4-dioxane and vinyl chloride. Both 1,4-dioxane and vinyl chloride in 2015 had peak concentrations in monitoring well 6-S-43, which is immediately downgradient of the City landfill. Additional extraction wells would be required near SR 20 to contain a hotspot consisting of relatively higher concentrations of 1,4-dioxane and vinyl chloride.

3.3 PHYTOREMEDIATION SCREENING

Phytoremediation was screened out because of the large depth to groundwater at the site. Phytoremediation has been successfully implemented at numerous sites with very shallow groundwater (depths less than 2 to 3 feet bgs). Groundwater at Area 6 ranges from 80 to 120 feet bgs. Tree roots would not reach these depths. Based on these conclusions, phytoremediation was screened out.

3.4 BIOMATS SCREENING

Biomats are engineered green remediation systems consisting of constructed photosynthetic microbial mats used to remove organic and inorganic contaminants from water. Microbial mats will non-selectively remove organic and inorganic compounds from water via biosorption and biodegradation of the degradable constituents. Biomats were evaluated to perform ex-situ treatment of extracted groundwater as a replacement to the existing air stripping system that is ineffective at treating 1,4-dioxane. A bench-scale, biomat study was performed by the Navy

(U.S. Navy 2011a). The bench-scale study was conducted by an independent contractor with biomat experience. The report is included as Appendix C.

Additional pilot testing was recommended to further evaluate a microbial mat with bioaugmented constructed treatment wetland system at the site. The proposed pilot test system consisted of at least four ponds capable of treating the full discharge flowrate of the existing treatment system of 200 gallons per minute (gpm). The size of each pond would be approximately 23,800 square feet (about 0.55 acre), and each pond would be at least 2 feet deep. It was recommended that the roots zones be augmented with Actinomycetes CB-1190 to enhance the biodegradation of 1,4-dioxane.

The team (Navy, EPA, and stakeholders) evaluation of the bench-scale test data concluded that bioaugmentation with Actinomycetes CB-1190 would be required to treat 1,4-dioxane. The ability to maintain a significant population of 1,4-dioxane-degrading bacteria would be very difficult under current field conditions, especially with the relatively low levels of 1,4-dioxane in the 200 gpm effluent. Additionally, the construction of a three to four acre wetland near the airfield would not be acceptable to NAS Whidbey Island operations due to the influx of birds impacting airport safety. The operation of a plate and tray bioreactor with microbial mats was not considered practical at the high flow rates associated with the treatment system. Based on these conclusions, biomats were screened out.

3.5 REACTIVE AND IMPERMEABLE BARRIERS SCREENING

Reactive barriers have been successfully constructed at numerous sites to treat VOCs in groundwater. Based on the VOC distribution, depth to water, and groundwater flow direction in the western plume area, a reactive barrier would be required along the majority of the western site boundary, the entire southern site boundary, and a portion of SR 20 (Figures 1-11 through 1-14). The barrier along the western site boundary would be required to contain VOCs that would migrate off site to the west under non-pumping conditions. Given the required barrier's length and depth, the cost to implement this technology would be significantly greater than other potential options. Also, reactive barriers have not been successfully constructed to treat 1,4-dioxane in groundwater.

Impermeable barriers would prevent migration of impacted groundwater from locations upgradient of the barrier location. This technology would contain contaminant mass, but not reduce or eliminate it. Additional technologies would be required to reduce or eliminate contaminant mass and to prevent groundwater from flowing around the impermeable barrier. In addition, construction of thousands of feet of impermeable barrier to depths between 100 and 130 feet bgs would not be cost effective. Based on these conclusions, reactive and impermeable barrier technologies were screened out.

3.6 IN-SITU CHEMICAL OXIDIZATION SCREENING

The Navy conducted a field-scale ISCO treatability study using catalyzed hydrogen peroxide (CHP) and alkaline-activated persulfate during the summer of 2014 (U.S. Navy 2015a). The treatability study was conducted in the northern portion of the western plume where TCE and 1,4-dioxane were both present in groundwater. Although ISCO is a technology that is generally intended to address high concentration source areas with limited areal extent, the results were considered to be positive for a large diluted plume. The ISCO treatability study concluded that ISCO is a marginal alternative for the large diluted 1,4-dioxane plume at NAS Whidbey Island. However, this conclusion is based on a single injection, it is expected that multiple injections would significantly enhance the performance of ISCO at the site.

Based on results of the treatability study, ISCO technology was retained. It is acknowledged that application of ISCO, as a stand-alone remedy, for large-scale diluted plumes is challenging because of difficulties in distributing the oxidant throughout the plume. ISCO has been retained as an alternative to pump and treat (P&T) technology. ISCO can also be used in combination with P&T.

3.7 ENHANCED REDUCTIVE DECHLORINATION SCREENING

ERD is a mature technology used at many sites contaminated with chlorinated compounds. ERD is believed to be effective for reducing the remaining chlorinated compounds (e.g., TCE) at the site but not 1,4-dioxane. ERD would be most effective in the concentrated portion of the western plume (Figure 1-13). However, based on historical results of ERD at other facilities, it is believed that EDR would not be effective for the much larger diluted southern plume area where only 1,4-dioxane and vinyl chloride are present (Figures 1-14 and 1-16). The component of groundwater flow in the western plume area will make control of the plume within this western boundary difficult in the absence of hydraulic control. Without hydraulic control, the plume will migrate off-site to the south-southwest, severely complicating or preventing altogether the delivery of ERD on off-facility properties over time; a portion of the plume will be lost. Therefore, continued pumping will be required during ERD implementation. As a result of this assessment, ERD has been retained as a combination technology to P&T in the western plume area only.

3.8 ADVANCED OXIDATION

Advanced oxidization was evaluated to perform ex-situ treatment of extracted groundwater as a replacement to the existing air stripping system that is ineffective at treating 1,4-dioxane. A bench-scale study was performed by the Navy (U.S. Navy 2011a). The bench-scale study was

conducted by the Temple University Water and Environmental Technology Center. Reports for the two phases of evaluation are included as Appendices D and E. An additional bench-scale treatability study was conducted by APTwater in 2017 to evaluate potential system design and is included as Appendix F.

Advanced oxidization was found to be effective at reducing VOC and 1,4-dioxane concentrations in groundwater from the site using an ex-situ treatment system. Ex-situ treatment using advanced oxidation was retained as a treatment technology employed in conjunction with groundwater extraction.

3.9 DISCHARGE TO THE AULT FIELD WASTEWATER TREATMENT FACILITY

Treating extracted groundwater via the Ault Field WWTF was retained for use in conjunction with groundwater extraction. This is a particularly applicable option for 1,4-dioxane because discharge limits are higher in surface water than in groundwater (bioaccumulation potential of 1,4-dioxane is lower in surface water receptors and therefore 1,4-dioxane represents a lower risk in surface water).

4.0 ALTERNATIVES

The objective of this section is to develop an appropriate range of remedial options that will achieve the revised RAOs at Area 6 addressing 1,4-dioxane in groundwater, as identified in Section 2.1.1. Alternatives have been developed to address contamination throughout the plume.

The purpose is to implement an integrated remedy of active treatment, plus MNA (passive), plus land use controls (LUCs). Groundwater modeling (Appendix B) predicts that conditions suitable for MNA could be achieved in ten to twelve years for Alternatives 2 and 5. The alternatives described below include a period for MNA that varies depending on the alternative.

Each alternative will transition from active remedial action to passive remedial action as part of the integrated remedy. Transition from the active remedy portion to MNA will occur when whichever one of the following conditions is met first, per plume:

- Groundwater concentrations of Table 2-2 COCs throughout the plume are equal to or less than their active treatment goal values (presented on Table 2-2) based on statistical mean concentration for two consecutive semi-annual events; or
- Groundwater concentrations of Table 2-2 COCs in a "majority" of extraction well samples approach asymptotic conditions, as identified using asymptote analysis via linear regression, or first order decay, or other statistical evaluation. A "majority" will be defined in the ROD Amendment.

4.1 DEVELOPMENT OF ALTERNATIVES

The remedial alternatives developed for the site are described in detail in this section and illustrated on Figures 4-1 through 4-4. These figures, designs, and assumptions are presented to generate cost estimates for alternative analysis.

Land use controls were specified in the OU 1 ROD and reinforced in the Explanation of Significant Differences (ESD) for OUs 1, 2, 3, 4, and 5 (U.S. Navy 2007). These LUCs are part of all the alternatives described herein. The LUCs currently in place at Area 6 are:

- No downgradient well drilling except for monitoring wells and or remediation system wells authorized by EPA and Ecology in approved plans
- Protect existing monitoring wells

- No use of groundwater from, or downgradient of, the area except for monitoring and. remediation as approved by EPA and Ecology
- Prevention of any disturbance to the landfill cap, except as necessary for authorized cap maintenance and maintenance activities
- Ensure that land use at Area 6 remains commercial and or industrial, which includes a prohibition on development and use of this property for residential housing, elementary and secondary schools, child care facilities, and playgrounds

All alternatives also include the following engineering support elements:

- Identification of ARARs and substantive requirements
- Design, including engineering design report, design drawings, and specifications
- Engineers estimate and bid support
- General project management, planning, coordination, and permitting support
- Preparation of a compliance monitoring plan
- Construction oversight and quality assurance
- Remedial action documentation and reporting

The alternatives also include monitoring during and following implementation to assess the effectiveness of the alternative, monitor changes in groundwater COC concentrations, and collect appropriate system operational data. Monitoring components are described for each alternative and include monitoring wells screened in the treatment areas or immediately downgradient of the site.

A period of MNA throughout the site plume will follow active treatment for all of the alternatives. MNA throughout the site plume will occur until groundwater beneath the site achieves the RG values at the established points of compliance. LUCs will be removed once the RGs are met. Annual costs for plume-wide MNA are the same amongst all alternatives and are captured as a line item in the cost estimates for each alternative based on the assumed length of MNA.

4.2 ALTERNATIVE 1: CONTINUE WITH CURRENT SYSTEM

Alternative 1 would continue operation and maintenance (O&M) of the existing P&T system and includes the following elements:

- Continued O&M of the existing network of up to eight extraction wells
- Continued routine monitoring of 35 groundwater monitoring wells, including semiannual depth gauging and annual sampling with analytical testing of VOCs and 1,4-dioxane
- Continued monitoring of influent to and effluent from the GETR system
- Continued documentation and reporting of the GETR system
- Continued 5-year reviews of the remedial action
- Implementation of plume-wide MNA LUCs
- Implementation of off-site LUCs
- Monitoring activities for 30 years
- Operate and maintain the existing tower air stripper for 5 years until it is replaced with a shallow tray stripper
- Replace existing air stripping tower system with high efficiency, shallow-tray air stripper after 5 years
- Operate and maintain the new tray air stripper for a period of 25 years

Specific description about technology, methods, and quantities are included for cost estimating purposes.

General Alternative Description

This alternative is retained throughout the process of alternative development and analysis as a baseline for comparison of other alternatives and to help ensure that unnecessary remedial action is not taken where the current action is appropriate. The “continue with the current system” alternative consists of allowing the site to remain in its present condition with continued operation of the GETR system with the existing air stripper tower. Groundwater extraction will

continue from the eight wells and routed to an aboveground treatment area for treatment using an air stripper. The treated water is then pumped to an infiltration swale, where the water infiltrates into the ground, evaporates, or gravity flows into the nearby stream.

No additional measures would be taken in this alternative to address 1,4-dioxane from the GETR system effluent.

The majority of tasks necessary to continue O&M of the existing GETR system are common elements to all five alternatives. The primary task not included as a common element described above is continued O&M of the existing tower air stripper. To implement this alternative, the existing tower air stripper would need to continue to operate. The tower air stripper will be replaced with a more efficient and easier to maintain shallow-tray air stripper after a period of 5 years. Tray-style air strippers will be used to strip off COCs because they are effective at removing VOCs from groundwater, have a small footprint, are less prone to scaling compared to packed column (tower) air strippers, and are easily serviced. Once treated, the groundwater would be routed to the existing effluent pipeline for ground infiltration (or evaporation) at the bio-infiltration swale. This alternative includes O&M of the existing and new air stripper for a total of 30 years and periodic preventative maintenance of the groundwater pumps and other system components.

Groundwater modeling (Appendix B Scenario 1) predicts that continued operation of the current GETR will result in MNA conditions for TCE in approximately 25 to 30 years. The current GETR does not address 1,4-dioxane in extracted groundwater.

Construction

Tasks necessary to implement Alternative 1 include the following:

- Contractor work plans
- Mobilization/demobilization
- Removal of existing tower air stripper
- Installation of new shallow tray air stripper
- Update of treatment system O&M manual for new air stripper

O&M

Continued O&M of the existing GETR system is assumed to be performed for 30 years. This includes operating the existing extraction wells and the aboveground treatment equipment. Alternative 1 includes O&M of the existing air stripper for 5 years and the new air stripper for 25 years. Other O&M activities include keeping the effluent discharge system to the swale functioning for 30 years.

Monitoring

Monitoring will include semiannual collection of groundwater samples from existing monitoring wells and semiannual well gauging, which is similar to what is currently being performed. Groundwater monitoring is necessary to allow continued assessment of the remediation effectiveness and changes in COC concentrations throughout the site. Monitoring will also include collection of remediation system operational data as part of ongoing O&M procedures. This includes recording total flow, flow rates, and concentrations of COCs in the influent to and effluent from the aboveground treatment equipment. Monitoring is assumed to continue for 30 years.

Integrated Remedy Action Points

Groundwater modeling (Appendix B, Scenario 1) predicts that continued operation of the existing system will reach 3 times the RG for TCE in approximately 30 years. This prediction is used as an action point as described below.

The active remedy portion will terminate and MNA will be initiated when one of the endpoint conditions presented in Section 4.0 is met.

4.3 ALTERNATIVE 2: CONTINUE P&T WITH EX-SITU GROUNDWATER TREATMENT USING ADVANCED OXIDATION PROCESS AND ADDITIONAL EXTRACTION WELLS

Alternative 2 consists of the following elements by plume area.

Off-Site (Southern) Plume

- Add extraction wells off-site to address the 1,4-dioxane plume through strategic placement along the northern shoulder of SR20
- Install an advanced oxidation process (AOP) (ex-situ hydrogen peroxide/ozone) for the southern plume

- Connecting discharge from the new extraction wells along the northern shoulder of SR 20 to a stand-alone southern ex-situ AOP system
- Installing a new pipeline to route treated effluent from the southern ex-situ AOP system to the existing discharge swale via the existing treatment pad
- Gathering relevant data to assess MNA rate
- Transition from active remedy portion to MNA will occur when whichever one of the endpoint conditions presented in Section 4.0 is met.
- LUCs from OU 1 ROD
- Groundwater use restrictions will be put in place where there is potential drinking water use and concentrations exceed the RGs downgradient of the identified plume
- Groundwater monitoring until RGs are met
- Completing 5-year reviews until RAOs have been achieved

On-Site (Western) Plume

- Optimize the extraction wells (maintain/add/subtract) with the objective to contain the plume
- Added AOP to amend treatment to address 1,4-dioxane. Replacing existing air stripper treatment system with an AOP system. Implementation of the AOP system will be initiated following one year of continuous operation of the southern AOP system. The one year of continuous operation will be used to determine if the AOP is working properly with site conditions and to apply any lessons learned to the western plant.
- Installing a new pipeline to route untreated effluent from the new western plume wells to the new northern AOP system at the existing treatment pad
- Gathering relevant data to assess MNA rate
- Transition from active remediation to MNA will occur when whichever one of the endpoint conditions presented in Section 4.0 is met.

- LUCs from OU 1 ROD
- Groundwater use restrictions will be put in place where there is potential drinking water use and concentrations exceed the RGs downgradient of the identified plume
- Groundwater monitoring until RGs are met
- Completing 5-year reviews until RAOs have been achieved

Elements Common to Both the Western and Southern Plumes

- Continued O&M of the existing network of up to eight extraction wells
- Continued routine monitoring of 35 groundwater monitoring wells, including semiannual depth gauging and annual sampling with analytical testing of VOCs and 1,4-dioxane
- Continued monitoring of influent to and effluent from the GETR system
- Continued documentation and reporting of the GETR system
- Continued 5-year reviews of the remedial action
- Implementation of plume-wide MNA LUCs

Specific description about technology, methods, and quantities are included for cost estimating purposes.

General Alternative Description

Specific description about technology, methods, and quantities are included for cost estimating purposes.

Off-Site (Southern) Plume

For the southern GETR system, up to five new extraction wells will be completed to a depth of approximately 150 feet, and each will have a submersible pump nominally rated at 20 gpm (40 gpm maximum) installed. The specific number and locations of extraction wells to be installed will be determined during remedial design. The new wells would be strategically placed along the northern shoulder of SR 20 and extend the downgradient reach in the southern plume.

Extracted groundwater will be routed through 6-inch-diameter double-walled piping installed underground to a new treatment pad located within the site boundary (Figure 4-1). Double-walled piping will be used in this area very near the site boundary to provide secondary containment.

The new southern treatment pad will be constructed from concrete with secondary containment features and have a new AOP unit contained in a permanent fabric cover structure. The southern AOP system will treat approximately 100 gpm of groundwater removed from the new extraction wells along the southern site boundary. Treated effluent from the southern treatment unit will be routed to a southern holding tank. This water will be pumped from the holding tank through a 6-inch-diameter single-walled piping to the surface infiltration area in the north. The alignment of the new pipe will be similar to the new untreated pipeline installed for the new extraction wells along the western perimeter so that they can be laid in a common trench. It is assumed that the existing discharge pipeline from the primary treatment system to the swale has enough capacity to handle 300 gpm if appropriately sized pumps are used from the holding tank. In general, new pipelines installed within the site limits of Area 6 will be single walled, and new pipelines installed off-site along SR 20 will be double walled. In addition, all pipelines will have cleanouts installed at a minimum of every 1,000 feet and air release valves will be installed at highpoints. Double-walled piping will also have manual leak detection monitoring points located at low points in the pipeline.

On-Site (Western) Plume

The implementation of this component of Alternative 2 will be initiated following one year of continuous operation of the off-site (southern) treatment system. The one year of continuous operation will be used to determine if the AOP is working properly with site conditions and to apply any lessons learned to the western plant. Extraction wells (existing and/or new) and changes to the treatment plant will be used to maintain containment and amend treatment in western-plume groundwater for TCE and 1,4-dioxane above the active treatment goal.

The extracted water will be treated aboveground (i.e., GETR), using an ex-situ treatment technology to treat COCs and 1,4-dioxane in groundwater that is different from the current system. The existing tower air stripper would be removed and replaced with a hydrogen peroxide/ozone treatment system. This system will also use AOP to destroy COCs and 1,4-dioxane in the influent from the well field. The existing holding tank would remain to help regulate influent to the hydrogen peroxide/ozone unit. Details about hydrogen peroxide/ozone treatment systems are described in greater detail in the following section.

This alternative will optimize the existing network of extraction wells to strategically place up to four new extraction wells with the existing three wells in the western plume. The specific

number of extraction wells will be determined during remedial design. Optimization of extraction wells could decrease capture of clean water from the western side of the plume.

The northern AOP system will treat approximately 200 gpm from the current treatment area with the up to four new wells. Some components of the existing GETR system will be reused for the northern AOP system, including the secondary containment pad, aboveground storage tank (holding tank), effluent pipeline, and surface water discharge swale. The major difference will be that the tower air stripper will be removed and replaced with a 40-foot-long cargo container with the AOP system. The northern hydrogen AOP system's cargo container will be installed on the existing secondary containment pad.

System Configuration

Figure 4-1 shows one conceptual extraction well and pipeline alignment which was used to generate the alternative cost estimate. The two new northern and southern AOP systems will be rated for an average flow rate of 200 and 100 gpm, respectively.

Groundwater Treatment

An AOP system will be used to treat VOCs and 1,4-dioxane in extracted groundwater in this alternative. Based on the well-known ozone plus hydrogen peroxide chemistry, the AOP uses multiple-step injection to produce the hydroxyl radical, the most powerful oxidant available for water treatment. A compact plug-flow reactor design efficiently destroys a wide range of organic compounds via a carefully controlled oxidative chain reaction. The result is a treatment process that is effective in treating 1,4-dioxane. This has been shown in previous bench-scale studies, compared to many conventional technologies, such as carbon adsorption, and does not have as high electrical consumption compared to ultraviolet-based oxidation systems or thermal regeneration resin adsorption systems. The AOP system will be able to operate in three different oxidation modes: AOP, ozone only, or alternating. COCs are completely destroyed to dissolved carbon dioxide and water without producing any process residuals or waste products.

The system needs electricity to create ozone at approximately 10 percent by weight from ambient air and a tank for hydrogen peroxide, delivered monthly. Hydrogen peroxide is needed in a concentration of 25 to 35 percent by weight and is relatively inexpensive at approximately \$4 per gallon, based on current market value. Estimates for a specific, commercially available AOP system indicate that less than 5 gallons per day of hydrogen peroxide would be consumed by the two AOP systems proposed by this alternative. Approximately 18 kilowatt (kW) of electricity (three-phase 480 volts) would be used by both systems included in this alternative. If monthly deliveries were made, no more than 200 gallons of hydrogen peroxide would be stored on site at any given time. The AOP system will be fully automated with low maintenance and designed to run without a full-time operator. For this site, each AOP system would be manufactured to fit

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Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 4.0

Date: 7/20/2018

Page 4-10

inside a typical 40-foot-long cargo container and shop tested off site before delivery. A concrete pad with secondary containment would be constructed for the southern system to connect the AOP system to site piping. Ozone sensors and floats would be mounted inside and outside the AOP equipment to shut down the system automatically if a leak occurs.

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Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 4.0

Date: 7/20/2018

Page 4-12

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Construction

Tasks necessary to implement Alternative 2 include the following:

- Securing access agreements for off-site equipment (Navy)
- Contractor design and work plans
- Specialty subcontractors (surveyor, utility locates)
- Mobilization
- Installing environmental protection
- Drilling up to five new extraction wells along the northern shoulder of SR 20 (6-inch diameter, 150 feet deep)
- Drilling up to four new extraction wells along western boundary (6-inch diameter, 120 feet deep)
- Constructing nine well head vaults and down-hole pumps and equipment (20 gpm each)
- Soil analytical testing from new well installations (four samples per boring)
- Removing existing tower air stripper
- Fabricating and installing one 200-gpm AOP system at existing treatment pad
- Installing double-walled 300-gallon hydrogen peroxide aboveground storage tank to feed northern AOP system
- Excavating and constructing new concrete secondary containment pad for new southern AOP system
- Adding new metered power drop for new southern AOP system equipment
- Fabricating and installing one 100-gpm AOP system at new southern treatment pad

- Installing double-walled 200-gallon hydrogen peroxide aboveground storage tank to feed southern AOP system
- Installing 2,000-gallon batch tank and effluent pump at new southern treatment pad
- Excavating trench and stockpiling soil (0 to 4 feet bgs) for new southern extraction well field pipeline to new southern treatment pad (total length approximately 2,500 feet)
- Installing double-walled piping from new southern wells to southern AOP system (6 inches, 2,500 feet long), including air release valves, cleanouts, and leak-detection monitoring points
- Excavating trench and stockpiling soil (0 to 3 feet bgs) for new effluent pipelines from the southern treatment system and new western extraction wells to the existing treatment pad (total length of approximately 5,000 feet)
- Single-walled piping from potential new western wells to northern AOP system (6 inches, 2,500 feet long): The majority (2,000 out of 2,500 feet) of this pipeline will be laid in a common trench with piping from the new southern wells.
- Single-walled treated water piping from new southern AOP system effluent to the existing northern AOP system batch tank for routing to the existing surface water swale (6 inches, 4,500 feet long)
- Investigation-derived waste (IDW) management and disposal of drill cuttings and asphalt
- General site restoration work
- AOP system startup with vendor-provided assistance
- Demobilization
- Contractor reporting and closeout submittals (e.g., as-built drawings)

Operation and Maintenance

O&M of the new southern GETR system is assumed to be performed for 17 years (based on model predictions). This includes operating the existing extraction wells, the new extraction

wells, and the new aboveground AOP treatment system. O&M of the new northern GETR system (western plume) is assumed to be performed for 9 years (based on model predictions). This includes operating the existing extraction wells, the new extraction wells, and the new aboveground AOP treatment system. O&M for all 19 extraction wells are included for 9 years in the north and 17 years in the south. Alternative 2 assumes O&M of the two AOP treatment systems will include inspections by one person weekly and maintenance visits by two people quarterly for one full day. Hydrogen peroxide deliveries will be made monthly by a local vendor to provide a total of 150 gallons to the site (100 gallons to the northern AOP and 50 gallons to the southern AOP). More significant maintenance is assumed to occur annually and will require two people for five days each year. Other O&M activities include keeping the effluent discharge system to the swale functioning for 17 years. These timing predictions were used for costing purposes.

Monitoring

Monitoring includes semiannual collection of groundwater samples from 35 existing groundwater monitoring wells and semiannual depth gauging. Sampling will include analytical testing for VOCs and 1,4-dioxane. Monitoring will allow assessment of the remediation effectiveness and changes in COC concentrations throughout the plume area. Routine monitoring will also include collection of remediation system operational data as part of ongoing O&M procedures. Quarterly influent and effluent sampling of each AOP treatment system will be completed for 30 years.

Integrated Remedy Action Points

Groundwater modeling (Appendix B, Scenario 8a) predicts that pumping under Alternative 2 conditions will be suitable for western plume TCE and 1,4-dioxane MNA in approximately nine years (3 times the RG for each). Under Alternative 2, groundwater modeling predicts that conditions will be suitable for southern plume 1,4-dioxane MNA in 17 years (3 times the RG for each). This prediction was used for alternative evaluation and costing purposes. Northern and southern system operation will be evaluated independently.

The active remedy portion will terminate and MNA initiated when one of the endpoint conditions presented in Section 4.0 is met.

4.4 ALTERNATIVE 3: IN-SITU GROUNDWATER TREATMENT WITH ISCO USING BASE-ACTIVATED PERSULFATE

Alternative 3 includes the following elements:

- Continuing O&M of the existing P&T system, including the existing tower air stripper, for 5 years to during the beginning of ISCO injections
- Continued documentation and reporting of the GETR system for 5 years
- Continued monitoring of influent to and effluent from the GETR system for 5 years
- Installing approximately 135 multiple-use injection points to treat the primary TCE plume
- Installing approximately 110 multiple-use injection points to treat the leading edge of the 1,4-dioxane plume along SR 20
- Injecting base-activated persulfate in the aquifer using the 245 reusable injection points
- Continually reinjecting in the same injection points until COCs are below RGs, reducing the number of injection wells used over time as areas clean up, and focusing additional treatment to hot spot areas
- Continuing semiannual monitoring of 35 groundwater monitoring wells plus 8 new wells, with analytical testing of VOCs and 1,4-dioxane for 10 years from years 6 through year 15
- LUCs from OU 1 ROD
- Groundwater use restrictions will be put in place where there is potential drinking water use and concentrations exceed the RGs downgradient of the identified plume
- Two additional 5-year reviews of the remedial action at years 10 and 15

Specific description about technology, methods, and quantities are included for cost estimating purposes.

General Alternative Description

This ISCO alternative will intercept and treat impacted groundwater migrating off site along the western and southwestern boundaries of the site and also along the southern leading edge of the plume near SR 20. The injection of ISCO reagents such as base-activated persulfate into the

saturated zone will chemically destroy COCs. One row of vertical injection wells will be installed across the entire width of the western and southern limits of the dissolved plume (Figure 4-2). No vapor control is needed, and no waste products are generated at the surface.

The area needing treatment is large, so ISCO will take multiple years to complete with numerous injection wells. To maintain capture of the groundwater while ISCO treatment is initially performed, this alternative assumes that the existing extraction wells and treatment equipment will continue to operate to recover groundwater with COCs from the subsurface in areas with TCE and 1,4-dioxane above RGs. The extracted water will be treated aboveground with the existing tower air stripper and discharged to the surface water swale exactly like Alternative 1. It is estimated that the existing P&T system will operate for 5 years until ISCO can prevent off-site migration and hydraulic containment is no longer required. At that point, the existing P&T system will be turned off.

Conventional drilling techniques will be used to install a total of 245 reusable injection points (i.e., wells). The 135 injection points along the western perimeter are assumed to be 110 feet deep, and the 110 injection points along the southern perimeter will be 140 feet deep. Each injection point will be constructed from 2-inch-diameter polyvinyl chloride well casing and have a 10-foot-long screened interval. This alternative assumes that it will be necessary to have one two-person crew injecting base-activated persulfate into the injection points full time to get enough oxidant into the formation to be effective. In addition, one full-time injection project manager/field supervisor will be needed. The crew will work four 10-hour days per week, 50 weeks per year to aggressively inject base-activated persulfate to the contaminated zone. The assumption is that the crew can inject oxidant and base into eight injection points per day. Therefore, during every 4-day work week, 32 points will be completed, taking approximately 8 weeks to complete a round of injection at all injection points at the site. If these injection frequencies can be maintained, each point would be used for injection at least six times per year.

This alternative assumes ISCO treatment with base-activated persulfate will be completed in 7 years using the following injection schedule:

- Years 1 through 4: rotating injection of all injection points (one full-time crew)
- Years 5 and 6: rotating injection of 50 percent of the injection points (one half-time crew)
- Year 7: rotating injection of 25 percent of the injection points (one quarter-time crew)

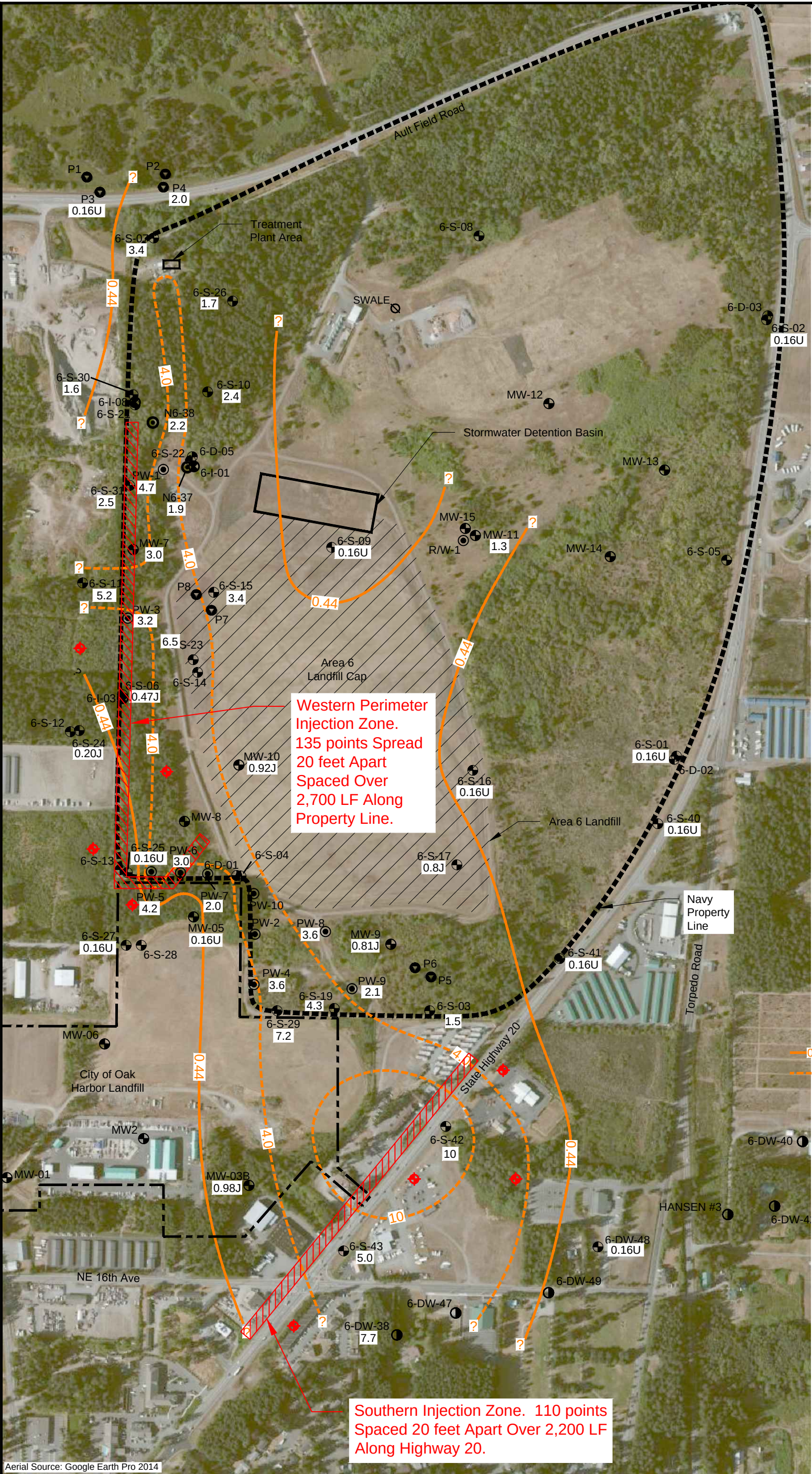
Figure 4-2 shows the conceptual location of injection wells and the assumed spacing which was used to generate the cost estimate for this alternative. ICs preventing the use of groundwater as a

drinking water source would be maintained because the site is a landfill. Sitewide MNA and ICs are included as components of this alternative.

Groundwater Treatment (Base-Activated Persulfate)

This alternative assumes ISCO will be used to treat COCs dissolved in groundwater using high pH (sodium hydroxide) activated sodium persulfate, also called base-activated persulfate. This process oxidizes the COCs in groundwater and leaves only water and residual sulfate. The base-activated persulfate ISCO process requires that the subsurface pH is increased to a minimum of 10.5 standard units to activate the persulfate. Water, persulfate, and sodium hydroxide are mixed in batches at the site using an industrial mixer. The oxidant (persulfate) and the base (sodium hydroxide) are supplied by a chemical vendor such as Peroxychem (formerly FMC Environmental) and delivered to the site for injection by a company trained to handle the chemicals and mixing, and injection equipment. Batches will be mixed for approximately 15 to 20 minutes and the pH tested to ensure that a high enough pH is achieved. Once each batch is homogenized and meets requirements, the activated persulfate mixture is injected into the desired injection point. The injection process can be done using one injection point (well) at a time, or a manifold to treat multiple injection points concurrently. The pressure and flow rate will be monitored frequently to accurately document the characteristics of the injection point and the volume injected. During the treatability study each well was injected with approximately 500 gallons of base-activated persulfate (U.S. Navy 2015a).

The ISCO process described above is similar to what was done during the treatability study (U.S. Navy 2015a). Results from the study indicated that COCs like TCE and 1,4-dioxane were successfully desorbed from soil. In addition, based on the results, it was concluded base-activated persulfate has the potential to reduce TCE and 1,4-dioxane concentrations to levels below the RG for TCE (5 µg/L) and the current MTCA Method B groundwater cleanup level for 1,4-dioxane (0.44 µg/L).



- Legend**
- New Groundwater Monitoring Well
 - Shallow Aquifer Groundwater Monitoring Well
 - Intermediate Aquifer Groundwater Monitoring Well
 - Deep Aquifer Groundwater Monitoring Well
 - Point-of-Compliance Groundwater Monitoring Well (Shallow Aquifer)
 - Piezometer
 - Private Well
 - Pumping Well
 - Swale (Outfall/Discharge)
 - MTCA Method B
 - 2014 1,4-Dioxane Concentration Contour

Note: This figure's design and assumptions are presented to generate cost estimates for alternative analysis.

Contour Source: U.S. Navy 2014c

FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055

Section 4.0

Date: 7/20/2018
Page 4-20

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Construction

Tasks necessary to implement Alternative 3 include the following components:

- Securing access agreements for off-site equipment/drilling (Navy)
- Contractor design and work plans
- Mobilization
- Specialty subcontractors (surveyor, utility locates)
- Drilling 110 reusable injection wells along the southern boundary (140 feet deep)
- Drilling 135 reusable injection wells along the western boundary (110 feet deep)
- Baseline analytical testing of groundwater in each injection well
- Drilling four new groundwater monitoring wells along the southern boundary (2 inches in diameter, 130 feet deep)
- Drilling four new groundwater monitoring wells along the western boundary (2 inches in diameter, 100 feet deep)
- Soil analytical testing from new groundwater monitoring well installations (four samples per boring)
- ISCO mixing and injection equipment
- Pumps and compressor to support injection process
- ISCO treatment with base-activated persulfate (continual treatment of all wells for 4 years)
- ISCO treatment with base-activated persulfate (treatment of 50 percent of the injection wells for 2 years during years 5 and 6)
- ISCO treatment with base-activated persulfate (treatment of 25 percent of the injection wells for 1 year during year 7)

- Decommissioning the existing GETR system after 5 years of operation
- IDW management and disposal
- Drilling services for injection point abandonment
- Demobilization
- Contractor reporting and closeout submittals (e.g., as-built drawings)

Operation and Maintenance

Continued O&M of the existing GETR system is assumed to be performed for 5 years. This includes operating the existing extraction wells and the aboveground treatment equipment. O&M of the extraction wells for the first 5 years is a common element to all alternatives. O&M for the ISCO portion of this alternative is not included because it is assumed to be completed under the construction phase of this project, even though it occurs over multiple years.

Monitoring

Monitoring includes semiannual collection of groundwater samples from 35 existing groundwater monitoring wells. Eight additional groundwater monitoring wells will also be monitored, four new wells each from the western and southern portions of the site. Sampling will include analytical testing for VOCs and 1,4-dioxane. Monitoring will allow assessment of the remediation effectiveness and changes in COC concentrations throughout the plume area. Quarterly influent and effluent sampling from the existing P&T system will be completed for 5 years when that system is assumed to be decommissioned.

Integrated Remedy Action Points

Injections will be terminated and MNA initiated when one of the following conditions is met:

- Injections will continue for up to 7 years and this technology will be reevaluated during the 5-year review or when one of the endpoint conditions presented in Section 4.0 is met.

4.5 ALTERNATIVE 4: IN-SITU GROUNDWATER TREATMENT WITH ISCO USING CATALYZED HYDROGEN PEROXIDE

Alternative 4 includes the following elements:

- Continuing O&M of the existing P&T system, including the existing tower air stripper, for 5 years during the beginning of ISCO injections
- Continued documentation and reporting of the GETR system for 5 years
- Continued monitoring of influent to and effluent from the GETR system for 5 years
- Installing approximately 180 multiple-use injection points to treat the primary TCE plume
- Installing approximately 150 multiple-use injection points to treat the leading edge of the 1,4-dioxane plume along SR 20
- Injecting modified Fenton's reagent in the aquifer using the 330 injection points
- Continually reinjecting until COCs are below RGs, reducing the number of injection wells used over time as areas meet RGS, and focusing additional treatment to hot spot areas
- Continuing semiannual monitoring of 35 groundwater monitoring wells plus 8 new wells, with analytical testing of VOCs and 1,4-dioxane for 10 years from years 6 through 15
- LUCs from OU 1 ROD
- Groundwater use restrictions will be put in place where there is potential drinking water use and concentrations exceed the RGs downgradient of the identified plume
- Two additional 5-year reviews of the remedial action at years 10 and 15

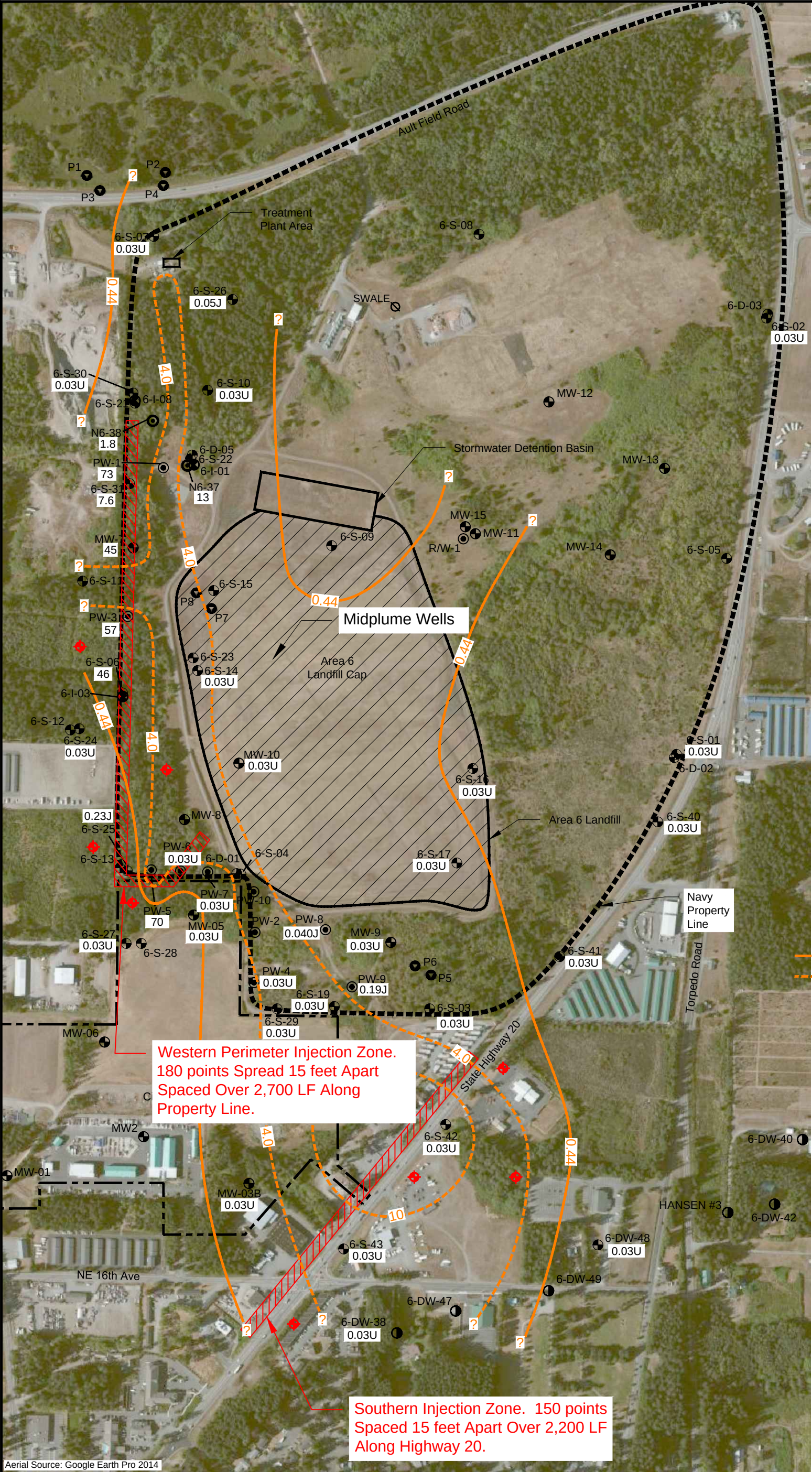
Specific description about technology, methods, and quantities are included for cost estimating purposes.

General Alternative Description

This alternative uses CHP for ISCO to destroy COCs exceeding RGs in the groundwater. The area needing treatment is large, so ISCO will take multiple years to complete. To maintain capture of the groundwater while ISCO treatment is initially performed, this alternative assumes the existing GETR equipment will continue to operate to recover groundwater. The extracted water will be treated aboveground with the existing tower air stripper and discharged to the surface water swale similar to Alternative 1. It is estimated that the existing P&T system will operate for 5 years until ISCO can prevent off-site migration and hydraulic containment is no longer required. At that point, the existing P&T system will be turned off.

CHP would be injected into reusable injection wells installed at regular intervals to chemically oxidize both dissolved- and sorbed-phase COCs. Figure 4-3 shows the conceptual location of injection wells and the assumed spacing which was used to generate the cost estimate for this alternative. The ISCO injection would be performed at all injection wells using a continuous cycle of events over a period of approximately 7 years. After 4 years, it is anticipated that some areas will be below RGs and the quantity of wells used for injection can be reduced. This alternative assumes all wells will be used for the first 4 years. In years 5 and 6, 50 percent of the wells will be used, and during the final 7th year of injection, only 25 percent of the wells will be used. Longer term MNA and ICs would be applicable to this alternative, as discussed previously.

CHP will be injected into these points at preselected intervals to chemically oxidize both dissolved- and sorbed-phase COCs. Vertical injection well locations would be constructed across the edge of where migration is occurring. This is where dissolved concentrations exceed RGs at the limits of the plume area. This alternative assumes approximately 330 evenly spaced injection points would be used for ISCO treatment. The chemical injections will only treat an area within about 10 to 15 feet from the injection well. Therefore, points would be approximately 15 feet apart and located throughout the areas where COCs exceed RGs. CHP reacts much faster than base-activated persulfate. This means peroxide will not advect out into the formation as far as base-activated persulfate. As a result, a tighter well spacing is required to achieve an effective radius from each well. This results in a larger number of injection wells for CHP. For the southern boundary of the site, approximately 150 evenly spaced injection points would be used for ISCO injections over 2,200 linear feet near SR 20. Along the western perimeter of the site, approximately 180 injection points would be used.



U.S. NAVY

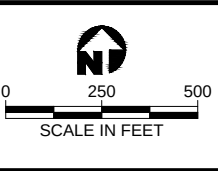


Figure 4-3
Alternative 4 - In Situ Groundwater Treatment
With ISCO Using Catalyzed Hydrogen Peroxide

Delivery Order 0055
Area 6, NAS Whidbey Island
FOCUSED FEASIBILITY
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FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 4.0

Date: 7/20/2018
Page 4-26

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The 180 injection points along the western perimeter are assumed to be 110 feet deep, and the 150 along the southern perimeter will be 140 feet deep. Each injection point will be reusable and constructed from 2-inch polyvinyl chloride well casing and have a 10-foot-long screened interval. This alternative assumes that it will be necessary to have one two-person crew injecting CHP into the injection points full time to get enough oxidant into the formation to be effective. In addition, one full-time injection project manager/field supervisor will be needed. The crew will work four 10-hour days per week, 50 weeks per year to aggressively inject oxidant into the contaminated zone. The assumption is that the crew can inject oxidant into three injection points simultaneously every 2.5 hours (12 points per day). Therefore, during every 4-day work week, 48 points will be completed and take approximately 7 weeks to complete a round of injection at all injection points at the site. If these injection frequencies can be maintained, each point would be used for injection approximately seven times per year.

This alternative assumes ISCO treatment with CHP will be completed in 7 years using the following injection schedule:

- Years 1 through 4: rotating injection of all injection points (one full-time crew)
- Years 5 and 6: rotating injection of 50 percent of the injection points (one half-time crew)
- Years 7: rotating injection of 25 percent of the injection points (one quarter-time crew)

ICs preventing the use of groundwater as a drinking water source would be maintained because the site is a landfill. Sitewide MNA and ICs are included as components of this alternative.

Groundwater Treatment (CHP)

The modified Fenton's process is also called CHP and generates hydroxyl powerful free radicals when a catalyst (iron) reacts with hydrogen peroxide. This in-situ remedial treatment technology destroys organic contamination through coexisting chemical oxidation and reduction. The process consists of injecting chelated iron catalysts and hydrogen peroxide into the contaminated aquifer where dissolved concentrations exceed RGs. The process is effective at neutral (pH 7) conditions unlike activated persulfate, which requires high pH. No vapor control is needed and no waste products are generated at the surface. The peroxide oxidization reaction is usually complete within less than 1 hour of injection, so there is very little migration of the oxidant in the aquifer. A closer well spacing is needed than with other oxidants because of the short half-life. However, the CHP reaction is very powerful and effective under a variety of conditions.

In-Situ Oxidative Technologies, Inc. is the primary service provider for injection of CHP and was subcontracted to provide the oxidant and perform the injections during the treatability study (U.S. Navy 2015a). The injection process includes connecting each well with various fittings and pressure gauges, diluting the hydrogen peroxide reagent to 12 percent, and homogenizing the catalyst with water using an industrial mixer. The CHP injection is a five-step process as shown below:

- Step 1: injection of water
- Step 2: injection of the catalyst (proprietary iron chelate complex)
- Step 3: second water flush
- Step 4: injection of the 12 percent hydrogen peroxide solution
- Step 5: third water flush

While injecting, the pressure and flow rate will be monitored on a frequent basis to determine injection well performance and document the volume injected. During the treatability study each well was injected with approximately 25 gallons of water, 400 gallons of catalyst, and 400 gallons of 12 percent hydrogen peroxide solution during each of the two injection efforts. This alternative assumes a total of 1,000 gallons of fluids will be injected into each well per event. The ISCO process described above is similar to what was done during the treatability study (U.S. Navy 2015a). Based on the results, it was concluded that CHP has the potential to reduce TCE and 1,4-dioxane concentrations to levels below the RG for TCE (5 µg/L) and the current MTCA Method B groundwater cleanup level for 1,4-dioxane (0.44 µg/L).

Construction

Tasks necessary to implement Alternative 4 include the following components:

- Securing access agreements for off-site equipment/drilling (Navy)
- Contractor design and work plans
- Mobilization
- Specialty subcontractors (surveyor, utility locates)
- Drilling 150 reusable injection wells along southern boundary (140 feet deep)
- Drilling 180 reusable injection wells along western boundary (110 feet deep)
- Baseline analytical testing of groundwater in each injection well

- Drilling four new groundwater monitoring wells along southern boundary (2 inches in diameter, 130 feet deep)
- Drilling four new groundwater monitoring wells along western boundary (2 inches in diameter, 100 feet deep)
- Soil analytical testing from new groundwater monitoring well installations (four samples per boring)
- ISCO mixing tanks and injection equipment
- ISCO treatment by modified Fenton's reagent (continual treatment of all wells for 4 years)
- ISCO treatment by modified Fenton's reagent (treatment of 50 percent of the injection wells for 2 years during years 5 and 6)
- ISCO treatment by modified Fenton's reagent (treatment of 25 percent of the injection wells for 1 year during year 7)
- Decommissioning the existing P&T system after 5 years of operation
- IDW management and disposal
- Drilling services for injection point abandonment
- Demobilization
- Contractor reporting and closeout submittals (e.g., as-built drawings)

Operation and Maintenance

Continued O&M of the GETR system is assumed to be performed for 5 years. This includes operating the existing extraction wells and the aboveground treatment equipment. O&M of the extraction wells for the first 5 years is a common element to all alternatives. No O&M for the ISCO portion of this alternative is included because it is assumed to be completed under the construction phase of this project, even though it occurs over multiple years.

Monitoring

Monitoring includes semiannual collection of groundwater samples from 35 existing groundwater monitoring wells and semiannual depth gauging. Eight additional groundwater monitoring wells will also be monitored, four new wells each from the western and southern portions of the site. Sampling will include analytical testing for VOCs and 1,4-dioxane. Monitoring will allow assessment of the remediation effectiveness and changes in COC concentrations throughout the plume area. Quarterly influent and effluent sampling from the existing P&T system will be completed for 5 years when that system is assumed to be decommissioned.

Integrated Remedy Action Points

Injections will be terminated and MNA initiated when one of the following conditions is met:

- Injections will continue for up to 7 years and this technology will be reevaluated during the 5-year review or when one of the endpoint conditions presented in Section 4.0 is met.

4.6 ALTERNATIVE 5: EXPANDED GROUNDWATER CAPTURE WITH ALL UNTREATED EFFLUENT DISCHARGED TO NAVY WWTF AT AULT FIELD

Alternative 5 includes the following elements:

- Removing existing air stripper treatment system and routing untreated water from all the extraction wells to the Navy WWTF at Ault Field
- Expanding capture zone along the leading edge of the 1,4-dioxane plume by strategically placing up to five new extraction wells along the northern shoulder of SR 20
- Expanding extraction network along the centerline of the western 1,4-dioxane and TCE plume by adding up to four new extraction wells
- Installing a new pipeline to route untreated effluent from the nine new western and southern plume wells to the existing treatment pad
- Installing a new pipeline to convey all water extracted directly to the Navy WWTF at Ault Field from the existing treatment pad

- Connecting the new pipeline to an existing sanitary sewer line near facility buildings
- Adding a carbon substrate management system to the Ault Field WWTF
- Continuing semiannual monitoring of 35 groundwater monitoring wells plus 8 new wells, with analytical testing of VOCs and 1,4-dioxane for 30 years from years 6 through 15
- Transition from active remedy portion to MNA in the western plume will occur when one of the endpoint conditions presented in Section 4.0 is met.
- Transition from active remedy portion to MNA in the southern plume will occur when one of the endpoint conditions presented in Section 4.0 is met.
- LUCs from OU 1 ROD
- Groundwater use restrictions will be put in place where there is potential drinking water use and concentrations exceed the RGs downgradient of the identified plume

Specific description about technology, methods, and quantities are included for cost estimating purposes.

General Alternative Description

This alternative relies on P&T remediation to clean up groundwater at the site. Existing and new extraction wells will be used to recover groundwater with COCs from the subsurface in areas with TCE and 1,4-dioxane above RGs. The major deviation from other alternatives is that the treatment will be completed off site by the existing Ault Field WWTF. All water extracted from the site will be routed underground in a new 8-inch-diameter, double-walled high-density polyethylene force main pipe to an existing sanitary sewer pipe near the airfield. The existing tower air stripper would be removed from the site and the existing effluent pipe to the surface swale capped. The existing holding tank will remain in place and be used to regulate discharge to the new effluent pipeline. Two new discharge pumps would be installed to transfer water from the existing batch tank through the new force main pipe. Figure 4-4 shows the conceptual location of additional extraction wells and the assumed alignment of the new pipelines which was used to generate the cost estimate for this alternative.

This alternative also expands the existing network of extraction wells to include up to nine more extraction wells. Up to four additional extraction wells would be strategically placed along the

centerline of the western TCE plume. A new 6-inch-diameter single-walled pipeline will be completed to route the additional flow from these potential four wells to the existing treatment pad batch tank. Each new extraction well will be completed to a depth of approximately 120 feet and have a submersible pump rated at 20 gpm (40 gpm maximum) installed.

To capture COCs near the leading edge of the southern plume, up to five new extraction wells will be completed to a depth of approximately 150 feet, and each will have a submersible pump rated at 20 gpm (40 gpm maximum) installed. The new wells will be strategically located along the southern site boundary to extend the capture zone downgradient to further reduce the off-site migration rates of 1,4-dioxane and vinyl chloride. Extracted groundwater will be routed in new 6-inch-diameter double-walled piping. Double-walled piping will also have manual leak detection monitoring points located at low points in the pipeline.

The new double-walled pipelines located outside the limits of the Area 6 landfill will also have cleanouts and secondary containment monitoring points, which are not shown. The cleanouts and monitoring points will be located in underground vaults. The new 8-inch double-walled pipeline is located entirely on base property, but the 6-inch double-walled pipeline from the new southern extraction wells is located on City of Oak Harbor property. As with all alternatives, long-term goals would be met when all COCs meet RGs. However, ICs preventing the use of groundwater as a drinking water source would be maintained because the site is a landfill. Sitewide MNA and ICs are included as components of this alternative.

Groundwater modeling (Appendix B Scenario 8a) predicts that pumping under Alternative 5 conditions will be suitable for western plume TCE and 1,4-dioxane MNA in approximately nine years (3 times the RG for each). Under Alternative 5, groundwater modeling predicts that conditions will be suitable for southern plume 1,4-dioxane MNA in 17 years (3 times the RG for each). Active treatment system operations will be terminated and the remedy will revert to MNA when one of the endpoint conditions presented in Section 4.0 is met.

Groundwater Treatment

This alternative assumes all untreated water from the extraction wells will be routed to the sewage treatment plant at Ault Field for treatment. No on-site treatment will be completed at Area 6. Aeration during extracted groundwater transport, sewage treatment plant equipment, and dilution from their other input streams will reduce concentrations of COCs. The February and March 2014 influent COC concentrations (U.S. Navy 2014b) are presented in Table 4-1.

FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 4.0

Date: 7/20/2018
Page 4-33

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- Legend**
- OU Operable Unit
 - LUC Land Use Control
 - OU LUC Area/Site Boundary
 - ◆ New Extraction Well

Note: This figure's design and assumptions are presented to generate cost estimates for alternative analysis.

Sources:
OU LUC Areas: Boundary survey conducted using RTK GPS by Tetra Tech, Inc., June 2013.
Aerial: Google Earth Pro

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The Ault Field WWTF National Pollutant Discharge Elimination System (NPDES) permit (No. WA 00346-8) dated February 1, 2011 does not specify a total toxic organics (sum of all toxic organic compounds in effluent) limit on any of the COCs or 1,4-dioxane; it will need to be revised for implementation of this alternative. However, total toxic organics limits are generally assigned at 1,000 µg/L. The total COC influent concentration in February 2014 was 102.89 µg/L. If the optimized extraction network proposed under this alternative were to triple the influent concentration, this untreated influent would still be below 1,000 µg/L. Also, the February and March 2014 untreated TCE influent concentrations were only 1 µg/L above the MTCA Method B surface water cleanup level for human health marine waters. Transport of TCE to the WWTF and the WWTF treatment process will reduce TCE concentrations below the MTCA Method B surface water level, even if concentrations are tripled by extraction optimization. The established MTCA Method B surface water levels for 1,1,1-TCA, 1,1-DCE, and vinyl chloride are orders of magnitude greater than the respective February and March 2014 untreated influent concentrations.

Table 4-1
Summary of February and March 2014 Influent Concentrations

Analyte	February 2014 (µg/L)	March 2014 (µg/L)	MTCA B Surface Water Cleanup Level (µg/L)
TCE	31	31	30 (HH Marine)
1,1,1-TCA	37	43	926,000 (Noncancer)
1,1-DCA	10	12	Not established
cis-1,1-DCE	6.8	6.1	Not established
1,1-DCE	15	14	7,100 (HH Marine)
Vinyl chloride	0.19	0.19	2.4 (HH Marine)
1,4-Dioxane	2.9	N/A	Not established
Total	102.89	NA	NA

Notes:

DCA - dichloroethane

DCE - dichloroethene

HH - human health

µg/L - microgram per liter

MTCA B - Model Toxics Control Act Method B

NA - not applicable

N/A - not analyzed

TCA - trichloroethane

TCE - trichloroethene

EPA's work plan for chemical problem formulation for 1,4-dioxane (USEPA 2015) concluded that based on the low hazard profile for 1,4-dioxane to aquatic organisms, risks to these organisms are expected to be low. Lack of hazard data precludes determination of risk to sediment and soil organisms. Therefore, further analysis of environmental risk is not planned, and risks to the surface waters of Puget Sound are not expected if there is residual 1,4-dioxane discharge from the Ault Field WWTF.

The untreated water from Area 6 has various chemicals present above RGs, but at relatively low concentrations. This type of influent to a sewage treatment plant is considered essentially clean water, which may dilute the biological conditions in their process. As a result, this alternative includes a carbon substrate management system to keep biological conditions within specifications at the WWTF.

The Ault Field WWTF has a design capacity of 0.85 million gallons per day (MGD) and a maximum capacity of 2.1 MGD. Average flow as of May 2014 was 0.33 MGD. If the 300-gpm effluent from the extraction system described for Alternative 5 is added to the WWTF, this equates to approximately 0.432 MGD, which more than doubles the May 2014 average flow. This will also bring the average total flow to 90 percent of design capacity and 36 percent of maximum capacity. Under these conditions, the flow brought to the WWTF from the extraction system will be considered "clean" water. This will detrimentally impact the balance required to maintain active biotic processes. Under Alternative 5, a carbon management system would be required to maintain the proper carbon balance to maintain active biotic processes.

Carbon Substrate Addition

This alternative will also require a revision to the NPDES permit. Minimum revisions are anticipated to be an adjustment to the permitted flow and addition of total toxic organics monitoring.

This alternative includes installation and O&M of a carbon substrate injection system at the existing WWTF to keep their biological conditions within specifications. The assumption is that the additional 300 gpm of flow from the landfill would upset the biological conditions at the WWTF, because the added water is essentially clean and would dilute the existing influent. To promote normal operating conditions a carbon source would be added to balance with the additional clean water flow at the WWTF. With carbon source addition, clean water from the extraction system would behave more like a typical influent stream to the WWTF.

This alternative assumes MicroC would be injected into the flow stream as the carbon substrate. MicroC is a manufactured product specifically designed to be a biodegradable carbon source (electron donor) for nitrogen removal at the WWTF. MicroC is a proven product that is safe,

and easy to use and would be stored on site in an aboveground storage tank. Consumption calculations indicate that approximately 250 gallons per day (0.18 gpm) would be needed to maintain a target biochemical oxygen demand (BOD) of 200 milligrams per liter (mg/L).

$$\text{MicroC Feed Rate (gpm)} = (\text{Target BOD} \times \text{Flow Rate}) / (\text{MicroC COD} \times \text{BOD/COD ratio})$$

Assumptions:

- Target biochemical oxygen demand (BOD): 200 mg/L
- Flow rate from extraction system: 300 gpm
- MicroC chemical oxygen demand (COD) content: 670,000 mg/L
- BOD/COD ratio: 1/2

BOD is used to define the amount of oxygen needed by aerobic biological organisms in water to break down organic material. To maintain a minimum 3-week supply at the site, a 6,000-gallon aboveground storage tank would be installed at the WWTF. The injection system would also include a control system, 500-gallon day tank, and feed pumps located in a small heated shed.

Construction

Tasks necessary to implement Alternative 5 include the following components:

- Contractor design and work plans
- Specialty subcontractors (surveyor, utility locates)
- Mobilization
- Installing environmental protection
- Obtaining franchise agreement with City of Oak Harbor for right-of-way access near SR 20
- Drilling five new extraction wells along SR 20 (6 inches in diameter, 150 feet deep)
- Drilling up to four new extraction wells along the centerline of the western plume (6 inches in diameter, 120 feet deep)
- Nine well head vaults and down-hole pumps and equipment (20 gpm each)

- Soil analytical testing from new extraction well installations (four samples per boring)
- Removing existing tower air stripper
- Removing surface asphalt 3 feet wide for crossing Ault Field Road
- Excavating trench and stockpiling soil (0 to 3 feet bgs) for all new extraction well pipelines (total length of approximately 7,500 feet)
- Single-walled piping from the potential new western plume wells to existing treatment pad batch tank (6 inches, 2,500 feet long): The majority (2,000 out of 2,500 feet) of this pipeline will be laid in a common trench with piping from the new southern plume wells.
- Double-walled piping from the new southern plume wells to southern site boundary (6 inches, 2,500 feet long)
- Single-walled water piping to connect the double-walled piping from the southern wells to the existing treatment pad batch tank (6 inches, 4,500 feet long)
- Excavating trench and stockpiling soil (0 to 4 feet bgs) for new combined effluent from the site to the sanitary sewer (total length of approximately 9,000 feet)
- Double-walled piping from existing treatment pad to connection point with existing sanitary sewer pipe near Ault Field (8 inches, 9,000 feet long)
- Installing air-release valves, cleanouts, and leak detection monitoring points in the new pipeline inside underground vaults
- Analytical sampling of soil from trench excavations for disposal purposes
- Off-site disposal of 50 percent of soil excavated to make room for pipe bedding
- Importing pipe bedding to the site and reusing stockpiled materials where possible
- Backfilling and compaction of excavation
- Asphalt paving areas where the road was trenched

- IDW management and disposal of drill cuttings and asphalt
- General site restoration work
- 6,000-gallon aboveground storage tank on concrete secondary containment pad
- Shed with power and heat for day tank, controls, and injection equipment
- Connecting new carbon substrate injection system to the existing infrastructure
- Demobilization
- Contractor reporting and closeout submittals (e.g., as-built drawings)

Operation and Maintenance

Continued O&M of the new extraction system is assumed to be performed for 17 years. This includes operating the existing extraction wells, nine new extraction wells, and two new effluent discharge pumps. O&M for all 19 extraction wells are included for 17 years in this alternative. However, O&M of the 10 existing extraction wells for the first 5 years is a common element to all alternatives and is accounted for separately in the cost estimate. Alternative 5 assumes O&M of the extraction wells and the two effluent discharge pumps will be completed by one person with monthly site visits. Maintenance visits by two people will be completed quarterly for two full days. More significant maintenance is assumed to occur annually and will require two people for 2 days each year.

Monitoring

Monitoring includes semiannual collection of groundwater samples from 35 existing groundwater monitoring wells and semiannual depth gauging. Sampling will include analytical testing for VOCs and 1,4-dioxane. Monitoring will allow assessment of the remediation effectiveness and changes in COC concentrations throughout the source area. Routine monitoring will also include checking leak detection monitoring points located in the low points of the double-walled pipelines and recording flow rates from each extraction well.

Integrated Remedy Action Points

Groundwater modeling (Appendix B, Scenario 8a) predicts that pumping under Alternative 5 conditions will be suitable for western plume TCE and 1,4-dioxane MNA in approximately nine years (3 times the RG for each). Under Alternative 5, groundwater modeling predicts that

conditions will be suitable for southern plume 1,4-dioxane MNA in 17 years (3 times the RG for each). Northern and southern system operation will be evaluated independently.

The active remedy portion will terminate and MNA will be initiated when one of the endpoint conditions presented in Section 4.0 is met.

4.7 ALTERNATIVE COMBINATIONS

A combination of Alternatives 2 and 4 could be employed with the objective of significantly reducing the overall GETR life cycle in the western plume. Hydrogen peroxide would be used with the partial Alternative 4 injections. These two represent the least expensive alternatives with the best evaluated potential to achieve RAOs. This option assumes that Alternative 2 would be fully implemented and Alternative 4 would be implemented at 30 percent of the full implementation.

Full implementation of Alternative 2 would facilitate containment and ex-situ treatment in the western and southern plumes, with 1,4-dioxane destruction through the ex-situ AOP systems. One hundred injection wells would be installed within the western plume to accelerate treatment and reduce the life-cycle costs for the P&T component of the western plume.

Groundwater modeling predicts that Alternative 2 would achieve western plume VOC RGs in approximately 17 years (Appendix B, Scenario 8a). Adding approximately 30 percent of Alternative 4 in the western plume only would further reduce this time to 12 years (U.S. Navy Appendix B, Scenario 9).

4.8 GROUNDWATER MODELING SIMULATIONS RESULTS

Groundwater model fate and transport simulations were performed to predict the site response to the proposed alternatives described above, including variations and combinations of these simulations. The modeling report is provided as Appendix B. Table 4-2 summarizes these scenarios, identifies which alternatives (or combinations) they represent, and the predicted time to achieve contaminant specific groundwater RGs.

Table 4-2
Summary of Groundwater Modeling Simulations

Scenario/Alternative	Scenario Details		Cleanup Time to RGs/3 X RG (years)		
			TCE	Vinyl Chloride	1,4-Dioxane
Scenario 1/ Alternative 1	Existing GETR System (Baseline)	PW-1 - operational at 26.5 gpm	30	>50	>50
		PW-2 - operational at 0 gpm			
		PW-3 - operational at 29 gpm			
		PW-4 - operational at 20 gpm			
		PW-5 - operational at 24 gpm			
		PW-6 - operational at 23.5 gpm			
		PW-7 - operational at 23.5 gpm			
		PW-8 - operational at 12.5 gpm			
		PW-9 - operational at 16 gpm			
		PW-10 - operational at 0 gpm			
Scenario 2/ Alternatives 3 and 4	Baseline		18	>50	>50
	ISCO Injections	70% reduction of mass. Spaced at approximate 200-foot intervals. Orientated within the 50 µg/l TCE plume and the 10 µg/l 1,4-Dioxane plume.			
Scenario 3/ Alternatives 3 and 4	Baseline		13	>50	>50
	ISCO Injections	70% reduction of mass. Spaced at approximate 100-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.			

Table 4-2 (Continued)
Summary of Groundwater Modeling Simulations

Scenario/Alternative	Scenario Details		Cleanup Time to RGs/3 X RG (years)		
			TCE	Vinyl Chloride	1,4-Dioxane
Scenario 3a/ Alternatives 3 and 4	ISCO Injections	70% reduction of mass. Spaced at approximate 100-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.	>50	>50	>50
Scenario 4/ Alternatives 3 and 4	Baseline		17	>50	>50
	ISCO Injections	50% reduction of mass. Spaced at approximate 100-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.			
Scenario 5/ Partial Alternative 2 or 5	Baseline		28	21	32
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
Scenario 5a/ Combination of Partial Alternatives 2 or 5 and Alternative 3 or 4	Baseline		18	17	24
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
	ISCO Injections	70% reduction of mass. Spaced at approximate 200-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.			
Scenario 6/ Combination of Partial Alternative 2 or 5 and Alternative 3 or 4	Baseline		33	21	>50
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			

Table 4-2 (Continued)
Summary of Groundwater Modeling Simulations

Scenario/Alternative	Scenario Details		Cleanup Time to RGs/3 X RG (years)		
			TCE	Vinyl Chloride	1,4-Dioxane
	Reinjection of Treated Groundwater	Injection wells PIW-1 to PIW-10 added. Spaced on approximate 80-foot centers. Operational injection rates of 10 gpm.			
Scenario 7/ Alternatives 3 or 4	In-Situ Barriers	Destruction of contaminant mass upon contact. An approximate 1300-foot barrier orientated along the longitudinal axis of the 50 µg/l TCE plume with containment at the south and southeast extent of the plume. An approximate 1800-foot barrier orientated perpendicular to the longitudinal axis of the 4 µg/l 1,4-Dioxane plume and parallel with State Route 20.	>50	25	>50
Scenario 8/ Alternative 2 or 5	Baseline (Modified)	Equal pumping rates from four additional pumping wells in the western plume wells PW-1, PW-3, PW-5, PW-6	18	21	32
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
Scenario 8a/ Alternative 2 or 5	Baseline (Modified)	Equal pumping rates from four additional pumping wells in the western plume wells PW-1, PW-3, PW-5, PW-6. Pumping from wells PW-4 and PW-9 suspended and this flow equally distributed between the eight wells identified above.	15/9	19/16	24/17
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
Scenario 9/ Combination of Alternative 2 or 5 and Alternatives 3	Baseline (Modified)	4 Additional pumping wells in the western plume and operational rates of 13.13 gpm at PW-1, PW-3, PW-5, PW-6, and the 4 new wells.	13	21	32

Table 4-2 (Continued)
Summary of Groundwater Modeling Simulations

Scenario/Alternative or 4	Scenario Details		Cleanup Time to RGs/3 X RG (years)		
			TCE	Vinyl Chloride	1,4- Dioxane
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
	ISCO Injections	70% reduction of mass. Spaced at approximate 200-foot intervals orientated within the 50 µg/l TCE plume.			
Scenario 10/ Variation of Alternative 2 or 5	Baseline (Modified)	4 Additional pumping wells in the western plume and operational rates of 13.13 gpm at PW-1, PW-3, PW-5, PW-6, and the 4 new wells.	18	>50	>50
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added and moved to the base southern boundary. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			

Scenario 1 represents the existing GETR currently operating at the site and represents Alternative 1. This simulation predicts that the existing GETR will reach the TCE RG of 5 µg/L in approximately 30 years. TCE is only present in the western plume. Since the existing GETR will not treat extracted groundwater for 1,4-dioxane, the existing GETR will not reach the proposed RG of 0.44 µg/L for 1,4-dioxane in groundwater. This simulation predicts that existing GETR will not meet the 0.1 µg/L RG for vinyl chloride in greater than 50 years.

Scenarios 2, 3, 4, and 7 represent variations of Alternatives 3 or 4, in-situ chemical oxidation only. These simulations predict variations on Alternatives 3 and 4 would achieve the TCE RG in times ranging from 13 to 50 years. These simulations predict that all variations on Alternatives 3 and 4 would not meet the vinyl chloride and 1,4-dioxane RGs in greater than 50 years.

Scenario 5 represents a partial Alternative 2 or 5. Additional extraction wells would be placed along the northern shoulder of SR 20 to address the southern plume, but does not include the additional extraction wells within the western plume. This simulation predicts that the TCE RG would be met in 28 years with the vinyl chloride and 1,4-dioxane RGs being met in 21 and 32 years, respectively.

Scenario 5a represents combination of partial Alternative 2 (same as Scenario 5) and Alternatives 3 or 4. This simulation predicts that the TCE RG would be met in 18 years with the vinyl chloride and 1,4-dioxane RGs being met in 17 and 24 years, respectively.

Scenario 6 represents a combination of partial alternative 2 or 5 (same as Scenario 5) and Alternatives 3 or 4, with a reinjection of treated water from the proposed southern extraction well field effluent along the southern property line of the site. This simulation predicts that the TCE RG would be met in 33 years. The vinyl chloride RG would be met in 21 years. The 1,4-dioxane RG would not be met in greater than 50 years. The predicted increase in time to achieve the RG relative to Scenario 5 is interpreted to be a result of the changed hydraulic gradient along the southern property line caused by the reinjection. This changed gradient fights against the extraction wells in the western plume and increases the migration rate of the southern plume.

Scenario 8 represents Alternatives 2 or 5 and includes the proposed extraction wells along SR 20 and the proposed extraction wells for the western plume. This simulation predicts that the TCE RG would be met in 18 years with the vinyl chloride and 1,4-dioxane RGs being met in 21 and 32 years, respectively.

Scenario 8a represents Alternatives 2 or 5 and includes the proposed extraction wells along SR 20 and the proposed extraction wells for the western plume. Scenario 8 predicts that pumping from wells PW-4 and PW-9 slow migration of the 1,4-dioxane in groundwater to the downgradient extraction wells along SR20. Scenario 8a suspends pumping from wells PW-4 and PW-8, and reallocates that flow evenly into the eight wells (4 existing and 4 new wells) in the

western plume. The result is shortened times to reach RGs in both the southern and western plumes. This simulation predicts that the TCE RG would be met in 15 years with the vinyl chloride and 1,4-dioxane RGs being met in 19 and 24 years, respectively. This simulation predicts that the 3 times the RG for TCE would be met in 9 years with 3 times the RGs for vinyl chloride and 1,4-dioxane met in 16 and 17 years, respectively.

Scenario 9 represents a combination of the full Alternatives 2 or 5 and Alternatives 3 or 4. This simulation predicts that the TCE RG would be met in 13 years with the vinyl chloride and 1,4-dioxane RGs being met in 21 and 32 years, respectively.

Scenario 10 represents Alternatives 2 or 5 and with proposed southern plume extraction wells along the southern site boundary instead of along SR 20, and includes the proposed extraction wells for the western plume. This simulation predicts that the TCE RG would be met in 18 years with the vinyl chloride and 1,4-dioxane RGs not being met in greater than 50 years.

4.9 ESTIMATED ALTERNATIVE COSTS

Costs

Costs were estimated for each alternative to evaluate if they are cost effective and how the alternatives compare to each other. Total capital implementation cost, total operational cost for 30 years, and present-worth implementation and operational costs are presented for each alternative in Appendix G. Operational costs include O&M, monitoring, and nonroutine and closure costs that are anticipated to occur over the life of the project. Total project cost is the straight addition of the capital cost and the total operational cost for the assumed 30 years of monitoring and maintenance. Annualized O&M and monitoring costs are calculated from their respective total cost divided by 30 years. The present-worth cost is composed of estimated capital implementation cost and the net present value of operational costs, including environmental monitoring costs and nonroutine O&M costs where appropriate. Present-worth analysis evaluates expenditures that occur over different time periods by discounting all future costs to a common base year. A discount rate of 3 percent was used, which assumes an interest rate of 6 percent minus the inflation rate of 3 percent. Present-worth costs represent the amount of money that, if invested in the base year (i.e., 2015) and dispersed as needed, would cover all anticipated costs associated with the alternative.

The equation used to calculate present worth is:

$$PW = ((1+i)^{n-1})/(i(1+i)^n)$$

Where: PW – present worth

i – interest rate
n – number of years

The cost estimates presented herein are considered order-of-magnitude estimates (i.e., the estimated costs are expected to be within –30 to +50 percent of the actual costs of the completed project). Implementation and operational costs are based on 2015 dollars. The validity of these costs (Appendix G) is subject to the assumptions used in the development of these alternatives. To improve the accuracy of the estimates, factors were applied to increase contractor cost (25 percent), engineering cost (15 percent), and operational cost (20 percent) categories independently to account for unlisted items. These three line items cover tasks and services that are unlisted because they are too detailed for this conceptual level of cost estimating and are based on engineering judgment and experience. In addition, Washington State sales tax has been added to the contractor cost category at a rate of 9.5 percent. Because of the accuracy level intended, the primary use of these estimates is to allow comparison between alternatives during the selection process, not for establishing project budgets.

The estimated total project cost (with and without present-worth analysis) to implement each alternative is summarized in Table 4-2. Estimated cost for Combined Alternatives 2 and 4 are summarized in Table 4-3. Individual cost estimates prepared for each alternative, with back up information are presented in Appendix G.

O&M - operation and maintenance Cost Evaluation

The total project capital and operational costs with present-worth and cost for each alternative are:

<u>Alternative</u>	<u>Total Project Capital and O&M Costs</u>	<u>Present Worth Cost</u>
1	\$19.31 million	\$12.8 million
2	\$18.58 million	\$14.5 million
3	\$44.93 million	\$41.8 million
4	\$41.31 million	\$38.6 million
5	\$20.4 million	\$16.0 million
Combined 2 and 4	\$31.76 million	\$27.6 million

Alternative 1 is the least expensive alternative. However, it does not address treatment of 1,4-dioxane because it continues with the existing treatment strategy. The existing GETR system would continue to have 1,4-dioxane in concentrations exceeding cleanup levels in effluent from the treatment plant. Alternative 2 is the second least expensive and lowest cost alternative that addresses 1,4-dioxane. Effluent concentrations of 1,4-dioxane would be below cleanup levels if Alternative 2 were implemented.

Net present worth for Combined Alternatives 2 and 4 is \$27,600,000. This is \$13,100,000 more than Alternative 2 alone.

If ERD is used, even a 20 to 50 percent decrease in injection media cost would not make this combination competitive with Alternative 2. It should be noted that ERD does not address 1,4-dioxane.

Table 4-3
Comparison of Alternative Costs

Task	Alternative 1: Continue with Current System	Alternative 2: Continue P&T With Ex-Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells North System 9 years South System 17 years	Alternative 3: In-Situ Groundwater Treatment With ISCO Using Base-Activated Persulfate	Alternative 4: In-Situ Groundwater Treatment With ISCO Using Catalyzed Hydrogen Peroxide	Alternative 5: Expanded Groundwater Capture With All Untreated Effluent Discharged to Navy WWTF at Ault Field North System 9 years South System 17 years
Implementation Costs					
Capital Direct Costs (Construction)	\$423,000	\$3,460,000	\$37,280,000	\$33,630,000	\$3,450,000
Unlisted Items and Services Assumed (%)	25%	25%	25%	25%	25%
Capital Indirect Costs (Engineering)	\$118,000	\$508,000	\$1,210,000	\$1,130,000	\$492,000
Unlisted Engineering Services Assumed	15%	15%	15%	15%	15%
Total Capital Implementation Costs	\$541,000	\$3,970,000	\$38,490,000	\$34,760,000	\$3,940,000
Operational Costs (30 years)					
Annual O&M Costs (North System)	\$305,000	\$222,000	\$158,000	\$158,000	\$358,000
Years of O&M Assumed (North System)	30	9	5	5	9
Annual O&M Costs (South System)	NA	\$139,000	NA	NA	\$194,000
Years of O&M Assumed (South System)	NA	17	NA	NA	17
Annual Monitoring Costs	\$289,000	\$301,000	\$308,000	\$308,000	\$300,000
Years of Monitoring Assumed	30	30	15	15	30
Nonroutine O&M and Closure Costs	\$1,026,000	\$1,215,000	\$1,049,000	\$1,151,000	\$934,000
Unlisted Operational Tasks Assumed	20%	20%	20%	20%	20%
Total Operational Costs	\$18,850,000	\$14,610,000	\$6,460,000	\$6,570,000	\$16,460,000

Table 4-3 (Continued)
Comparison of Alternative Costs

Task	Alternative 1: Continue with Current System	Alternative 2: Continue P&T With Ex-Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells North System 9 years South System 17 years	Alternative 3: In-Situ Groundwater Treatment With ISCO Using Base-Activated Persulfate	Alternative 4: In-Situ Groundwater Treatment With ISCO Using Catalyzed Hydrogen Peroxide	Alternative 5: Expanded Groundwater Capture With All Untreated Effluent Discharged to Navy WWTF at Ault Field North System 9 years South System 17 years
TOTALS					
Total Capital and Operational Costs	\$19,391,000	\$18,580,000	\$44,930,000	\$41,310,000	\$20,400,000
Present-Worth Implementation Costs	\$483,000	\$3,870,000	\$35,740,000	\$32,450,000	\$3,840,000
Present-Worth Operational Costs	\$12,260,000	\$10,290,000	\$5,210,000	\$5,290,000	\$11,810,000
Site Inspection and Overhead	\$77,000	\$310,000	\$715,000	\$649,000	\$307,000
Agency Oversight	\$19,300	\$77,400	\$178,700	\$123,900	\$76,800
Total Project Present Worth^a	\$12,800,000	\$14,500,000	\$41,800,000	\$38,600,000	\$16,000,000

^aPresent-worth costs were calculated using a 3% discount rate with a base year of 2015.

Notes:

Discount Rate (3%) = Interest Rate (6%) – Inflation (3%)

ISCO – in-situ chemical oxidation

O&M - operation and maintenance

P&T - pump and treat

WWTF - wastewater treatment facility

Table 4-4
Estimated Cost for Combined Alternatives 2 and 4

Task	Modified AOP Alternative: Ex-Situ AOP System for Western Plume for 13 Years and Southern Plume for 30 Years	Modified CHP Alternative: ISCO Using CHP, 100 Points in Source Area	Combined Alternatives: Ex-Situ AOP and With CHP in Source Area
Implementation Costs			
Capital Direct Costs (Construction)	\$3,460,000	\$11,360,000	\$14,820,000
Unlisted Items and Services Assumed	25%	25%	25%
Capital Indirect Costs (Engineering)	\$508,000	\$640,000	\$1,148,000
Unlisted Engineering Services Assumed	15%	15%	15%
Total Capital Implementation Costs	\$3,970,000	\$12,000,000	\$15,970,000
Operational Costs (30 years)			
Annual O&M, Monitoring Costs, Western Plume	\$445,000	\$0	NA
Years of O&M Assumed	13	0	13
Annual O&M, Monitoring Costs, Southern Plume ^a	\$219,000	\$116,000	NA
Years of Monitoring Assumed	30	15	30
Nonroutine O&M and Closure Costs	\$1,353,000	\$335,000	\$1,688,000
Unlisted Operational Tasks Assumed	20%	20%	20%
Total Operational Costs	\$13,710,000	\$2,080,000	\$15,790,000
TOTALS			
Total Capital and Operational Costs	\$17,680,000	\$14,080,000	\$31,760,000
Present-Worth Implementation Costs	\$3,870,000	\$11,250,000	\$15,120,000
Present-Worth Operational Costs	\$9,850,000	\$1,970,000	\$11,820,000
Site Inspection and Overhead	\$310,000	\$225,000	\$535,000
Agency Oversight	\$77,400	\$56,300	\$133,700
Total Project Present Worth^b	\$14,100,000	\$13,500,000	\$27,600,000

^aModified CHP O&M, monitoring costs for western plume only

^bPresent-worth costs were calculated using a 3% discount rate with a base year of 2015.

Notes:

Discount rate (3%) = interest rate (6%) – inflation (3%)

CHP - catalyzed hydrogen peroxide

ISCO – in-situ chemical oxidation

NA - not applicable

4.10 SUSTAINABILITY

A sustainability analysis of each alternative was completed using the SiteWise™ tool for green and sustainable remediation (GSR). SiteWise was jointly developed by Battelle, the Navy, and the U.S. Army Corps of Engineers. It is designed to calculate the environmental footprint of remedial alternatives that are typically used by the industry. The objectives of completing a sustainability analysis are to allow consideration of GSR metrics during the remedy selection or design process and identify the aspects of a particular remedy that cause the greatest footprint for each metric.

Six GSR metrics calculated in SiteWise were chosen for comparison of the five alternatives. The following is a summary of each metric:

- Greenhouse gas emissions: Emissions generated by site activities during execution of a remediation alternative: The largest source of greenhouse gas emissions is typically consumption of fossil fuels, including the manufacture of materials from fossil fuel components.
- Total energy used: The total amount of energy consumed by the execution of an alternative: It includes the energy consumption of renewable and nonrenewable resources from transportation, equipment use, pumps, motors, wastewater treatment, the manufacturing of materials, etc.
- Electricity Usage: The amount of electricity consumed by the execution of an alternative, such as from electrical equipment use, pumps, motors, etc.
- Water consumption: The quantity of potable water consumed by the execution of a remediation alternative: Water consumption is associated with remediation components such as electrical use (water consumed during generation of electricity) and resource consumption.
- On-site particulate matter (PM)10 emissions: PM emitted into the atmosphere by remediation activity on the project site or formed by gaseous pollutants emitted by activities on the project site: PM10 particulates are defined as particles with a diameter of 10 micrometers or less (USEPA 2012). PM10 emissions affect human health and environment in the form of air quality and are derived from energy use, such as from transportation and equipment use.
- Total PM10 emissions: PM10 emissions generated by the execution of all remediation activities for an alternative, including off-site activities such as transportation to and from the site, wastewater treatment, electricity generation,

and the manufacture of materials: Total PM10 emissions include the on-site PM10 emissions above.

4.10.1 SiteWise Results

Table 4-4 summarizes the results of the GSR analysis completed in SiteWise for the five alternatives. The analysis included assessment of the construction (remedial action contractor), long-term monitoring and operation, and closure phases. Common elements in the long-term monitoring and operation phases, such as existing equipment operation and monitoring, were included in the analysis of each alternative. Common elements in the closure phase, such as the decommissioning of existing wells, were not included. The results in Table 4-4 indicate the total metrics for all three phases of a given alternative. A discussion of the results for each of the six metrics follows below.

Greenhouse Gas Emissions

Alternative 5 resulted in the highest greenhouse gas emissions generated by remediation. This is due to equipment use during construction and material production of a carbon source (MicroC) for management of BOD at the Ault Field WWTP. Because Alternative 1 consists of no action other than operating and maintaining the current GETR system, the analysis indicates that it generates the lowest amounts of greenhouse gases. Alternatives 2, 3, and 4, which consist of in-situ and ex-situ treatments, are estimated to have roughly twice the emissions as Alternative 1, but still relatively lower greenhouse gas emissions than Alternative 5.

Total Energy Used

Alternatives 3 and 4 consist of in-situ treatment by chemical injections and are estimated to consume the largest quantities of renewable and nonrenewable energy. The largest source of energy consumption for these alternatives is the installation of injection wells, performance of injections, and regular transportation of injection reagents. Alternative 1, continue with current system, is estimated to consume the relative lowest energy, because it involves the least amount of transportation and equipment use.

Electricity Usage

Alternative 2, ex-situ ozone treatment, and Alternative 5, discharge of groundwater to the WWTF, are estimated to consume the largest amounts of electricity. This is because of the electrical demand of pumps and motors required by the well, discharge, and booster pumps in both alternatives and the AOP systems in Alternative 2. Alternatives 3 and 4, which consist of in-situ treatment using injections, are estimated to use the relative lowest amounts of electricity.

Table 4-5
Summary of SiteWise Results

Sustainability Metric	Alternative 1: Continue with Current System	Alternative 2: Continue P&T With Ex-Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells	Alternative 3: In-Situ Groundwater Treatment With ISCO Using Base-Activated Persulfate	Alternative 4: In-Situ Groundwater Treatment With ISCO Using Catalyzed Hydrogen Peroxide	Alternative 5: Expanded Groundwater Capture With All Untreated Effluent Discharged to Navy WWTF at Ault Field
Greenhouse gas emissions (metric ton)	2,300	4,600	4,400	5,400	32,000
Total energy used (MMBtu)	72,000	180,000	690,000	910,000	510,000
Electricity usage (MWH)	12,000	24,000	3,600	3,600	21,000
Water consumption (gallon)	6,500,000	12,000,000	4,100,000	12,000,000	11,000,000
On-site PM10 emissions (metric ton)	0.00019	0.011	0.21	0.29	0.013
Total PM10 emissions (metric ton)	2.0	4.2	4.2	6.9	19

Notes:

Bolded value indicates the highest result for a given metric.

ISCO – in-situ chemical oxidation

MMBtu - million British thermal units

MWH - megawatt hour

P&T - pump and treat

PM10 - particulate matter of 10 micrometers or less

WWTF - wastewater treatment facility

Water Consumption

For the five alternatives, the sources of water consumption include the use of potable water and electricity usage. Alternative 2, ex-situ ozone treatment, Alternative 4, in-situ treatment using CHP, and Alternative 5, discharge of effluent water to the WWTF, are estimated to consume the largest amounts of water. For Alternatives 2 and 5, the sources of water consumption are primarily the electrical demands discussed above. For Alternative 4, high water consumption is largely associated with the potable water used for injections and reagent mixing.

On-Site PM10 Emissions

Alternatives 3 and 4, in situ treatment using injections, are estimated to emit the highest amounts of PM. The primary sources of particulate emissions include equipment use during the initial construction and performance of injections. Alternatives 1, 2, and 5, which consist of ex situ treatment, are estimated to have relatively low on-site particulate emissions because of limited equipment use following initial construction.

Total PM10 Emissions

Total particulate emissions (on site and off site) are highest for Alternative 5, discharge of groundwater to the WWTF, because of the large amount of consumables (MicroC) and equipment use during construction and treatment at the WWTF. The total PM10 emissions for Alternatives 2, 3, and 4 are substantially lower than Alternative 5. These alternatives are higher than Alternative 1 based on the amounts of consumables, material manufacture and transportation, and equipment use.

4.10.2 Relative Rankings

The sustainability of Alternatives 2 through 5 have been ranked by evaluation category. Alternative 1 has not been included in this ranking because it does not address 1,4-dioxane. Alternatives are ranked on a weighted basis by summing the results for each metric and dividing individual alternative results by the sum of that metric. Lower normalized ranking scores correspond to more favorable sustainability performance. Table 4-5 shows the ranking results.

Based on the average ranking at the bottom of Table 4-5, the alternatives are ranked for sustainability as follows:

1. Alternatives 2 and 3
2. Alternative 4
3. Alternative 5

Table 4-6
Alternative SiteWise Rankings

Sustainability Metric	Alternative 2: Continue P&T With Ex-Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells	Alternative 3: In-Situ Groundwater Treatment With ISCO Using Base-Activated Persulfate	Alternative 4: In-Situ Groundwater Treatment With ISCO Using Catalyzed Hydrogen Peroxide	Alternative 5: Expanded Groundwater Capture With All Untreated Effluent Discharged to Navy WWTF at Ault Field
Greenhouse emissions	0.10	0.09	0.12	0.69
Total energy used	0.08	0.30	0.40	0.22
Electricity usage	0.46	0.07	0.07	0.40
Water consumption	0.31	0.10	0.31	0.28
On-site PM10 emissions	0.02	0.40	0.55	0.02
Total PM10 emissions	0.12	0.12	0.20	0.55
Normalized ranking score	0.18	0.18	0.27	0.36

Notes:

Lower score indicates more favorable sustainability performance.

Ranking score for each sustainability metric is weighted average.

ISCO – in-situ chemical oxidation

PM10 – particulate matter of 10 micrometers or less

P&T - pump and treat

WWTF - wastewater treatment facility

5.0 DETAILED ANALYSIS OF ALTERNATIVES

The detailed analysis of alternatives consists of the analysis and presentation of the relevant information needed to allow decision makers to select a site remedy. Each alternative has been assessed against the evaluation criteria described in this section.

The specific statutory requirements for remedial actions that must be addressed in the ROD and supported by this FFS report are listed below. Remedial actions must:

- Be protective of human health and the environment
- Attain ARARs (or provide grounds for invoking a waiver)
- Be cost-effective
- Utilize permanent solutions and alternative treatment technologies or resource recovery technologies to the maximum extent practicable
- Satisfy the preference for treatment that reduces toxicity, mobility, or volume as a principal element or provide an explanation in the ROD as to why it does not

In addition, CERCLA places an emphasis on evaluating long-term effectiveness and related considerations for each of the alternative remedial actions. These statutory considerations include:

- The long-term uncertainties associated with land disposal
- The goals, objectives, and requirements of the Solid Waste Disposal Act
- The persistence, toxicity, and mobility of hazardous substances and their constituents, and their propensity to bioaccumulate
- Short- and long-term potential for adverse health effects from human exposure
- Long-term maintenance costs
- The potential for future remedial action costs if the alternative remedial action in question were to fail
- The potential threat to human health and the environment associated with excavation, transportation, and disposal or containment

5.1 EVALUATION CRITERIA

Nine evaluation criteria have been developed to address the CERCLA requirements and considerations listed above and the additional technical and policy considerations that have proven to be important for selecting among remedial alternatives. These evaluation criteria serve as the basis for conducting the detailed analyses for this FFS and for subsequently selecting an appropriate remedial action. The evaluation criteria with the associated statutory considerations are:

- Overall protection of human health and the environment
- Compliance with ARARs
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, and volume through treatment
- Short-term effectiveness
- Implementability
- Cost
- State acceptance
- Community acceptance

5.1.1 Threshold Criteria

Assessments against the first two criteria relate directly to statutory findings that must ultimately be made in the ROD. Therefore, these are categorized as threshold criteria in that each alternative must meet them. These two criteria are:

- Overall protection of human health and the environment – This criterion describes how the alternative, as a whole, achieves and maintains protection of human health and the environment.
- Compliance with ARARs – This criterion describes how the alternative complies with ARARs, or if a waiver is required and how it is justified. The assessment also addresses other information from advisories, criteria, and guidance that the lead and support agencies have agreed is to be considered.

5.1.2 Primary Balancing Criteria

The five criteria listed below are grouped together because they represent the primary criteria upon which the analysis is based.

- Long-term effectiveness and permanence – The assessment of alternatives against this criterion evaluates the long-term effectiveness of alternatives in maintaining

protection of human health and the environment after response objectives have been met.

- Reduction of toxicity, mobility, and volume through treatment – The assessment against this criterion evaluates the anticipated performance of the specific treatment technologies an alternative may employ.
- Short-term effectiveness – The assessment against this criterion examines the effectiveness of alternatives in protecting human health and the environment during the construction and implementation of a remedy until response objectives have been met.
- Implementability – This assessment evaluates the technical and administrative feasibility of alternatives and the availability of required goods and services.
- Cost – This assessment evaluates the capital and O&M costs of each alternative.

5.1.3 Modifying Criteria

The final two criteria, state or support agency acceptance and community acceptance, will be evaluated following comment on this FFS and the proposed plan. These criteria will be addressed once a final decision is being made and the ROD is being prepared. The criteria are:

- State (support agency) acceptance – This assessment reflects the state's (or support agency's) apparent preferences among or concerns about alternatives.
- Community acceptance – This assessment reflects the community's apparent preferences among or concerns about alternatives.

5.1.4 Alternative Rating Scale

Each alternative will be evaluated against the nine CERCLA criteria using the following scale:

- Poor
- Adequate
- Good
- Excellent
- Superior

The rationale and assigned ratings are presented in Section 5.2.

5.2 INDIVIDUAL ANALYSIS OF ALTERNATIVES

5.2.1 Alternative 1: Continue with Current System

Alternative 1 - Overall Protection of Human Health and the Environment

Continue with current system is the 1993 ROD alternative. This decision was made based on the information available at that time and was expected to provide overall protection of human health and the environment. Identification of the emergent chemical 1,4-dioxane at the site in 2003 changed conditions at the site. The groundwater extraction and treatment system installed under the 1993 ROD does not treat 1,4-dioxane from extracted groundwater. As a result, groundwater containing 1,4-dioxane greater than the current MTCA Method B groundwater cleanup level of 0.44 µg/L is currently being reinfiltrated back to groundwater in the northern portion of the western plume, although concentrations in the treated water effluent have been declining over time and downgradient extraction wells capture it again and keep it in recirculation on-site. The current system is also not capturing 1,4-dioxane or vinyl chloride in the southern plume. Based on the presence of vinyl chloride above the RG and 1,4-dioxane in groundwater at concentrations greater than the current MTCA Method B groundwater cleanup level in the southern plume, and the existing treatment systems' inability to remove it from extracted groundwater, conditions at the site have the potential to present a greater than 1×10^{-6} cancer risk and/or a noncancer hazard index greater than 1, if drinking water is considered to be a complete exposure pathway. Therefore, the "continue with current system" alternative would not provide *overall protection of human health and the environment*.

Alternative 1 - Compliance with ARARs

The existing groundwater extraction and treatment system was not designed to treat 1,4-dioxane in groundwater extracted from the western plume. Groundwater containing vinyl chloride above the RG and 1,4-dioxane above the MTCA B cleanup level is not being captured or contained by the current system. As such, Alternative 1 is currently not in compliance with ARARs within plume boundaries, because this alternative does not meet the MTCA Method B 1,4-dioxane groundwater cleanup level; therefore, the Alternative 1 would not comply with ARARs.

- ***Alternative 1 - Balancing Criteria***

Since this alternative does not meet the threshold criteria as defined by CERCLA, therefore, the balancing criteria of long-term effectiveness and permanence, reduction of toxicity, mobility, and volume through treatment, short-term effectiveness, implementability, and cost were not evaluated.

State and community acceptance will be evaluated once state and public input are received.

5.2.2 Alternative 2: Continue P&T With Ex-Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells

Alternative 2 - Overall Protection of Human Health and the Environment

Groundwater modeling (Appendix B, Scenario 8) predicts that the proposed expanded pumping network for this alternative would maintain containment and amend the treatment technology of the western plume and expanding the capture and treatment of the southern plume. The proposed advanced oxidization treatment systems are commercially available technology that has been shown to successfully remove both VOCs and 1,4-dioxane from groundwater.

The proposed extraction system is expected to reduce VOC and 1,4-dioxane concentrations in groundwater to RGs. As previously stated, potential residual impacts to vadose zone soil was identified during the treatability study just north of PW-1. If VOC concentrations in groundwater samples from source area monitoring locations go asymptotic at concentrations above RGs or acceptable MNA levels, source area measures and/or further fate and transport assessment and risk assessment could be implemented to address this residual risk. These measures could include soil vapor extraction or a more detailed analysis of potential off-property drinking water receptors and appropriate mitigation (i.e., restrictions on groundwater as a drinking water source, providing alternative water sources other than groundwater, etc.).

Based on the groundwater model predictions and the documented performance of the proposed advanced oxidization systems (including site-specific bench-scale tests), it is expected that this alternative will provide overall protection of human health and the environment.

Based on this evaluation, Alternative 2 will provide *overall protection of human health and the environment*.

Alternative 2 - Compliance with ARARs

Compliance with ARARs is summarized in Table 5-1.

Table 5-1
Summary of Alternatives Compliance with ARARs

ARAR	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Combined Alternatives 2 and 4
Chemical-Specific ARARs						
RCRA Subpart C – Characteristics of Hazardous Waste	Yes	Yes	Yes	Yes	Yes	Yes
Safe Drinking Water Act - MCLs for organics	No	Yes	Yes	Yes	Yes	Yes
Washington State Model Toxics Control Act (MTCA)	No	Yes	Yes	Yes	Yes	Yes
Clean Water Act (Water Quality Standards)	No	Yes	Yes	Yes	Yes	Yes
National Oil and Hazardous Substances Pollution Contingency Plan (NCP)	ETB	Yes	Yes	Yes	Yes	Yes
Location-Specific ARARs						
Migratory Bird Treaty Act	Yes	Yes	Yes	Yes	Yes	Yes
Bald and Golden Eagle Protection Act	Yes	Yes	Yes	Yes	Yes	Yes
Executive Order 11990 (Protection of Wetlands)	Yes	Yes	Yes	Yes	Yes	Yes
Archeological Resources Protection Act	Yes	Yes	Yes	Yes	Yes	Yes
Action-Specific ARARs						
RCRA, Subtitle D, Solid Waste Regulations	Yes	Yes	Yes	Yes	Yes	Yes
Standards Applicable to Transporters of Hazardous Waste	Yes	Yes	Yes	Yes	Yes	Yes
Groundwater Monitoring Program	Yes	Yes	Yes	Yes	Yes	Yes
Clean Water Act - NPDES Industrial Wastewater Discharge Permits	Yes	Yes	Yes	Yes	Yes	Yes
RCRA, Subtitle C, Regulations for Hazardous Waste	Yes	Yes	Yes	Yes	Yes	Yes
RCRA, Subtitle D, Regulations for Hazardous Waste	Yes	Yes	Yes	Yes	Yes	Yes
Air Emission Standards for Process Vents and Equipment Leaks	Yes	Yes	Yes	Yes	Yes	Yes
State of Washington Hazardous Waste Management Act	Yes	Yes	Yes	Yes	Yes	Yes
State of Washington Solid Waste Management Act	Yes	Yes	Yes	Yes	Yes	Yes
State of Washington Fugitive Dust Control Measures	Yes	Yes	Yes	Yes	Yes	Yes
State of Washington Clean Air Act	Yes	Yes	Yes	Yes	Yes	Yes

Notes:

ARAR - applicable or relevant and appropriate requirement
 Alt – alternative

MCLs – maximum contaminant levels

NPDES – National Pollutant Discharge Elimination System

RCRA – Resource Conservation and Recovery Act

Chemical-Specific ARARs. Alternative 2 will comply with chemical-specific ARARs. RCRA Subpart C and D requirements would relate to off-site disposal of materials and waste generated during remedy construction and O&M. Compliance with these requirements is not process specific. Characterization and designation of generated waste streams will determine which RCRA requirements (C or D) apply.

Commercially available AOP systems have met the discharge requirements specified in the Safe Drinking Water Act and MTCA at other sites with these contaminants. Vendors have conducted predesign testing to refine processes and dosing prior to design finalization. An additional bench-scale treatability study was conducted by APTwater in 2017 to evaluate potential system design and is included as Appendix F.

Groundwater modeling (Appendix B) predicts that the proposed expanded extraction system would contain and capture the western and southern groundwater plumes. Containment and capture of the plumes will result in compliance with the Clean Water Act and NCP.

Location-Specific ARARs. Construction and O&M can be completed in a manner that will not impact bird habitat or wetlands. This would comply with the Migratory Bird Treaty Act, Bald and Golden Eagle Protection Act, and Executive Order 11990 (Protection of Wetlands). If archeological artifacts are encountered during remedy construction, work can be suspended to investigate inadvertent discoveries of items of potential cultural significance. This would comply with the Archeological Resources Protection Act.

Action-Specific ARARs. Alternative 2 will comply with action-specific ARARs. RCRA Subtitle D, Solid Waste Regulations, and Standards Applicable to Transporters of Hazardous Waste requirements would be able to meet documentation requirements for any materials requiring off-site transport and disposal. The current semiannual monitoring program and annual land use controls inspection program for the site are being used to satisfy these requirements. The monitoring plan would be revised with agency participation based on performance monitoring needs of Alternative 2. This would meet the Groundwater Monitoring Program requirement.

An NPDES permit will not be required for this alternative. RCRA Subtitles C and D requirements would be met as discussed in the preceding subsections for this alternative. Systems would be designed to meet Air Emission Standards for Process Vents and Equipment Leaks, as appropriate. Waste handling and construction plans would be prepared to meet State of Washington Hazardous Waste Management Act, Solid Waste Management Act, State of Washington Fugitive Dust Control Measures, and as necessary.

Overall Compliance Assessment. Alternative 2 will comply with ARARs.

Alternative 2 - Long-Term Effectiveness and Permanence

Groundwater extraction, which began in 1995, has successfully contained the western plume, reduced its lateral extent, and decreased VOC concentrations by over an order of magnitude. This demonstrates long-term effectiveness of groundwater extraction at Area 6. The continuity of the aquifer across the site and relative homogeneity indicate that groundwater extraction in the southern plume should also be effective. Groundwater modeling (Appendix B) predicts that the proposed expanded extraction system would contain and fully capture the western and southern groundwater plumes. The documented performance of the commercially available AOP system at similar sites and the site specific bench-scale treatability study (Appendix F) establishes this technology's ability to remove VOCs and 1,4-dioxane from groundwater.

Removal of VOCs and 1,4-dioxane from groundwater under Alternative 2 would be permanent. In the event that the plume is not fully captured, this risk could be managed by flow rate adjustments and, if necessary, installation of additional extraction wells. Based on trends analyses, influent concentrations are approaching asymptotic conditions under the current pumping scenario. However, potentially adding strategically placed extraction wells under Alternative 2 would optimize the treatment. Under Alternative 2, in the event that VOC concentrations in groundwater samples go asymptotic above RGs or acceptable MNA levels, source area measures would be implemented to further diminish residual contamination. These measures could include soil vapor extraction.

Controls for this alternative would be adequate to ensure long-term permanence and effectiveness. Groundwater extraction systems have a demonstrated long-term effectiveness at this and numerous sites across the country. The proposed AOP system has a documented performance that also demonstrates the adequacy of controls for long-term effectiveness. Existing land use controls would be maintained and adjusted as required to ensure long-term protection of exposure during implementation of Alternative 2.

The *long-term effectiveness and permanence* of Alternative 2 is rated as "excellent." Model uncertainty with respect to plume containment and capture is the reason this alternative was not rated as superior.

Alternative 2 - Reduction of Toxicity, Mobility, and Volume Through Treatment

Western and southern plume containment and capture via groundwater extraction will result in reduction of contaminant mobility. Impacted groundwater extraction and treatment via the AOP systems will result in reduction of toxicity and volume. Both of these technologies have demonstrated effectiveness for this criterion.

It is expected that this alternative would successfully reduce COC concentrations in the western and southern plumes to RGs over time. As previously stated, the data gap analysis (U.S. Navy 2015c) concluded that TCE in vadose zone soil has the potential to act as a source to groundwater. If vadose zone soil poses a residual source to groundwater at concentrations that are above RGs or above an acceptable natural attenuation level, this uncertainty could be managed, if required, with additional residual source removal methods.

Reduction of toxicity, mobility, and volume through treatment of Alternative 2 is rated as “excellent.” Model uncertainty with respect to plume containment and capture is the reason this alternative was not rated as superior.

Alternative 2 - Short-Term Effectiveness

Alternative 2 will require drilling, excavation, and pipeline installation along the northwestern shoulder of SR 20. This could pose a low, short-term risk to the community for fugitive dust and construction traffic. Drilling and excavation on site should pose a far lower risk to the community. Hydrogen peroxide would be delivered on an approximate monthly basis to the two treatment system locations and would pose a low, short-term risk to the community during each transport cycle.

Workers have the potential to be exposed to very low contaminant concentrations during drilling and sampling activities. Exposure to site contaminants during installation of the AOP systems is expected to be minimal. Risks due to contaminant exposure could be adequately addressed through implementation of a site specific health and safety plan.

The areas in which the remedy would be constructed are not sensitive ecological areas. Therefore, no significant environmental impacts are expected as a result of remedy construction for Alternative 2.

Groundwater modeling (Appendix B, Scenario 8) predicts that RGs would be achieved in the western plume in about 18 years or less for Alternative 2. The southern plume is predicted to achieve the MTCA Method B cleanup level for 1,4-dioxane in about 30 years or less.

Based on the limited short-term risk to the community and workers and the longer time to achieve RGs, Alternative 2 is rated as “good” for *short-term effectiveness*.

Alternative 2 – Implementability

This alternative will require construction of concrete treatment system pads with secondary containment, installation of two AOP treatment systems, construction of a limited amount of subsurface pipeline, and installation of nine groundwater extraction wells. Electrical service will

also need to be delivered to the southern treatment system. These types of construction and installation activities are standard operations with well established procedures. This alternative utilizes the existing infrastructure to the maximum extent possible.

Based on these considerations, Alternative 2 is rated at “good” for *implementability*.

Alternative 2 – Cost

Total capital and operational costs for Alternative 2 are estimated at \$18,580,000 and net present worth costs are estimated at \$14,500,000 with 9 years of northern system operation, 17 years of southern system operation, and the 30 years of monitoring. Based on the range of estimated costs for all alternatives, Alternative 2 ranks second least expensive of all of the alternatives. As a result, Alternative 2 is rated as “excellent” for *Cost*.

Alternative 2 - State and Community Acceptance

State and community acceptance will be evaluated once state and public input is received. Planned community involvement is described in Section 6.

5.2.3 Alternative 3: In-Situ Groundwater Treatment With ISCO Using Base-Activated Persulfate

Alternative 3 - Overall Protection of Human Health and the Environment

Groundwater modeling (Appendix B, Scenario 3) predicts that the proposed Alternative 3 would achieve RGs in the western plume in about 13 years with a limited amount of operation time for the existing groundwater extraction and treat system for plume control. Alternative 3 would achieve RGs for the portion of the southern plume upgradient of the injection line. The portion of the southern plume downgradient of the injection line would continue to migrate downgradient. This alternative will depend on natural attenuation of the southern plume that migrates downgradient of the line of injection wells and a baseline risk assessment that evaluates 1,4-dioxane risk to downgradient receptors. The model is, however, a predictive tool that only simulates future groundwater behavior and remedial action. The proposed ISCO technology is commercially available with a proven record of reliable and successful performance at oxidizing both VOCs and 1,4-dioxane in groundwater at similar sites. Although ISCO is generally designed for application to smaller areas of high contaminant concentration, a treatability study at the site showed that the technology is a marginal potential technology based on the single injections performed for the study (U.S. Navy 2015b). Multiple injections are expected to show that this technology would successfully destroy VOCs and 1,4-dioxane. As previously stated, potential residual impacts to vadose zone soil was identified during the treatability study just north of PW-1. If VOC concentrations in groundwater samples from source area monitoring

locations go asymptotic at concentrations above RGs or acceptable MNA levels, source area measures and/or further fate and transport assessment and risk assessment could be implemented to address this residual risk.

Based on this evaluation, Alternative 3 would provide *overall protection of human health and the environment*.

Alternative 3 - Compliance with ARARs

Compliance with ARARs is summarized in Table 5-1.

Chemical-Specific ARARs. Alternative 3 will comply with chemical-specific ARARs. RCRA Subpart C and D requirements would relate to off-site disposal of materials and waste generated during remedy construction and O&M. Compliance with these requirements is not process specific. Characterization and designation of generated waste streams will determine which RCRA requirements (C or D) apply.

It is expected that ISCO with persulfate will meet the RGs specified in the Safe Drinking Water Act and MTCA, although sulfate levels in groundwater may exceed the secondary drinking water standard of 250 mg/L.

Groundwater modeling (Appendix B) predicts that Alternative 3 would contain and destroy the western groundwater plume. It will capture and contain that portion of the southern plume upgradient of the injection line. Containment and capture of the plumes will result in compliance with the Clean Water Act and NCP.

Location-Specific ARARs. Construction and O&M can be completed in a manner that will not impact bird habitat or wetlands. This would comply with the Migratory Bird Treaty Act, Bald and Golden Eagle Protection Act, and Executive Order 11990 (Protection of Wetlands). If archeological artifacts are encountered during remedy construction, work can be suspended to investigate the inadvertent discovery of items of potential cultural significance. This would comply with the Archeological Resources Protection Act.

Action-Specific ARARs. Alternative 3 will comply with action-specific ARARs. RCRA Subtitle D, Solid Waste Regulations, and Standards Applicable to Transporters of Hazardous Waste requirements would be able to meet documentation requirements for any materials requiring off-site transport and disposal. The current semiannual monitoring program and annual land use controls inspection program for the site are being used to satisfy these requirements. The monitoring plan would be revised with agency participation based on performance monitoring needs of Alternative 3. This would meet the Groundwater Monitoring Program requirement.

An NPDES permit will not be required for this alternative. This alternative would need to meet the substantive requirements of the Washington State Underground Injection Control permit administered by Ecology. RCRA Subtitle C and D requirements would be met as discussed in the preceding subsections for this alternative. There would be no process-related air emissions. Waste handling and construction plans would be prepared to meet State of Washington Hazardous Waste Management Act, Solid Waste Management Act, Fugitive Dust Control Measures, and Clean Air Act as necessary.

Overall Compliance Assessment. Alternative 3 is expected to comply with ARARs.

Alternative 3 - Long-Term Effectiveness and Permanence

The groundwater model (Appendix B) shows that a small portion of the western plume would escape with ISCO application along the western site boundary. However, Alternative 3 assumes that operation of the existing groundwater extraction and treatment system will maintain plume control until the ISCO barrier is established.

Destruction of contaminant mass in groundwater via oxidization with persulfate would be permanent. No process-related controls are required for Alternative 3. Injections would be delivered by on-site personnel for the duration of the action. Controls on the existing groundwater extraction and treatment system have performed sufficiently. Existing land use controls would be maintained and adjusted as required to ensure long-term protection of exposure during implementation of Alternative 2.

The *long-term effectiveness and permanence* of Alternative 3 is rated as “good.” Model predictions with respect to plume containment and capture are the reasons this alternative was not rated higher. The success of this alternative is also directly related to the ability to set up the ISCO barriers along the western side boundary and along SR 20, and downgradient risk posed by that portion of the southern plume that migrates downgradient of the ISCO barrier.

Alternative 3 - Reduction of Toxicity, Mobility, and Volume Through Treatment

Western and southern plume containment and destruction via ISCO extraction will result in reduction of mobility via oxidization, although some short term increases in contaminant mobility may occur because of desorption of contaminants from the soil and incomplete oxidation in the aqueous phase. It will not reduce mobility of that portion of the southern plume south of SR 20.

It is expected that this alternative would successfully reduce COC concentrations in the western plume to RGs over time and the portion of the 1,4-dioxane plume upgradient of SR 20. As indicated above, there is uncertainty in long-term effectiveness because residual contamination in

the vadose zone and/or incomplete oxidation. As previously stated, the data gap analysis (U.S. Navy 2015c) concluded that TCE in vadose zone soil has the potential to act as a source to groundwater. If vadose zone soil poses a residual source to groundwater at concentrations that are above RGs or an acceptable natural attenuation level, this uncertainty could be managed, if required, with additional residual source removal methods.

Reduction of toxicity, mobility, and volume through treatment of Alternative 3 is rated as “good.” Model predictions with respect to plume containment and capture and the portion of the southern plume that will migrate downgradient of the injection line is the reason this alternative was not rated higher.

Alternative 3 - Short-Term Effectiveness

Alternative 3 will require installation of approximately 110 injection wells along the northwestern shoulder of SR 20. This could pose a short-term risk to the community because of construction traffic. Drilling on site should pose a far lower risk to the community. Although traffic control and signage would be employed as appropriate, injection activities along SR 20 could pose a traffic risk to the community for the duration of the action. Regular persulfate oxidant deliveries would pose sporadic risk to the community during each transport/injection cycle.

Workers are not expected to be exposed to hazardous materials during remedy construction. They have the potential to be exposed to very low contaminant concentrations during remedy construction, primarily drilling. However, these risks could be mitigated through implementation of a site specific health and safety plan and use of personal protective equipment. Workers have the potential to be exposed to persulfate and sodium hydroxide during injections. Personal protective equipment and management procedures have successfully mitigated worker exposure to these chemicals at numerous sites across the country.

The areas in which the remedy would be constructed are not sensitive ecological areas. Therefore, no significant environmental impacts are expected as a result of remedy construction for Alternative 3.

Based on the sporadic short-term risk to the community and workers and the longer time to achieve RGs, Alternative 3 is rated as “adequate” for *short-term effectiveness*. The number of wells installed along SR 20 and the duration and frequency of chemical injections are the reasons this alternative was not rated higher.

Alternative 3 – Implementability

Installation of injection wells is a standard industry procedure. However, installation and eventual abandonment of 245 injection wells would be a challenging and costly endeavor. Installation of 110 injection wells along SR 20 is challenging in that this is a high use state highway with aboveground and subsurface utilities. Drilling in this environment occurs routinely, but not at this scale. Frequent and long-term injections in this high-traffic setting will also be challenging. For these reasons, Alternative 3 is rated as “adequate” for *implementability*.

Alternative 3 – Cost

Total capital and operational costs for Alternative 3 are estimated at \$44,930,000, and net present worth costs are estimated at \$41,800,000 over a 7-year period. Based on the range of estimated costs for all alternatives, Alternative 3 ranks sixth in cost. As a result, Alternative 3 is rated as “poor” for *cost*.

Alternative 3 - State and Community Acceptance

State and community acceptance will be evaluated once state and public input is received. Planned community involvement is described in Section 6.

5.2.4 Alternative 4: In-Situ Groundwater Treatment With ISCO Using Catalyzed Hydrogen Peroxide

Alternative 4 is identical to Alternative 3 with the exception that CHP would be used as the oxidant. As a result, this alternative has been assigned ratings that are equivalent to Alternative 3.

Alternative 4 - Overall Protection of Human Health and the Environment

Alternative 4 would provide *overall protection of human health and the environment*.

Alternative 4 - Compliance with ARARs

Compliance with ARARs is summarized in Table 5-1. Based on the equivalent evaluation for Alternative 3, Alternative 4 is expected to comply with ARARs.

Alternative 4 - Long-Term Effectiveness and Permanence

Based on the equivalent evaluation for Alternative 3, the *long-term effectiveness and permanence* of Alternative 4 is rated as “good.”

Alternative 4 - Reduction of Toxicity, Mobility, and Volume Through Treatment

Based on the equivalent evaluation for Alternative 3, *reduction of toxicity, mobility, and volume through treatment* of Alternative 4 is rated as “good.”

Alternative 4 - Short-Term Effectiveness

Alternative 4 will require installation of 180 injection wells along the northwestern shoulder of SR 20, which is 70 wells more than Alternative 3. CHP has a much shorter reaction time and persistence in groundwater compared to activated persulfate. This characteristic requires more closely spaced injection wells to ensure adequate coverage along the line injection wells.

Based on the equivalent evaluation for Alternative 3, Alternative 4 is rated as “adequate” for *short-term effectiveness*. The number of wells installed along SR 20, and the duration and frequency of chemical injections are the reasons this alternative was not rated higher.

Alternative 4 – Implementability

Based on the equivalent evaluation for Alternative 3, Alternative 4 is rated as “adequate” for *implementability*.

Alternative 4 – Cost

Total capital and operational costs for Alternative 4 are estimated at \$41,310,000, and net present worth costs are estimated at \$38,600,000 over 7 years. Based on the range of estimated costs for all alternatives, Alternative 4 ranks fifth. As a result, Alternative 4 is rated as “poor” for cost.

Alternative 4 - State and Community Acceptance

State and community acceptance will be evaluated once state and public input is received. Planned community involvement is described in Section 6.

5.2.5 Alternative 5: Expanded Groundwater Capture With All Untreated Effluent Discharged to Navy WWTF at Ault Field

Alternative 5 is very similar to Alternative 2, except that the extracted water would be conveyed to the existing WWTP at Ault Field via a new pipeline.

Alternative 5 - Overall Protection of Human Health and the Environment

Groundwater modeling (Appendix B, Scenario 8) predicts that the proposed expanded extraction network for this alternative would contain and capture both the western and southern plumes.

The model is, however, a predictive tool that only simulates future groundwater behavior and remedial action. The proposed extraction system is expected to reduce VOC and 1,4-dioxane concentrations in groundwater to RGs.

Removal of VOCs and 1,4-dioxane from groundwater under Alternative 5 would be permanent. In the event that the plume is not fully captured, this risk could be managed by flow rate adjustments and, if necessary, installation of additional extraction wells. Based on trends analyses, influent concentrations are approaching asymptotic conditions under the current pumping scenario. However, potentially adding strategically placed extraction wells under Alternative 2 would optimize the treatment. Under Alternative 2, in the event that VOC concentrations in groundwater samples go asymptotic above RGs or acceptable MNA levels, source area measures would be implemented to further diminish residual contamination. These measures could include soil vapor extraction.

Based on this evaluation, Alternative 5 will provide *overall protection of human health and the environment*.

Alternative 5 - Compliance with ARARs

Compliance with ARARs is summarized in Table 5-1.

Chemical-Specific ARARs. Alternative 5 will comply with chemical-specific ARARs. RCRA Subpart C and D requirements would relate to off-site disposal of materials and waste generated during remedy construction and O&M. Compliance with these requirements is not process specific. Characterization and designation of generated waste streams will determine which RCRA requirements (C or D) apply.

With addition of the carbon substrate injection system, the Ault Field WWTF is expected to meet revised NPDES discharge limits.

Groundwater modeling (Appendix B) predicts that the proposed expanded extraction system would contain and capture the western and southern groundwater plumes. Containment and capture of the plumes will result in compliance with the Clean Water Act and NCP.

Location-Specific ARARs. Construction and O&M can be completed in a manner that will not impact bird habitat or wetlands. This would comply with the Migratory Bird Treaty Act, Bald and Golden Eagle Protection Act, and Executive Order 11990 (Protection of Wetlands). If archeological artifacts are encountered during remedy construction, work can be suspended to investigate the inadvertent discovery of items of potential cultural significance. This would comply with the Archeological Resources Protection Act.

Action-Specific ARARs. Alternative 5 will comply with action-specific ARARs. RCRA Subtitle D, Solid Waste Regulations, and Standards Applicable to Transporters of Hazardous Waste requirements would be able to meet documentation requirements for any materials requiring off-site transport and disposal. The current semiannual monitoring program and annual land use controls inspection program for the site are being used to satisfy these requirements. The monitoring plan would be revised with agency participation based on performance monitoring needs of Alternative 5. This would meet the Groundwater Monitoring Program requirement.

The Ault Field WWTF operates under an existing NPDES permit. A revision of this permit will be required for this alternative. RCRA Subtitle C and D requirements would be met as discussed in the preceding subsections for this alternative. Systems would be designed to meet Air Emission Standards for Process Vents and Equipment Leaks, as appropriate. Waste handling and construction plans would be prepared to meet State of Washington Hazardous Waste Management Act, Solid Waste Management Act, Fugitive Dust Control Measures, and Clean Air Act as necessary.

Overall Compliance Assessment. Alternative 5 will comply with ARARs.

Alternative 5 - Long-Term Effectiveness and Permanence

Based on the evaluation for Alternative 2, Alternative 5 is rated “excellent” for *long-term effectiveness and permanence*.

Alternative 5 - Reduction of Toxicity, Mobility, and Volume Through Treatment

The evaluation for Alternative 2 is very similar for Alternative 5. However, the rating for Alternative 5 has been reduced because the WWTF will not directly treat 1,4-dioxane in groundwater. It would rely on dilution to reduce 1,4-dioxane contraction in extracted groundwater prior to discharge. Therefore, Alternative 5 is rated “good” for *reduction of toxicity, mobility, and volume through treatment*.

Alternative 5 - Short-Term Effectiveness

Alternative 5 will require drilling, excavation, and pipeline installation as described for Alternative 2. Additional excavation pipeline installation will be required for connection to the Ault Field sanitary sewer system. This would incrementally increase the complexity of the construction effort.

Based on the evaluation for Alternative 2, Alternative 5 is rated as “good” for *short-term effectiveness*.

Alternative 5 – Implementability

Alternative 5 will require drilling and well installations as described for Alternative 2. Additional excavation and pipeline installation work will be required for connection to the Ault Field sanitary sewer system. This would incrementally increase the complexity of the construction effort compared to Alternative 2.

Based on the evaluation for Alternative 2 and increased level of complexity for the additional pipeline installation that needs to cross Ault Field Road and extend onto Ault Field, Alternative 5 is rated as “adequate” for *implementability*.

Alternative 5 – Cost

Total capital and operational costs for Alternative 5 are estimated at \$20,400,000, and net present worth costs are estimated at \$16,000,000 with 9 years of northern system operation, 17 years of southern system operation, and the 30 years of monitoring. Based on the range of estimated costs for all alternatives, Alternative 5 ranks third. As a result, Alternative 5 is rated as “good” for cost.

Alternative 5 - State and Community Acceptance

State and community acceptance will be evaluated once state and public input is received. Planned community involvement is described in Section 6.

5.2.6 Combined Alternatives 2 and 4

Combined Alternatives 2 and 4 - Overall Protection of Human Health and the Environment

This alternative combines the full implementation of Alternative 2 and partial implementation of Alternative 4 in the western plume area only. Based on the evaluation for Alternative 2, Combined Alternatives 2 and 4 will provide *overall protection of human health and the environment*.

Combined Alternatives 2 and 4 - Compliance with ARARs

Compliance with ARARs is summarized in Table 5-1.

Chemical-Specific ARARs. Combined Alternatives 2 and 4 will comply with chemical-specific ARARs. RCRA Subpart C and D requirements would relate to off-site disposal of materials and waste generated during remedy construction and O&M. Compliance with these requirements is

not process-specific. Characterization and designation of generated waste streams will determine which RCRA requirements (C or D) apply.

Commercially available AOP systems have met the discharge requirements specified in the Safe Drinking Water Act and MTCA at other sites with these contaminants. Vendors should conduct predesign testing to refine processes and dosing prior to design finalization. Addition of CHP injection in the western plume is expected to decrease the time to achieve RGs.

Groundwater modeling (Appendix B) predicts that the proposed expanded extraction system would contain and capture the western and southern groundwater plumes. Containment and capture of the plumes will result in compliance with the Clean Water Act and NCP. Addition of ISCO in the western plume will not impact the ability of this alternative to meet these requirements.

Location-Specific ARARs. Construction and O&M can be completed in a manner that will not impact bird habitat or wetlands. This would comply with the Migratory Bird Treaty Act, Bald and Golden Eagle Protection Act, and Executive Order 11990 (Protection of Wetlands). If archeological artifacts are encountered during remedy construction, work can be suspended to investigate the inadvertent discovery of items of potential cultural significance. This would comply with the Archeological Resources Protection Act.

Action-Specific ARARs. Combined Alternatives 2 and 4 will comply with action-specific ARARs. RCRA Subtitle D, Solid Waste Regulations, and Standards Applicable to Transporters of Hazardous Waste requirements would be able to meet documentation requirements for any materials requiring off-site transport and disposal. The current semiannual monitoring program and annual land use controls inspection program for the site are being used to satisfy these requirements. The monitoring plan would be revised with agency participation based on performance monitoring needs of Alternative 2. This would meet the Groundwater Monitoring Program requirement.

An NPDES permit will not be required for this combination of alternatives. RCRA Subtitle C and D requirements would be met as discussed in the preceding subsections for this alternative. Systems would be designed to meet Air Emission Standards for Process Vents and Equipment Leaks, as appropriate. Waste handling and construction plans would be prepared to meet State of Washington Hazardous Waste Management Act, Solid Waste Management Act, Fugitive Dust Control Measures, and Clean Air Act as necessary.

Overall Compliance Assessment. Combined Alternatives 2 and 4 will comply with ARARs.

Combined Alternatives 2 and 4 - Long-Term Effectiveness and Permanence

Alternative 2 was rated as “excellent” for long-term effectiveness and permanence. Addition of ISCO in the western plume would not downgrade this rating. Combined Alternatives 2 and 4 is rated as “excellent” for *long-term effectiveness and permanence*.

Combined Alternatives 2 and 4 - Reduction of Toxicity, Mobility, and Volume Through Treatment

Alternative 2 was rated as “excellent” for *reduction of toxicity, mobility, and volume through treatment*. Addition of ISCO in western plume would not downgrade this rating. Combined Alternatives 2 and 4 is rated as “excellent” for *reduction of toxicity, mobility, and volume through treatment*.

Combined Alternatives 2 and 4 - Short-Term Effectiveness

Addition of ISCO technology to the western plume area will significantly increase the amount of drilling required on site, which will increase the amount of exposure workers have to drilling activities. This will also require operation of the two AOP systems with regular chemical deliveries and continuous delivery and injection of CHP. These two operations would need to be performed concurrently for up to 7 years. Based on the evaluation for Alternative 2 and the increased complexity, Combined Alternatives 2 and 4 is rated as “adequate” for *short-term effectiveness*.

Combined Alternatives 2 and 4 – Implementability

Addition of ISCO technology to the western plume area will significantly increase the amount of drilling required on site and the number of wells that need to be decommissioned at the conclusion of the action. This will increase the complexity of the action and the amount of materials that need to be disposed of at the end of the action. This will also require operation of the two AOP systems with regular chemical deliveries and continuous delivery and injection of CHP. These two operations would need to be performed concurrently for up to 7 years. Based on the evaluation for Alternative 2 and the increased complexity, Combined Alternatives 2 and 4 is rated as “adequate” for *implementability*.

Combined Alternatives 2 and 4 – Cost

Total capital and operational costs for Combined Alternatives 2 and 4 are estimated at \$31,760,000, and net present worth costs are estimated at \$27,600,000 over 30 years. This alternative ranks fourth in terms of costs. As a result, Combined Alternatives 2 and 4 is rated as “adequate” for *cost*.

Combined Alternatives 2 and 4 - State and Community Acceptance

State and community acceptance will be evaluated once state and public input is received. Planned community involvement is described in Section 6.

5.3 COMPARATIVE ANALYSIS

Alternative 1 (continue with current system) does not meet the threshold criteria and is therefore not included in this comparative analysis. Alternatives 2 and 5 are basically the same alternative with treatment process differences. Alternatives 3 and 4 are also similar and differ primarily in the type of oxidant and the number of injection wells. Figure 5-1 graphically illustrates results of the comparative analysis.

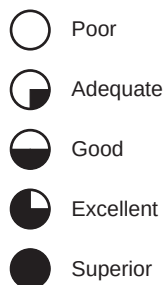
5.3.1 Overall Protection of Human Health and the Environment

Alternatives 2 and 5 would provide overall protection of human health and the environment to the same general degree. Alternative 2 would return treated groundwater to the aquifer via surface reinfiltration. Alternative 5 would return groundwater to the surface water of Puget Sound via discharge from the Ault Field WWTF. Alternative 2 provides better protection of the environment by returning groundwater to the aquifer from which it would be extracted. For these reasons Alternative 2 is rated “superior” and Alternative 5 is rated “excellent” for *overall protection of human health and the environment*.

Alternatives 3 and 4 would provide overall protection of human health and the environment. ISCO was defined as marginal for this large, dilute plume. However, this conclusion is based on a single injection, it is expected that multiple injections would significantly enhance the performance of ISCO at the site. Treating large dilute plumes with ISCO as the primary treatment component has challenges. Delivery of the oxidant to impacted groundwater is the single biggest challenge. These alternatives rely on setting up ISCO barriers along the western site boundary and SR 20. Operation of the existing groundwater extraction and treatment system would provide hydraulic control at least until the ISCO barriers have been established. These alternatives would also allow a portion of the southern plume to go untreated and therefore must rely on natural attenuation. Alternatives 3 and 4 are rated as “good” for *overall protection of human health and the environment* compared to Alternatives 2 and 5 for the following reasons:

- The uncertainty regarding plume control after the ISCO barrier is established
- The uncertainty of the required frequency and well density to establish and maintain the ISCO barrier along the western site boundary and SR 20

CERCLA Criteria	Alternative 1 Continue with Current System	Alternative 2 Continue P&T With Ex Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells	Alternative 3 In Situ Groundwater Treatment with ISCO Using Base-Activated Persulfate	Alternative 4 In Situ Groundwater Treatment with ISCO Using Catalyzed Hydrogen Peroxide	Alternative 5 Expanded Groundwater Capture With All Untreated Effluent Discharged to Nay WWTF at Ault Field	Combined Alternatives 2 and 4
Overall Protection of Human Health and the Environment						
Compliance with ARARs						
Long-Term Effectiveness and Permanence	Not Rated					
Reduction of Toxicity, Mobility, and Volume Through Treatment	Not Rated					
Short-Term Effectiveness	Not Rated					
Implementability	Not Rated					
Cost	Not Rated					
State and Community Acceptance	Not Rated	Not Rated	Not Rated	Not Rated	Not Rated	Not Rated



Notes:

AOP advanced oxidation process

ARARs applicable or relevant and appropriate requirements

ISCO in situ chemical oxidation

WWTF wastewater treatment facility

U.S. NAVY

Figure 5-1
Comparative Evaluation of Alternatives

DO 0055
Area 6
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NO. 1

Combined Alternatives 2 and 4 has all the components of Alternative 2 and removes much of the uncertainty for Alternative 4. As a result, Combined Alternatives 2 and 4 is rated as “superior” for *Overall Protection of Human Health and the Environment*.

5.3.2 Compliance with ARARs

Compliance with ARARs is summarized in Table 5-1.

Chemical-Specific ARARs

All alternatives have been judged to meet chemical-specific ARARs. Alternatives 2, 5, and Combined Alternatives 2 and 4 reduce uncertainty regarding meeting RGs (Safe Drinking Water Act and MTCA) relative to Alternatives 3 and 4. Reliance on an NPDES permit and surface water discharge of treated groundwater reduces the rating of Alternative 5 relative to Alternative 2. The uncertainty of Alternatives 3 and 4 to maintain plume control, injection frequency, and injection radius of influence reduce the rating for these alternatives relative to Alternatives 2, 5, and Combined Alternatives 2 and 4.

Location-Specific ARARs

All alternatives will meet location-specific ARARs equally.

Action-Specific ARARs

All alternatives will meet action-specific ARARs equally.

Overall ARAR Compliance Assessment

Based on the assessments presented in Section 4 and above, overall alternative compliance with ARARs is rated below by alternative:

- Alternative 2 “superior”
- Alternative 3 “good”
- Alternative 4 “good”
- Alternative 5 “excellent”
- Combined Alternatives 2 and 4 “superior”

5.3.3 Long-Term Effectiveness and Permanence

Alternatives 2, 5, and Combined Alternatives 2 and 4 have the lowest uncertainty for maintaining plume control and treating groundwater. Some uncertainty exists relative to residual source mass to groundwater in the former source area vadose zone soil.

As previously stated, the data gap analysis (U.S. Navy 2015c) concluded that TCE in vadose zone soil has the potential to act as a source to groundwater. If vadose zone soil poses a residual source to groundwater at concentrations that are above RGs or above an acceptable natural attenuation level, this uncertainty could be managed, if required, with additional residual source removal methods.

The modeling used to predict plume extent and the timeframe to reach the transition point between active and passive cleanup (and to reach RGs) used Mod Flow, a well-accepted methodology that is the industry standard. However, using this methodology may result in optimistic time predictions when compared to using Mod Flow and incorporating matrix diffusion. Matrix diffusion could be simulated by assuming a very low concentration constant source assigned to low permeability zones. There are no significant, low permeability zones identified within the shallow aquifer. A low permeability layer forms the base of the shallow aquifer at the site. Because the model does not incorporate matrix diffusion there is some uncertainty in the timeframes estimated to reach RGs.

Alternatives 3 and 4 have uncertainty relative to maintaining plume control. This uncertainty is related to the injection frequencies and injection well density required to maintain plume control and the rate of contaminant mass destruction. These alternatives have the same residual vadose zone soil source uncertainty as Alternatives 2, 5, and Combined Alternatives 2 and 4. As a result, the rating for Alternatives 3 and 4 have been reduced relative to Alternatives 2, 5, and Combined Alternatives 2 and 4.

Controls for all alternatives are well established by application of these technologies at other sites across the country.

Ratings for long-term effectiveness and performance are:

- Alternative 2 “excellent”
- Alternative 3 “good”
- Alternative 4 “good”
- Alternative 5 “excellent”
- Combined Alternatives 2 and 4 “excellent”

5.3.4 Reduction of Toxicity, Mobility, and Volume Through Treatment

Individually, Alternative 2 and Combined Alternatives 2 and 4 were rated highest for reduction of toxicity, mobility, and volume through treatment. This is because of the lower uncertainty for groundwater extraction to contain the plumes, reduce their mobility, and treat the extracted groundwater. Alternative 5 rating was reduced because the WWTF will not directly treat 1,4-dioxane in extracted groundwater. It would rely on dilution to decrease 1,4-dioxane

concentrations prior to discharge. Alternatives 3 and 4 have higher uncertainty in all three criteria. For these reasons, the alternatives were rated as follows:

- Alternative 2 “excellent”
- Alternative 3 “good”
- Alternative 4 “good”
- Alternative 5 “good”
- Combined Alternatives 2 and 4 “excellent”

5.3.5 Short-Term Effectiveness

Individually, Alternatives 2, 5, and Combined Alternatives 2 and 4 were rated highest for short-term effectiveness. These alternatives represent the least amount of effort required off Navy property that would expose the community and workers to potential construction hazards and inconveniences. Alternatives 3 and 4 would require a much longer construction time along SR 20 for injection well installation. Combined Alternatives 2 and 4 would expose workers to risks for a longer period of time by installing up to 100 injection wells within the Area 6 boundary, in addition to the exposure from Alternative 2 actions. Based on these conditions, the short-term effectiveness alternative ratings are:

- Alternative 2 “good”
- Alternative 3 “adequate”
- Alternative 4 “adequate”
- Alternative 5 “good”
- Combined Alternatives 2 and 4 “adequate”

5.3.6 Implementability

Alternatives 2 and 5 were rated best for implementability. Alternative 5 also requires installation and maintenance of a carbon substrate management system at the Ault Field WWTF. These complications result in a lower rating relative Alternative 2.

Alternatives 3 and 4 are rated lower because of the higher level of off-site infrastructure installation and long-term injections required along SR 20. These alternatives require installation of 110 to 180 injection wells along SR 20, depending on the alternative. Following installation, crews would need to occupy these locations multiple times per year to inject oxidant to create the ISCO barrier.

Based on these considerations, alternatives were rated for implementability as follows:

- Alternative 2 “good”
- Alternative 3 “adequate”
- Alternative 4 “adequate”
- Alternative 5 “adequate”
- Combined Alternatives 2 and 4 “adequate”

5.3.7 Estimated Cost

Cost is rated based on the estimated cost for each alternative to achieve RGs and RAOs. Estimated costs are summarized in Tables 4-2 and 4-3.

Alternatives are rated for total cost as follows:

- Alternative 2 “superior”
- Alternative 3 “poor”
- Alternative 4 “poor”
- Alternative 5 “excellent”
- Combined Alternatives 2 and 4 “adequate”

5.4 ALTERNATIVES ASSESSMENT

Results of the comparative evaluation of alternatives are summarized on Figure 5-1.

Alternatives 3 and 4 are the lowest rated alternatives because of the uncertainty with respect to plume containment and reduction of mobility. This results in lower ratings for the threshold criteria as well.

Alternative 2 is the highest rated alternative. It is also rated equivalent to the Combined Alternatives 2 and 4 for the following:

- Overall protection of human health and the environment
- Compliance with ARARS
- Long-term effectiveness and permanence
- Reduction of toxicity, mobility, and volume through treatment

Alternative 2 is rated higher than the Combined Alternatives 2 and 4 for the following:

- Short-term effectiveness

- Implementability
- Cost

The portion of Alternative 4 that is included in the combination alternative can be applied to Alternative 2 at any time and at any level. If reaching the RGs in a portion of the western plume proves problematic or an accelerated restoration time is desired and it is cost effective, a portion of Alternative 4 can be strategically added at a significantly reduced level.

Alternatives have been numerically rated by assigning values from 1 (lowest rating) to 5 (highest rating) as follows:

1	Poor rating
2	Adequate rating
3	Good rating
4	Excellent rating
5	Superior rating

Table 5-2 summarizes results of the numerical rating.

Table 5-2
Summary of Comparative Numerical Rating for Alternatives

CERCLA Criteria	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Combined Alternatives 2 and 4
Overall protection of human health and the environment	1	5	3	3	4	5
Compliance with ARARs	1	5	3	3	4	5
Long-term effectiveness and permanence	Not rated	4	3	3	4	4
Reduction of toxicity, mobility, and volume through treatment	Not rated	4	3	3	3	4
Short-term effectiveness	Not rated	3	2	2	3	2
Implementability	Not rated	3	2	2	2	2
Cost	Not rated	5	1	1	4	2
State and community acceptance	Not rated	Not rated	Not rated	Not rated	Not rated	Not rated
Total	Not rated	29	17	17	24	24

Alternatives have been numerically rated by assigning values from 1 (lowest rating) to 5 (highest rating) as follows:

- 1 Poor rating
- 2 Adequate rating
- 3 Good rating
- 4 Excellent rating
- 5 Superior rating

Results of the numerical rating are as follows:

- Alternative 2 – 29
- Alternative 5 – 24
- Combined Alternatives 2 and 4 – 24
- Alternative 3 – 17
- Alternative 4 – 17
- Alternative 1 – Does not meet threshold criteria, not rated

Based on this semi-quantitative evaluation, Alternative 2 (Continue P&T With Ex-Situ Groundwater Treatment Using Advanced Oxidation Process and Additional Extraction Wells) rates the highest.

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AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 5.0

Date: 7/20/2018

Page 5-30

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6.0 PUBLIC INVOLVEMENT

Once the preferred alternative is identified, the Navy will publish a notification in the Whidbey News Times (the local newspaper) announcing the date, time, and location of a public meeting to present the proposed plan and preferred alternative. The public notice will also identify the timing of the public comment period. The Navy will also identify and send this notice directly to downgradient property owners in an attempt to ensure comprehensive dissemination of this information.

FINAL FFS
AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 6.0

Date: 7/20/2018
Page 6-2

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AREA 6, NAS WHIDBEY ISLAND, OAK HARBOR, WA
Naval Facilities Engineering Command Northwest
Contract No. N44255-09-D-4001
Delivery Order 0055, Mod 2

Section 7.0

Date: 7/20/2018

Page 7-4

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APPENDIX A

Area 6 Groundwater Concentration Trends Evaluation

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Table A-1
Rationale for Determination That Concentrations of Volatile Organic Compounds
Are Decreasing With Time

Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Results
Negative	Negative	Negative	>95%	Decreasing trend
Positive	Negative	Negative	<95% but >50%	Flat to decreasing
Positive	Positive	Negative	<50% but >5%	Flat to increasing
Positive	Positive	Positive	<5%	Increasing trend

Notes:

LCL - lower confidence limit

UCL - upper confidence limit

Table A-2
Concentration Trends Analysis Summary for Trichloroethene in Groundwater Samples 2008 – 2014 at OU 1 Area 6

Well	Number of Results	Number of Detects	Number of Detects Above CUL	Average Conc. (µg/L)	Minimum Conc. (µg/L)	Maximum Conc. (µg/L)	Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Result
Source Area Wells											
6-S-10	8	0	0	0.03	0.03	0.03	NA	NA	NA	NA	Flat trend
6-S-30	10	0	0	0.03	0.03	0.07	-0.015	-0.094	-0.173	>95%	Decreasing trend
6-S-31	12	12	12	12.3	7.6	17	-0.073	-0.113	-0.154	>95%	Decreasing trend
N6-37	12	12	11	30.4	4	97	-0.162	-0.355	-0.547	>95%	Decreasing trend
N6-38	12	12	1	2.9	1.8	5.5	-0.063	-0.139	-0.215	>95%	Decreasing trend
PW-1	12	12	12	88	63	130	-0.081	-0.111	-0.142	>95%	Decreasing trend
Mid-Plume Wells											
6-S-06	10	10	10	68.2	46	110	-0.098	-0.130	-0.163	>95%	Decreasing trend
6-S-14	9	0	0	0.03	0.03	0.03	NA	NA	NA	NA	Flat trend
6-S-24	12	1	0	0.13	0.03	0.5	-0.183	-0.421	-0.659	>95%	Decreasing trend
MW-7	12	12	12	59.9	45	80	-0.075	-0.100	-0.125	>95%	Decreasing trend
MW-10	12	1	0	0.17	0.03	0.5	-0.220	-0.473	-0.726	>95%	Decreasing trend
PW-3	13	13	13	78.1	55	110	-0.107	-0.129	-0.152	>95%	Decreasing trend
Capture Zone Wells											
6-S-25	12	7	0	0.11	0.03	0.24	0.385	0.177	-0.031	<50% but >5%	Flat to increasing
6-S-27	10	0	0	0.03	0.03	0.07	-0.015	-0.094	-0.174	>95%	Decreasing trend
MW-5	12	0	0	0.04	0.03	0.07	-0.068	-0.138	-0.207	>95%	Decreasing trend
PW-4	10	0	0	0.08	0.027	0.5	-0.034	-0.305	-0.575	>95%	Decreasing trend
PW-5	10	10	10	79.6	68	110	-0.057	-0.092	-0.127	>95%	Decreasing trend
PW-6	10	4	0	0.15	0.03	0.5	-0.370	-0.558	-0.746	>95%	Decreasing trend
PW-7	10	0	0	0.08	0.027	0.5	-0.034	-0.305	-0.575	>95%	Decreasing trend
PW-8	10	2	0	0.08	0.027	0.5	-0.050	-0.320	-0.589	>95%	Decreasing trend
PW-9	9	2	0	0.04	0.027	0.07	0.265	0.114	-0.036	<50% but >5%	Flat to increasing
Downgradient Wells											
6-S-03	10	0	0	0.08	0.03	0.5	-0.048	-0.311	-0.575	>95%	Decreasing trend
6-S-19	10	0	0	0.08	0.027	0.5	-0.034	-0.303	-0.573	>95%	Decreasing trend
6-S-29	12	0	0	0.04	0.03	0.07	-0.067	-0.137	-0.206	>95%	Decreasing trend

Table A-2 (Continued)
Concentration Trends Analysis Summary for Trichloroethene in Groundwater Samples 2008 – 2014 at OU 1 Area 6

Well	Number of Results	Number of Detects	Number of Detects Above CUL	Average Conc. (µg/L)	Minimum Conc. (µg/L)	Maximum Conc. (µg/L)	Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Result
Downgradient Wells (Continued)											
6-S-41	8	0	0	0.03	0.03	0.03	NA	NA	NA	NA	Flat trend
6-S-42	8	0	0	0.03	0.03	0.03	NA	NA	NA	NA	Flat trend
6-S-43	8	0	0	0.03	0.03	0.03	NA	NA	NA	NA	Flat trend
MW-9	10	1	0	0.04	0.03	0.07	-0.032	-0.115	-0.197	>95%	Decreasing trend

Notes:

Conc. – concentration

CUL - cleanup level

LCL - lower confidence limit

NA - not available

µg/L - microgram per liter

UCL - upper confidence limit

Table A-3
Concentration Trends Analysis Summary for 1,1,1-Trichloroethane in Groundwater Samples 2008 – 2014 at OU 1 Area 6

Well	Number of Results	Number of Detects	Number of Detects Above CUL	Average Conc. (µg/L)	Minimum Conc. (µg/L)	Maximum Conc. (µg/L)	Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Result
Source Area Wells											
6-S-10	8	8	0	0.62	0.27	1.4	0.626	0.277	-0.071	<50% but >5%	Flat to increasing
6-S-30	10	10	0	19.5	5	45	0.111	-0.131	-0.373	<95% but >50%	Flat to decreasing
6-S-31	12	12	0	47.2	26	79	0.031	-0.062	-0.156	<95% but >50%	Flat to decreasing
N6-37	12	12	0	7.53	0.87	25	-0.137	-0.328	-0.520	>95%	Decreasing trend
N6-38	12	12	0	34.4	15	63	-0.058	-0.328	-0.249	>95%	Decreasing trend
PW-1	12	12	0	41.0	27	59	-0.082	-0.113	-0.143	>95%	Decreasing trend
Mid-Plume Wells											
6-S-06	10	10	9	459	120	890	-0.120	-0.299	-0.478	>95%	Decreasing trend
6-S-14	8	4	0	0.03	0.03	0.03	NA	NA	NA	NA	Flat trend
6-S-24	12	12	0	128	89	170	-0.022	-0.066	-0.109	>95%	Decreasing trend
MW-7	12	12	0	30.7	23	37	-0.047	-0.082	-0.117	>95%	Decreasing trend
MW-10	12	5	0	0.12	0.03	0.5	-0.066	-0.311	-0.557	>95%	Decreasing trend
PW-3	12	12	0	116	60	160	-0.030	-0.090	-0.150	>95%	Decreasing trend
Capture Zone Wells											
6-S-25	12	12	4	207	75	760	-0.176	-0.299	-0.422	>95%	Decreasing trend
6-S-27	10	10	0	1.13	0.67	2.2	-0.051	-0.136	-0.221	>95%	Decreasing trend
MW-5	12	12	4	240	5.5	790	1.024	0.603	0.181	<5%	Increasing trend
PW-4	10	10	0	6.95	4.9	10.0	0.119	0.050	-0.019	<50% but >5%	Flat to increasing
PW-5	10	10	2	180	120	350	-0.142	-0.206	-0.270	>95%	Decreasing trend
PW-6	10	10	0	4.35	1.3	14	0.233	-0.021	-0.275	<95% but >50%	Flat to decreasing
PW-7	10	10	0	0.48	0.32	0.73	-0.075	-0.120	-0.165	>95%	Decreasing trend
PW-8	10	9	0	0.32	0.18	0.50	-0.028	-0.115	-0.202	>95%	Decreasing trend
PW-9	9	9	0	0.34	0.13	0.63	-0.262	-0.357	-0.452	>95%	Decreasing trend

Table A-3 (Continued)
Concentration Trends Analysis Summary for 1,1,1-Trichloroethane in Groundwater Samples 2008 – 2014 OU 1 Area 6

Well	Number of Results	Number of Detects	Number of Detects Above CUL	Average Conc. (µg/L)	Minimum Conc. (µg/L)	Maximum Conc. (µg/L)	Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Result
Downgradient Wells											
6-S-03	10	10	0	2.81	1.9	4.0	-0.048	-0.089	-0.130	>95%	Decreasing trend
6-S-19	10	10	0	1.24	0.49	1.9	-0.016	-0.136	-0.255	>95%	Decreasing trend
6-S-29	12	12	0	0.97	0.41	1.7	-0.058	-0.125	-0.191	>95%	Decreasing trend
6-S-41	8	8	0	0.03	0.03	0.04	-0.024	-0.103	-0.182	>95%	Decreasing trend
6-S-42	8	8	0	3.50	2.4	4.4	-0.105	-0.148	-0.191	>95%	Decreasing trend
6-S-43	8	8	0	0.27	0.22	0.39	0.190	0.072	-0.046	<50% but >5%	Flat to increasing
MW-9	10	8	0	0.14	0.03	0.5	0.330	0.001	-0.327	<50% but >5%	Flat to increasing

Notes:

Conc. – concentration

CUL - cleanup level

LCL - lower confidence limit

µg/L - microgram per liter

UCL - upper confidence limit

Table A-4
Concentration Trends Analysis Summary for Vinyl Chloride in Groundwater Samples 2008 – 2014 OU 1 Area 6

Well	Number of Results	Number of Detects	Number of Detects Above CUL	Average Conc. (µg/L)	Minimum Conc. (µg/L)	Maximum Conc. (µg/L)	Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Result
Mid-Plume Wells											
6-S-06	10	7	1	0.06	0.03	0.11	0.286	0.163	0.041	<5%	Increasing trend
MW-10	12	12	12	0.52	0.23	1.2	0.082	-0.048	-0.179	<95% but >50%	Flat to decreasing
Capture Zone Wells											
PW-4	10	10	10	0.27	0.17	0.43	0.015	-0.071	-0.157	<95% but >50%	Flat to decreasing
PW-5	10	10	9	0.14	0.10	0.24	-0.125	-0.183	-0.242	>95%	Decreasing trend
PW-6	10	10	10	0.27	0.19	0.45	0.006	-0.089	-0.185	<95% but >50%	Flat to decreasing
PW-7	10	10	10	0.53	0.39	0.83	-0.048	-0.100	-0.152	>95%	Decreasing trend
PW-8	10	10	10	0.49	0.37	0.70	-0.026	-0.076	-0.126	>95%	Decreasing trend
PW-9	9	9	9	0.52	0.38	0.75	0.039	-0.060	-0.158	<95% but >50%	Flat to decreasing
Downgradient Wells											
6-S-03	10	10	10	0.24	0.13	0.39	-0.185	-0.217	-0.249	>95%	Decreasing trend
6-S-19	10	10	10	1.04	0.63	1.5	-0.006	-0.088	-0.170	>95%	Decreasing trend
6-S-29	12	12	12	0.92	0.51	1.4	-0.095	-0.135	-0.175	>95%	Decreasing trend
6-S-41	8	0	0	0.03	0.03	0.03	NA	NA	NA	NA	Flat
6-S-42	8	8	8	0.20	0.15	0.30	0.025	-0.099	-0.223	<95% but >50%	Flat to decreasing
6-S-43	8	8	8	2.76	1.8	3.7	0.211	0.091	-0.028	<50% but >5%	Flat to increasing
MW-9	10	10	10	0.45	0.34	0.66	0.028	-0.040	-0.107	<95% but >50%	Flat to decreasing

Notes:

Conc. – concentration

CUL - cleanup level

LCL - lower confidence limit

µg/L - microgram per liter

NA - not available

UCL - upper confidence limit

Table A-5
Concentration Trends Analysis Summary for 1,4-Dioxane in Groundwater Samples 2008 – 2014 OU 1 Area 6

Well	Number of Results	Number of Detects	Number of Detects Above CUL	Average Conc. (µg/L)	Minimum Conc. (µg/L)	Maximum Conc. (µg/L)	Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Result
Source Area Wells											
6-S-10	10	10	10	4.21	2.9	7.2	-0.081	-0.150	-0.220	>95%	Decreasing trend
6-S-30	10	10	10	3.49	1.6	6.0	-0.084	-0.166	-0.247	>95%	Decreasing trend
6-S-31	12	12	12	4.47	2.5	6.7	-0.077	-0.120	-0.162	>95%	Decreasing trend
N6-37	9	9	9	3.08	1.9	5.6	-0.162	-0.218	-0.274	>95%	Decreasing trend
N6-38	9	9	9	3.47	2.2	8.2	-0.130	-0.231	-0.333	>95%	Decreasing trend
PW-1	10	10	10	7.48	4.4	14	-0.105	-0.174	-0.242	>95%	Decreasing trend
Mid-Plume Wells											
6-S-06	10	10	9	2.15	0.4	9.1	-0.193	-0.435	-0.678	>95%	Decreasing trend
6-S-14	12	12	12	9.12	6.5	13	-0.027	-0.068	-0.110	>95%	Decreasing trend
6-S-15	4	4	4	3.28	2.8	3.7	0.351	-0.025	-0.400	<95% but >50%	Flat to decreasing
6-S-24	8	6	2	0.37	0.16	0.8	0.477	0.103	-0.270	<50% but >5%	Flat to increasing
MW-7	12	12	12	5.17	3.0	8.1	-0.055	-0.105	-0.154	>95%	Decreasing trend
MW-10	10	10	10	1.96	0.53	4.7	-0.011	-0.238	-0.464	>95%	Decreasing trend
PW-3	12	12	12	5.16	3.2	7.5	-0.020	-0.076	-0.131	>95%	Decreasing trend
Capture Zone Wells											
6-S-25	8	2	0	0.22	0.16	0.42	0.383	0.157	-0.070	<50% but >5%	Flat to increasing
6-S-27	8	0	0	0.16	0.16	0.16	NA	NA	NA	NA	Flat trend
MW-5	10	3	3	0.72	0.16	3.9	-0.221	-0.496	-0.770	>95%	Decreasing trend
PW-4	12	12	12	5.71	3.3	8.7	-0.117	-0.156	-0.195	>95%	Decreasing trend
PW-5	9	9	9	3.90	2.6	5.0	0.143	0.040	-0.062	<50% but >5%	Flat to increasing
PW-6	12	12	12	3.78	2.8	5.7	-0.020	-0.069	-0.119	>95%	Decreasing trend
PW-7	10	10	0	2.95	2.0	4.0	-0.009	-0.075	-0.142	>95%	Decreasing trend
PW-8	10	10	10	4.60	2.2	6.3	0.172	0.064	-0.044	<50% but >5%	Flat to increasing
PW-9	9	9	9	3.21	2.1	5.2	-0.025	-0.143	-0.262	>95%	Decreasing trend
Downgradient Wells											
6-S-03	12	12	12	4.27	1.5	7.6	-0.121	-0.205	-0.289	>95%	Decreasing trend
6-S-19	10	10	10	6.30	3.2	10	0.021	-0.098	-0.217	<95% but >50%	Flat to decreasing

Table A-5 (Continued)
Concentration Trends Analysis Summary for 1,4-Dioxane in Groundwater Samples 2008 – 2014 OU 1 Area 6

Well	Number of Results	Number of Detects	Number of Detects Above CUL	Average Conc. (µg/L)	Minimum Conc. (µg/L)	Maximum Conc. (µg/L)	Slope of 95% UCL	Slope of Decay Rate	Slope of 95% LCL	Confidence That Trend Is Downward	Interpretation of Result
6-S-29	12	12	12	10.5	7	20	0.056	-0.038	-0.132	<95% but >50%	Flat to decreasing
6-S-41	11	8	7	0.70	0.16	1.8	0.193	-0.072	-0.337	<95% but >50%	Flat to decreasing
6-S-42	11	11	11	12.83	5.3	18	0.191	0.092	-0.007	<50% but <5%	Flat to increasing
6-S-43	11	11	11	3.97	1.8	8.4	0.279	0.173	0.066	<5%	Increasing trend
6-DW-38	11	8	9	3.22	0.16	7.7	0.746	0.364	-0.017	<50% but <5%	Flat to increasing
MW-9	10	9	10	1.68	0.81	3.0	-0.159	-0.226	-0.292	>95%	Decreasing trend

Notes:

Conc. – concentration

CUL - cleanup level

LCL - lower confidence limit

µg/L - microgram per liter

NA - not available

UCL - upper confidence limit

Figure A-1
TCE in Source Area Well 6-S-31

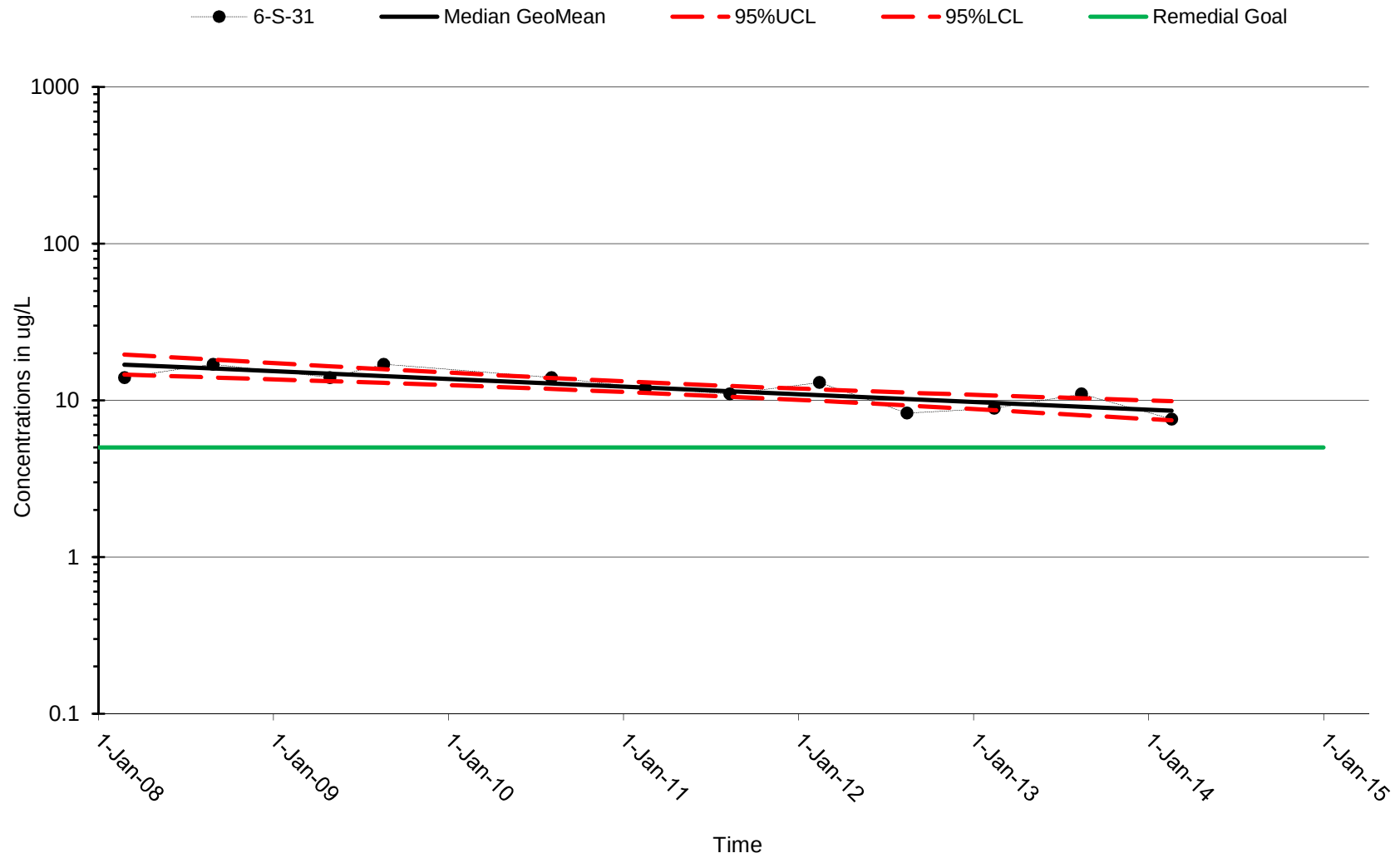


Figure A-2
TCE in Source Area Well N6-37

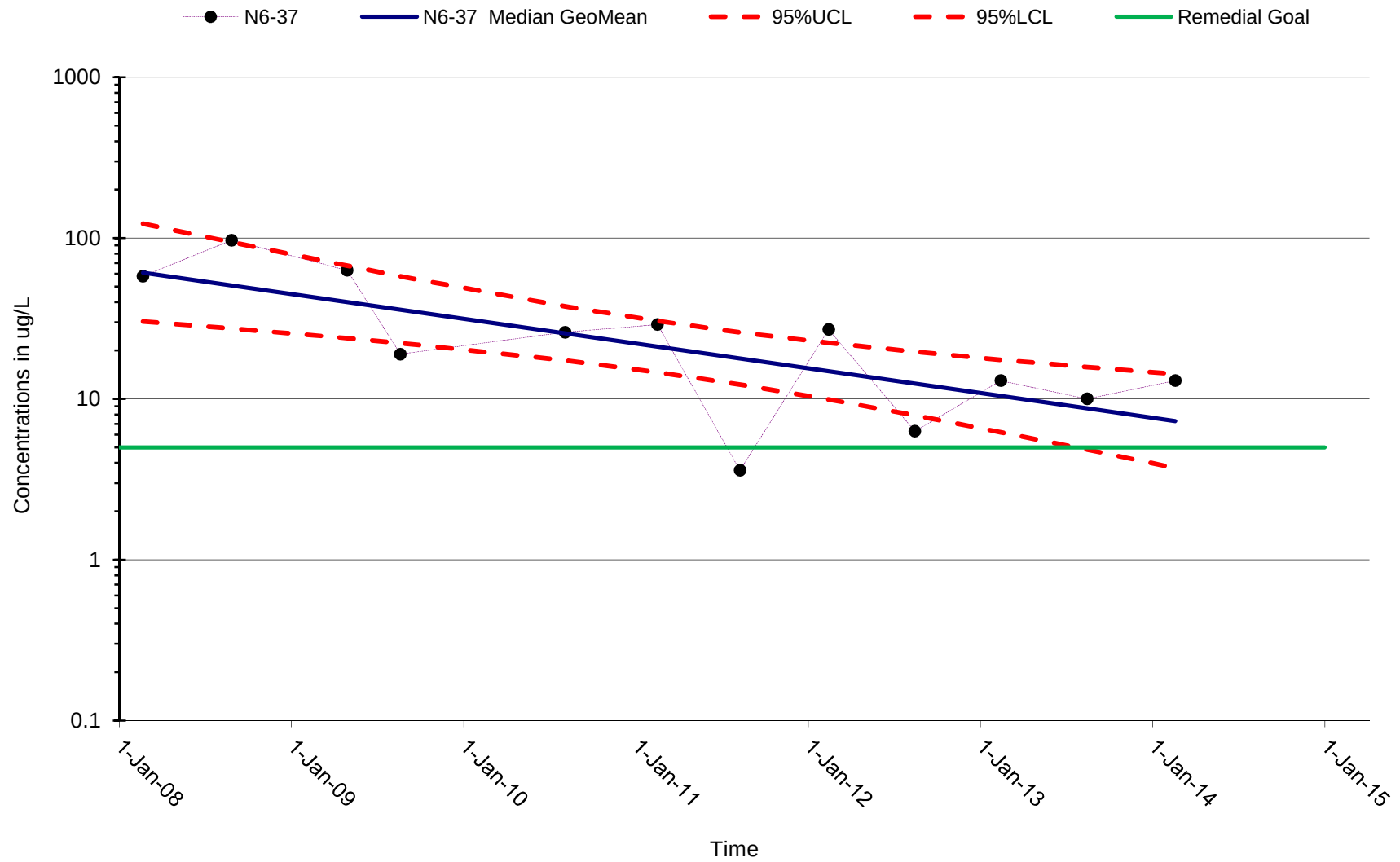


Figure A-3
TCE in Source Area Recovery Well PW-1

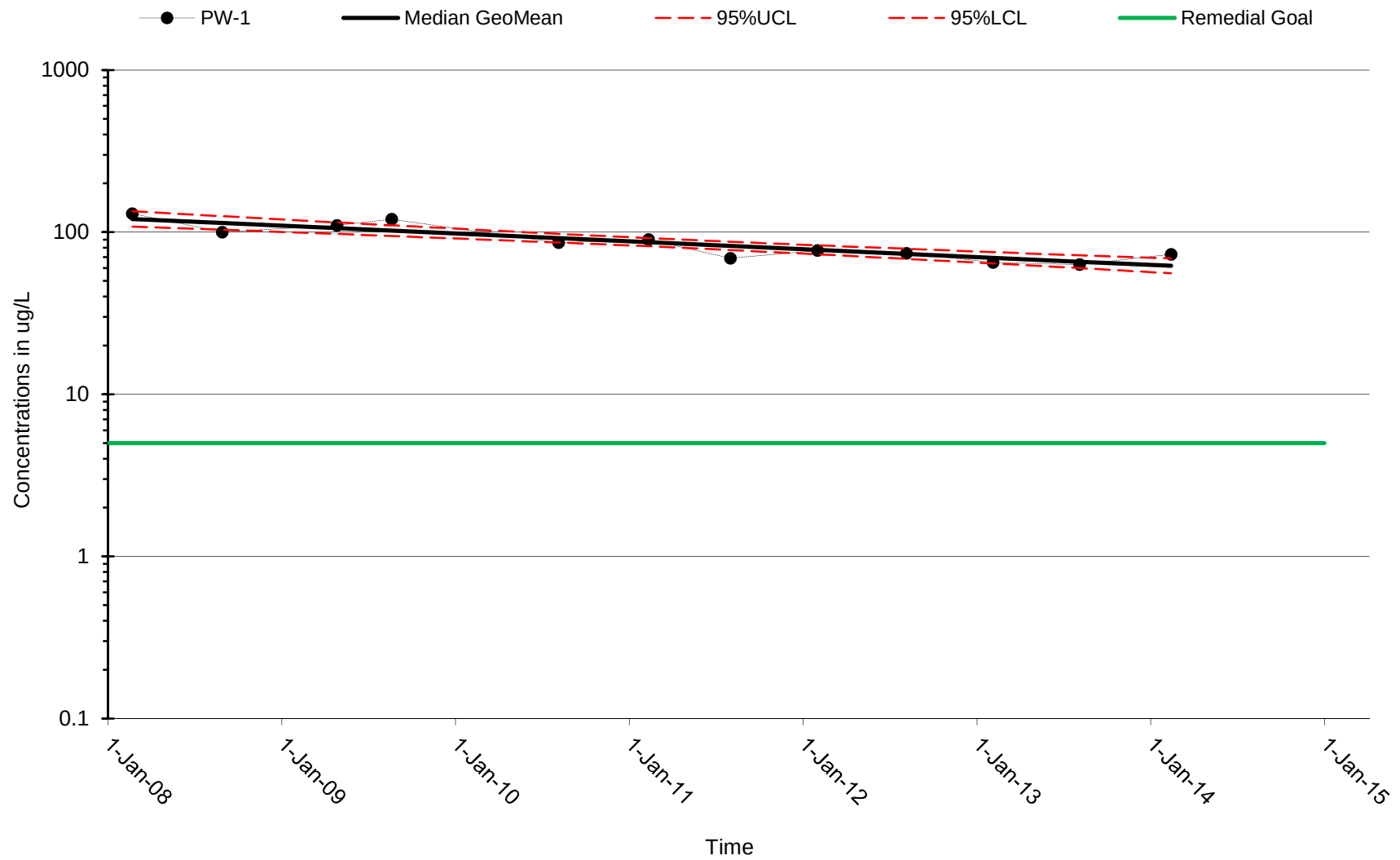


Figure A-4
1,4-Dioxane in Source Area Well 6-S-10

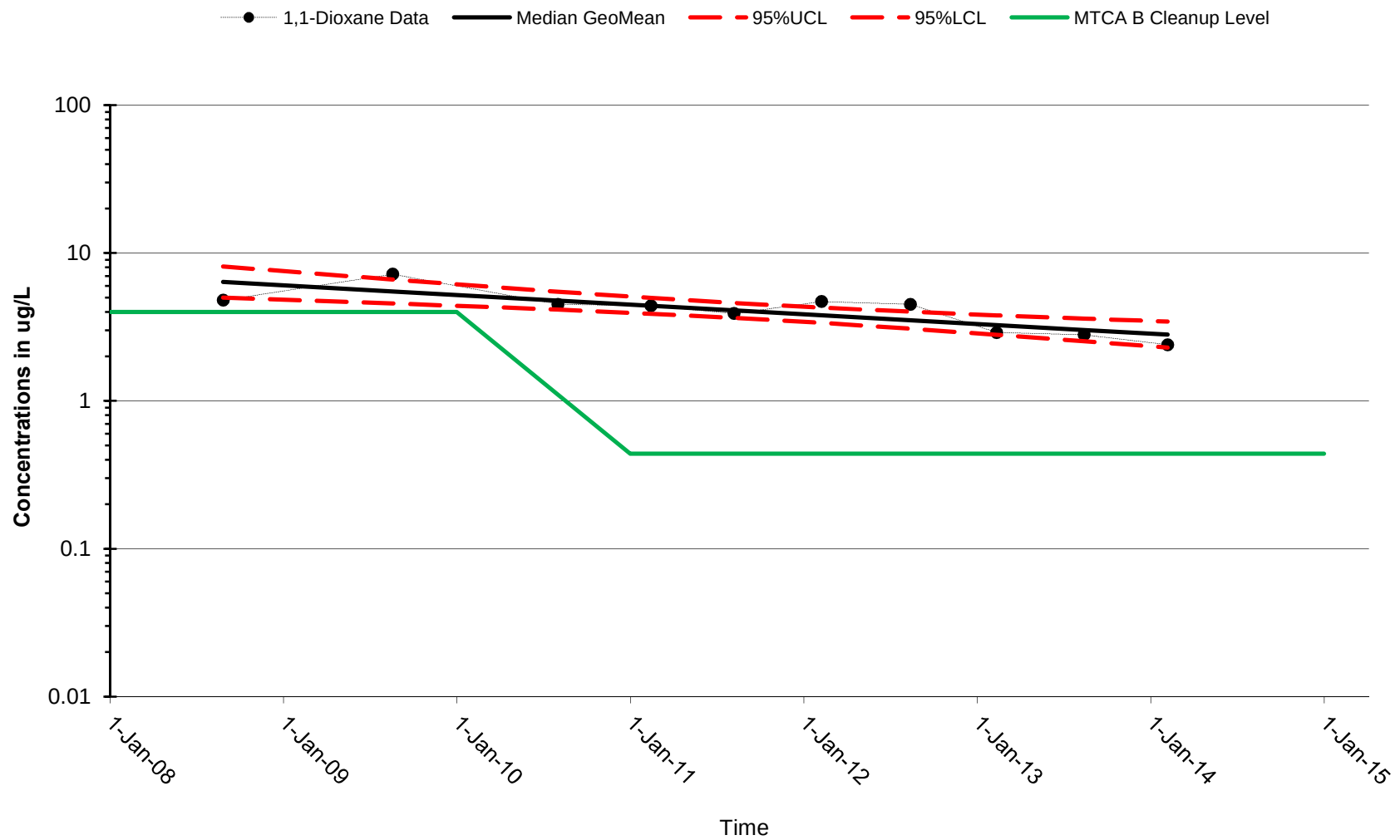


Figure A-5
1,4-Dioxane in Source Area Well 6-S-30

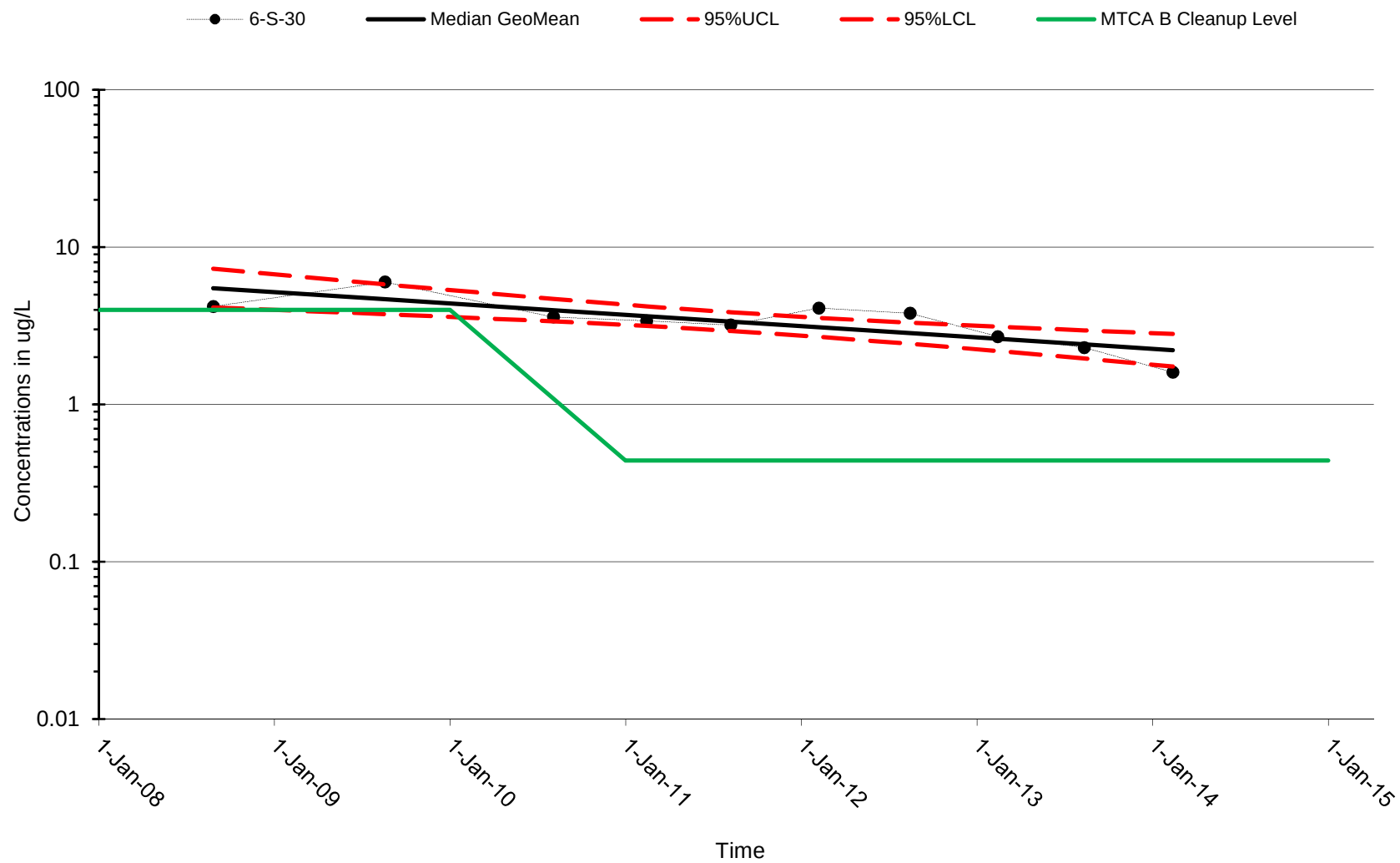


Figure A-6
1,4-Dioxane in Source Area Well 6-S-31

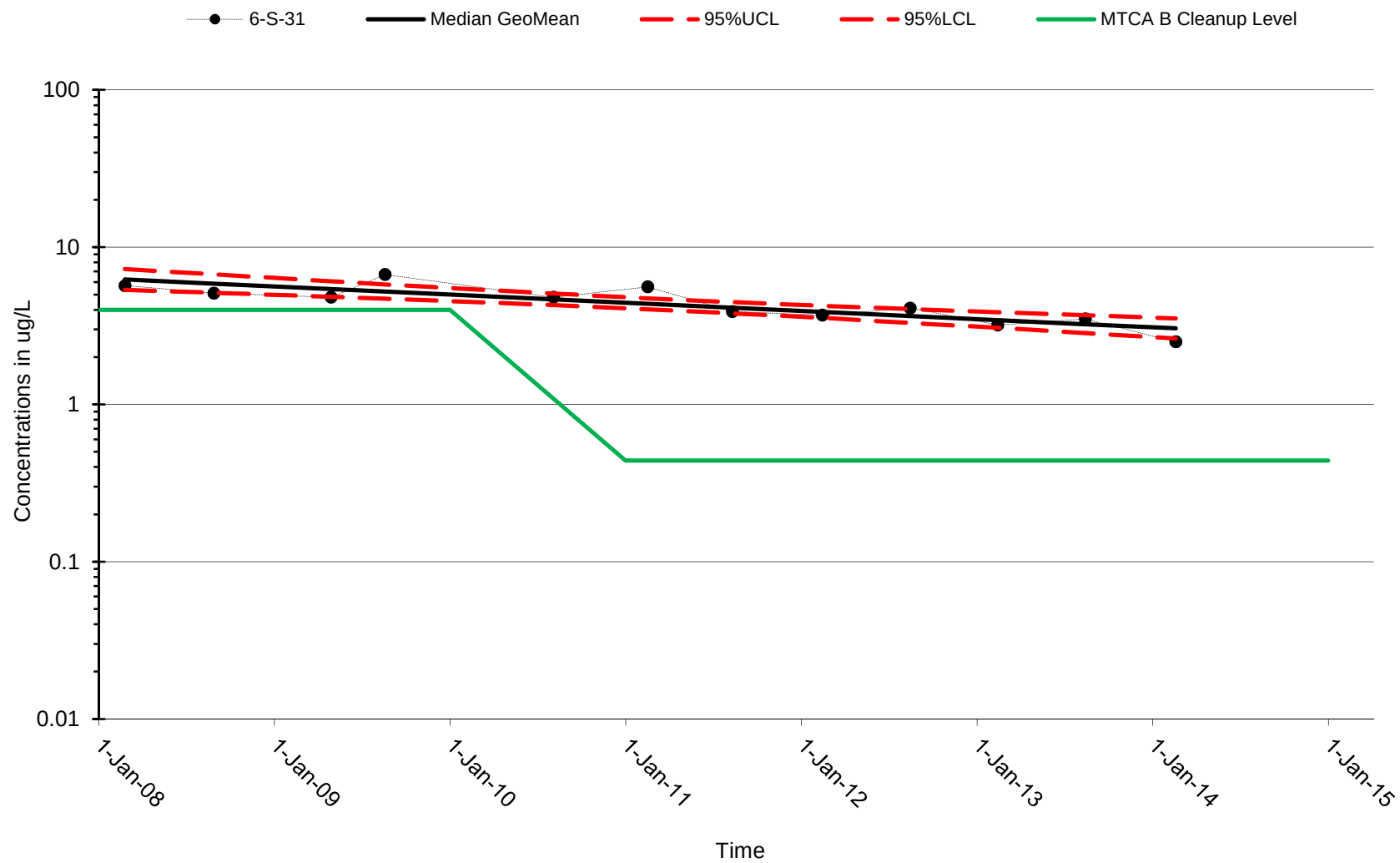


Figure A-7
1,4-Dioxane in Source Area Well N6-37

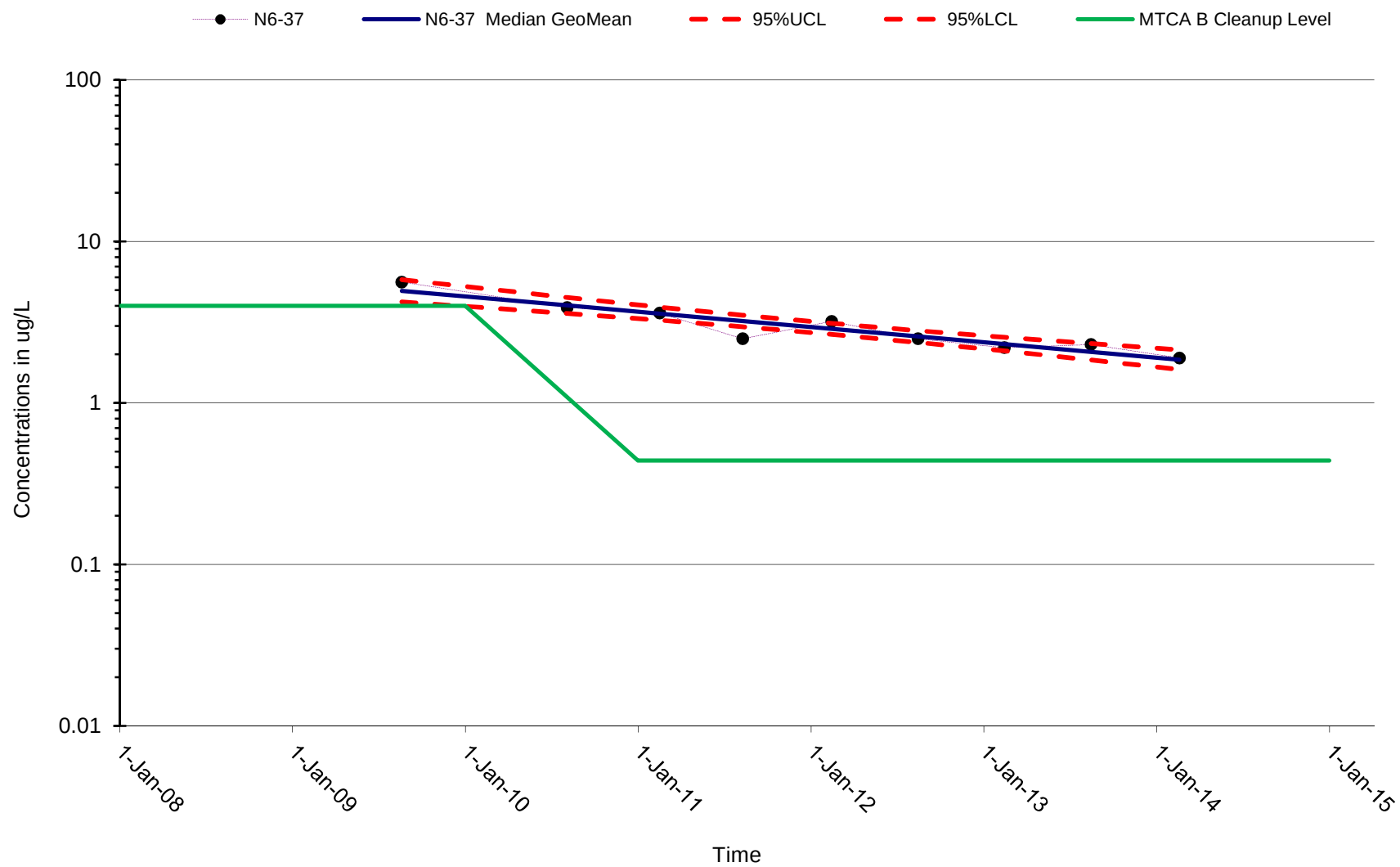


Figure A-8
1,4-Dioxane in Source Area Well N6-38

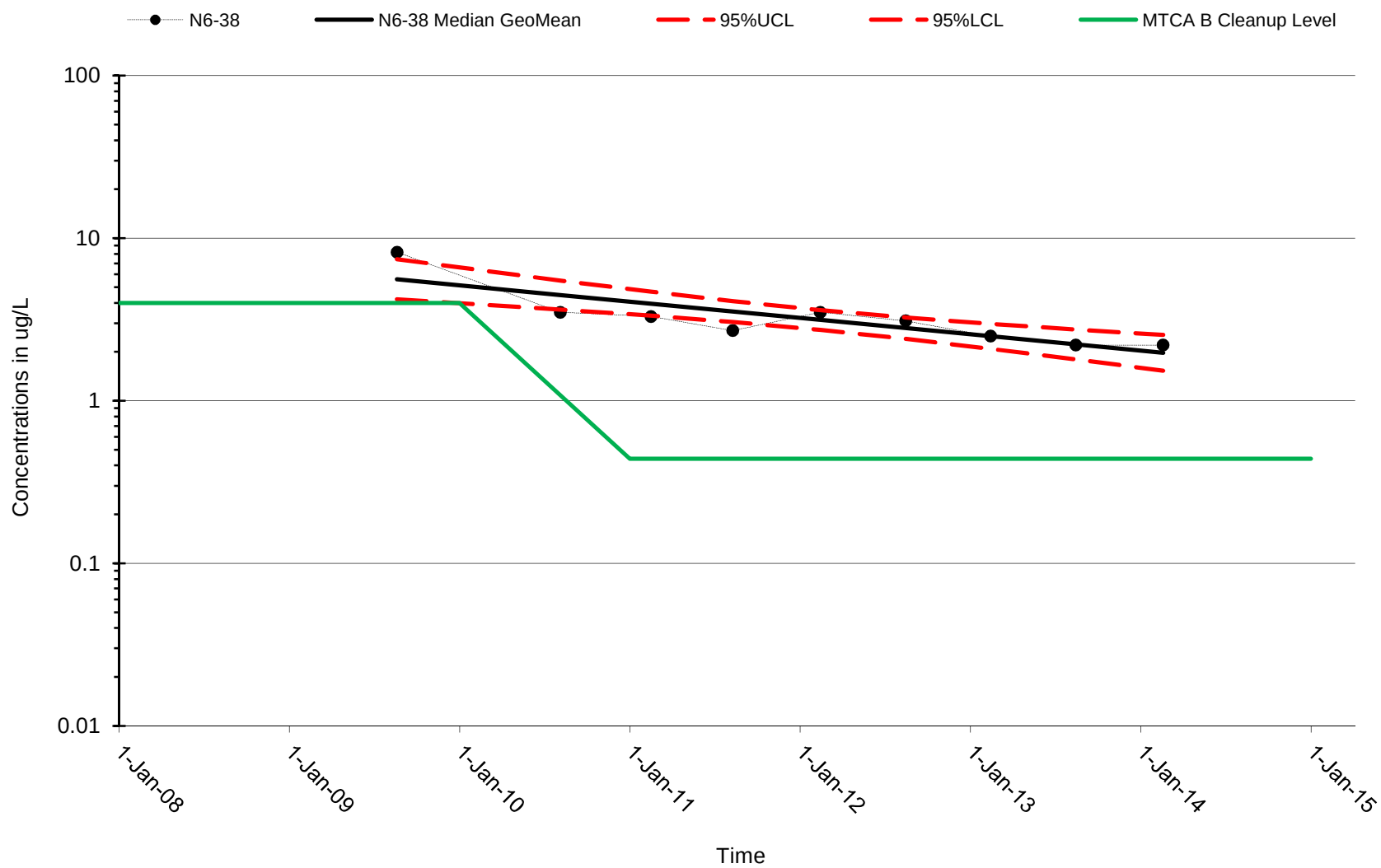


Figure A-9
1,4-Dioxane in Source Area Recovery Well PW-1

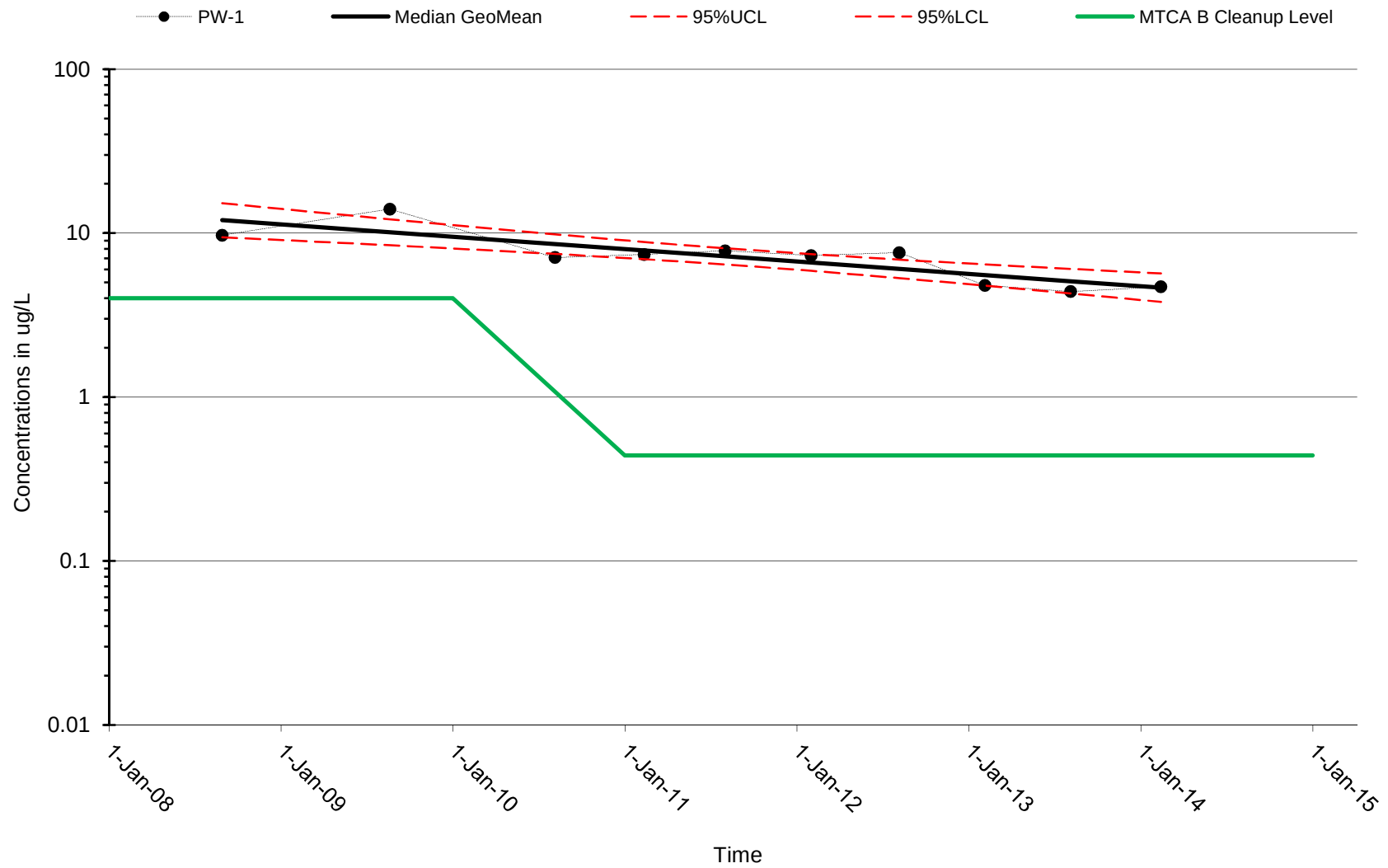


Figure A-10
TCE in Mid-Plume Well 6-S-06

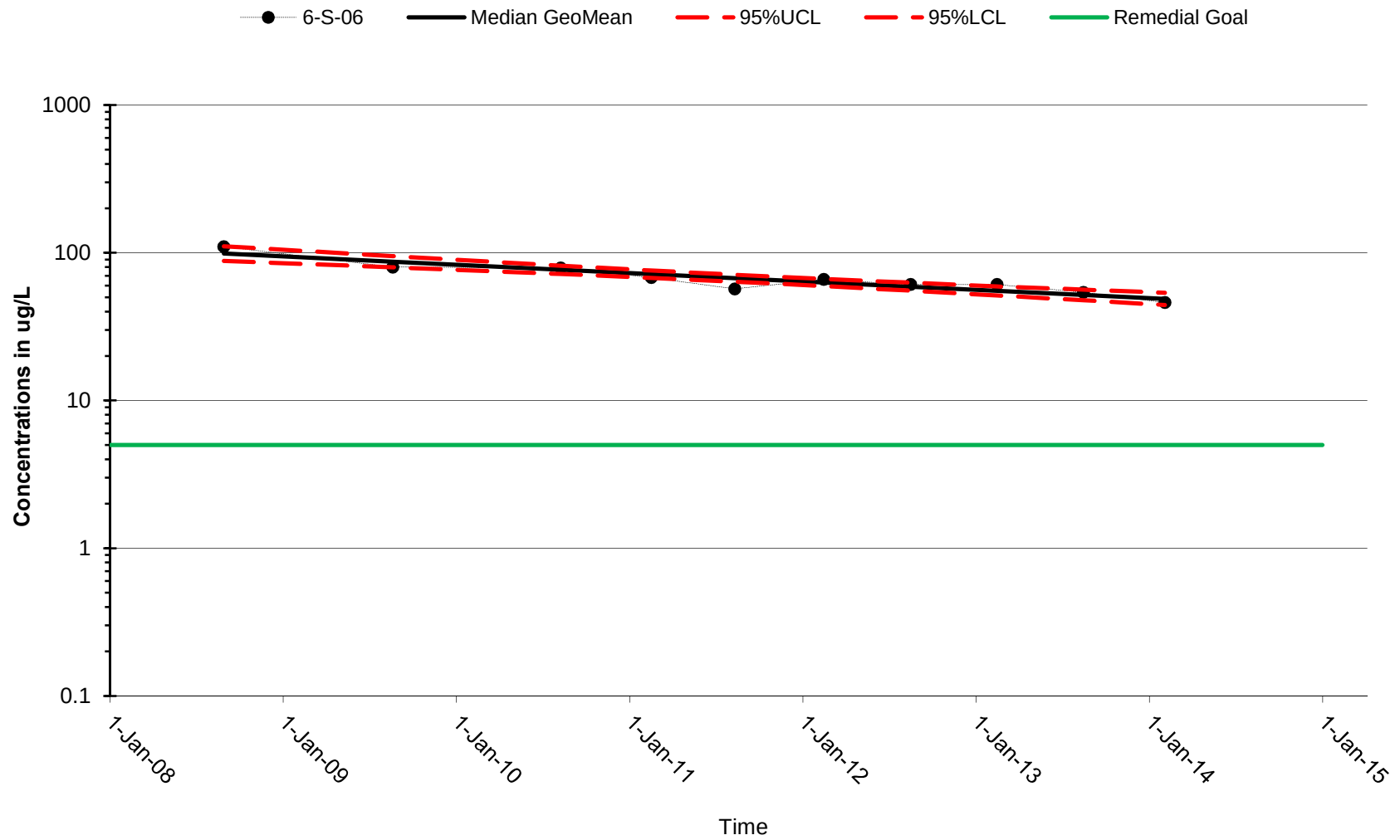


Figure A-11
TCE in Mid-Plume Area Well MW-7

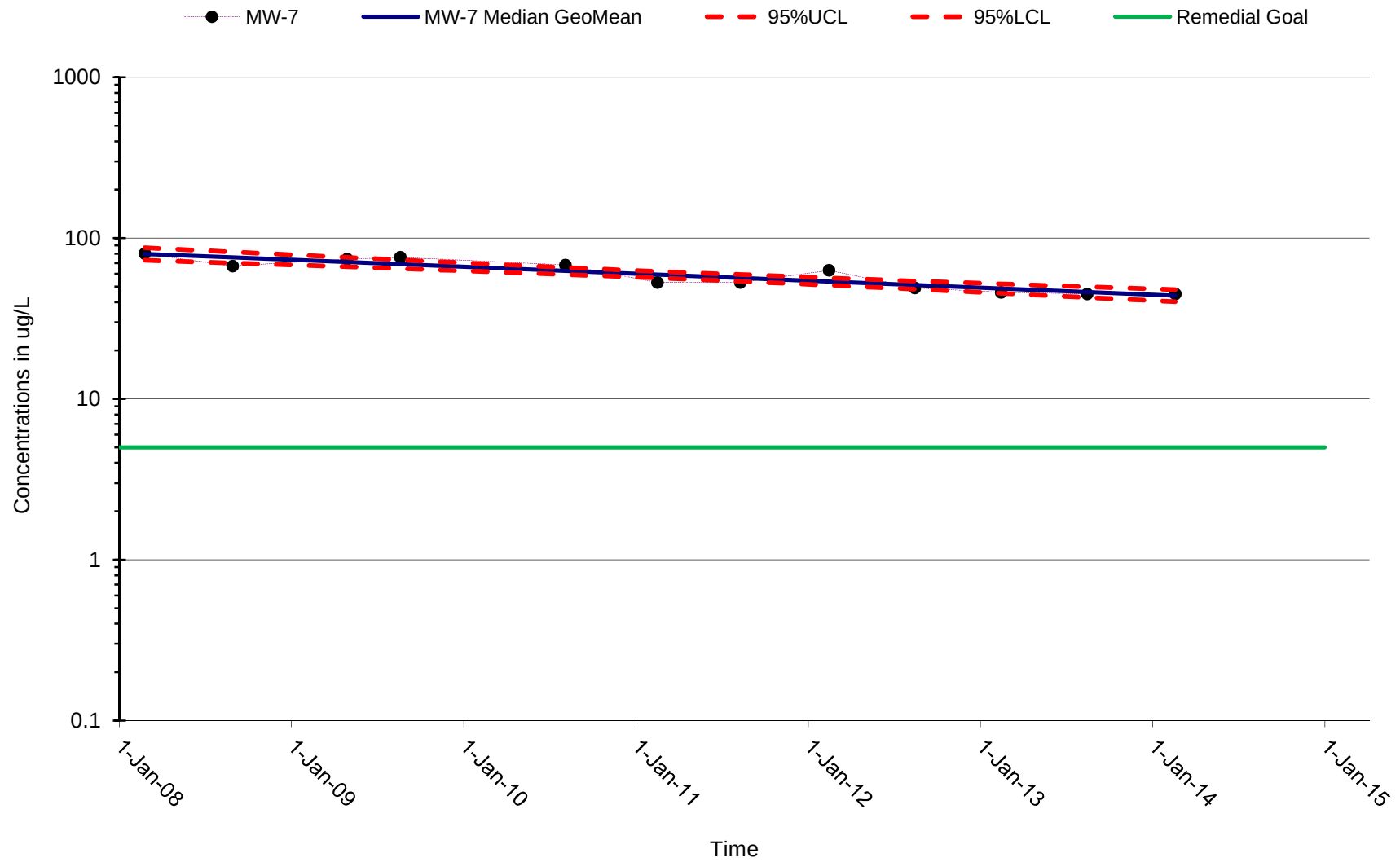


Figure A-12
TCE in Mid-Plume Area Recovery Well PW-3

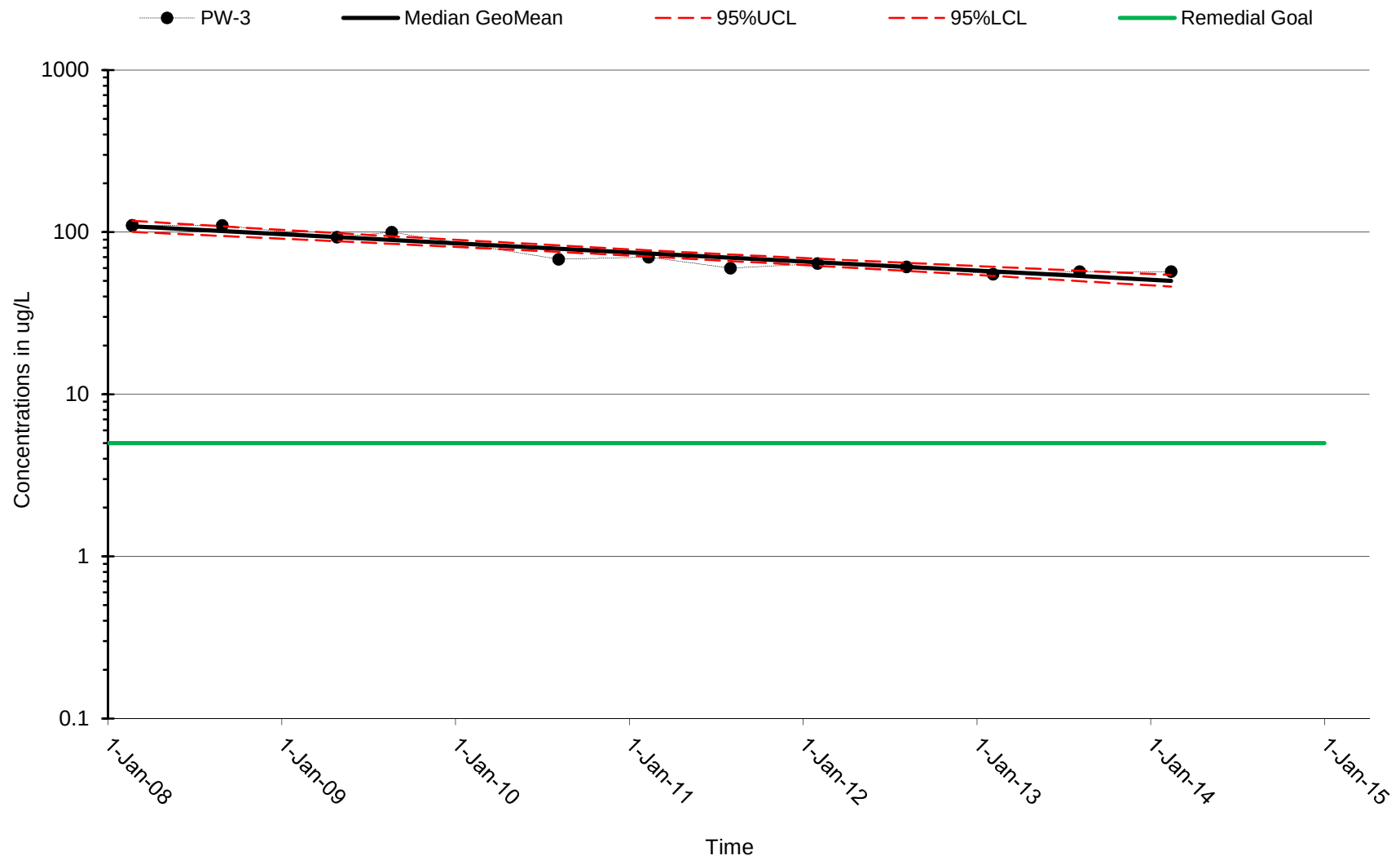


Figure A-13
1,1,1-TCA in Mid-Plume Well 6-S-06

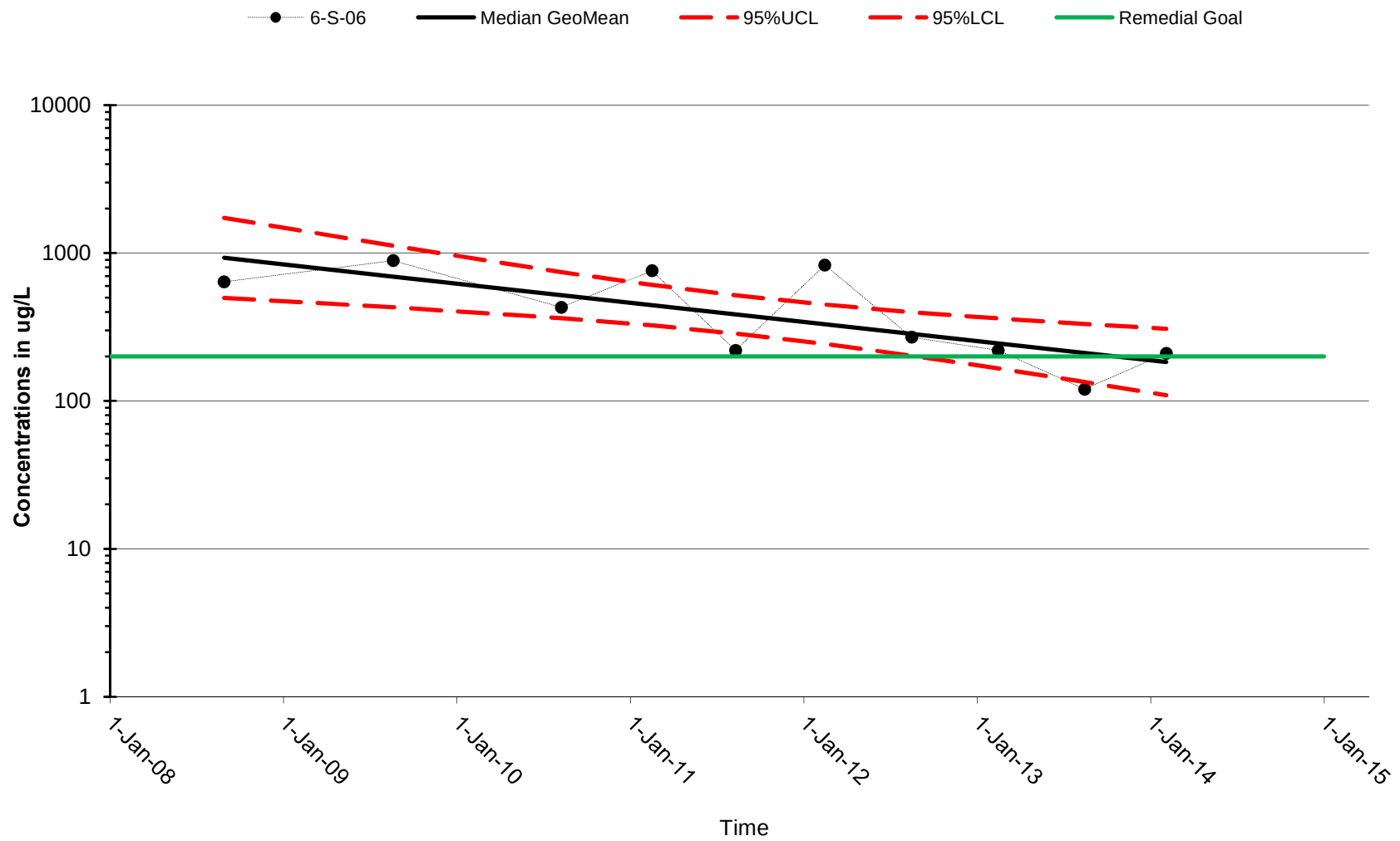


Figure A-14
1,4-Dioxane in Mid-Plume Well 6-S-06

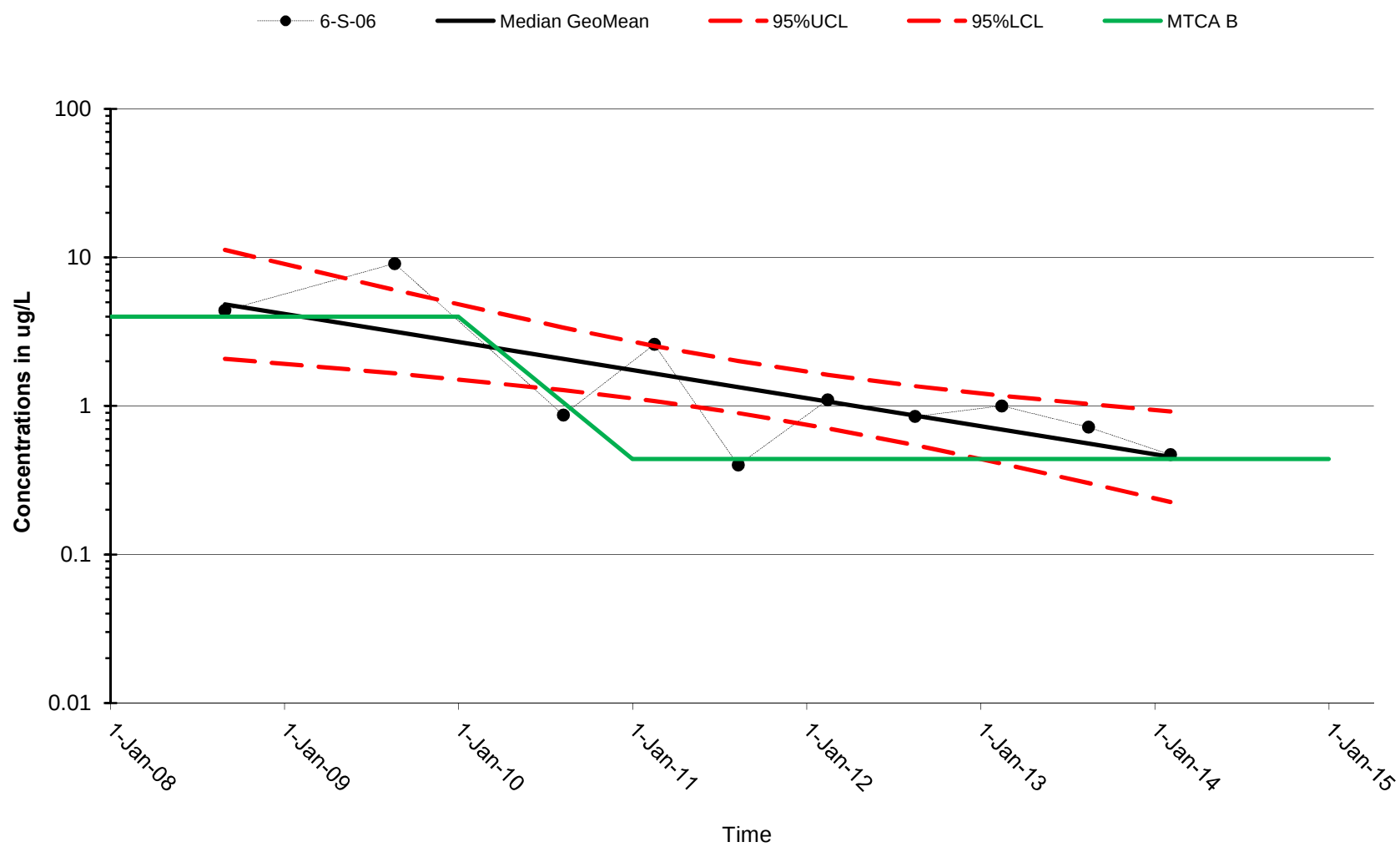


Figure A-15
1,4-Dioxane in Mid-Plume Area Well 6-S-14

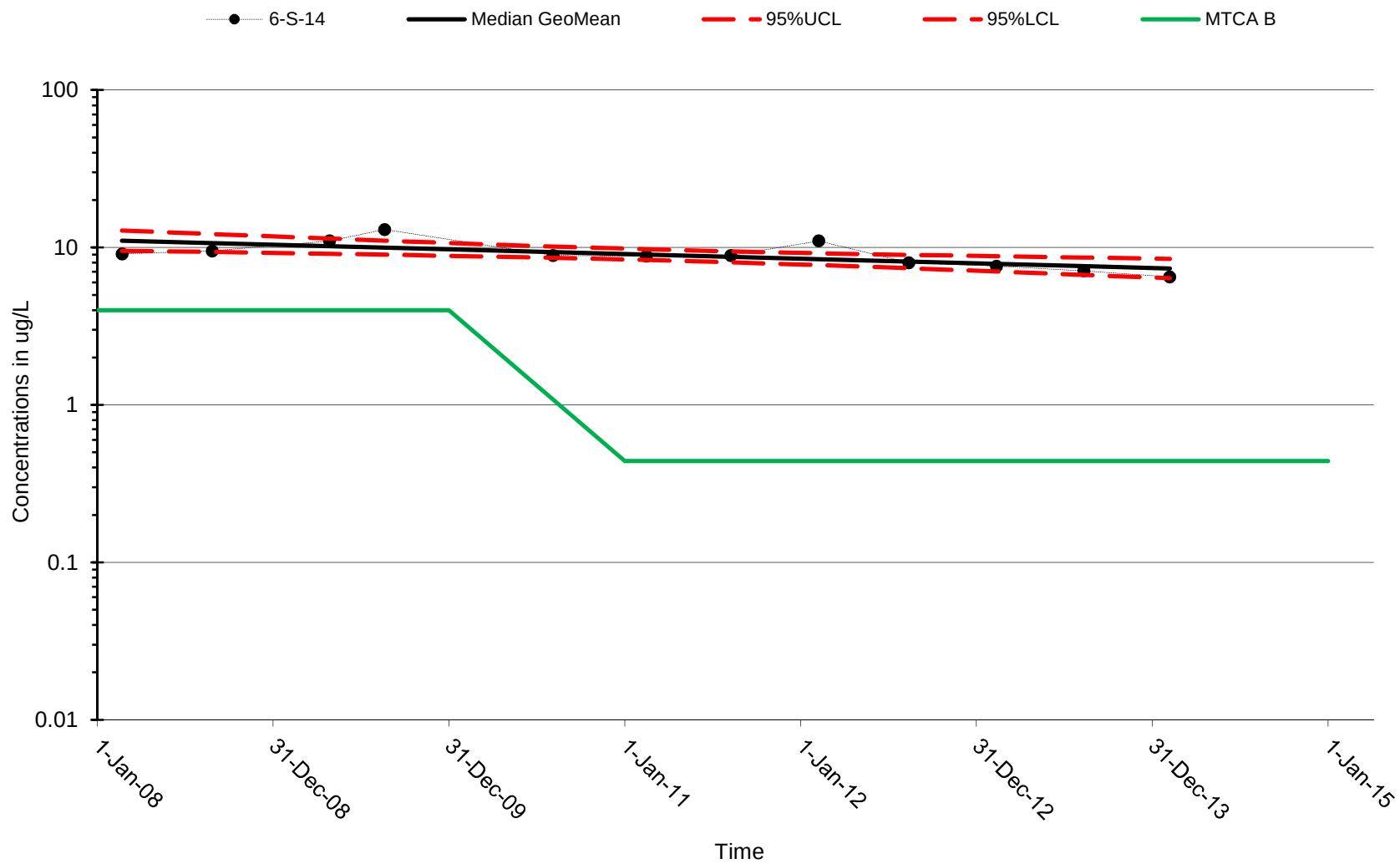


Figure A-16
1,4-Dioxane in Mid-Plume Area Well 6-S-15

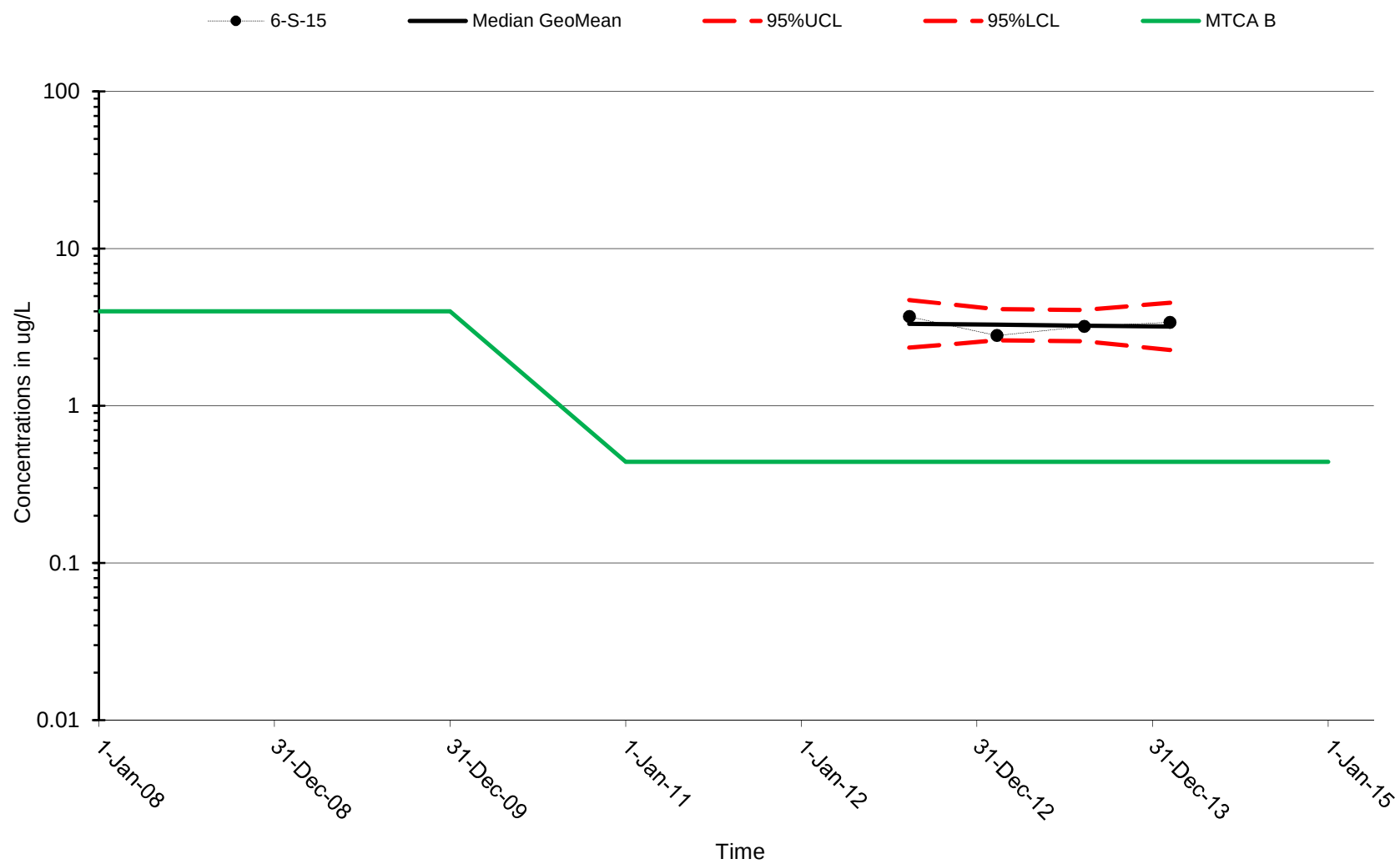


Figure A-17
1,4-Dioxane in Mid-Plume Area Well 6-S-24

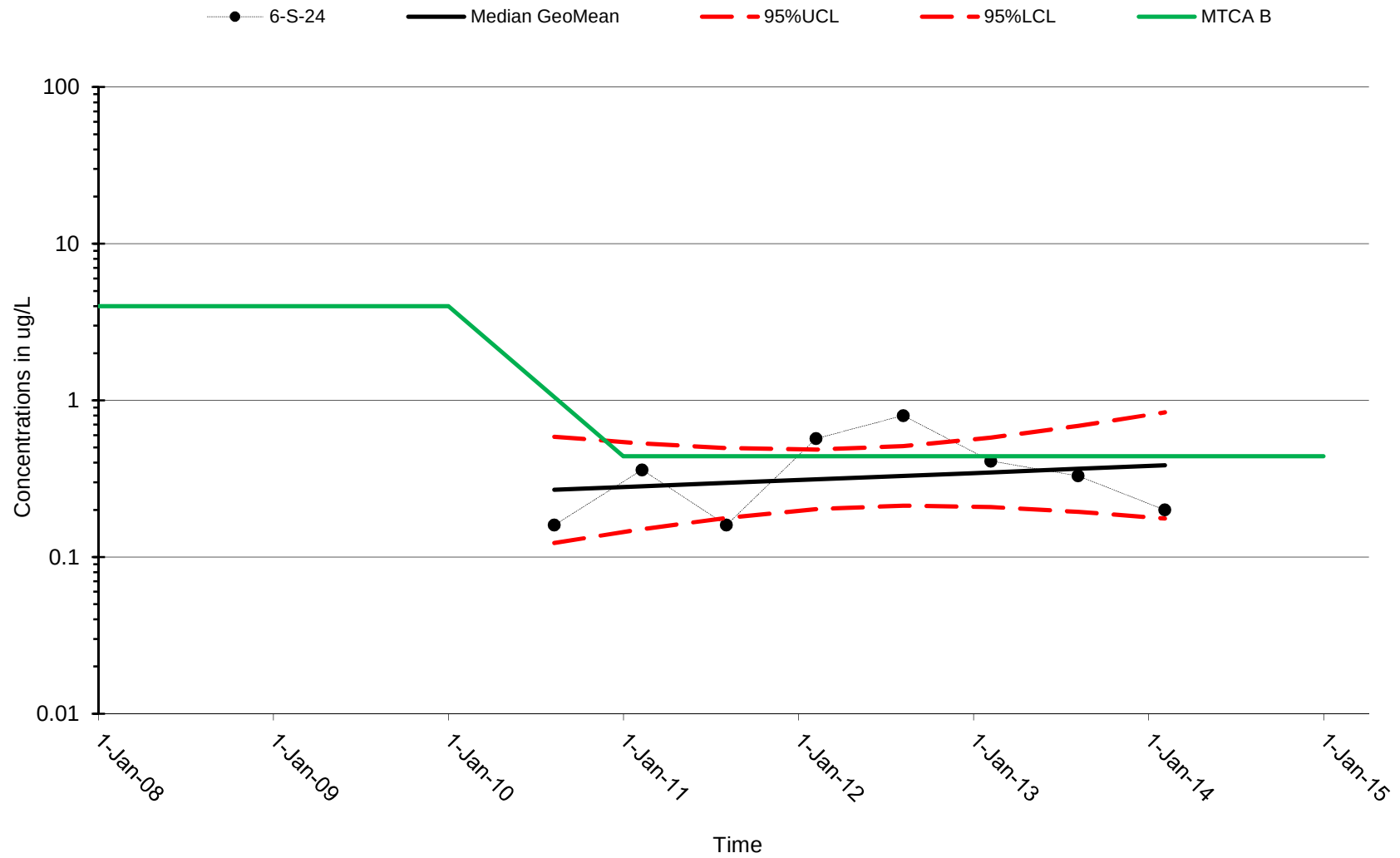


Figure A-18
1,4-Dioxane in Mid-Plume Area Well MW-7

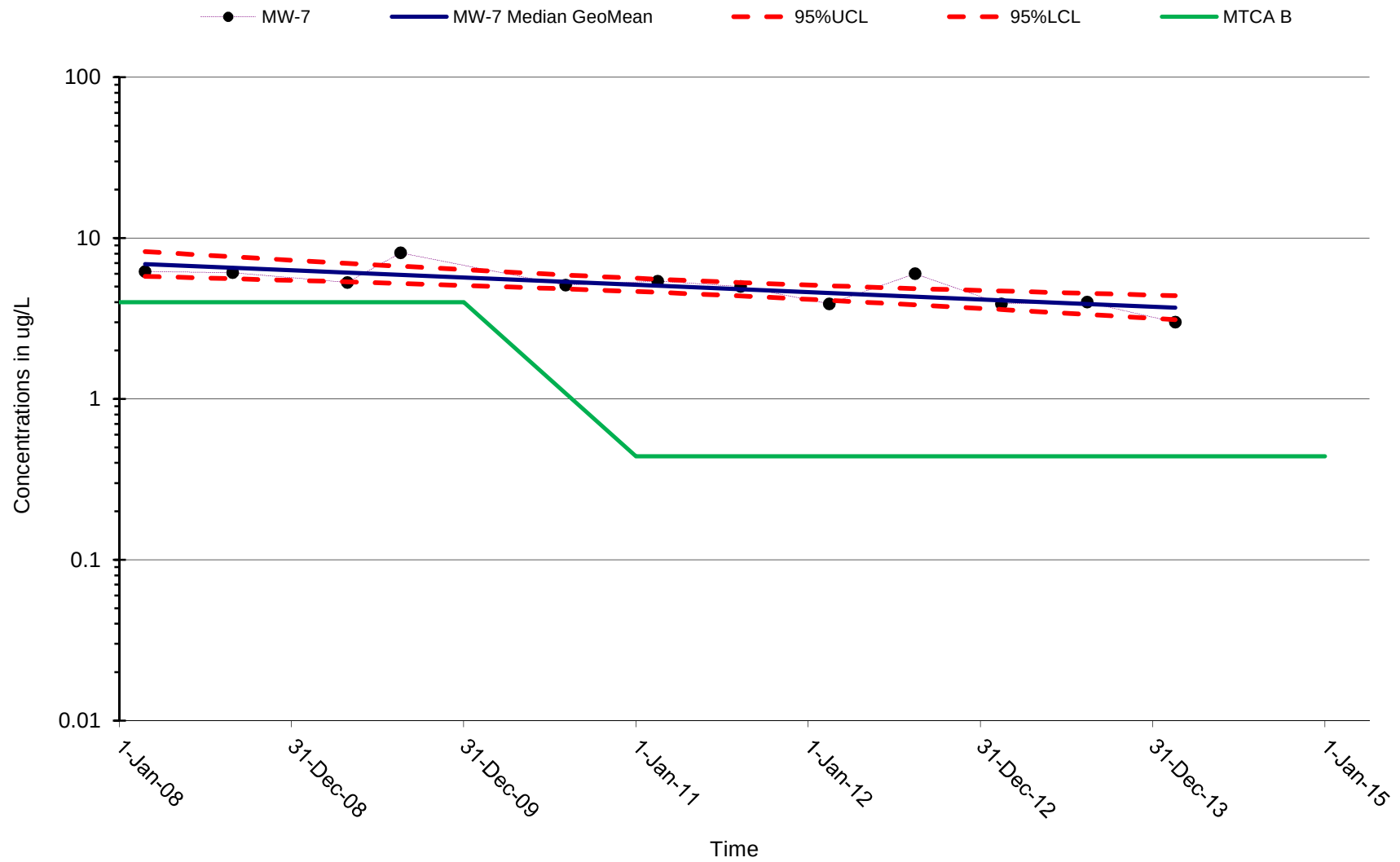


Figure A-19
1,4-Dioxane in Mid-Plume Well MW-10

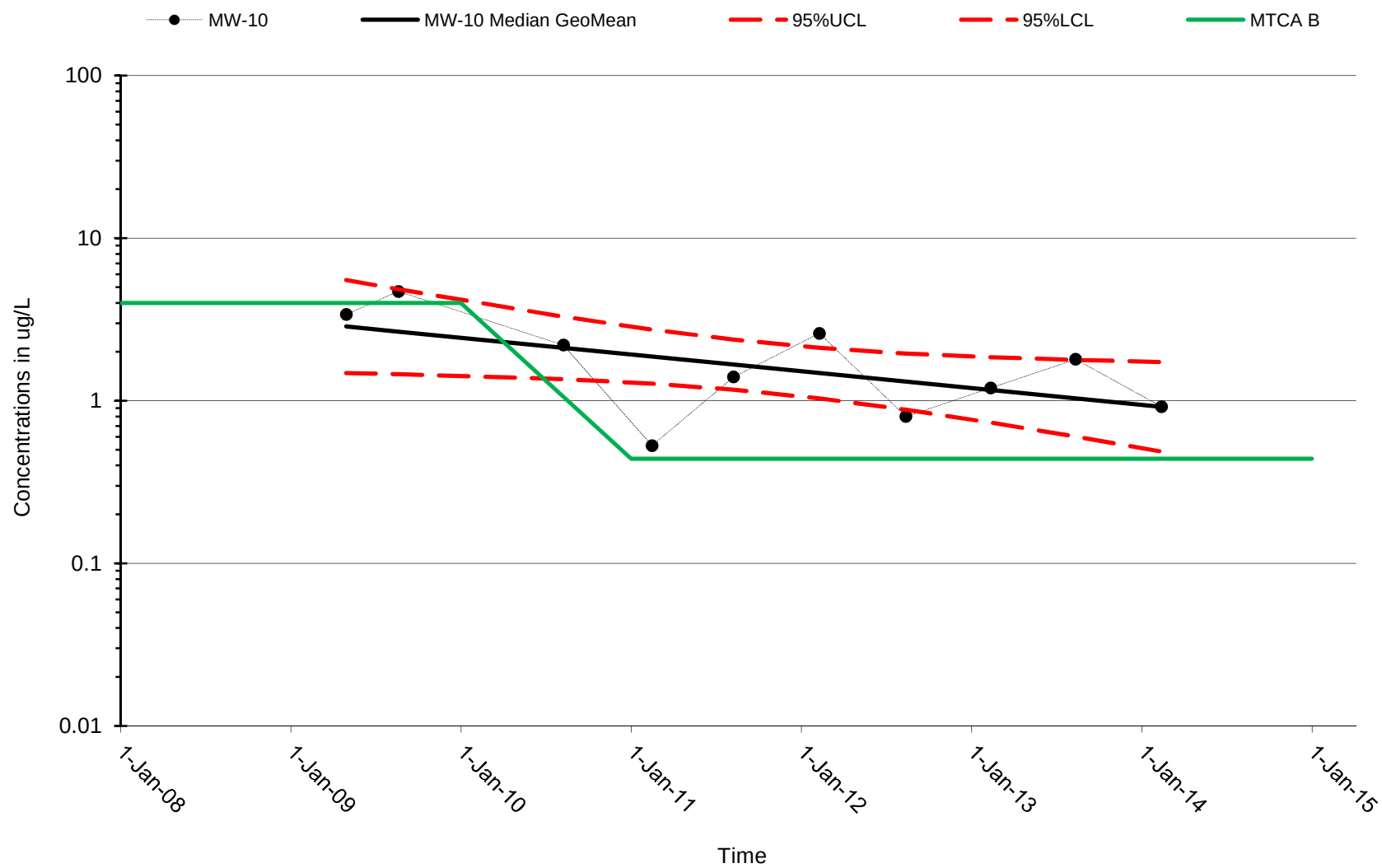


Figure A-20
1,4-Dioxane in Mid-Plume Area Recovery Well PW-3

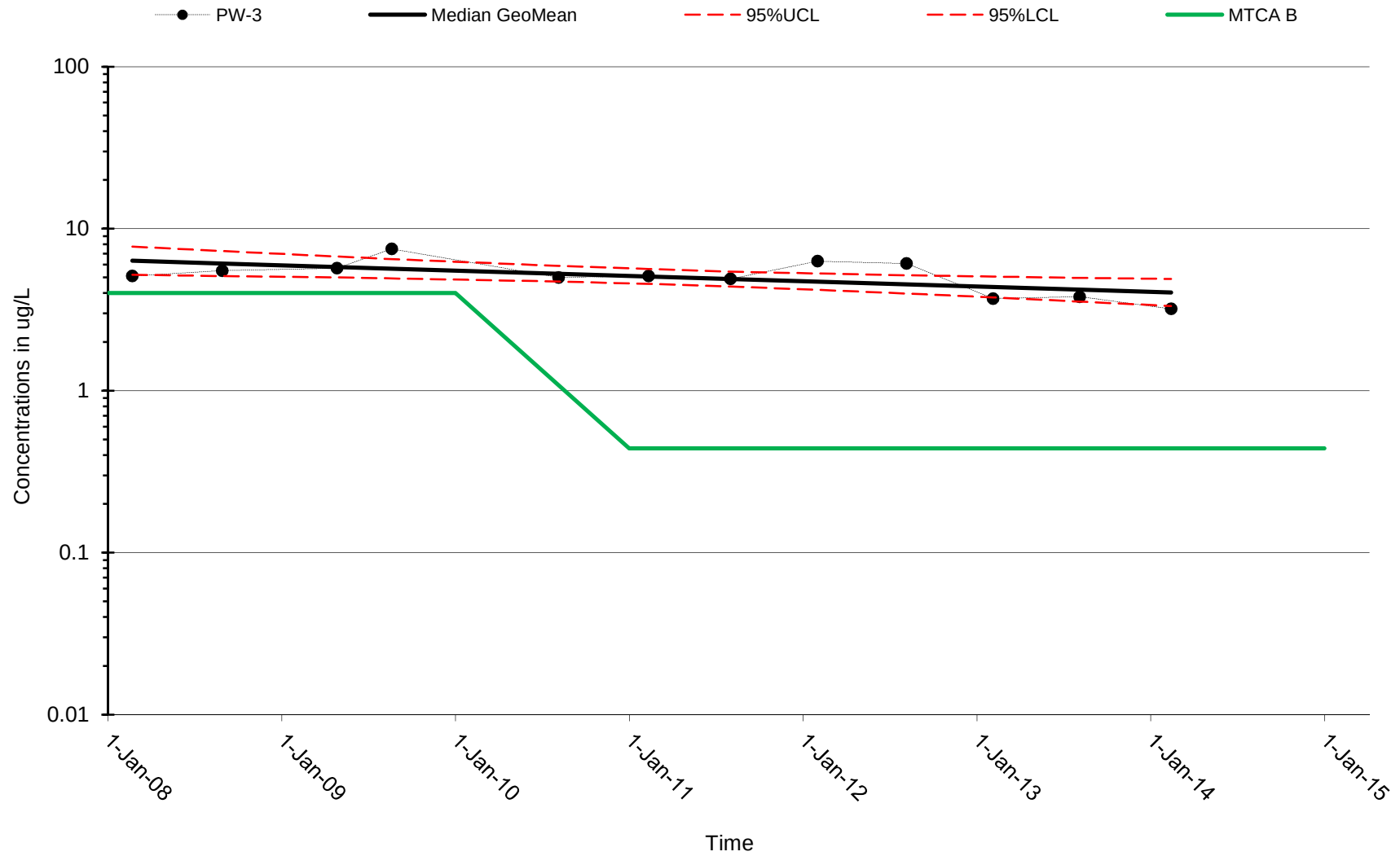


Figure A-21
TCE in Capture Zone Recovery Well PW-5

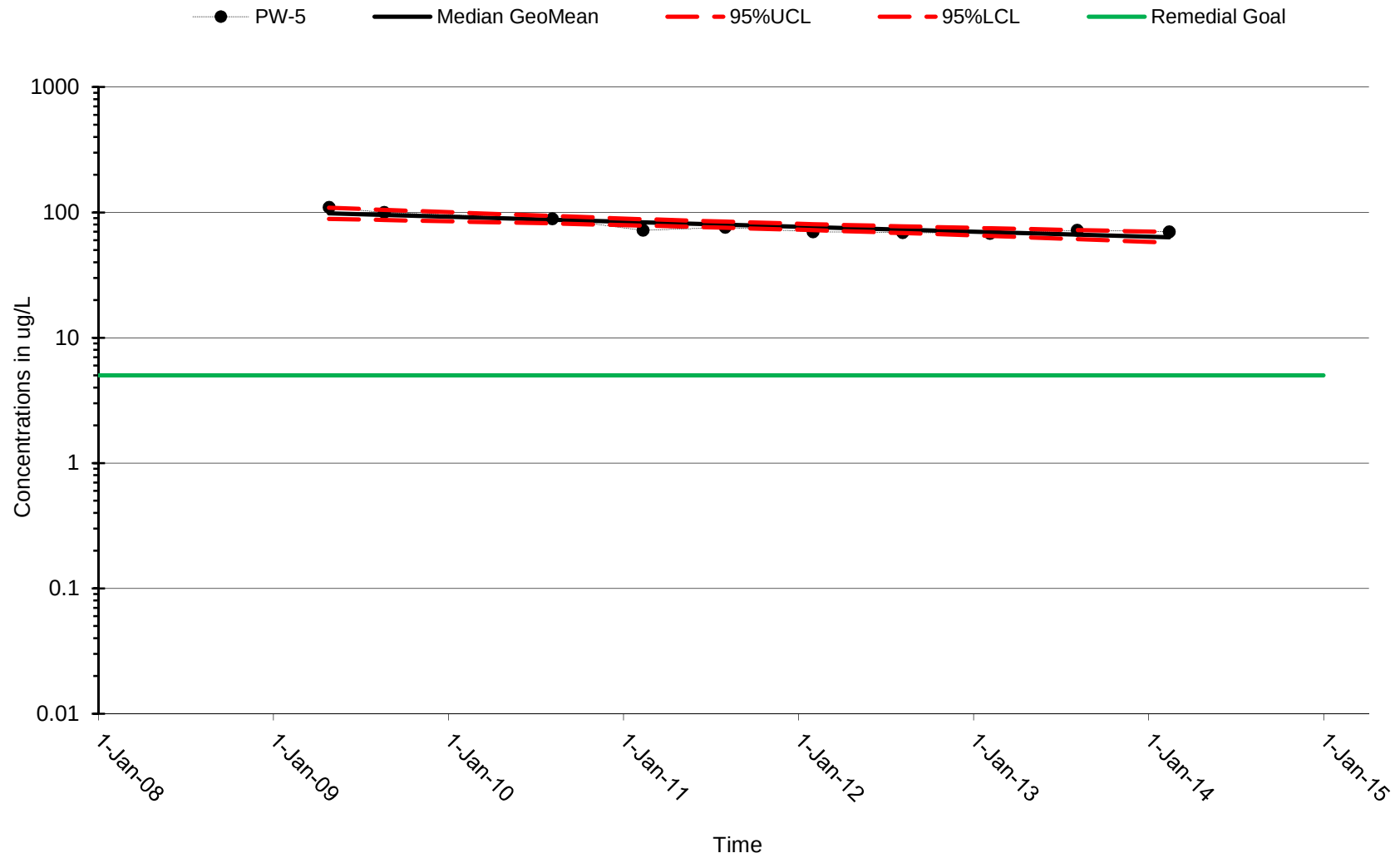


Figure A-22
1,1,1-TCA in Capture Zone Well 6-S-25

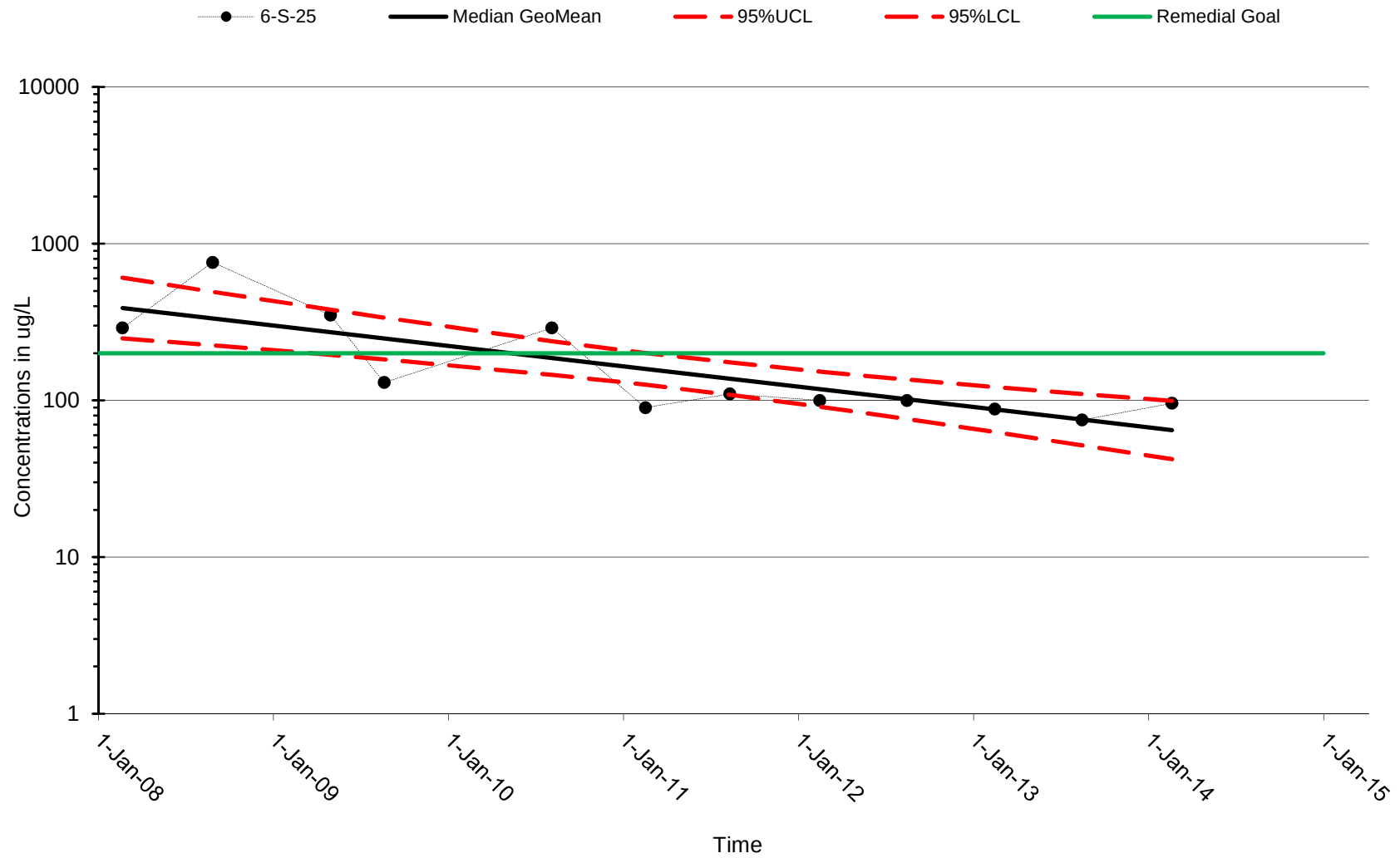


Figure A-23
1,1,1-TCA in Capture Zone Well MW-5

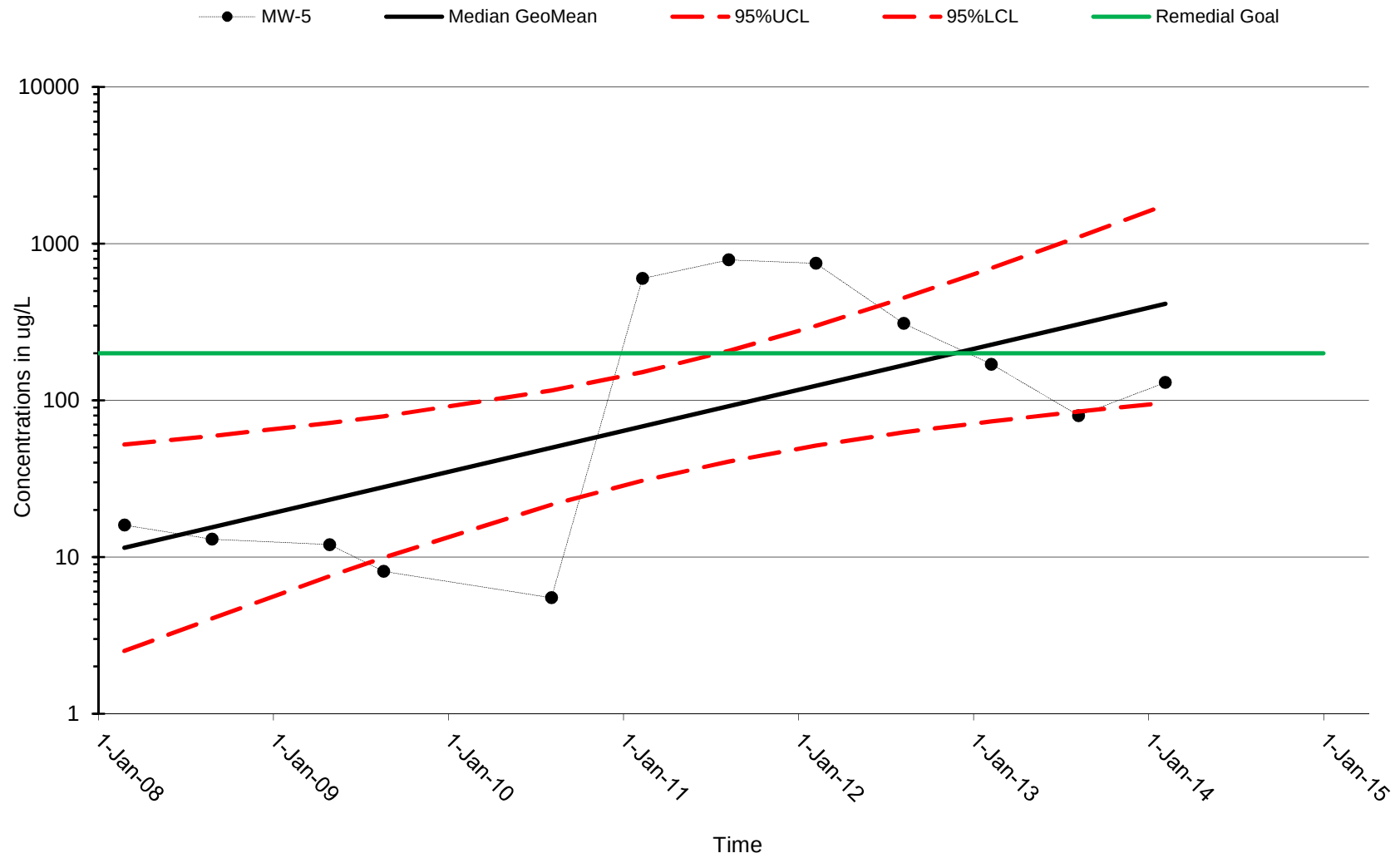


Figure A-24
1,1,1-TCA in Capture Zone Recovery Well PW-5

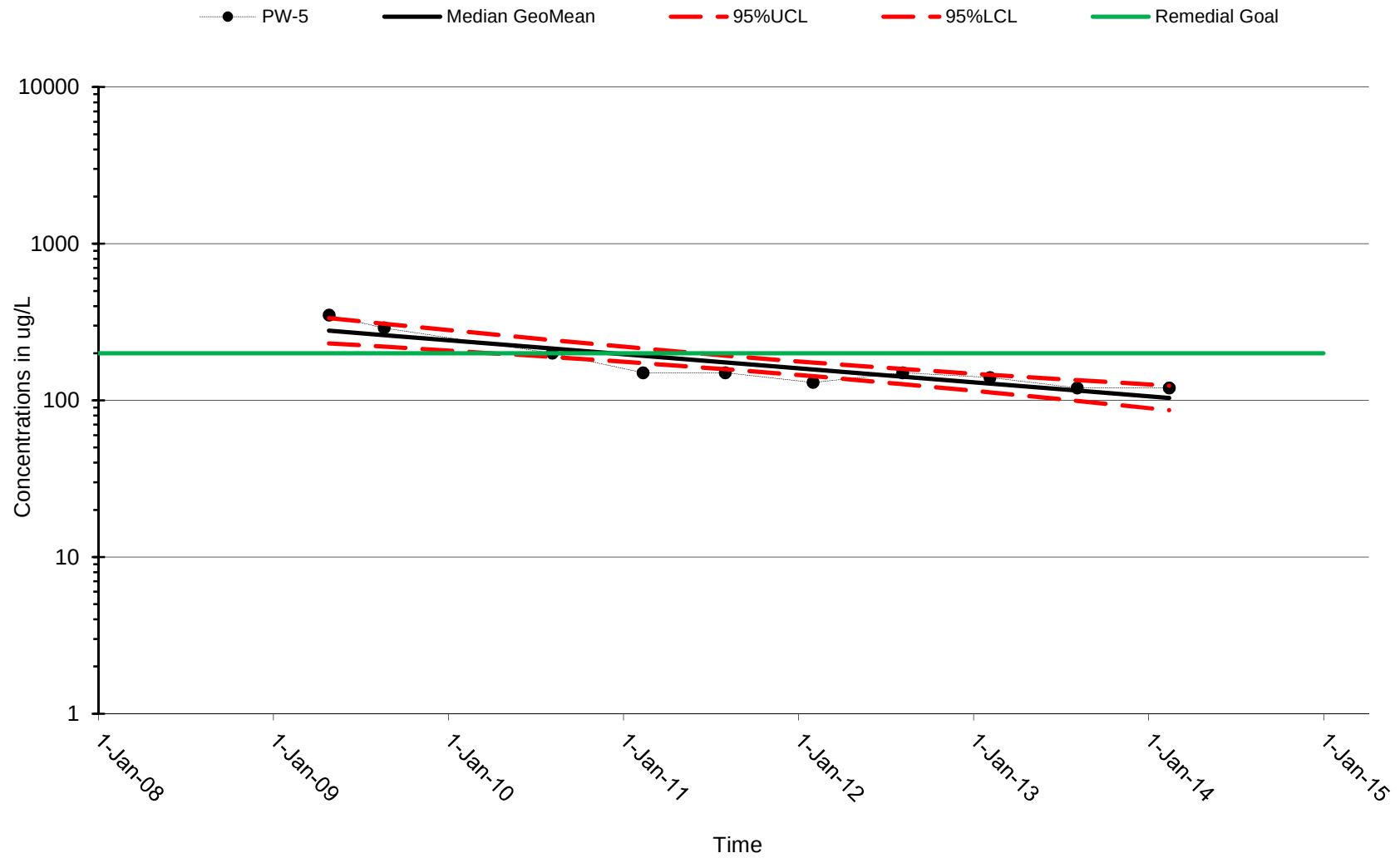


Figure A-25
1,4-Dioxane in Capture Zone Well MW-5

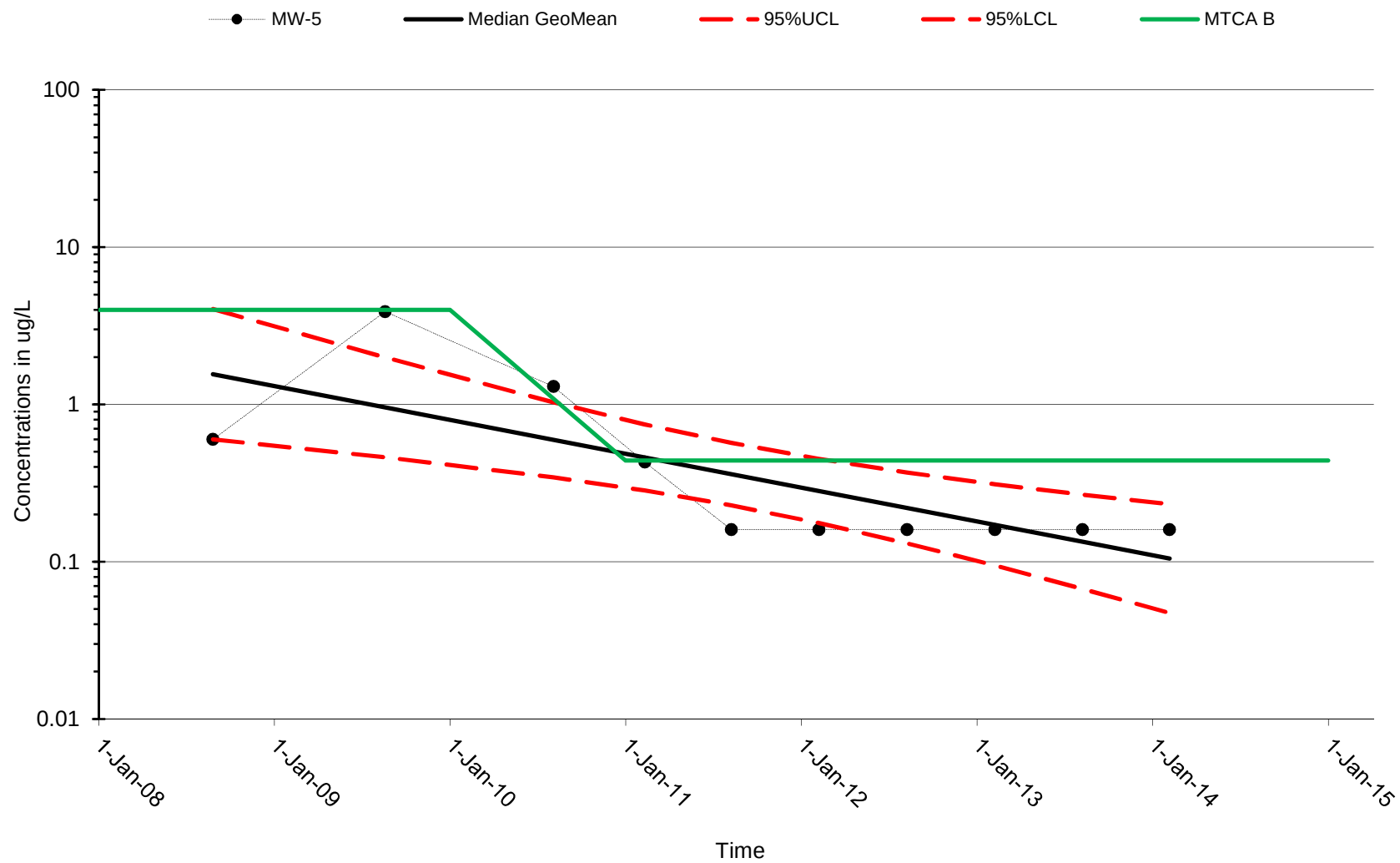


Figure A-26
1,4-Dioxane in Capture Zone Recovery Well PW-4

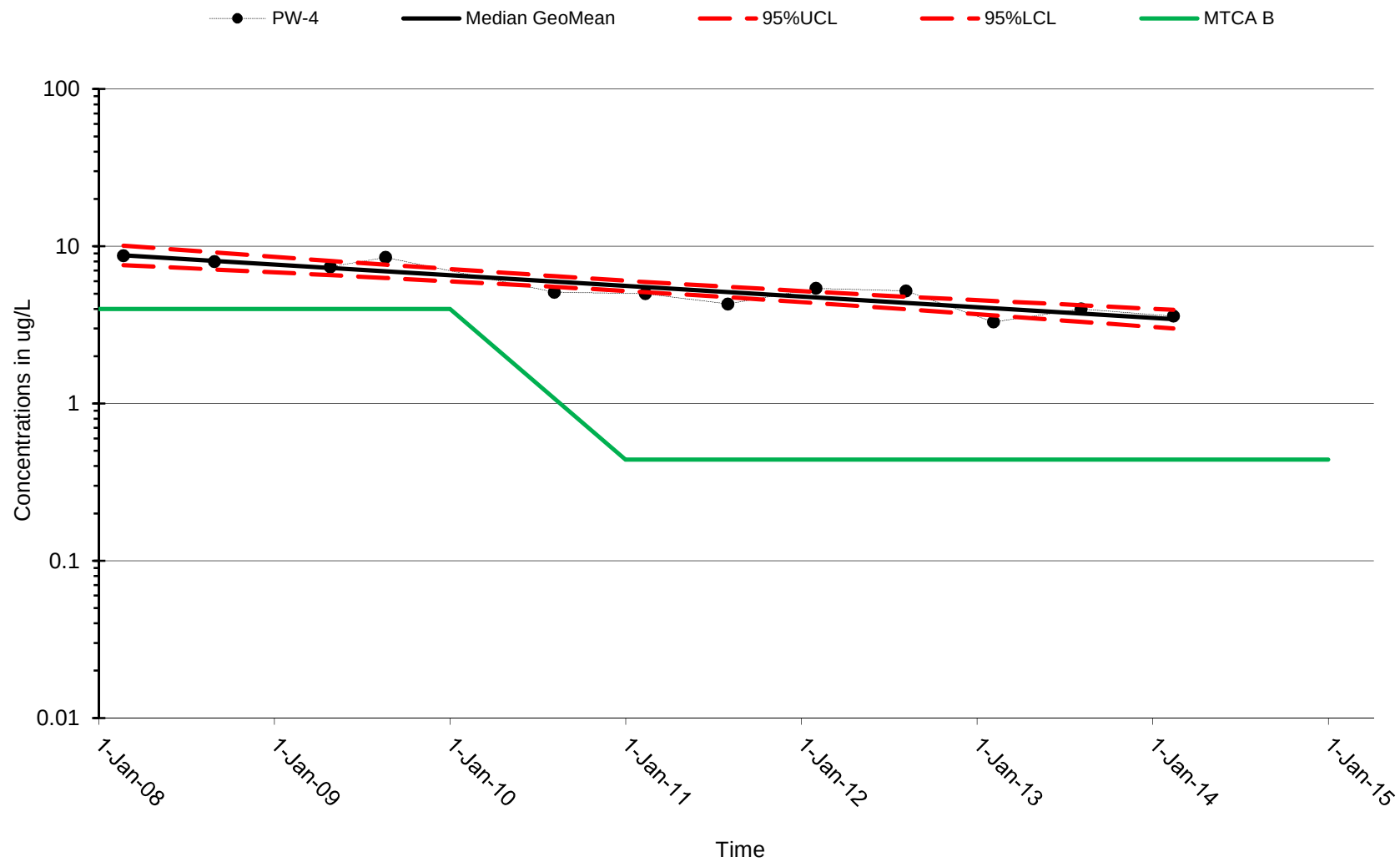


Figure A-27
1,4-Dioxane in Capture Zone Recovery Well PW-5

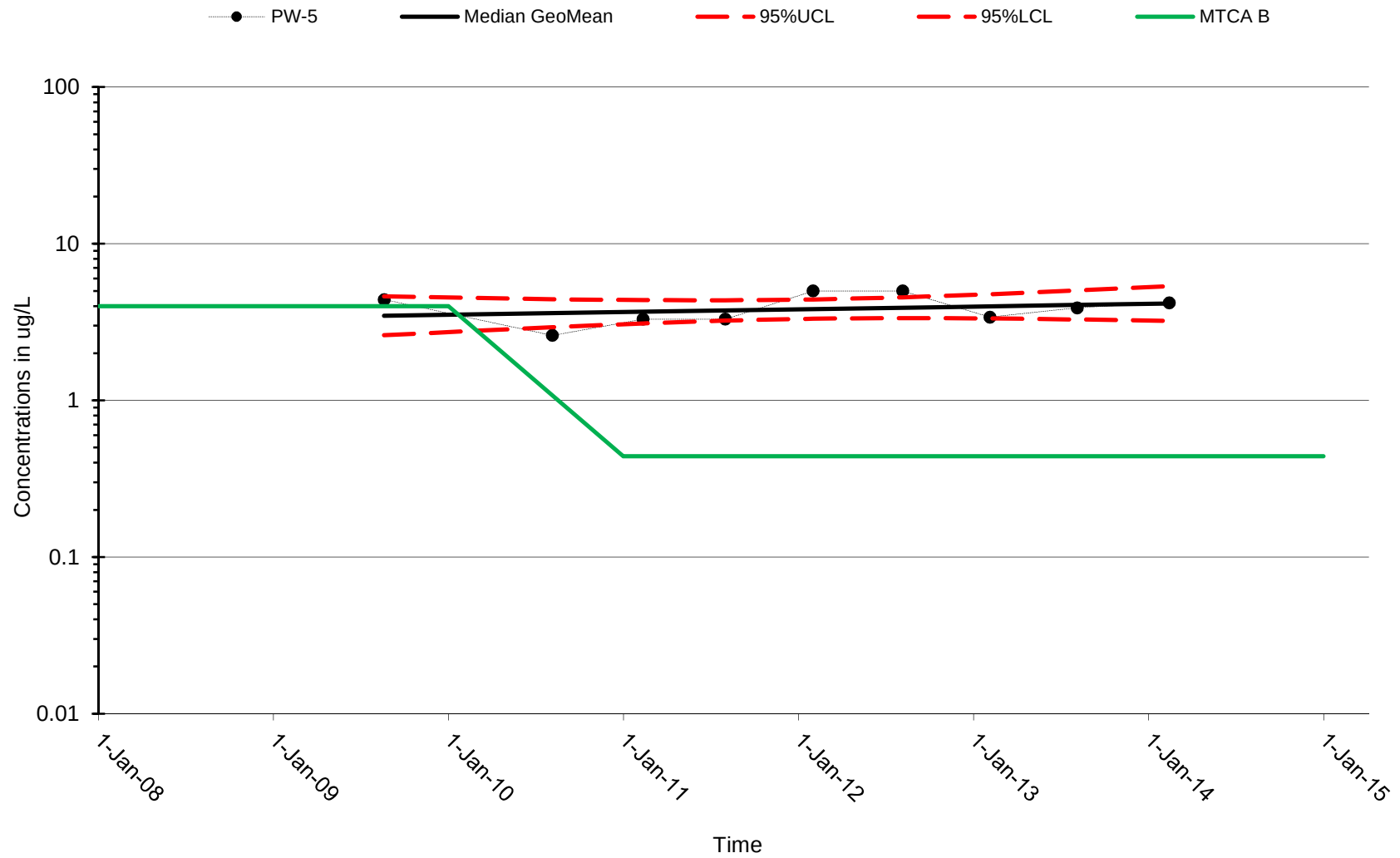


Figure A-28
1,4-Dioxane in Capture Zone Recovery Well PW-6

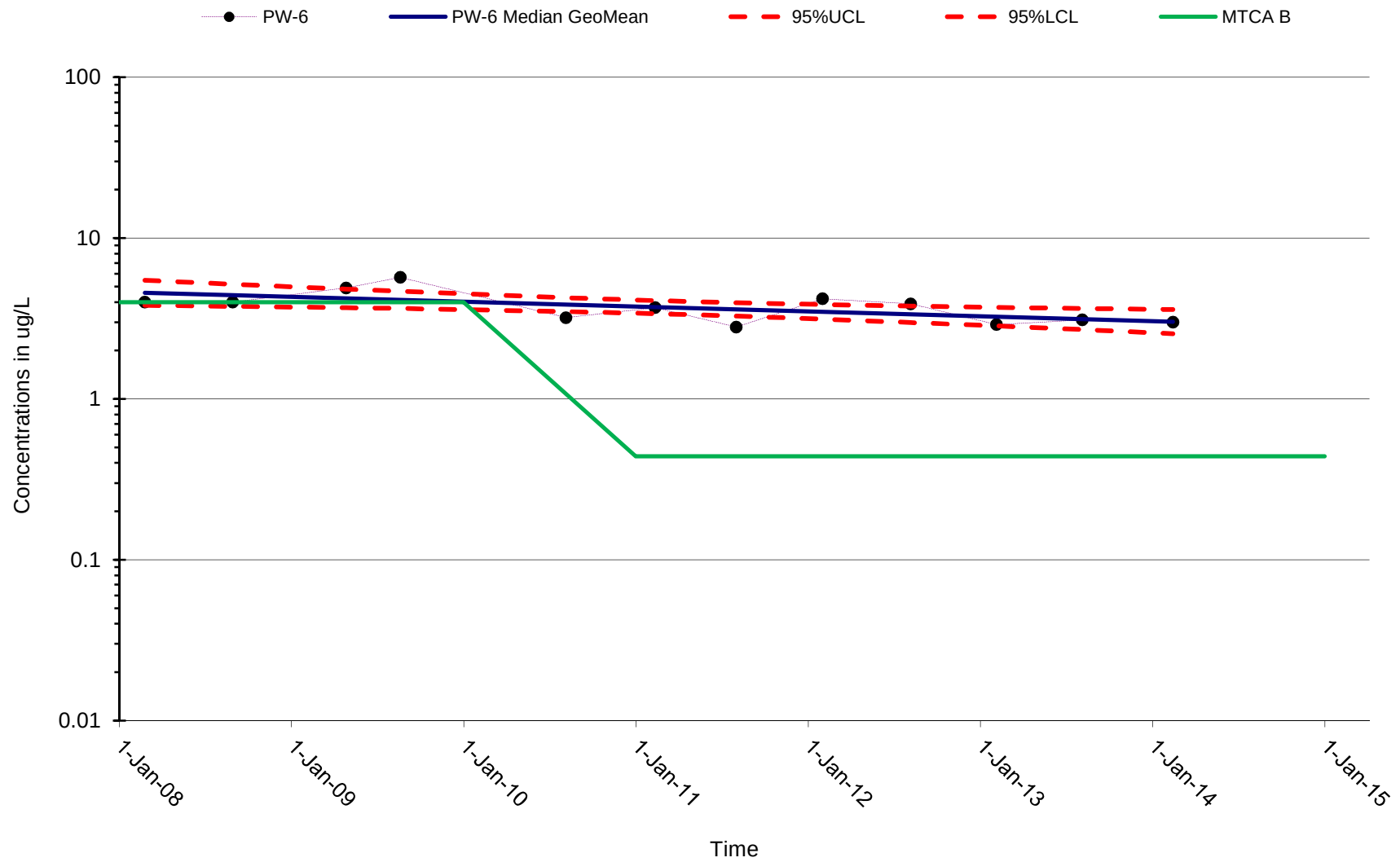


Figure A-29
1,4-Dioxane in Capture Zone Recovery Well PW-7

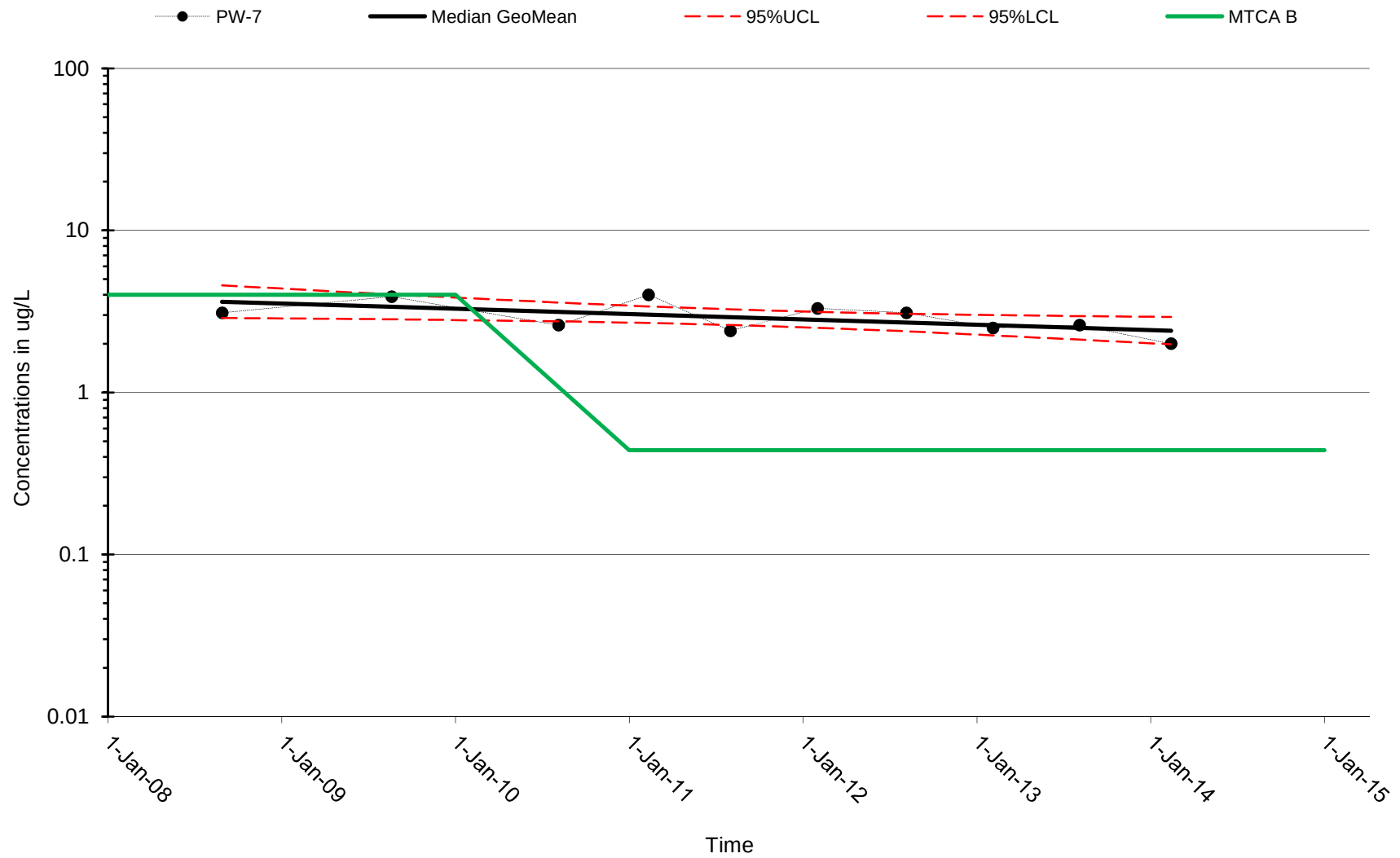


Figure A-30
1,4-Dioxane in Capture Zone Recovery Well PW-8

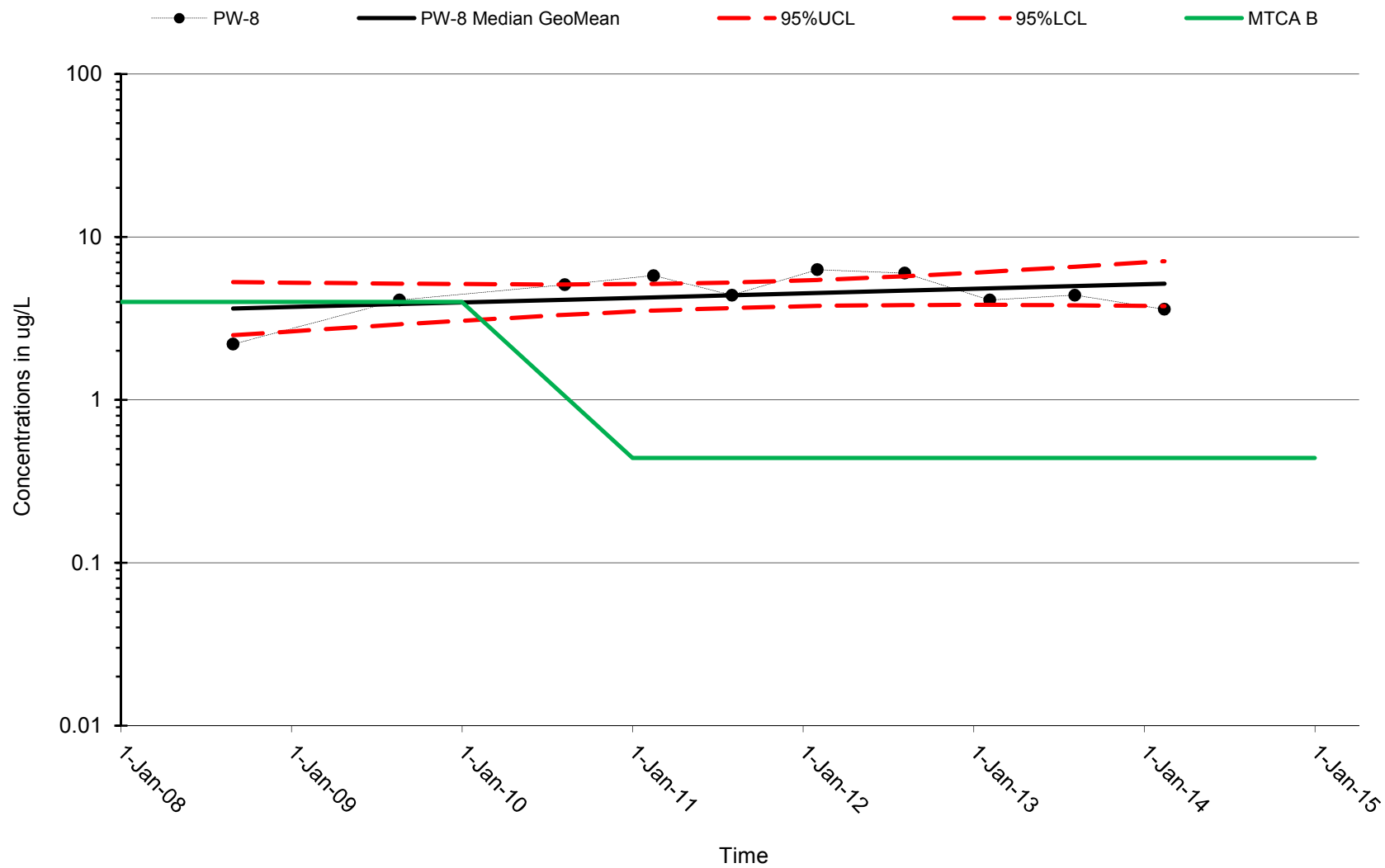


Figure A-31
1,4-Dioxane in Capture Zone Recovery Well PW-9

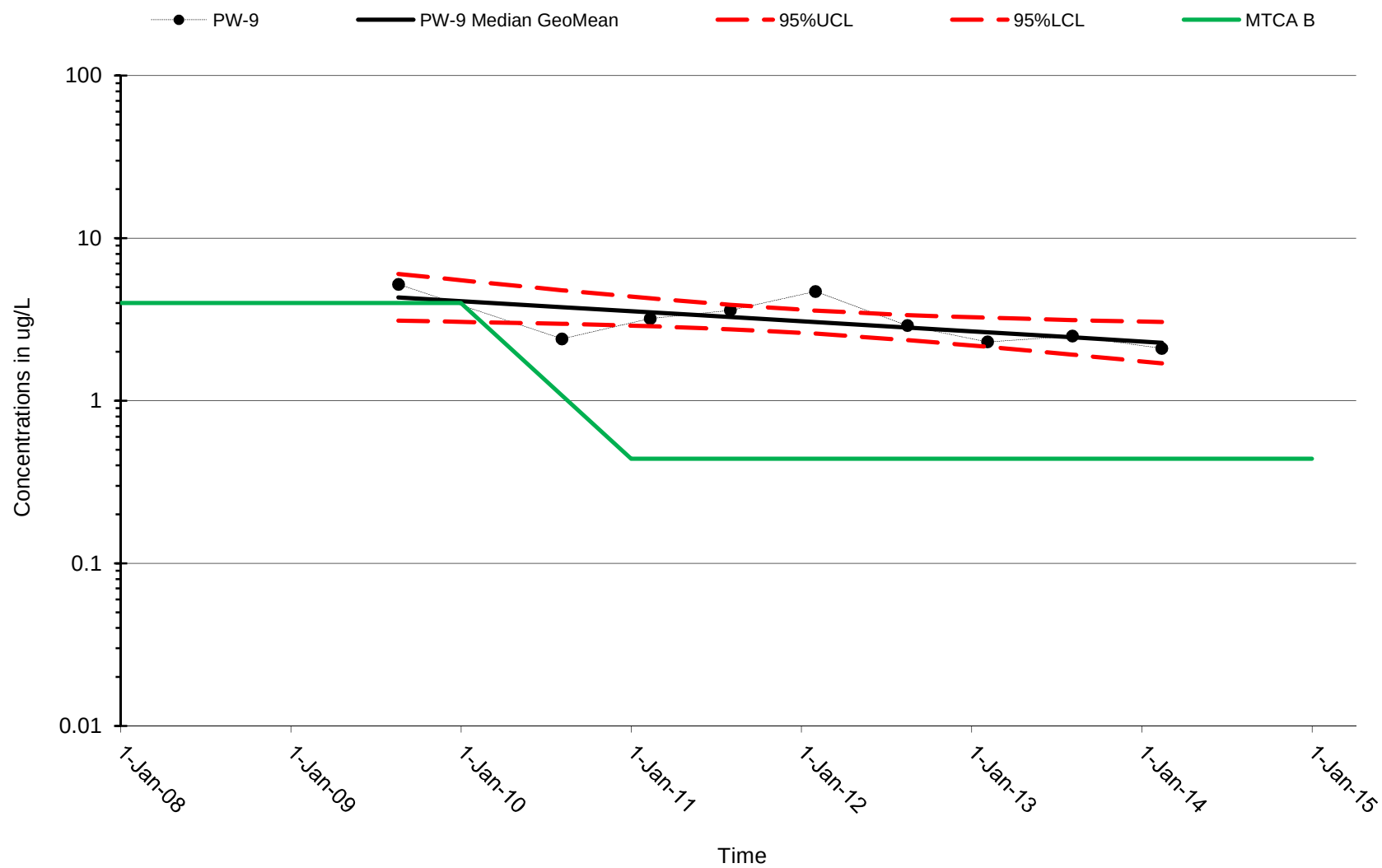


Figure A-32
Vinyl Chloride in Production Well PW-4

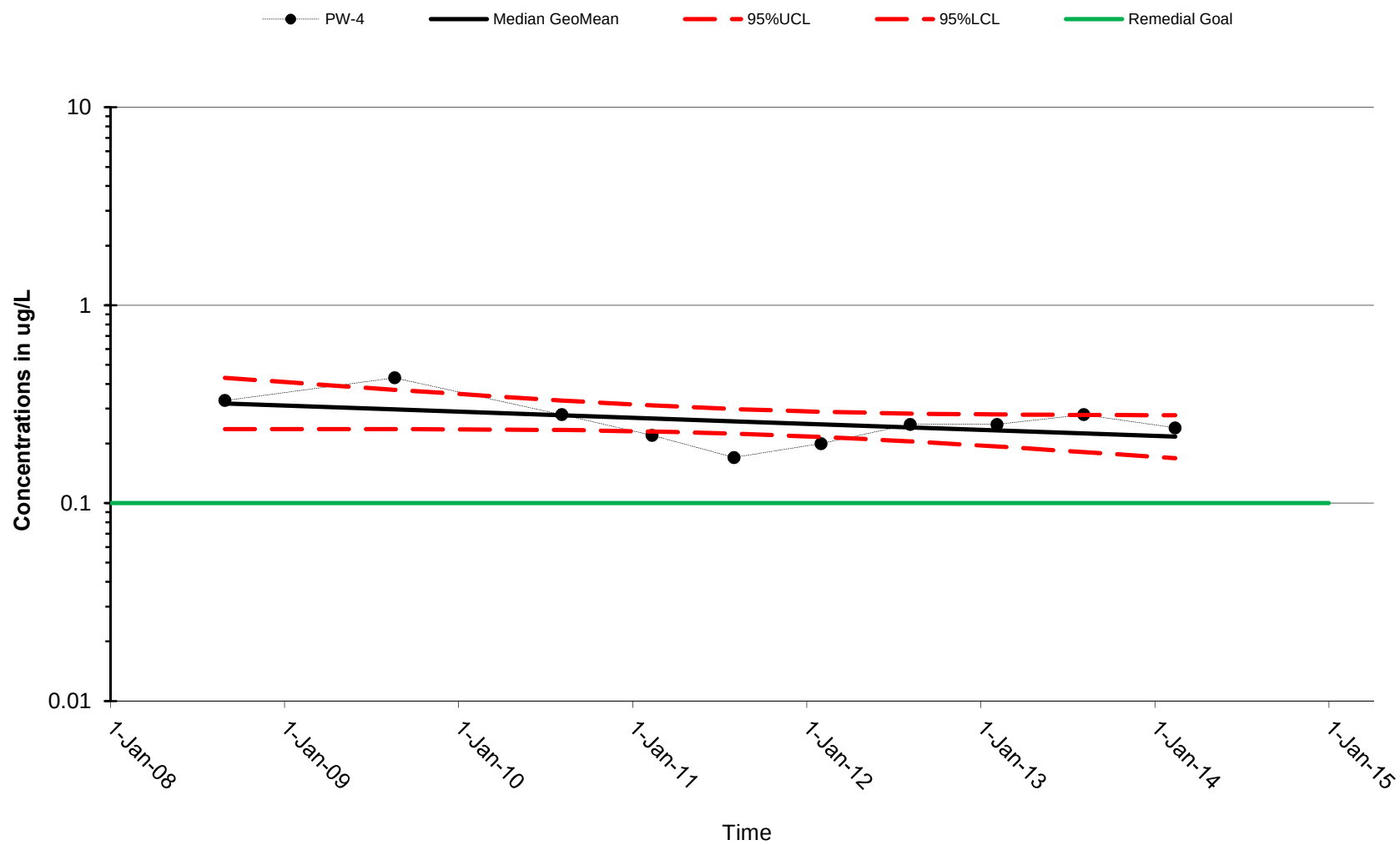


Figure A-33
Vinyl Chloride in Production Well PW-5

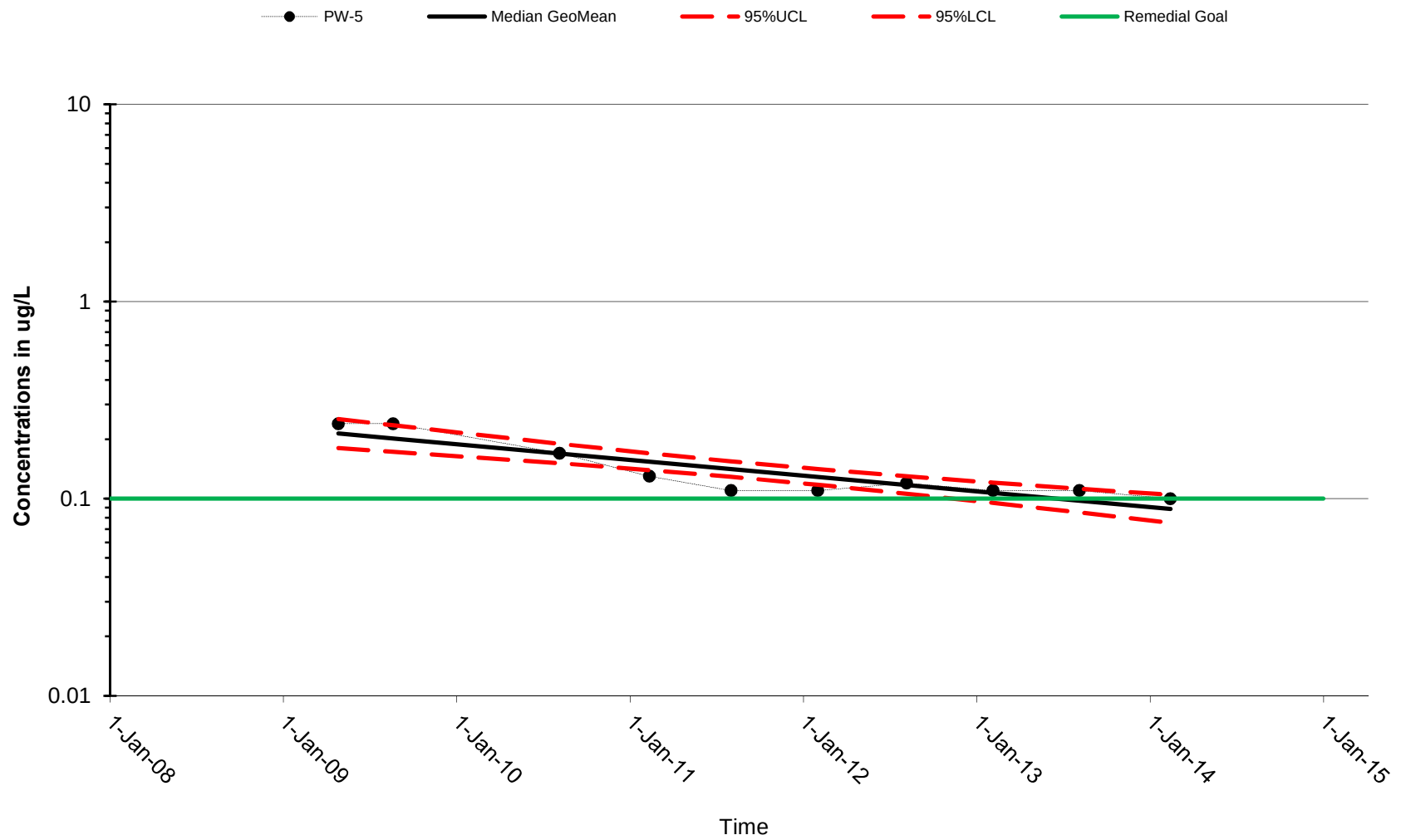


Figure A-34
Vinyl Chloride in Production Well PW-6

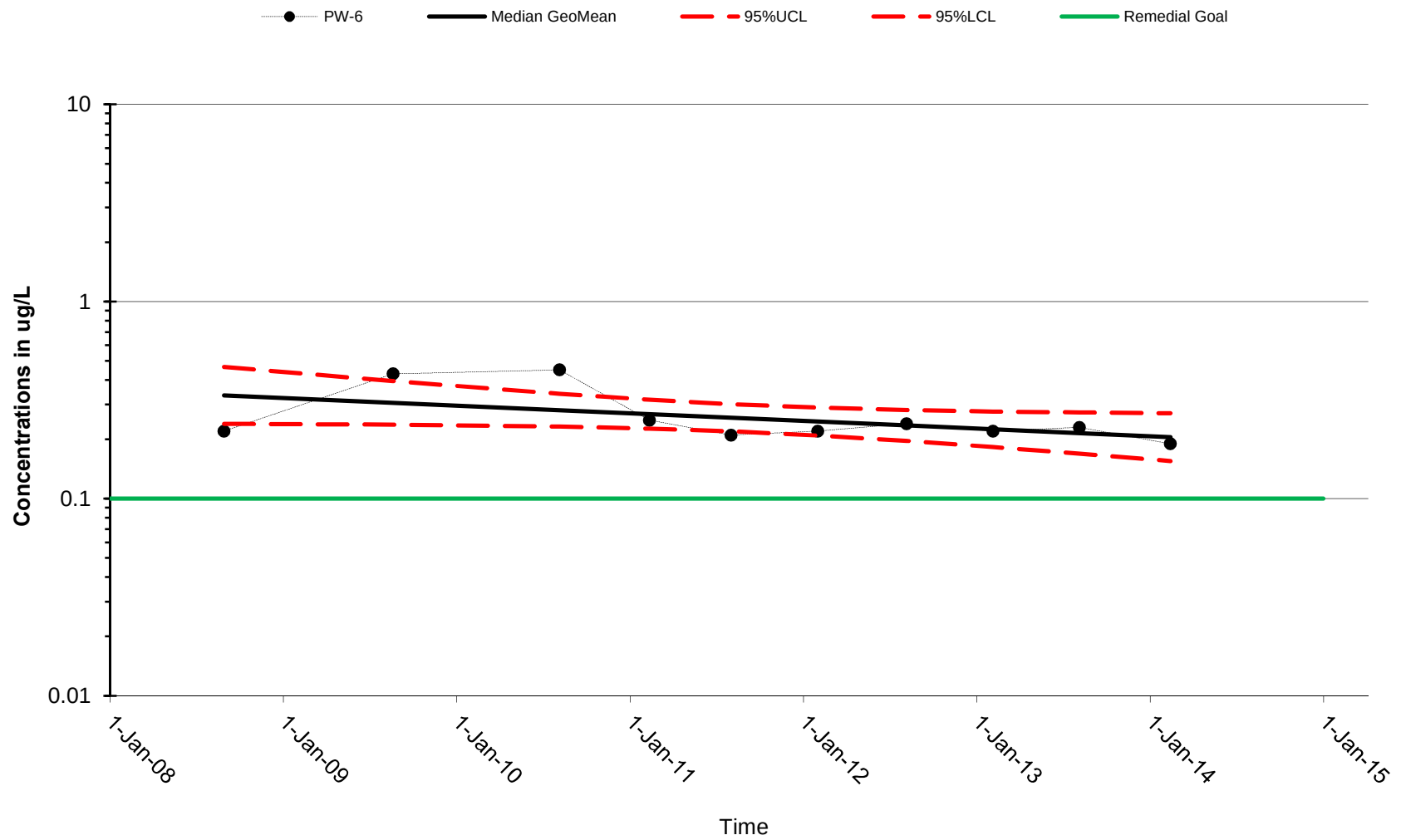


Figure A-35
Vinyl Chloride in Production Well PW-7

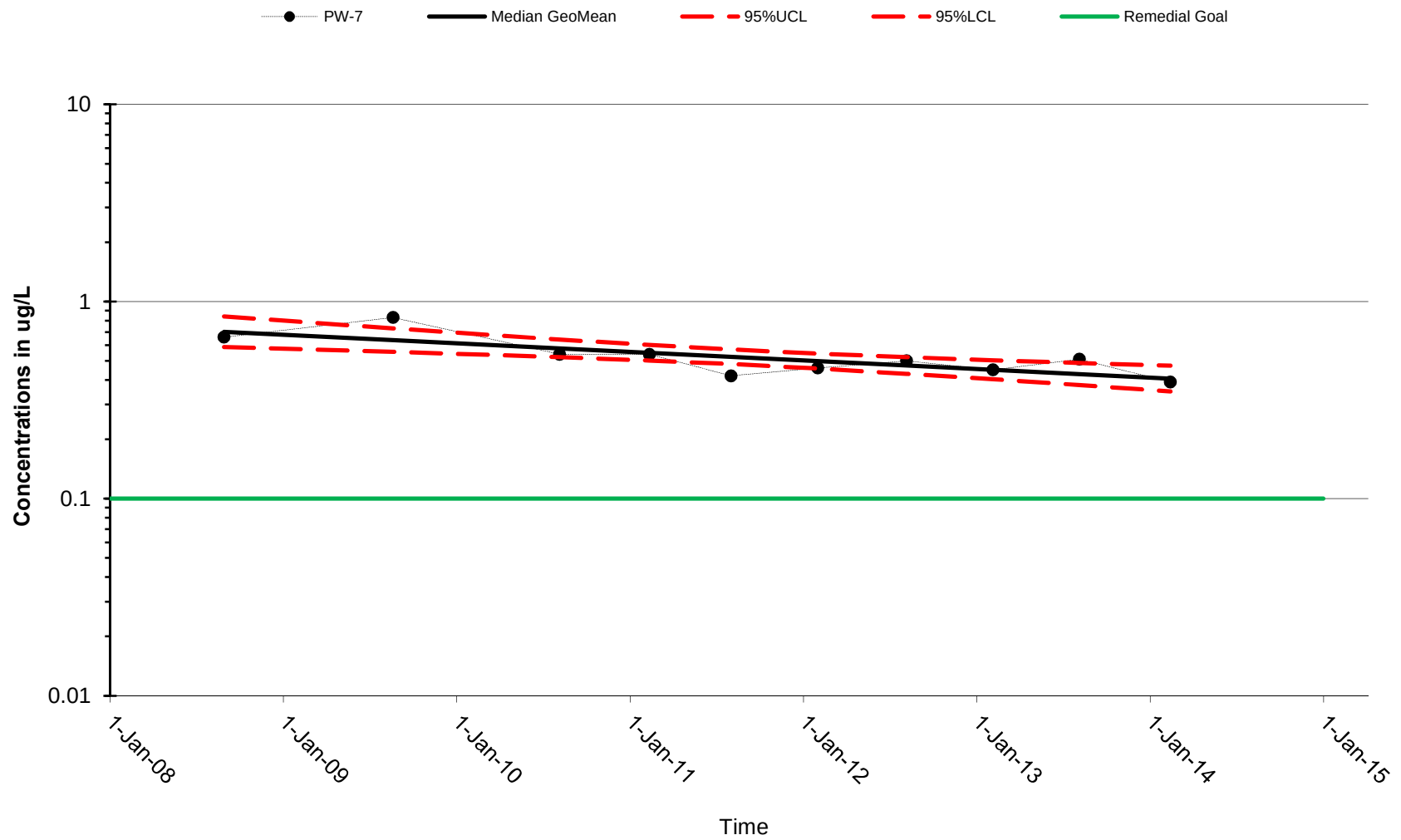


Figure A-36
Vinyl Chloride in Production Well PW-8

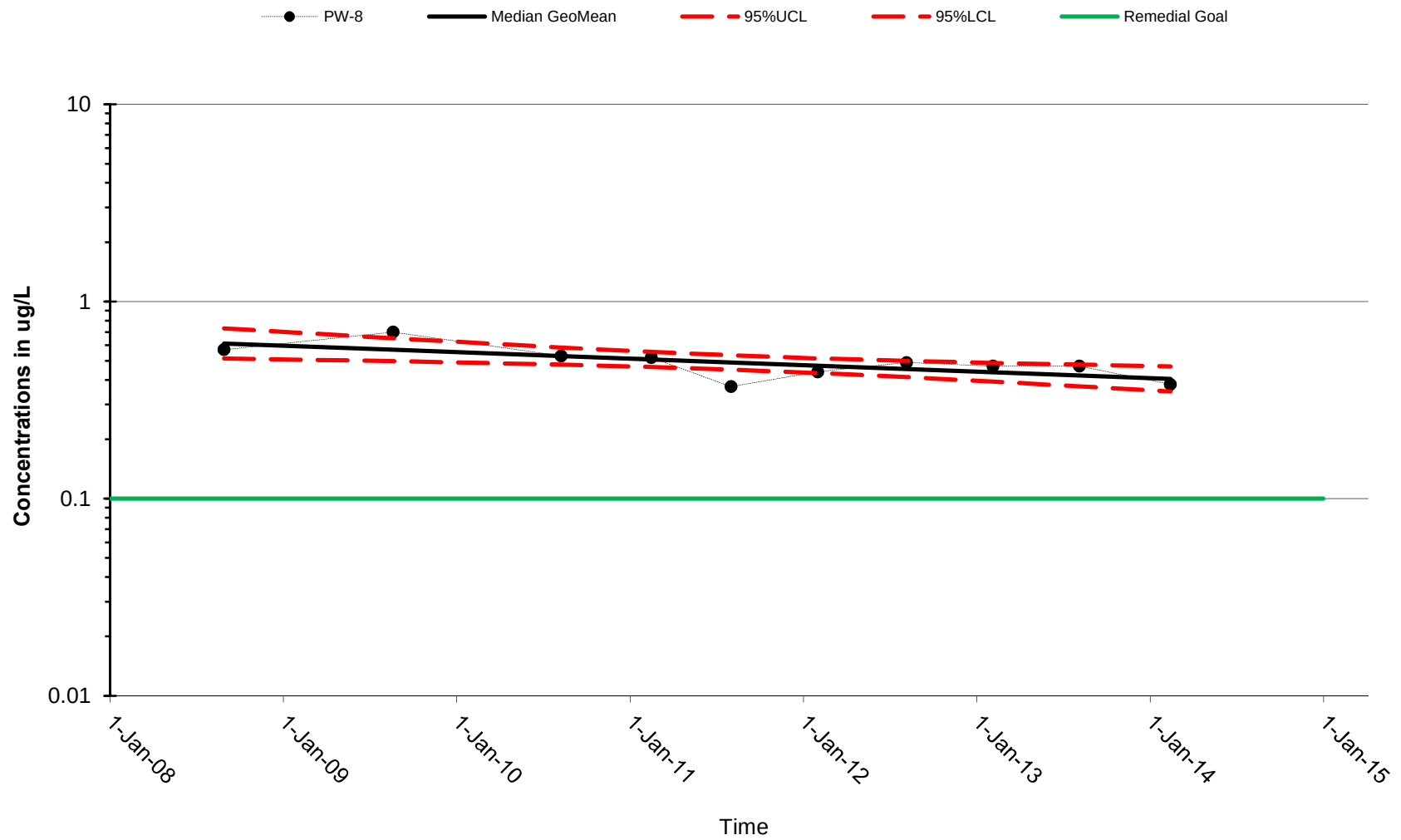


Figure A-37
Vinyl Chloride in Production Well PW-9

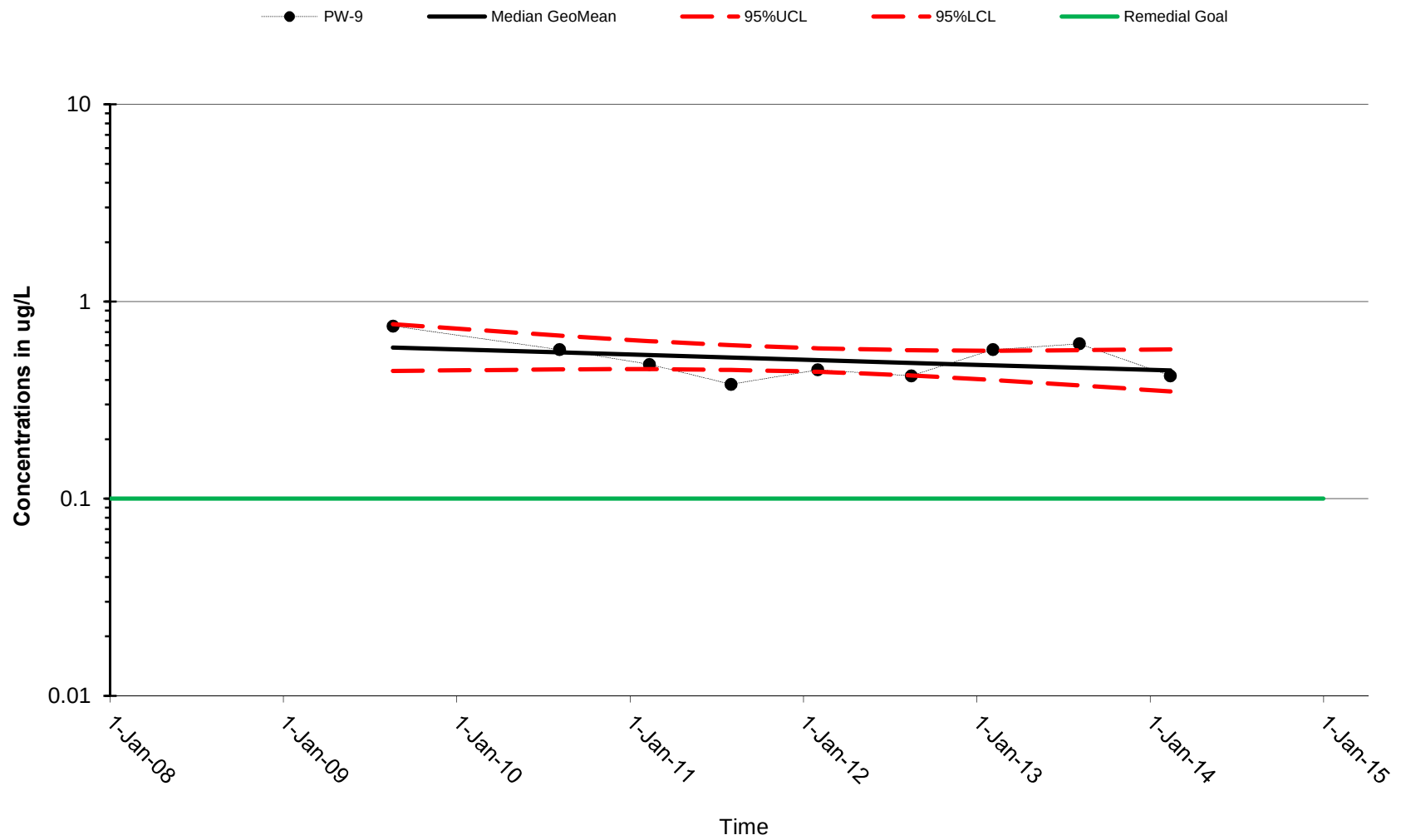


Figure A-38
1,4-Dioxane in Downgradient Well 6-S-03

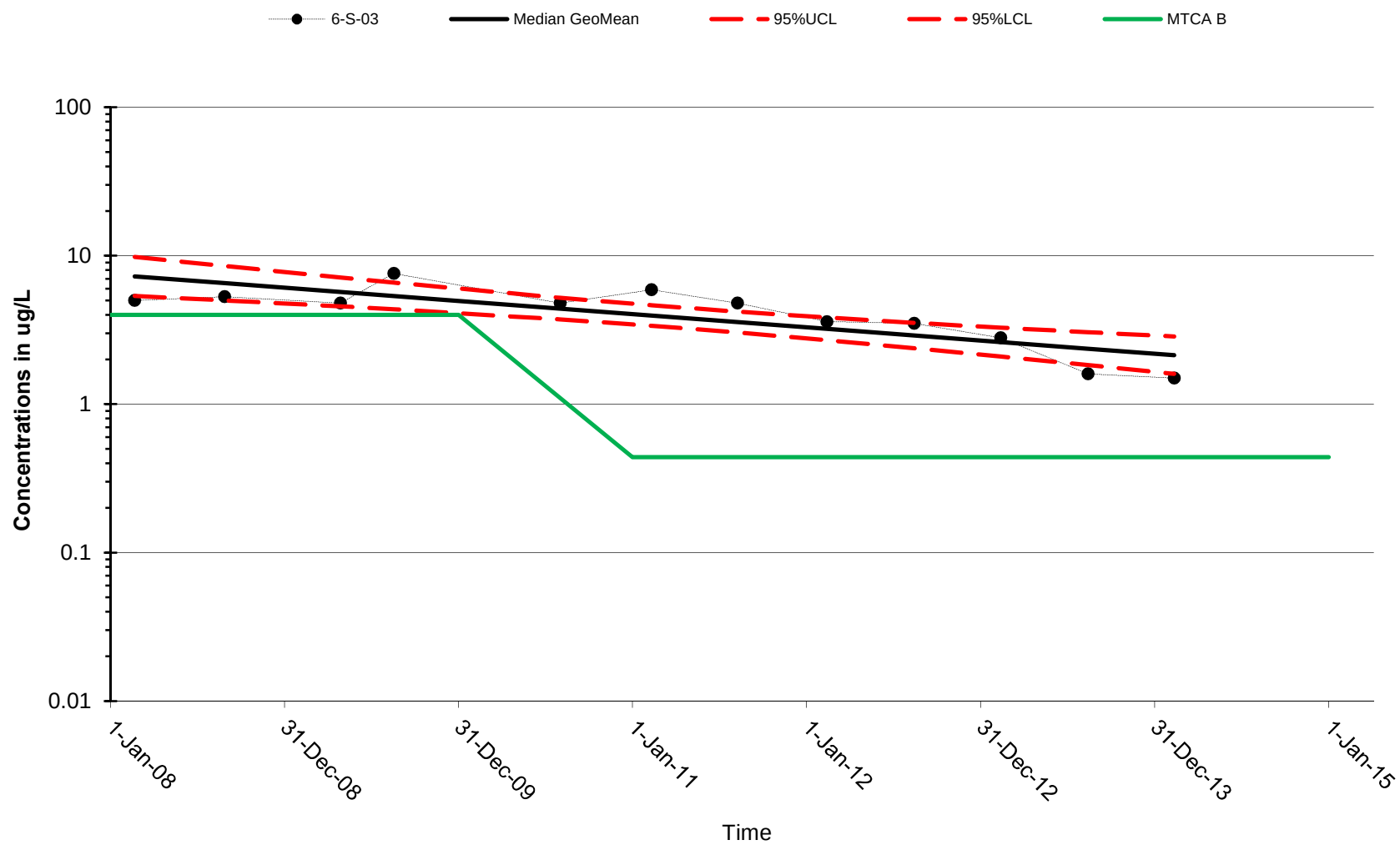


Figure A-39
1,4-Dioxane in Downgradient Well 6-S-19

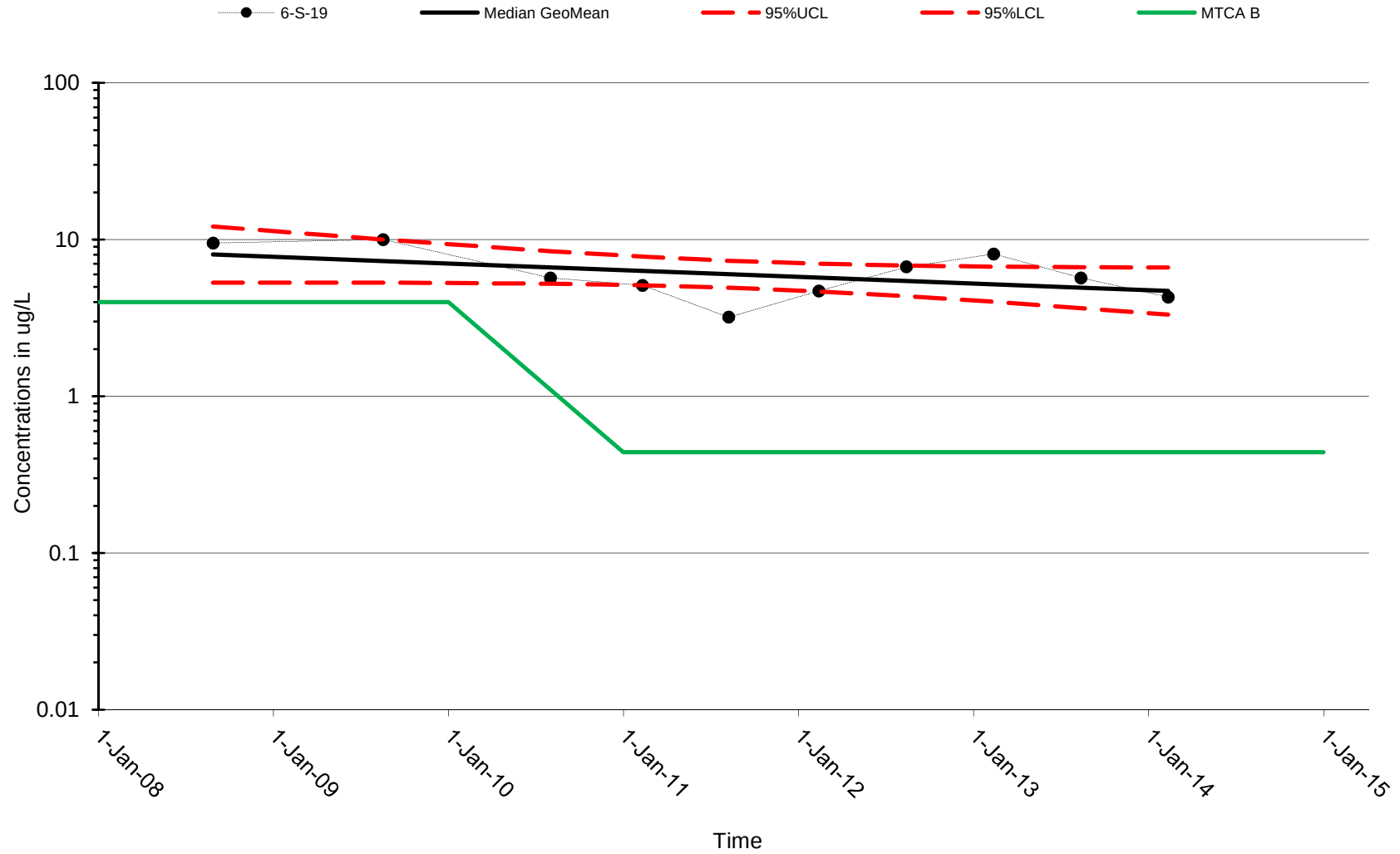


Figure A-40
1,4-Dioxane in Downgradient Well 6-S-29

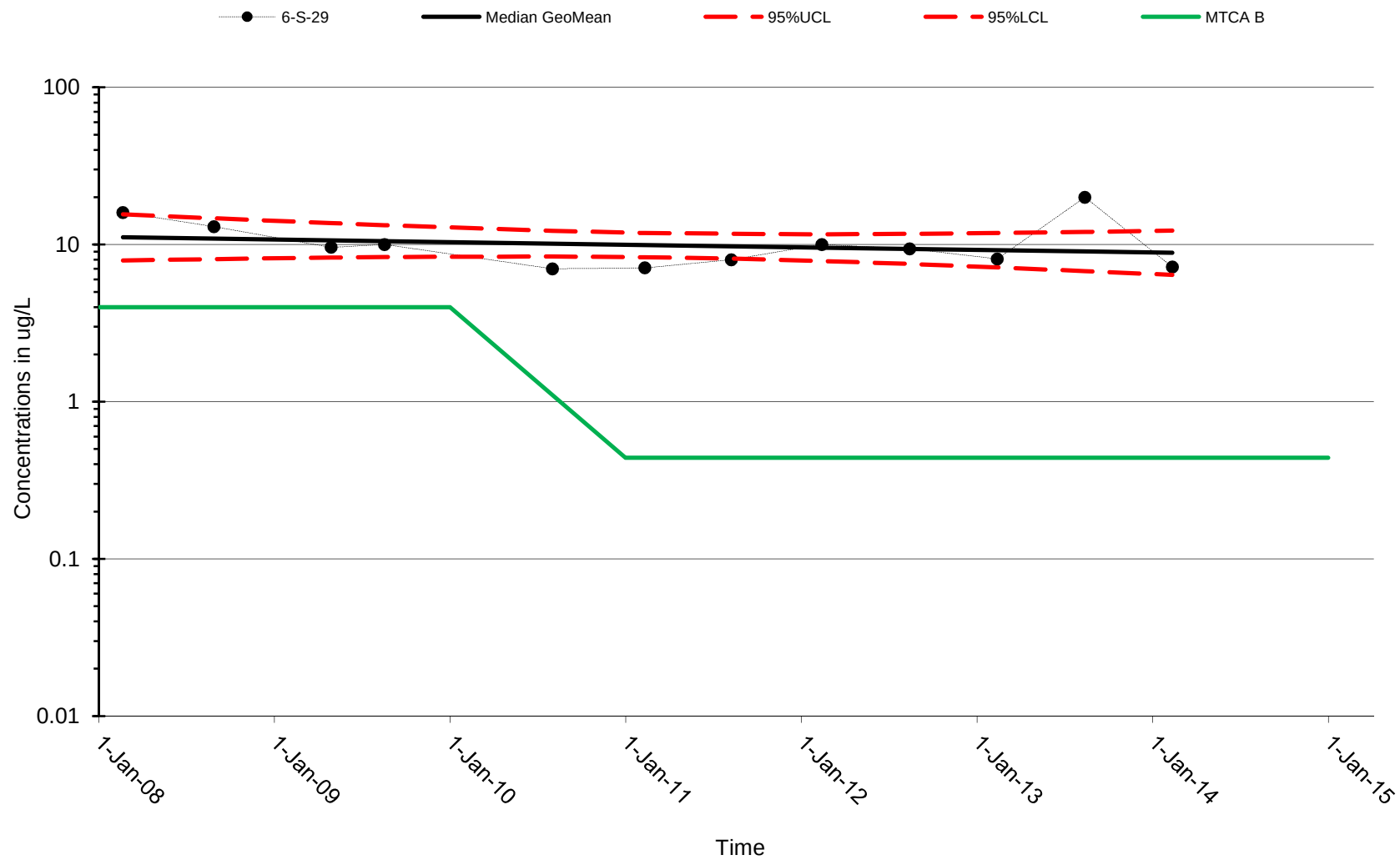


Figure A-41
1,4-Dioxane in Downgradient Well 6-S-41

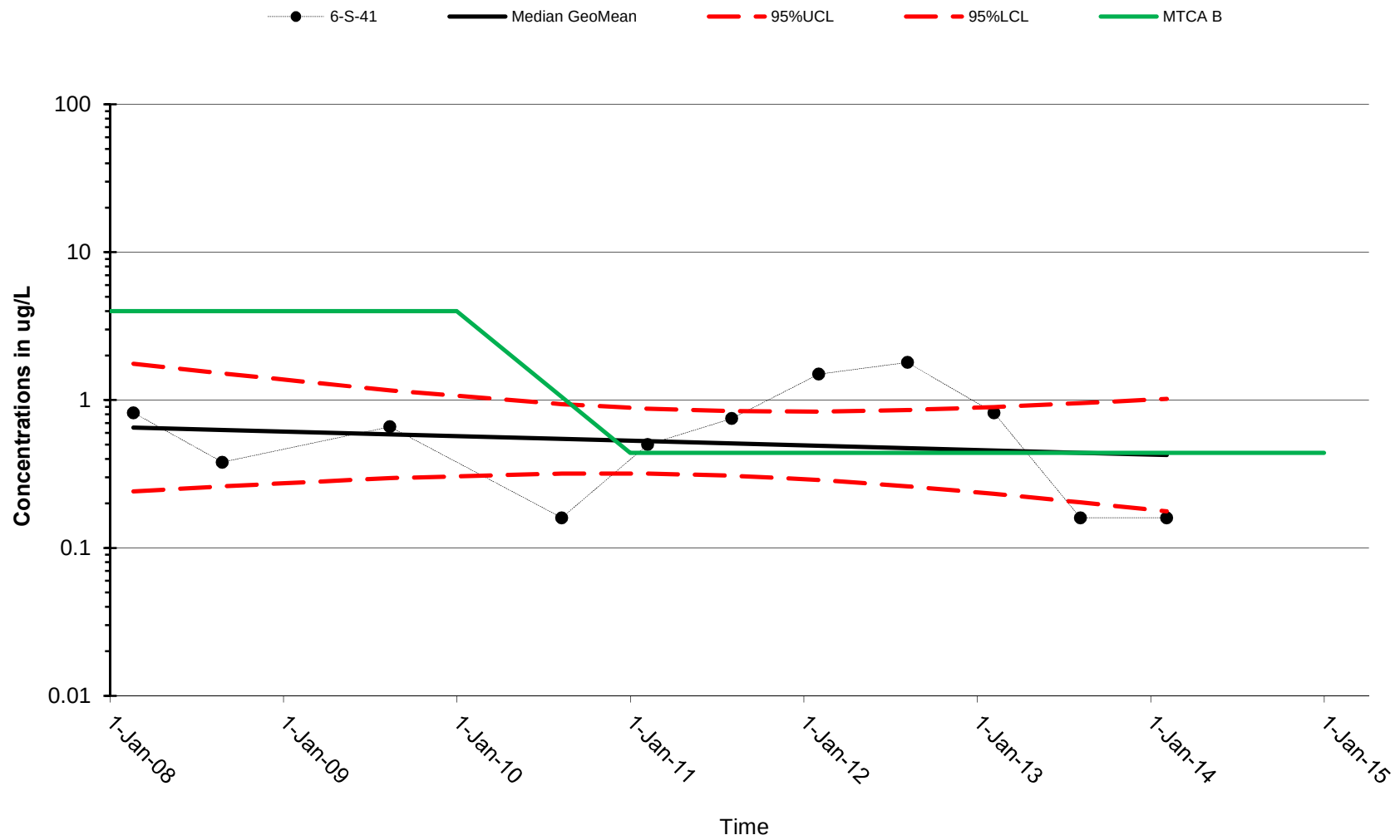


Figure A-42
1,4-Dioxane in Downgradient Well 6-S-42

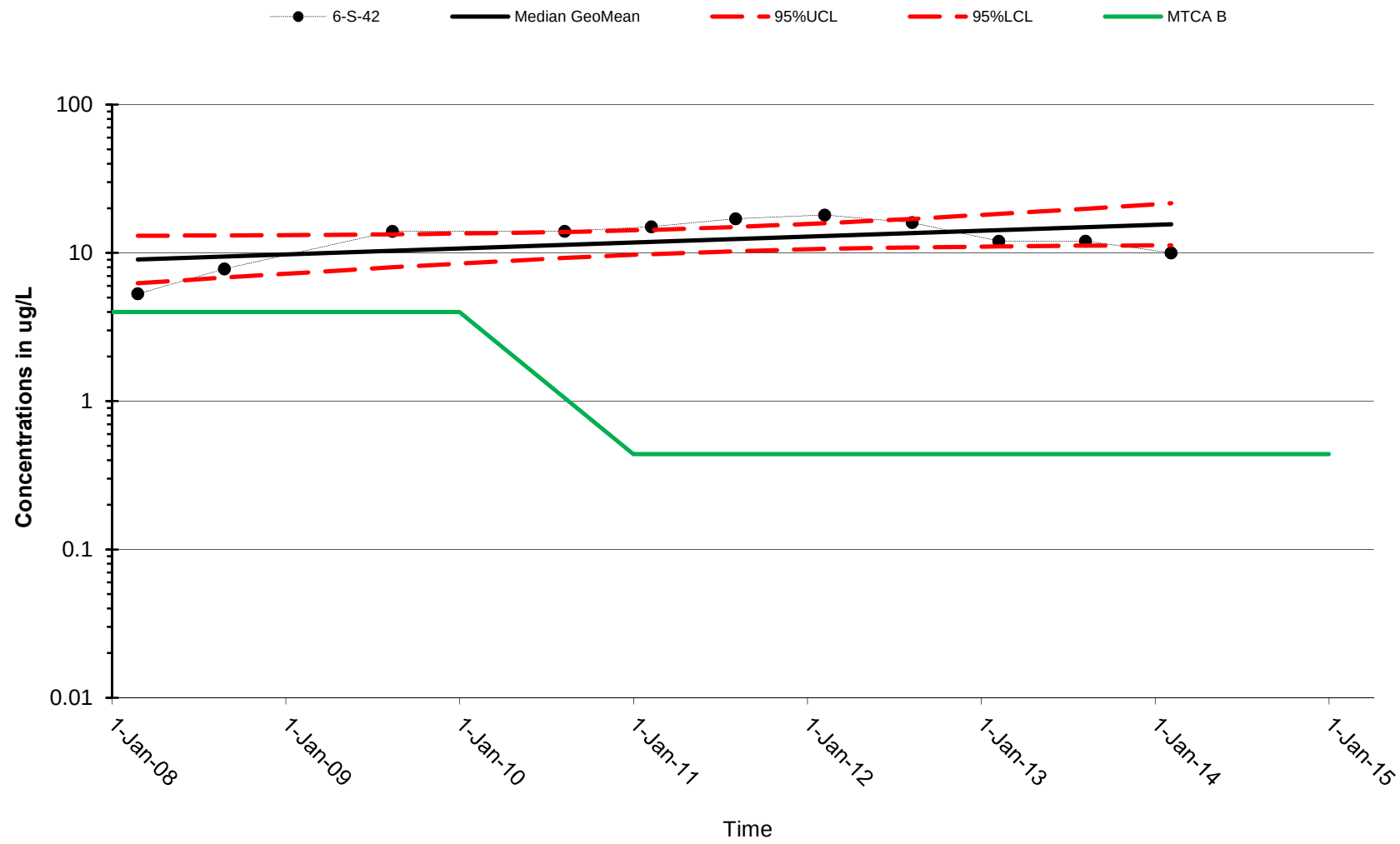


Figure A-43
1,4-Dioxane in Downgradient Well 6-S-43

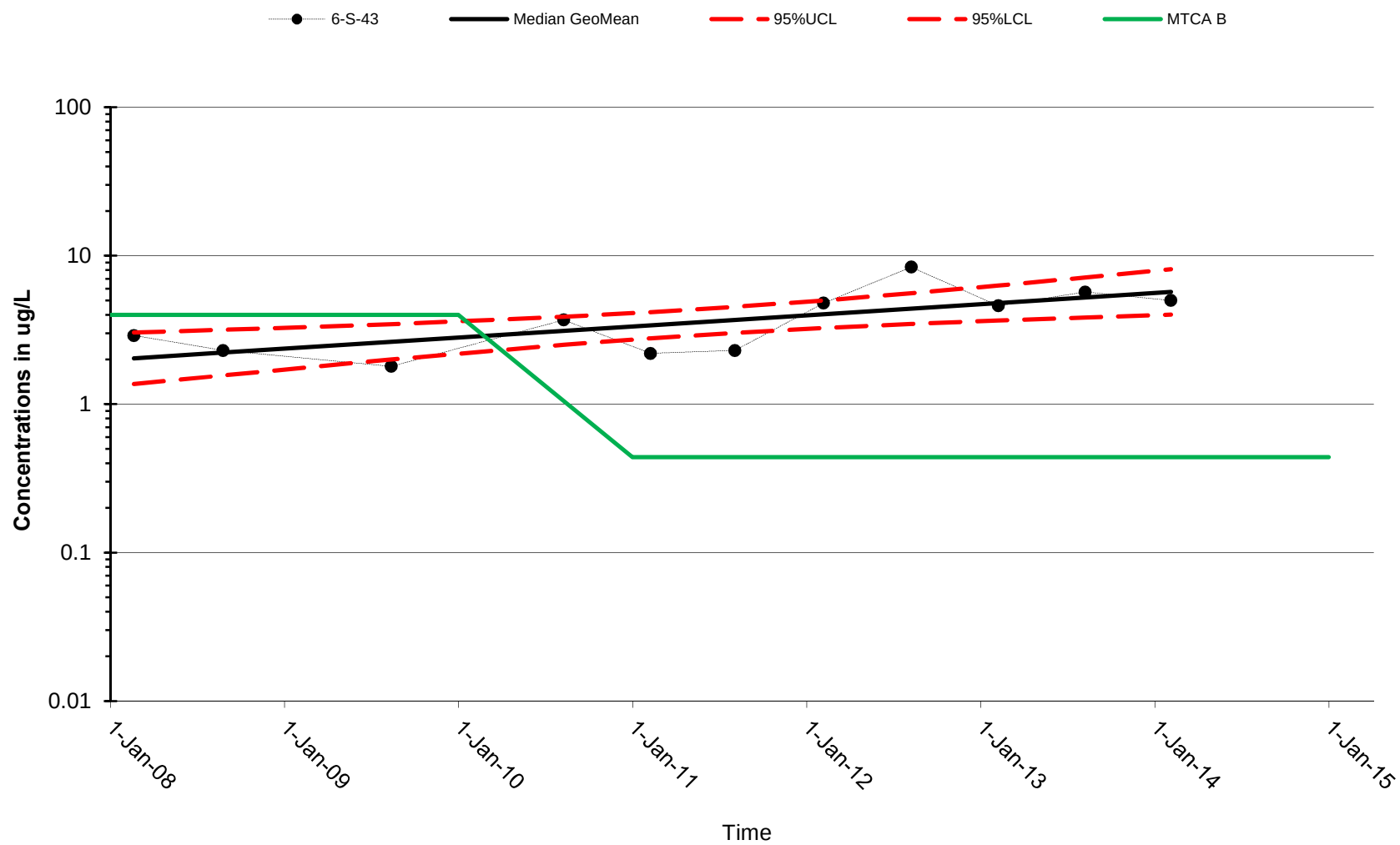


Figure A-44
1,4-Dioxane in Domestic Well 6-DW-38

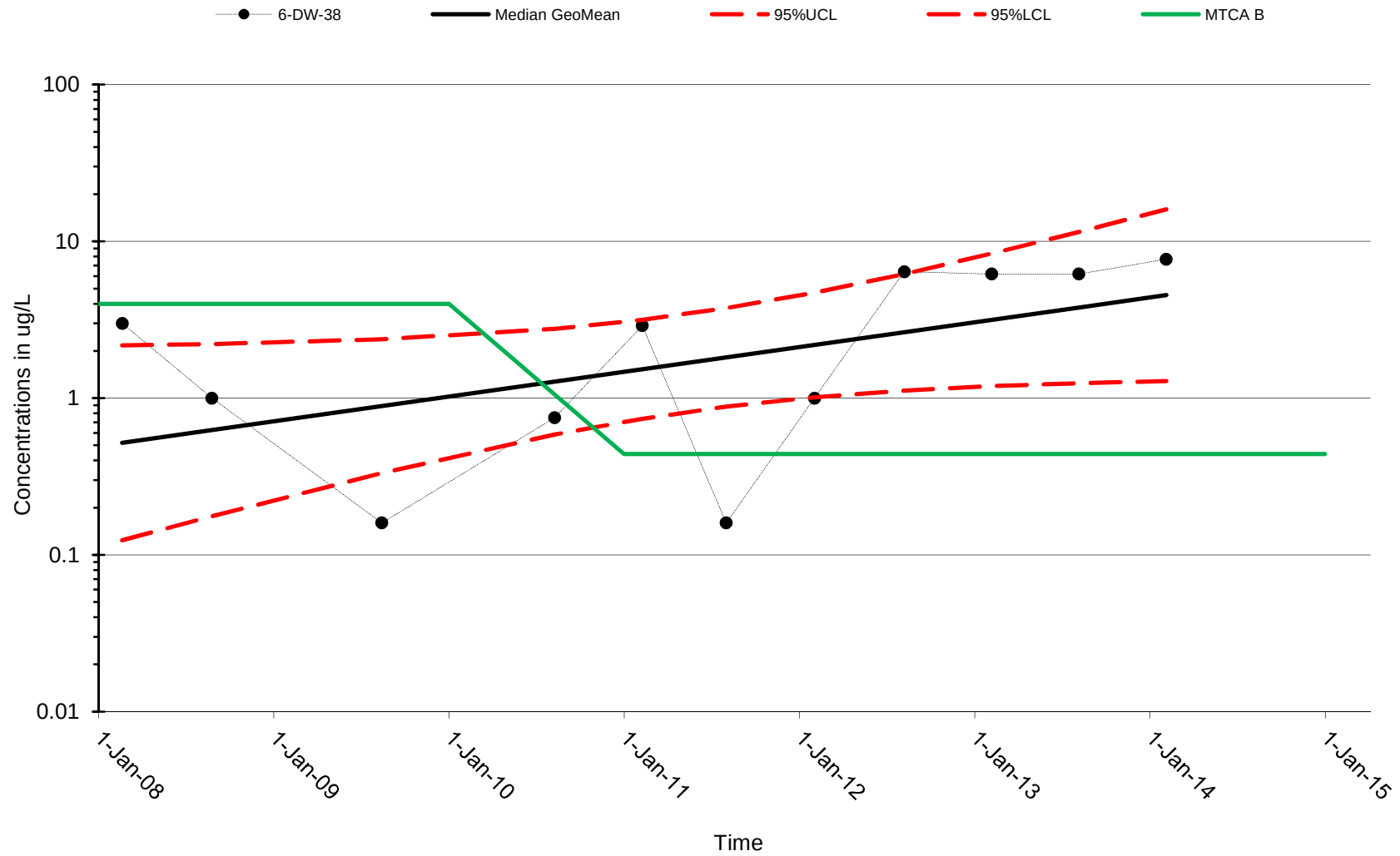


Figure A-45
1,4-Dioxane in Downgradient Well MW-9

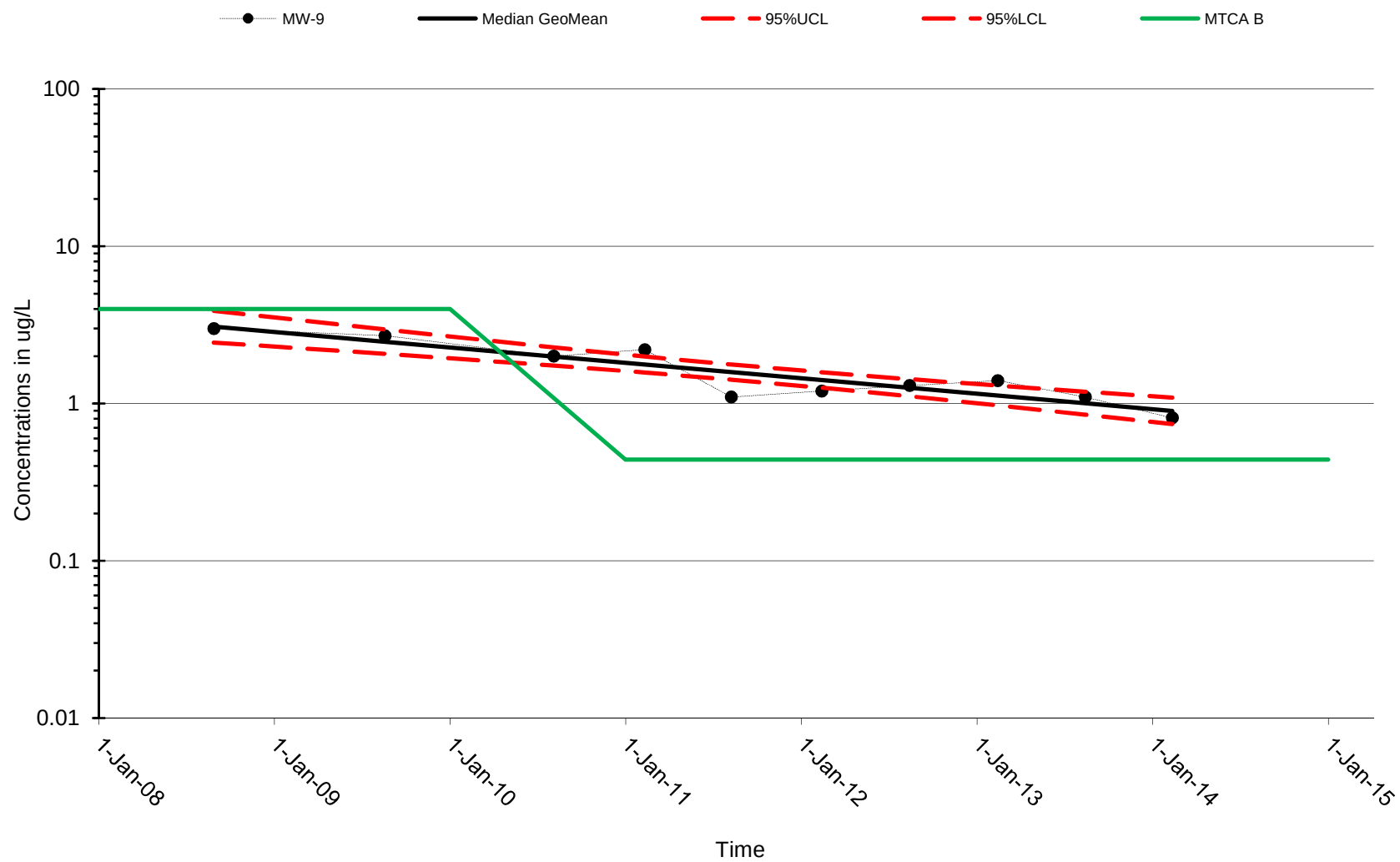


Figure A-46
Vinyl Chloride in Downgradient Well 6-S-03

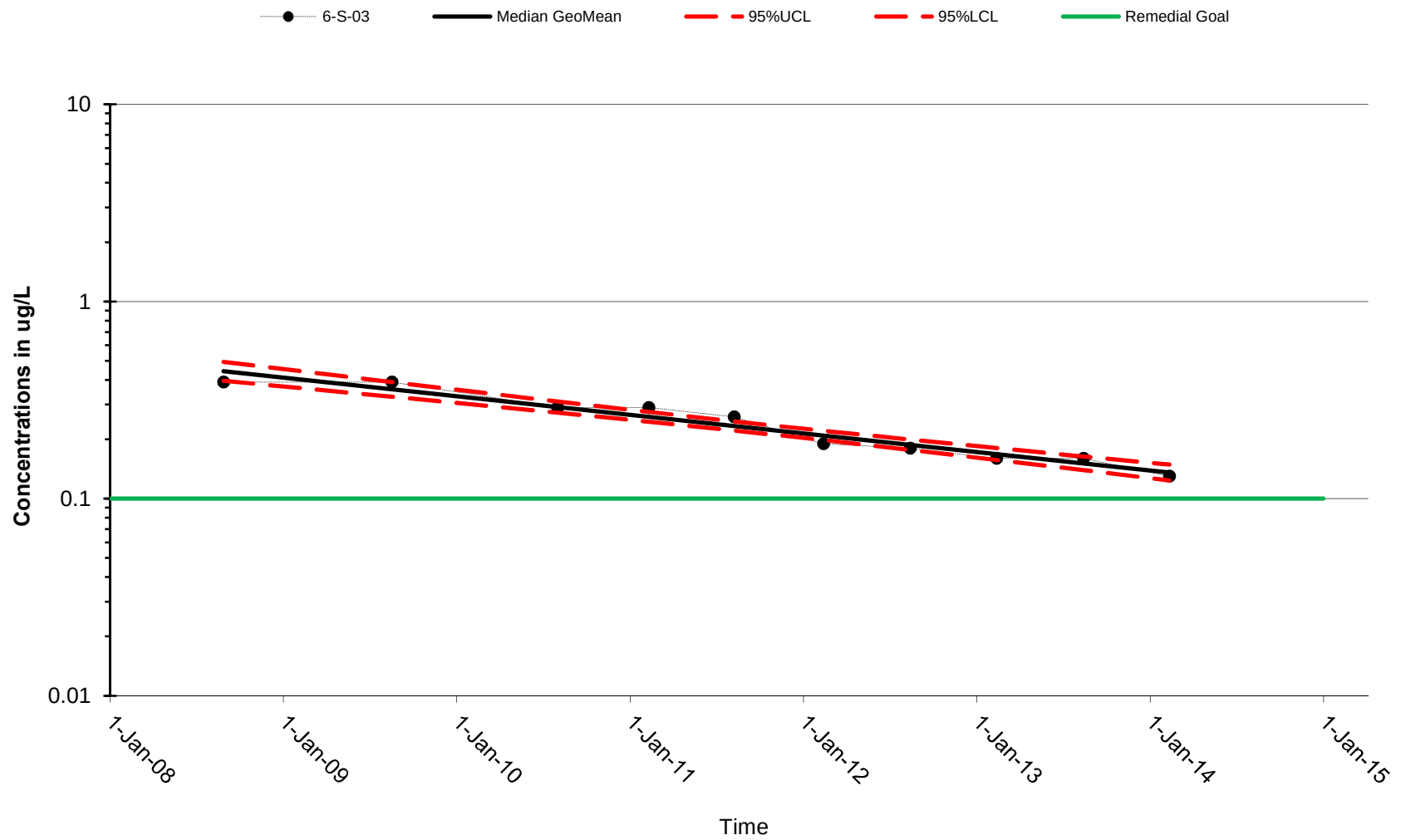


Figure A-47
Vinyl Chloride in Downgradient Well 6-S-19

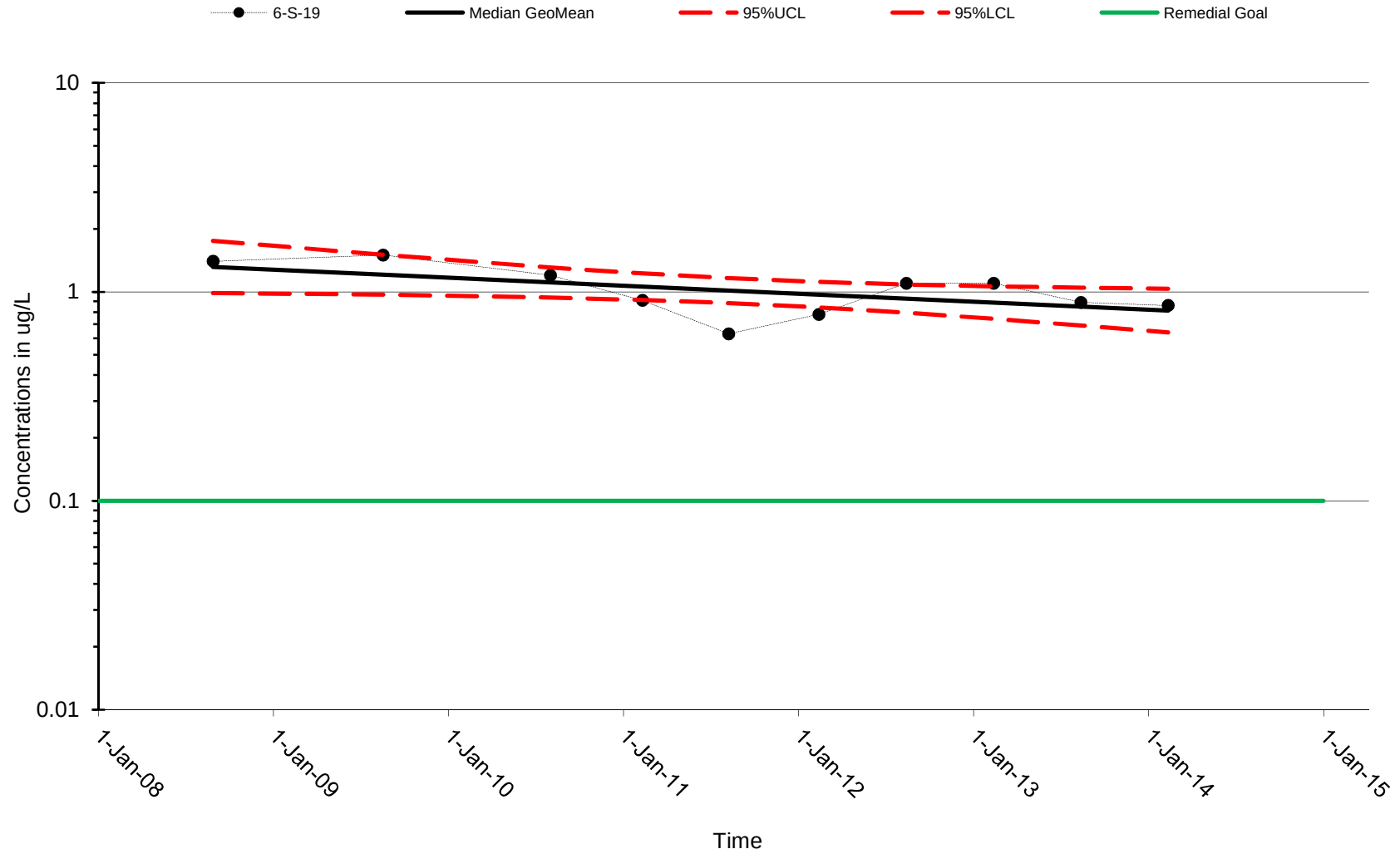


Figure A-48
Vinyl Chloride in Downgradient Well 6-S-29

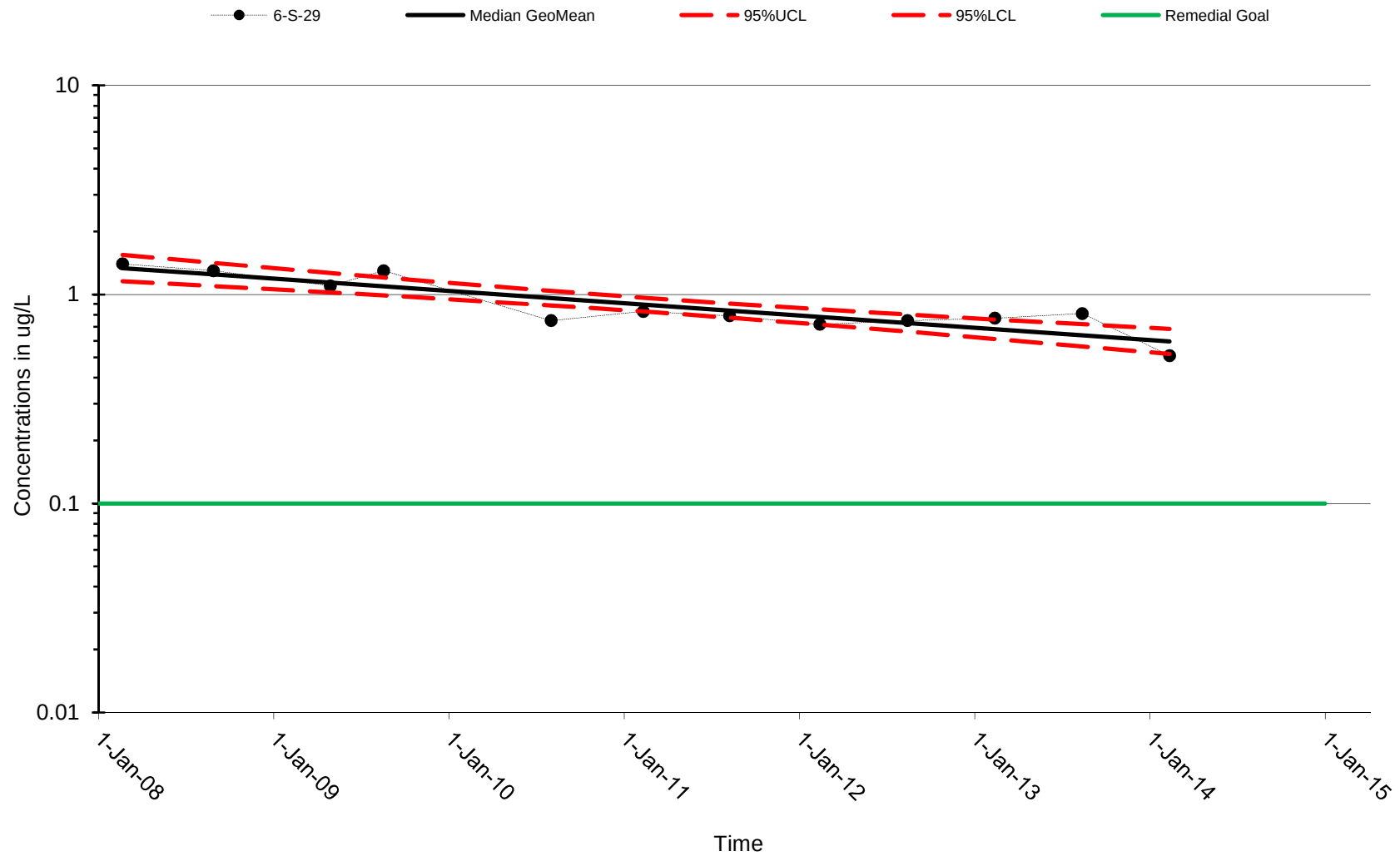


Figure A-49
Vinyl Chloride in Downgradient Well 6-S-42

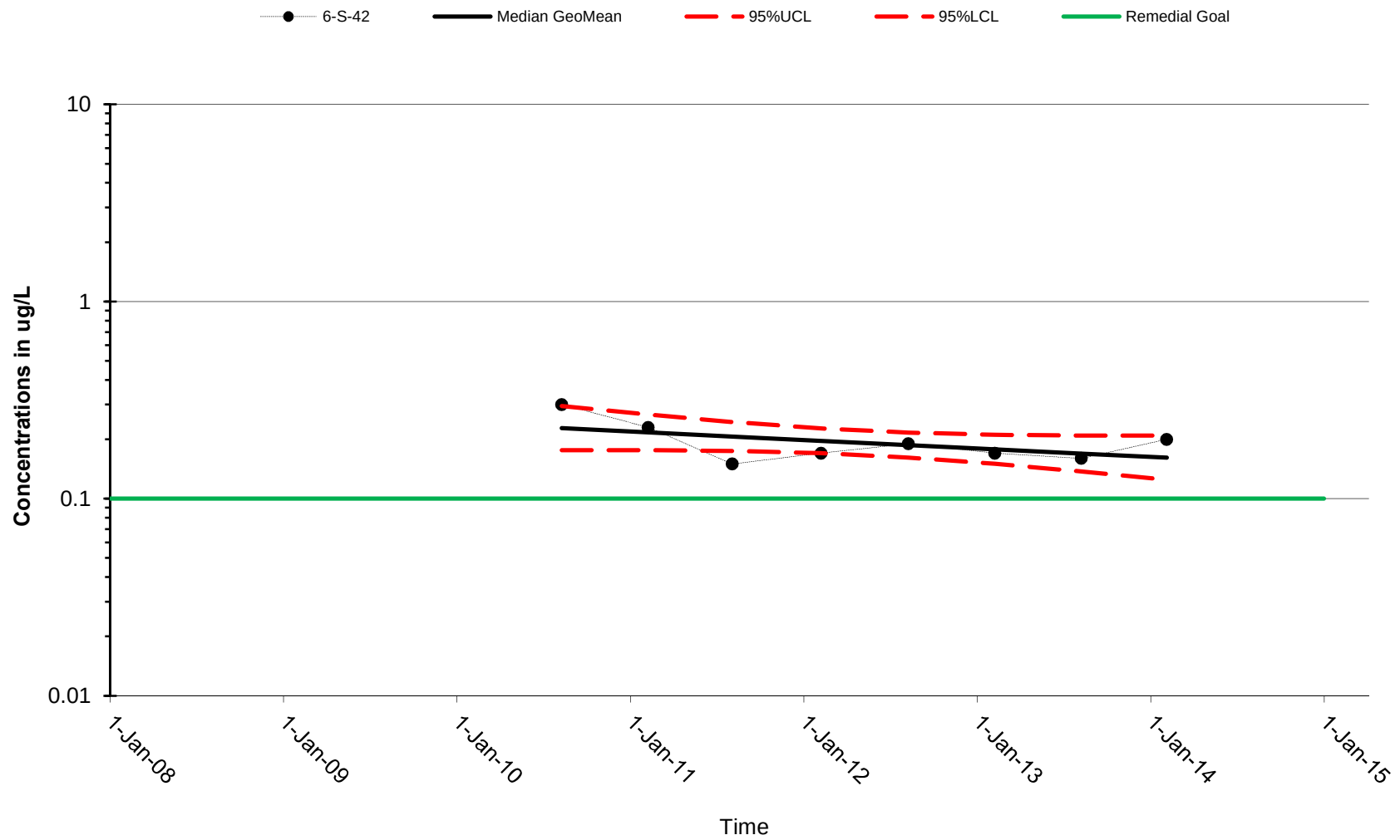


Figure A-50
Vinyl Chloride in Downgradient Well 6-S-43

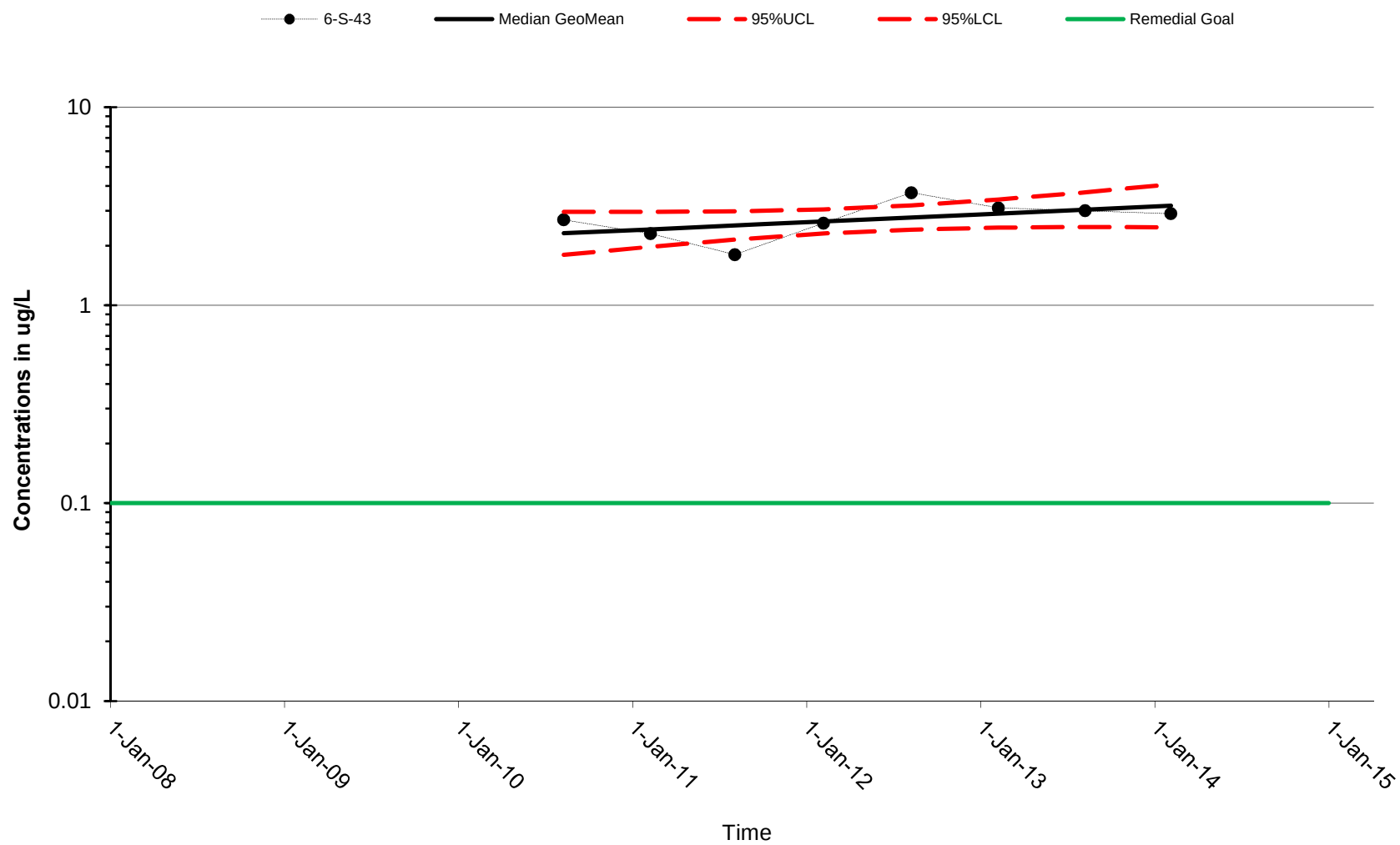
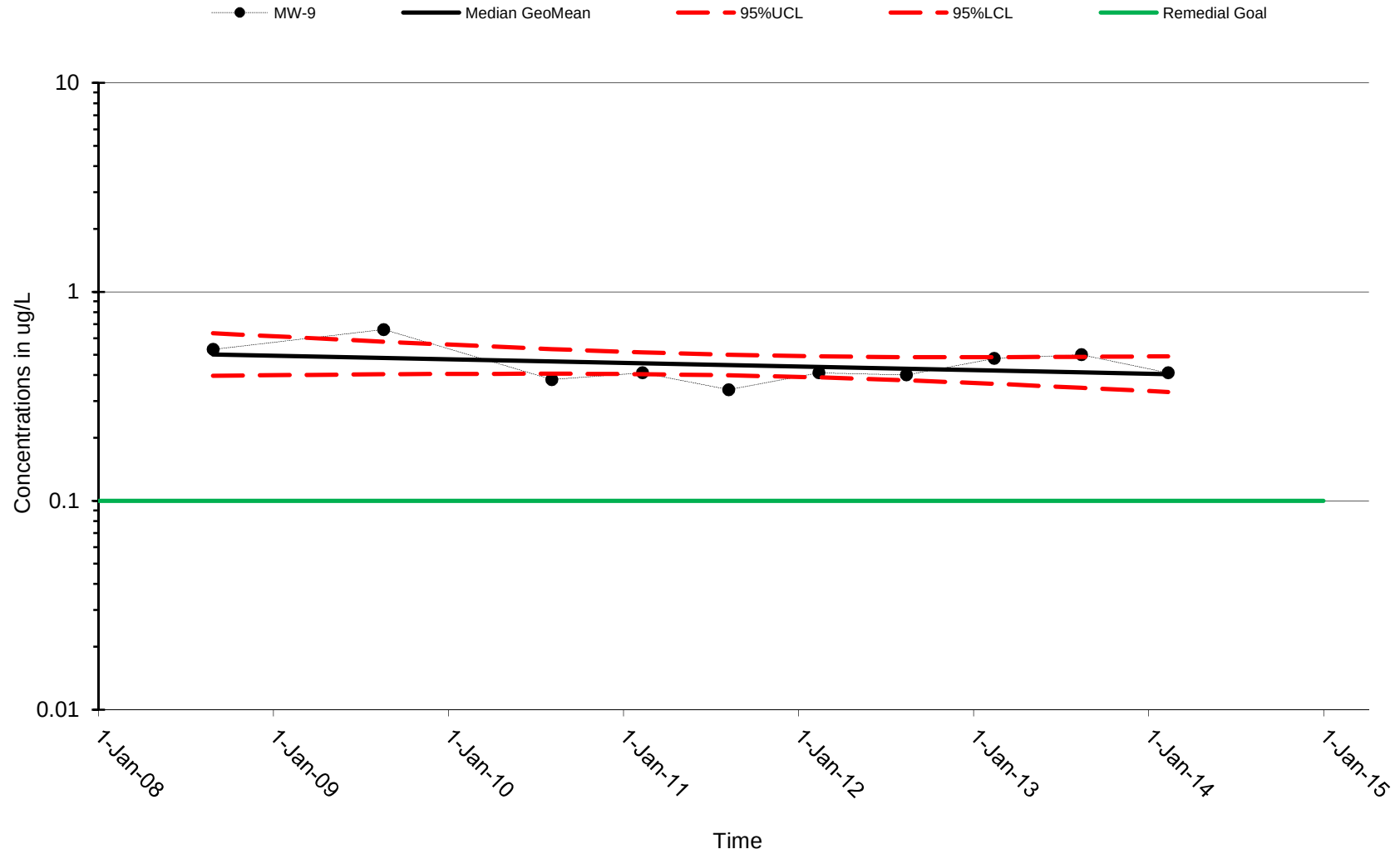


Figure A-51
Vinyl Chloride in Downgradient Well MW-9



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APPENDIX B

Groundwater Modeling Report

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Naval Air Station Whidbey Island (Area 6) Groundwater Flow and Transport Model Development and Results

Naval Air Station Whidbey Island
Oak Harbor, Washington

Prepared for:

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July 2015



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TABLE OF CONTENTS

1	Introduction.....	1
	1.1 Project Description.....	1
	1.2 Model Development.....	1
	1.3 Report Organization.....	1
2	Model Software	2
	2.1 Modflow Groundwater Flow Model	2
	2.2 MT3DMS Transport Model.....	2
	2.3 Groundwater Modeling System (GMS) Interface.....	2
3	Model Development.....	3
	3.1 MODflow Flow Model	3
	3.1.1 Model Domain and Grid	3
	3.1.2 Hydraulic Conductivity.....	4
	3.1.4 Initial and Boundary Conditions	4
	3.1.5 Extraction Wells.....	5
	3.2 Mt3DMS Transport Model	5
	3.2.1 Dispersion	5
	3.2.2 Effective Porosity.....	6
	3.2.3 Retardation.....	6
	3.2.4 Degradation.....	7
	3.2.5 Vadose Source	7
4	Model Evaluation and results	8
	4.1 Flow Model Calibration Evaluation.....	8
	4.2 Flow Model Sensitivity Evaluation	9
	4.2.1 Net Recharge Rate	10
	4.2.2 Horizontal Hydraulic Conductivity.....	10
	4.2.3 Heads in General Head Boundary.....	11
	4.2.4 Conductance in General Head Boundary.....	11
	4.3 FATE AND TRANSPORT Model Sensitivity Evaluation.....	11
	4.3.1 Organic Carbon.....	12
	4.3.2 Horizontal Hydraulic Conductivity.....	12
	4.3.3 Dispersivity	13
	4.3.4 Recharge	13
	4.4 Fate and Transport Model VERIFICATION	13
	4.4.1 Qualitative Verification	14
	4.4.2 Qualitative Verification Results.....	14
	4.4.3 Quantitative Verification	14
	4.4.4 Quantitative Verification Results.....	15
	4.5 Fate and Transport Model Simulations.....	15
5	Summary.....	21
6	Model Uncertainty and Limitations	22

TABLE OF CONTENTS

Table of Contents (Continued)

7	References	23

Tables

Table 1	Fate and Transport Model Simulation Results

Figures

Figure 1	Site Location
Figure 2	Model Domain Boundary
Figure 3	Geologic Cross-Section A-A'
Figure 4	Geologic Cross-Section B-B'
Figure 5	Geologic Cross-Section C-C'
Figure 6	Observed Ground Surface Elevations
Figure 7	Truncated Ground Surface Elevations
Figure 8	General Head Boundary Locations
Figure 9	Extraction Well Locations
Figure 10	TCE in Groundwater
Figure 11	Vinyl Chloride in Groundwater
Figure 12	1,4-Dioxane in Groundwater
Figure 13	Model Calibration Monitoring Wells
Figure 14	Flow Model Sensitivity-Recharge
Figure 15	Flow Model Sensitivity-Hydraulic Conductivity
Figure 16	Flow Model Sensitivity-General Head Boundary Heads
Figure 17	Flow Model Sensitivity- General Head Boundary Conductance
Figure 18	Sensitivity Evaluation Locations
Figure 19	Fate and Transport Model Sensitivity-Total Organic Carbon
Figure 20	Fate and Transport Model Sensitivity-Hydraulic Conductivity
Figure 21	Fate and Transport Model Sensitivity-Dispersivity
Figure 22	Fate and Transport Model Sensitivity-Recharge
Figure 23	TCE Qualitative Verification
Figure 24	Vinyl Chloride Qualitative Verification
Figure 25	1,4-Dioxane Qualitative Verification

TABLE OF CONTENTS

Figures (Continued)

Figure 26	TCE Quantitative Verification
Figure 27	Vinyl Chloride Quantitative Verification
Figure 28	1,4-Dioxane Quantitative Verification
Figure 29	Simulated and Observed TCE Correlation
Figure 30	Scenario 2 (TCE)
Figure 31	Scenario 2 (Vinyl Chloride)
Figure 32	Scenario 2 (1,4-Dioxane)
Figure 33	Scenario 3 (TCE)
Figure 34	Scenario 3 (Vinyl Chloride)
Figure 35	Scenario 3 (1,4-Dioxane)
Figure 36	Scenario 3a (TCE)
Figure 37	Scenario 3a (Vinyl Chloride)
Figure 38	Scenario 3a (1,4-Dioxane)
Figure 39	Scenario 4 (TCE)
Figure 40	Scenario 4 (Vinyl Chloride)
Figure 41	Scenario 4 (1,4-Dioxane)
Figure 42	Scenario 5 (TCE)
Figure 43	Scenario 5 (Vinyl Chloride)
Figure 44	Scenario 5 (1,4-Dioxane)
Figure 45	Scenario 5a (TCE)
Figure 46	Scenario 5a (Vinyl Chloride)
Figure 47	Scenario 5a (1,4-Dioxane)
Figure 48	Scenario 6 (TCE)
Figure 49	Scenario 6 (Vinyl Chloride)
Figure 50	Scenario 6 (1,4-Dioxane)
Figure 51	Scenario 7 (TCE)
Figure 52	Scenario 7 (Vinyl Chloride)
Figure 53	Scenario 7 (1,4-Dioxane)
Figure 54	Scenario 8 (TCE)
Figure 55	Scenario 8 (Vinyl Chloride)
Figure 56	Scenario 8 (1,4-Dioxane)

TABLE OF CONTENTS

Figures (Continued)

Figure 57	Scenario 9 (TCE)
Figure 58	Scenario 9 (Vinyl Chloride)
Figure 59	Scenario 9 (1,4-Dioxane)
Figure 60	Scenario 10 (TCE)
Figure 58	Scenario 9 (Vinyl Chloride)
Figure 59	Scenario 9 (1,4-Dioxane)

Attachments

Attachment 1	AVI Model Files

1 INTRODUCTION

1.1 PROJECT DESCRIPTION

This report documents steady-state groundwater flow and transport modeling results for the Area 6 at Naval Air Station (NAS) Whidbey Island (site) located approximately 1.5 miles north of the town of Oak Harbor, WA (Figure 1). This report documents the development of the groundwater flow model and associated fate and transport model used to simulate the mechanisms of migration of chlorinated volatile organic compounds (CVOC) and 1,4-dioxane dissolved in groundwater beneath the site. The calibrated and verified three-dimensional screening model was used as a tool in the evaluation of several proposed groundwater remediation strategies designed to accelerate on-going remediation at the site.

1.2 MODEL DEVELOPMENT

Previous models have been developed for Area 6 however, upon review of preliminary model inputs it was determined that assumptions regarding subsurface conditions were not representative of conditions beneath the site. Therefore, the flow model components were revised and coupled with a fate and transport component. The objective of the modeling effort was to simulate the migration of site contaminants under 2012 conditions and assess proposed strategies for the remediation of dissolved contaminants in groundwater beneath the site.

1.3 REPORT ORGANIZATION

Following this introductory section, the report is organized into the following sections:

- Section 2: Model Software
- Section 3: Model Development
- Section 4: Model Evaluation and Results
- Section 5: Summary
- Section 6: Model Uncertainty and Limitations
- Section 7: References

Supporting tables, figures and attachments follow the text.

2 MODEL SOFTWARE

2.1 MODFLOW GROUNDWATER FLOW MODEL

The computer code selected to simulate the groundwater flow component was MODFLOW-2000 (MF2K), a three-dimensional, cell-centered, finite difference, saturated flow model developed by the USGS (McDonald and Harbaugh, 1988; Hill et al., 2000). This code was used due to MF2K's wide acceptance by both industry and regulators for its ability to accurately simulate a wide variety of groundwater flow conditions. Based on the information available, the uncertainty associated with site information, and the modeling objective, MF2K was considered an appropriate groundwater flow code for the model. Model simulations were created using Aquaveo's Groundwater Modeling System (GMS) software, version 9.0 (Aquaveo, 2013). GMS provides a graphical interface to MF2K.

2.2 MT3DMS TRANSPORT MODEL

Contaminant transport simulations were conducted using the MT3DMS groundwater contaminant transport model code (Zheng and Wang, 1999). MT3DMS is an improved version of the MT3D model developed in 1990 (Zheng, 1990). MT3DMS has improved numerical solvers that make model simulations more stable and help prevent model-induced numerical oscillations. GMS provides an interface that links MF2K simulated groundwater flow field information to MT3DMS. MT3DMS uses this information to simulate contaminant transport. Similar to MF2K, MT3DMS is widely accepted by environmental scientists, and associated professionals, for simulating conditions observed at the site and were considered an appropriate contaminant transport code for the model.

2.3 GROUNDWATER MODELING SYSTEM (GMS) INTERFACE

GMS is a comprehensive graphical user interface (GUI) for performing groundwater simulations and also provides various powerful tools for data interpolation and figure generation. GMS was developed by the Environmental Modeling and Research Laboratory (EMRL) in partnership with Waterways Experiment Station (WES) and used as a supplementary tool to assist with data preparation and interpolation, pre- and post-processing, and generating figures (EMRL 2005). The model was constructed using GMS version 9.0 as developed by Aquaveo, formerly EMRL.

3 MODEL DEVELOPMENT

3.1 MODFLOW FLOW MODEL

3.1.1 Model Domain and Grid

The model encompasses the approximately 260-acre site with a domain area of approximately 354 acres, centered on the site (Figure 2). The model domain was spatially divide into a grid containing 3,421,652 total grid cells; spatially discretized into 883 columns in width, 775 rows in length (all cells are 15 feet by 15 feet) and five vertical layers .

The five layers of the model represent the five uppermost hydrogeologic units interpreted from logs of borings drilled at the site. Cross-sectional diagrams of site geology used to guide model development are presented on Figures 3 through 5, respectively. Layer 1 of the model corresponds to the sands and gravels of the Vashon Recessional Outwash and the silty, fine sands of the Vashon till unit. This layer has a variable thickness, due to site topography. Ground surface elevations, comprising the top of Layer 1, range from 226.84 feet mean sea level (msl) feet to 155 feet msl. Layer 1 is simulated as having a thickness ranging from 5 feet to 76 feet.

Based on interpreted site geology the average elevation at which the Vashon Advance outwash unit first occurs is 150 feet msl. Due to site topography, this elevation is above ground surface at locations near the east and west boundaries of the model domain which necessitated extending the lower elevation of the Vashon Till unit (Layer 1) throughout the model domain. The site is located along a topographical high (ridge) running approximately from north to south with the ground surface sloping away to the east and west.

To prevent model layer 1 from having a thicknesses of zero the ground surface elevations represented by the top elevation in Layer 1 were assigned a value of 155 feet msl if they were less than that elevation. The bottom, elevation of Layer 1 in the URS model was assigned a constant value of 150 feet msl. Contoured topography data presented in Figures 6 and 7 illustrate the difference in observed surface elevation data versus the truncated ground surface elevations simulated in the model, respectively.

Layer 2 corresponds to gravelly sands and sands of the Vashon Advance outwash unit. It was assigned a uniform thickness of 100 feet and is partially saturated. Layers 3 through 5 represent three of the four sections comprising the Whidbey Formation. Layer 3 represents the silts and other fine grained soils of the Whidbey 1 unit and was simulated as having uniform thickness of 36 feet. Layer 4 represents the sands and silty sands of the Whidbey 2 unit and has a thickness of

17 feet. Layer 5 of the model represents the silts and clays of the Whidbey 3 unit and has a uniform thickness of 32 feet.

3.1.2 Hydraulic Conductivity

Horizontal hydraulic conductivity and vertical anisotropy values were applied to each grid cell within the model domain. Horizontal conductivity values varied from layer to layer based on pumping or slug test data collected from site wells; however the overall distribution of conductivity values from pumping test data varied to such a degree that the conductivity for each individual layer was assumed to be uniform.

Hydraulic conductivity values derived from data collected from wells within a model layer (based on well screen intervals) were averaged. Average values were used as guidance values for assigning initial conductivities to each layer. Final conductivity values were based on site lithology, professional judgment, and model calibration. Vertical conductivity values were assigned through the use of the vertical anisotropy property due to a lack of field data.

Anisotropy values were assigned based on observed lithology in each model layer. Layer 1 was assigned a conductivity value of 45 feet/day, with the landfill cap assigned a values of 0.1 foot/day. Layer 2 was given a value of 48.25 feet/day, followed by Layers 3, 4 and 5 having values of 7.5, 1.29 and 0.78 feet/day, respectively. Anisotropy values for Layers 1 through 5 were 150, 500, 250, 250, and 250, respectively.

3.1.3 Recharge

Previous site investigations estimate that precipitation effectively recharges the unconfined aquifer (model Layer 2) at rates ranging from 3.5 inches/year (in/yr) (IT Corporation, 1997) to 12 in/yr (Sapik et al, 1988). The URS model conservatively assumed a uniform recharge rate of 3.5 inches/year. This low rate reduces the potential for plume dilution by recharging precipitation as much as possible while remaining physically based. It should also be noted that groundwater typically occurs at depths from 90 feet bgs to greater than 100 feet bgs. This is a significant distance for infiltrated precipitation to percolate prior to actually recharging the upper aquifer. In addition, isolated perched water tables are known to exist across the site and will further reduce the amount of effective recharge to the upper aquifer.

3.1.4 Initial and Boundary Conditions

The model has general head boundary (GHB) boundary conditions assigned to all model boundaries. GHB locations are presented on Figure 8. General heads were assigned based on the approximate elevation of the potentiometric surface for each model layer, with GHB nodes being adjusted to their final values during model calibration. In general, GHB node heads were

assigned higher elevations along the northern boundary of the model and decrease to the lowest elevations at the southern boundary of the model, consistent with the north to south flow of groundwater observed at the site. GHB boundaries were also assigned along the eastern and western boundaries of the model to minimize any boundary affects that may otherwise be caused by assigning a specified flux conditions (specified head boundaries, no flow boundaries) along these borders.

3.1.5 Extraction Wells

The model includes all 8 operating and 2 non-operating extraction wells. Off-site pumping occurs within the model domain but was not accounted for in the model and is assumed to have no impact on plume capture and containment on-site. Off-site pumping wells are sensitive down gradient receptors and may play a larger role in influencing plume migration for plumes that migrate beyond the Area 6 boundary. Site extraction wells are shown on Figure 9.

3.2 MT3DMS TRANSPORT MODEL

The MODFLOW groundwater flow model was coupled with a contaminant transport model developed using the MT3DMS code to simulate the migration of the CVOC and 1,4-Dioxane plumes at the site. The transport model utilizes the same model domain, layers, and spatial discretization as the flow model described above. The fate-and-transport model was used to simulate the migration of 2012 dissolved CVOC and 1,4-Dioxane concentration distributions. Initial concentration distributions derived from 2012 sample data are shown on Figures 10 through 12, respectively.

Simulated transport processes include advection, dispersion, and adsorption (retardation). The modeled processes are discussed below.

3.2.1 Dispersion

Dispersion refers to the process whereby a dissolved contaminant will be spatially distributed longitudinally (along the direction of groundwater flow), transversely (perpendicular to groundwater flow), and vertically (downward or upward or both) because of mechanical mixing and chemical diffusion in the aquifer. These processes contribute to the development of the plume shapes and dimensions (the spatial concentration distributions of the dissolved contaminant mass in the aquifer). Selection of values for dispersivity (the parameter used here to represent dispersion) is a difficult process, given the impracticability of measuring dispersion in the field; however, simple estimation techniques based on the length of the contaminant plumes are available.

A large number of field data compiled by Gelhar, Welty, and Rehfeldt (1992) suggest that longitudinal dispersivity is a function of the travel distance and the aquifer type. For porous media and plume length scales on the order of a few hundred feet to a few thousand feet, the longitudinal dispersivity varies between 1% and 10% of the travel distance. Transverse and vertical dispersivity are often set to be 10% and 5% of the longitudinal dispersivity, respectively (Aziz et al., 2000; Domenico and Schwartz, 1997; ASTM, 1995). For this transport model, the longitudinal dispersivity was set to 100 feet.

3.2.2 Effective Porosity

Effective porosity affects the mobile-phase dissolved contaminant mass (excluding dissolved contaminant mass trapped in the residual pore moisture) and groundwater seepage velocity (linear velocity). Greater effective porosity leads to more mobile-phase dissolved contaminant mass in groundwater. However, greater effective porosity leads to slower groundwater seepage velocity, thus reducing the hydrodynamic dispersion.

The effective porosity has a significant effect on contaminant transport due to its significant effect on groundwater seepage velocities and hydrodynamic dispersion processes. Based on the soil materials (clays, silts, and sands) observed during monitoring well installation efforts, the effective porosity was set to an average value of 0.25 for all layers.

3.2.3 Retardation

Several geochemical reactions influencing the transport of contaminants result in the retardation of contaminant migration. The dominant retarding reaction is the adsorption of contaminants to the surface of soil particles. Adsorption reduces the migration of dissolved contaminants moving through the groundwater by holding contaminant mass on the surface of soil particles. The retardation factor is the ratio of the groundwater seepage velocity to the rate that organic chemicals migrate in the groundwater. The degree of retardation depends on aquifer and constituent properties.

The retardation factor is often estimated from soil properties and chemical data using the following variables: bulk density (ρ_b), effective porosity (n), organic carbon-water partition coefficient (K_{oc}), and fraction of organic carbon in uncontaminated soil (f_{oc}). The following expression was used to determine the retardation factor (Wiedemeier et al., 1999):

$$R_e = 1 + \frac{K_d \rho_b}{n}$$

where:

K_d is distribution coefficient and $K_d = f_{oc} \times K_{oc}$

Organic carbon-water partition coefficients were set to values of 18 liters per kilogram (L/kg) for TCE, 0.005 L/kg for 1,4-Dioxane, and 4 L/kg for VC. Using these assigned input values, the retardation factors were calculated by the MT3DMS model code using the retardation factor equation shown above.

3.2.4 Degradation

The model was developed based on the assumption that site contaminants are not undergoing significant biodegradation or chemical transformation. This assumption is conservative because it leads to higher estimated contaminant concentrations than the assumption that biodegradation or chemical transformations act to reduce contaminant mass.

3.2.5 Vadose Source

No residual sources from the unsaturated zone (vadose zone) were simulated.

4 MODEL EVALUATION AND RESULTS

4.1 FLOW MODEL CALIBRATION EVALUATION

The model was calibrated to data collected during third quarter 2012 (3Q12) from 29 active shallow aquifer, site monitoring wells (SEAALASKA, 2012). Monitoring wells used for calibration are shown on Figure 13. Calibration is graphically depicted for each target (monitoring well) with a colored vertical bar. The center of the target bar corresponds to the observed head. The top of the target corresponds to the observed head plus the calibration target interval (e.g., 0.1 foot). The bottom of the target corresponds to the observed head minus the target interval. The color of the bar represents the residual (difference between observed and computed heads). If the bar lies entirely within the target interval, the color of the bar is green. If the bar is outside the interval, but the residual (difference between observed and computed heads) is less than 200%, the bar is yellow. If the residual is greater than 200%, the bar is red.

In addition, residual error statistics were calculated to quantify the average error throughout the model. Three ways of expressing the average difference between simulated and measured heads (groundwater elevations) are commonly used (Anderson and Woessner, 1992).

1. The mean error (ME) is the mean difference between measured heads (h_m) and simulated heads (h_s).

$$ME = \frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i$$

where n is the number of calibration points. The ME is simple to calculate, but it can be misleading because both negative and positive differences are incorporated in the mean, which may cancel out the error. Hence, a small ME may not indicate a good calibration, by itself.

2. The mean absolute error (MAE) is the mean of the absolute values of the differences in measured and simulated heads. This value provides a better estimate of the mean error regardless of the direction (positive or negative) of the error.

$$MAE = \frac{1}{n} \sum_{i=1}^n |(h_m - h_s)_i|$$

3. The root mean squared error (RMSE), or the standard deviation, is the average of the squared differences in the measured and simulated heads. This criterion looks at the average error without considering negative or positive differences. Evaluation of both the ME and MAE helps the modeler understand systematic average error over the model domain, along with the magnitude of that error.

$$RMS = \left[\frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i^2 \right]^{0.5}$$

In general the groundwater flow model is considered calibrated based on the calibration statistics derived from the above calculations comparing simulated and observed site water level data. The model ME, the mean difference between simulated and observed groundwater elevations, was 0.02 foot. The MAE, the mean of the absolute difference between simulated and observed groundwater elevations, was 0.34 foot. The RMSE, the standard deviation of the difference between simulated and observed groundwater elevations, was 0.59 foot. Consequently, the average error across the model domain was about 0.02 foot $\pm$ 0.59 foot. This is within the calibration target range of $\pm$ 1.0 foot established prior to initiating calibration. The flow model was therefore considered adequately calibrated to be used to develop a transport model for the site.

Overall, the calculated relative head error of the model, i.e. the RMSE divided by the range of observed groundwater elevations (15.74 feet), was 4.0%. A 4.0% relative error was well within the predetermined relative flow error criterion of 10% for the model; therefore, this is another indicator that flow model calibration is adequate to simulate groundwater flow conditions at the site.

Another criterion of model calibration is the correlation between the observed heads and simulated heads. The correlation coefficient derived from observed and simulated water levels from all 29 active monitoring wells was calculated as 99.7%, meaning there is a 99.7% correlation between observed and simulated heads for all of the monitoring wells used for calibration.

4.2 FLOW MODEL SENSITIVITY EVALUATION

A model response or prediction depends on the governing equations it solves, the mechanisms and structure of the model, and the values of the model parameters. It is imperative to evaluate how much error is acceptable for a model parameter value and how much uncertainty will be inherent in model predictions based on the parameters being evaluated. A sensitivity analysis is a means of evaluating model uncertainty by systematically altering the value of one of the model parameters and examining the associated change in the model response.

After flow model calibration, quantitative sensitivity analyses were performed using flow model parameters whose values were uncertain and likely to affect the flow simulation results. The calibrated flow model was used as the baseline simulation, and simulation results of sensitivity runs were compared with that of the baseline simulation.

The flow sensitivity analysis evaluated model uncertainties associated with horizontal hydraulic conductivity, vertical hydraulic conductivity, conductance of the GHB, heads specified for the GHB and net recharge rate. To quantify the sensitivities of model results to the selected parameters the relative head error was calculated for each sensitivity run.

The results of the sensitivity runs suggested that the flow model is most sensitive to net recharge rate and horizontal hydraulic conductivity. The model is moderately sensitive to the heads specified for the GHB. As outlined in Section 4.2.4, the conductance of the GHB was the least sensitive parameter in the flow model. Overall, model sensitivity results indicate that the flow model input parameters chosen produce the lowest amount of overall model error with respect to increasing or decreasing that specific parameter. The detailed results of this sensitivity analysis are discussed hereafter. Sensitivity analysis results are presented in Figures 14 through 17, respectively.

4.2.1 Net Recharge Rate

Changing the net recharge rate affects groundwater flow conditions. Specifically, net recharge introduces downward groundwater flow, increases lateral flow, and can cause water mounding. Consequently, net recharge increases can result in faster lateral and vertical contaminant migration.

A sensitivity analysis was performed with respect to the net recharge rate by globally increasing and decreasing the net recharge rate by 50%. The results of the sensitivity runs show that with a net recharge increase of 50%, the average mean error of simulated heads became -1.51 feet, resulting in a relative head error of 7.8%. Similarly, reducing net recharge by 50% resulted in an average mean error of 1.56 feet, resulting in a relative head error of 8.0%.

4.2.2 Horizontal Hydraulic Conductivity

In the horizontal plane, hydraulic conductivity determines the groundwater flow rate in the aquifer and consequently the rate of contaminant migration. It also determines the rate at which water can be pumped from the aquifer without causing undesirable effects, such as excessive drawdown, and consequently the rate at which dissolved contaminants may be removed from the aquifer.

Sensitivity analyses were performed on horizontal hydraulic conductivities by globally increasing and decreasing horizontal hydraulic conductivities by 50%. The results of sensitivity runs show that when horizontal hydraulic conductivities were increased by 50%, the average mean error of simulated heads became -0.59 feet, resulting in a relative head error of 5.4%. On

the other hand, reducing horizontal hydraulic conductivity by 50% the average mean error of simulated heads became 1.44 feet, resulting in a relative head error of 7.6%.

4.2.3 Heads in General Head Boundary

Similar to specified heads along a fixed-head boundary condition, the specified heads along a GHB (head specified for the external source) determine the simulated head values at the model domain boundaries and the inflow/outflow rates of the model domain. Higher heads of GHB lead to higher simulated heads in the model domain and a higher inflow/outflow flux.

Sensitivity runs with respect to the GHB heads were performed by globally increasing and decreasing all heads in the GHB by 1.0 foot. The results of the sensitivity runs indicate that when increasing the heads specified in the GHB by 1.0 foot, the average mean error of simulated heads became -0.81 feet, resulting in a relative head error of 5.7%. On the other hand, reducing the heads specified in the GHB by 1.0 foot the average mean error of simulated heads became 0.77 feet, resulting in a relative head error of 5.7%.

4.2.4 Conductance in General Head Boundary

Conductance along the GHB is a measure of the response of inflow/ outflow along the GHB to the head change outside of the model domain (external source). Or, simply speaking, it is a measure of how easy water flows in or out of the model along the GHB. Conductance along the GHB depends on the hydraulic conductivity between the actual boundary (where the external source is specified) and the domain boundary.

Sensitivity runs with respect to conductance values along the GHB were conducted by globally increasing and decreasing the conductance values of GHB by 50%. The results of the sensitivity runs indicate that when the conductance values of the GHB were increased by 50%, the average mean error of simulated heads became -0.01 feet, resulting in a relative head error of 4.0%. On the other hand, reducing conductance along the GHB by 50%, the average mean error of simulated heads became -0.01 feet, resulting in a relative head error of 4.0%.

4.3 FATE AND TRANSPORT MODEL SENSITIVITY EVALUATION

Similarly to the parameters used to build the flow model, fate and transport model parameters were also selected and varied to assess model sensitivity. The fate and transport model sensitivity evaluation assessed the models sensitivity associated with organic carbon, horizontal hydraulic conductivity, dispersivity, and recharge. To quantify the sensitivity to each parameter, 14 random locations were selected within the 2012 TCE plume. Selected locations are shown on Figure 18.

The fate and transport of the plume was simulated forward through time for a period of 10 years. After this period the simulated concentrations at the 14 previously selected locations were recorded. Following this simulation, one of the preselected model parameters was varied and the model was again simulated forward through time, starting in 2012, for the 10 year period. The simulated concentrations at the 14 locations were then recorded and a relative error was calculated and compared to the baseline.

The results of the sensitivity runs suggested that the fate and transport model is most sensitive to organic carbon and horizontal hydraulic. The model is moderately sensitive to dispersivity. The effective recharge rate was the least sensitive parameter. Overall, model sensitivity results indicate that the fate and transport model is more sensitive to its associated input parameters than is the flow model. Sensitivity analysis results also indicate that certain parameters that have the highest degree of sensitivity should be field verified to ensure that the chosen parameters most accurately reflect field conditions. The detailed results of this sensitivity analysis are discussed hereafter. Sensitivity analysis results are presented in Figures 19 through 22, respectively.

4.3.1 Organic Carbon

Organic carbon directly affects the distribution coefficient, which determines the amount of contaminant mass adsorbed to the surface of soil particles. Consequently, organic carbon significantly affects the total contaminant mass in the aquifer (both dissolved in groundwater and adsorbed on soils) and the retardation factor. As a result, the fraction of organic carbon strongly affects the cleanup time.

A sensitivity analysis was performed with respect to organic carbon by increasing and decreasing organic carbon values (using the sorption parameter) by 50%. The results of the sensitivity runs show that an organic carbon increase of 50% subsequently increases TCE concentrations on average which results in a relative error of 7.9% when compared with baseline. Reducing organic carbon by 50% resulted in an average decrease of TCE concentrations, resulting in a relative error of 9.2%.

4.3.2 Horizontal Hydraulic Conductivity

In the horizontal plane, hydraulic conductivity determines the groundwater flow rate in the aquifer and consequently the rate of contaminant migration. It also determines the rate at which water can be pumped from the aquifer without causing undesirable effects, such as excessive drawdown, and consequently the rate at which dissolved contaminants may be removed from the aquifer.

Sensitivity analyses were performed on horizontal hydraulic conductivities by globally increasing and decreasing horizontal hydraulic conductivities by 50%. The results of sensitivity runs show that when horizontal hydraulic conductivities were increased by 50%, the average TCE concentrations decreased, resulting in a relative error of 8.4%. A reduction of horizontal hydraulic conductivity by 50% increased average TCE concentrations, resulting in a relative error of 8.3%.

4.3.3 Dispersivity

Dispersivity was used as the parameter that represents dispersion. Dispersion refers to the process whereby a dissolved contaminant will be spatially distributed longitudinally (along the direction of groundwater flow), transversely (perpendicular to groundwater flow), and vertically (downward or upward or both) because of mechanical mixing and chemical diffusion in the aquifer. These processes contribute to the development of the plume shapes and dimensions (the spatial concentration distributions of the dissolved contaminant mass in the aquifer).

A sensitivity analysis was performed with respect to dispersivity by increasing and decreasing dispersivity values by 50%. The results of the sensitivity runs show that with a dispersivity increase of 50%, average TCE concentrations decreased, resulting in a relative error of 6.1%. Reducing dispersivity by 50% resulted in an average increase of TCE concentrations, resulting in a relative error of 5.0%.

4.3.4 Recharge

The effective recharge is the influx of water, primarily rainfall, from the ground surface into the aquifer. In reality, recharge to the aquifer is equal to rainfall minus several intercepted quantities including interception from vegetation and impervious surfaces, water retained at the surface that is evaporated back to the atmosphere, soil retention returned to the atmosphere as evapotranspiration, and overland flows and runoff as stream flow.

A sensitivity analysis was performed with respect to recharge by increasing and decreasing the recharge value by 50%. The results of the sensitivity runs show that with a recharge increase of 50%, a slight increase in average TCE concentrations are noted, resulting in a relative error of 3.4%. Similarly, reducing recharge by 50% resulted in a slight decrease of average TCE concentrations, resulting in a relative error of 3.3%.

4.4 FATE AND TRANSPORT MODEL VERIFICATION

A fate and transport model is rarely calibrated using specific information about contaminant releases (e.g., masses of original releases, times of releases, etc.) because the factors are usually

not known with enough certainty. Consequently, transport model verification was conducted by simulating historical conditions and comparing the simulated results to measured concentration data. Transport model verifications were performed with TCE, VC, and 1,4-dioxane.

The simulation times for the verification runs were determined based on the availability and the uncertainty associated with the historical groundwater concentration data. For the transport verification runs, TCE, VC, and 1,4-dioxane concentration data from 1997, 1997, and 2003 were used as the initial concentration conditions, respectively. The verification simulations extended from 1997 to 2012 in the cases of TCE and VC, and from 2003 to 2012 for 1,4-Dioxane. The fate and transport of contaminants were simulated for their respective periods, and the simulated concentration results at the end of simulation periods were compared to sampled concentration data for 2012. Due to the steady-state nature of the model only a single set of flow rates could be simulated for the verification period. Historic flow rates from site extraction wells have varied to different degrees during their operating period making it difficult to select a “representative” flow rate for a given verification period. Therefore; flows rates simulated during flow model calibration were similarly used in verification scenarios for the fate and transport model.

4.4.1 Qualitative Verification

Qualitative fate and transport model verification consisted of comparing the spatial distributions of simulated contaminants with 2012 observed (field measured) data. The purpose of this verification was to provide a general assessment of the input flow and fate and transport models input parameters effects on contaminant distributions.

4.4.2 Qualitative Verification Results

The simulated and observed concentrations of TCE, VC, and 1,4-Dioxane are shown Figures 23, 24, and 25, respectively. The spatial distributions of the simulated and observed concentration distributions are generally consistent in their overall extents. The plumes vary along the perimeters, but maintain the distributions of hotspot areas.

4.4.3 Quantitative Verification

Quantitative fate and transport verification simulation consisted of comparing the amount of contaminant mass (as pounds of contaminant in the dissolved phase) between the 2012 simulated and observed TCE, VC, and 1,4-Dioxane data sets. An additional verification, utilizing the TCE plume only, consisted of selecting 14 points within the plume and comparing the simulated concentrations at those points with observed concentrations at the same location. The TCE plume was the only plume utilized in this scenario because it has the most complete data set of the

contaminants simulated and is the most fully delineated simulation. Quantitative verification results are presented on Figures 26, 27, 28, and 29, respectively.

4.4.4 Quantitative Verification Results

The model simulated TCE mass in 2012 consists of 8,000 pounds of contaminant in the dissolved phase compared to 6,000 pounds in the observed 2012 data set. This equates to a difference of 25%. The model simulated VC mass consists of 155 pounds of contaminant in the dissolved phase compared to 120 pounds in the observed data set. This equates to a difference of 22%. The model appears to be slightly less conservative of mass for TCE and VC. The model is conservative of contaminant mass for 1,4-dioxane. The model predicts 1,464 pounds of mass will remain at the end of the verification period for 1,4-Dioxane. The observed mass value of 1,800 pounds differs by 23%.

The 14 locations selected to assess concentrations within the TCE plume are shown on Figure 29. The simulated and observed concentrations at these locations have a percentage error of 4.7%. This indicates that while the model may be less conservative with low concentration mass along the TCE plume boundary it conserves hotspot concentrations as well as accurately simulates the overall distribution of mass within the plume.

4.5 FATE AND TRANSPORT MODEL SIMULATIONS

After verifying the fate and transport model, the groundwater model components were ready for simulating scenarios to evaluate several proposed remediation strategies. The transport model was used to simulate eight predictive scenarios. A 50-year transport simulation time was used for all scenarios. The simulation period ranged from 2015 to 2064. These scenarios assess the abilities of the proposed remedial strategies to reduce contaminant concentrations below their respective remedial goals or cleanup levels. The remedial goals for TCE and VC are 5 µg/L and 0.029 µg/L, respectively. A remedial goal has not been established for 1,4-dioxane. As a result, the Washington Model Toxics Control Act Method B groundwater cleanup level of 0.44 µg/L was used for 1,4-dioxane.

Simulated remedial strategies include utilizing current site operational extraction wells, the installation of additional extraction wells, the installation of injection wells, and in-situ chemical oxidation (ISCO) injection. ISCO injection would be conducted at specific locations within the TCE and 1,4-dioxane contaminant plume. The VC plume would also be treated by the injections occurring in the 1,4-Dioxane plume. Due to the steady state nature of the model yearly ISCO injections were simulated by assigning a contaminant decay rate within a model grid cell where an injection was proposed to occur, such that the contaminant mass within that cell would be

reduced by the anticipated effectiveness of the ISCO injection (i.e. 50% or 70% contaminant concentration reduction) on a yearly basis. Specifications for each scenario are as follows:

Scenario 1 simulates TCE, VC, and 1,4-dioxane remediation assuming current groundwater pumping (baseline) conditions. This simulation assumes that 1,4-dioxane is removed from the treated effluent. The current system does not remove 1,4-dioxane from groundwater, which is then discharged to the surface and allowed to reinfiltrate.

Scenario 2 simulates TCE, VC, and 1,4-dioxane remediation assuming current groundwater condition plus yearly ISCO injections reducing contaminant mass by 70% at lines of injection wells spaced at 200-foot intervals, oriented perpendicular to the longitudinal axis of the 50 µg/L TCE plume boundary and at lines of injection wells spaced at approximately 200-foot intervals with in the 10 µg/L 1,4-dioxane plume boundary. Injection wells were simulated such that they would effectively reduce all mass by the assumed percentage within the row of model grid cells in which ISCO was simulated. Scenario 2 is presented on Figures 30, 31, and 32, respectively.

Scenario 3 simulates TCE, VC, and 1,4-dioxane remediation assuming current groundwater condition plus yearly ISCO injections reducing contaminant mass by 70% at lines of injection wells spaced at 100-foot intervals, oriented perpendicular to the longitudinal axis of the 50 µg/L TCE plume boundary and at lines of injection wells spaced at approximately 200-foot intervals with in the 4 µg/L 1,4-Dioxane plume boundary. Scenario 3 is presented on Figures 33, 34, and 35, respectively.

Scenario 3a simulates TCE, VC, and 1,4-dioxane remediation assuming no groundwater extraction plus yearly ISCO injections reducing contaminant mass by 70% at lines of injection wells spaced at 100-foot intervals, oriented perpendicular to the longitudinal axis of the 50 µg/L TCE plume boundary and at lines of injection wells spaced at approximately 200-foot intervals with in the 4 µg/L 1,4-dioxane plume boundary. Scenario 3a is presented on Figures 36, 37, and 38, respectively.

Scenario 4 simulates TCE, VC, and 1,4-dioxane remediation assuming current groundwater condition plus yearly ISCO injections reducing contaminant mass by 50% at lines of injection wells spaced at 100-foot intervals, oriented perpendicular to the longitudinal axis of the 50 µg/L TCE plume boundary and at lines of injection wells spaced oriented approximately from northeast to southwest at approximately 200-foot intervals within the 4 µg/L 1,4-dioxane plume boundary. Scenario 4 is presented on Figures 39, 40, and 41, respectively.

Scenario 5 simulates TCE, VC, and 1,4-dioxane remediation assuming current groundwater (baseline) conditions with the addition of five extraction wells spaced on approximately centers

of 300-feet, located adjacent to the west side of State Route 20 (SR20) near the southern site boundary. The five extraction wells were simulated at operational flow rates of 20 gallons per minute (gpm). Scenario 5 is presented on Figures 42, 43, and 44, respectively.

Scenario 5a simulates TCE, VC, and 1,4-dioxane remediation assuming current groundwater (baseline) conditions with the addition of five extraction wells spaced on approximately centers of 300-feet, located adjacent to the west side of SR20 near the southern site boundary plus yearly ISCO injections reducing contaminant mass by 70% at lines of injection wells spaced at 200-foot intervals, oriented perpendicular to the longitudinal axis of the 50 µg/L TCE plume boundary and at lines of injection wells spaced at approximately 200-foot intervals within the 4 µg/L 1,4-Dioxane plume boundary. The five extraction wells were simulated at operational flow rates of 20 gpm. Simulated ISCO areas are presented on Figure 21. Scenario 5a is presented on Figures 45, 46, and 47, respectively.

Scenario 6 simulates TCE, VC, and 1,4-Dioxane remediation assuming current groundwater (baseline) conditions with the addition of five extraction wells spaced on approximately centers of 300-feet, located adjacent to the west side of SR20 near the southern site boundary. The five extraction wells were simulated at operational flow rates of 20 gpm. This scenario also simulates the reinjection of treated groundwater at 10 injection wells on approximate centers of 80-feet, located along the southern site boundary. The 10 injection wells were simulated at operational injection rates of 10 gpm. Scenario 6 is presented on Figures 48, 49, and 50, respectively.

Scenario 7 simulates TCE, VC, and 1,4-dioxane remediation assuming no groundwater extraction plus construction of insitu barriers, placed in two locations, which destroy contaminant mass upon contact. An approximate 1,300-foot insitu barrier is orientated parallel to and within the longitudinal axis of the 50 µg/l TCE plume with containment at the south and southeast extent of the plume. An additional approximate 1,800-foot insitu barrier is orientated perpendicular to the longitudinal axis of the 4 µg/l 1,4-Dioxane plume and parallel with State Route 20. Scenario 7 is presented on Figures 51, 52, and 53, respectively.

Scenario 8 simulates TCE, VC, and 1,4-dioxane remediation assuming modifications to current groundwater (baseline) conditions including the addition of five extraction wells spaced on approximate centers of 300-feet, located adjacent to the west side of SR20 near the southern site boundary. Modifications to baseline consist of an additional 4 new site pumping wells (NPW-1 to 4) located in the western plume and operating at rates of 13.13 gpm. Additionally, operational rates for site wells PW-1, PW-3, PW-5, and PW-6 are modified to 13.13 gpm. The five extraction wells were simulated at operational flow rates of 20 gpm. Scenario 8 is presented on Figures 54, 55, and 56, respectively.

Scenario 9 simulates TCE, VC, and 1,4-dioxane remediation assuming modifications to current groundwater (baseline) conditions including the addition of five extraction wells spaced on approximately centers of 300-feet, located adjacent to the west side of SR20 near the southern site boundary plus yearly ISCO injections reducing contaminant mass by 70% at lines of injection wells spaced at 200-feet intervals, oriented perpendicular to the longitudinal axis of the 50 µg/L TCE plume boundary. Modifications to baseline consist of an additional 4 new site pumping wells (NPW-1 to 4) located in the western plume and operating at rates of 13.13 gpm. Additionally, operational rates for site wells PW-1, PW-3, PW-5, and PW-6 are modified to 13.13 gpm. The five extraction wells were simulated at operational flow rates of 20 gpm. Simulated ISCO areas are presented on Figure 21. Scenario 9 is presented on Figures 57, 58, and 59, respectively.

Scenario 10 simulates TCE, VC, and 1,4-dioxane remediation assuming modifications to current groundwater (baseline) conditions including the addition of five extraction wells spaced on approximate centers of 200-feet, located along the southern site boundary. Modifications to baseline consist of an additional 4 new site pumping wells (NPW-1 to 4) located in the western plume and operating at rates of 13.13 gpm. Additionally, operational rates for site wells PW-1, PW-3, PW-5, and PW-6 are modified to 13.13 gpm. The five extraction wells were simulated at operational flow rates of 20 gpm. Scenario 8 is presented on Figures 60, 61, and 62, respectively.

4.6 FATE AND TRANSPORT MODEL SIMULATION RESULTS

Results of fate and transport model simulations are described below. Scenario details and clean-up times are presented on Table 1. Additionally, AVI files for the scenarios have been created and are included in Attachment 1 as a CD.

Scenario 1 Under baseline conditions TCE is the only contaminant predicted to be below its associated cleanup level at the end of the 50-year simulation period. TCE concentrations are predicted to fall below the cleanup level in 30 years. VC and 1,4-dioxane concentrations are not predicted to be below their respective clean up levels at the end of the 50 year simulation period. 1,4-Dioxane coincident with TCE along the western property boundary would not be removed but re-circulated by extraction and discharge in this area. VC and 1,4-dioxane mass south of the operating extraction wells would not be captured and migrates to the southeast of SR20.

Scenario 2 In this scenario the time to cleanup for TCE contamination is slightly improved, falling below the cleanup level in 18 years. VC and 1,4-dioxane are predicted to be remediated at an accelerated rate but are not predicted reach cleanup level concentrations during the 50 year

simulation period. Mass not captured by operating extraction wells or remediated due to ISCO injections migrates to the southeast of SR20.

Scenario 3 In this scenario the time to cleanup for TCE contamination is even more reduced versus Scenario 2. TCE concentrations are predicted to fall below the cleanup level in 13 years. VC and 1,4-dioxane remediation continues to be predicted at an accelerated rate in the ISCO zone but are not predicted to reach cleanup level concentrations during the 50 year simulation period. Mass not captured by operating extraction wells or remediated due to ISCO injections migrates to the southeast of SR20.

Scenario 3a In this scenario, none of the simulated contaminants are predicted to fall below their respective cleanup level concentrations within the model simulation period. TCE is predicted to migrate off site to the south and southwest while VC and 1,4-dioxane migrate to the southeast.

Scenario 4 In this scenario, the cleanup time of TCE is increased when compared to Scenario 3. TCE concentrations fall below the cleanup level in 17 years. Similar to previous scenarios, VC and 1,4-dioxane are not predicted to fall below their respective clean up levels during the simulation period. Contamination remaining in groundwater is predicted to migrate towards the southeast.

Scenario 5 All contaminants are predicted to be reduced below their respective cleanup levels within the 50-year simulation period. TCE is expected to be reduced below cleanup levels in 28 years. VC and 1,4-Dioxane concentrations are predicted to be reduced below cleanup levels in 21 and 32 years, respectively.

Scenario 5a In this scenario, cleanup time is reduced for all contaminants when compared to Scenario 5. TCE is expected to be reduced below cleanup levels in 18 years while VC and 1,4-Dioxane concentrations are predicted to be reduced below cleanup levels in 17 and 24 years, respectively.

Scenario 6 In this scenario, cleanup times are increased for TCE and VC when compared to Scenario 5a. Additionally, 1,4-dioxane is not predicted to fall below its respective clean up level during the simulation period. TCE and VC concentrations are expected to be reduced below their cleanup levels in 33 and 21 years, respectively. 1,4-Dioxane contamination remaining in groundwater is predicted to migrate towards the southeast.

Scenario 7 In this scenario, VC is the only contaminant predicted to be below its cleanup level at the end of the simulation period. VC concentrations are predicted to fall below the cleanup level in 25 years. TCE and 1,4-dioxane mass not destroyed by insitu barriers are predicted to migrate off site to the south and southwest (TCE) and southeast (1,4-Dioxane).

Scenario 8 All contaminants are predicted to be reduced below their respective cleanup levels within the 50-year simulation period. Similar to Scenario 5a, TCE is expected to be reduced below cleanup levels in 18 years while similar to Scenario 5, VC and 1,4-Dioxane concentrations are predicted to be reduced below cleanup levels in 21 and 32 years, respectively.

Scenario 9 All contaminants are predicted to be reduced below their respective cleanup levels within the 50-year simulation period. Similar to Scenario 3, TCE is expected to be reduced below its cleanup level in 13 years, which is the fastest simulated cleanup time for TCE. Similar to Scenarios 5 and 8, VC and 1,4-Dioxane concentrations are predicted to be reduced below cleanup levels in 21 and 32 years, respectively.

Scenario 10 In this scenario, TCE is the only contaminant predicted to be below its cleanup level at the end of the simulation period. TCE concentrations are predicted to fall below the cleanup level in 18 years. VC and 1,4-Dioxane mass remaining in groundwater is predicted to migrate to the southeast.

5 SUMMARY

The 3-D steady state groundwater flow and fate and transport model developed for the site is considered ready for use as a tool to assess groundwater remediation efforts based on the results of model calibration and verification. This model was used to assess a series of proposed remedial strategies and their ability to accelerate remedial objectives. Twelve scenarios were simulated incorporating various levels of effort utilizing ISCO to reduce hotspot concentrations along with the addition of proposed extraction wells and injection wells in latter scenarios. Based on this model effort, the following conclusions and recommendations were derived:

- Scenario 5a represents the optimized scenario for contaminant clean-up at the site. This scenario is predicted to achieve remedial objectives for TCE within 18 years and both VC (17 years) and 1,4-dioxane (24 years) within the shortest simulated timeframe. Whereas TCE is predicted to reach cleanup goals sooner in Scenarios 3 and 9 (13 years), Scenario 5a is one of only four scenarios in which all three contaminants are predicted to reach cleanup levels within the model simulation period and includes optimized cleanup times for two of the three COCs.

This conclusion is based exclusively on predicted time to reach cleanup goals. This conclusion does not consider cost implications or the merits of this Scenario against the nine criteria specified in the Comprehensive Environmental Response, Compensation, and Liability Act.

6 MODEL UNCERTAINTY AND LIMITATIONS

This groundwater transport model can be a powerful tool, if used appropriately, to assist in making management decisions for this site. Use of this model is subject to some limitations; like any computer model, it has inherent uncertainty. This does not, however, preclude its use to help make cleanup decisions. To the contrary, this model should be used whenever possible as a tool to assess current operations and to help implement response actions.

Any groundwater flow and transport model is a simplification of the natural environment and, therefore, has recognized limitations. Hence, some uncertainty exists in the ability of any numeric model to completely predict groundwater flow and contaminant transport. Considerable effort was expended to minimize model uncertainty by using real-world values as realistic model input whenever available and by conducting numerous model simulations to calibrate and verify the model. Uncertainty of the model output results from uncertainties in the conceptual model, input parameters, and the ability of the numerical model to effectively simulate field conditions.

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Table 1. Fate and Transport Model Simulation Results					
Scenario	Scenario Details		Cleanup Time (years)		
			TCE	VC	1,4-Dioxane
Scenario 1	Groundwater Extraction (Baseline)	PW-1 - operational at 26.5 gpm	30	>50	>50
		PW-2 - operational at 0 gpm			
		PW-3 - operational at 29 gpm			
		PW-4 - operational at 20 gpm			
		PW-5 - operational at 24 gpm			
		PW-6 - operational at 23.5 gpm			
		PW-7 - operational at 23.5 gpm			
		PW-8 - operational at 12.5 gpm			
		PW-9 - operational at 16 gpm			
		PW-10 - operational at 0 gpm			
Scenario 2	Baseline		18	>50	>50
	ISCO Injections	70% reduction of mass. Spaced at approximate 200-foot intervals. Orientated within the 50 µg/l TCE plume and the 10 µg/l 1,4-Dioxane plume.			
Scenario 3	Baseline		13	>50	>50
	ISCO Injections	70% reduction of mass. Spaced at approximate 100-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.			
Scenario 3a	ISCO Injections	70% reduction of mass. Spaced at approximate 100-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.	>50	>50	>50
Scenario 4	Baseline		17	>50	>50
	ISCO Injections	50% reduction of mass. Spaced at approximate 100-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.			
Scenario 5	Baseline		28	21	32
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
Scenario 5a	Baseline		18	17	24
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
	ISCO Injections	70% reduction of mass. Spaced at approximate 200-foot intervals orientated within the 50 µg/l TCE plume and approximate 200-foot intervals orientated within the 4 µg/l 1,4-Dioxane plume.			
Scenario 6	Baseline		33	21	>50
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
	Reinjection of Treated Groundwater	Injection wells PIW-1 to PIW-10 added. Spaced on approximate 80-foot centers. Operational injection rates of 10 gpm.			
Scenario 7	Insitu Barriers	Destruction of contaminant mass upon contact. An approximate 1300-foot barrier orientated along the longitudinal axis of the 50 µg/l TCE plume with containment at the south and southeast extent of the plume. An approximate 1800-foot barrier orientated perpendicular to the longitudinal axis of the 4 µg/l 1,4-Dioxane plume and parallel with State Route 20.	>50	25	>50
Scenario 8	Baseline (Modified)	4 Additional pumping wells in the western plume and operational rates of 13.13 gpm at PW-1, PW-3, PW-5, PW-6, and the 4 new wells.	18	21	32
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
Scenario 9	Baseline (Modified)	4 Additional pumping wells in the western plume and operational rates of 13.13 gpm at PW-1, PW-3, PW-5, PW-6, and the 4 new wells.	13	21	32
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			
	ISCO Injections	70% reduction of mass. Spaced at approximate 200-foot intervals orientated within the 50 µg/l TCE plume.			
Scenario 10	Baseline (Modified)	4 Additional pumping wells in the western plume and operational rates of 13.13 gpm at PW-1, PW-3, PW-5, PW-6, and the 4 new wells.	18	>50	>50
	Additional Groundwater Extraction	Extraction wells PEW-1 to PEW-5 added and moved to the base southern boundary. Spaced on approximate 300-foot centers. Operational flow rates of 20 gpm.			

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Figure 1.
Site Location
NAS Whidbey (Area 6) Groundwater Model



Figure 2.
Model Domain Boundary
NAS Whidbey (Area 6) Groundwater Model

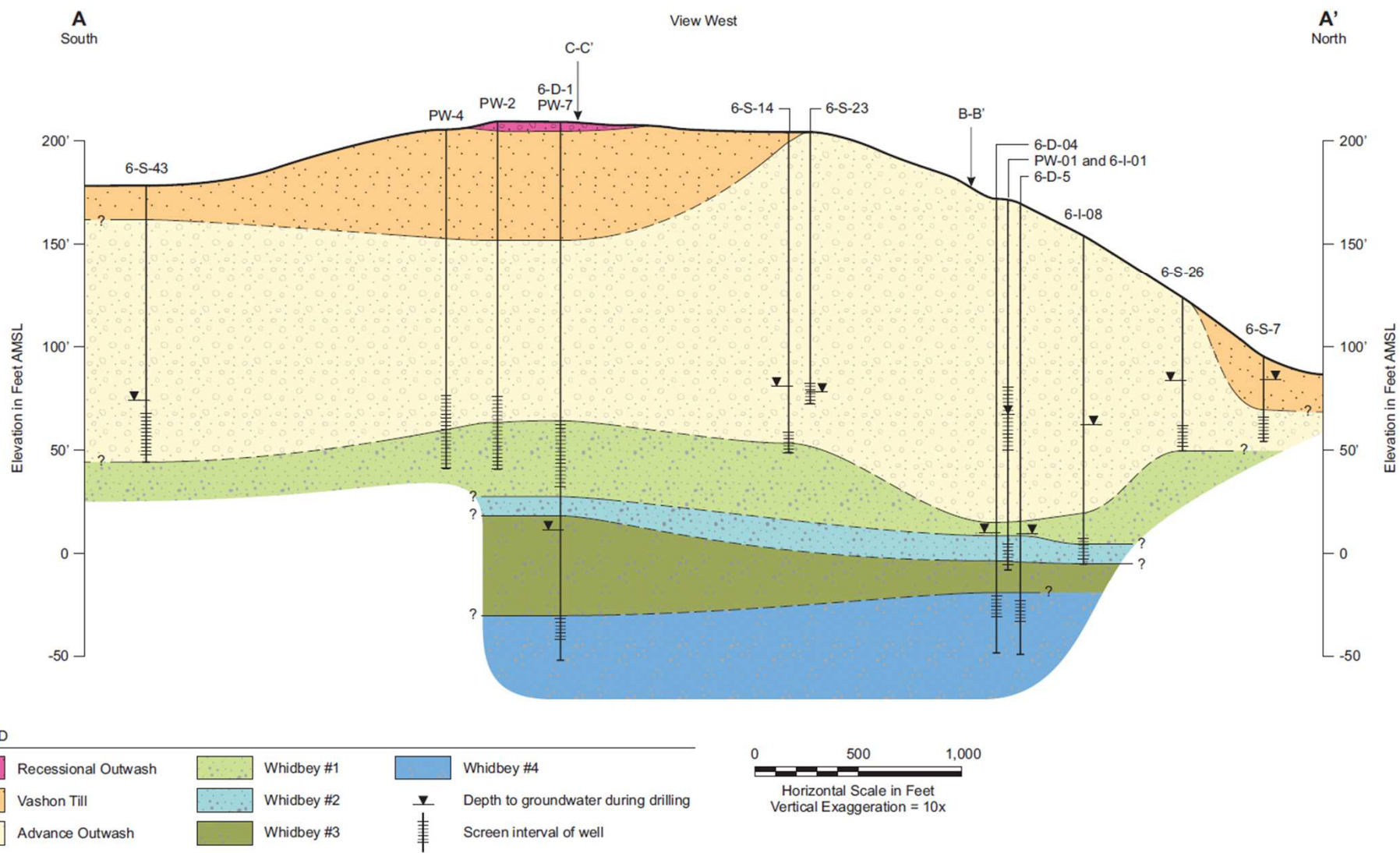


Figure 3.
Geologic Cross-Section A-A'
 NAS Whidbey (Area 6) Groundwater Model

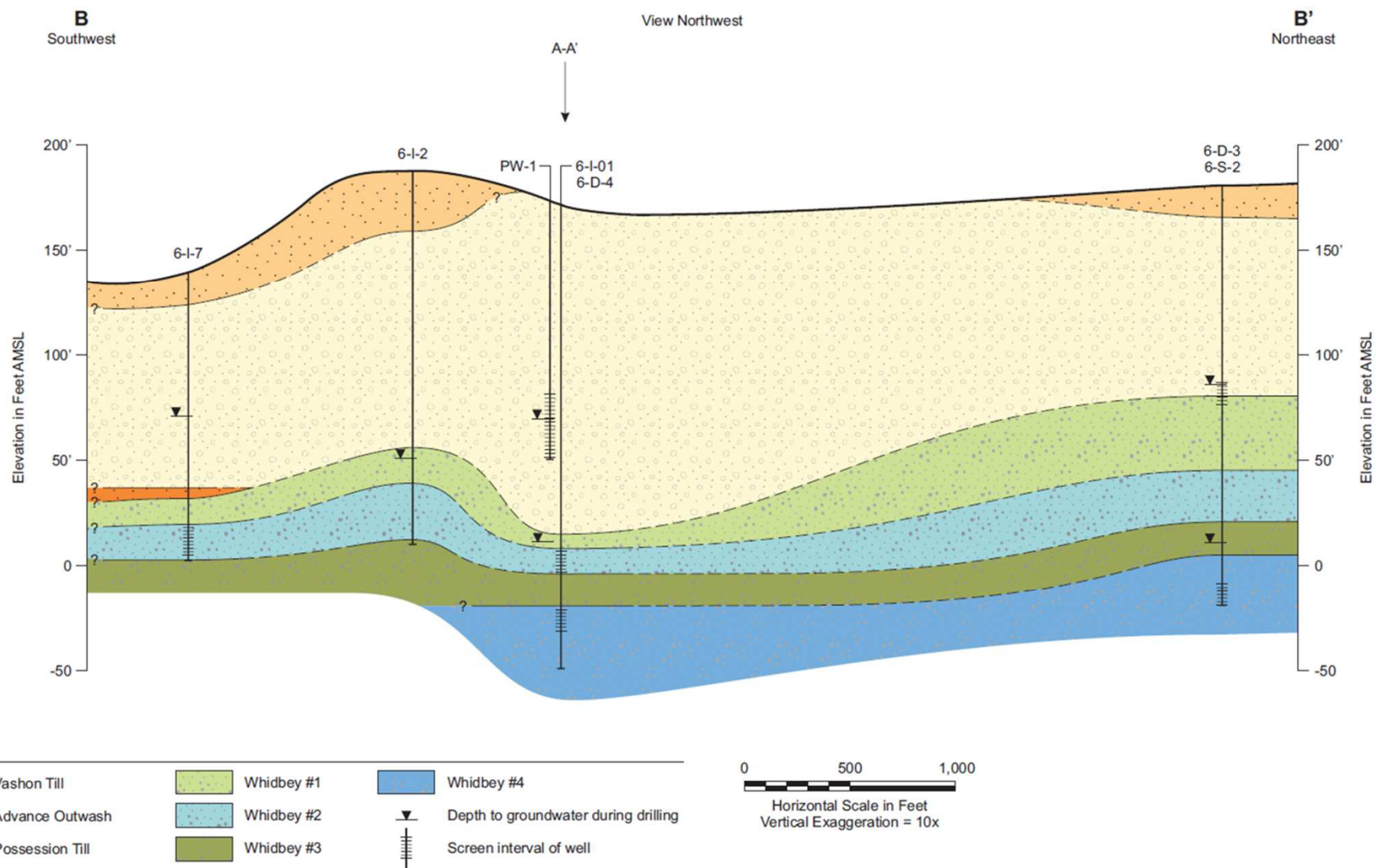
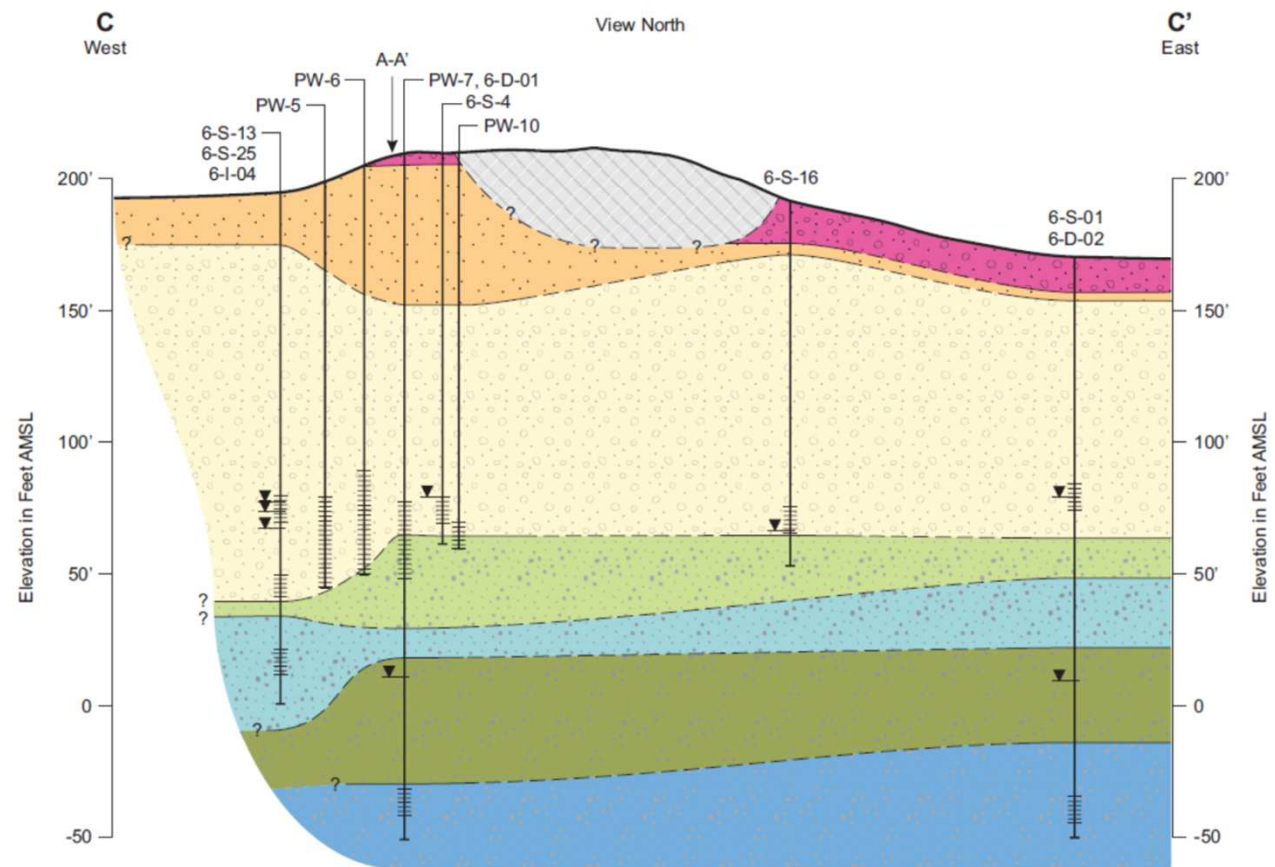


Figure 4.
Geologic Cross-Section B-B'
NAS Whidbey (Area 6) Groundwater Model



LEGEND

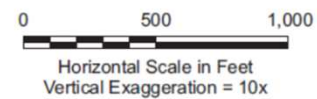
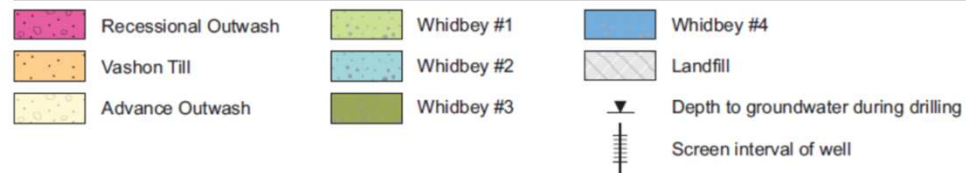
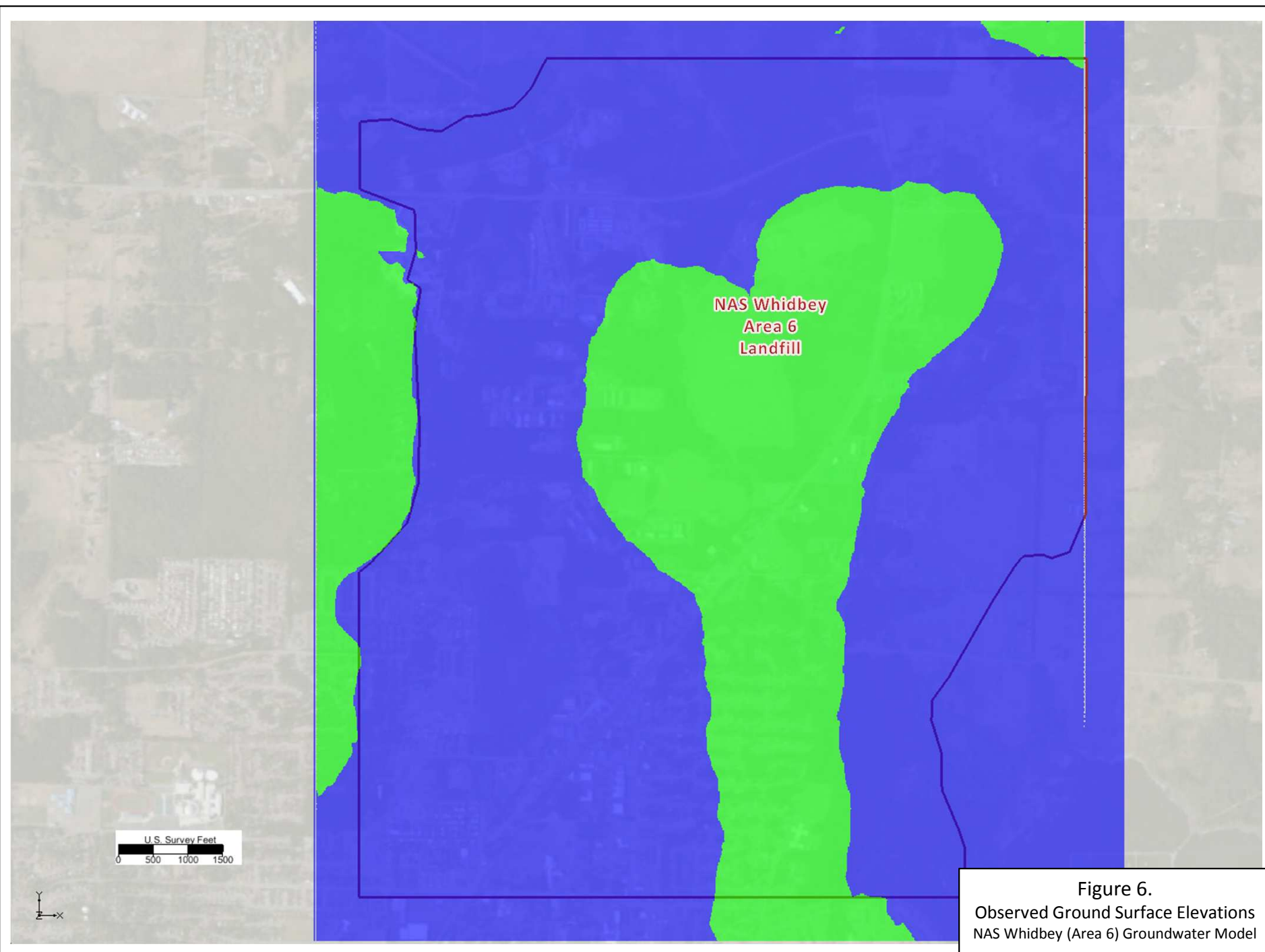


Figure 5.
Geologic Cross-Section C-C'
NAS Whidbey (Area 6) Groundwater Model



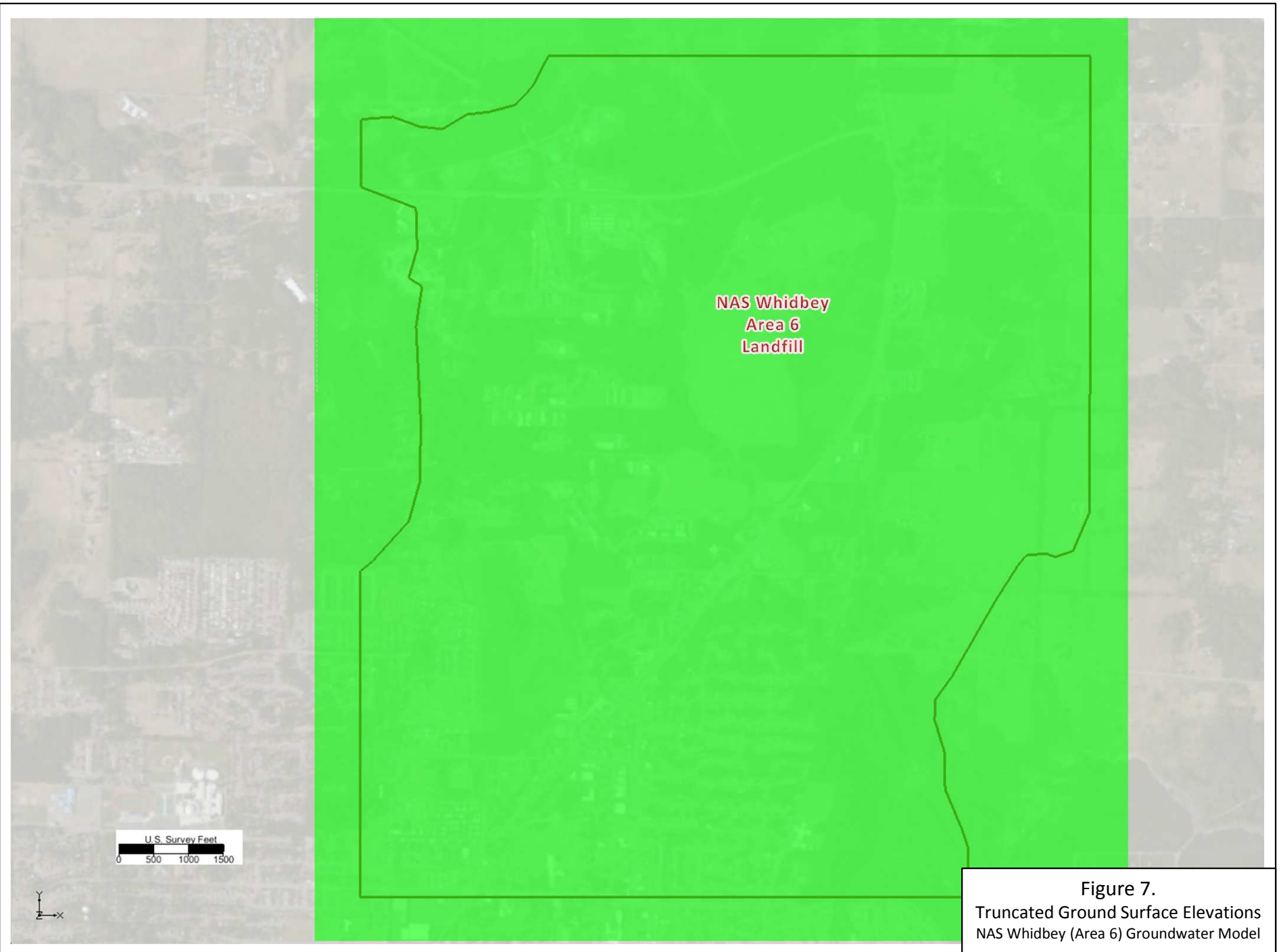




Figure 8.
GHB Boundary Locations
NAS Whidbey (Area 6) Groundwater Model



Figure 9.
Extraction Well Locations
NAS Whidbey (Area 6) Groundwater Model

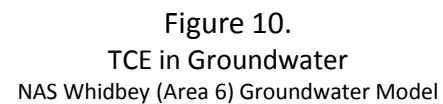


Figure 10.

TCE in Groundwater

NAS Whidbey (Area 6) Groundwater Model

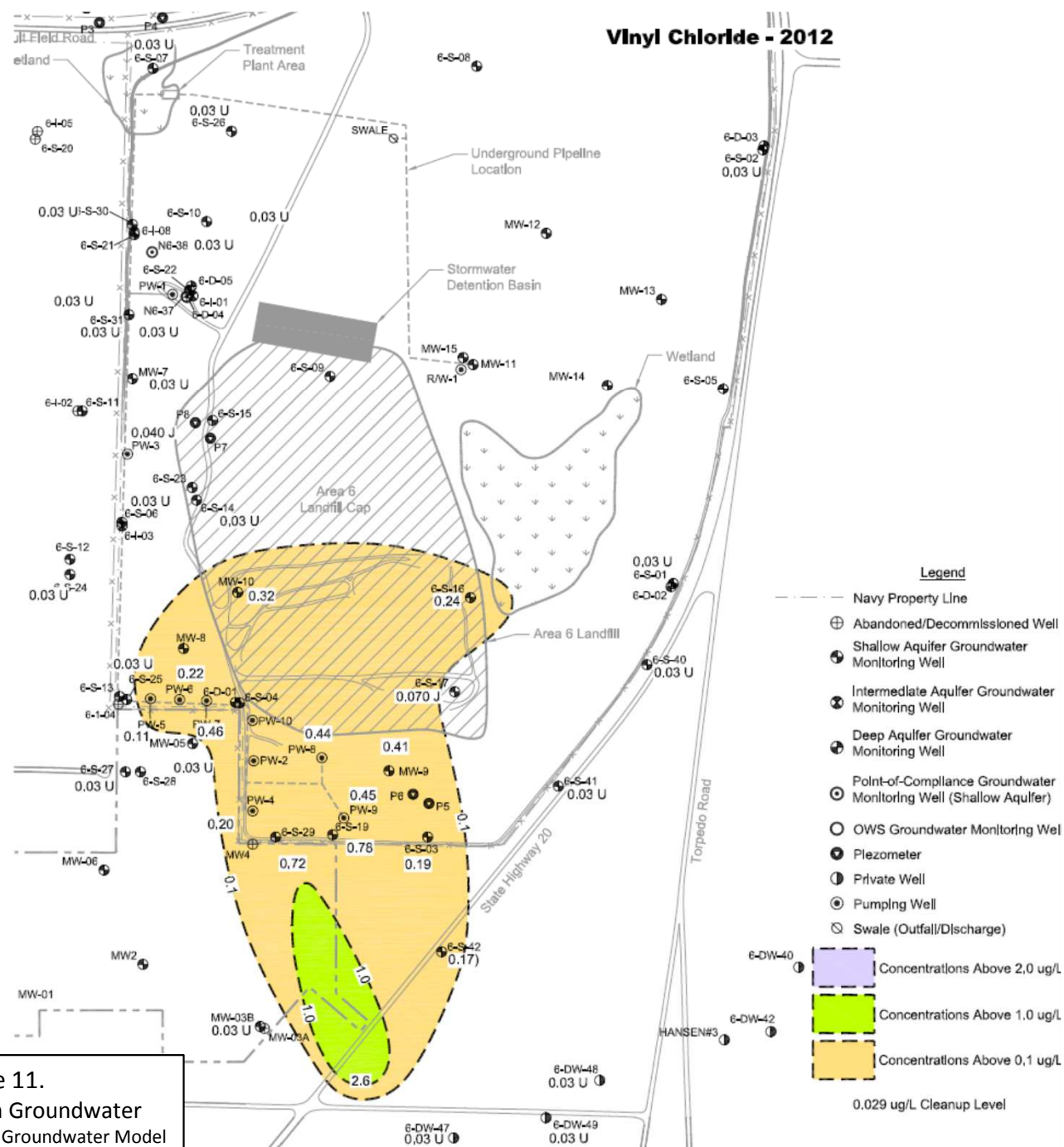


Figure 11.
Vinyl Chloride in Groundwater
NAS Whidbey (Area 6) Groundwater Model

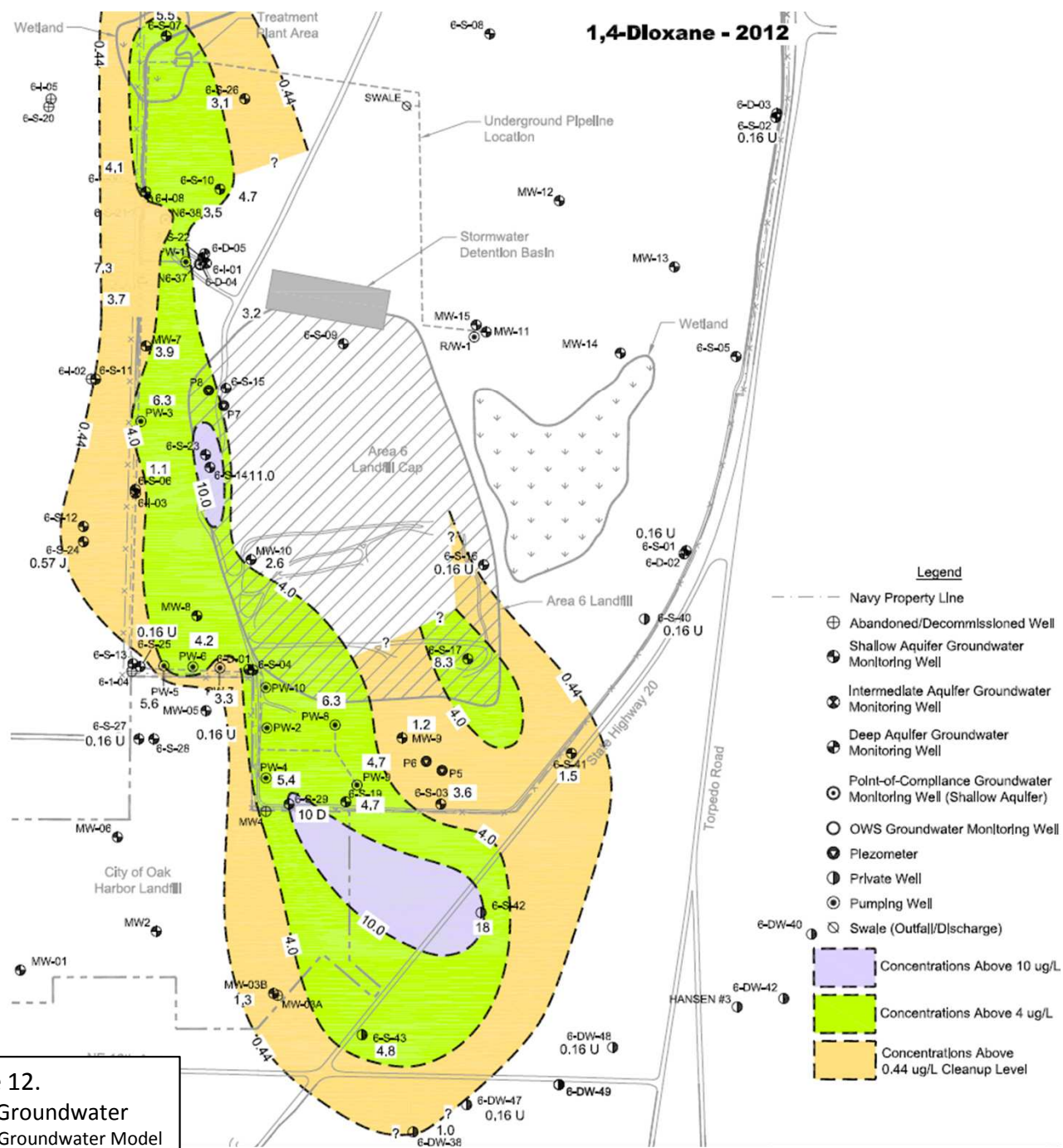
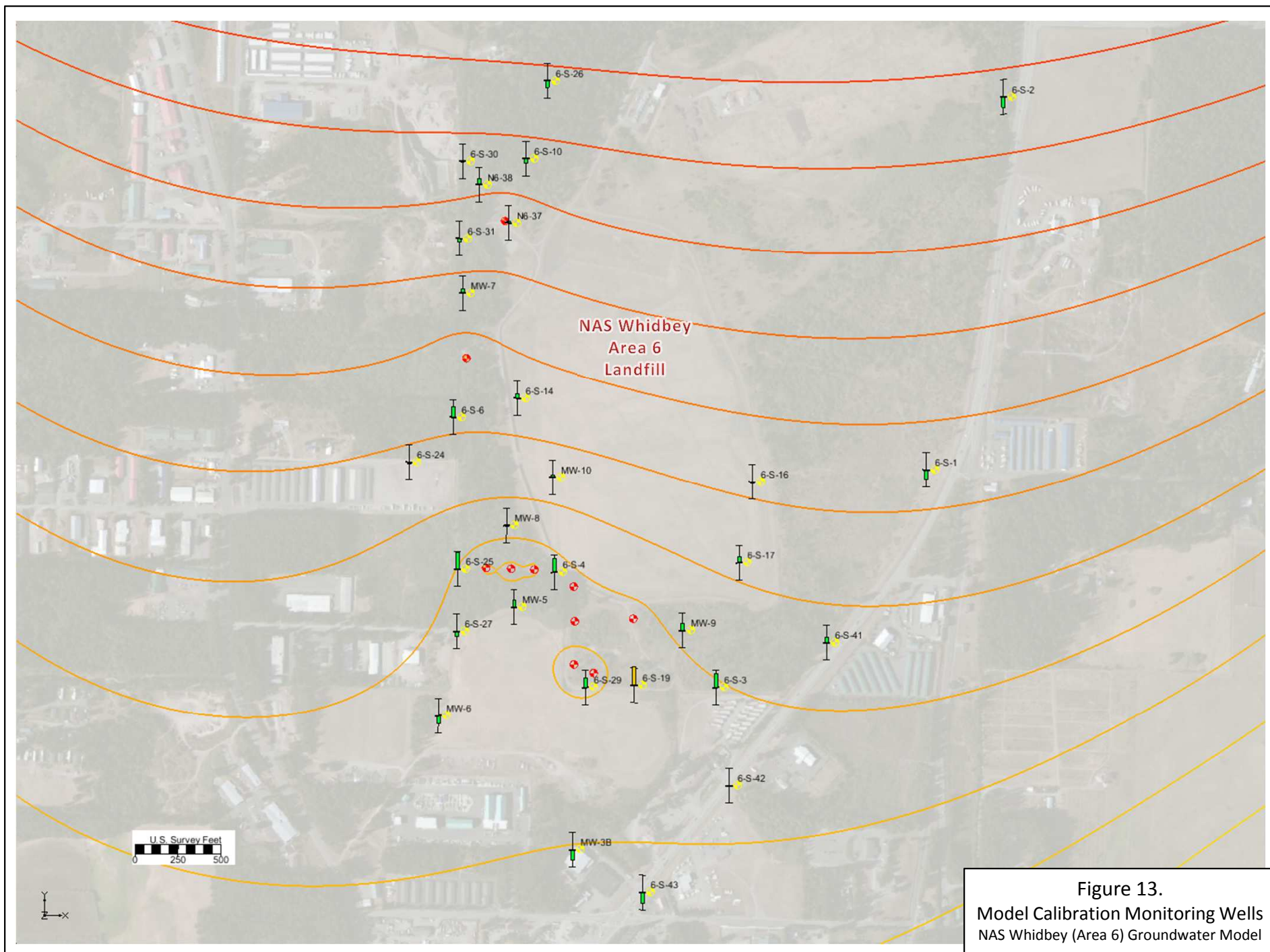


Figure 12.
1,4-Dioxane in Groundwater
NAS Whidbey (Area 6) Groundwater Model



Flow Model Sensitivity (Recharge)

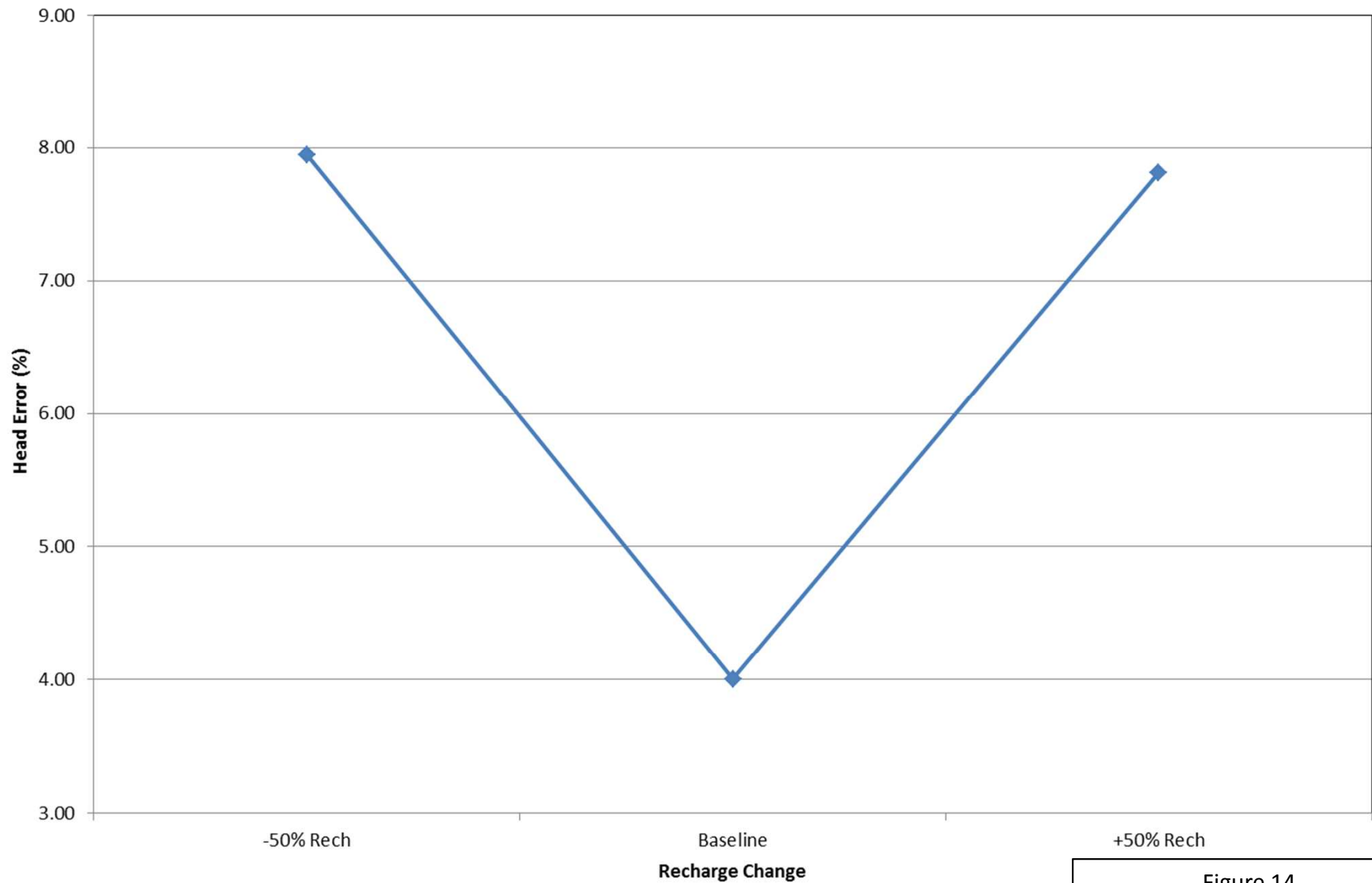


Figure 14.
Recharge
NAS Whidbey (Area 6) Groundwater Model

Flow Model Sensitivity (Hydraulic Conductivity)

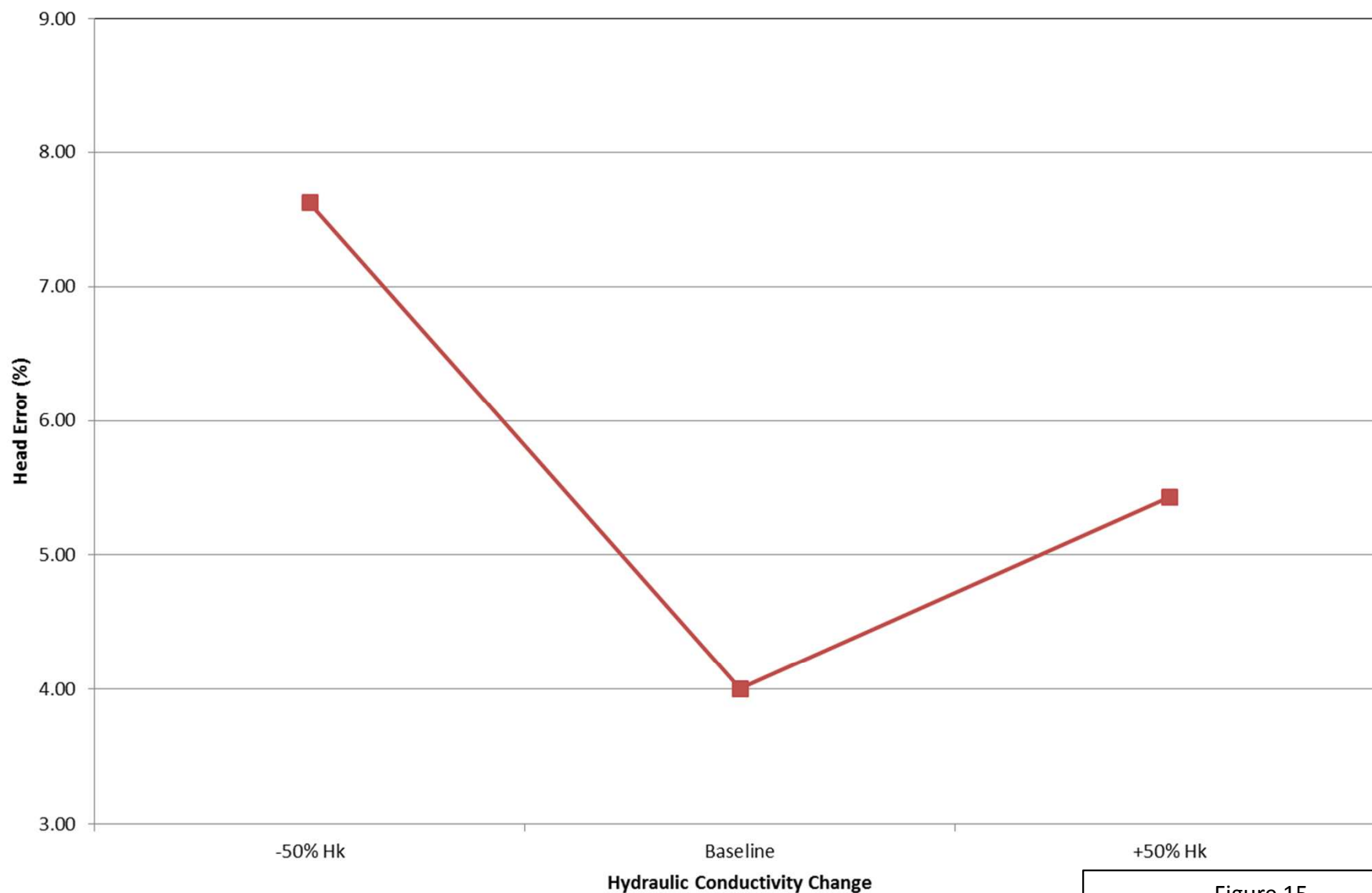


Figure 15.
Hydraulic Conductivity
NAS Whidbey (Area 6) Groundwater Model

Flow Model Sensitivity (General Head Boundary Heads)

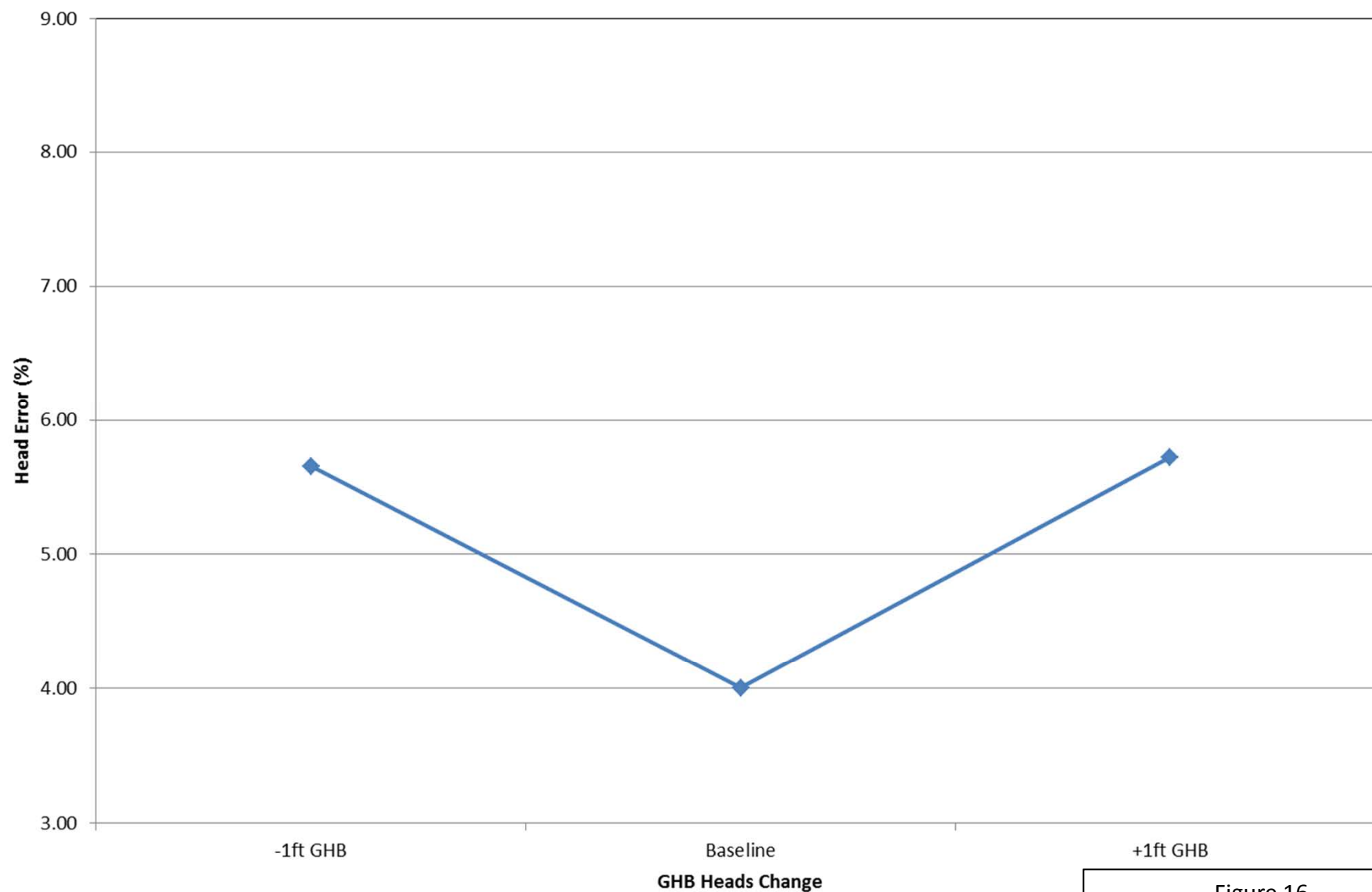


Figure 16.
GHB-Heads
NAS Whidbey (Area 6) Groundwater Model

Flow Model Sensitivity (General Head Boundary Conductance)

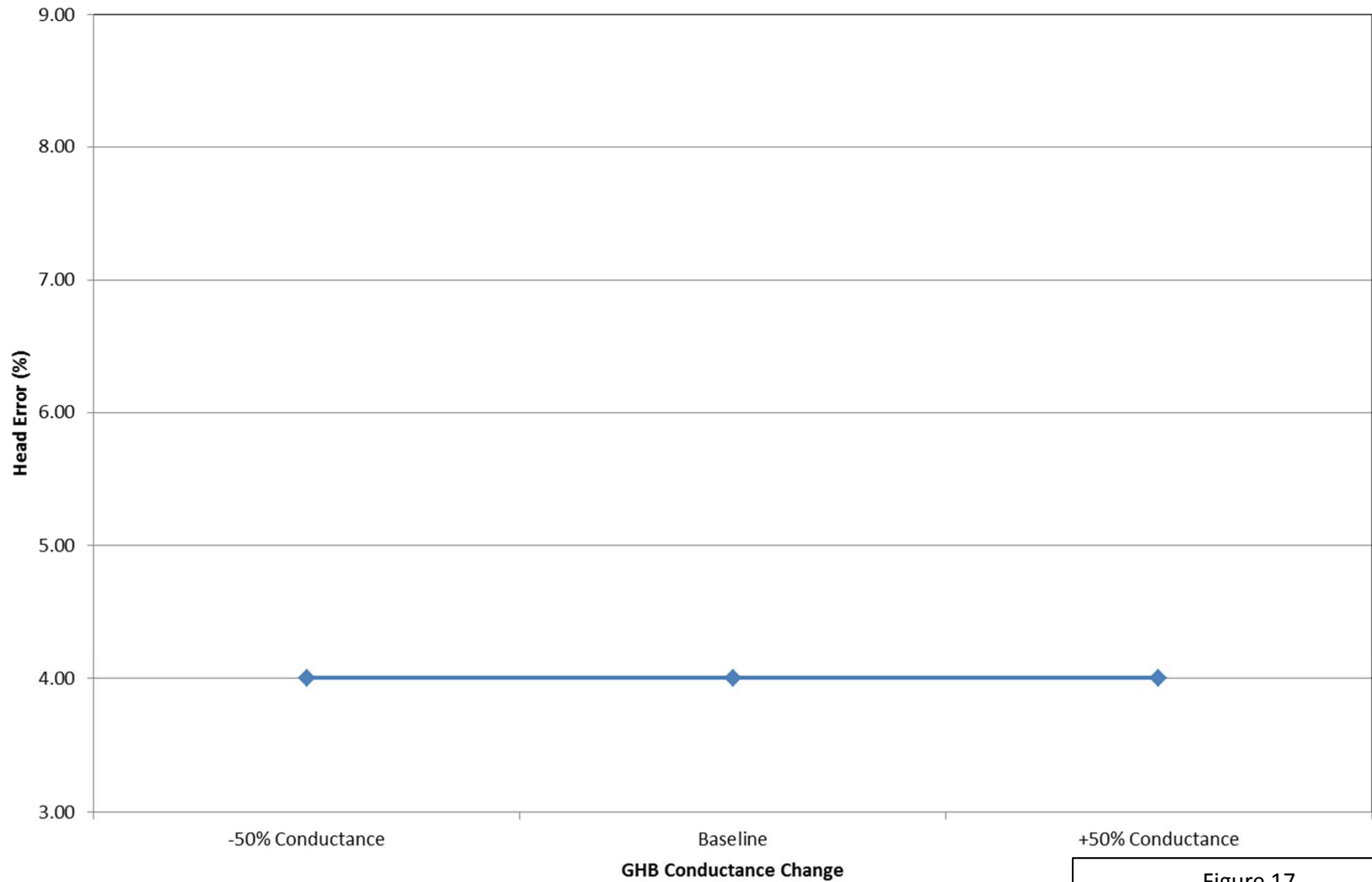
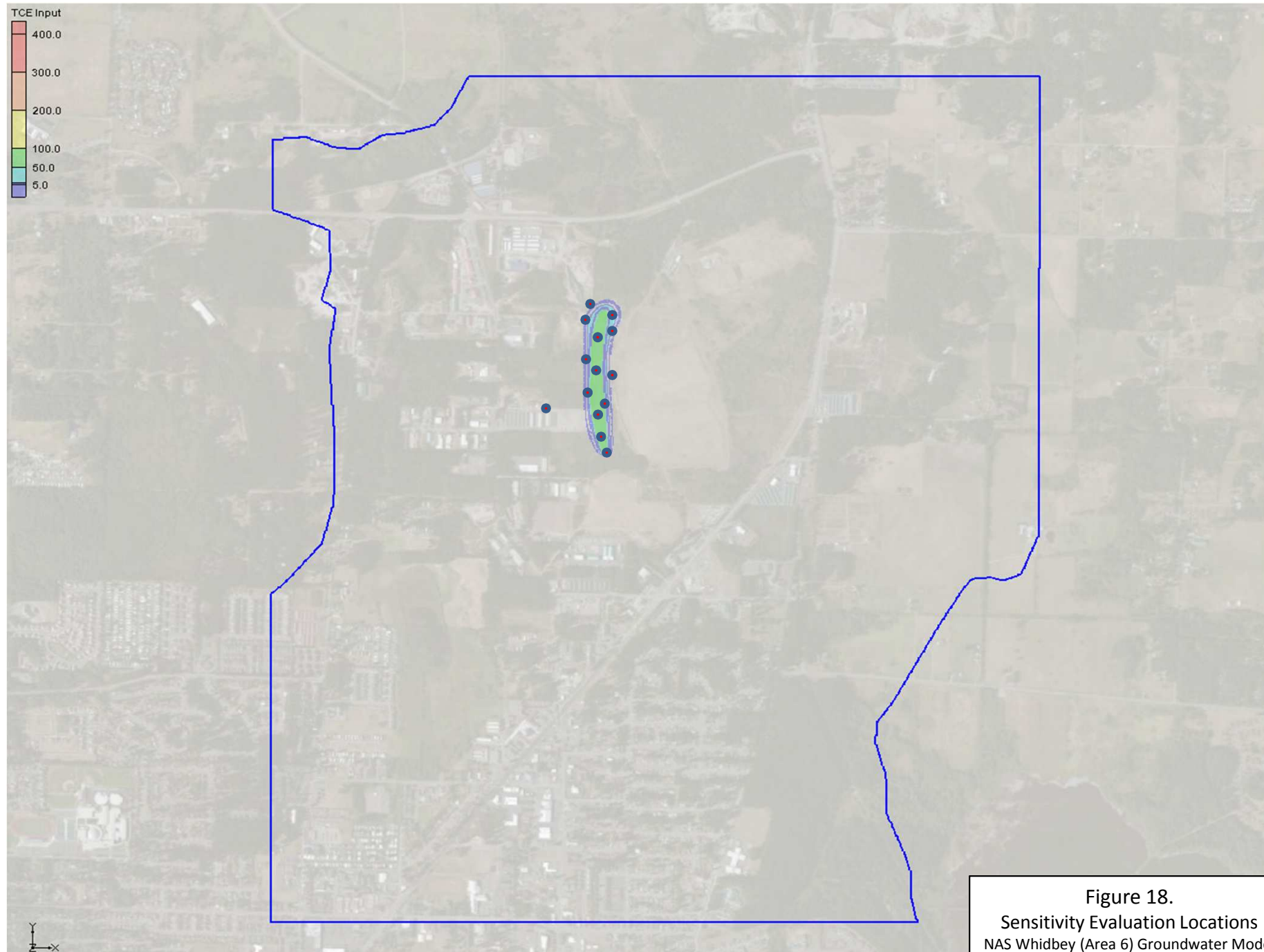


Figure 17.
GHB-Conductance
NAS Whidbey (Area 6) Groundwater Model



Fate and Transport Model Sensitivity (Total Organic Carbon)

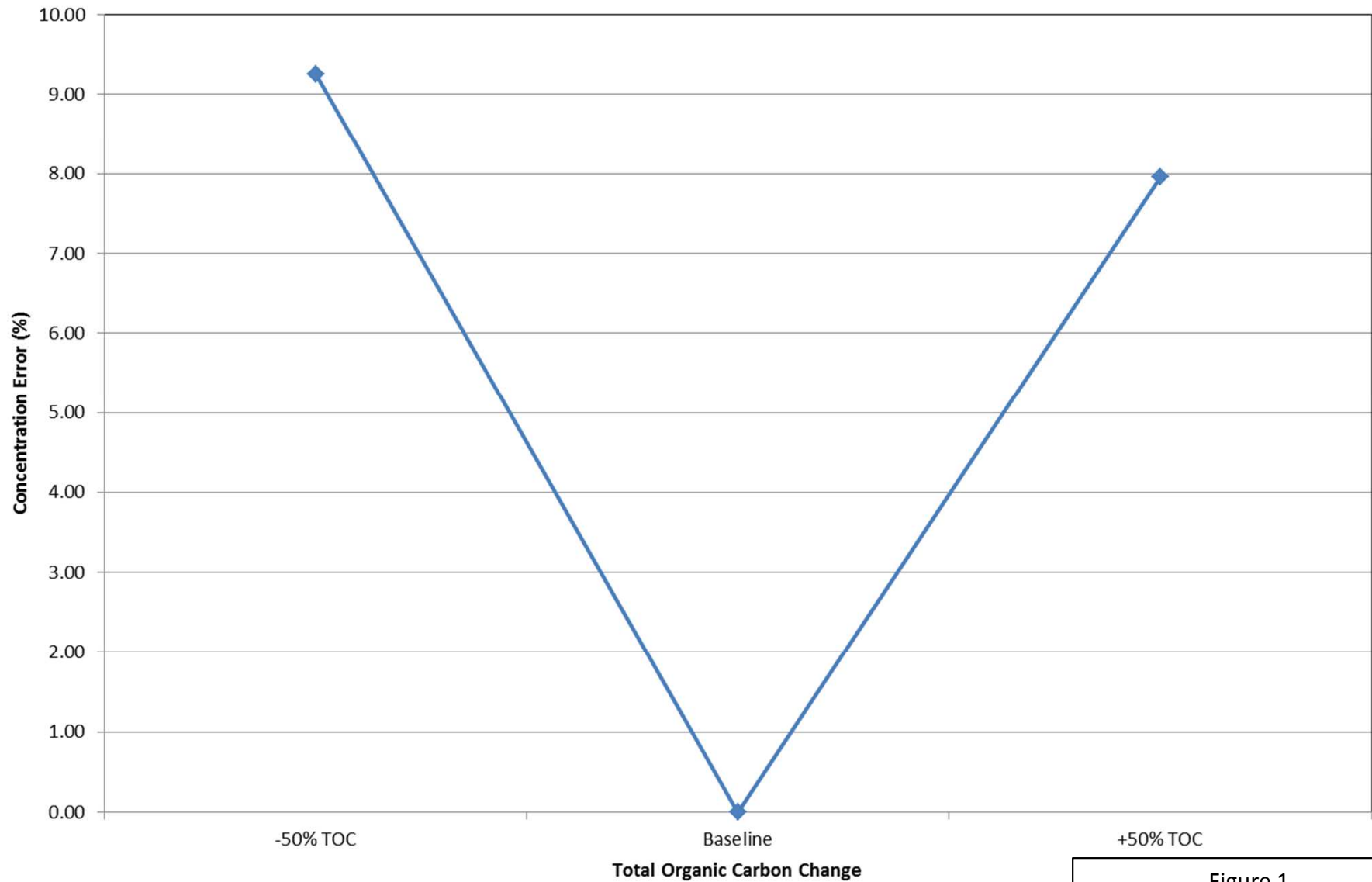


Figure 1.
Site Location
NAS Whidbey (Area 6) Groundwater Model

Fate and Transport Model Sensitivity (Hydraulic Conductivity)

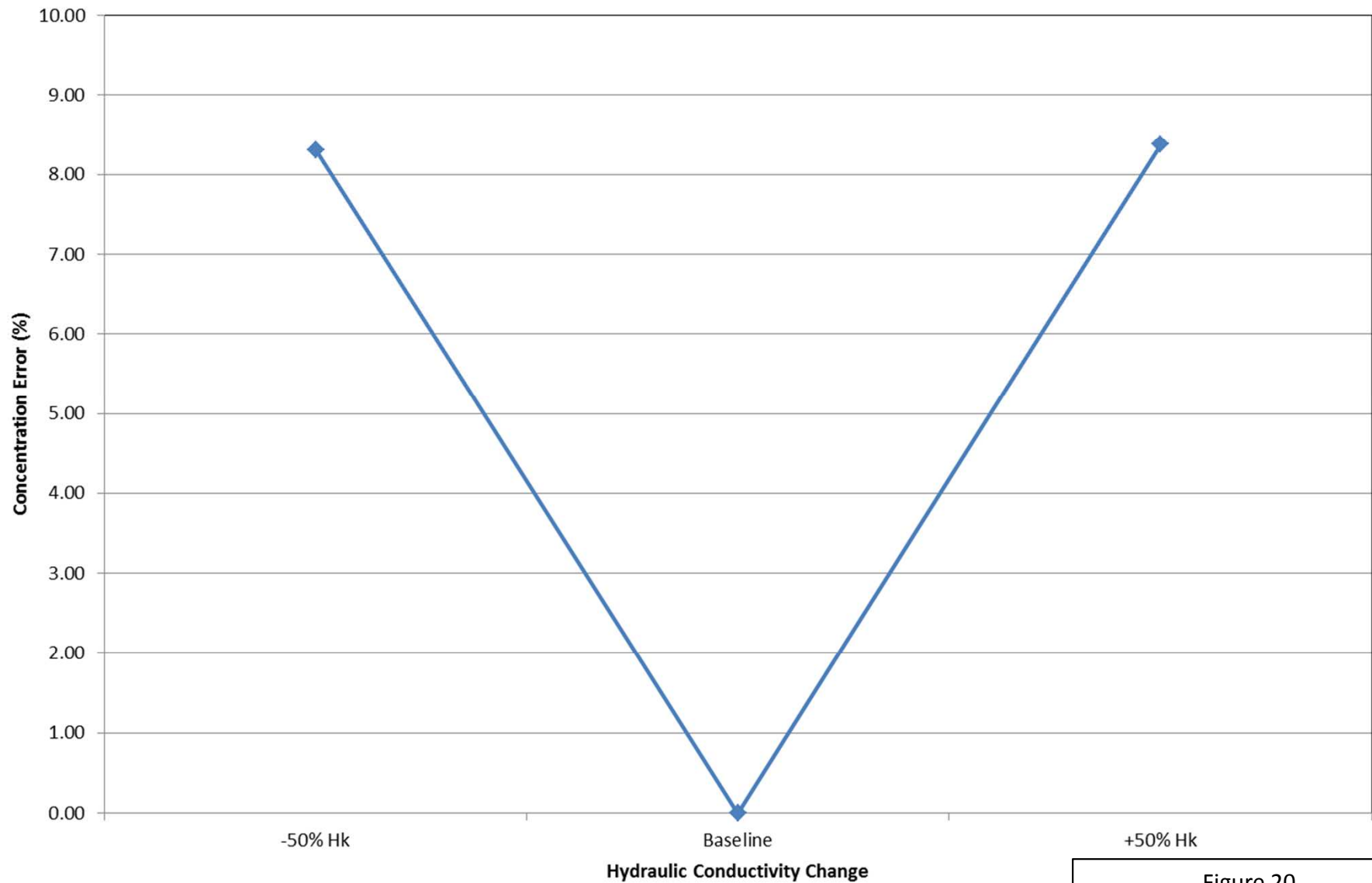


Figure 20.
Hydraulic Conductivity
NAS Whidbey (Area 6) Groundwater Model

Fate and Transport Model Sensitivity (Dispersivity)

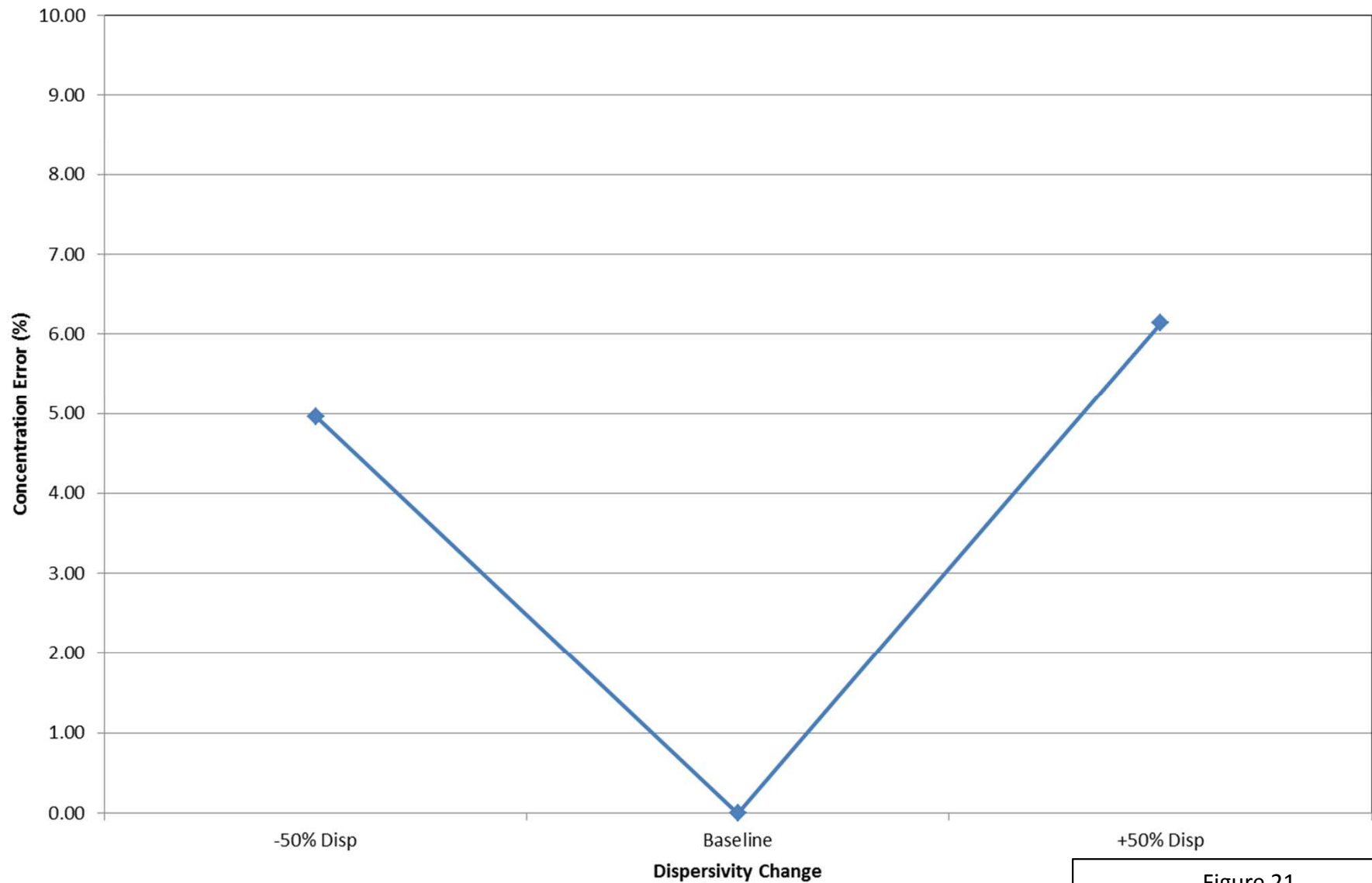


Figure 21.
Dispersivity
NAS Whidbey (Area 6) Groundwater Model

Fate and Transport Model Sensitivity (Recharge)

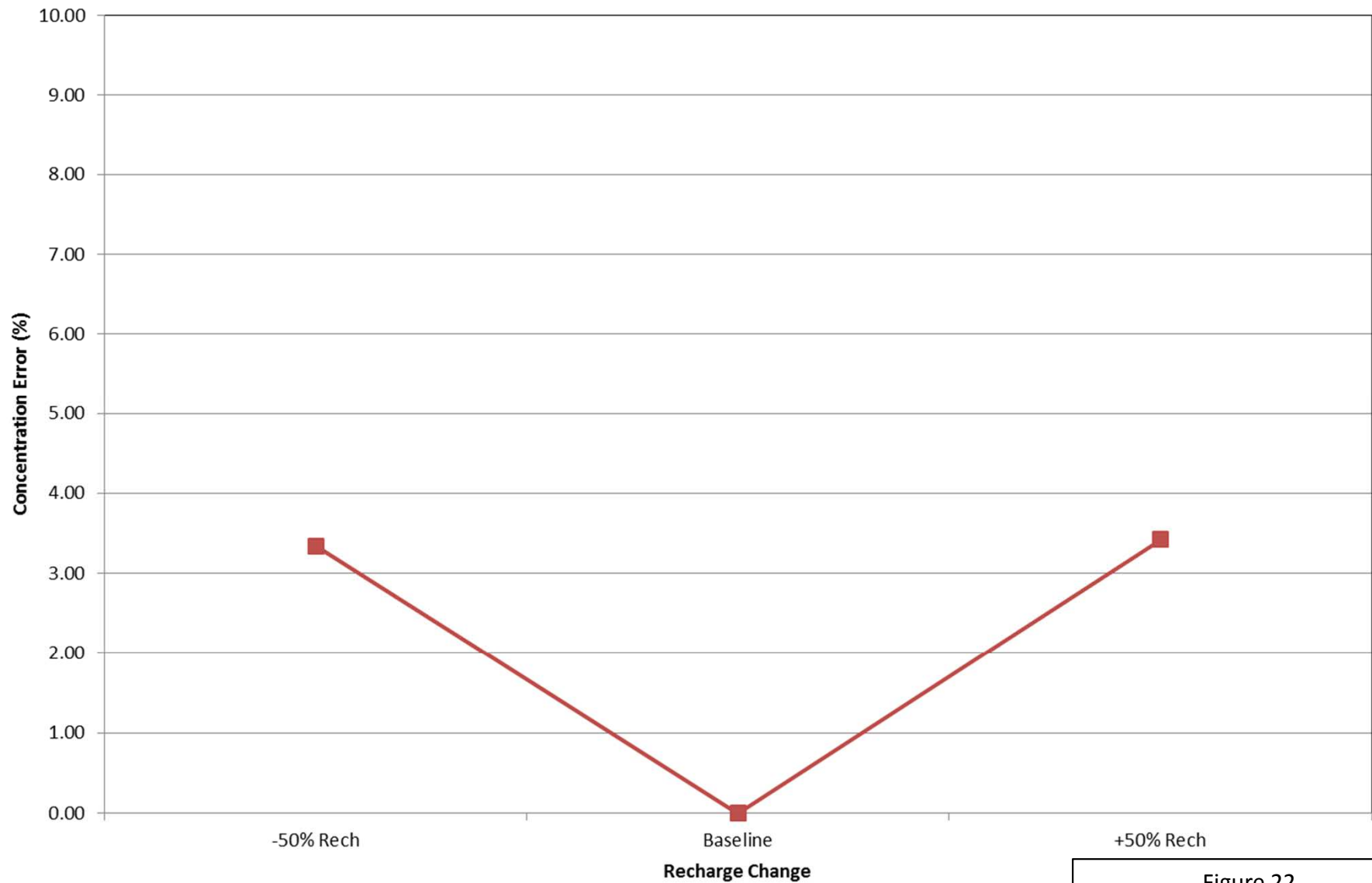
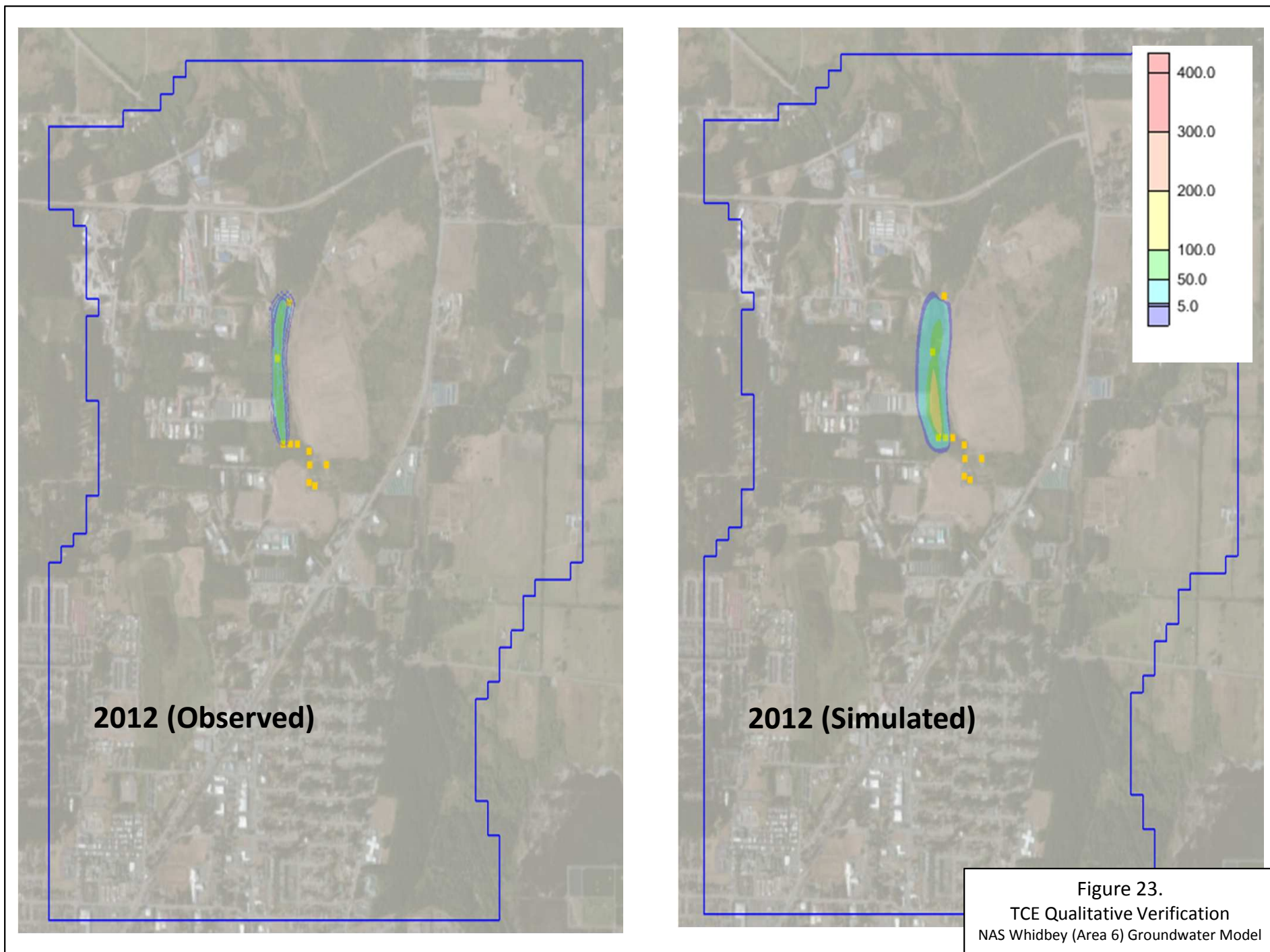


Figure 22.
Recharge
NAS Whidbey (Area 6) Groundwater Model



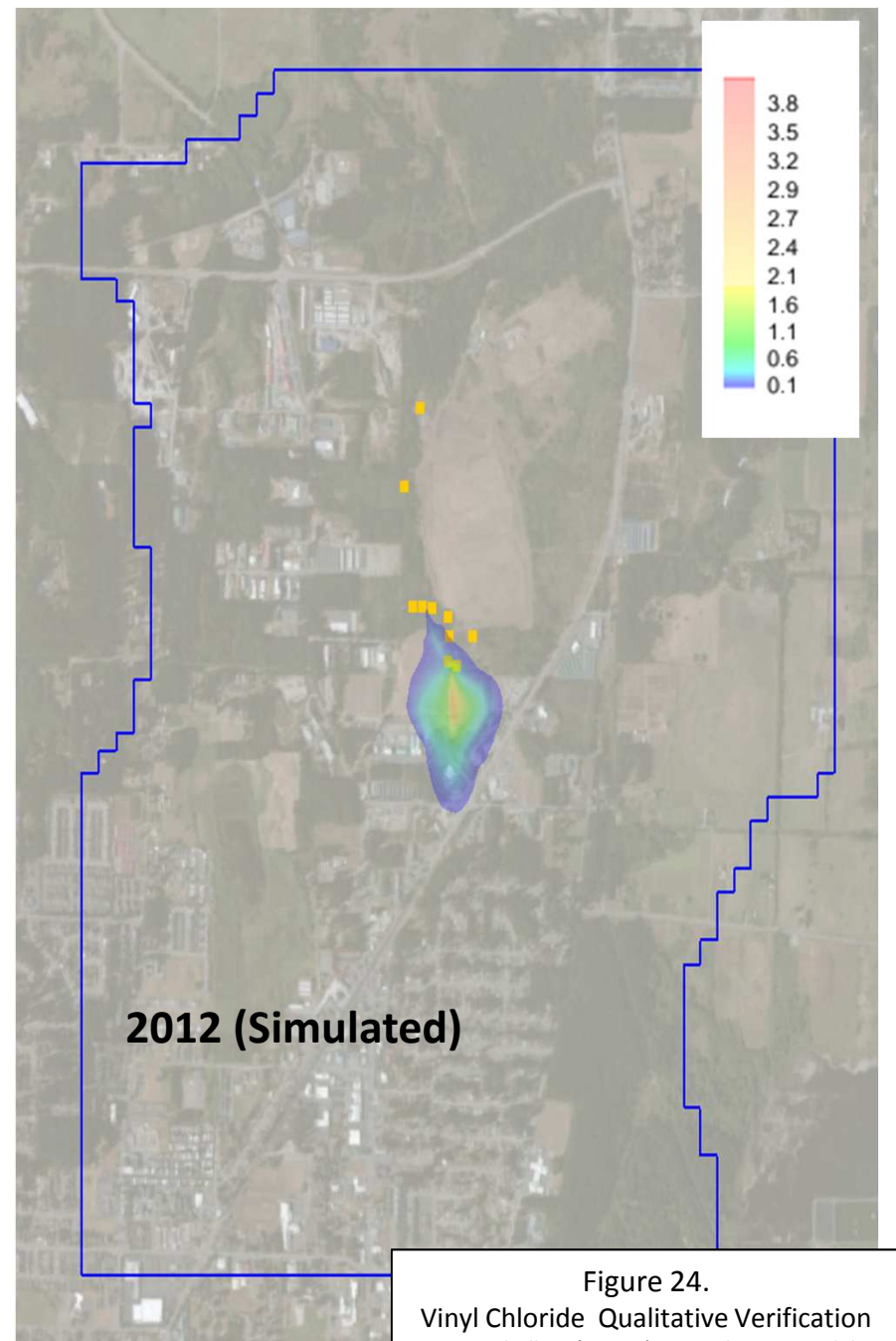
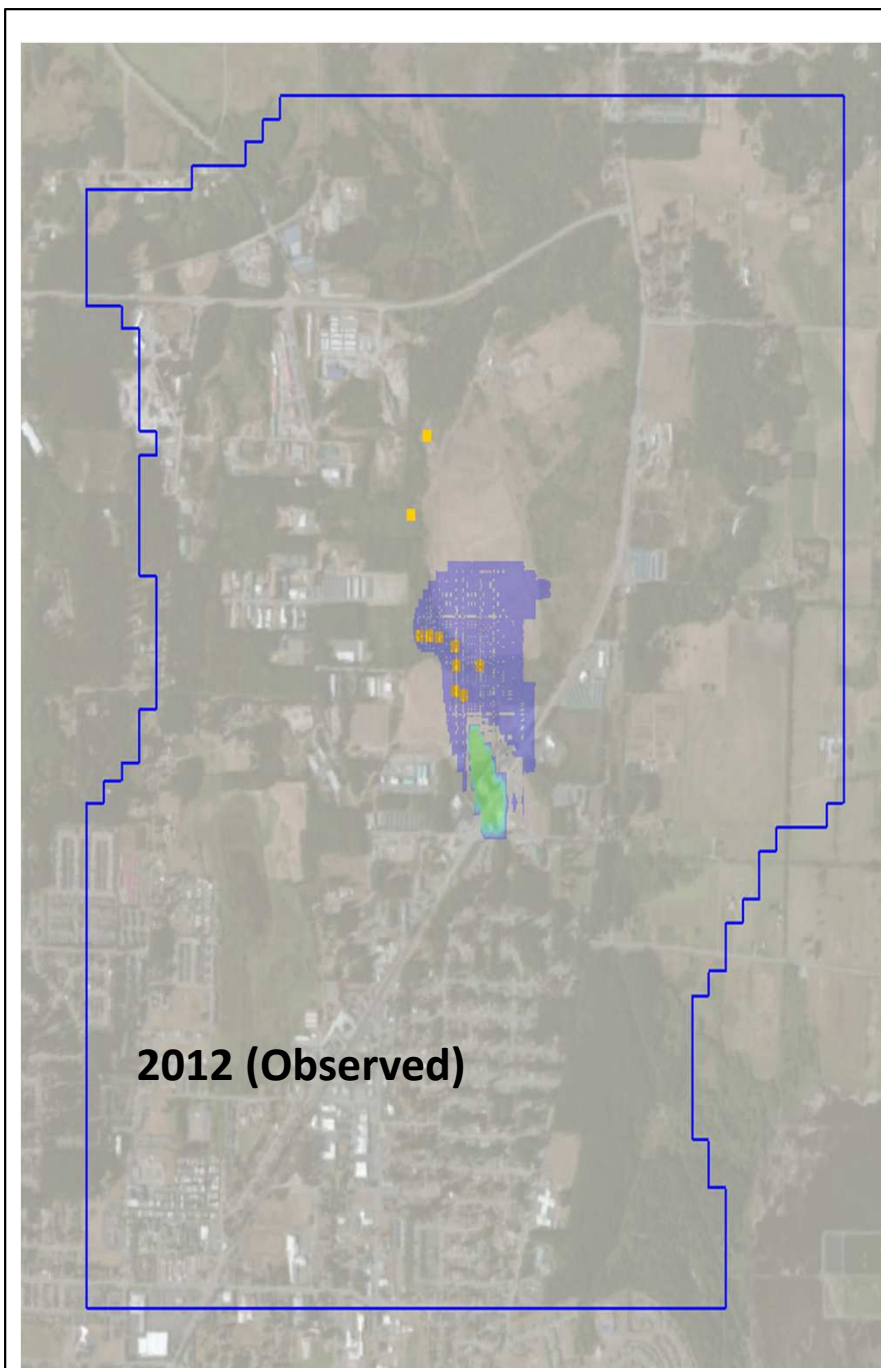


Figure 24.
Vinyl Chloride Qualitative Verification
NAS Whidbey (Area 6) Groundwater Model

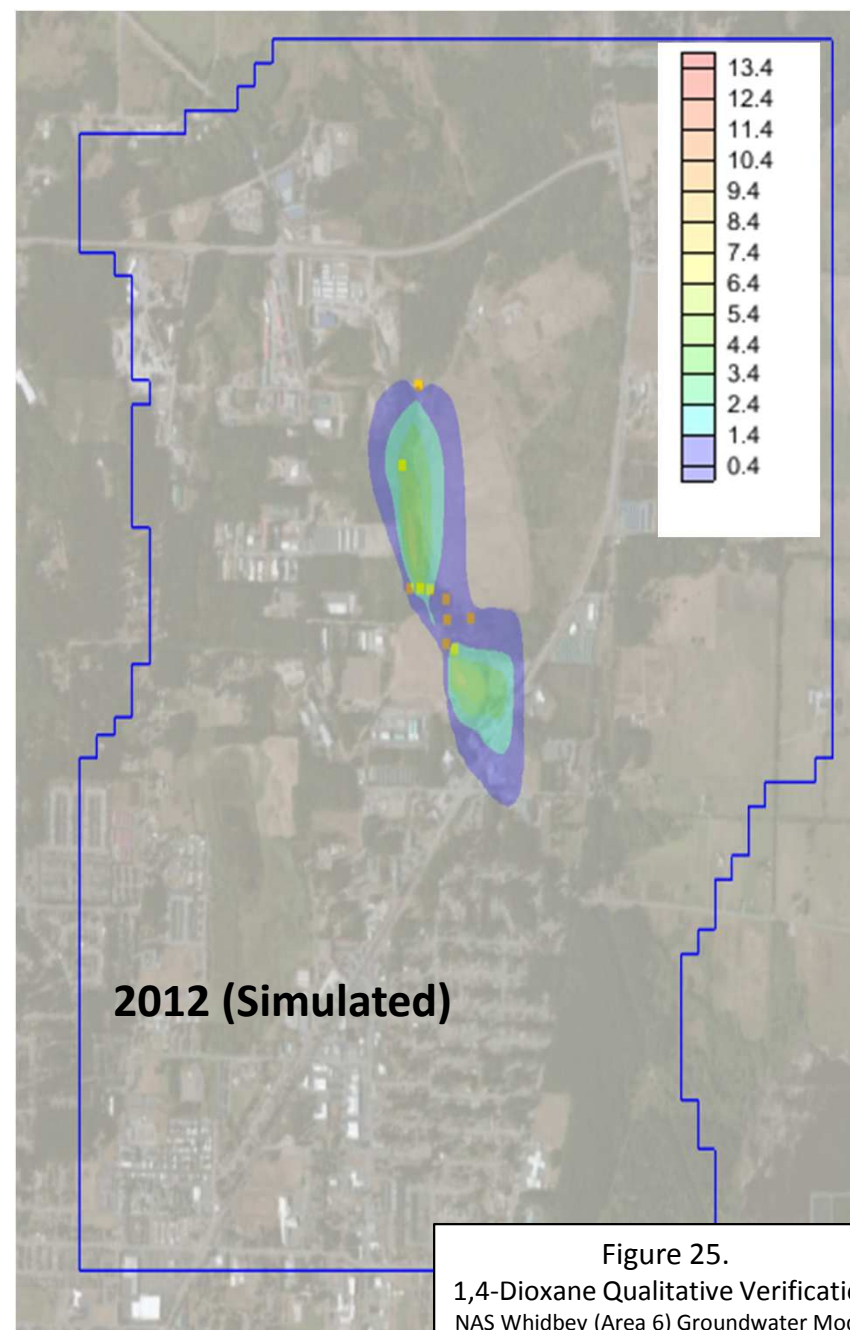
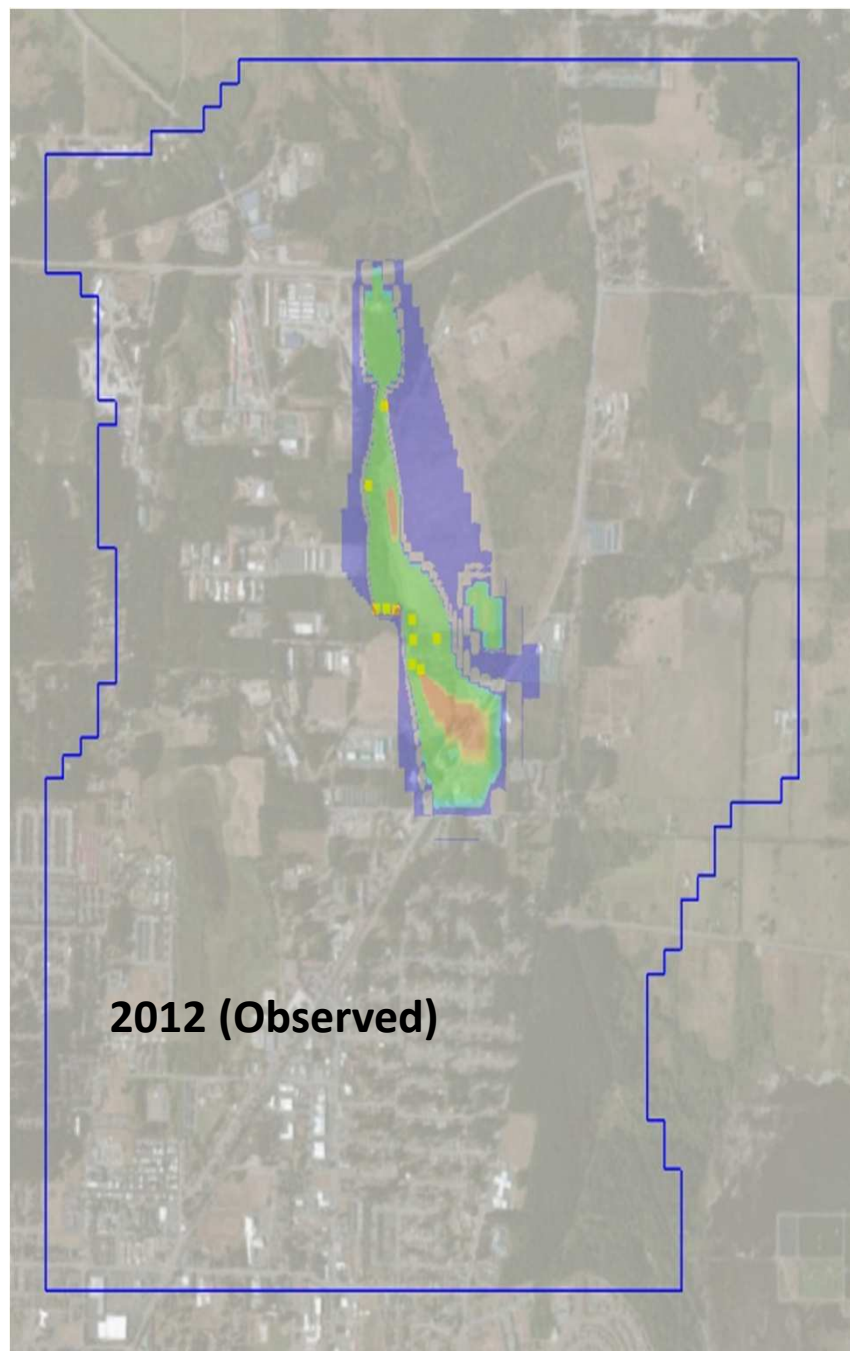


Figure 25.
1,4-Dioxane Qualitative Verification
NAS Whidbey (Area 6) Groundwater Model

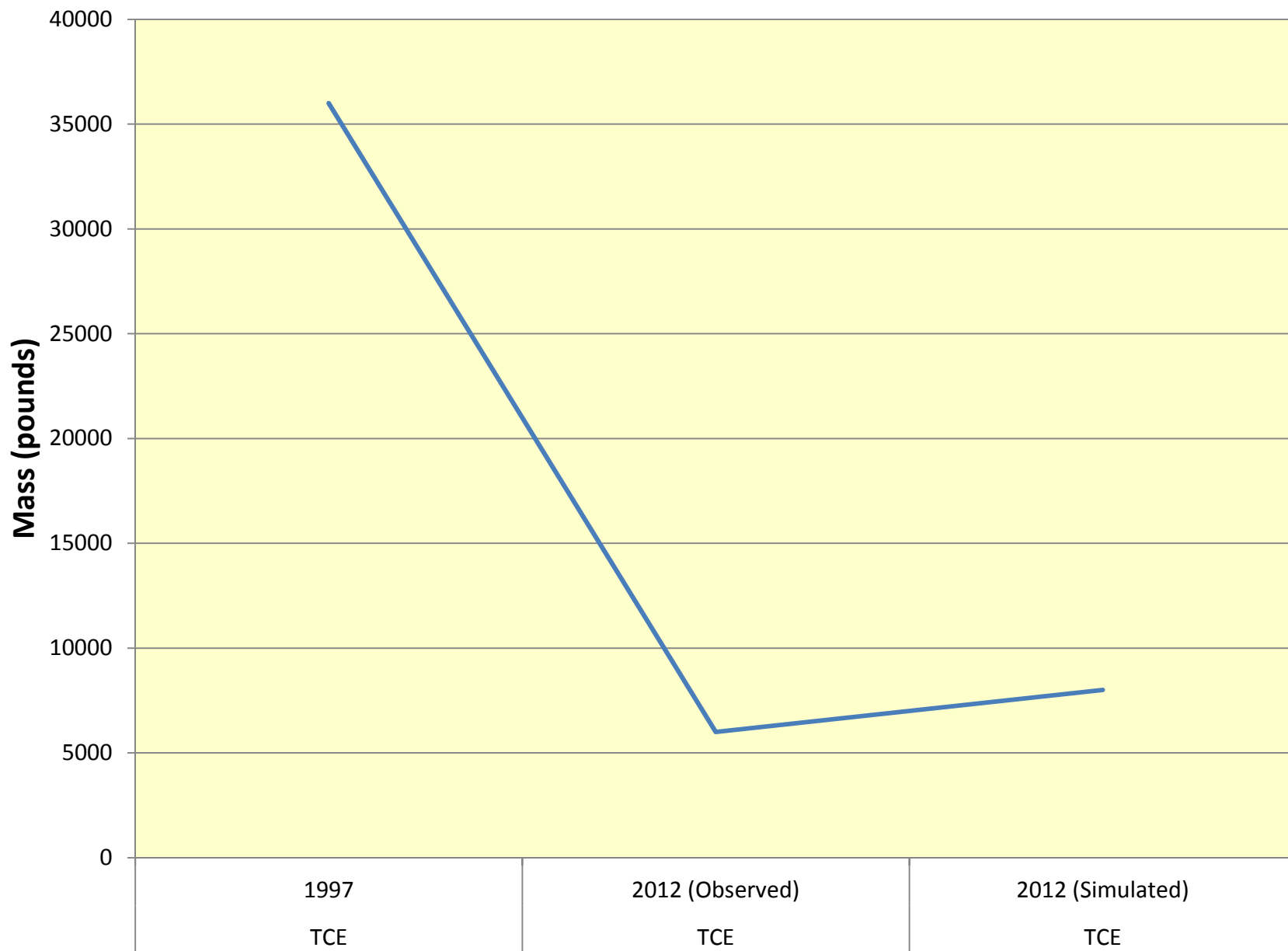


Figure 26.
TCE Quantitative Verification
NAS Whidbey (Area 6) Groundwater Model

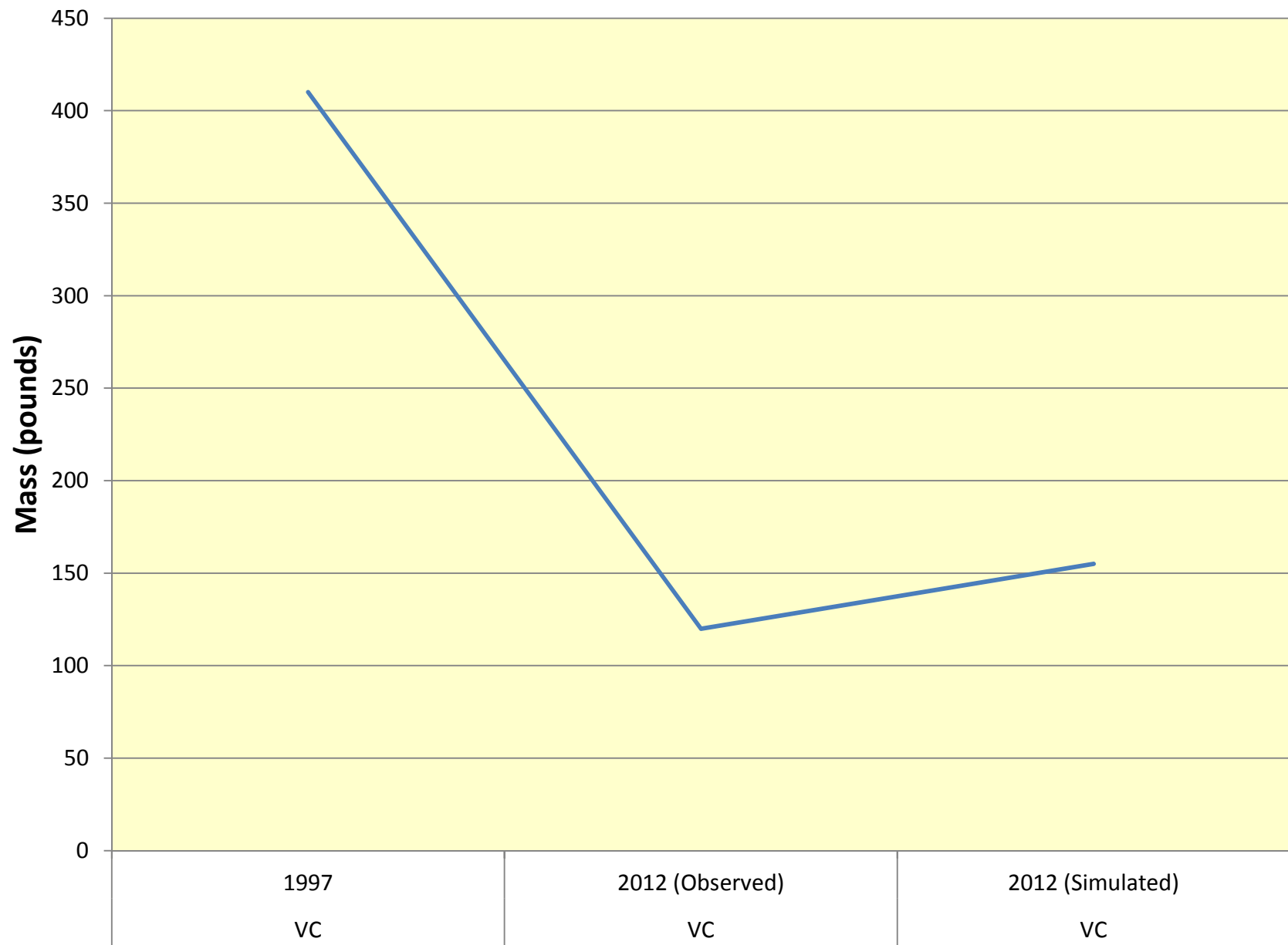


Figure 27.
Vinyl Chloride Quantitative Verification
NAS Whidbey (Area 6) Groundwater Model

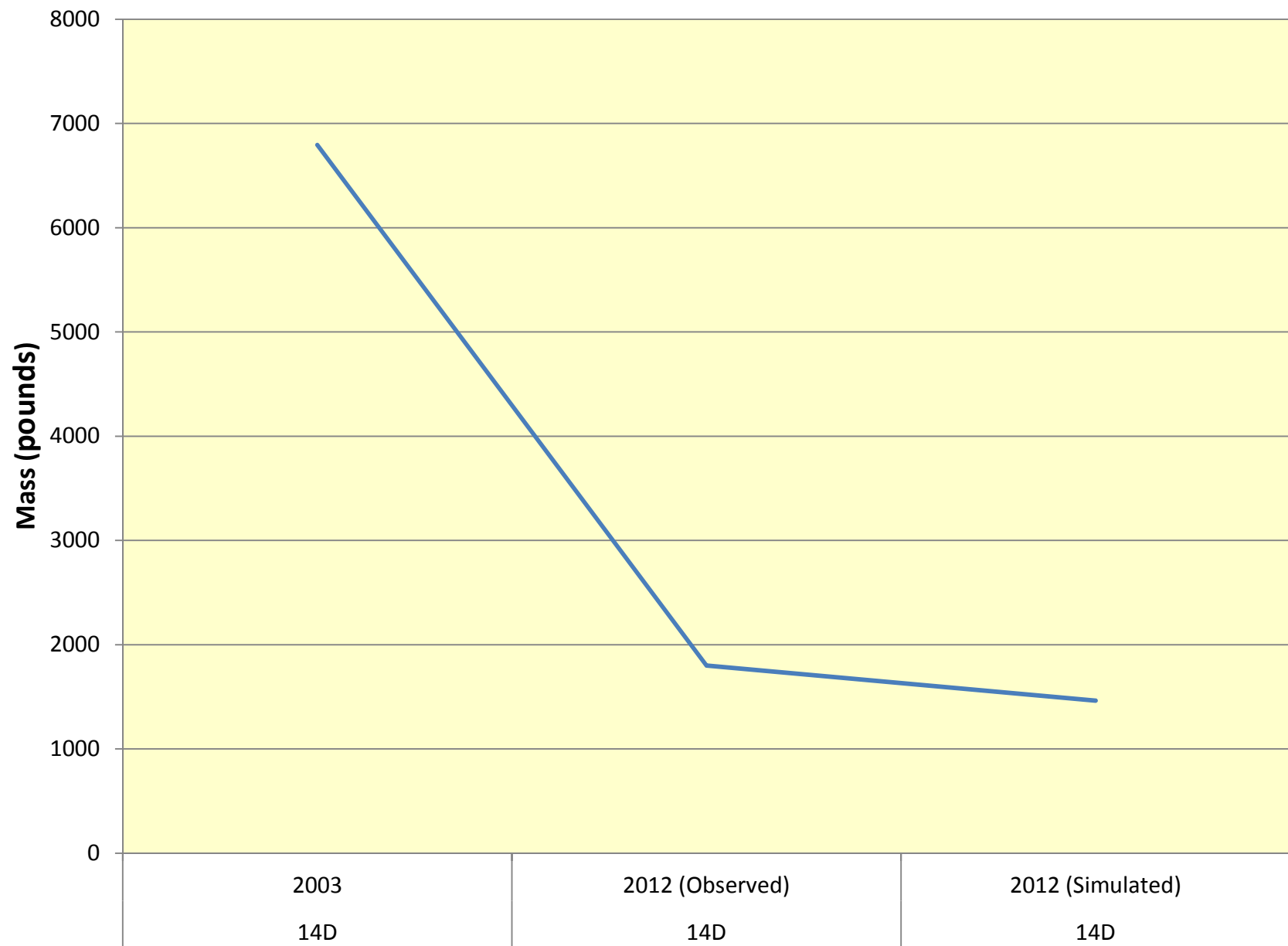


Figure 28.
1,4-Dioxane Quantitative Verification
NAS Whidbey (Area 6) Groundwater Model

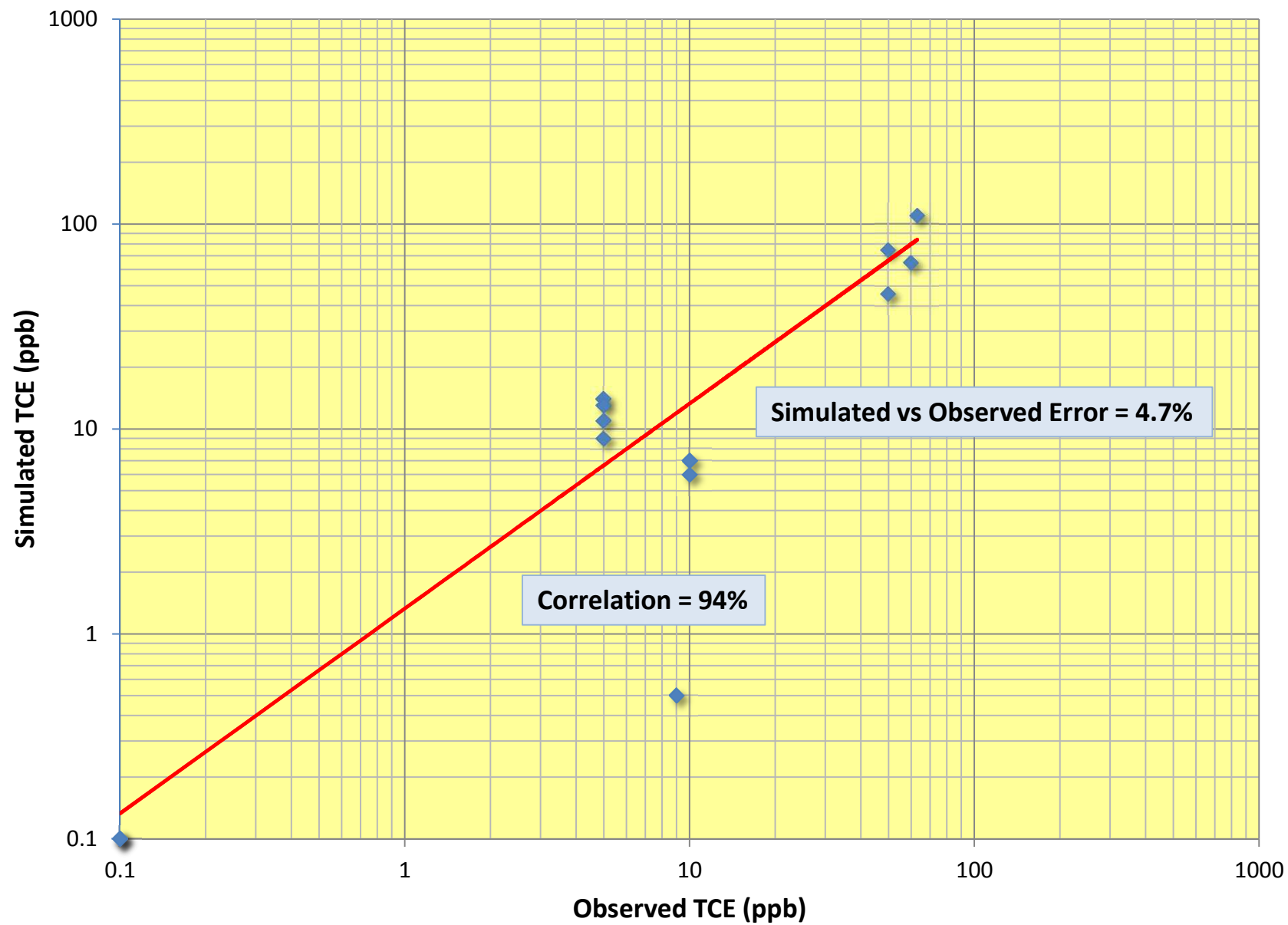


Figure 29.
Simulated and Observed TCE Correlation
NAS Whidbey (Area 6) Groundwater Model

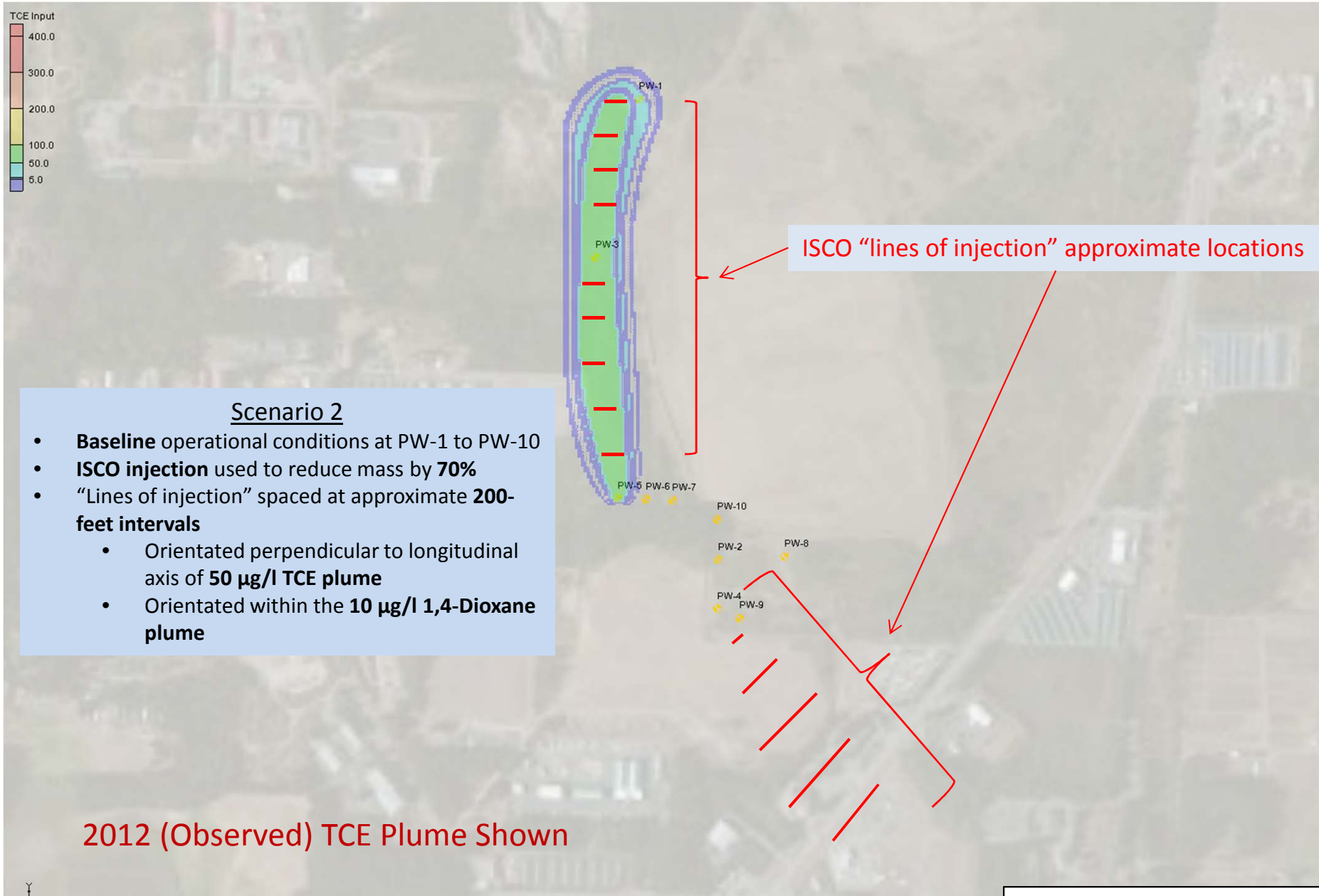
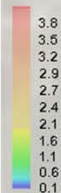


Figure 30.
Scenario 2 (TCE)
NAS Whidbey (Area 6) Groundwater Model

VC Input



Scenario 2

- **Baseline** operational conditions at PW-1 to PW-10
- **ISCO injection** used to reduce mass by **70%**
- “Lines of injection” spaced at approximate **200-foot intervals**
 - Orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
 - Orientated within the **10 µg/l 1,4-Dioxane plume**

2012 (Observed) Vinyl Chloride Plume Shown

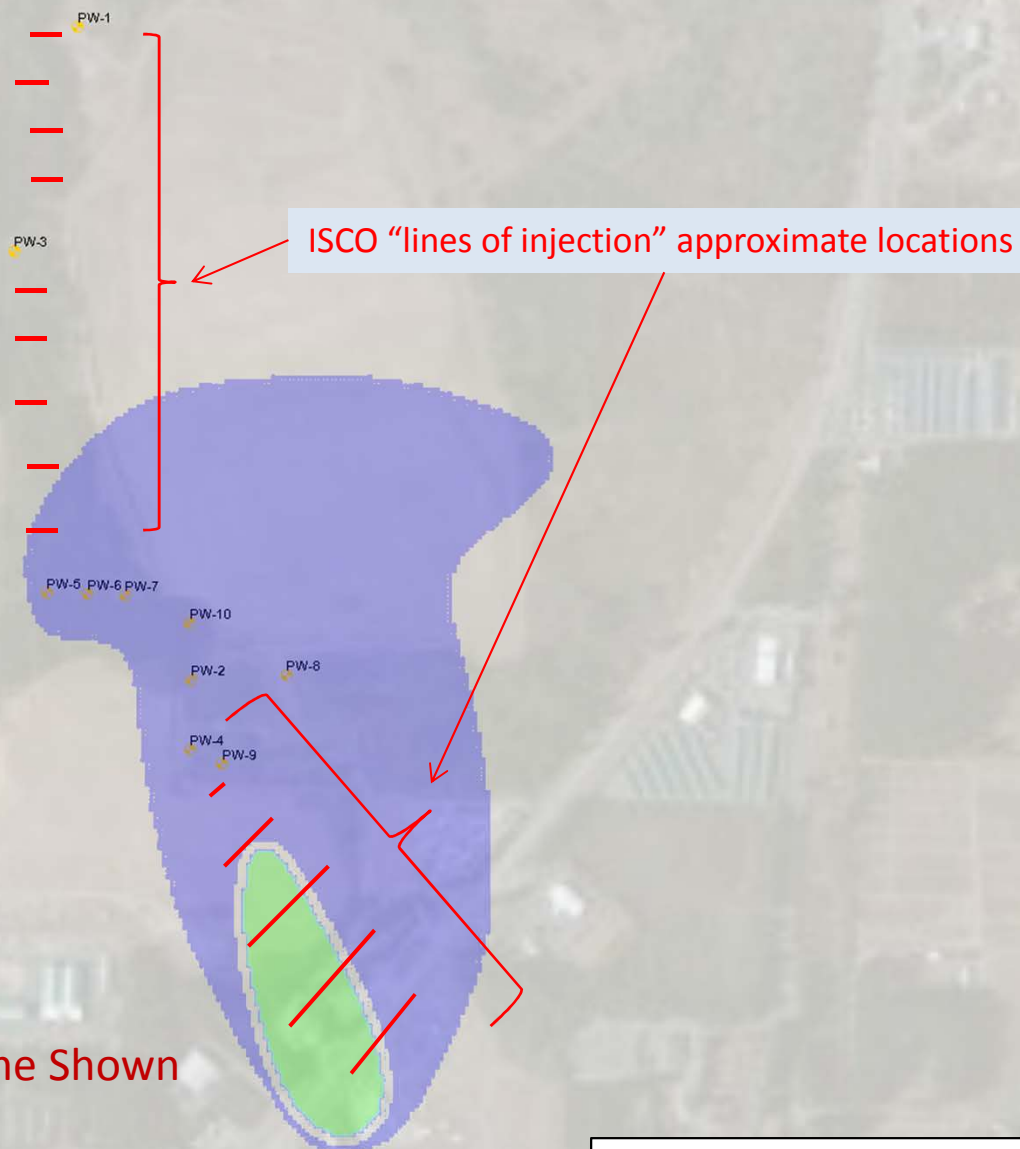


Figure 31.
Scenario 2 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model

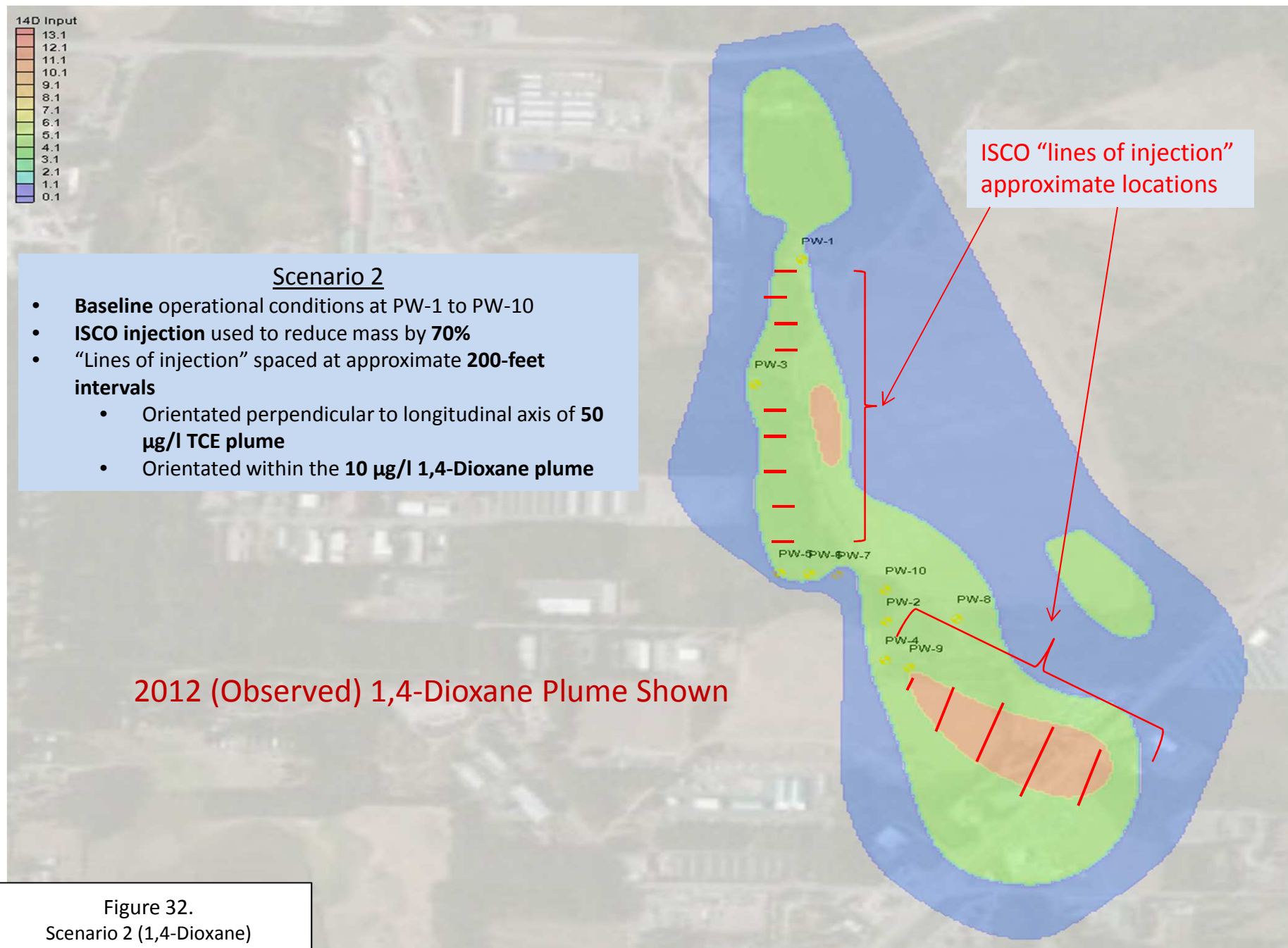


Figure 32.
Scenario 2 (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model

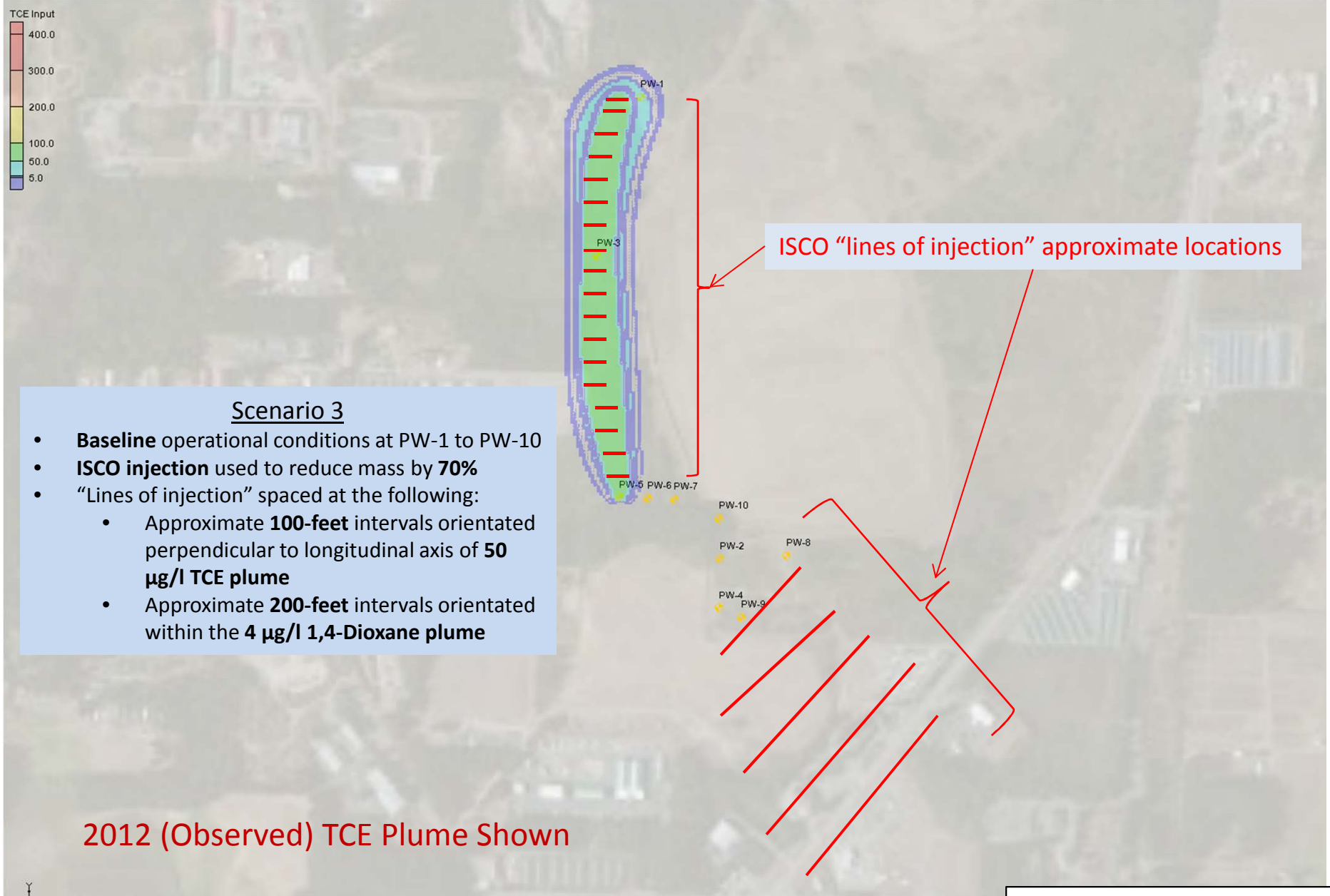
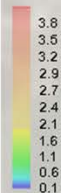


Figure 33.
Scenario 3 (TCE)
NAS Whidbey (Area 6) Groundwater Model

VC Input



Scenario 3

- **Baseline** operational conditions at PW-1 to PW-10
- **ISCO injection** used to reduce mass by **70%**
- "Lines of injection" spaced at the following:
 - Approximate **100-feet** intervals orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
 - Approximate **200-feet** intervals orientated within the **4 µg/l 1,4-Dioxane plume**

2012 (Observed) Vinyl Chloride Plume Shown

ISCO "lines of injection" approximate locations



Figure 34.
Scenario 3 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model

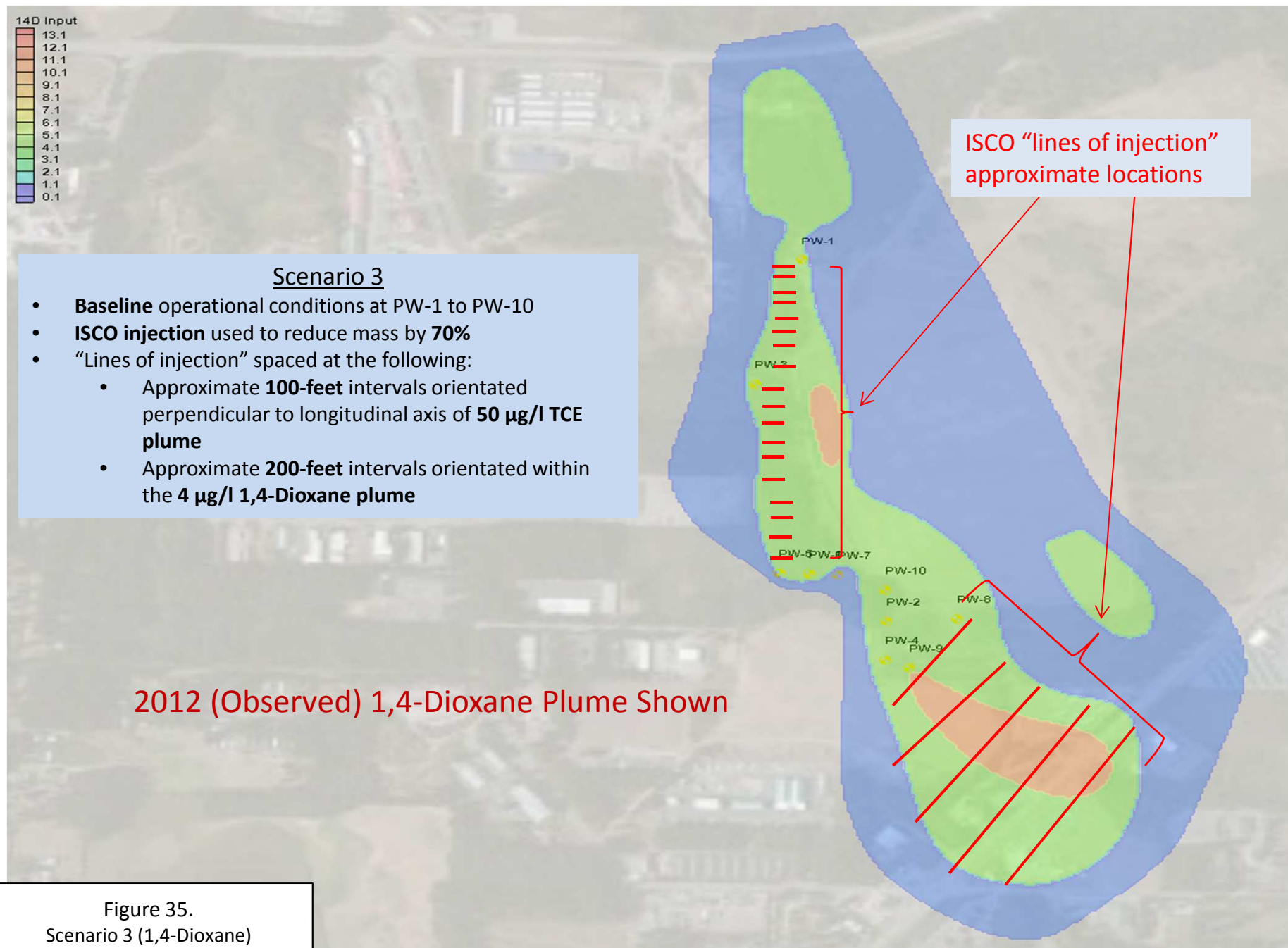


Figure 35.
Scenario 3 (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model

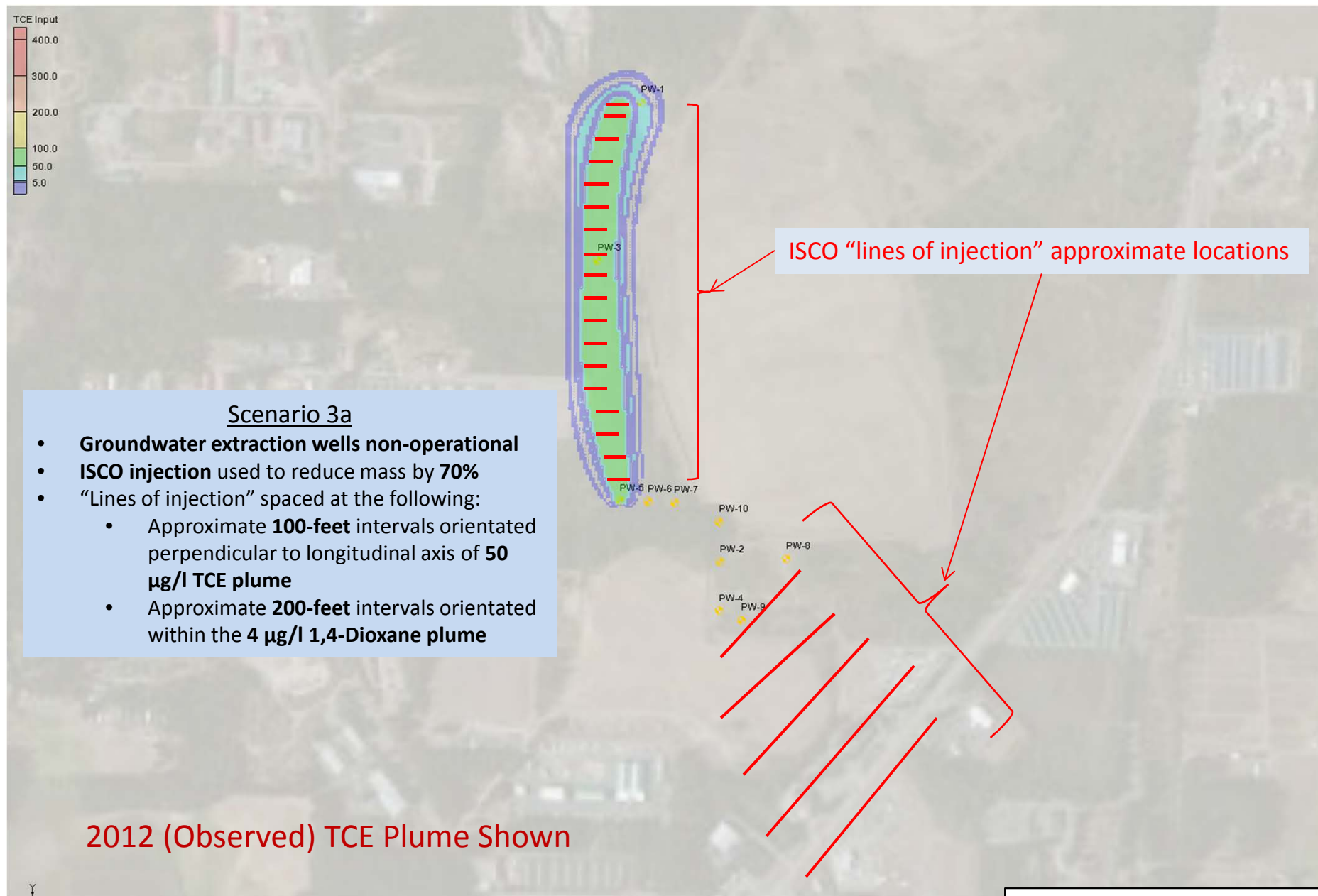
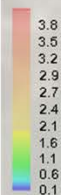


Figure 36.
Scenario 3a (TCE)
NAS Whidbey (Area 6) Groundwater Model

VC Input



Scenario 3a

- **Groundwater extraction wells non-operational**
- **ISCO injection** used to reduce mass by **70%**
- "Lines of injection" spaced at the following:
 - Approximate **100-feet** intervals orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
 - Approximate **200-feet** intervals orientated within the **4 µg/l 1,4-Dioxane plume**

2012 (Observed) Vinyl Chloride Plume Shown

ISCO "lines of injection" approximate locations



Figure 37.
Scenario 3a (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model

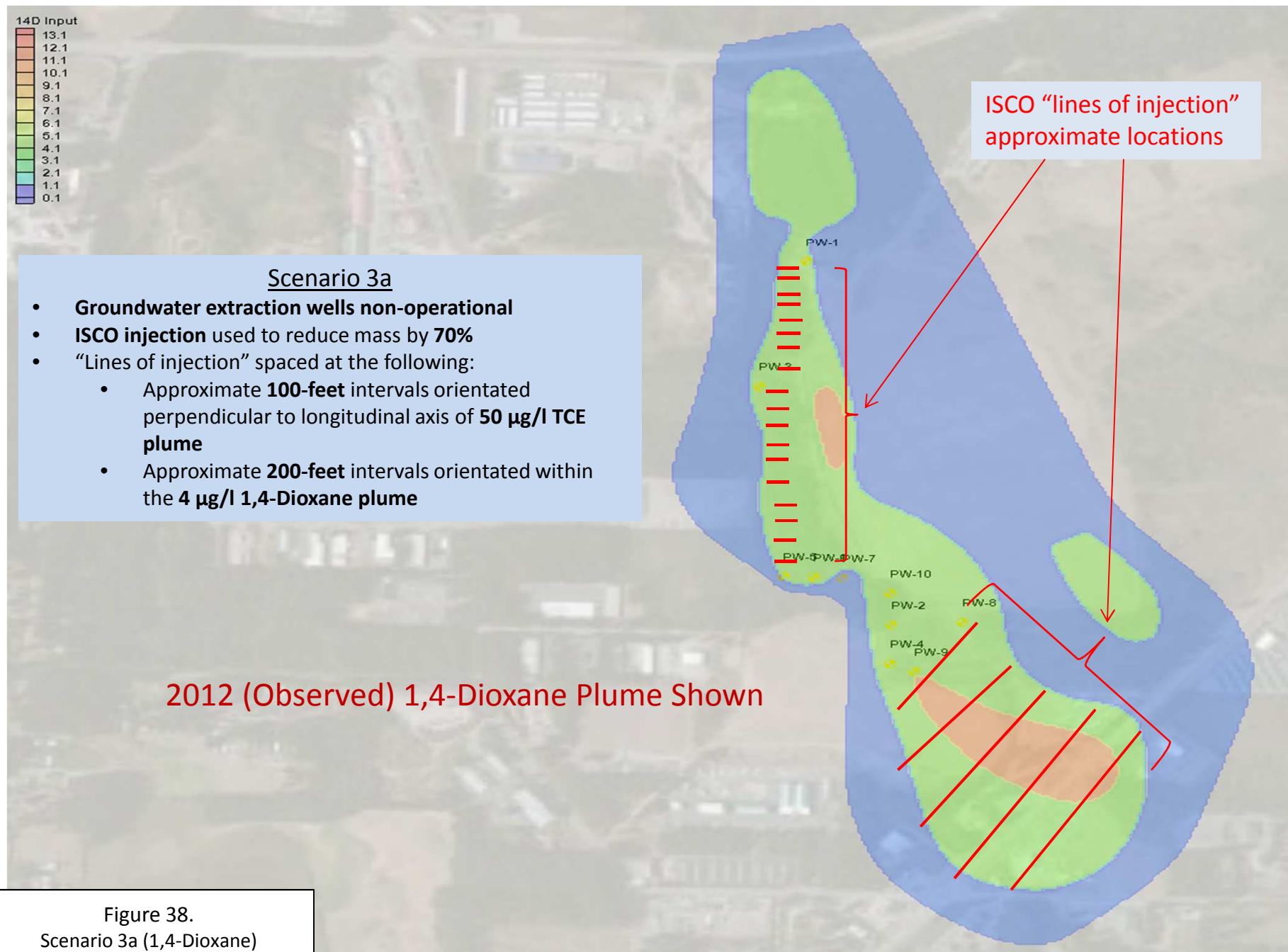


Figure 38.
Scenario 3a (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model

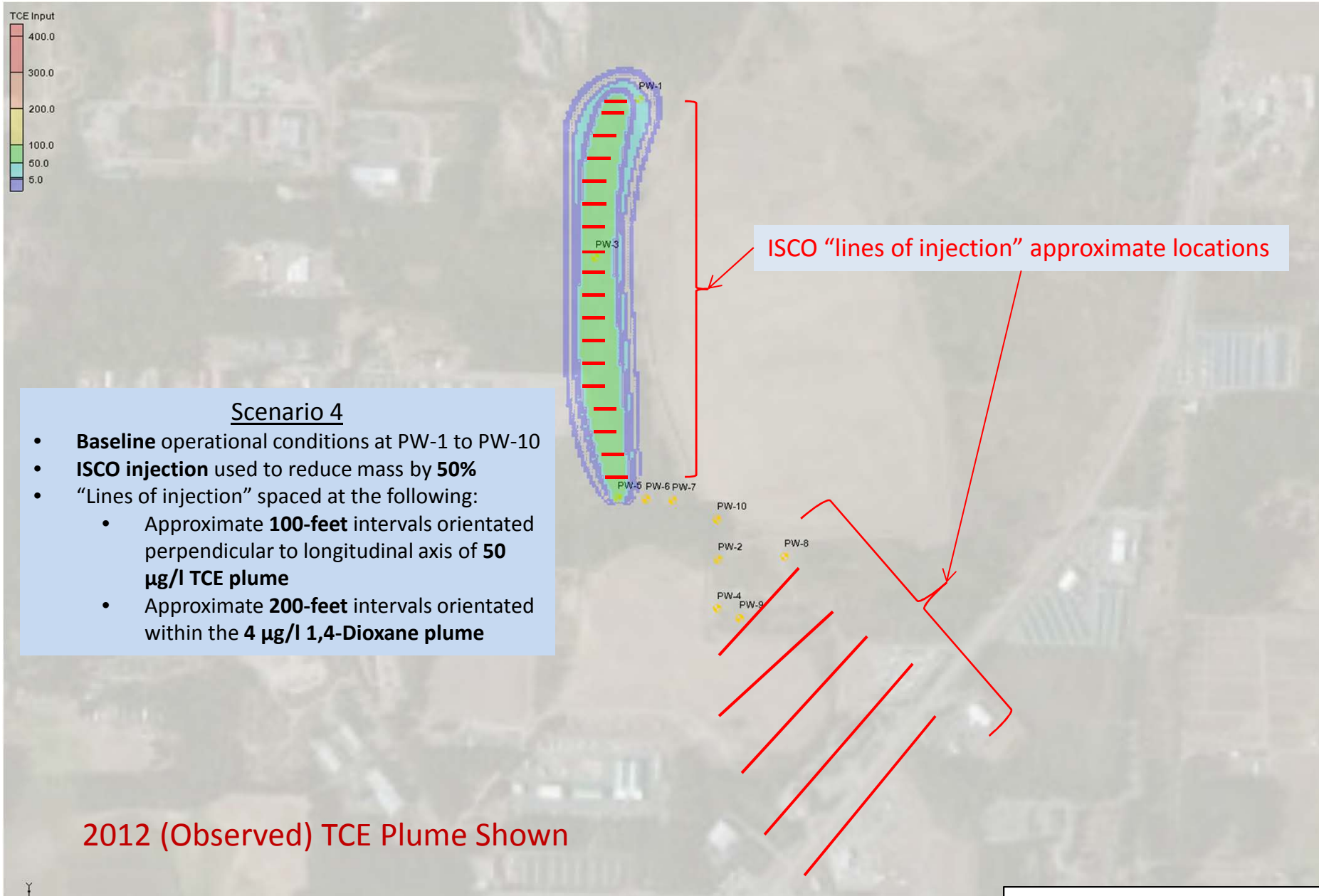
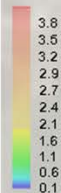


Figure 39.
Scenario 4 (TCE)
NAS Whidbey (Area 6) Groundwater Model

VC Input



Scenario 4

- **Baseline** operational conditions at PW-1 to PW-10
- **ISCO injection** used to reduce mass by **50%**
- “Lines of injection” spaced at the following:
 - Approximate **100-feet** intervals orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
 - Approximate **200-feet** intervals orientated within the **4 µg/l 1,4-Dioxane plume**

2012 (Observed) Vinyl Chloride Plume Shown

ISCO “lines of injection” approximate locations



Figure 40.
Scenario 4 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model

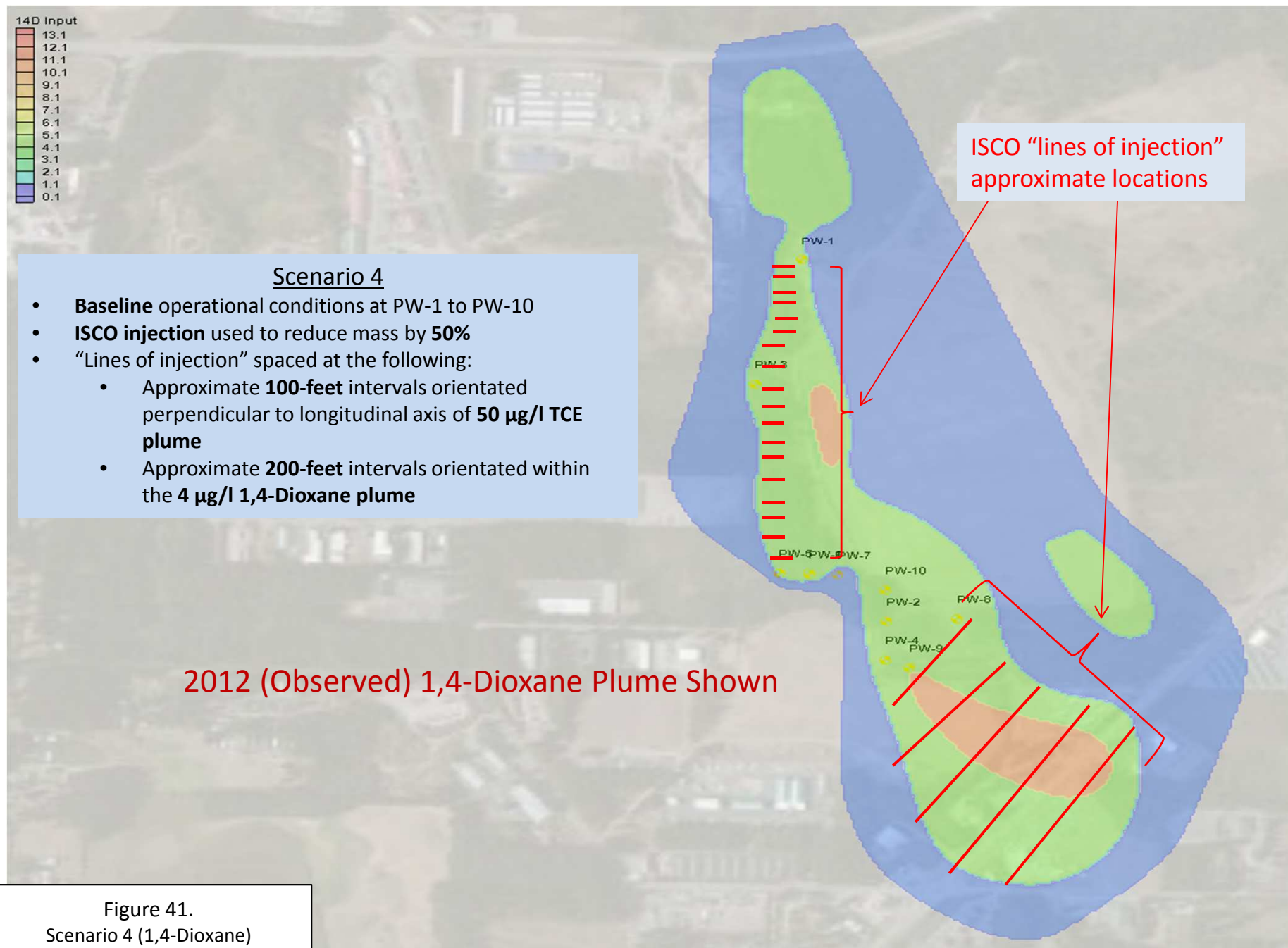
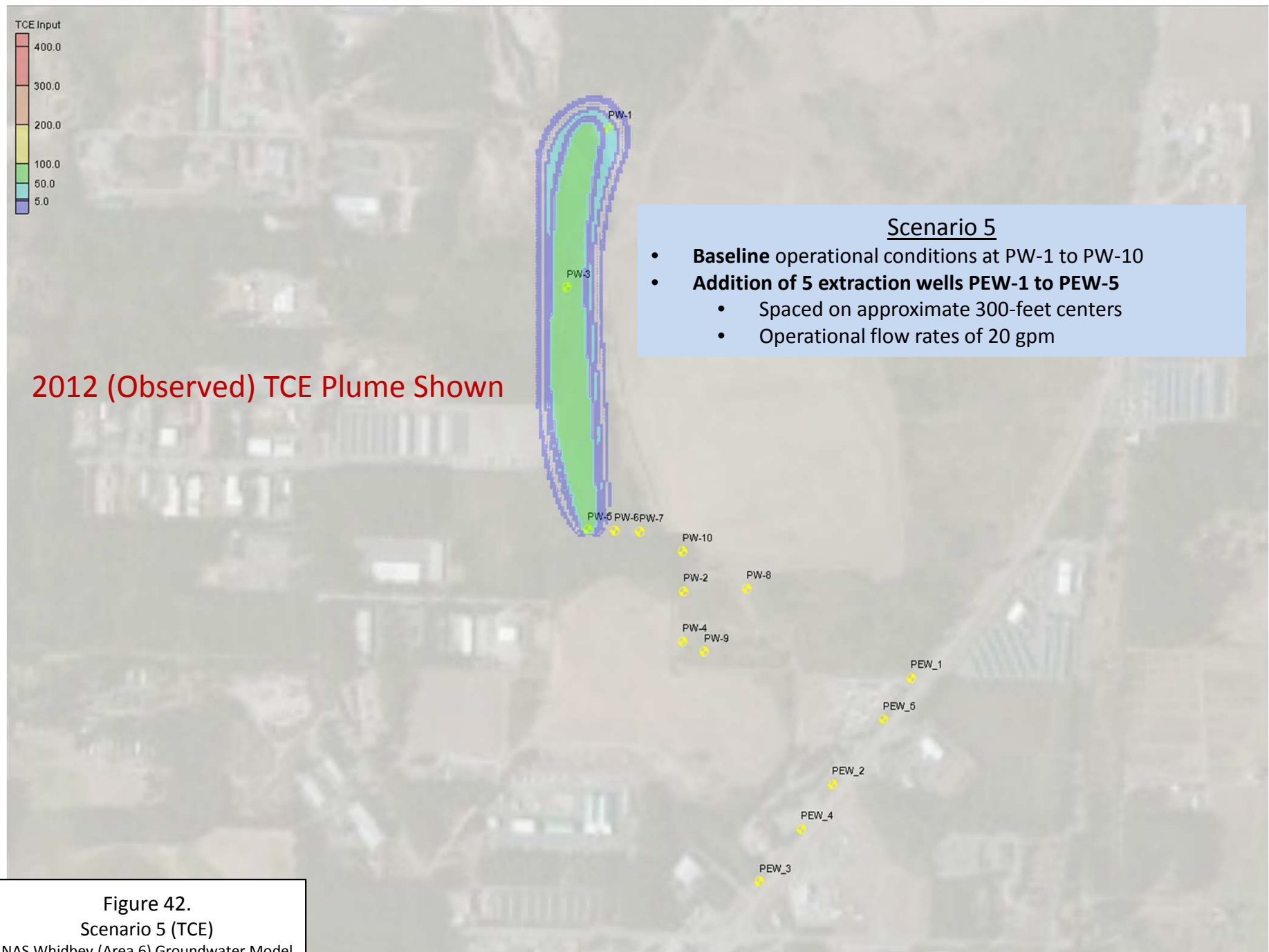
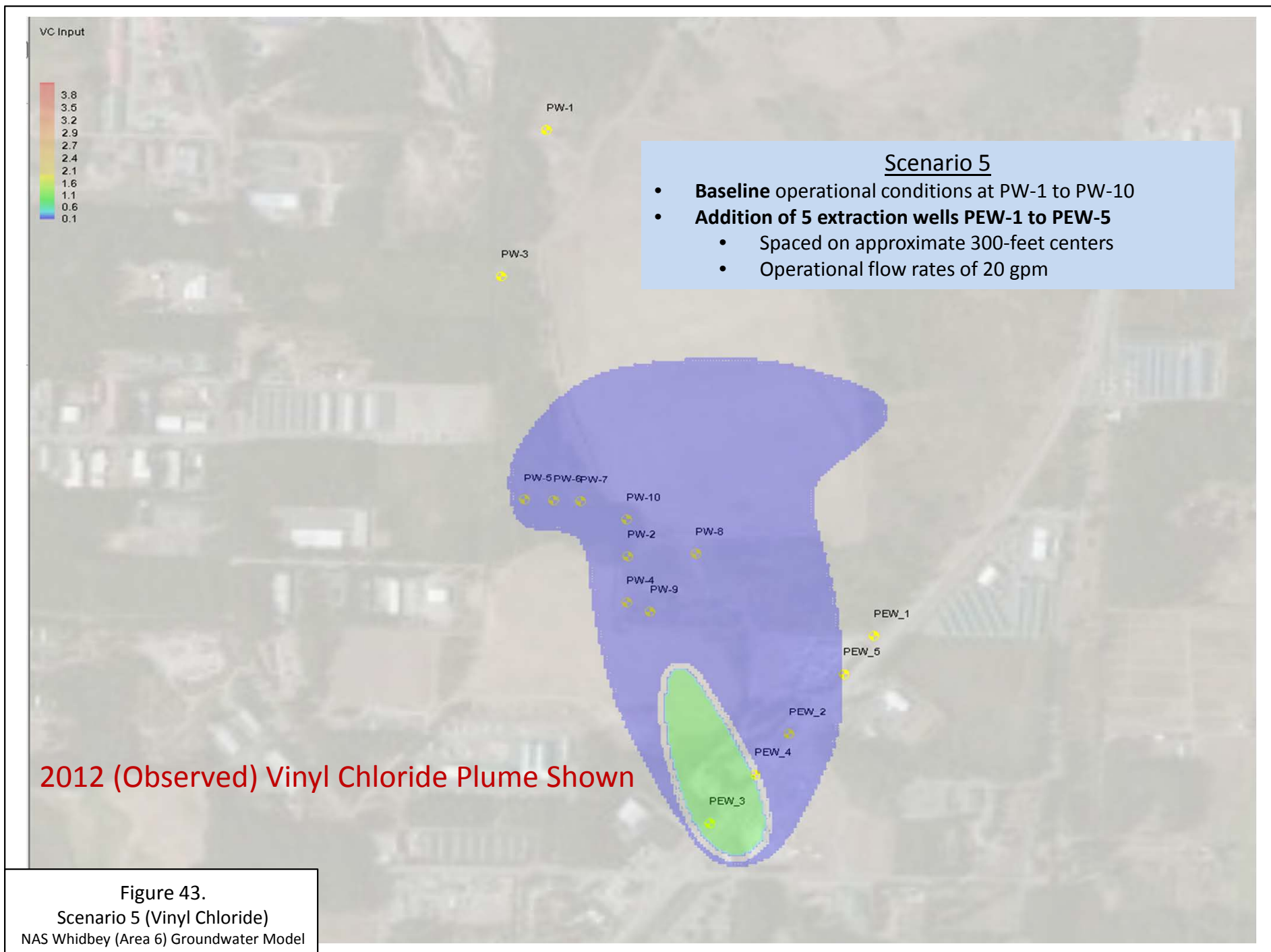


Figure 41.
Scenario 4 (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model





14D Input
13.1
12.1
11.1
10.1
9.1
8.1
7.1
6.1
5.1
4.1
3.1
2.1
1.1
0.1

Scenario 5

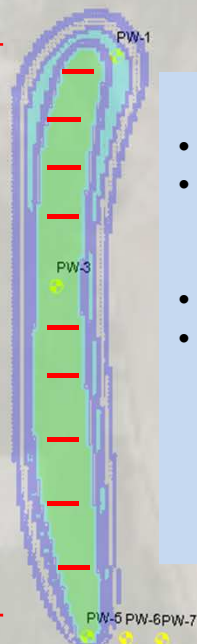
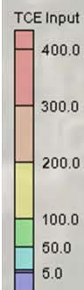
- **Baseline** operational conditions at PW-1 to PW-10
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-feet centers
 - Operational flow rates of 20 gpm

2012 (Observed) 1,4-Dioxane Plume Shown



Figure 44.

Scenario 5 (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model



Scenario 5a

- **Baseline** operational conditions at PW-1 to PW-10
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-foot centers
 - Operational flow rates of 20 gpm
- **ISCO injection** used to reduce mass by **70%**
- "Lines of injection" spaced at the following:
 - Approximate **200-feet** intervals orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
 - Approximate **200-feet** intervals orientated within the **4 µg/l 1,4-Dioxane plume**

ISCO "lines of injection" approximate locations

2012 (Observed) TCE Plume Shown

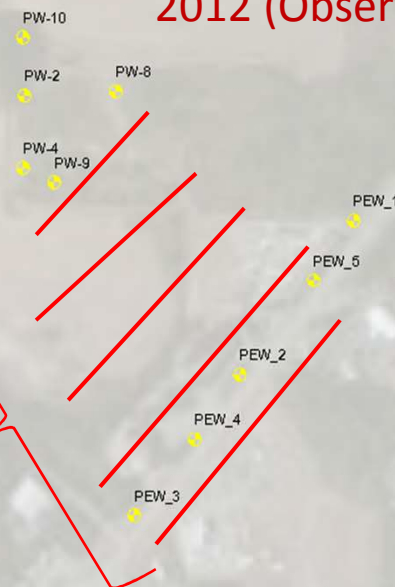
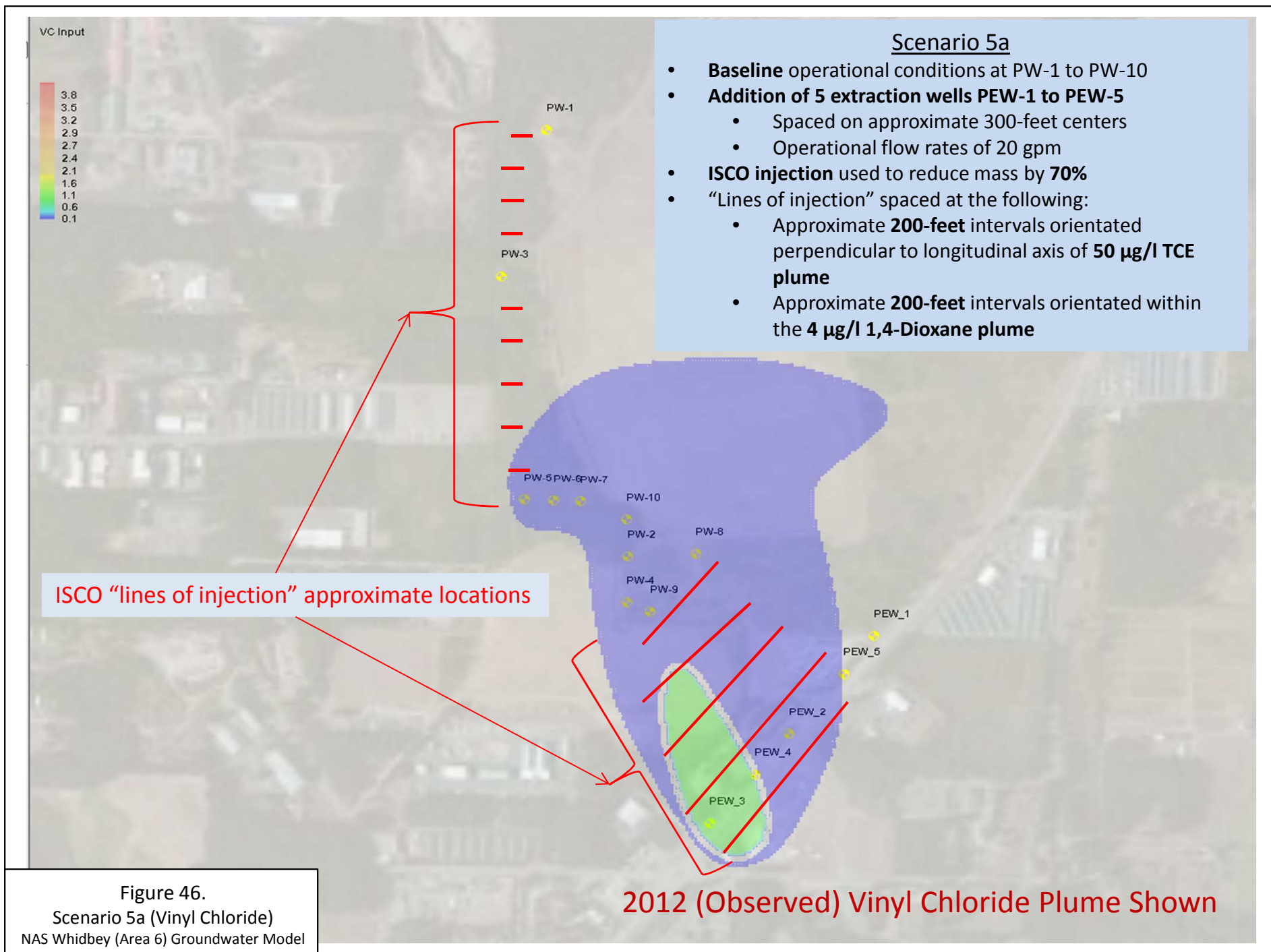
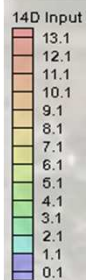


Figure 45.

Scenario 5a (TCE)

NAS Whidbey (Area 6) Groundwater Model





Scenario 5a

- **Baseline** operational conditions at PW-1 to PW-10
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-foot centers
 - Operational flow rates of 20 gpm
- **ISCO injection** used to reduce mass by **70%**
- "Lines of injection" spaced at the following:
 - Approximate **200-feet** intervals orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
 - Approximate **200-feet** intervals orientated within the **4 µg/l 1,4-Dioxane plume**

2012 (Observed) 1,4-Dioxane Plume Shown

ISCO "lines of injection"
approximate locations

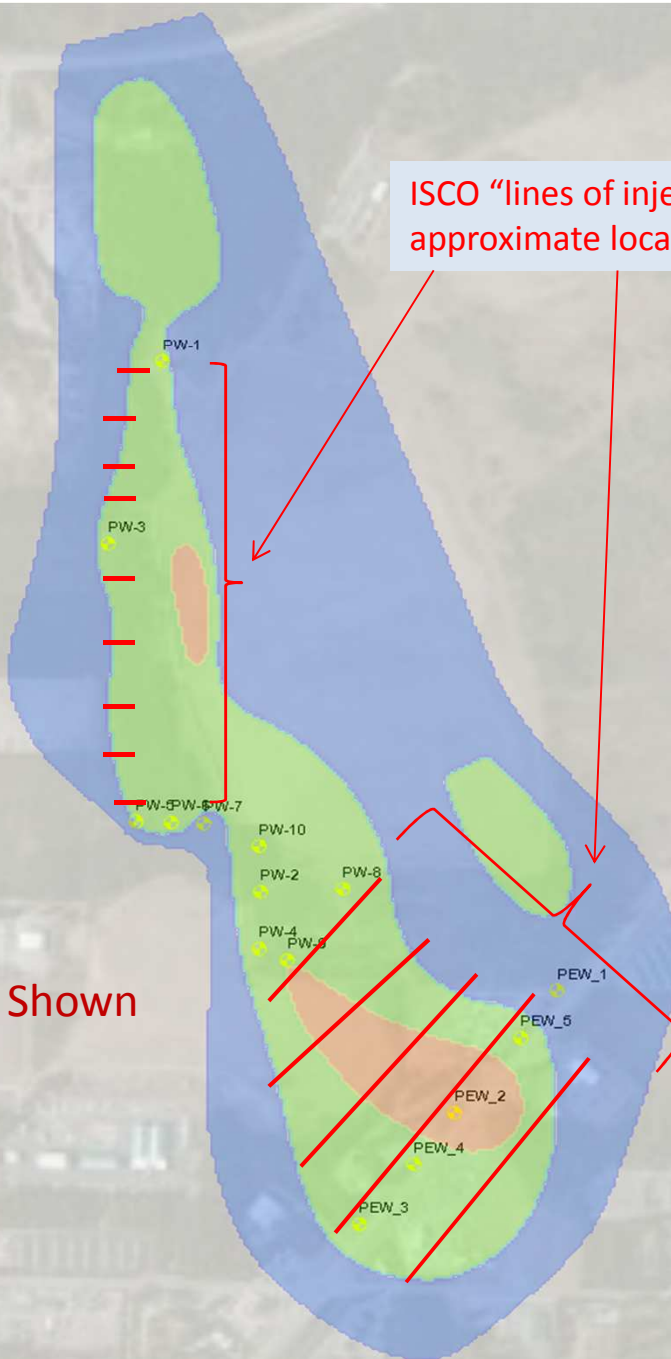
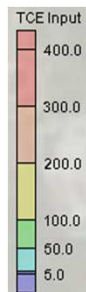


Figure 47.

Scenario 5a (1,4-Dioxane)

NAS Whidbey (Area 6) Groundwater Model



Scenario 6

- **Baseline** operational conditions at PW-1 to PW-10
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-foot centers
 - Operational flow rates of 20 gpm
- **Reinjection of treated groundwater (PIW-1 to PIW-10)**
 - Spaced on approximate 80-foot centers
 - Operational injection rates of 10 gpm

2012 (Observed) TCE Plume Shown

Injection wells PIW-1 to PIW-10

Figure 48.
Scenario 6 (TCE)

NAS Whidbey (Area 6) Groundwater Model

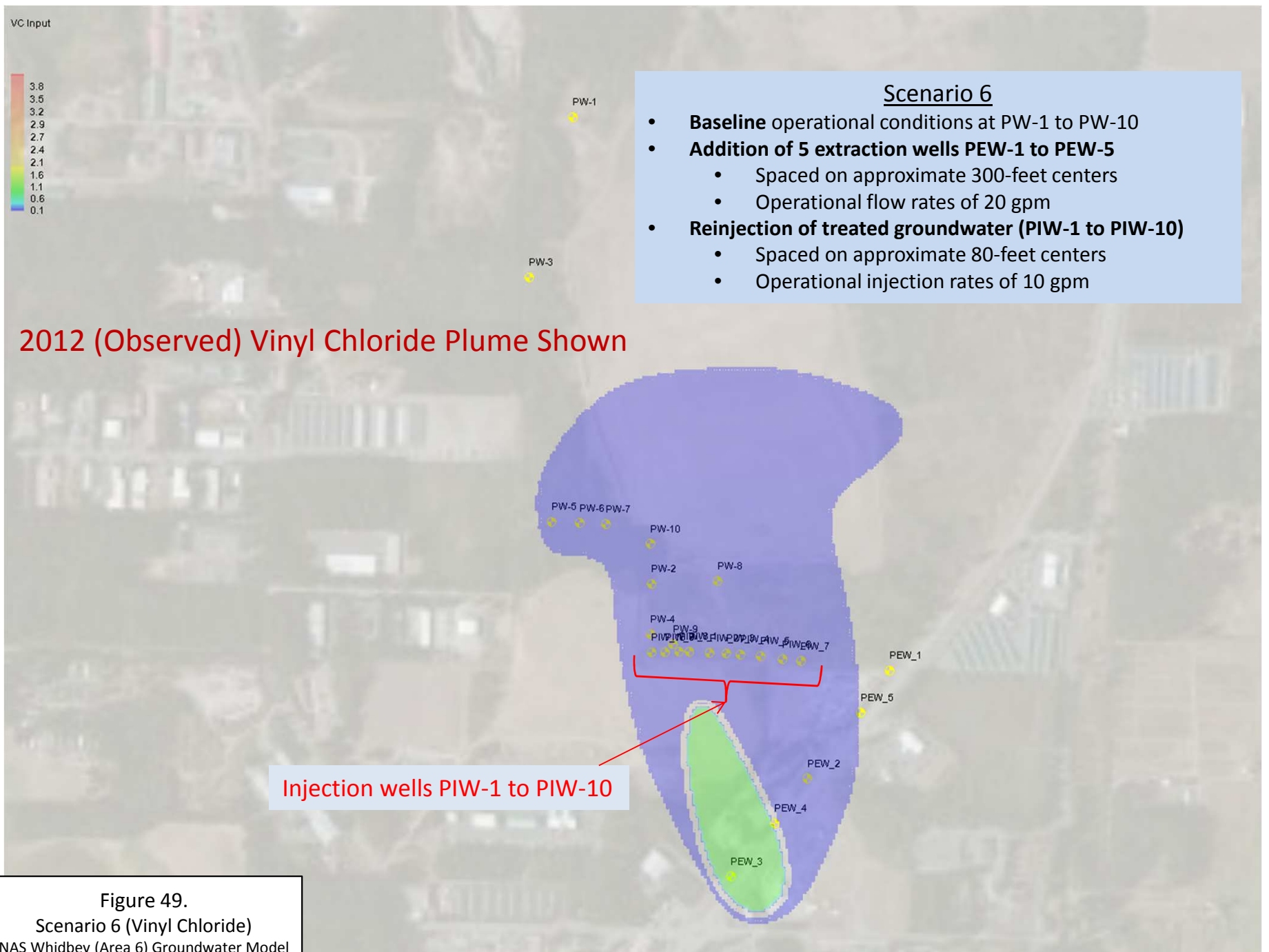
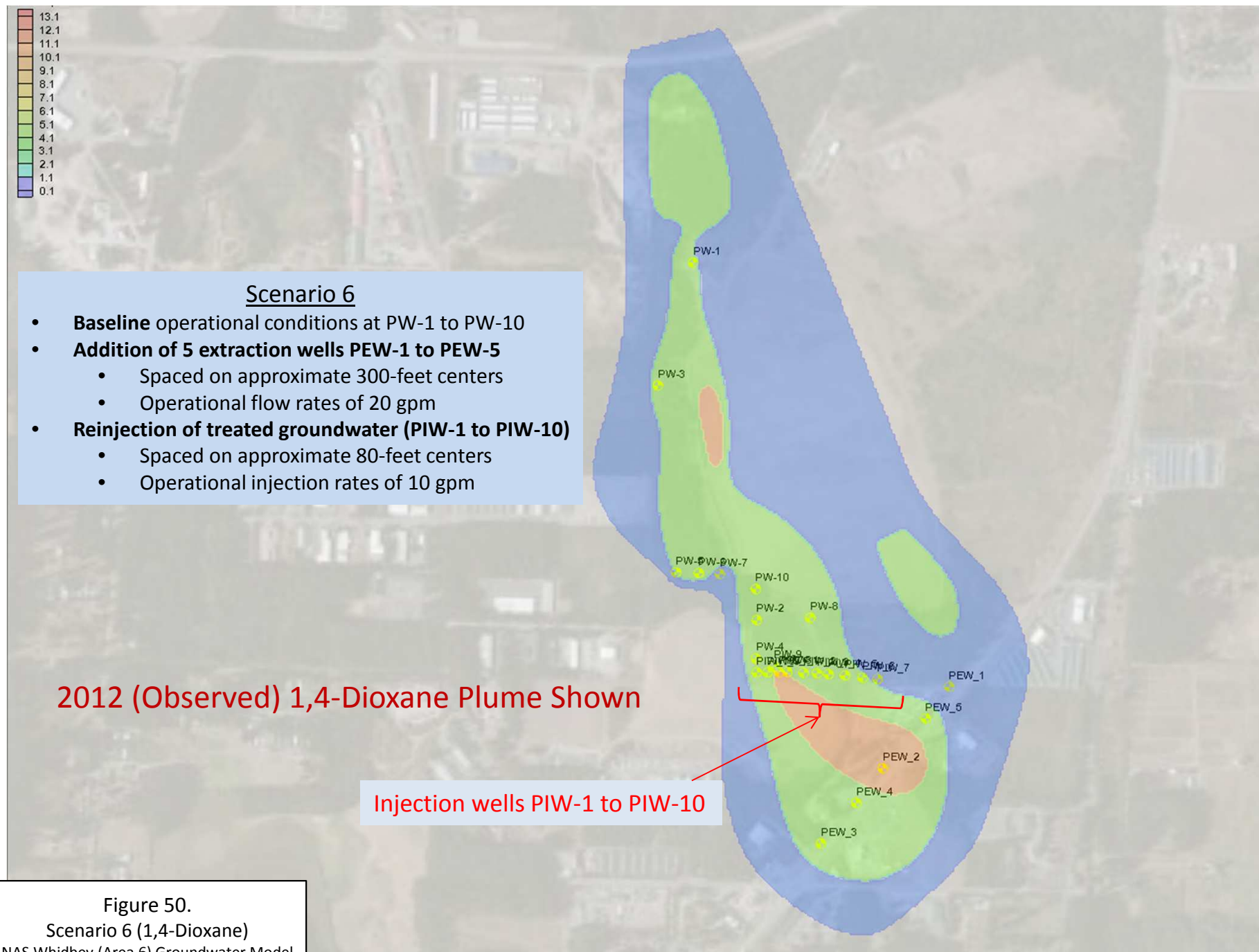
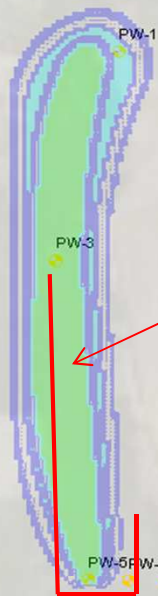
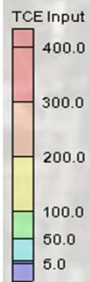


Figure 49.
Scenario 6 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model





Insitu barrier approximate locations

Scenario 7

- **Groundwater extraction wells non-operational**
- **Insitu barriers** which destroy mass upon contact placed in the following locations:
 - An approximate 1300-foot barrier orientated along the longitudinal axis of the **50 µg/l TCE plume** with containment at the south and southeast extent of the plume
 - An approximate 1800-foot barrier orientated perpendicular to the longitudinal axis of the **4 µg/l 1,4-Dioxane plume** and parallel with State Route 20

2012 (Observed) TCE Plume Shown

Figure 51.
Scenario 7(TCE)
NAS Whidbey (Area 6) Groundwater Model

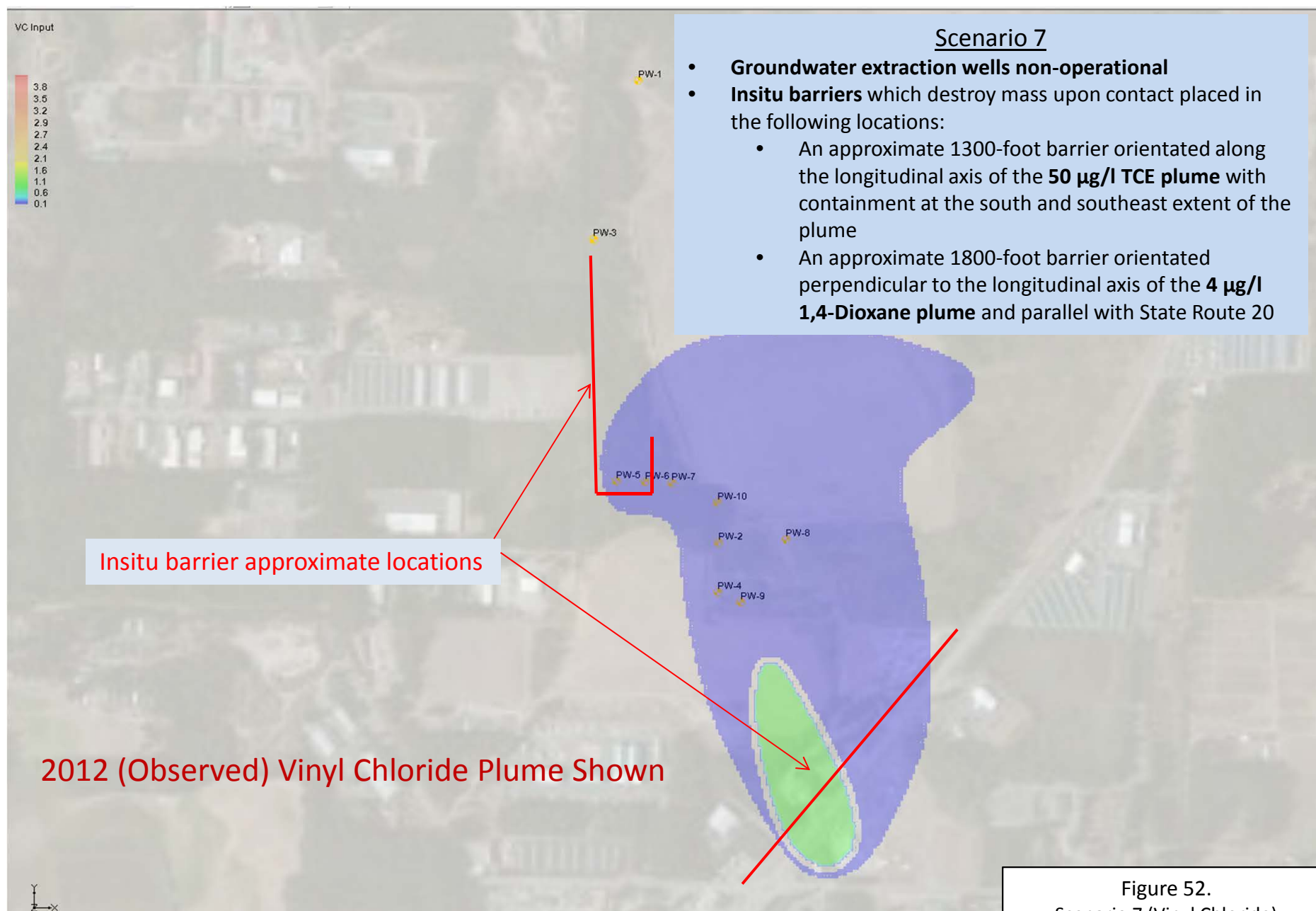


Figure 52.
Scenario 7 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model

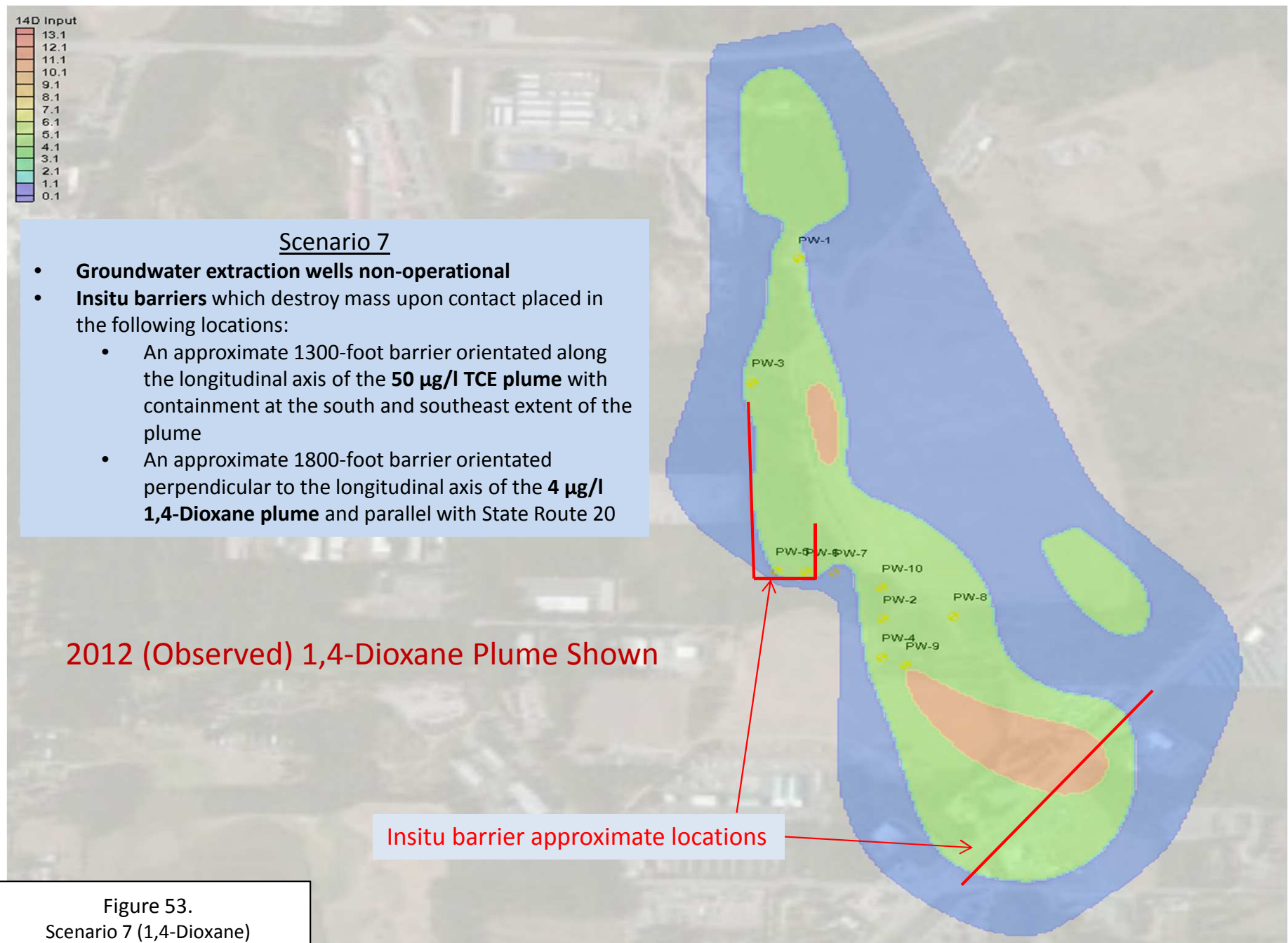


Figure 53.
Scenario 7 (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model

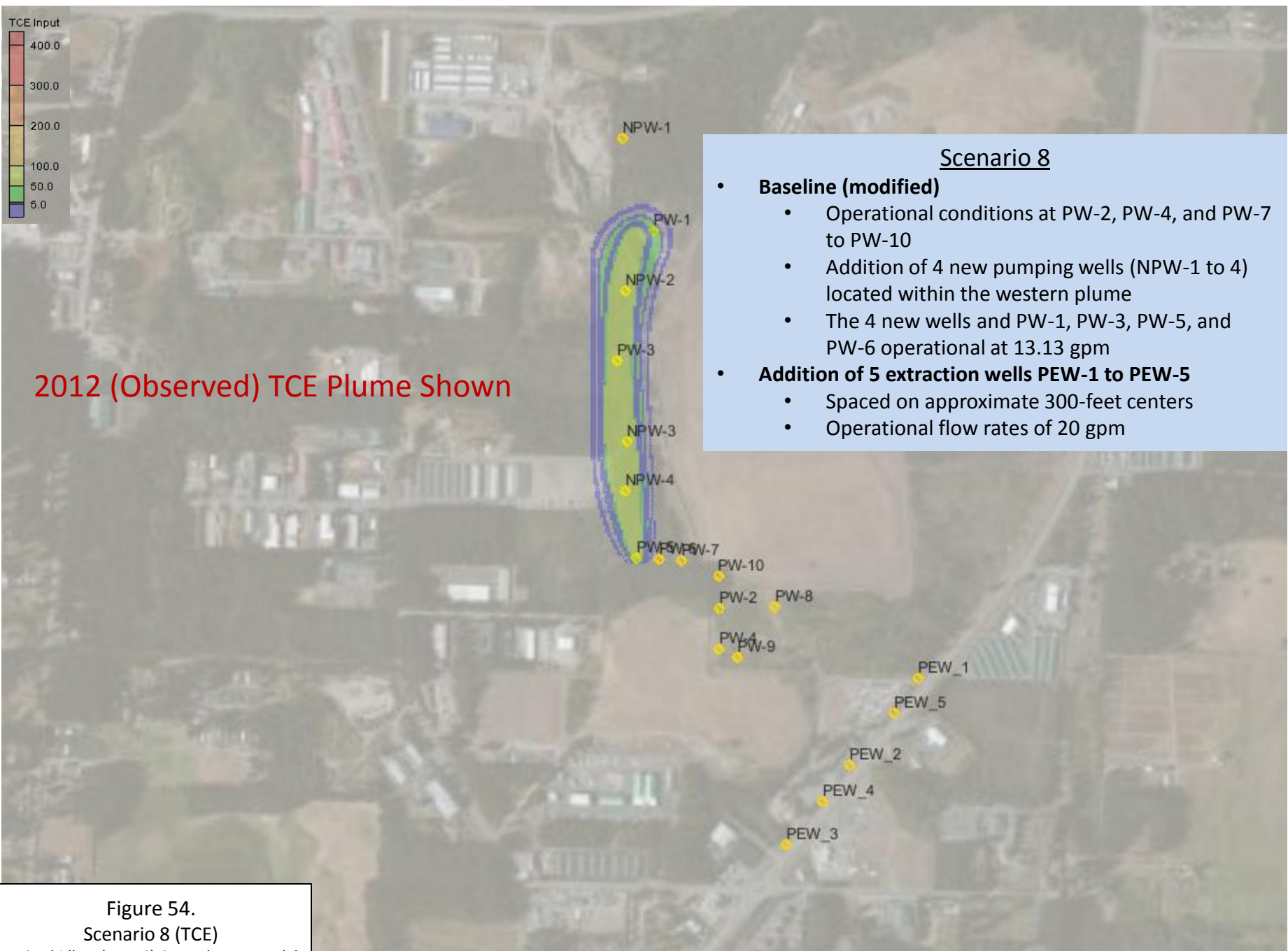
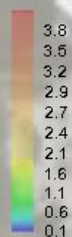


Figure 54.
Scenario 8 (TCE)
NAS Whidbey (Area 6) Groundwater Model

VC Input



Scenario 8

- **Baseline (modified)**
 - Operational conditions at PW-2, PW-4, and PW-7 to PW-10
 - Addition of 4 new pumping wells (NPW-1 to 4) located within the western plume
 - The 4 new wells and PW-1, PW-3, PW-5, and PW-6 operational at 13.13 gpm
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-foot centers
 - Operational flow rates of 20 gpm

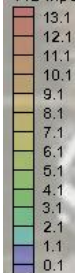
2012 (Observed) Vinyl Chloride Plume Shown



Figure 55.

Scenario 8 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model

14D Input



Scenario 8

- **Baseline (modified)**
 - Operational conditions at PW-2, PW-4, and PW-7 to PW-10
 - Addition of 4 new pumping wells (NPW-1 to 4) located within the western plume
 - The 4 new wells and PW-1, PW-3, PW-5, and PW-6 operational at 13.13 gpm
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-foot centers
 - Operational flow rates of 20 gpm

2012 (Observed) 1,4-Dioxane Plume Shown

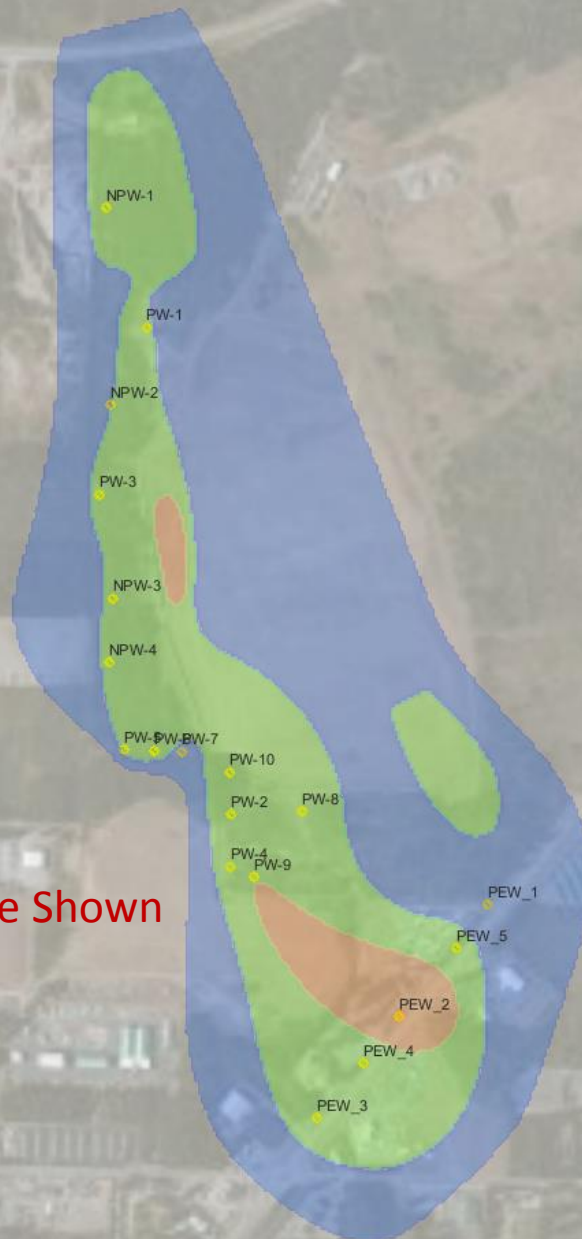
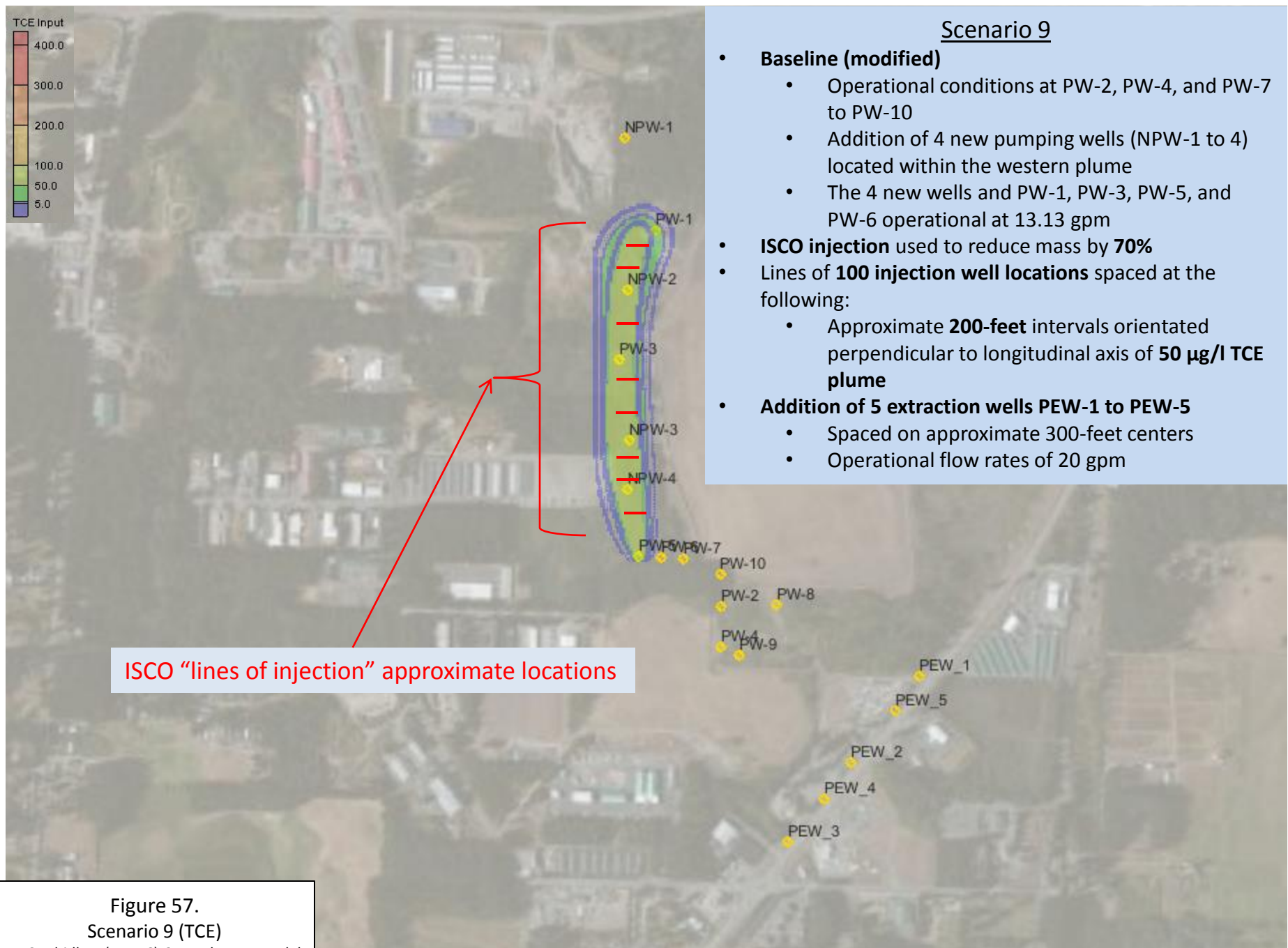


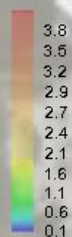
Figure 56.

Scenario 8 (1,4-Dioxane)

NAS Whidbey (Area 6) Groundwater Model



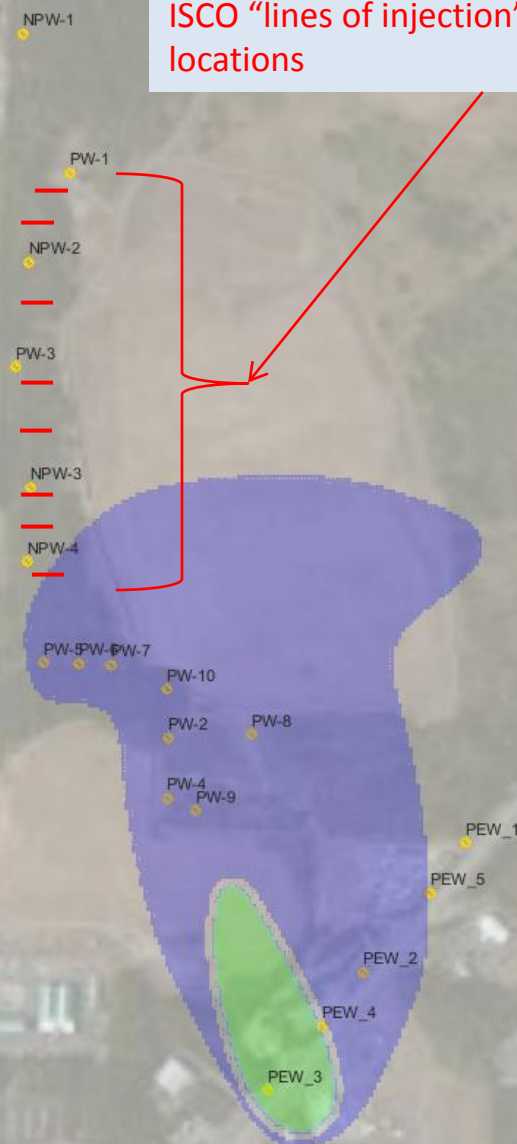
VC Input



Scenario 9

- **Baseline (modified)**
 - Operational conditions at PW-2, PW-4, and PW-7 to PW-10
 - Addition of 4 new pumping wells (NPW-1 to 4) located within the western plume
 - The 4 new wells and PW-1, PW-3, PW-5, and PW-6 operational at 13.13 gpm
- **ISCO injection** used to reduce mass by **70%**
- Lines of **100 injection well locations** spaced at the following:
 - Approximate **200-feet** intervals orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-feet centers
 - Operational flow rates of 20 gpm

ISCO "lines of injection" approximate locations

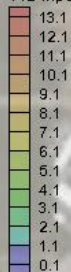


2012 (Observed) Vinyl Chloride Plume Shown

Figure 58.

Scenario 9 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model

14D Input



Scenario 9

- **Baseline (modified)**
 - Operational conditions at PW-2, PW-4, and PW-7 to PW-10
 - Addition of 4 new pumping wells (NPW-1 to 4) located within the western plume
 - The 4 new wells and PW-1, PW-3, PW-5, and PW-6 operational at 13.13 gpm
- **ISCO injection** used to reduce mass by **70%**
- Lines of **100 injection well locations** spaced at the following:
 - Approximate **200-feet** intervals orientated perpendicular to longitudinal axis of **50 µg/l TCE plume**
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - Spaced on approximate 300-feet centers
 - Operational flow rates of 20 gpm

ISCO "lines of injection" approximate locations

2012 (Observed) 1,4-Dioxane Plume Shown

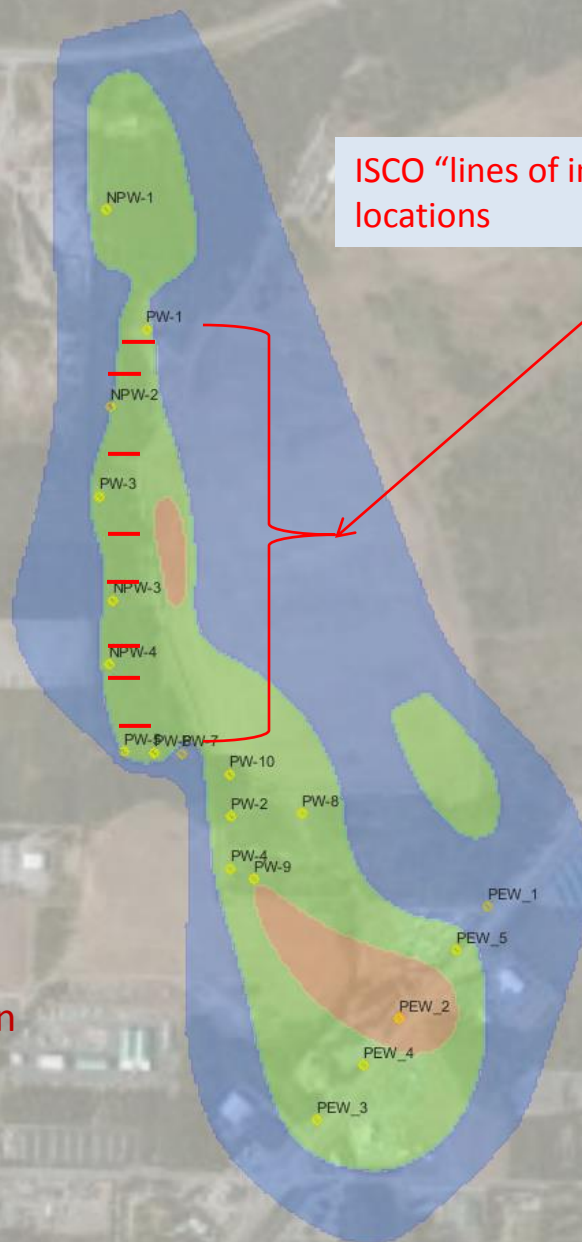
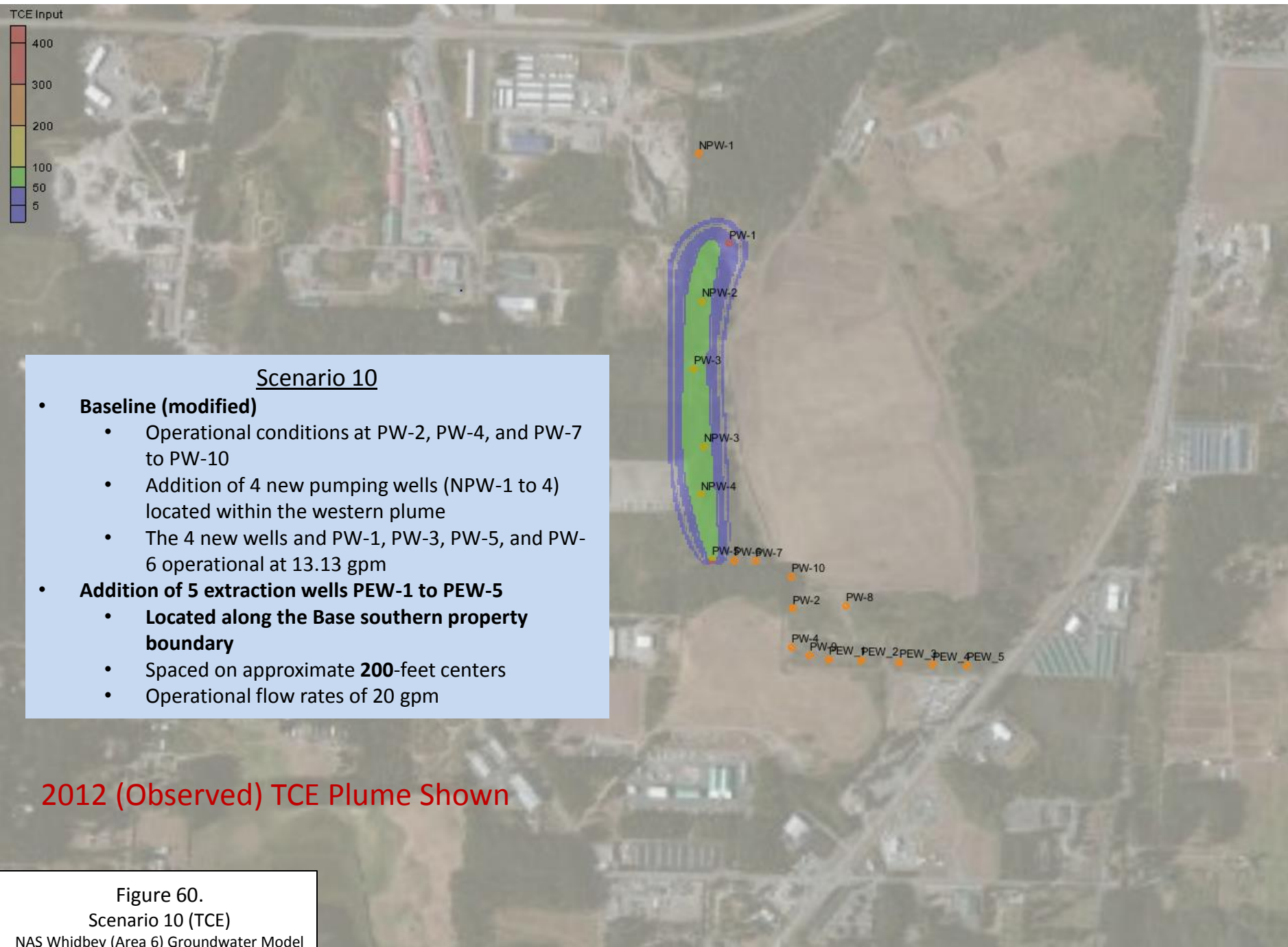
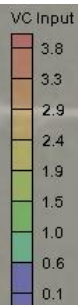


Figure 59.

Scenario 9 (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model





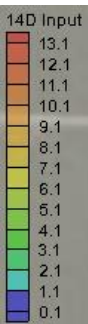
Scenario 10

- **Baseline (modified)**
 - Operational conditions at PW-2, PW-4, and PW-7 to PW-10
 - Addition of 4 new pumping wells (NPW-1 to 4) located within the western plume
 - The 4 new wells and PW-1, PW-3, PW-5, and PW-6 operational at 13.13 gpm
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - **Located along the Base southern property boundary**
 - Spaced on approximate **200-foot** centers
 - Operational flow rates of 20 gpm



2012 (Observed) Vinyl Chloride Plume Shown

Figure 61.
Scenario 10 (Vinyl Chloride)
NAS Whidbey (Area 6) Groundwater Model



2012 (Observed) 1,4-Dioxane Plume Shown

Scenario 10

- **Baseline (modified)**
 - Operational conditions at PW-2, PW-4, and PW-7 to PW-10
 - Addition of 4 new pumping wells (NPW-1 to 4) located within the western plume
 - The 4 new wells and PW-1, PW-3, PW-5, and PW-6 operational at 13.13 gpm
- **Addition of 5 extraction wells PEW-1 to PEW-5**
 - **Located along the Base southern property boundary**
 - Spaced on approximate **200-foot** centers
 - Operational flow rates of 20 gpm



Figure 62.
Scenario 10 (1,4-Dioxane)
NAS Whidbey (Area 6) Groundwater Model

APPENDIX C

Bench Scale Feasibility Tests for 1,4-Dioxane Green Remediation Using Microbial Mats and Enhanced Constructed Treatment Wetlands

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Bench Scale Feasibility Tests for 1,4-Dioxane Green Remediation Using Microbial Mats and Enhanced Constructed Treatment Wetlands

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Table of Contents

Table of Figures.....	3
Reference of Tables.....	4
Acronymns.....	5
1.0 Introduction.....	6
Description of Naval Air Station Whidbey Island Area 6	
2.0 Objective	7
Primary purpose of project	
3.0 Rationale	7
Green remediation system.....	
4.0 Technology Description.....	8
4.1 Innovative Robust Microbial Mats Aquatic Treatment System.....	8
4.2 Biodegradation of Organic Compounds.....	9
4.3 Phytoremediation	9
4.4 Technology Maturity.....	10
4.5 Environmental Benefits.....	11
4.6 Throughput potential.....	11
4.7 Enhanced Constructed Treatment Wetlands.....	11
5.0 Whidbey Island Area 6 Site Visit.....	12
5.1 Bench Scale Tests in Greenhouse and Ambient Conditions	14
5.2 Laboratory Analysis	16
5.3 Results of Bench Scale Tests	16
6.0 Microbial Mat Bioreactor (MMB) Coupled with Bioaugmented Constructed Treatment Wetland (BCTW)	19
7.0 Challenges and Discovery of a Potential Effective In-Situ Remediation Technology....	22
8.0 Summary and Conclusions.....	23
9.0 Recommendations	24
10.0 Cited and Useful References	26

Table of Figures

Figure 1 Schematic Cross-Section of Microbial Mat.....	8
Figure 2 Production of Oxygen and Accompanying Changes in pH and Redox Conditions in a Sealed Microbial Mat Bioreactor Mounted with DO, pH and ORP probes.....	9
Figure 3 Dioxane degradation in soil microcosms amended with CB1190, root exudate (RE), both, or none (Kelley et al.,2001).....	10
Figure 4 Conceptual Development of the Small Scale Microbial Mat Bioreactor Designed to Treat dioxane Wastewater from existing pump-and-treat system.....	11
Figure 5 Greenhouse Tests: Multiple Batch Microbial Mat Bioreactors (Left =Day 1; Right = Day 3).....	15
Figure 6 Batch Microbial Mat (left) and Bacteria (right) Treated Bioreactors.....	15
Figure 7 Relative effectiveness of dioxane removal from NAS Whidbey Island groundwater by CB1190 and microbial mats inoculated with CB1190 after 16 days of incubation in ambient conditions.....	18
Figure 8 Compiled results of dioxane removal from NAS Whidbey Island groundwater for the different treatment after 31 days of incubation in a greenhouse during winter months.....	19
Figure 9 Conceptual Design of the Microbial Mat/BCTW Treatment Setup.....	20
Figure 10 Microbial Mat Plate-and-shelve bioreactor operated in series with a CB1190 bioaugmented containerized constructed treatment wetland under ambient conditions.....	20
Figure 11 Rate of removal of dioxane from microbial mat and bioaugmented CTW bioreactor.....	21
Figure 12 Schematic of full scale BCTW operated in series. Treated water flows by gravity....	25

Reference of Tables

Table 1 Biogeochemical parameters needed to support the enhanced bioremediation of dioxane.....	13
Table 2 Initial concentration of dioxane in 55 gallon drums of influent and effluent groundwater shipped from NAS Whidbey Island for use in bench scale tests.....	14
Table 3 Results of the initial bench scale screening tests used to determine the most effective treatment for influent and effluent NAS Whidbey groundwater conducted under ambient conditions. The different treatment included: Microbial Mats Only; Biostimulated (Butanol or Tetrahydrofuran (THF)); Bioaugmented – Bacteria Only and Microbial Mat plus Bacteria.....	17
Table 4 Results of bench scale screen tests conducted to identify most effective treatment for dioxane spiked influent and effluent NAS Whidbey groundwater. All tests were performed under ambient conditions for 6 days. The different treatment included: Microbial Mats Only; Biostimulated (Butanol or Tetrahydrofuran (THF)); Bioaugmented – Bacteria Only and Microbial Mat plus Bacteria.....	18
Table 5 Concentration of dioxane measured during bioremediation in microbial mat and constructed treatment wetland bioreactors operated in series.....	22
Table 6 Additional results for dioxane and CVOCs bioremediation of Plant Influent and Effluent in microbial mat and BCTW bioreactors operated in series.....	22
Table 7 Concentration of dioxane in untreated and MuniRem treated influent NAS Whidbey Island groundwater.....	23

ACRONYMS AND ABBREVIATIONS

BCTW	Bioaugmented Constructed Treatment Wetland
CB1190	<i>Amycolata</i> sp
CTW	Constructed Treatment Wetland
CVOCs	Chlorinated Volatile Organic Compounds
DCA	Dichloroethane
DCE	Dichloroethene
DIC	Dissolved Inorganic Carbon
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
ECTW	Enhanced Constructed Treatment Wetland
EL	Empirical Laboratories, LLC
Fe Tot	Total Iron
Fe ²⁺	Ferrous Iron
Fe ³⁺	Ferric Iron
GETR	Groundwater Extraction, Treatment and Recharge System
MMB	Microbial Mat Bioreactor
MTCA	Model Toxics Control Act
NASWI	Naval Air Station Whidbey Island
NAVFAC NW	Naval Facilities Engineering Command Northwest
ORP	Oxidation Reduction Potential
POU	Point of Use
ppb	Parts per Billion
QA/QC	Quality Assurance/Quality Control
RAO	Recent Remedial Action Operation
RE	Root Exudate
ROD	Record of decision
TC	Total Carbon
TCA	1,1,1-trichloroethane
TCE	Trichloroethene
Temp	Temperature
THF	Tetrahydrofuran
TOC	Total Organic Carbon
URS	URS Corporation
USEPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
µg/L	Micrograms per Liter

1.0 Introduction

Naval Facilities Engineering Command Northwest (NAVFAC NW) requested URS to evaluate the use of green sustainable technologies to remediate 1,4-dioxane (dioxane) contaminated groundwater at the Naval Air Station Whidbey Island (NASWI). As part of the project, PLANTECO Environmental Consultants, LLC (PLANTECO) was subcontracted by URS to conduct a bench scale study to demonstrate/validate the efficacy of applying an engineered green remediation system consisting of constructed microbial mats and wetlands to remediate the dioxane contaminated groundwater.

The contaminated groundwater occurs in a 260-acre tract within Area 6 in the southeast corner of Ault Field. Within Area 6, there are two areas where wastes are known to have been discarded. Liquid wastes were disposed of at the former industrial waste disposal area at a time when regulatory requirements had not been established. These wastes reportedly consisted of solvents, oily sludge, thinners, and other compounds. Waste disposal began in 1969 and ended in the early 1980s. The former industrial waste disposal area is approximately 15 feet by 40 feet. During operation, it was a pit (also called the former waste oil pit) approximately 10 feet deep. Prior to remedy implementation, it was filled and covered with natural vegetation.

A separate portion of Area 6 was used for Navy household municipal waste disposal from 1969 to 1992. This landfill operations area was approximately 40 acres and is now covered with a synthetic cap, soil, and natural vegetation. The synthetic cap prevents infiltration of rainwater. The presence of vinyl chloride and dioxane in groundwater down-gradient of the landfill indicates that some solvent sludges were disposed of in the landfill.

There are two distinct groundwater plumes present at Area 6. The first plume is referred to as the western groundwater plume, which originates from the former industrial waste disposal areas (i.e., the former waste oil pit). Multiple VOCs were detected at concentrations exceeding risk levels in the western groundwater plume. The second plume is referred to as the southern groundwater plume and is in the southern part of the landfill where contaminants originate from the capped landfill (i.e., landfill leachate is the source).

An interim action record of decision (ROD) was developed that resulted in installation of a groundwater containment and treatment system to prevent the continued spread of contaminants from the former industrial waste disposal area in the shallow aquifer beneath Area 6 and to reduce the risk of impact to existing and future groundwater users. The system called for in the final ROD also addresses the southern groundwater plume. The system consists of 10 groundwater extraction wells with 8 currently operating, an equalization tank, particulate filters, packed column air stripper, discharge piping, and miscellaneous pumps, controls, instrumentation, and appurtenances. Two of the ten wells are not in operation (PW-2 and PW-10) as they either do not produce enough water (PW-2) or are newly installed and do not have extraction equipment installed (PW-10). The remaining eight extraction wells extract contaminated groundwater and send the water to an air stripping treatment plant. Trichloroethene, 1,1,1-trichloroethane, 1,1-dichloroethane, 1,1-dichloroethene, cis-1,2-dichloroethene, and vinyl chloride were identified as chemicals of concern in groundwater. Following treatment, the effluent is routed to an up-gradient groundwater recharge system where a wetland has formed. The pump and treat system has been operated, with minor interruptions, since 1995.

In 2002, the United States Environmental Protection Agency (USEPA) asked that the solvent stabilizer dioxane, a common additive to 1,1,1-trichloroethane (TCA), one of the primary VOC contaminants at Area 6, be sampled for at NASWI. dioxane was first detected in on-site wells in 2003, and in a private off-site well in 2005.

The existing air-stripping treatment technology does not remove dioxane because of the compound's relatively low vapor pressure. 1,4 dioxane continues to be re-introduced into the shallow aquifer at the site via the treated effluent. Although, the location of that re-introduction has changed several times, it has generally been up-gradient of the extraction wells, causing a second dioxane plume. Recent Remedial Action Operation (RAO) monitoring has detected levels of dioxane that exceed Model Toxics Control Act (MTCA) Method B clean up levels of 4 micrograms per liter ($\mu\text{g/L}$) and Island County Health Department action level of 3 $\mu\text{g/L}$ in off-site Navy wells. USEPA has informed Ecology that levels were detected above MTCA, Method B clean up levels; Navy has informed Island County Health Department that levels were detected above their action level. The Navy is currently assessing the need for a ROD amendment to establish a dioxane cleanup level. In order to complete this task, the Navy has the immediate need for bench scale feasibility studies to select an effective 1,4 dioxane treatment technology.

2.0 Objective

The primary purpose of this project is to complete a bench scale feasibility study on the efficacy of microbial mats and/or phytoremediation to remove dioxane from groundwater pumped to the surface and propose a green remediation process for full scale application. The specific objectives include:

- A site visit at the current Groundwater Extraction, Treatment and Recharge System (GETR) at Navy Air Station, Whidbey Island (NASWI).
- Collect and ship influent and effluent (pretreated and post treated) groundwater from the pump and treat plant to PLANTECO's Athens, GA facility for use in the bench scale feasibility study.
- Collect and analyze data necessary for proper evaluation of the proposed treatment technology.
- Collect data necessary for evaluating the feasibility of the proposed treatment technology as it relates to the current site and plant conditions.
- Prepare a report detailing the advantages and disadvantages of the proposed treatment technology.

3.0 Rationale

PLANTECO has developed an engineered green remediation system consisting of constructed photosynthetic microbial mats to remove organic and inorganic contaminants from water. Microbial mats will rapidly and non-selectively remove organic and inorganic compounds from water via biosorption and biodegradation of the degradable constituents. Heavy metals are reductively transformed and/or sequestered in the microbial mats at high concentrations.

This natural solar driven, green and sustainable treatment system is designed to semi-passively remove dioxane from groundwater pumped to the surface and polish the effluent in small

constructed treatment wetland(s) planted with selected indigenous wetland plants. PLANTECO will enhance the performance of the engineered green remediation system as needed by adding dioxane degrading bacteria (*Amycolata* sp. CB1190) to the constructed treatment wetland. A microbial mat aquatic treatment system operated in series with an enhanced constructed treatment wetland (ECTW) is robust and reduces the size of the ECTW required to treat the dioxane to the desired goal below 3 ppb. This coupled enhanced biotreatment system is capable of maintaining biological activity during winter months though at a somewhat reduced rate. Because the treatment system relies solely on solar energy and is semi-passive, the cost savings exceed that of more energy intensive systems.

4.0 Technology Description

4.1 Innovative Robust Microbial Mats Aquatic Treatment System – A constructed microbial mat bioremediation system utilizes innocuous, naturally occurring, living organisms to rapidly biosorb and degrade dioxane in water using aerobic and reductive transformation pathways. Since mats are both nitrogen-fixing and photosynthetic, they comprise a self-sufficient, solar-driven ecosystem. Microbial mats have few growth requirements, and will flourish even under harsh environmental conditions. The mats have been shown to rapidly biosorb dissolved phase organic contaminants from water in a matter of seconds to minutes. The absorbed organics are degraded by bacterial consortia that live symbiotically in the mat system, and non-degradable compounds (e.g., metals) are sequestered in the mat tissue.

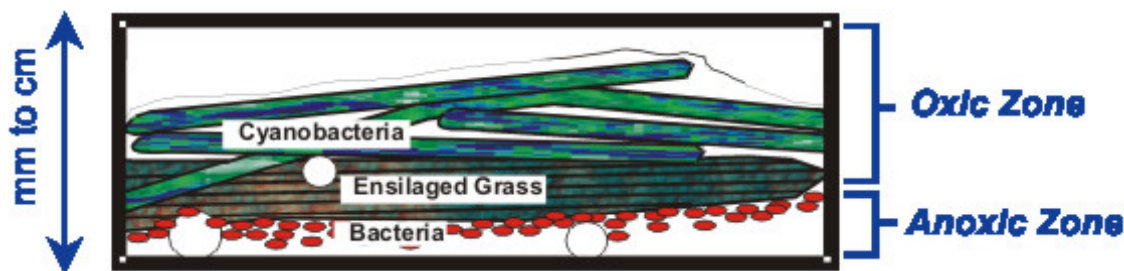


Figure 1 Schematic Cross-Section of Microbial Mat

The 3.5 billion-year survival history of microbial mats testifies to their successful ability to adapt to and survive hostile environments through cellular- and community-mediated activities. Constructed microbial mats have been studied in great detail by members of PLANTECO's research team and other investigators. The microbial mat ecosystem is comprised of self-associating cyanobacteria (*Oscillatoria* sp., formerly known as blue-green algae), purple autotrophic bacteria, and other microorganisms organized into a layered structure which is held together with polysaccharide slime (**Figure 1**). Although mats are not classified as plants, they are photosynthetic and can be grown like plants, harvested, and dried until needed. Rapid growth and development (stratification) of constructed microbial mats is enhanced by mixing ensilaged grass (silage) and nutrients to mat inocula in water. Mats grow rapidly at a biomass production rate of $14.96 \text{ g m}^{-2}\text{d}^{-1}$ (Bender et al, 1989) and can saturate the surface water layer with up to 12 mg/L of dissolved oxygen during photosynthesis on a sunny day (**Figure 2**). The overall oxygen concentration in the system can be controlled by manipulating the activity of oxygen-producing phototrophic bacteria through the control of light intensity.

Microbial mats are able to simultaneously sequester heavy metals and degrade organic contaminants. The different metabolic zones (micro-environments) within the mat enable a variety of bioremediation reactions, like anoxic bioreduction of metals (e.g. Cr(VI) to Cr(III), Se(IV or VI) to Se(0)), metabolism of perchlorate and explosives, sequestration and metabolism of petrochemicals, dechlorination of chlorinated solvents (e.g. trichloroethylene, perchloroethylene, carbon tetrachloride, etc.), or nitrification under highly oxidic conditions. The constructed microbial mats used by PLANTECO are completely non-toxic and do not produce offensive odors.

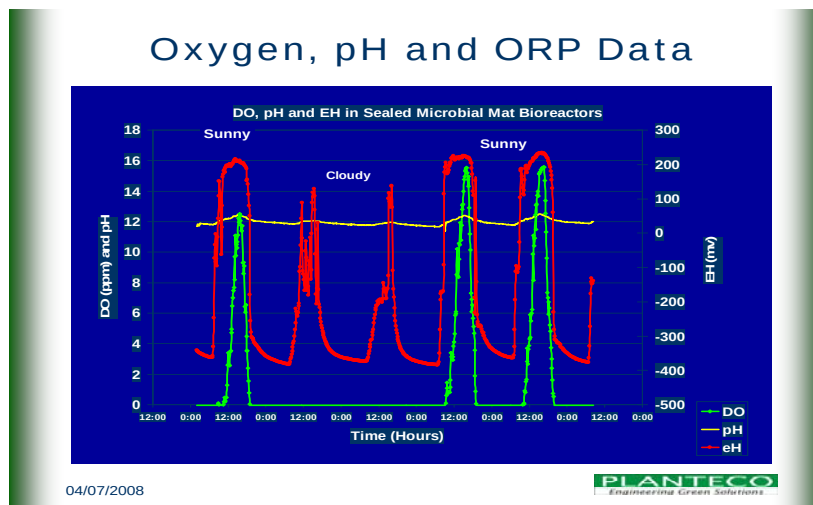


Figure 2 Production of Oxygen and Accompanying Changes in pH and Redox Conditions in a Sealed Microbial Mat Bioreactor Mounted with DO, pH and ORP probes.

4.2 Biodegradation of Organic Compounds – Multiple bacteria capable of mineralizing dioxane have been identified and isolated. Thus, bioremediation of dioxane may be enhanced by bioaugmentation. Microbial mats have been shown to rapidly biosorb dissolved phase organic contaminants from water in a matter of seconds to minutes. The mats are photoautotrophs that can saturate the aqueous phase with oxygen (up to 12 mg/L) during daylight hours and have the potential to degrade organics through oxidative pathways. At night the mats rapidly consume oxygen in the system and provide an anaerobic environment where organic contaminants can be reductively degraded. Sorbed organics are subsequently transformed and incorporated into the microbial mats, providing a carbon source. The efficacy of biodegradation of dioxane using microbial mats is further enhanced by supplying tetrahydrofuran (THF) or butanol to the treatment system.

4.3 Phytoremediation – Phytoremediation has been shown to be effective for removal of dioxane from water at both the bench and field scale. The specific phytoremediation mechanisms involved in the removal of dioxane from water are uptake and phytovolatilization, and enhanced rhizodegradation. In multiple published bench and field tests, the enhancement of rhizodegradation of dioxane has been achieved by supplying bacteria and/or root exudate to stimulate rapid mineralization of dioxane (Figure 3). Since the application for NAS Whidbey

Island is intended for groundwater pumped to the surface, depth limitation is not of concern. The climate is well suited for plant growth.

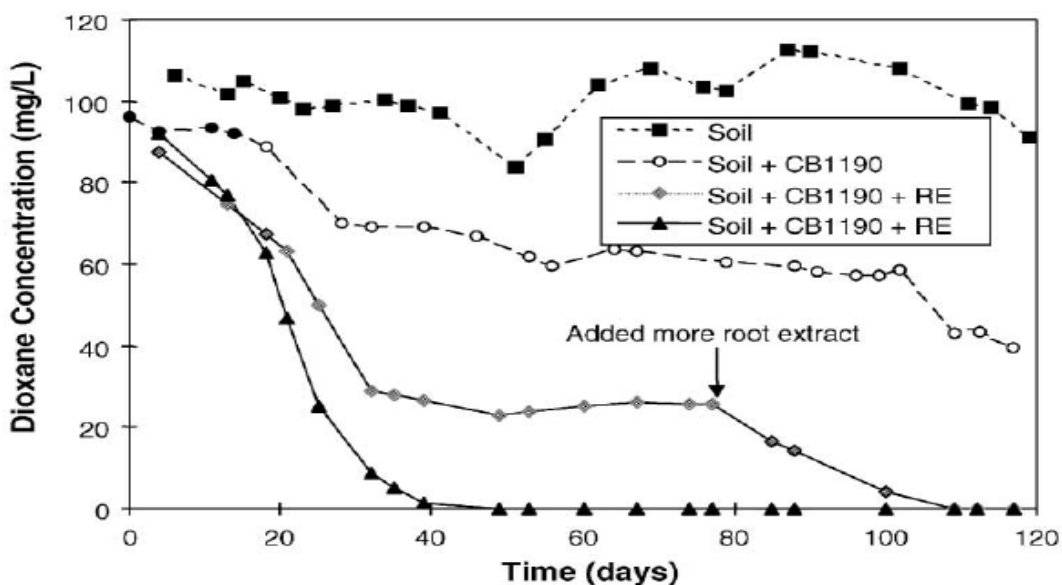


Figure 3. Dioxane degradation in soil microcosms amended with CB1190, root exudate (RE), both, or none (Kelley et al., 2001).

4.4 Technology Maturity – Multiple tests have been performed by PLANTECO to evaluate and demonstrate the efficacy of microbial mats and aquatic plants (phytoremediation) to treat multiple groups of dissolved contaminants in water. **Figure 3** shows PLANTECO's three-phase approach used to evaluate and apply microbial mat aquatic treatment systems at multiple sites. The phases of development include: Phase I – batch and bioreactor tests (kinetics, biodegradation rates, transformation products, and toxicological tests); 2) Phase II – pilot-scale of a prototype bioreactor; and 3) Phase III – full scale operation, construction, and installation of units. Phase I proves the feasibility of using microbial mats as a green sustainable technology for point of use (POU) treatment of small volumes of waste streams. Following the completion of this initial process development phase, additional testing (Phase II) is performed to further develop robust small-scale microbial mat bioreactors for facilities such as wastewater treatment plants before full-scale implementation (Phase III).

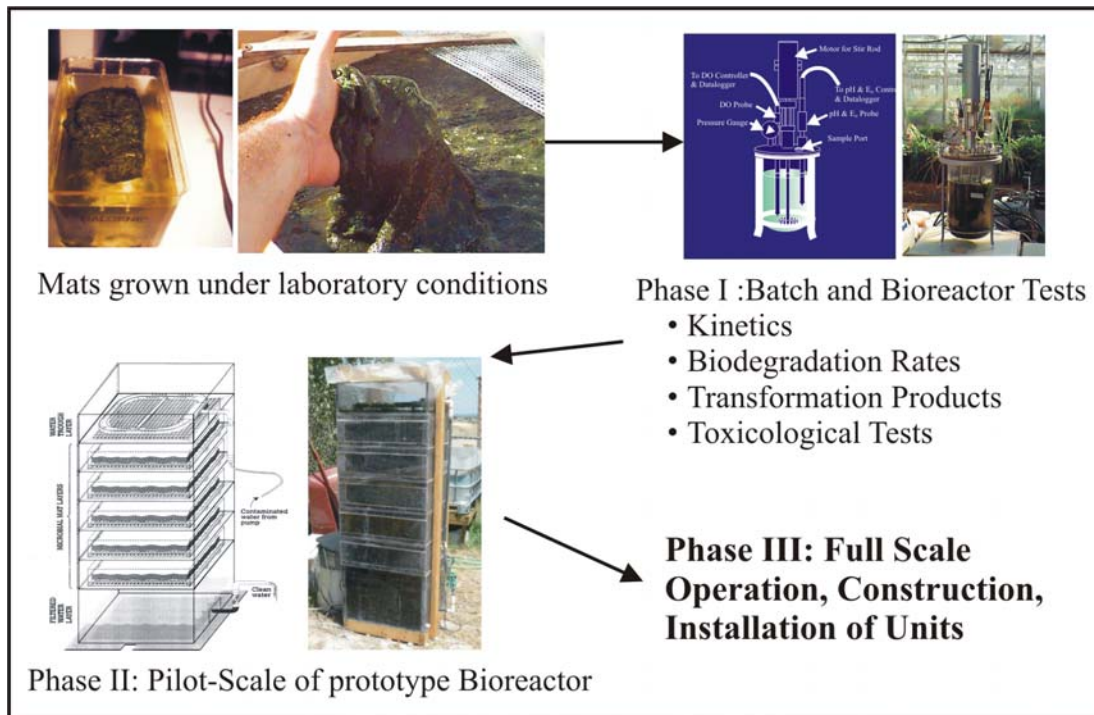


Figure 4. Conceptual Development of the Small Scale Microbial Mat Bioreactor Designed to Treat dioxane Wastewater from existing pump-and-treat system

4.5 Environmental Benefits – A microbial mat coupled with constructed treatment wetland will provided the Navy with a **green remediation** approach. Microbial mats comprise a self-sufficient, solar-driven ecosystem with nitrogen-fixing and photosynthetic capabilities. Such a system can operate with minimal power consumption and can often be sustained with only a solar powered pumping system or via gravity drainage, both of which require no outside electrical power. The spent microbial mat can be dried to significantly reduce the mass for disposal, composted and disposed of as a non-hazardous waste, except in cases where the waste stream contained toxic trace metals. Alternatively, the mat can be incinerated, which will result in a very small volume of ash waste. The wetlands will ensure that the treated water is of reusable quality and fit for discharge into the environment without additional concerns of residuals. The natural green remediation system should significantly improve the site aesthetics and build a healthy ecosystem.

4.6 Throughput potential - The throughput potential of a microbial mat treatment system can be easily adapted to different concentrations and volumes of waste streams. The light intensity provided to the microbial mats can be varied to optimize the rate of biomass production and consequently, the rate of metabolism of the dioxane. Also, the microbial mat bioreactor can be sized to treat waste streams at a desired rate. Generally, the modular plate-and-shelf microbial mat bioreactor is very efficient. Larger or smaller systems can be built to accommodate different flow rates. More sustainable designs couple pre-treatment using microbial mats and polishing of effluent with selected indigenous wetland plants.

4.7 Enhanced Constructed Treatment Wetlands – Enhanced Constructed Treatment Wetlands (ECTWs) are built by man to mimic the structure and function of natural wetlands and remove

contaminants transported through them. Both natural and manmade wetlands are self-sustaining systems that utilize many of the aspects of phytoremediation to clean up the environment. They are characterized by rich and diverse microbial communities that passively biotransform various pollutants. Unlike more conventional remediation systems, which focus on a particular contaminant or class of contaminants, constructed treatment wetlands (CTWs) use multiple natural processes to unselectively and simultaneously remediate various classes of contaminants. CTWs also provide a habitat for various flora which passively bioremediate both soils and groundwater. The passive nature of the system often leads to lower capital and maintenance costs which make CTWs a lower cost option when compared to more conventional remediation systems.

Metals are primarily removed by CTWs through physical, chemical and biological processes (Figure 5). The primary physical process is settling. Chemical removal methods include precipitation, adsorption and ion exchange. Biological removal is primarily through phyto-processes such as phytoaccumulation, phytodegradation and Phytovolatilization. Specific processes include (Hedin et al., 1994 and Sobolewski, 1997, 1999):

- Filtration and settling of solids,
- Sorption onto organic matter (Cu, Ni, and U),
- precipitation through:
 - oxidation and hydrolysis (Al, Fe³⁺, Mn)
 - formation of carbonates (Cu, Mn, Ni, Fe)
 - formation of insoluble sulfides (Ag, Cd, Hg, As, Cu, Pb, and Zn),
 - binding to iron and manganese oxides(As, Co, Cu, Fe, Mn, Ni, Co, Pb, U, and Zn), and
- bacterial reduction (Cr, Cu, Se, and U)

5.0 Whidbey Island Area 6 Site Visit

PLANTECO staff conducted a site visit at Whidbey Island on November 23-24, 2010 for the purpose of assessing the scope of the groundwater contamination, gathering data on the existing treatment approach, a visual site layout assessment, and to collect site sediment and water samples for bench scale feasibility tests. Untreated influent and treated effluent groundwater were collected in 55 gallon metal drums each at the pump-and-treat plant. The groundwater samples were shipped to PLANTECO's facility in Monroe, Georgia and used in the bench scale feasibility tests. Surface water samples were collected from multiple locations at the effluent point at the treated groundwater discharge point for dioxane analysis. Specifically, the effluent water samples were collected in 500-mL sample bottles in the Swale, about 300 ft to the west of the Swale, then about 200 ft down to the west of the man made creek from the discharge pipe of the treated groundwater effluent. The effluent water samples were analyzed for dioxane and the plant influent samples were analyzed for volatile organic compounds (VOC's.) Results are shown on Table 2.

Samples of cattails, grasses, and willow tree cuttings were collected from the wetland that has developed within the discharge area for use in the feasibility studies. Algae and sediment samples were also collected from within the creek. The sediment samples were sent to the laboratory of Dr. Rebecca E. Parales for analysis to determine the presence or absence of

dioxane degrading bacteria. Dr. Pirales is a Professor of Microbiology at the University of California, Davis and a foremost expert on bioremediation of dioxane. She has isolated and cultured dioxane degrading bacteria used in bioremediation and phytoremediation studies published in the peer reviewed literature.

PLANTECO also requested the collection of additional biogeochemical data during upcoming field monitoring events in fall 2010 (see Table 1 below).

Table 1. Biogeochemical parameters needed to support the enhanced bioremediation of dioxane.

Parameter	Acronym	Method	Sampling Locations	Number of Events - Two
Dissolved Oxygen	DO	Electrodes	Pumping Wells, Monitoring Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Oxidation Reduction Potential	ORP	Electrodes	Pumping Wells, Monitoring Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Total Organic Carbon	TOC	EPA 415.1	Pumping Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Total Carbon	TC	EPA 415.1	Pumping Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Dissolved Organic Carbon	DOC	EPA 415.1	Pumping Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Dissolved Inorganic Carbon	DIC	EPA 415.1	Pumping Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
pH	pH	Electrodes	Pumping Wells, Monitoring Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Temperature	Temp	Electrodes	Pumping Wells, Monitoring Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Total Iron	Fe Tot	ICPMS	Pumping Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Ferric Iron	Fe ³⁺	EPA Method ApplEnvMic7-87-1536 SM 3500-Fe	Pumping Wells, Plant Influent, Stripping Tower Influent, Plant Effluent	Late September or Early October & Early December
Ferrous Iron	Fe ²⁺	EPA Method	Pumping Wells, Plant Influent,	Late September or

		ApplEnvMic7-87-1536 SM 3500-Fe	Stripping Tower Influent, Plant Effluent	Early October & Early December
dioxane Bacteria Presence		Prof Parales **	Pumping Wells, Plant Influent, Stripping Tower Influent, Plant Effluent (SW1 and SW2 as 2007 sampling)	One Event

Table 1 Additional biogeochemical data to be monitored.** Rebecca E. Parales, Ph.D., Professor of Microbiology, 226 Briggs Hall, University of California, Davis, One Shields Avenue, Davis, CA 95616 TEL. 530-754-5233 office/ -5234 lab Email reparales@ucdavis.edu

Table 2. Initial concentration of dioxane in 55 gallon drums of influent and effluent groundwater shipped from NAS Whidbey Island for use in bench scale tests.

Site Sample	dioxane	1,1-Dichloroethane	1,1-Dichloroethene	cis-1,2-Dichloroethane	1,1,1-Trichloroethane	Trichloroethene	Vinyl Chloride
	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
PE (Discharge at Swale)	2.17	NA	NA	NA	NA	NA	NA
SW-1 (Swale by road)	2.37	NA	NA	NA	NA	NA	NA
SW-2(200 ft below Swale)	2.01	NA	NA	NA	NA	NA	NA
WHPEC-0 (Plant Effluent)	1.32	NA	NA	NA	NA	NA	NA
WHPEC-1 (Plant Influent)	1.28	NA	NA	NA	NA	NA	NA
WHPEC-1A (Plant Influent)	NA	18.7	9.44	5.00	15.6	16.2	ND

5.1 Bench Scale Tests in Greenhouse and Ambient Conditions. Two sets of bench scale tests were conducted to identify the most suitable bioremediation approach for dioxane in Whidbey Island groundwater. One set of treatment was incubated in a greenhouse while the other set of treatments was incubated in the natural environment at a field site in Monroe, GA in order to assess how weather effects would influence the outcome of the tests. The bench tests were conducted from October 2010 to April 2011. Due to the severe weather conditions of the Georgia 2011 winter season, characterized by ice storms and record snow fall, the outcome of tests conducted under these natural conditions were significantly impacted.

For all batch tests performed during this study, multiple 3-L Applikon® fermentation vessels and 8-L glass vessels were used as bioreactors (**Figure 4 & 5**). For microbial mat treatments, each bioreactor contained approximately 3-L of the dioxane contaminated effluent groundwater and approximately 200 g (wet weight) of the living microbial mat. A total of six identical 8 liter glass reactors were used for the biostimulation and bioaugmentation tests. Three of the six glass

reactors contained the plant influent groundwater and the remaining three contained the plant effluent groundwater (**Figure 6**).



Figure 5. Greenhouse Tests: Multiple Batch Microbial Mat Bioreactors (Left =Day 1; Right = Day 3)



Figure 6. Batch Microbial Mat (left) and Bacteria (right) Treated Bioreactors

Due to the low initial concentration of dioxane detected in the NAS Whidbey Island plant influent and effluent groundwater used in the initial screen tests (Table 3), the groundwater in the 55 gallon drums was spiked with neat dioxane. The new initial dioxane concentration in the spike influent and effluent groundwater was 3810 ppb and 3610, respectively. The higher concentrations allowed for the collection of enough time course (kinetics) data required to estimate the biodegradation rate constants and half-life for dioxane.

To test the efficacy of biostimulation and co-metabolism of dioxane, 4 mL of tetrahydrofuran (THF) or 4 mL of butanol was added to the bioreactor containing dioxane effluent groundwater. For bioaugmentation tests, 5-mL of *Amycolata* sp. (CB1190) provided by Dr Rebecca E. Parales

(Professor of Microbiology), University of California, Davis. The *Amycolata* sp. samples received from Dr. Paraless were immediately frozen and stored in a freezer until used. Since the bacteria was stored in nutrient media containing dioxane, the concentration of dioxane increased initially in solution before beginning to decrease due to biodegradation (see Table 3). The control treatments contained only the dioxane contaminated groundwater.

The greenhouse treatments were started on 11/12/2010 and the treated samples were collected and shipped out for laboratory analysis on 11/18/2010; 6 days of incubation. A second set of bench scale tests conducted in the greenhouse lasted for 31 days. The treatments under natural (ambient) conditions in Table 4 lasted 16 days.

5.2 Laboratory Analysis

The water samples were collected from the bioreactors at predetermined time intervals and shipped to Empirical Laboratories, LLC (EL) in Nashville, TN. (Navy-accredited laboratory) for analysis. To achieve higher sensitivity in the laboratory analysis three 1-L samples were collected from each reactor and analyzed for dioxane using EPA Method 8270C. The method detection limit for dioxane in NAS Whidbey Island groundwater was 0.24 µg/L. The chlorinated volatile organic compounds (CVOCs) present in the plant influent groundwater were analyzed using EPA Method 8260B.

Because large sample sizes were required for laboratory analysis in order to maintain a rigorous QA/QC, the entire liquid content of each treatment bioreactor was sacrificed for analysis at a predetermined time interval. Reanalysis of samples and duplicates was performed on samples that showed unacceptable recovery of the internal standards. A summary of the different test conducted is shown in Table 3 below.

5.3 Results of Bench Scale Tests

Due to the unexpectedly low concentrations of dioxane measured in the NAS Whidbey Island plant influent and effluent groundwater (Table 3), the initial screen tests whose results are presented in Table 3 were deemed inadequate to select the most effective treatment for further investigation in subsequent tests. Note that the higher concentrations of dioxane detected in bioaugmented treatments were attributed to the presence of dioxane in the CB1190 samples.

The data collected from multiple bioreactors showed that bacteria only treatment was most effective for dioxane in NASWI groundwater than microbial mats, THF and butanol treatments in any combination (Table 3). The preliminary conclusion was confirmed in subsequent tests conducted with the spiked dioxane contaminated NASWI groundwater (Table 4). The compiled results in Table 4 and influent groundwater treatment results in Figures 6 and 7 confirmed the effectiveness of the bioaugmentation with bacterial only treatment than the treatments with microbial mats, tetrahydrofuran and butanol with or without CB1190 bacteria. Thus, the CB1190 only treatments showed the highest dioxane degradation activity in both the influent and effluent treated groundwater. From the compiled results the effectiveness of bioaugmentation is evident.

Table 3. Results of the initial bench scale screening tests used to determine the most effective treatment for influent and effluent NAS Whidbey groundwater conducted under ambient conditions. The different treatment included: Microbial Mats Only; Biostimulated (Butanol or Tetrahydrofuran (THF)); Bioaugmented – Bacteria Only and Microbial Mat plus Bacteria
U: The presence of a "U" indicates that the analyte was analyzed for but was not detected or the concentration of the analyte quantitated below the DL. N/A: Parameter was not analyzed for the corresponding sample.

Site Sample	dioxane	1,1-Dichloroethane	1,1-Dichloroethene	cis-1,2-Dichloroethane	1,1,1-Trichloroethane	Trichloroethene	Vinyl Chloride
	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
WI-1A (Plant Influent)	N/A	U	U	U	U	U	U
WIB-1A (Plant Influent + Bacteria)	N/A	U	U	U	U	U	U
WIBMM-1A (Plant Influent + Bacteria + MiMa)	N/A	1.98	0.45	0.34	0.79	1.06	U
ETHFMM-1 (Plant Effluent + THF + MiMa)	0.78	N/A	N/A	N/A	N/A	N/A	N/A
EMM-1 (Plant Effluent + MiMa)	0.59	N/A	N/A	N/A	N/A	N/A	N/A
EBMM-1 (Plant Effluent + Butanol + MiMa)	U	N/A	N/A	N/A	N/A	N/A	N/A
WI-1 (Plant Influent)	0.85	N/A	N/A	N/A	N/A	N/A	N/A
WE-1 (Plant Effluent)	0.78	N/A	N/A	N/A	N/A	N/A	N/A
WIB-1 (Plant Influent + Bacteria)	14.30	N/A	N/A	N/A	N/A	N/A	N/A
WIBMM-1 (Plant Influent + Bacteria + MiMa)	39.20	N/A	N/A	N/A	N/A	N/A	N/A
WEB-1 (Plant Effluent + Bacteria)	13.30	N/A	N/A	N/A	N/A	N/A	N/A
WEBMM-1 (Plant Effluent + Bacteria + MiMa)	48.00	N/A	N/A	N/A	N/A	N/A	N/A

Table 4. Results of bench scale screen tests conducted to identify most effective treatment for dioxane spiked influent and effluent NAS Whidbey groundwater. All tests were performed under ambient conditions for 6 days. The different treatment included: Microbial Mats Only; Biostimulated (Butanol or Tetrahydrofuran (THF)); Bioaugmented – Bacteria Only and Microbial Mat plus Bacteria

Description	Sample	dioxane (µg/L)
Effluent from Drum	WIPEC-E	3810
Green House Effluent + Bacteria + Butanol + Microbial Mats	GWEBBMM	6150
Green House Effluent + Bacteria + Tetrahydrofuran + Microbial Mats	GWEBTMM	4220
Green House Effluent + Bacteria + Microbial Mats	GWEMM	4570
Green House Effluent (big container) + Bacteria (5 mL)	GWB5	6910
Green House Effluent (small 500 mL containers) + Bacteria + Butanol	GWBB	8310
Green House Effluent (small 500 mL containers)+ Bacteria + Tetrahydrofuran	GWBTHF	8690
Monroe Site Influent	WI-2	3610
Monroe Site Influent plus Bacteria	WIB-2	1330
Monroe Site Influent + Bacteria + Microbial Mats	WIBMM-2	2250
Monroe Site Effluent	WE-2	874
Monroe Site Effluent + Bacteria	WEB-2	352
Monroe Site Effluent + Bacteria + Microbial Mats	WEBMM-2	6260

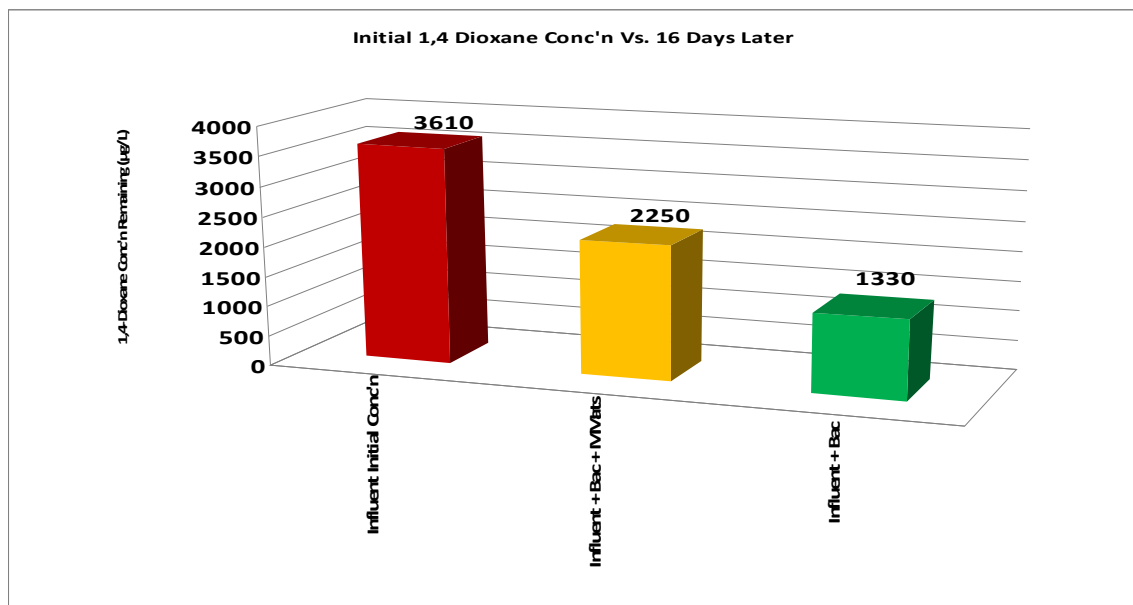


Figure 7. Relative effectiveness of dioxane removal from NAS Whidbey Island groundwater by CB1190 and microbial mats inoculated with CB1190 after 16 days of incubation in ambient conditions.

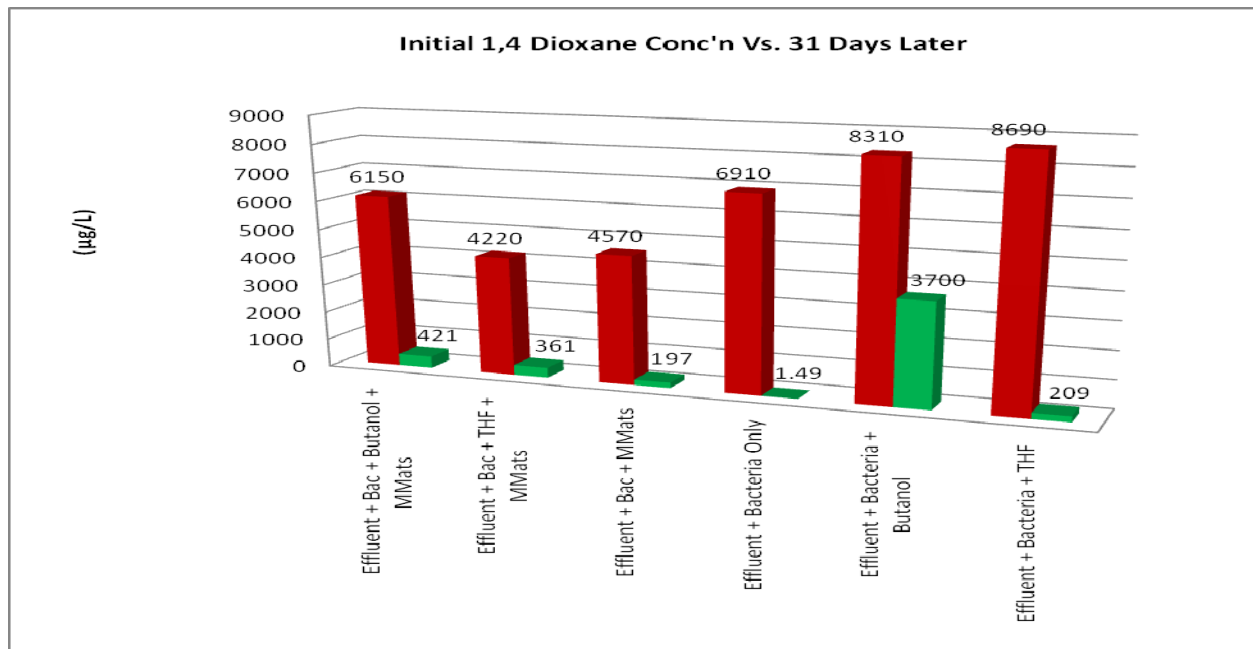


Figure 8. Compiled results of dioxane removal from NAS Whidbey island groundwater for the different treatment after 31 days of incubation in a greenhouse during winter months.

The results of the above tests confirmed that bioaugmentation with CB1190 bacteria or indigenous dioxane bacteria (if present at the site) should be considered as part of any remediation approach proposed for bioremediation of dioxane in NAS Whidbey Island influent or effluent groundwater. To implement a more sustainable green and sustainable remediation system for groundwater pumped to the surface, a two-phase treatment system consisting of a Microbial Mat Bioreactor (MMB) and Biostimulated Constructed Treatment Wetlands (BCTW) operated in series was selected. The designed microbial mat pretreatment operated in series with a constructed treatment wetland bioaugmented with dioxane degrading bacteria is described in detail below.

6.0 Microbial Mat Bioreactor (MMB) Coupled with Bioaugmented Constructed Treatment Wetland (BCTW) – A bench scale pilot test was set up to test a two-phase passive treatment system in series (Figures 8 and 9). The effluent groundwater was initially treated in a plate-and-shelf microbial mat bioreactor (MMB) to remove the dissolved and suspended iron as well as remove some fraction of the dioxane by biosorption and degradation. The Field Pilot test begun on March 15, 2011 and ended on April 30th, 2011

The microbial mat bioreactor consisted of 5 porous shelves approximately 20 x 24 inches each (480 in² or 3.3 ft²). The microbial mats were grown on 1.5 inch thick synthetic plastic fiber that completely filled each shelf. The total volume of the fiber material was estimated at 25 ft³, and the total surface area of the microbial mat is estimated at 625 ft². At the base of the bioreactor

was a catchment tank that held approximately 30 gallons of the treated water. Effluent was pumped into the top of the bioreactor where it sequentially flows by gravity through the five constructed microbial mat shelves and collected in the catchment tank. The bioreactor catchment tank was fitted with a submersible pump and a float switch. As the water level in the tank rose the float switch activated the pump to propel the treated effluent to the next phase of treatment or disposal. The entire unit was approximately 8 feet high, and each shelf is easily accessible and removable. The design allows for the spent microbial mat in each of the five shelves to be replaced easily without interrupting the treatment. The plate-and-shelf model of PLANTECO's microbial mat bioreactor has previously been used to treat wastewater at a flow rate of 2-4 gallons per minute (gpm).

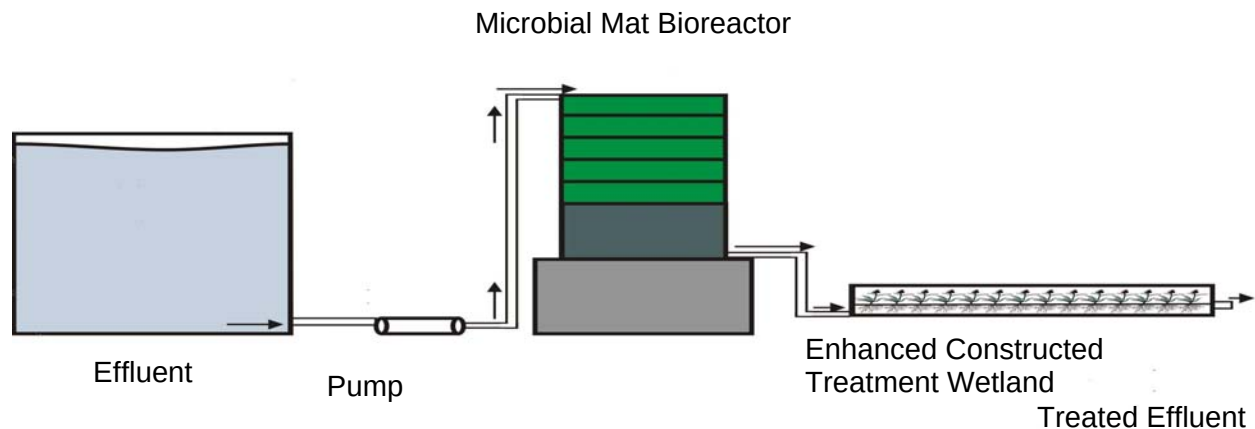


Figure 9. Conceptual Design of the Microbial Mat/BCTW Treatment Setup



Figure 10 Microbial Mat Plate-and-shelf bioreactor operated in series with a CB1190 bioaugmented containerized constructed treatment wetland under ambient conditions.

The MMB pre-treated effluent groundwater was pumped into containerized CTW holding pre-rooted plants collected from NAS Whidbey Island. Bioaugmentation was achieved by adding 20-mL of CB1190 to the CTW to enhance dioxane biodegradation. The selected plants chosen to use in the wetland were cattails, willows, and grass that were brought back from the site where the effluent is currently being discharged. Since the plants are native to the site, they will have a greater survival rate and availability for any future full scale phytoremediation involving wetland plants.

Results of Coupled Microbial Mat Bioreactor and Bioaugmented Constructed Treatment Wetland Treatments.

The removal of dioxane from MMB treated effluent groundwater and in the BCTW over the course of the study is shown in Figure 11 and Table 5. The groundwater was treated in the plate-and-shelf microbial mat bioreactor for 24 hours prior to discharge into the BCTW.

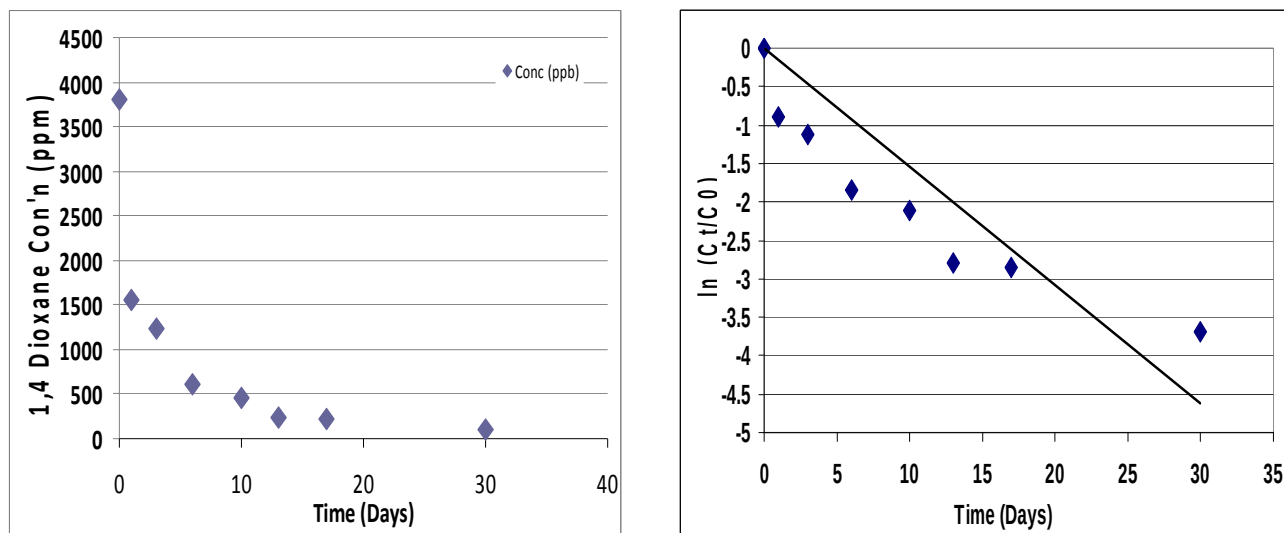


Figure 11. Rate of removal of dioxane from microbial mat and bioaugmented CTW bioreactors.

The concentration of dioxane decreased by 50% after 24 hours in the MMB and 90% removal was achieved in 12 days. The rate of dioxane removal from the BCTW was described by pseudo-first order kinetics. The half-life for treatment of dioxane in the BCTW was about 4 days. About 5% of the mass of dioxane removal was attributed to sampling.

The initial fast rate of removal over the first 12 days was attributed primarily to biodegradation by CB1190 and less to uptake into the plants (Kelley et al., 2001). It is well documented in the peer reviewed literature that the mineralization of dioxane in planted systems is significantly enhanced by bioaugmentation using CB1190 (Li et al., 2010 and references therein). Considering the low plant density and the age of the plants (mix of willows, cattails and grasses), the loss of water by evaporation should be higher than by transpiration. Evaporative loss of water from a CTW would cause the concentration of dioxane to decrease at a slower rate than if the plant transpiration dominated the water loss.

Table 5. Concentration of dioxane measured during bioremediation in microbial mat and constructed treatment wetland bioreactors operated in series.

Description	pH	1,4-Dioxane Conc.'s (ppb)	Remarks
Initial conc.'s in 55 gallon drum	4.24	3810	
24 hrs of treatment in MMB; influent into BCTW	NA	1560	Initial Conc.'s in CTW
72-hr of treatment in MMB and 48 hrs in BCWT	4.86	1230	
6 days of treatment in MMB and 5-days in BCWT	6	603	Reanalyzed
10 days of treatment in MMB and 9-days in BCWT	6	460	
13 days of treatment in MMB and 12-days in BCWT	5	235	
17 days of treatment in MMB and 16-days in BCWT	5	222	
31 days of treatment in MMB and 30-days in BCWT	NA	96.2	

Below are additional results from treatment of the Plant Influent and Effluent groundwater left over from the tests reported above. Therefore, these results mainly reconfirm the results from previous tests, except that CVOCs present in the Plant Influent groundwater was monitored.

Table 6. Additional results for dioxane and CVOCs bioremediation of Plant Influent and Effluent in microbial mat and BCTW bioreactors operated in series.

Sample Description	1,4-Dioxane (µg/L)	1,1-DCA (µg/L)	1,1-DCE (µg/L)	cis-1,2-DCA (µg/L)	1,1,1-TCA (µg/L)	1,1,1,2-TCA (µg/L)
PECWI-07 (Influent GW after 24-h treatment in Microbial Mat reactor)	3310	11.9	3.01	3.94	BDL	BDL
PECWI-09 (Influent GW after 19-days treatment in BCTW)	50.00	BDL	BDL	BDL	BDL	BDL
PECWI-10 (Influent GW after 24-days treatment in BCTW) Remaining Effluent GW added	47.17	BDL	BDL	BDL	BDL	BDL
PECWI-11 (after 28 days in BCTW)	8.35	BDL	BDL	BDL	BDL	BDL

BDL = Below Detection Limit (1.25 µg/L)

7.0 Challenges and Discovery of a Potentially Effective In-Situ Remediation Technology

Throughout the bench scale test there were several challenges that were faced. The first challenge that was encountered was that after the first treatment dioxane was undetected in several samples, therefore the effluent and influent had to be spiked to show the efficacy of the bench scale test. Another challenge that was unpredictable was the unusual cold weather and snowing in Georgia during the winter months of 2011 which slowed the progress of tests conducted in Monroe, Georgia under natural conditions. Except for the microbial mat bioreactor at least 6 inches of ice formed in the bioreactors and did not completely thaw until March 2011. All the wetland plants collected from NAS Whidbey Island and shipped to Georgia hibernated. To keep to the project schedule, a new supply of the plant samples was collected from the effluent discharge wetland area and shipped to Georgia. The samples were pre-rooted in the greenhouse before transported to the CTW tank in the field. The high concentration of iron in the NAS Whidbey Island groundwater samples posed significant challenges. The dissolved and suspended iron precipitated and/or adsorbed onto reactor walls and sampling equipment used in the study. The microbial mats were however effective in sequestering and precipitating the iron from solution as observed in Figures 4 and 5 above. For this reason, the final treatment system couple microbial mat treatment to remove iron and the contaminants of concern from the groundwater prior to polishing in a containerized CTW.

In limited tests conducted with MuniRem[®] (see MuniRem details below), the iron was instantly precipitated out of solution as a dark colored iron sulfide. In addition to precipitating out iron from solution, MuniRem degraded the chlorinated organics and dioxane. The MuniRem treatment lasted only three days removed 50% of the initial dioxane in the influent NAS Whidbey island groundwater; specifically the concentration of dioxane decreased from 3310 ppb to 1790 ppb in three days. Since the goal was not to treat dioxane, the mass of MuniRem reagent added to the reactor was not optimized for dioxane, iron and the chlorinated organics treatment.

Table 7. Concentration of dioxane in untreated and MuniRem treated influent NAS Whidbey Island groundwater.

Sample Description	1,4-dioxane	1,1-DCA	1,1-DCE	cis-1,2-DCA	1,1,1-TCA	TCE	VC
	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
PECWI-07 (Influent from 55 gallon drum)	3310	11.9	3.01	3.94	BDL	0.88	BDL
PECWI-07M (1 gallon of Influent + 100 g of MuniRem [®])	1790	BDL	BDL	BDL	BDL	BDL	BDL
PECWI-07T (Influent treated on Microbial Mat reactor for 3 days)	3440	BDL	BDL	BDL	BDL	BDL	BDL

8.0 Summary and Conclusions

The goal of this study was to evaluate at the bench scale green sustainable technologies to remediate 1,4-dioxane contaminated groundwater at the Naval Air Station Whidbey Island (NASWI). Bench scale feasibility tests were conducted under greenhouse and natural conditions during Fall, Winter and Spring months. The tests conducted in a greenhouse were repeated under natural conditions. The bench scale feasibility tests conducted with NASWI groundwater identified bioaugmentation with CB1190 (a 1,4-dioxane degrading natural bacteria) as a potentially cost-effective green remediation alternative for dioxane. To accommodate NASWI's need for a green remediation technology for pump-and-treat groundwater contaminated with dioxane, a coupled bioremediation treatment system consisting of a plate-and-shelf microbial mat bioreactor (MMB) and bioaugmented containerized constructed treatment wetland (BCTW) was selected for further testing.

The NAS Whidbey Island plant effluent groundwater was pre-treated in a MMB for 24 hours to sequester iron and biosorb some fraction of the dioxane. The pre-treated groundwater was pumped into a containerized CTW holding pre-rooted plant collected from NASWI. Bioaugmentation was achieved by adding bacteria (CB1190) to the CTW to enhance dioxane biodegradation. The selected plants chosen for use in the wetland were cattails, willows, and grass collected from the area where the NAS Whidbey Island treated groundwater is discharged. The concentration of dioxane decreased by 50% after 24 hours in the MMB and 90% removal was achieved in the BCTW after 12 days. The rate of dioxane removal from the BCTW was described by pseudo-first order kinetics. The half-life for treatment of dioxane in the BCTW was about 3.5 days. The results of this study confirmed that phytoremediation applied as a BCTW is potentially effective for treatment of the dioxane contaminated groundwater.

Microbial mats and MuniRem were successful in mitigating the challenges of fouling by iron dissolved and suspended in the groundwater. In the process it was inadvertently discovered that MuniRem mitigated the fouling by iron and also treated dioxane and the CVOCs rapidly. Therefore, MuniRem should be considered as an in-situ technology for remediation of CVOCs and dioxane in NASWI groundwater. Pilot studies will be needed to generate data for a full scale design and application.

This bench scale feasibility study results have identified green biological and abiotic approaches for cleanup of NASWI groundwater in-situ and ex-situ.

9.0 Recommendations

Following treatment of 1,4-dioxane and CVOCs in groundwater at NASWI, the effluent is routed to an upgradient groundwater recharge system where a wetland has formed. The pump and treat system has been operated, with minor interruptions, since 1995 treats CVOCs but not dioxane. Based on the feasibility study results the proposed remedy may include a passive microbial mat treatment pond in plant effluent discharge location with multiple cells of constructed treatment wetlands. To effectively treat dioxane in the effluent groundwater, a treatment system consisting of multiple cells of bioaugmented constructed treatment wetland is proposed in the existing wetland area where the effluent groundwater is discharged. Of the four proposed ponds, the first pond will contain microbial mats that will sequester the dissolved and suspended iron that interferes with the performance of the BCTW system. Microbial mats are grazed on by fish,

so the microbial mat pond will harbor no fish. The microbial mats have demonstrated effectiveness for biosorption/biodegradation CVOs and dioxane, though at a slower rate than a CTW. The passive microbial mat treatment pond in plant effluent discharge location will also elevate the temperature of the water during winter months; the above freezing temperatures are beneficial to biodegradation in winter. The microbial mat treated effluent water will flow by gravity into a bioaugmented constructed treatment wetland for dioxane treatment. To maintain a high population of dioxane degrading bacteria, the three CTW would need to be aerobic. A pilot microbial mat and bioaugmented CTW system will precede the full scale application of the proposed approach.

Based on current plant treatment capacity and discharge volume, the ponds sizes have been estimated as follows:

Residence Time of Water in CTW = 24 Hours

Discharge from Plant = 168 gpm

Volume of Treated Water Discharged = 2,500,000 gpd

Runoff from Surrounding Areas = 14 cfs (15 acres wooded, 13 acres grass)

Consideration is given to offsite flow that would increase the volume during peak precipitation.

Pond size to handle 24 hr 100 yr rain event

Depth of pond = 2 ft and 1 ft free board

Square Pond = 154 ft (W x L)

Rectangular Pond = 109 ft x 218 ft

Pond size to handle plant treated effluent with swale installed to divert runoff water

Square Pond = 127 ft (W x L)

Rectangular Pond = 90 ft x 180 ft

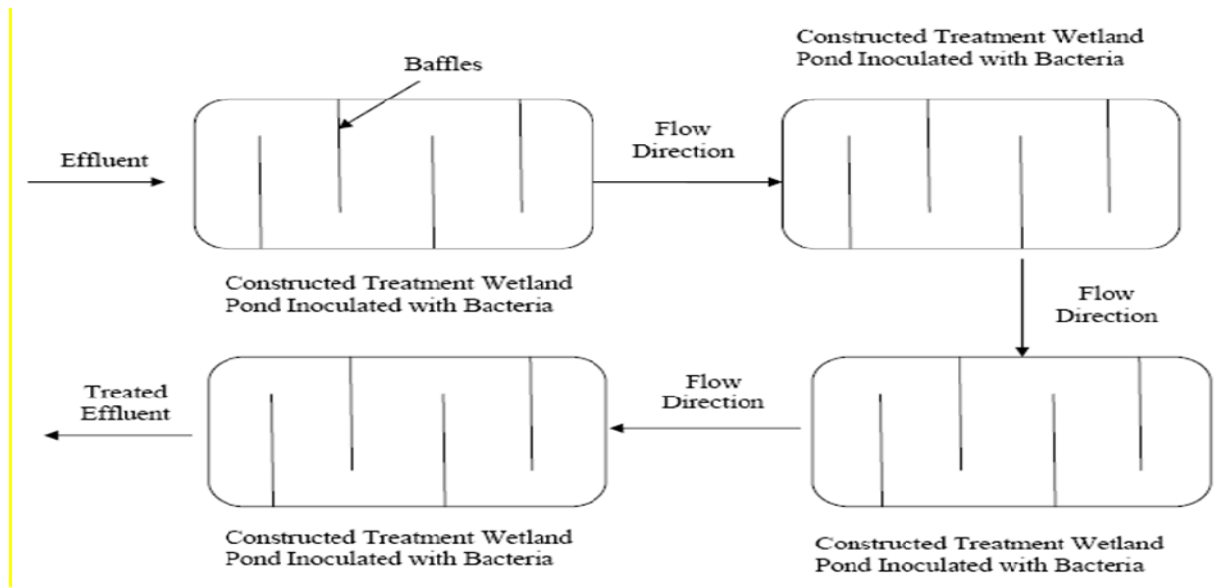


Figure 12 Schematic of full scale BCTW operated in series. Treated water flows by gravity.

For in-situ groundwater applications, the mode of application would be injection of CB1190 or isolated indigenous 1,4-dioxane degrading bacteria into the site groundwater at optimum pH buffered with suitable carbonates. The supply of a suitable oxygen releasing compound would

be necessary, if the NAS Whidbey Island groundwater chemistry shows low dissolved oxygen content.

Preliminary data collected during this feasibility study shows that PLANTECO's MuniRem technology is effective for in-situ remediation of the CVOCs and dioxane simultaneously. MuniRem[®], voted 2010 Better World Technology by the Association of University Technology Managers (AUTM) is featured in The 2010 Better World Report. MuniRem is formulated from bulk reductant(s) and naturally occurring buffers into a water miscible powder called MuniRex. In the presence of water, the active ingredient in MuniRem[®] (MuniRex) generates free radicals that react very rapidly to completely degrade oxidized organic compounds, such as explosives, propellants and chlorinated solvents. No waste products are generated by the use of MuniRem whose main reagent belongs to the same family of sulfur oxides as persulfate.

An in-situ groundwater remediation system using MuniRem will be preceded by limited column tests (3 months) that will generate data for the design of pilot and full scale applications. A MuniRem treatment system would be effective over many years, the exact duration of which will be determined by the level of dissolved oxygen in the ground water. Dynamic flow-through column tests should provide data needed to estimate the life of an in-situ MuniRem remediation system installed at NASWI. Installation will require specially designed geoprobes that are currently available and used in similar applications. Costing of MuniRem will be highly dependent on the data collected during the pre-design column tests.

Ultimately, the successful application of any one of the in-situ remediation systems would lead to the shut down of the pump-and-treat system and a reduced monitoring regime.

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APPENDIX D

Removal of 1,4-Dioxane from Groundwater Using Ozone based Advanced Oxidation Process

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To Whom It May Concern

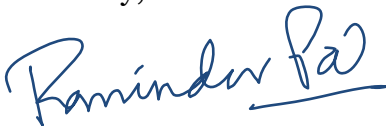
November 14, 2017

At the Water and Environmental Technology (WET) Center, we conducted two groundwater treatment studies for Naval Facilities Engineering Command Northwest (NAVFAC NW) on the 1,4-dioxane groundwater contamination at Area 6 at Naval Air Station Whidbey Island (NASWI). The WET Center was contracted by NAVFAC NW through URS (now AECOM) to conduct the bench-scale tests.

In the first study, the iron content in the groundwater shipped to us in steel drums was very high (in the range of 300 mg/L) whereas the iron content was much lower (in the range of 1 mg/L) in the new batch of groundwater shipped to us in PTFE drums for the second study. During the second study it was determined that the high iron content (300 mg/L) was due to the leaching of iron from the steel shipping drums (even though they were epoxy coated). New batches of groundwater samples were shipped to WET Center in PTFE drums, and the iron content in the samples was approximately 0.05 - 1.23 mg/L.

Unfortunately the first study report "Removal of 1,4-Dioxane from Groundwater Using Ozone based Advanced Oxidation Process" was issued prior to discovering the drum iron leaching issue. The report discusses high concentrations of iron in the site water and recommends pretreatment of iron (raising the pH to precipitate out the iron then filter). The high iron concentration is not representative of Area 6 groundwater conditions. The recommended pretreatment of iron is not necessary based on actual site iron groundwater concentrations. Please consider this letter as an amendment to the previously issued "Removal of 1,4-Dioxane from Groundwater Using Ozone based Advanced Oxidation Process" Report.

Sincerely,



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Director, National Science Foundation (NSF) IUCRC -Water and Environmental
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FINAL REPORT

Removal of 1,4-Dioxane from Groundwater Using Ozone based Advanced Oxidation Process

Submitted to

**URS Inc. and Naval Facilities Engineering Command Northwest
(NAVFAC NW)**

By

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Table of Contents

LIST OF TABLES.....	II
LIST OF FIGURES	II
1. INTRODUCTION	1
2. PROJECT OBJECTIVES	3
3. EXPERIMENTAL METHODS.....	3
3.1 CHEMICALS AND REAGENTS	3
3.2 ANALYTICAL METHOD.....	3
3.3 CALIBRATION STANDARDS	4
3.4 OZONE IN AIR PHASE.....	4
3.5 OZONE IN WATER PHASE.....	5
3.6 OZONATION EXPERIMENTAL SETUP.....	6
4. RESULTS AND DISCUSSION	7
4.1 GROUNDWATER CHARACTERIZATION	7
4.2 GROUNDWATER OZONATION.....	7
5. CONCLUSIONS.....	18
6. RECOMMENDED TREATMENT STRATEGY AT THE SITE.....	19
APPENDIX – A.....	I
APPENDIX B.....	XII

LIST OF TABLES

Table 1: Physical / Chemical property data for 1,4-Dioxane.....	2
Table 2: Characterization of influent and effluent groundwater samples.....	7
Table 3: Removal of 1,4-dioxane in the presence of H_2O_2 alone; Reaction time = 20 min; experiment done in triplicate.	8
Table 4: Ozonation of groundwater effluent spiked with 1, 4-dioxane; ozone weight % = 5	9
Table 5: Groundwater effluent (aerated and filtered) ozonation; H_2O_2 = 30mg/L.....	10
Table 6: Iron and Manganese in unfiltered and filtered effluent (after raising pH and filtration)	11
Table 7: Concentration ($\mu\text{g/L}$) data of VOCs from Ozonation of Influent Groundwater Sample with 5mg/L H_2O_2	17
Table 8: Concentration ($\mu\text{g/L}$) data of volatile organics, Ozonation of Groundwater Effluent with 5mg/L H_2O_2	17

LIST OF FIGURES

Figure 1: Sample calibration curve for 1,4-dioxane.....	4
Figure 2: Ozonated groundwater effluent sample after 30 minutes of ozonation.....	8
Figure 3: Aerated groundwater sample.....	9
Figure 4: Groundwater effluent, Aerated filtered and addition of H_2O_2 (30mg/L)	10
Figure 5: C/C_0 vs. time (ozonation of groundwater with 30 mg/L H_2O_2). The groundwater was pre-aerated and pre-filtered.	11
Figure 6a: GW aerated and pH raised to 10.....	12
Figure 6b: iron precipitating at pH 10.....	12
Figure 7: Final sample, aerated, pH raised to 10 and then filtered using sand filters	12
Figure 8: C/C_0 vs. time data for the removal of 1,4-dioxane; pH 10	12
Figure 9: Ozonation of groundwater in the presence of 5mg/L peroxide; C/C_0 vs. time; pH 10.....	13
Figure 10: Ozonation of groundwater in the presence of 1,4-dioxane and VOC's; C/C_0 vs. time; ozone = 5wt% pH = 10; COD of 180mg/L; 5mg/L H_2O_2	14
Figure 11: C/C_0 vs. time data for the removal of 1,4-dioxane from groundwater in the presence of VOC's; COD ~ 40mg/L.....	15
Figure 12: Concentration vs. time data for removal of 1,4-dioxane from influent and effluent, 5mg/L of H_2O_2 ; COD = 40mg/L.....	16
Figure 13: Concentration vs. time data for removal of 1,4-dioxane from influent and effluent, 10mg/L of H_2O_2 ; COD = 40mg/L.....	18

1. INTRODUCTION

This report describes the results from the laboratory bench-scale tests performed to evaluate the removal of 1,4-dioxane present in site groundwater using ozone based advanced oxidation process. The Naval Facilities Engineering Command Northwest (NAVFAC NW) had requested, via contract to URS Inc, to conduct a 1,4-dioxane investigation for a site at Naval Air Station Whidbey Island (NASWI). The NASWI base has a region, within Area 6, which has contaminated groundwater. Currently, there is an existing groundwater treatment system in operation. This treatment system entails an equalization tank, particulate filters, and a packed tower air stripper to remove chlorinated VOCs such as trichloroethene (TCE), 1,1,1-trichloroethane (1,1,1-TCA), 1,1-dichloroethane (1,1-DCA), 1,1-dichloroethene (1,1-DCE), cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride (VC). The current treatment system is meeting its treatment objectives and permit limits. However, the groundwater samples have had some detects of 1,4-dioxane in the recent past. In 2003, it was first detected in on-site wells, and in a private off-site well in 2005. It was desired to examine, at laboratory scale, the advanced oxidation processes (AOPs) for the simultaneous removal of 1,4-dioxane and chlorinated VOCs from the site groundwater.

1,4-Dioxane is classified as an emerging contaminant (EC), and its environmental regulations are becoming stringent. It is primarily used as a stabilizer for industrial solvents (chlorinated solvents or volatile organic compounds, (VOCs)) to prevent their breakdown during the manufacturing process. Releases of chlorinated solvents are considered to be the primary source of 1,4-dioxane in the environment. It has been detected in surface and ground waters at many places in the United States. The USEPA has classified 1,4-dioxane as a Group B2 probable human carcinogen of low carcinogenic hazard. There is sufficient evidence for the carcinogenicity of 1,4-dioxane in experimental animals (USDHHS, 2002). According to EPA's IRIS, the carcinogenic risk from oral exposure to 1,4-dioxane is $1.1\text{E-}2$ mg/Kg/day. The maximum contamination limit (MCL) for drinking water has not been established. However, many state governments have set advisory levels for this compound. For example, the state of California has an action levels at $3\mu\text{g/L}$ (ppb). The Island County Health Department has set an action level of $3\mu\text{g/L}$ (ppb) for 1,4-dioxane in off-site Navy wells. Table 1 shows its physical-chemical properties. It has very high aqueous solubility, very low Henry's constant, and very low biodegradation coefficient. Due to these properties, it is difficult to efficiently remove 1,4-

dioxane from water using air stripping, carbon adsorption or by biodegradation. It migrates rapidly in the groundwater, and there is very little retardation due to sorption on particles due to its very low K_{ow}.

Table 1: Physical / Chemical property data for 1,4-Dioxane

Property	
CAS	123-9-1
Molecular formula	C ₄ H ₈ O ₂
Molecular Weight	88.1
Melting point (°C at 760mm HG)	11.8
Boiling point (°C at 760mm HG)	101.1
Density (g/mL at 20°C)	1.0329
Water solubility (mg/L at 20°C)	Miscible
Log K _{ow}	-0.27
K _{oc}	1.23
Vapor Pressure (mm Hg at 20°C)	30
Henry Law constant (atm m ³ /mole)	4.88x 10 ⁻⁶
Log Bioconcentration factor	-0.44 calculated
Odor threshold (mg/m ³	9.8 (2.7ppm)

Groundwater was obtained from the NAS Whidbey island site. A site visit was performed and the samples were collected by URS Inc. and were shipped to WET Center. Approximately 50 gallons of influent and 50 gallons of effluent were shipped. Prior to shipping, the water was acidified (using hydrochloric acid) to prevent any bacterial growth and precipitation of iron and manganese. It is likely that some of the chlorinated VOC's were lost due to volatilization during the shipment process. There may be some loss of 1,4-dioxane and other organics due to sorption on the container surface.

2. PROJECT OBJECTIVES

The primary objective of this project was to perform laboratory scale experiments to examine the destruction of 1,4-dioxane and volatile organic compounds in groundwater using ozone. Specific objectives were:

1. Characterize the groundwater for contaminants (1,4-dioxane, chlorinated solvents), bromide, bromate, iron, manganese, pH, alkalinity, dissolved oxygen and chemical oxygen demand.
2. Examine the potential of precipitation of Fe/Mn..
3. Determine the optimum reaction time, ozone dosage and peroxide dosage for the simultaneous removal of 1,4-dioxane and chlorinated VOC's.
4. Identify optimum conditions for ozone mass transfer.

3. EXPERIMENTAL METHODS

3.1 CHEMICALS AND REAGENTS

The following chemicals (maximum purity) were obtained from Sigma-Aldrich: 1,4-dioxane (99.9%), 1,4-dioxane-d8 (99%), methylene chloride (99%) and sodium sulfate (99%). Methanol (HPLC grade) was obtained from Fisher Scientific Inc. Supelclean™ coconut charcoal SPE tube cartridges (bed weight – 2gm; 6ml volume) were obtained from Sigma Aldrich.

Potassium indigo trisulfonate ($C_{16}H_7K_3N_2O_{11}S_3$), phosphoric acid (H_3PO_4 , 85%) and hydrogen peroxide (H_2O_2 , 30 wt%) were obtained from Sigma Aldrich. Potassium phosphate monobasic (Laboratory Grade), sodium phosphate monobasic (ACS), sulfuric acid (ACS) and sodium thiosulfate (ACS) were obtained from Fisher Scientific. Potassium iodide (KI, ≥99%) and sodium phosphate monobasic (KH_2PO_4 , ≥99%) were obtained from Acros Organics.

3.2 ANALYTICAL METHOD

Quantitative analysis of 1,4-dioxane was performed using solid phase extraction followed by gas chromatography/mass spectrometry (GC/MS) analysis. Solid phase analysis was performed using EPA method 522. A 250ml sample was passed through the SPE cartridges at a flow rate of 5 to 10 mL/min. The cartridges were then eluted using 5 ml of methylene chloride and a known amount of internal standard (1,4-dioxane d8) was added. Small amount of sodium sulfate was added to the mixture to remove any moisture content. The sample was then analyzed on GC/MS. The GC/MS analysis was performed using Agilent 7890 GC coupled with 5975C MS. Auto injections were made using splitless mode and the injection volume was 3μL. Injection

temperature was 250°C and the head pressure was 60kPa of Helium. Initial temperature of the oven was 45°C, held for 4.5 minutes and then ramped to 100°C at a rate of 12°C/min. The temperature was then ramped to 240°C at a rate of 25°C/min and held for 1.3 minutes. Transfer line temperature to the MS was maintained at 250°C and the Electron Energy was 70eV. Samples were sent to Lancaster Laboratories, PA for analysis of chlorinated solvents, iron, manganese and bromide content.

3.3 CALIBRATION STANDARDS

Stock solution of 1,4-dioxane was prepared in water at 250mg/L and stored at 4°C. From this stock solution, calibration standards were prepared by spiking approximate amounts of stock into 250mL of deionized water. The calibration standards ranged from 0.25µg/L to 100µg/L. A fixed amount of internal standard (1,4-dioxane-d₈) was added to each sample after SPE extraction to account for any losses that may have occurred during the sample processing. Figure 1 shows the calibration curve for 1,4-dioxane. Coefficient of determination (R²) value was 0.995 for the calibration curve.

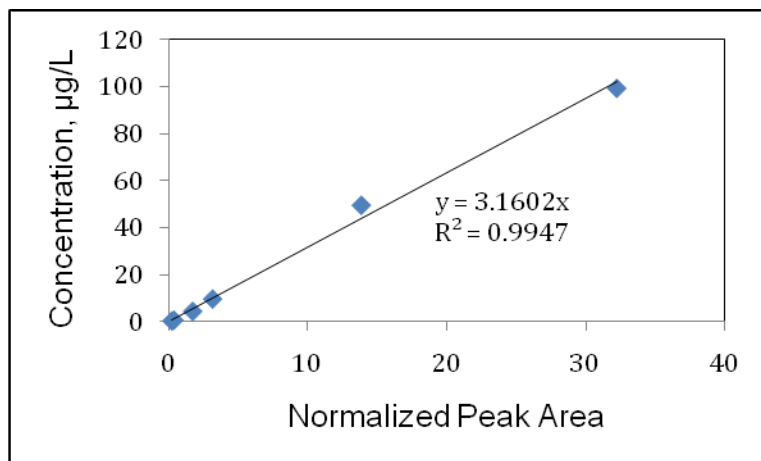


Figure 1: Sample calibration curve for 1,4-dioxane

3.4 OZONE IN AIR PHASE

The ozone concentrations in the air phase were measured using potassium iodide (KI) wet chemistry testing. The KI wet chemistry method is based on the principle that iodide ion is oxidized by ozone to form iodine when ozone gas is bubbled through a solution of KI. When bubbling is stopped, the KI solution is adjusted with sulfuric acid to pH 2, or lower. The liberated iodine is titrated using standardized sodium thiosulfate. The mass of ozone reacted is determined based on a theoretical ozone/iodine stoichiometry of 1.0.



The iodine formed in the above reaction is titrated directly with thiosulfate ion:



Potassium iodide stock reagent (2%) was prepared by dissolving 10g KI, 2.91 g of disodium hydrogen phosphate ($Na_2HPO_4 \cdot 2H_2O$), and 1.75 g of mono potassium dihydrogen phosphate (KH_2PO_4) in 4L of distilled water. Sulfuric acid (2N) was prepared by adding 56 ml concentrated sulfuric acid to 944 ml distilled water. Sodium thiosulfate ($Na_2S_2O_3$) stock solution was prepared by dissolving 250gm of pentahydrate sodium thiosulfate ($Na_2S_2O_3 \cdot 5H_2O$) granules into 1L of distilled water. Sodium thiosulfate ($Na_2S_2O_3$) (0.1N) was prepared by adding 100 ml of 1N $Na_2S_2O_3$ stock solution to 900 ml of distilled water.

A Class-A burette was filled with 50 ml of $Na_2S_2O_3$ (0.1N) titrant. 400 ml of 2% KI solution was added to two gas washing bottles. Ozone was bubbled through the KI solution for a fixed time. About 10 ml of 2N H_2SO_4 was quickly added to each gas-washing bottle to lower the pH of the solution below 2. The liquid from each gas-washing bottle was then transferred to a 1L flask and titrated with $Na_2S_2O_3$ solution. Mass of ozone trapped in KI is calculated using Equation 3.3.

$$O_{3_{mass}} = 24 \times V_t \times N_t \quad 3.3$$

Where $O_{3_{mass}}$ = mass of ozone trapped in KI, mg

V_t = Volume of sodium thiosulfate titrant used, ml

N_t = Normality of sodium thiosulfate, mg/meq

3.5 OZONE IN WATER PHASE

The ozone concentration in the aqueous phase was measured using indigo-trisulfonate method (Bader and Hoigne, 1981). The indigo method is based on the principle that in acidic solution, potassium trisulfonate ($C_6H_7N_2O_{11}S_3K_3$) is discolored by aqueous ozone and the degree of discoloration is compared to a blank solution of the dye. The decrease in the absorbance is linear with increasing ozone concentration.

Indigo solution was prepared by adding distilled water (500ml), concentrated phosphoric acid (1ml), and potassium indigo-trisulfonate (770mg) to a volumetric flask and diluted to 1L with

distilled water. A 1:100 dilution exhibits an absorbance of $0.2 \pm 0.010\text{cm}^{-1}$ at 600nm, and the solution should be discarded when absorbance falls below 0.16units/cm. This stock solution is stable for about 4 months when stored in the dark (standard methods). The working solution was made up immediately before use by dilution of 100 ml of the above indigo stock solution to 1L with distilled water and adding 10g of sodium dihydrogen phosphate and 7ml phosphoric acid to it. 100 ml glass bottles were taken and 10 ml of working solution was introduced into each along with 87 ml distilled water. One bottle was filled with 3ml of ozone free water and other with 3ml of ozonated water. The ozone samples were introduced by immersing the pipette to the bottom of the bottle and gently shaking so that no ozone degassing occurred. The difference in absorption of light at 600nm between the blank and samples was measured using HACH DR/4000U spectrophotometer. The ozone concentration was then determined using Equation 3.4.

$$C = \frac{V \times \Delta A}{f \times b \times V_t} \quad 3.4$$

Where C is the concentration of ozone in mg/L; ΔA the difference in absorbance; $f = 0.42$ (corresponding to the absorption coefficient for aqueous ozone); b the path length (1cm); V_t and V are the total volume (100ml) and volume of sample added (3ml), respectively.

3.6 OZONATION EXPERIMENTAL SETUP

The ozonation experimental setup comprises of an ozone generator, bubble column, degassing unit, and destruct unit. The ozone generator (OZAT CFS-1 2G) was obtained from Ozonia Ltd. It is capable of generating ozone concentrations of up to 5wt% in the product gas when using air and, up to 13% when using oxygen. Air and oxygen were supplied from Airgas, Inc. Experimental setup consists of two columns equipped with a porous gas diffuser (pore diameter ranging from 30 to 100 microns). The first column served for absorption while the second column served for desorption. Water can be circulated between the two columns. The excess ozone from the reactors is sent to the destruct unit. The columns were designed and the diffusers were custom built to fit the column. The pump was purchased from FMI metering Inc. Valves, pressure relief valves and check valves with stainless steel piping were used.

4. RESULTS AND DISCUSSION

4.1 GROUNDWATER CHARACTERIZATION

In this report, **Groundwater Influent** is being referred to the groundwater coming into the treatment plant at the site. **Groundwater Effluent** is being referred to the final effluent at the site i.e. after packed tower aeration and bag filtration.

The influent and effluent groundwater samples obtained from the NAS Whidbey island was characterized for pH, dissolved oxygen, chemical oxygen demand, salinity, total organic carbon, iron, manganese, bromide and 1,4-dioxane. Table 2 shows the characteristics and the analysis methods used. No bromide was detected in influent or effluent water samples. High The method detection limits are shown in Appendix B – Table 1.

Table 2: Characterization of influent and effluent groundwater samples

CHARACTERISTIC	INFLUENT	EFFLUENT	METHOD
pH	6.3	6.4	pH meter
Dissolved Oxygen, mg/L	2.1	1.1	DO meter
Salinity, ng/L	1.2	1.2	Salinity meter
Total Organic Carbon, mg/L	11.7	15.9	SM 20 5310C
Iron, mg/L	319.0	217.0	SW 846 6010B
Manganese, mg/L	1.6	1.5	SW 846 6010B
Bromide	ND	ND	EPA 300
1,4-dioxane, µg/L	3.0	3.0	Modified EPA 522
COD, mg/L	39	37	Hach COD Kits

ND: non-detect

4.2 GROUNDWATER OZONATION

Initial concentration of 1,4-dioxane in groundwater effluent was approximately 3µg/L. The groundwater was spiked to achieve about 10µg/L of 1,4-dioxane to achieve higher concentration. A series of experiments were conducted, and are summarized below.

Experiment 1: Due to the high iron content in groundwater, initial experiments were conducted by adding hydrogen peroxide (H_2O_2) to the groundwater and allowing it to react for 20 minutes. Different concentrations of peroxide were tested, and data for 30mg/L peroxide test is shown in Table 3. Approximately 50% removal of 1,4-dioxane after 20 minutes of reaction was observed. The presence of H_2O_2 did not have a significant effect on the removal of 1,4-dioxane.

Table 3: Removal of 1,4-dioxane in the presence of H_2O_2 alone; Reaction time = 20 min; experiment done in triplicate.

SAMPLE	1,4-Dioxane	% Removal
Spiked Groundwater	12.1	
Groundwater + 30 mg/L H_2O_2	5.5	56
	5.7	54
	5.9	53

Experiment 2: Further experiments were carried out in presence of ozone. Initially, a 12L sample of groundwater effluent was spiked with approximately 100 $\mu\text{g/L}$ of 1,4-dioxane and ozonated. Table 4 shows the removal of 1,4-dioxane from groundwater effluent in presence of ozone. Due to the high iron content, the ozonated sample turned to reddish brown color after ozonation. Mass transfer of ozone could not be performed due to the high iron content. Figure 2 shows the final ozonated sample. Only 20% removal of 1,4-dioxane was observed after 60 minutes of ozonation. This is due to the interference from high iron content.



Figure 2: Ozonated groundwater effluent sample after 30 minutes of ozonation

Table 4: Ozonation of groundwater effluent spiked with 1, 4-dioxane; ozone weight % = 5

Ozonation time, minutes	1,4-dioxane, µg/L	% Removal
Initial sample	90.0	
5 min	88.1	2
10 min	95	–
15 min	96	–
20 min	101	–
30 min	117	–
45 min	77	13
60 min	69	22

Experiment 3: Due to the low removal of 1,4-dioxane from groundwater by direct ozonation, the water sample was first aerated for 30 minutes and then filtered using sand filters for further experiments. The aerated sample is shown in Figure 3. Due to the high iron content, the sand filters had to be backwashed after every 5 L of water filtered. After aeration and sand filtration, the groundwater sample was a clear liquid. The aerated and filtered sample was then ozonated in the presence of 30 mg/L of H₂O₂. However, addition of peroxide to the clear sample resulted in a dark brown color liquid, as shown in Figure 4. No precipitates or suspension was observed.



Figure 3: Aerated groundwater sample

Figure 4 shows the water sample (aerated, filtered) after addition of peroxide to the water sample. This indicated that the presence of additional iron in the solution. Table 5 shows the removal of 1,4-dioxane from the aerated and filtered groundwater effluent. Only 60% removal of 1,4-dioxane was observed after 20 minutes of ozonation. Figure 5 shows the C/C_0 vs. time data for the removal of 1,4-dioxane. There was an initial reduction in 1,4-dioxane concentration. It is likely that the peroxide reacted with iron and ozone and was consumed in the initial few minutes. Further addition of peroxide was not examined as it may not be cost effective.

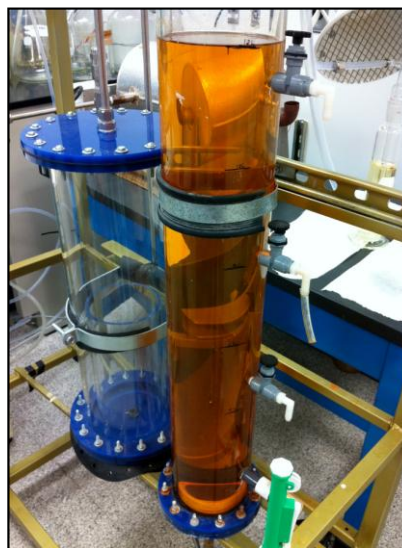


Figure 4: Groundwater effluent, Aerated filtered and addition of H_2O_2 (30mg/L)

Table 5: Groundwater effluent (aerated and filtered) ozonation; H_2O_2 = 30mg/L

Ozonation time, minutes	1,4-dioxane, $\mu\text{g/L}$	% Removal
Initial Sample	38.2	
1 min	16.2	57
3 min	15.1	60
5 min	15.7	59
10 min	15.8	59
15 min	14.5	62
20 min	14.7	62

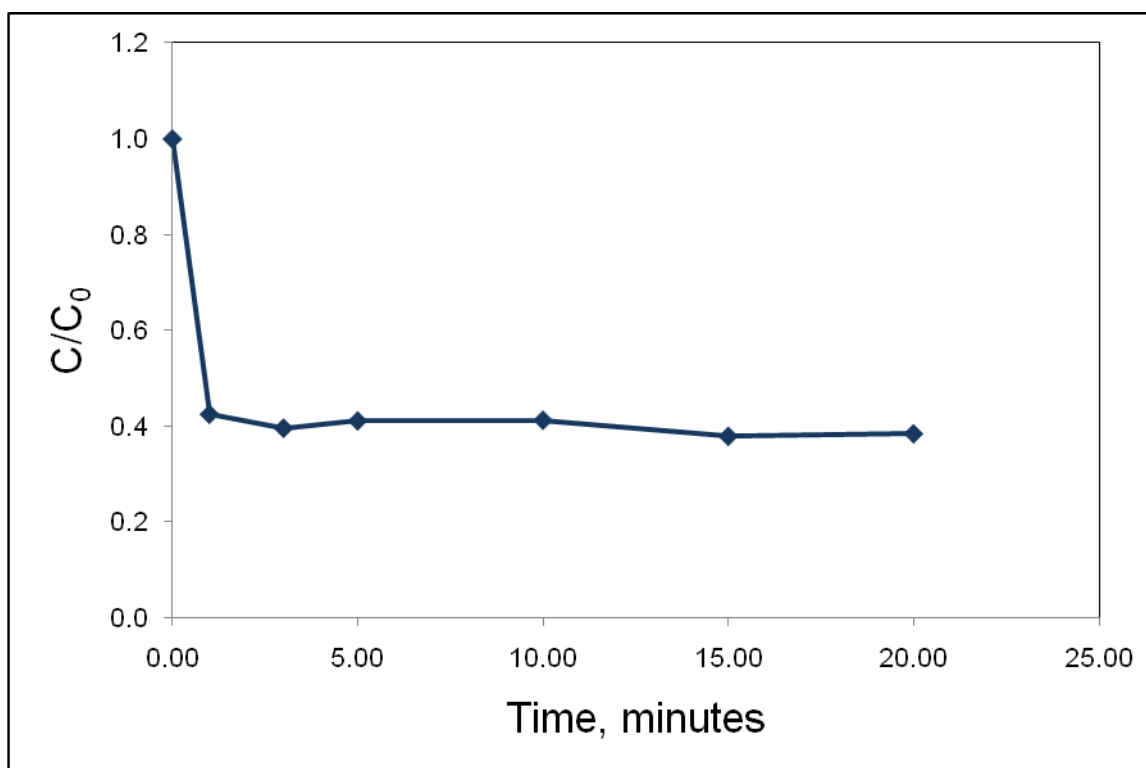


Figure 5: C/C_0 vs. time (ozonation of groundwater with 30 mg/L H_2O_2). The groundwater was pre-aerated and pre-filtered.

Experiment 4: In order to enhance the removal of 1,4-dioxane, the iron in the water sample needed to be precipitated out. For further experiments, the groundwater was aerated and the pH was increased to 10 by using NaOH. As the sample pH was raised to 10, the suspended iron turned to green color and started precipitating out. Figures 6a and 6b show the sample after raising the pH to 10 and after precipitation, respectively. The sample was then filtered using sand filters, and a clear water solution was observed as shown in Figure 7. Table 6 shows the iron and manganese content in the unfiltered groundwater effluent (as received) and filtered (pH 10) groundwater effluent. By raising the pH to 10 and filtration, almost complete removal of iron and manganese was achieved.

Table 6: Iron and Manganese in unfiltered and filtered effluent (after raising pH and filtration)

Sample	Iron, mg/L	Manganese, mg/L
Unfiltered Effluent	204	1.5
Filtered Effluent	0.1	ND



Figure 6a: GW aerated and pH raised to 10

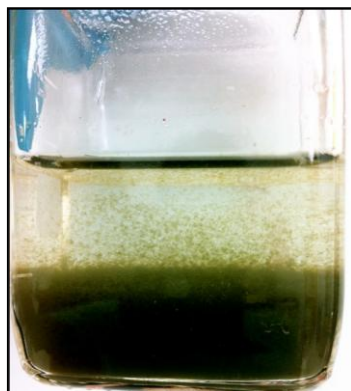


Figure 6b: Iron precipitating at pH 10



Figure 7: Final sample, aerated, pH raised to 10 and then filtered using sand filter7s

The filtered groundwater was then spiked with 1,4-dioxane and ozonated. Figure 8 shows the removal of 1,4-dioxane (C/C_0 vs. time) from effluent. Appendix A – Table A1 shows the concentration and ozone mass balance data. After 15 minutes of ozonation, the concentration of 1,4-dioxane dropped to 3.4 μ g/L. The target concentration for this study was less than 3.0 μ g/L of 1,4-dioxane.

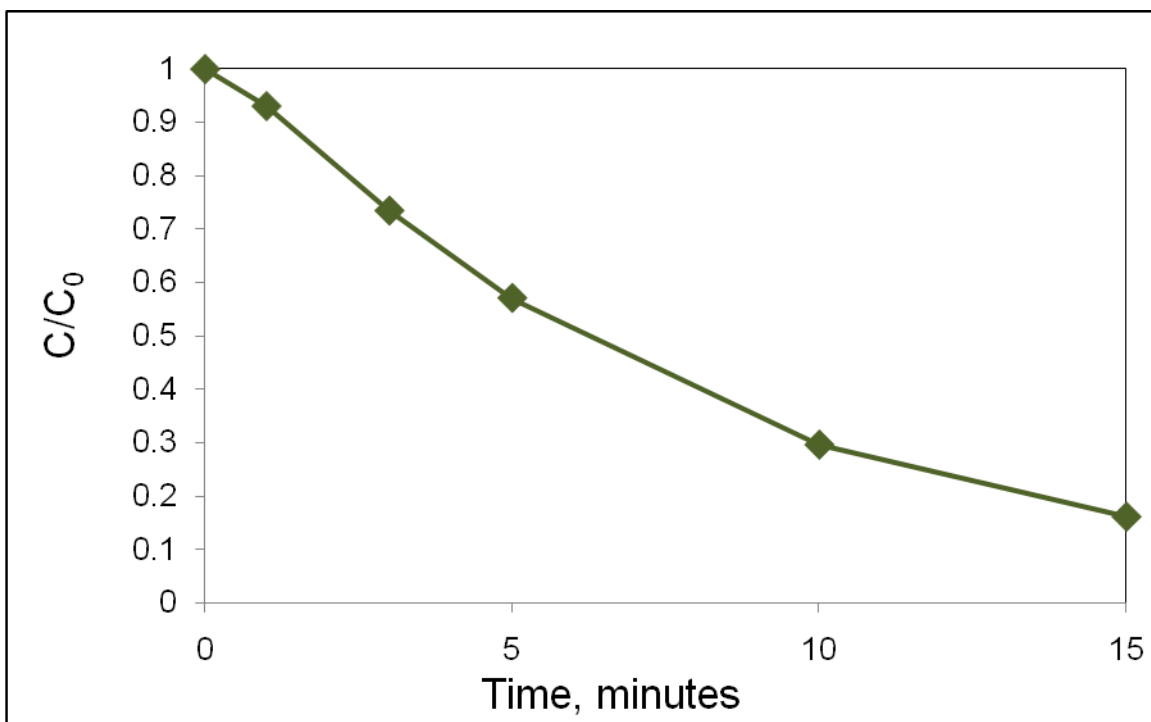


Figure 8: C/C_0 vs. time data for the removal of 1,4-dioxane; pH10

Experiment 5: In order to enhance the removal of 1,4-dioxane, 5mg/L of H_2O_2 was added to the groundwater sample and then ozonated. Figure 9 shows the removal (C/C_0 vs. time) of 1,4-dioxane in the presence of peroxide. It was observed that the concentration of 1,4-dioxane reduced to approximately 1.9 $\mu\text{g/L}$ within 15 minutes of ozonation, and within 30 minutes complete removal of 1,4-dioxane was observed. Concentration and ozone mass balance data is shown in Appendix A – Tables A2 and A3.

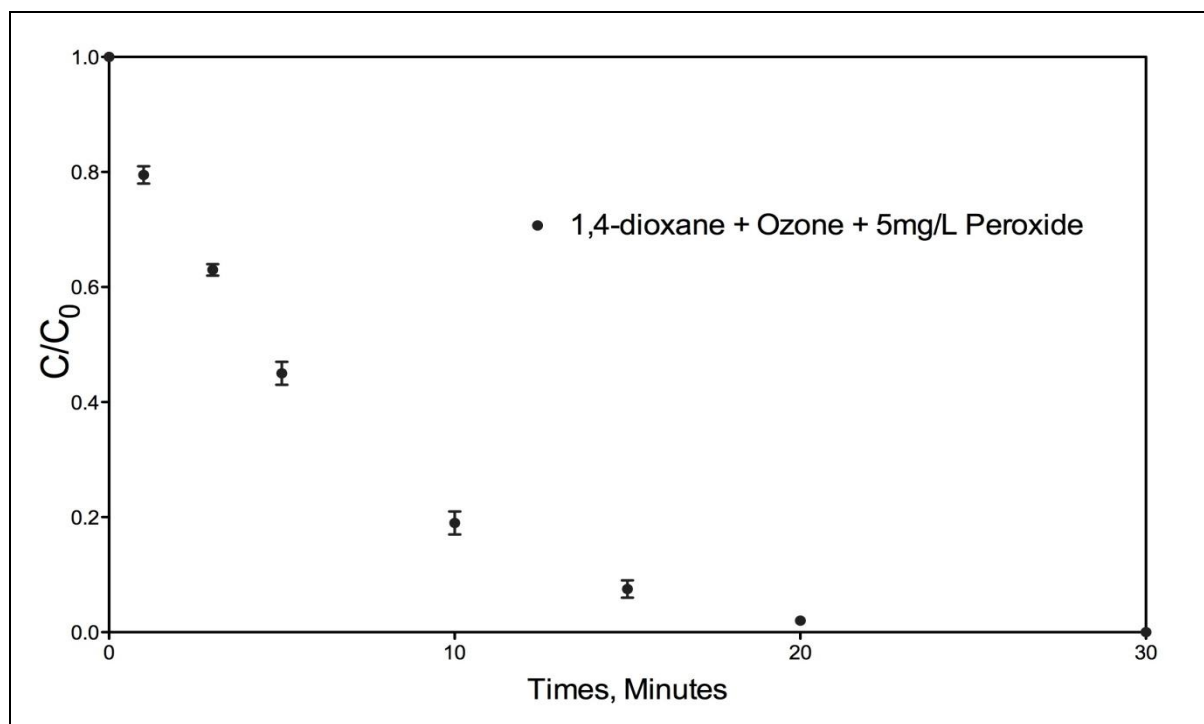


Figure 9: Ozonation of groundwater in the presence of 5mg/L of Peroxide; C/C_0 vs. time; pH10

Experiment 6: A similar experiment was conducted with influent and effluent groundwater samples but in the presence of VOCs and 1,4-dioxane. Both the samples were spiked with chlorinated VOC's and 1,4-dioxane. Chlorinated VOC stocks were prepared in methanol, and adding these analytes resulted in a high background COD (180 mg/L). Figure 10 shows the C/C_0 vs. time data for the removal of 1,4-dioxane. Approximately 20 - 30% removal was observed. This was due to the presence of high COD in the groundwater samples from methanol. The ozone and peroxide were scavenged by the methanol in the solution. Concentration and ozone mass balance data is shown in Appendix A – Tables A4 and A5.

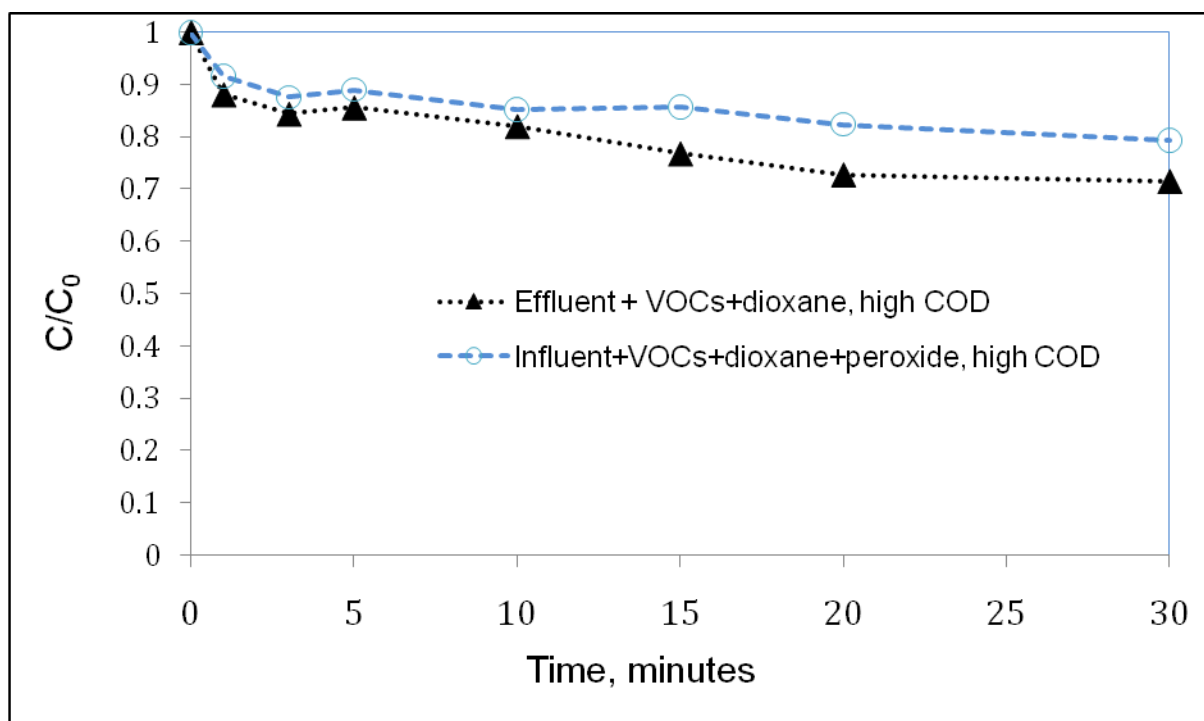


Figure 10: Ozonation of groundwater in the presence of 1,4-dioxane and VOC's; C/C_0 vs. time; ozone = 5wt%; pH = 10; COD of 180mg/L; 5mg/L of H_2O_2

Experiment 7: New stock solutions were prepared for chlorinated VOC analytes at high concentration. Experiments were performed at low COD (~40 mg/L) by adding small amounts of high concentration VOC stock solution to the groundwater samples. Figure 11 shows the C/C_0 vs. time data for the removal of 1,4-dioxane from groundwater effluent in the presence of VOC's. Only 60% removal of 1,4-dioxane was observed after 30 minutes of ozonation. The removal of VOC's was not monitored in these samples.

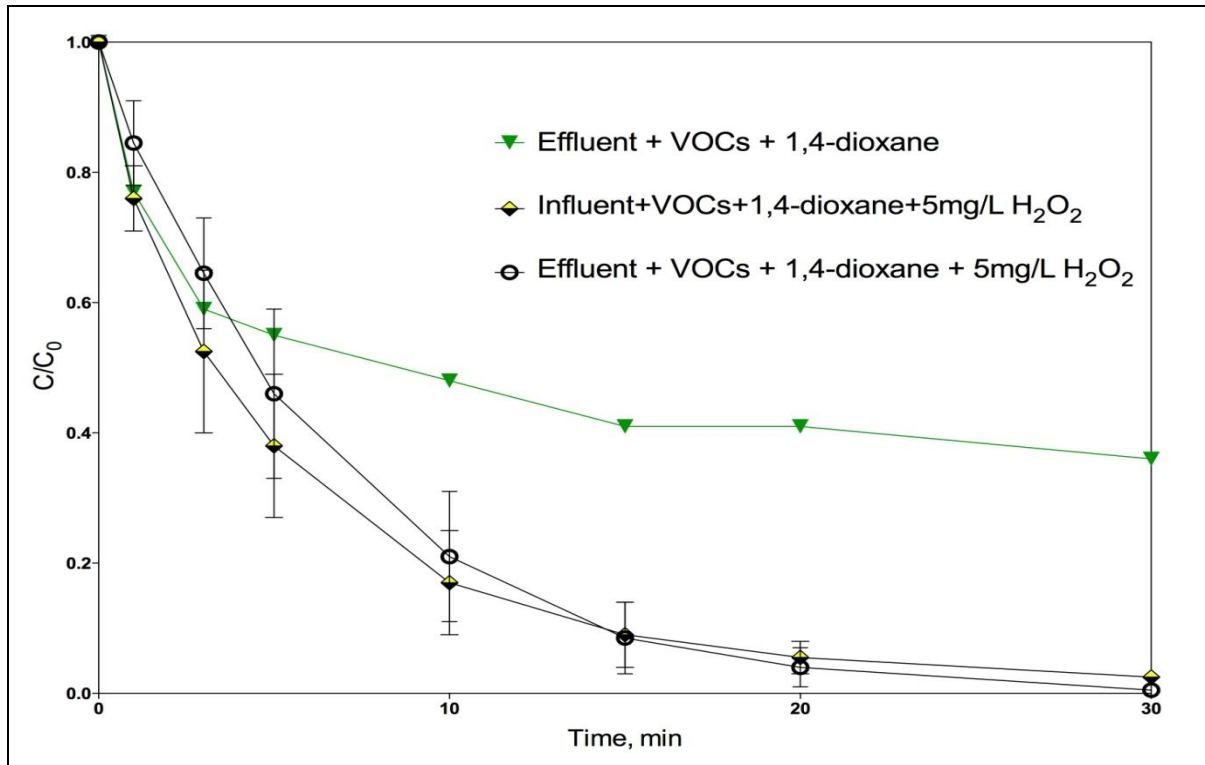


Figure 11: C/C_0 vs. time data for removal of 1,4-dioxane from groundwater in the presence of VOC's; COD ~ 40mg/L

Experiment 8: A modification was made to the test conditions of Experiment 7 (described above), by the addition of 5 mg/L of peroxide. The groundwater samples were then ozonated. Figures 11 (as C/C_0 vs. time) and 12 (as concentration vs. time) show the removal of 1,4-dioxane from ozonation of both influent and effluent groundwater in the presence of VOCs and 5mg/L of peroxide. The target concentration of 3 μ g/L of 1,4-dioxane was achieved in approximately 10 – 15 minutes.

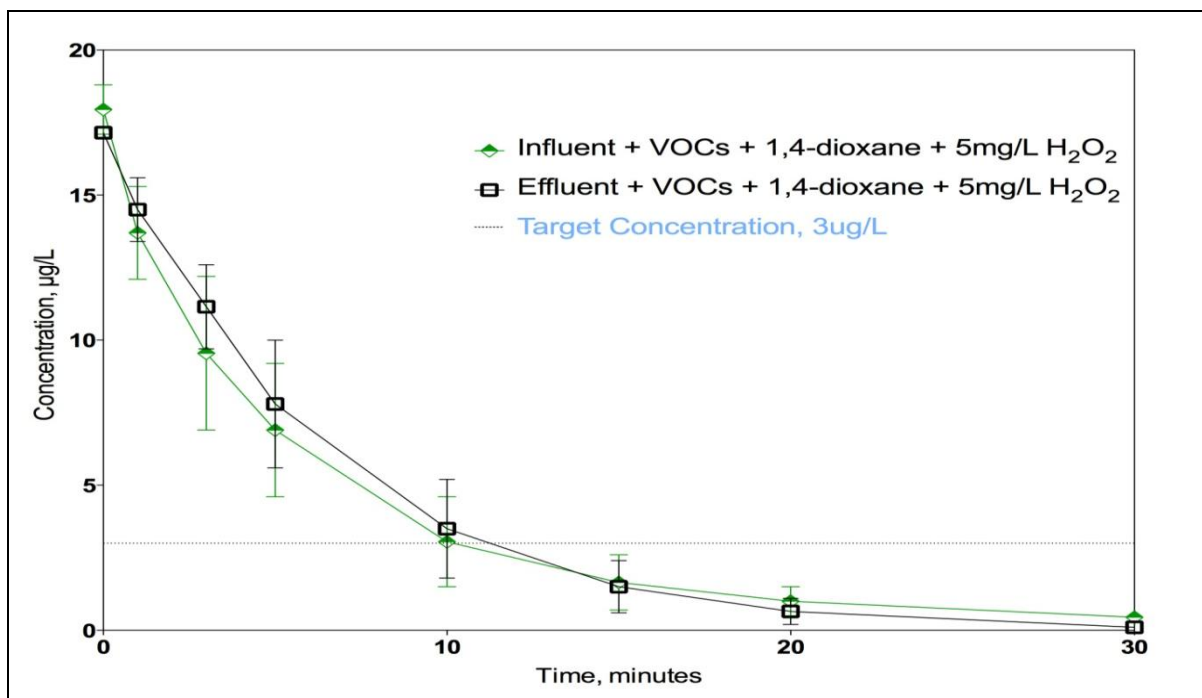


Figure 12: Concentration vs. time data for removal of 1,4-dioxane from influent and effluent, 5mg/L of H₂O₂; COD = 40mg/L

Tables 7 and 8 show the removal of chlorinated VOCs from influent and effluent groundwater samples, respectively. Water samples were sent to Lancaster Laboratories for analysis of VOCs. In the influent groundwater sample, 1,1-dichloroethene and cis 1,2-dichloroethene were completely removed within 5 minutes, and TCE and 1,1,1-trichloroethane were completely removed after 30 minutes of ozonation. Only a 40% removal of 1,1-dichloroethane was observed after 30 minutes of ozonation, however the measured concentrations were extremely low. Similar results were observed for effluent sample with the exception of 1,1,1-trichloroethane. Approximately 77% removal of 1,1,1-trichloroethane was observed after 30 minutes of ozonation, however the measured concentrations were extremely low. Concentration and ozone mass balance data are shown in Appendix A – Tables A6 – A10.

Table 7: Concentration (µg/L) data of VOCs from Ozonation of Influent Groundwater Sample with 5mg/L H₂O₂

Compound	Initial	1 minute	5 minutes	15 minutes	30 minutes
1,1-Dichloroethane	5	6	6	4	3
1,1-Dichloroethene	5	2	ND	ND	ND
Cis 1,2-Dichloroethene	9	6	ND	ND	ND
1,1,1-Trichloroethane	3	3	3	2	ND
Trichloroethene	1900	1500	400	1	ND

Table 8: Concentration (µg/L) data of volatile organics, Ozonation of Groundwater Effluent with 5mg/L H₂O₂

Compound	Initial	1 minute	5 minutes	15 minutes	30 minutes
1,1-Dichloroethane	7	6	6	5	3
1,1-Dichloroethene	20	2	ND	ND	ND
Cis 1,2-Dichloroethene	10	2	ND	ND	ND
1,1,1-Trichloroethane	9	7	6	4	2
Trichloroethene	360	650	17	ND	ND

Experiment 9: For the test conditions described in Experiment 8 above, the peroxide dosage was increased to 10mg/L of peroxide. Figure 13 shows the removal of 1,4-dioxane from the influent groundwater sample. Addition of 10mg/L of peroxide did not significantly enhance the removal. Concentration and ozone mass balance data is shown in Appendix A – Table A11.

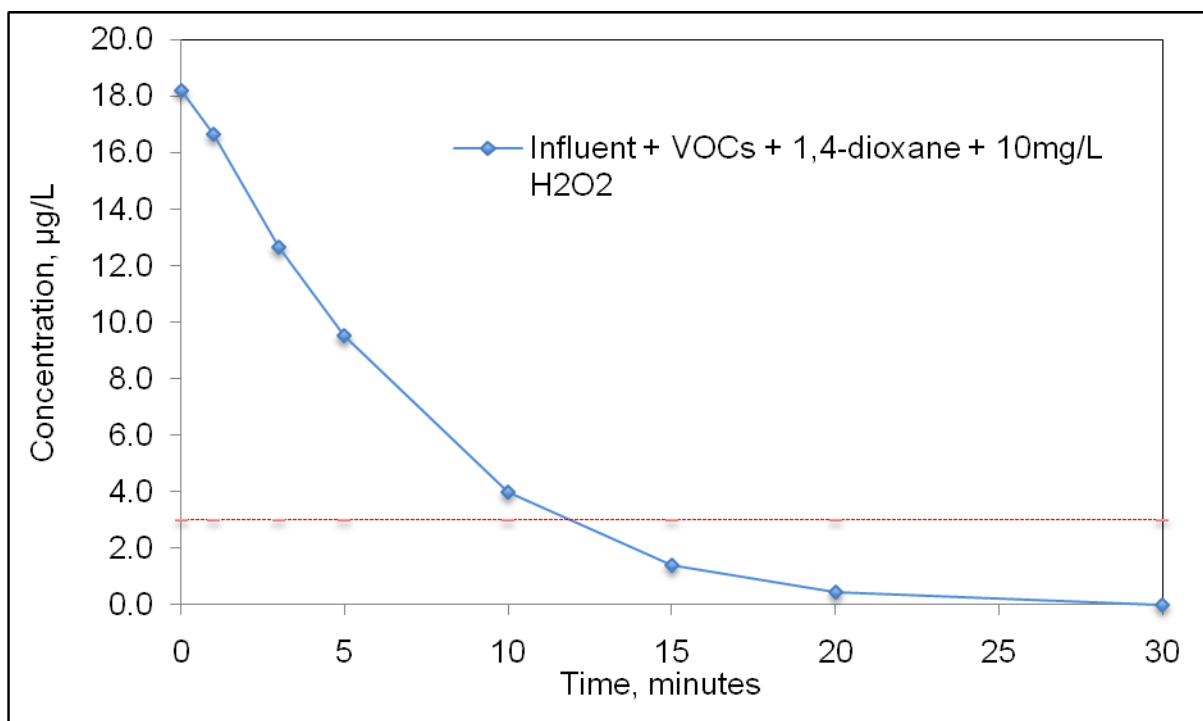


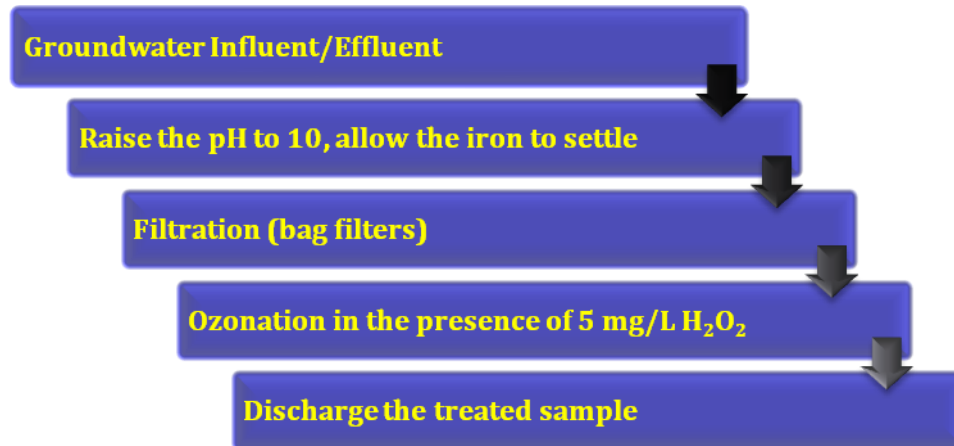
Figure 13: Concentration vs. time data for removal of 1,4-dioxane from influent groundwater in the presence of 10mg/L of H_2O_2 ; COD = 40 mg/L

5. CONCLUSIONS

- Analysis of the influent and effluent groundwater showed that very high concentration of iron is present.
- Aeration or ozonation or addition of peroxide leads to oxidation of iron in the groundwater, and results in thick orange colored solution.
- The iron present in the groundwater interferes in 1,4-dioxane removal using ozone w/o peroxide.
- The iron in the groundwater needs to be precipitated out in order to enhance the removal of 1,4-dioxane by ozonation.
- Raising the pH to 10 followed by filtration, removed the iron and its precipitates from the groundwater. Ozone in the presence of 5mg/L of H_2O_2 removed 1,4-dioxane to below desired level ($\leq 3\mu\text{g/L}$) in 10 to 15 minutes of contact time. This was observed for influent and effluent groundwater samples which had been pretreated to pH10 and sand filtration. Increasing the peroxide dosage to 10 mg/L did not enhance 1,4-dioxane removal. High removal of chlorinated VOCs (especially TCE) was observed, and the final concentrations were at or near the detection limits.

6. RECOMMENDED TREATMENT STRATEGY AT THE SITE

The following treatment strategy is recommended at the site:



This would also eliminate the iron precipitation and clogging of the discharge pipes (current issue). The effluent will be clear water. If the recommended treatment strategy is applied to the influent groundwater, it would eliminate the iron precipitation currently occurring in the packed aeration tower. The recommended strategy could be applied after the packed aeration tower i.e. to the effluent groundwater.

Pilot Testing at the site is recommended to:

1. Validate the treatment strategy
2. Determine engineering design parameters for full scale system
3. Determine the cost of the treatment process
4. Determine long term operational and maintenance issues

APPENDIX – A

Table A1: Ozone Mass transfer data, Groundwater effluent, aerated, raised pH to 10 and filtered. Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1055mg/hr

SAMPLE	Dioxane	D8	Norm.	Conc. ug/L	% Removal		
GW	51242	7735	6.6	20.9			
1	48052	7795	6.2	19.5	6.9		
3	38407	7890	4.9	15.4	26.5		
5	28665	7575	3.8	12.0	42.9		
10	15449	7876	2.0	6.2	70.4		
15	8245	7724	1.1	3.4	83.9		
Ozone in Air Phase							
Ozonation Time, min			1	3	5	10	15
Titrant Volume, ml			0.1	0.6	1.1	2	3.4
Sampling time, sec			29.9	30.1	30.1	30.2	30.1
Concentration, mg/hr			14.4	86.1	157.9	286.1	488.0
Ozone in Water Phase							
Ozonation Time, min			1	3	5	10	15
Absorbance, blank			0.17	0.17	0.17	0.17	0.17
Absorbance, Sample			0.169	0.166	0.164	0.163	0.161
Concentration, mg/L			0.1	0.3	0.5	0.6	0.7
Mass Balance							
Ozonation Time, min			1	3	5	10	15
Ozone Dosage, mg/L			1.5	4.4	7.3	14.6	22.0
Ozone input, mg			17.6	52.7	87.9	175.8	263.7
Mass in Air, mg			0.1	1.8	5.9	24.4	56.6
Mass in Water, mg			1.0	3.7	5.5	6.3	7.9
Total (air + water), mg			1.1	5.5	11.3	30.6	64.5
Ozone Consumed, mg			16.5	47.2	76.6	145.2	199.2
Ozone Consumed, mg/L			1.4	4.0	6.7	12.9	18.1

Table A2: Ozonation of groundwater effluent; Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1073mg/hr; 5mg/L of H₂O₂

SAMPLE	Dioxane	D8	Norm.	Conc. ug/L	% Removal
GW	59747	8716	6.9	21.7	
GW + H2O2	51432	8086	6.4	20.1	7.2
1 min	46894	8409	5.6	17.6	18.6
3 min	38878	8929	4.4	13.8	36.5
5 min	28228	8754	3.2	10.2	53.0
10 min	12182	8367	1.5	4.6	78.8
15 min	4942	8253	0.6	1.9	91.3
Ozone in Air Phase					
Ozonation Time, min	1	3	5	10	15
Titant Volume, ml	0.1	0.5	0.9	1.3	1.3
Sampling time, sec	30.2	30.2	30.3	30.3	30.2
Concentration, mg/hr	14.3	71.5	128.3	185.3	186.0
Ozone in Water Phase					
Ozonation Time, min	1	3	5	10	15
Absorbance, blank	0.176	0.176	0.176	0.176	0.176
Absorbance, Sample	0.176	0.176	0.175	0.175	0.175
Concentration, mg/L	0.0	0.0	0.1	0.1	0.1
Mass Balance					
Ozonation Time, min	1	3	5	10	15
Ozone Dosage, mg/L	1.5	4.5	7.5	14.9	22.4
Ozone input, mg	17.9	53.6	89.4	178.8	268.2
Mass in Air, mg	0.1	1.5	4.9	17.9	33.4
Mass in Water, mg	0.0	0.0	0.9	0.9	0.9
Total (air + water), mg	0.1	1.5	5.8	18.8	34.3
Ozone Consumed, mg	17.8	52.1	83.6	160.0	233.9
Ozone Consumed, mg/L	1.5	4.4	7.3	14.2	21.3

Table A3: Ozonation of groundwater effluent (duplicate); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1103mg/hr; 5mg/L of H₂O₂

SAMPLE	Dioxane	D8	Norm.	Conc. µg/L	% Removal		
0	99265	16888	5.9	18.6			
1	78991	17198	4.6	14.5	21.9		
3	62530	17224	3.6	11.5	38.2		
5	45942	18109	2.5	8.0	56.8		
10	18011	18001	1.0	3.2	83.0		
15	6589	19146	0.3	1.1	94.1		
20	2512	19397	0.1	0.4	97.8		
30	0	19005	0.0	<0.25	>98%		
Ozone in Air Phase							
Ozonation Time, min	1	3	5	10	15	20	30
Titrant Volume, ml	0.1	0.7	1	1.2	1	1.3	1.6
Sampling time, sec	30.2	30	29.8	30.1	30.2	30	30.2
Concentration, mg/hr	14.3	100.8	145.0	172.2	143.0	187.2	228.9
Ozone in Water Phase							
Ozonation Time, min	1	3	5	10	15	20	30
Absorbance, blank	0.155	0.155	0.155	0.155	0.155	0.155	0.155
Absorbance, Sample	0.154	0.152	0.15	0.149	0.147	0.145	0.142
Concentration, mg/L	0.1	0.2	0.4	0.5	0.6	0.8	1.0
Mass Balance							
Ozonation Time, min	1	3	5	10	15	20	30
Ozone Dosage, mg/L	1.5	4.7	8.1	16.6	25.5	35.0	54.1
Ozone input, mg	18.4	55.2	91.9	183.9	275.8	367.8	551.7
Mass in Air, mg	0.1	2.0	6.1	19.4	32.5	46.2	80.9
Mass in Water, mg	1.0	2.8	4.5	5.3	6.9	8.3	10.5
Total (air + water), mg	1.1	4.8	10.7	24.6	39.3	54.6	91.4
Ozone Consumed, mg	17.3	50.3	81.3	159.2	236.5	313.2	460.2
Ozone Consumed, mg/L	1.4	4.3	7.1	14.3	21.9	29.8	45.1

Table A4: Ozonation of groundwater influent (with 1,4-dioxane and VOC's, COD $\approx$ 180mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1019mg/hr; 5mg/L of H₂O₂

SAMPLE	Dioxane	D8	Norm.	Conc. µg/L	% Removal			
0 min	94168	17335	5.4	17.2				
1 min	86409	17381	5.0	15.7	8.5			
3 min	86500	18187	4.8	15.0	12.4			
5 min	92552	19150	4.8	15.3	11.0			
10 min	80917	17496	4.6	14.6	14.9			
15 min	86028	18491	4.7	14.7	14.4			
20 min	88833	19852	4.5	14.1	17.6			
30 min	85792	19929	4.3	13.6	20.8			
Ozone in Air Phase								
Ozonation Time, min		1	3	5	10	15	20	30
Titrant Volume, ml		0.2	0.3	0.4	0.7	0.6	0.8	1.1
Sampling time, sec		30	30.2	30.3	30.1	30	29.9	30.2
Concentration, mg/hr		28.8	42.9	57.0	100.5	86.4	115.6	157.4
Ozone in Water Phase								
Ozonation Time, min		1	3	5	10	15	20	30
Absorbance, blank		0.157	0.157	0.157	0.157	0.157	0.157	0.157
Absorbance, Sample		0.157	0.157	0.156	0.156	0.155	0.155	0.156
Concentration, mg/L		0.0	0.0	0.1	0.1	0.2	0.2	0.1
Mass Balance								
Ozonation Time, min		1	3	5	10	15	20	30
Ozone Dosage, mg/L		1.4	4.4	7.6	15.7	24.5	34.0	53.1
Ozone input, mg		17.0	50.9	84.9	169.8	254.6	339.5	509.3
Mass in Air, mg		0.2	1.4	3.1	9.7	17.4	25.9	48.6
Mass in Water, mg		0.0	0.0	0.9	0.9	1.6	1.6	0.8
Total (air + water), mg		0.2	1.4	4.0	10.5	19.1	27.4	49.4
Ozone Consumed, mg		16.7	49.5	80.9	159.3	235.6	312.1	459.9
Ozone Consumed, mg/L		1.4	4.3	7.2	14.8	22.8	31.5	48.5

Table A5: Ozonation of groundwater influent (with 1,4-dioxane and VOC's, COD ≈180mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1141mg/hr

SAMPLE	Dioxane	D8	Norm.	Conc. µg/L	% Removal			
0 min	147099	23999	6.1	19.4				
1 min	115626	21415	5.4	17.1	11.9			
3 min	109064	21084	5.2	16.3	15.6			
5 min	117692	22438	5.2	16.6	14.4			
10 min	110683	22017	5.0	15.9	18.0			
15 min	103829	22056	4.7	14.9	23.2			
20 min	96655	21659	4.5	14.1	27.2			
30 min	93136	21245	4.4	13.9	28.5			
Ozone in Air Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Titrant Volume, ml	0.2	0.5	0.7	0.9	1.1	1.5	2.2	
Sampling time, sec	30	30.2	30.3	30.1	30	29.9	30.2	
Concentration, mg/hr	28.8	71.5	99.8	129.2	158.4	216.7	314.7	
Ozone in Water Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Absorbance, blank	0.161	0.161	0.161	0.161	0.161	0.161	0.161	
Absorbance, Sample	0.16	0.16	0.158	0.156	0.153	0.141	0.137	
Concentration, mg/L	0.1	0.1	0.2	0.4	0.6	1.6	1.9	
Mass Balance								
Ozonation Time, min	1	3	5	10	15	20	30	
Ozone Dosage, mg/L	1.6	4.8	7.9	15.9	23.8	31.7	47.6	
Ozone input, mg	19.0	57.1	95.1	190.2	285.4	380.5	570.7	
Mass in Air, mg	0.2	1.9	4.8	14.3	26.3	41.9	86.2	
Mass in Water, mg	1.0	0.9	2.7	4.3	6.6	15.7	18.1	
Total (air + water), mg	1.2	2.8	7.4	18.6	32.8	57.6	104.3	
Ozone Consumed, mg	17.8	54.2	87.7	171.7	252.5	322.8	466.4	
Ozone Consumed, mg/L	1.5	4.7	7.9	16.0	24.5	32.6	49.2	

Table A6: Ozonation of groundwater effluent (with 1,4-dioxane and VOC's, COD $\approx$ 40mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1053mg/hr

SAMPLE	Dioxane	D8	Norm.	Conc. µg/L	% Removal			
0 min	102297	17852	5.7	18.1				
1 min	78567	17843	4.4	13.9	23.2			
3 min	60414	17976	3.4	10.6	41.3			
5 min	53489	16892	3.2	10.0	44.7			
10 min	48341	17700	2.7	8.6	52.3			
15 min	43877	18503	2.4	7.5	58.6			
20 min	42314	18223	2.3	7.3	59.5			
30 min	36501	17743	2.1	6.5	64.1			
Ozone in Air Phase								
Ozonation Time, min		1	3	5	10	15	20	30
Titrant Volume, ml		0	0.2	0.6	1.1	1.5	1.7	2
Sampling time, sec		30	30.1	30	29.9	30	30	30
Concentration, mg/hr		0.0	28.7	86.4	158.9	216.0	244.8	288.0
Ozone in Water Phase								
Ozonation Time, min		1	3	5	10	15	20	30
Absorbance, blank		0.154	0.154	0.154	0.154	0.154	0.154	0.154
Absorbance, Sample		0.149	0.145	0.139	0.118	0.107	0.102	0.099
Concentration, mg/L		0.4	0.7	1.2	2.9	3.7	4.1	4.4
Mass Balance								
Ozonation Time, min		1	3	5	10	15	20	30
Ozone Dosage, mg/L		1.5	4.5	7.8	16.2	25.3	35.1	54.8
Ozone input, mg		17.5	52.6	87.7	175.5	263.2	351.0	526.5
Mass in Air, mg		0.0	0.5	2.4	12.6	28.2	47.4	91.8
Mass in Water, mg		4.8	8.3	13.3	30.7	38.5	40.9	41.4
Total (air + water), mg		4.8	8.7	15.7	43.3	66.7	88.3	133.2
Ozone Consumed, mg		12.8	43.9	72.1	132.2	196.5	262.7	393.2
Ozone Consumed, mg/L		1.1	3.8	6.5	12.3	19.0	26.5	41.5

Table A7: Ozonation of groundwater influent (with 1,4-dioxane and VOC's, COD $\approx$ 41mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1253mg/hr; 5mg/L H₂O₂

SAMPLE	Dioxane	D8	Norm.	Conc. µg/L	% Removal			
0 min	99662	18470	5.4	17.1				
1 min	71258	18557	3.8	12.1	28.8			
3 min	39493	18199	2.2	6.9	59.8			
5 min	25712	17521	1.5	4.6	72.8			
10 min	8006	16832	0.5	1.5	91.2			
15 min	3527	16463	0.2	0.7	96.0			
20 min	2507	16821	0.1	0.5	97.2			
30 min	2148	17022	0.1	0.4	97.7			
Ozone in Air Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Titrant Volume, ml	0.4	0.9	1	1.5	1.7	2.8	2.3	
Sampling time, sec	30	29.9	29.9	30	30	29.9	30	
Concentration, mg/hr	57.6	130.0	144.5	216.0	244.8	404.5	331.2	
Ozone in Water Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Absorbance, blank	0.152	0.152	0.152	0.152	0.152	0.152	0.152	
Absorbance, Sample	0.152	0.152	0.152	0.151	0.142	0.121	0.104	
Concentration, mg/L	0.0	0.0	0.0	0.1	0.8	2.5	3.8	
Mass Balance								
Ozonation Time, min	1	3	5	10	15	20	30	
Ozone Dosage, mg/L	1.7	5.4	9.3	19.3	30.1	41.8	65.3	
Ozone input, mg	20.9	62.6	104.4	208.8	313.2	417.6	626.4	
Mass in Air, mg	0.5	3.6	8.2	23.2	42.4	69.5	130.8	
Mass in Water, mg	0.0	0.0	0.0	0.9	8.2	24.4	36.1	
Total (air + water), mg	0.5	3.6	8.2	24.1	50.6	93.8	166.9	
Ozone Consumed, mg	20.4	59.0	96.2	184.7	262.6	323.8	459.5	
Ozone Consumed, mg/L	1.7	5.1	8.6	17.2	25.4	32.7	48.5	

Table A8: Ozonation of groundwater influent, duplicate (with 1,4-dioxane and VOC's, COD $\approx$ 41mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 1210mg/hr; 5mg/L H₂O₂

SAMPLE	Dioxane	D8	Norm.	Conc. µg/L	% Removal			
0 min	102397	17208	6.0	18.8				
1 min	88756	18375	4.8	15.3	18.8			
3 min	70181	18106	3.9	12.2	34.9			
5 min	50655	17359	2.9	9.2	51.0			
10 min	25506	17360	1.5	4.6	75.3			
15 min	13283	16427	0.8	2.6	86.4			
20 min	7651	16632	0.5	1.5	92.3			
30 min	2762	17274	0.2	0.5	97.3			
Ozone in Air Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Titrant Volume, ml	0.4	0.5	0.5	0.9	1.3	1.7	0.8	
Sampling time, sec	30	29.9	29.9	30	30	29.9	30	
Concentration, mg/hr	115.2	144.5	144.5	259.2	374.4	491.2	230.4	
Ozone in Water Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Absorbance, blank	0.212	0.212	0.212	0.212	0.212	0.212	0.212	
Absorbance, Sample	0.212	0.212	0.212	0.212	0.207	0.205	0.199	
Concentration, mg/L	0.0	0.0	0.0	0.0	0.4	0.6	1.0	
Mass Balance								
Ozonation Time, min	1	3	5	10	15	20	30	
Ozone Dosage, mg/L	1.7	5.2	9.0	18.7	29.1	40.3	63.0	
Ozone input, mg	20.2	60.5	100.8	201.6	302.4	403.2	604.8	
Mass in Air, mg	1.0	5.3	10.1	26.9	53.3	89.4	149.5	
Mass in Water, mg	0.0	0.0	0.0	0.0	4.1	5.5	9.8	
Total (air + water), mg	1.0	5.3	10.1	26.9	57.4	94.9	159.3	
Ozone Consumed, mg	19.2	55.2	90.7	174.7	245.0	308.3	445.5	
Ozone Consumed, mg/L	1.6	4.8	8.1	16.3	23.7	31.1	47.0	

Table A9: Ozonation of groundwater effluent (with 1,4-dioxane and VOC's, COD $\approx$ 45mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 954mg/hr; 5mg/L H₂O₂

SAMPLE	Dioxane	D8	Norm.	Conc. µg/L	% Removal			
0 min	85872	15761	5.4	17.2				
1 min	64625	15264	4.2	13.4	22.3			
3 min	46572	15177	3.1	9.7	43.7			
5 min	28253	15835	1.8	5.6	67.3			
10 min	8678	14925	0.6	1.8	89.3			
15 min	3091	16963	0.2	0.6	96.7			
20 min	1044	16206	0.1	0.2	98.8			
30 min	0	15553	0.0	0.0	100.0			
Ozone in Air Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Titrant Volume, ml	0.2	0.3	0.5	0.6	0.8	0.7	1	
Sampling time, sec	30.1	29.9	29.9	30	30	30.1	29.9	
Concentration, mg/hr	57.4	86.7	144.5	172.8	230.4	200.9	289.0	
Ozone in Water Phase								
Ozonation Time, min	1	3	5	10	15	20	30	
Absorbance, blank	0.211	0.212	0.212	0.212	0.212	0.212	0.212	
Absorbance, Sample	0.208	0.203	0.21	0.207	0.205	0.207	0.197	
Concentration, mg/L	0.2	0.7	0.2	0.4	0.6	0.4	1.2	
Mass Balance								
Ozonation Time, min	1	3	5	10	15	20	30	
Ozone Dosage, mg/L	1.3	4.1	7.1	14.7	22.9	31.8	49.7	
Ozone input, mg	15.9	47.7	79.5	158.9	238.4	317.9	476.8	
Mass in Air, mg	0.5	2.9	6.7	20.0	36.8	54.7	95.5	
Mass in Water, mg	2.9	8.3	1.8	4.3	5.7	3.9	11.3	
Total (air + water), mg	3.3	11.2	8.5	24.2	42.5	58.7	106.8	
Ozone Consumed, mg	12.6	36.5	71.0	134.7	195.9	259.2	370.0	
Ozone Consumed, mg/L	1.0	3.2	6.4	12.5	19.0	26.2	39.0	

Table A10: Ozonation of groundwater effluent, duplicate (with 1,4-dioxane and VOC's, COD $\approx$ 45mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 893mg/hr; 5mg/L H₂O₂

Sample	Dioxane	D8	Norm.	Conc. ug/L	% Removal		
0	72780	13445	5.4	17.1			
1	70189	14259	4.9	15.6	9.1		
3	59687	15009	4.0	12.6	26.5		
5	47150	14844	3.2	10.0	41.3		
10	24169	14636	1.7	5.2	69.5		
15	10981	14641	0.8	2.4	86.1		
20	5035	14089	0.4	1.1	93.4		
30	1018	15069	0.1	0.2	98.8		
Ozone in Air Phase							
Ozonation Time, min	1	3	5	10	15	20	30
Titrant Volume, ml	0.1	0.2	0.2	0.7	0.9	0.9	1.2
Sampling time, sec	30	30	29.9	30.1	30.2	30.1	30
Concentration, mg/hr	28.8	57.6	57.8	200.9	257.5	258.3	345.6
Ozone in Water Phase							
Ozonation Time, min	1	3	5	10	15	20	30
Absorbance, blank	0.212	0.212	0.212	0.212	0.212	0.212	0.212
Absorbance, Sample	0.212	0.212	0.212	0.212	0.211	0.209	0.21
Concentration, mg/L	0.0	0.0	0.0	0.0	0.1	0.2	0.2
Mass Balance							
Ozonation Time, min	1	3	5	10	15	20	30
Ozone Dosage, mg/L	1.2	3.8	6.6	13.8	21.5	29.8	46.5
Ozone input, mg	14.9	44.6	74.4	148.8	223.2	297.6	446.4
Mass in Air, mg	0.2	1.7	3.6	14.4	33.5	55.0	105.3
Mass in Water, mg	0.0	0.0	0.0	0.0	0.8	2.4	1.5
Total (air + water), mg	0.2	1.7	3.6	14.4	34.3	57.3	106.8
Ozone Consumed, mg	14.6	43.0	70.8	134.4	188.9	240.3	339.6
Ozone Consumed, mg/L	1.2	3.7	6.3	12.5	18.3	24.3	35.8

Table A11: Ozonation of groundwater effluent, duplicate (with 1,4-dioxane and VOC's, COD $\approx$ 41mg/L); Feed gas is Air; Flow rate = 5%; Power = 90W; Pressure = 3.5bar; ozone weight = 5%; ozone generated = 893mg/hr; 10mg/L H₂O₂

Sample	Dioxane	D8	Norm.	Conc. µg/L	% Removal		
0	87962	15256	5.8	18.2			
1	75405	14300	5.3	16.7	8.5		
3	56295	14020	4.0	12.7	30.4		
5	44989	14917	3.0	9.5	47.7		
10	17756	14039	1.3	4.0	78.1		
15	6249	14061	0.4	1.4	92.3		
20	2122	14617	0.1	0.5	97.5		
30	0	16549	0.0	0.0	100.0		
Ozone in Air Phase							
Ozonation Time, min	1	3	5	10	15	20	30
Titrant Volume, ml	0.3	0.4	0.5	0.9	0.7	1.1	0.6
Sampling time, sec	30.3	30.4	30.3	30.5	30.5	30.4	30.3
Concentration, mg/hr	85.5	113.7	142.6	255.0	198.3	312.6	171.1
Ozone in Water Phase							
Ozonation Time, min	1	3	5	10	15	20	30
Absorbance, blank	0.206	0.206	0.206	0.206	0.206	0.206	0.206
Absorbance, Sample	0.205	0.205	0.204	0.205	0.204	0.205	0.203
Concentration, mg/L	0.1	0.1	0.2	0.1	0.2	0.1	0.2
Mass Balance							
Ozonation Time, min	1	3	5	10	15	20	30
Ozone Dosage, mg/L	1.4	4.4	7.6	15.8	24.6	34.1	53.2
Ozone input, mg	17.0	51.1	85.1	170.3	255.4	340.5	510.8
Mass in Air, mg	0.7	4.0	8.3	24.9	43.8	65.0	105.4
Mass in Water, mg	1.0	0.9	1.8	0.9	1.6	0.8	2.3
Total (air + water), mg	1.7	5.0	10.1	25.7	45.4	65.8	107.6
Ozone Consumed, mg	15.4	46.1	75.1	144.6	210.0	274.7	403.2
Ozone Consumed, mg/L	1.3	4.0	6.7	13.5	20.4	27.7	42.5

APPENDIX B

Table B1: Limits of detections

Analyte	Method Detection Limit
Iron	0.0522 mg/L
Manganese	0.84 µg/L
1,4-dioxane	0.25 µg/L
1,1-Dichloroethane	1 µg/L
1,1-Dichloroethene	0.9 µg/L
Cis 1,2-Dichloroethene	1 µg/L
1,1,1-Trichloroethane	1 µg/L
Trichloroethene	1 µg/L

APPENDIX E

Removal of 1,4-Dioxane and VOCs from Groundwater of Naval Air Station (NAS) Whidbey Island Site using Activated Persulfate

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To Whom It May Concern

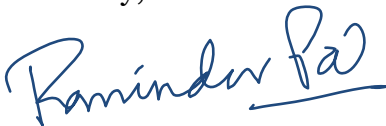
November 14, 2017

At the Water and Environmental Technology (WET) Center, we conducted two groundwater treatment studies for Naval Facilities Engineering Command Northwest (NAVFAC NW) on the 1,4-dioxane groundwater contamination at Area 6 at Naval Air Station Whidbey Island (NASWI). The WET Center was contracted by NAVFAC NW through URS (now AECOM) to conduct the bench-scale tests.

In the first study, the iron content in the groundwater shipped to us in steel drums was very high (in the range of 300 mg/L) whereas the iron content was much lower (in the range of 1 mg/L) in the new batch of groundwater shipped to us in PTFE drums for the second study. During the second study it was determined that the high iron content (300 mg/L) was due to the leaching of iron from the steel shipping drums (even though they were epoxy coated). New batches of groundwater samples were shipped to WET Center in PTFE drums, and the iron content in the samples was approximately 0.05 - 1.23 mg/L.

Unfortunately the first study report "Removal of 1,4-Dioxane from Groundwater Using Ozone based Advanced Oxidation Process" was issued prior to discovering the drum iron leaching issue. The report discusses high concentrations of iron in the site water and recommends pretreatment of iron (raising the pH to precipitate out the iron then filter). The high iron concentration is not representative of Area 6 groundwater conditions. The recommended pretreatment of iron is not necessary based on actual site iron groundwater concentrations. Please consider this letter as an amendment to the previously issued "Removal of 1,4-Dioxane from Groundwater Using Ozone based Advanced Oxidation Process" Report.

Sincerely,



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Professor and Chairman, Civil and Environmental Engineering Department
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Confidential

FINAL DRAFT REPORT

**Removal of 1,4-Dioxane and VOCs from Groundwater of Naval Air Station
Whidbey Island (NASWI) Site using Activated Persulfate**

Submitted to

Naval Facilities Engineering Command Northwest (NAVFAC NW)

By

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TABLE OF CONTENTS

1. INTRODUCTION	1
2. SCOPE OF WORK	2
3. EXPERIMENTAL METHODS	3
3.1 CHEMICALS AND REAGENTS	3
3.2 ANALYTICAL METHODS	3
3.3 CALIBRATION STANDARDS	4
3.4 QA/QC AND METHOD DETECTION LIMITS	5
3.5 EXPERIMENTAL SETUP	6
4. RESULTS AND DISCUSSION	6
4.1 GROUNDWATER CHARACTERIZATION	6
4.2 EXPERIMENTS	7
4.2.1 Activation of persulfate with pH.....	7
4.2.2. Activation of persulfate with pH and Fe^{2+}	8
4.2.3 Removal of VOCs from Groundwater via sonication	9
4.2.4 Removal of 1,4-dioxane and VOCs using UV photolysis.....	11
4.3 COST ANALYSIS.....	15
4.3.1 Cost of the Chemicals.....	15
6.3.1 Energy costs (calculated based on lab scale reactor)	16
4.3.2 UV Reactor cost:	16
5. CONCLUSIONS.....	16
6. RECOMMENDATIONS	17

LIST OF TABLES

TABLE 1: QA/QC AND METHOD REPORTING LIMITS	5
TABLE 2: GROUNDWATER CHARACTERISTICS	7
TABLE 3: TREATMENT REQUIREMENTS	7
TABLE 4: GROUNDWATER INFLUENT, PERSULFATE ACTIVATION WITH PH	8
TABLE 5: GROUNDWATER INFLUENT, PERSULFATE ACTIVATION WITH PH AND FERROUS SULFATE.....	8
TABLE 6: GROUNDWATER SONICATION, 15 MINUTES, P = 0.19kW; SAMPLE VOLUME = 150ML, PH 7	10
TABLE 7: GROUNDWATER SONICATION, 15 MINUTES, P = 0.19kW; SAMPLE VOLUME = 150ML, PH 3	10
TABLE 8: GROUNDWATER SONICATION, 15 MINUTES, P = 0.19kW; SAMPLE VOLUME = 150ML, PH 3	11
TABLE 9: GROUNDWATER INFLUENT, EXPOSED TO UV LIGHT, PH 7, UV DOSAGE = 5000MJ/CM ²	12
TABLE 10: REMOVAL OF VOCs USING UV/PERSULFATE; UV DOSAGE: 5000MJ/CM ² (CBD STUDIES)	12
TABLE 11: REMOVAL OF VOCs USING UV/PERSULFATE; 5000MJ/CM ² ; 150MG/L PERSULFATE (USING CBD).....	13

TABLE 12: REMOVAL OF VOCs USING UV/PERSULFATE; FLOW THROUGH REACTOR; REACTOR VOLUME = 2L; PERSULFATE = 150MG/L	13
TABLE 13: REMOVAL OF VOCs USING UV/PERSULFATE; FLOW THROUGH REACTOR; REACTOR VOLUME = 2L; PERSULFATE = 150MG/L	14
TABLE 14: REMOVAL OF VOCs USING UV/PERSULFATE (GW INFLUENT SAMPLE); FLOW THROUGH REACTOR; REACTOR VOLUME = 2.6L; PERSULFATE = 150MG/L; FLOW RATE = 210ML/MIN; RETENTION TIME = 12MIN; UV DOSAGE ~ 6000MJ/CM ²	14
TABLE 15: REMOVAL OF VOCs USING UV/PERSULFATE (PW9 SAMPLE, pH 3); FLOW THROUGH REACTOR; REACTOR VOLUME = 2.6L; PERSULFATE = 150MG/L; FLOW RATE = 210ML/MIN; RETENTION TIME = 12MIN; UV DOSAGE = 6100MJ/CM ²	15
TABLE 16: COST ANALYSIS FOR THE CHEMICALS (ASSUMING 300GPM FLOW, 365 DAYS AND 24HR OPERATION)	15

LIST OF FIGURES

FIGURE 1: IRON LEACHING OUT FROM THE DRUMS	2
FIGURE 2: CALIBRATION CURVES	5
FIGURE 3: CBD UNIT AND UV FLOW REACTOR	6
FIGURE 4: SONICATION OF 1,4-DIOXANE SPIKED IN MILLI-Q WATER.	9
FIGURE 5: TREATMENT SCHEME 1	17
FIGURE 6: TREATMENT SCHEME 2	18
FIGURE 7: TREATMENT SCHEME 3	18
FIGURE 8: TREATMENT SCHEME 4	19

1. Introduction

The NASWI base has a region, within Area 6, which has contaminated groundwater. Currently, there is an existing groundwater treatment system in operation. This treatment system entails an equalization tank, particulate filters, and a packed tower air stripper to remove chlorinated VOCs such as trichloroethene (TCE), 1,1,1-trichloroethane (1,1,1-TCA), 1,1-dichloroethane (1,1-DCA), 1,1-dichloroethene (1,1-DCE), cis-1, 2-dichloroethene (cis-1, 2-DCE), and vinyl chloride (VC). The current treatment system is meeting its treatment objectives and permit limits. However, the groundwater samples have had some detects of 1,4-dioxane in the recent past. In 2003, it was first detected in on-site wells, and in a private off-site well in 2005.

NASWI/URS contacted WET Center to identify a suitable treatment technology for the simultaneous removal of 1,4-dioxane and VOCs. Phase I of the project-involved development of ozone based AOP for the removal of 1,4-dioxane and VOCs. It was determined that iron content in the water interfered with the treatment system and needed to be precipitated prior to ozonation. However, it was desired that only one treatment system be used at the Site to remove all the contaminants of interest.

The initial focus of this study was to remove iron and contaminants. However, it was determined that the high iron content (300mg/L) was due to the leaching of iron from the drums (even though they were epoxy coated, Figure 1). **Note that we had done significant amount of work before this drum corrosion aspect was determined.** New sets of samples were shipped to WET Center in PTFE drums, and the iron content in the samples was approximately 0.05 – 1.23mg/L. Since iron was no longer considered to be a problem, the project objectives were modified to test the removal of 1,4-dioxane and VOCs from groundwater using activated persulfate process. Persulfate can also be activated by heat, caustic, ultraviolet light (UV) and peroxide. Ultrasound could also be used for activation of the persulfate anion resulting in the production of highly reactive activated sulfate radicals ($\text{SO}_4^{\cdot-}$). However, the presence of Fe^{2+} can enhance the formation of sulfate radicals (Equations 2, 3 and 4).



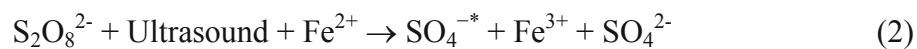


Figure 1: Iron Leaching out from the drums

2. Scope of work

- a) Design experiments for various dosages of chemicals (persulfate, iron, caustic), pH, UV, and ultrasound dosage and wavelengths. Based upon the site water characterization and background matrix, suitable dosages of chemicals (persulfate, iron, caustic), UV and ultrasound need to be selected. The matrix of experiments to be conducted will be prepared accordingly.

- b) Perform laboratory experiments on the removal of 1,4-dioxane and chlorinated VOCs from groundwater of NASWI site using activated persulfate. The persulfate will be activated using ultrasound, caustic, UV, and iron. Control tests with persulfate (without activation) only, ultrasound only; UV only and caustic only will be conducted. An optimum combination of the above activators will be identified (e.g. ultrasound + caustic)
- c) Analyze the potential of any precipitate formation
- d) Perform data analysis and determine the optimum process conditions such as retention time; dosages of persulfate, ultrasound, caustic and iron; and pH
- e) Analyze and determine the best persulfate activation method for the NASWI site groundwater
- f) Perform preliminary calculations for energy requirement and process cost for pilot testing.

3. Experimental Methods

3.1 Chemicals and Reagents

The following chemicals (minimum purity) were obtained from Sigma-Aldrich: 1,4-dioxane (99.9%), 1,4-dioxane-d8 (99%), Vinyl Chloride (99%), 1,1-dichloroethane (99%), 1,1-dichloroethene (99%), trichloroethylene (98%), 1,1,1-trichloroethane (98%), methylene chloride (99%) and sodium sulfate (99%). Methanol (HPLC grade) was obtained from Fisher Scientific Inc.

3.2 Analytical Methods

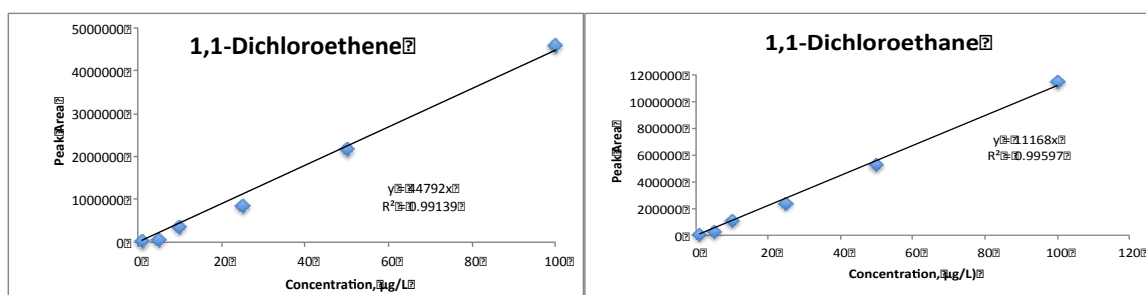
Quantitative analysis of 1,4-dioxane, 1,1,1-TCA, TCE was performed using liquid-liquid extraction followed by gas chromatography/mass spectrometry (GC/MS) analysis. A 100ml sample, spiked with internal standard (dioxane-d8) was liquid extracted with 25ml of dichloromethane. The organic phase was separated and a small amount of anhydrous sodium sulfate was added to remove any moisture content. The sample was then analyzed on GC/MS. The GC/MS analysis was performed using Agilent 7890 GC coupled with 5975C MS. Auto

injections were made using splitless mode and the injection volume was 3 μ L. Injection temperature was 250°C and the head pressure was 60kPa of Helium. Initial temperature of the oven was 45°C, held for 4.5 minutes and then ramped to 100°C at a rate of 12°C/min. The temperature was then ramped to 240°C at a rate of 25°C/min and held for 1.3 minutes. Transfer line temperature to the MS was maintained at 250°C and the Electron Energy was 70eV.

Quantitative analysis of Vinyl Chloride, 1,1-DCE, 1,1-DCA and cis-1,2-DCA was performed using GC/MS coupled with a purge and trap following EPA method 624. An inert gas is bubbled through a 10mL water sample contained in a specially designed purging chamber at ambient temperature. The purgeables are efficiently transferred from the aqueous phase to the vapor phase. The vapor is swept through a sorbent trap where the purgeables are trapped. After purging is completed, the trap is heated and back-flushed with the inert gas to desorb the purgeables onto a gas chromatographic column. The gas chromatograph is temperature programmed to separate the purgeables, which are then detected with a mass spectrometer.

3.3 Calibration Standards

Stock solutions of VOCs was prepared in methanol at 250mg/L and stored at 4°C. From this stock solution, calibration standards were prepared by spiking approximate amounts of stock into deionized water (for 1,1-DCE, Vinyl Chloride, 1,1-DCA and cis-1,2-DCA) or dichloromethane (1,4-dioxane, TCE and 1,1,1-TCA). Figure 2 shows the calibration curves of 1,4-dioxane and VOCs. The coefficient of determination (R^2) value was greater than 0.98 for all the compounds.



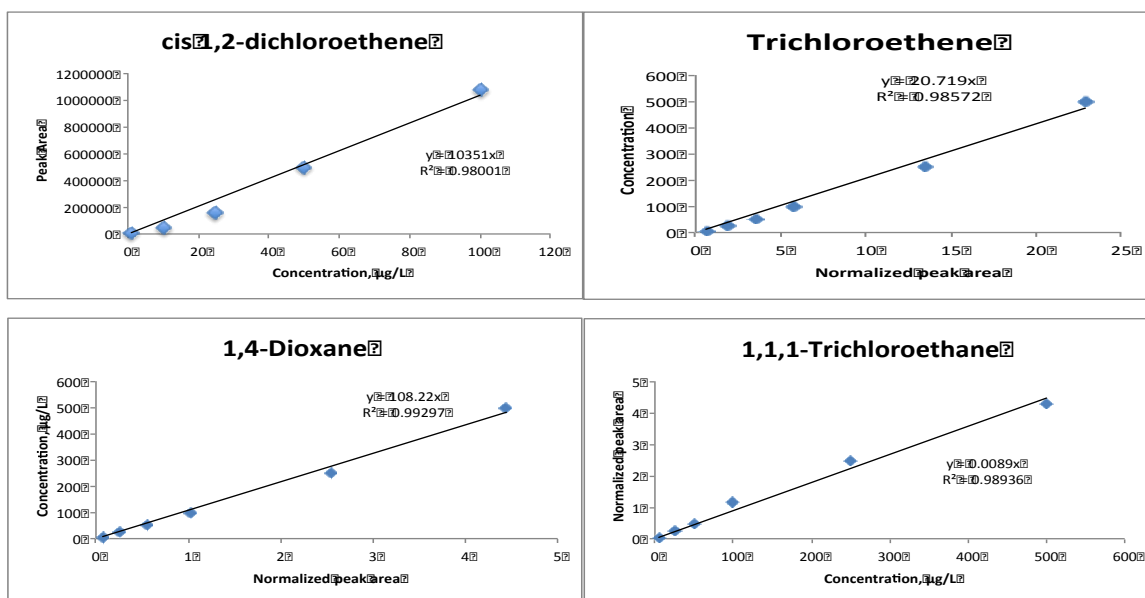


Figure 2: Calibration curves

3.4 QA/QC and method detection limits

Table 1 shows the instrument reproducibility and the analytical method performance. The relative standard deviation (RSD) was less than 11% for all the compounds. The samples were spiked with $1\mu\text{g/L}$ of the standards, extracted and analyzed. The average recovery efficiencies were within the EPA specified range for all the compounds.

Table 1: QA/QC and method reporting limits

Analyte	Concentration, $\mu\text{g/L}$					Average Recovery Efficiency (%)	RSD (%)	Method Reporting Limits, $\mu\text{g/L}$
	S1	S2	S3	S4	S5			
1,4-dioxane	0.9	1.1	1.0	0.9	0.9	96	9.3	0.5
Vinyl Chloride	1.1	0.9	1.1	1.2	1.0	106	10.7	0.1
1,1-DCE	1.1	1.1	1.2	1.0	1.1	110	5.1	0.1
1,1-DCA	1.3	1.2	1.1	1.3	1.2	120	7.4	0.1
Cis 1,2-DCA	0.7	0.6	0.7	0.6	0.7	70	9.7	0.1
TCE	0.9	1.1	1.0	1.1	0.9	100	10	0.5
1,1,1-TCA	1.1	1.2	1.0	1.1	0.9	106	10.7	0.5

3.5 Experimental Setup

Bench scale UV experiments were conducted using a collimated beam device (CBD unit). Figure 4 shows the CBD unit. The groundwater sample was placed in a petri dish and exposed to UV light. Flow-through UV experiments were conducted in a WEDECO-LBX3 UV reactor equipped with a single low pressure UV-C lamp (Figure 3). The reactor volume was 2.6L.

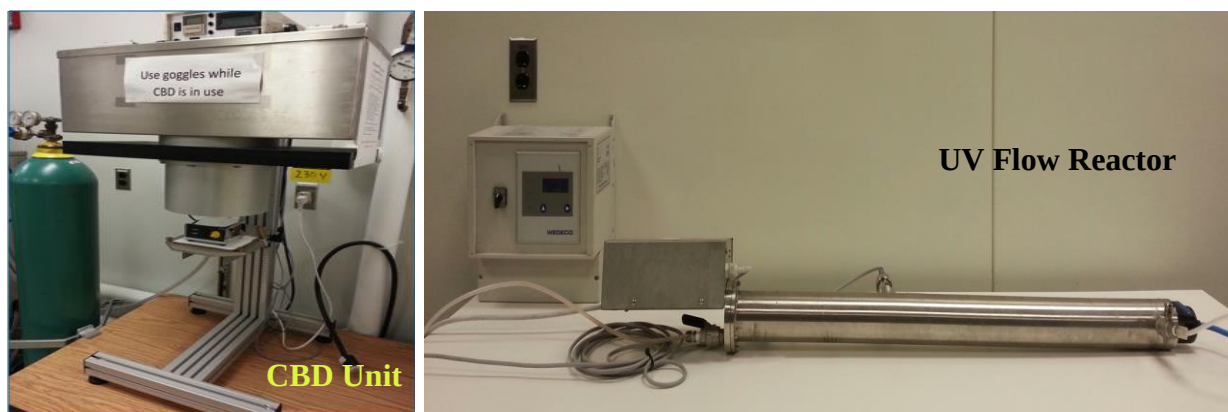


Figure 3: CBD unit and UV flow reactor

4. Results and Discussion

4.1 Groundwater Characterization

In this report, **Groundwater Influent** is being referred to the groundwater coming into the treatment plant at the site. The influent and PW-9 groundwater samples obtained from the NAS Whidbey island were characterized for calcium, magnesium, iron, total hardness, BOD and COD. Table 2 shows the characteristics of the groundwater samples. Table 3 shows the treatment requirements for 1,4-dioxane and VOCs.

Table 2: Groundwater Characteristics

Sample	Ca (mg/L)	Mg (mg/L)	Total Hardness (as CaCO ₃ , mg/L)	Iron, mg/L	COD, mg/L	BOD, mg/L
Influent (<i>NO</i> H ₂ SO ₄)	58.0	79.4	472	1.23	22.5	14.8
Influent with H ₂ SO ₄	57.5	75.2	453	0.39	4.8	NA
PW9 (<i>NO</i> H ₂ SO ₄)	105	115	734	0.05	8.1	1.8
PW9 with H ₂ SO ₄	105	119	755	0.78	11.4	9.8

NA: not applicable

Table 3: Treatment requirements

Analyte	Treatment requirement, Concentration in µg/L
Vinyl Chloride	0.02
1,1-DCE	7
1,1-DCA	800
Cis 1,2-DCE	70
TCE	5
1,1,1-TCA	200
1,4-Dioxane	0.44

4.2 Treatability experiments

4.2.1 Activation of persulfate with pH

Experiments were carried out by addition of persulfate and adjusting the groundwater pH to 3. Table 4 shows the removal of VOCs and 1,4-dioxane by addition of 100mg/L of persulfate. Samples were analyzed for 1,4-dioxane and VOCs after 5, 10, 15 and 30 minutes of reaction. It was observed that the treatment requirements were not met (Table 4).

Table 4: Groundwater Influent, Persulfate activation with pH

Analyte	Initial Concentration µg/L	Concentration, µg/L (Percentage Removal, %) pH 3 + 100mg/L of Persulfate			
		5 min	10 min	15 min	30 min
Vinyl Chloride	1.8	0.8 (55)	0.8 (53)	0.8 (57)	0.8 (55)
1,1-DCE	54.1	23.4 (57)	21.3 (61)	20.8 (62)	17.7 (67)
1,1-DCA	50.7	23.4 (54)	24.6 (52)	24.3 (52)	28.5 (44)
Cis 1,2-DCE	11.4	6.8 (40)	7.7 (32)	7.0 (38)	5.7 (50)
TCE	48.6	28.8 (41)	29.0 (40)	29.2 (40)	27.8 (43)
1,1,1-TCA	28.1	18.6 (34)	17.6 (37)	15.8 (44)	13.6 (52)
1,4-Dioxane	6.6	5.5 (17)	5.4 (18)	5.7 (13)	5.6 (14)

Data in RED are higher than the treatment requirement

4.2.2. Activation of persulfate with pH and Fe²⁺

To enhance the activation of persulfate, Fe²⁺ was added. Table 5 shows the removal of VOCs and 1,4-dioxane by addition of 100mg/L of persulfate and 100mg/L of ferrous sulfate. Samples were analyzed for 1,4-dioxane and VOCs after 15 and 30 minutes of reaction. A slight enhancement in the removal of 1,4-dioxane and VOCs was observed, however, the treatment requirements were not met (Table 5).

Table 5: Groundwater Influent, Persulfate activation with pH and Ferrous Sulfate

Analyte	Initial Concentration µg/L	Concentration, µg/L (Percentage Removal, %) pH 3, 100mg/L Persulfate and 100mg/L ferrous sulfate	
		15 min	30 min
Vinyl Chloride	1.8	0.7 (63)	0.8 (56)
1,1-DCE	54.1	10.4 (81)	9.4 (83)
1,1-DCA	50.7	26.7 (47)	30.1 (41)
Cis 1,2-DCE	11.4	3.9 (66)	3.7 (68)
TCE	48.6	20.5 (58)	21.6 (56)
1,1,1-TCA	28.1	15.0 (47)	15.4 (45)
1,4-Dioxane	6.6	4.2 (36)	3.9 (41)

Data in RED are higher than the treatment requirement

4.2.3 Removal of VOCs from Groundwater via sonication

At the Water and Environmental Technology (WET) Center, Temple University, we have been researching on methods to efficiently remove 1,4-dioxane from Milli-Q Water. In preliminary experiments (DI water studies), it was determined that ultrasound can degrade 1,4-dioxane. With the addition of persulfate and Fe^{2+} , ultrasound degradation of 1,4-dioxane was significantly enhanced (Figure 4).

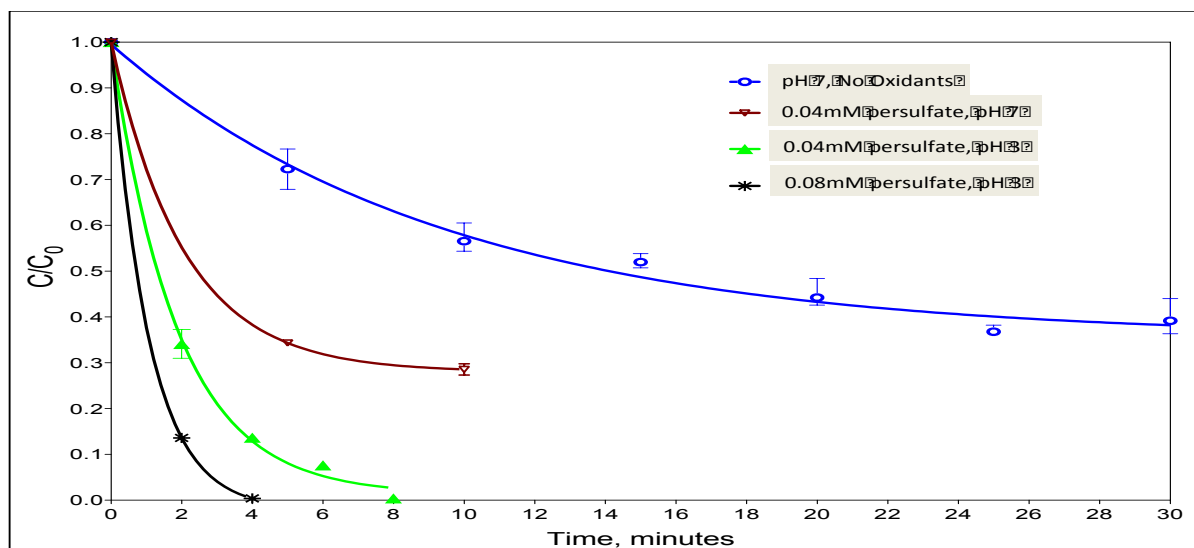


Figure 4: Sonication of 1,4-dioxane (spiked in milli-Q water).

4.2.3a) Sonication of groundwater, pH 7: The groundwater was subjected to 15-minute sonication. Table 6 shows the removal of 1,4-dioxane and VOCs during sonication in the presence and absence of persulfate at pH 7. It was observed that addition of persulfate during enhanced the removal of 1,4-dioxane and VOCs via sonication, however the treatment requirements were not met under both the condition. Also, there was formation of iron oxide precipitates.

Table 6: Groundwater sonication, 15 minutes, P = 0.19kW; Sample Volume = 150mL, pH 7

Analyte	Initial Concentration µg/L	Concentration, µg/L (Percentage Removal, %)	
		pH 7	pH 7 + 100 mg/L Persulfate
Vinyl Chloride	1.8	2.1 (0)	1.7 (6)
1,1-DCE	54.1	12.8 (76)	9.2 (83)
1,1-DCA	50.7	6.1 (88)	9.2 (82)
Cis 1,2-DCE	11.4	3.7 (68)	3.3 (71)
TCE	48.6	11.3 (77)	7.1 (85)
1,1,1-TCA	28.1	6.9 (75)	7.4 (74)
1,4-Dioxane	6.6	5.1 (22)	4.1 (38)

Data in RED are higher than the treatment requirements

4.2.3b) Sonication of groundwater, pH 3: Table 7 shows the removal of 1,4-dioxane and VOCs during sonication in the presence and absence of persulfate at pH 3. It was observed that addition of persulfate enhanced the removal of 1,4-dioxane and VOCs via sonication, however the treatment requirements were not met under both the condition. Addition of excess persulfate (500mg/L) resulted in lower removal of VOCs and 1,4-dioxane.

Table 7: Groundwater sonication, 15 minutes, P = 0.19kW; Sample Volume = 150mL, pH 3

Analyte	Initial Concentration, µg/L	Concentration, µg/L (Percentage Removal, %)		
		No Persulfate	100mg/L Persulfate	500mg/L Persulfate
Vinyl Chloride	1.8	2.0 (0)	0.9 (52)	0.5 (73)
1,1-DCE	54.1	16.5 (69)	1.3 (98)	2.1 (96)
1,1-DCA	50.7	16.5 (68)	8.0 (84)	8.2 (84)
Cis 1,2-DCE	11.4	4.7 (59)	1.6 (86)	1.6 (86)
TCE	48.6	9.5 (81)	8.2 (83)	10.8 (78)
1,1,1-TCA	28.1	8.5 (70)	6.4 (77)	8.2 (71)
1,4-Dioxane	6.6	4.8 (27)	3.6 (46)	4.0 (40)

Data in RED are higher than the treatment requirements

To enhance the reaction further, ferrous sulfate was added during the sonication process. Table 8 shows the removal of 1,4-dioxane and VOCs during sonication in the presence and absence of persulfate and ferrous sulfate at pH 3. It was observed that addition of persulfate and

ferrous sulfate significantly enhanced the removal of 1,4-dioxane and VOCs via sonication, however, the treatment requirements were not met. Addition of excess persulfate and ferrous sulfate (250mg/L) resulted in slightly lower removal of TCE, 1,1,1-TCA, 1,1-DCA and 1,4-dioxane.

Table 8: Groundwater sonication, 15 minutes, P = 0.19kW; Sample Volume = 150mL, pH 3

Analyte	Initial Concentration µg/L	Concentration, µg/L (Percentage Removal, %)		
		100mg/L Persulfate + 100mg/L Ferrous Sulfate	150mg/L Persulfate + 150mg/L Ferrous Sulfate	250mg/L Persulfate + 250mg/L Ferrous Sulfate
Vinyl Chloride	1.8	0.5 (71)	0.4 (79)	ND (100)
1,1-DCE	54.1	1.7 (97)	1.6 (97)	2.7 (95)
1,1-DCA	50.7	7.1 (86)	10.3 (80)	1.6 (97)
Cis 1,2-DCE	11.4	ND (100)	ND (100)	ND (100)
TCE	48.6	3.8 (92)	3.1 (94)	4.6 (91)
1,1,1-TCA	28.1	5.7 (80)	6.3 (78)	7.2 (74)
1,4-Dioxane	6.6	0.8 (87)	0.5 (92)	1.3 (80)

Data in **RED** are higher than the treatment requirements

4.2.4 Removal of 1,4-dioxane and VOCs using UV Light

4.2.4a) UV/Persulfate process, pH 7: Series of experiments were carried out in the presence of UV light. The groundwater sample was initially exposed to UV light under CBD in the presence and absence of presence of persulfate at pH 7. Table 9 shows the removal of VOCs and 1,4-dioxane from groundwater when exposed to 5000mJ/cm² of UV dosage and in the presence of persulfate. It was observed that addition of persulfate slightly enhanced the removal, however, the treatment objectives were not met.

Table 9: Groundwater Influent, exposed to UV light, pH 7, UV dosage = 5000mJ/cm²

Analyte	Initial Concentration µg/L	Concentration, µg/L (Percentage Removal, %)		
		No Persulfate	10mg/L persulfate	100mg/L persulfate
Vinyl Chloride	1.8	1.0 (44)	0.9 (51)	0.6 (63)
1,1-DCE	54.1	20.8 (62)	16.7 (69)	8.4 (85)
1,1-DCA	50.7	17.4 (66)	19.8 (61)	15.5 (70)
Cis 1,2-DCE	11.4	4.9 (57)	3.5 (69)	1.2 (90)
TCE	48.6	21.9 (55)	15.2 (69)	11.7 (76)
1,1,1-TCA	28.1	15.2 (46)	11.2 (60)	10.5 (63)
1,4-Dioxane	6.6	6.2 (5)	5.1 (23)	3.4 (49)

Data in RED are higher than the treatment requirements

4.2.4b) UV/Persulfate process, pH 3: The groundwater sample was exposed to UV light under CBD in the presence and absence of presence of persulfate at pH 3. Table 10 shows the removal of VOCs and 1,4-dioxane from groundwater when exposed to 5000mJ/cm² of UV dosage and in the presence of persulfate. It was observed that addition of persulfate slightly enhanced the removal. UV dosage of 5000 mJ/cm² in the presence of 150 mg/L of persulfate removed the VOCs, 1,4-dioxane and treatment objectives were met.

Table 10: Removal of VOCs using UV/Persulfate; UV Dosage: 5000mJ/cm² (CBD Studies)

Analyte	Initial Concentration µg/L	Concentration, µg/L (Percentage Removal, %)			
		50mg/L persulfate	75mg/L persulfate	100mg/L persulfate	150mg/L persulfate
Vinyl Chloride	0.4	0.2 (62)	0.2 (62)	0.1 (67)	ND (100)
1,1-DCE	45.1	2.9 (94)	3.0 (93)	3.8 (92)	1.3 (97)
1,1-DCA	23.5	2.7 (88)	3.5 (85)	3.4 (85)	ND (100)
Cis 1,2-DCE	12.3	ND (100)	ND (100)	ND (100)	ND (100)
TCE	17.7	4.8 (73)	5.4 (70)	5.1 (71)	4.9 (72)
1,1,1-TCA	10.6	5.1 (52)	3.9 (64)	3.9 (63)	3.8 (64)
1,4-Dioxane	4.9	ND (100)	ND (100)	ND (100)	ND (100)

Data in RED are higher than the treatment requirements

Triplicate experiments were conducted using UV dosage of 5000 mJ/cm² and 150mg/L persulfate at pH 3. Table 11 shows the removal of VOCs and 1,4-dioxane. The treatment objectives were met.

Table 11: Removal of VOCs using UV/Persulfate; 5000mJ/cm²; 150mg/L Persulfate (using CBD)

Analyte	Initial Concentration, µg/L	Concentration, µg/L (Percentage Removal, %)		
Vinyl Chloride	0.4	ND (100)	0.1 (80)	ND (100)
1,1-DCE	45.1	1.3 (97)	3.3 (93)	2.0 (96)
1,1-DCA	23.5	ND (100)	1.4 (94)	0.6 (97)
Cis 1,2-DCE	12.3	ND (100)	ND (100)	ND (100)
TCE	17.7	4.9 (72)	4.3 (76)	4.6 (74)
1,1,1-TCA	10.6	3.8 (64)	ND (100)	ND (100)
1,4-Dioxane	4.9	ND (100)	ND (100)	ND (100)

4.2.4c) UV/Persulfate process, flow through experiments: A series of flow through experiments were conducted in the presence of 150 mg/L of persulfate, pH 3 and UV light. Table 12 shows the removal of VOCs and 1,4-dioxane when the sample was passed through a 2 Liter UV reactor. The sample flow rate was 210 ml/min resulting in a 9.5 min retention time and a UV dosage of 3700mJ/cm² UV dosage. Treatment requirements were not met.

Table 12: Removal of VOCs using UV/Persulfate; Flow through reactor; Reactor volume = 2L; persulfate = 150mg/L Flow rate = 210ml/min; UV Dosage = 3700mJ/cm²; Retention time = 9.5min

Analyte	Initial Concentration, µg/L	Concentration, µg/L (Percentage Removal, %)			
Vinyl Chloride	1.2	0.2 (82)	0.2 (82)	0.2 (82)	0.2 (82)
1,1-DCE	35.9	9.1 (75)	9.3 (74)	9.2 (74)	9.3 (74)
1,1-DCA	38.2	3.8 (90)	4.1 (89)	4.3 (89)	4.7 (88)
Cis 1,2-DCE	11.2	ND (100)	ND (100)	ND (100)	ND (100)
TCE	47.3	6.6 (86)	7.0 (85)	7.4 (84)	6.6 (86)
1,1,1-TCA	13.3	4.1 (69)	3.8 (71)	1.6 (88)	3.3 (75)
1,4-Dioxane	5.1	ND (100)	ND (100)	ND (100)	ND (100)

Data in RED are higher than the treatment requirements

The sample flow rate was reduced to 140 ml/min resulting in a 14 min retention time and 5000mJ/cm² UV dosage. Treatment requirements were met for all the VOCs except for TCE (Table 13).

Table 13: Removal of VOCs using UV/Persulfate; Flow through reactor; Reactor volume = 2L; persulfate = 150mg/L; Flow rate = 140ml/min; UV Dosage = 5000mJ/cm²; UV intensity ~ 6.5mW/cm²; Retention time = 14min

Analyte	Initial Concentration, µg/L	Concentration, µg/L (Percentage Removal, %)		
Vinyl Chloride	1.2	ND (100)	ND (100)	ND (100)
1,1-DCE	35.9	7.0 (80)	6.8 (81)	6.9 (81)
1,1-DCA	38.2	3.8 (90)	4.1 (89)	4.3 (89)
Cis 1,2-DCE	11.2	ND (100)	ND (100)	ND (100)
TCE	47.3	7.3 (85)	7.5 (84)	7.2 (85)
1,1,1-TCA	13.3	2.6 (80)	2.5 (82)	2.2 (84)
1,4-Dioxane	5.1	ND (100)	ND (100)	ND (100)

Data in RED are higher than the treatment requirements

Groundwater influent Sample was passed through a 2.6L UV reactor. The sample flow rate was 210 ml/min resulting in a 12 min retention time and UV dosage of 6000mJ/cm². Data is shown in Table 14. Treatment requirements were met for all the VOCs.

Table 14: Removal of VOCs using UV/Persulfate (GW Influent Sample); Flow through reactor; Reactor volume = 2.6L; persulfate = 150mg/L; Flow rate = 210ml/min; Retention time = 12min; UV Dosage ~ 6000mJ/cm²

Analyte	Initial Concentration, µg/L	Concentration, µg/L (Percentage Removal, %)		
Vinyl Chloride	1.7	ND (100)	ND (100)	ND (100)
1,1-DCE	35.9	4.0 (89)	3.7 (90)	3.8 (89)
1,1-DCA	38.2	ND (100)	ND (100)	ND (100)
Cis 1,2-DCE	11.2	ND (100)	ND (100)	ND (100)
TCE	47.3	ND (100)	ND (100)	ND (100)
1,1,1-TCA	13.3	ND (100)	ND (100)	ND (100)
1,4-Dioxane	5.1	ND (100)	ND (100)	ND (100)

PW-9 groundwater sample was passed through a 2.6 Liter UV reactor. The sample flow rate was 210 ml/min resulting in a 12 min retention time and ~6100mJ/cm² UV dosage. Data is shown in Table 15. Treatment requirements were met for all the compounds.

Table 15: Removal of VOCs using UV/Persulfate (PW9 Sample, pH 3); Flow through reactor; Reactor volume = 2.6L; persulfate = 150mg/L; Flow rate = 210ml/min; Retention time = 12min; UV Dosage = 6100mJ/cm²

Analyte	Initial Concentration, µg/L	Concentration, µg/L (Percentage Removal, %)		
Vinyl Chloride	0.7	ND (100)	ND (100)	ND (100)
1,1-DCE	0.2	ND (100)	ND (100)	ND (100)
1,1-DCA	16.4	ND (100)	ND (100)	ND (100)
Cis 1,2-DCE	ND	ND (100)	ND (100)	ND (100)
TCE	7.2	ND (100)	ND (100)	ND (100)
1,1,1-TCA	ND	ND (100)	ND (100)	ND (100)
1,4-Dioxane	3.9	ND (100)	ND (100)	ND (100)

4.3 Cost analysis

Cost analysis for the chemicals required and electricity requirements were calculated based on a flow of 300 GPM, and a 24hr operation.

4.3.1 Cost of the Chemicals

Table 16 shows the bulk cost of the chemicals, amount and cost of the chemical required to treat 1000 gal of groundwater, and amount and cost of the chemical for a 1-year operation (300GPM and 24hr operation for 365days).

Table 16: Cost Analysis for the chemicals (assuming 300GPM flow, 365 days and 24hr operation)

CHEMICAL	Bulk Cost	Chemical(s) required to treat 1000 gal of GW	Cost of the chemical to treat 1000gal of GW (\$)	Amount of chemical required for 1year	Total Cost for 1 year
Sodium Persulfate (Na ₂ S ₂ O ₈)	\$1.2/lb.	0.567 kg (1.3 lb.)	1.48	89,405 kg (197,105 lb.)	\$ 236,520
Nitric Acid (HNO ₃)	\$300/ton	1040 mL	0.28	163,987 L	\$ 73,794
Sodium Hydroxide (NaOH)	\$500/ton	0.9 kg (1.9 lb.)	0.45	141,912 kg (313,023 lb.)	\$ 70,956
TOTAL			\$ 2.21		\$ 381,270

6.3.1 Energy costs (calculated based on lab scale reactor)

Volume of Lab Reactor: 2.6L

Flow rate: 0.2L/min = 12L/hr

Power of the Lamp: 100W = 0.1kW

Energy Consumption: 100W ÷ 12L/hr = 8.3W hr/L

Energy Consumption for 1000 Gal: 1000 gal X 3.78 L/gal X 8.3 W hr/L = 31.4 kWh

Electricity cost for 1000 Gal: 31.4 kWh X \$0.06/kWh = \$1.9

Energy cost for UV reactor: \$1.9 per 1000 gal of Groundwater

Total operating cost (Energy & Chemicals): \$ 4.11 per 1000 gal of Groundwater treated

4.3.2 UV Reactor cost (Confidential Information of vendor):

Based on the bench-scale studies, the full-scale treatment system would need 6 LBX 1000 UV reactors equipped with 240 lamps. Each lamp is rated at 0.6kW, so the total power requirement is 144kW. The total cost of the equipment (including a dosing station, mixer, A/C container and PLC controller) is approximately \$800,000 (from Xylem /Wedeco; Confidential Information of vendor)

5. Conclusions

- Analysis of groundwater influent and PW-9 sample showed very high concentrations of Ca and Mg.
- Activation of persulfate with pH alone and pH with the presence of Fe^{2+} did not provide any significant removal of the VOCs and 1,4-dioxane
- Sonication of the samples at pH 7 (in the presence of persulfate) resulted in formation of iron oxide precipitation
- Sonication (in the presence of persulfate and Fe^{2+}) at pH 3 significantly enhanced the removal, however, the treatment requirements were not met
- CBD studies showed that an UV dosage of $5000\text{mJ}/\text{cm}^2$ in the presence of 150 mg/L of persulfate met the treatment requirements

- Flow through experiments ($\sim 6000 \text{ mJ/cm}^2$ UV dosage and 150 mg/L persulfate) showed complete removal of the VOCs and 1,4-dioxane

6. Recommendations

Based on the results of the study, the following four treatment schemes are recommended:

1. Reduce the pH of groundwater to 3, add 150 mg/L of persulfate and expose the sample to 6000 mJ/cm^2 of UV light. Neutralize and discharge the treated water (Figure 5); OR
2. Pretreat the groundwater to remove Ca, Mg and Fe; add persulfate and expose the sample to UV light and discharge the treated groundwater (no pH adjustment would be required Figure 6), and the energy cost is expected to be much lower; OR
3. Pretreat the groundwater to remove Ca, Mg and Fe; add peroxide and ozonate the sample and discharge the treated groundwater (Figure 7). The overall treatment cost is expected to be much lower; OR
4. Pretreat the groundwater to remove Ca, Mg and Fe; add chemicals (persulfate or peroxide, etc.) and sonicate the sample and discharge the treated groundwater (Figure 8). The process is expected to be much more efficient with pretreatment.

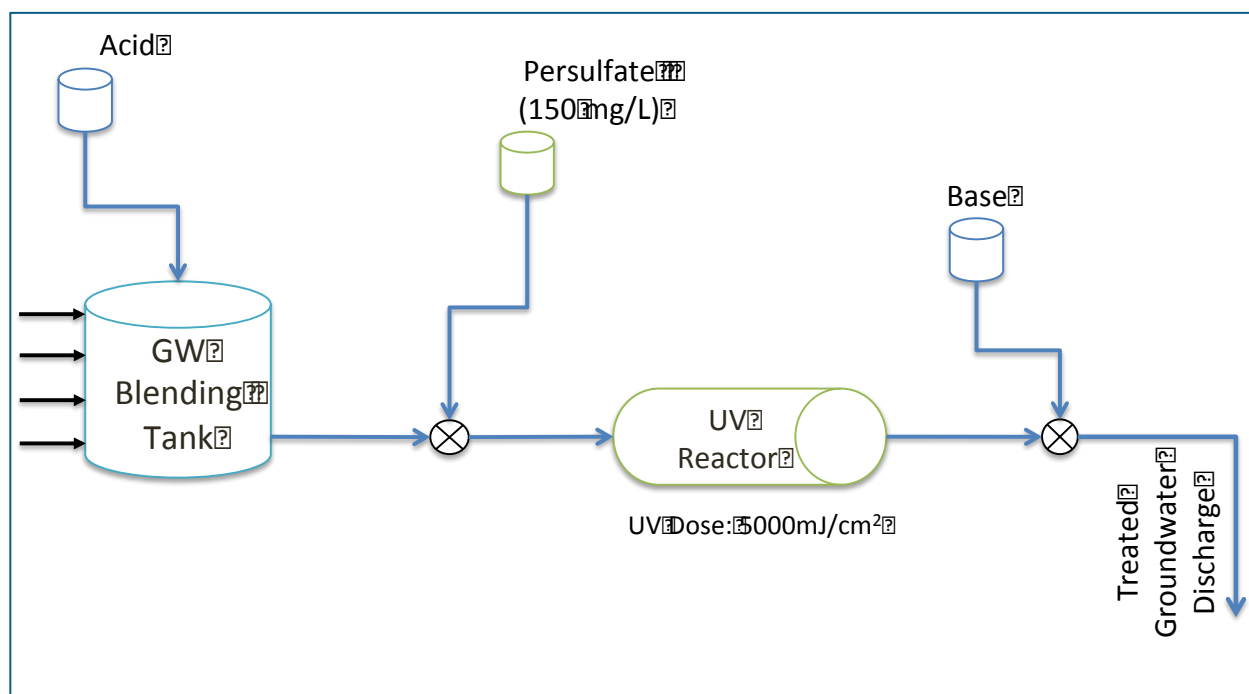


Figure 5: Treatment scheme 1

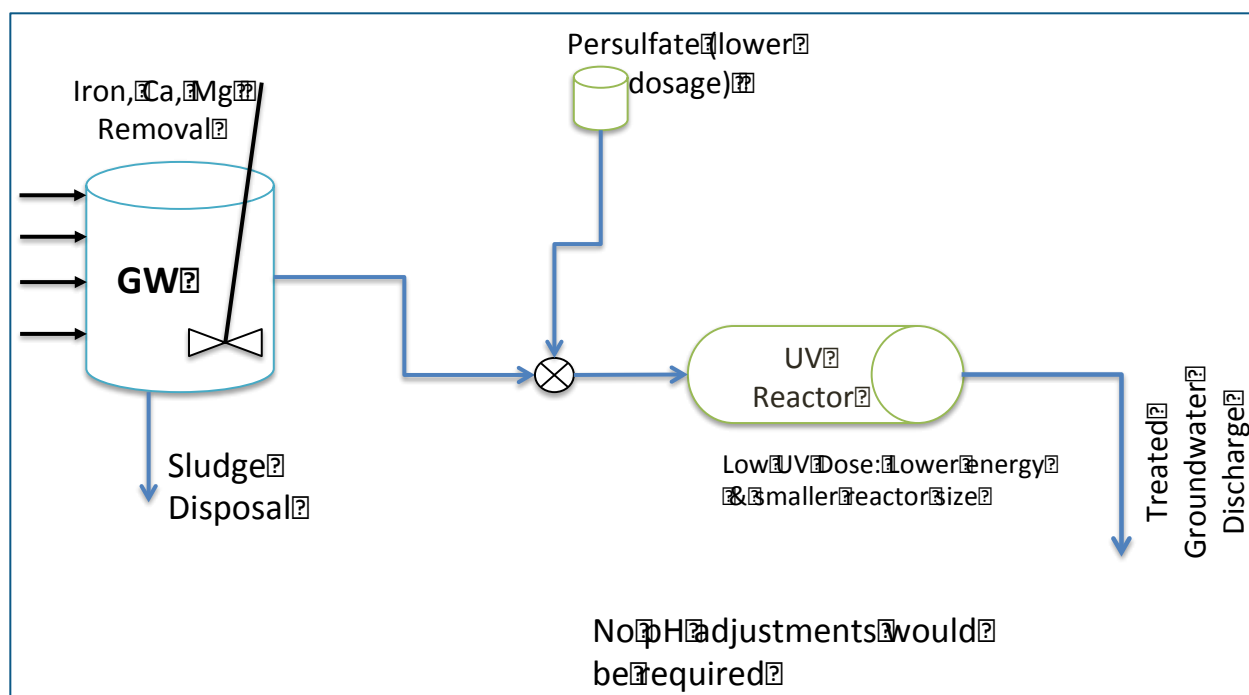


Figure 6: Treatment scheme 2

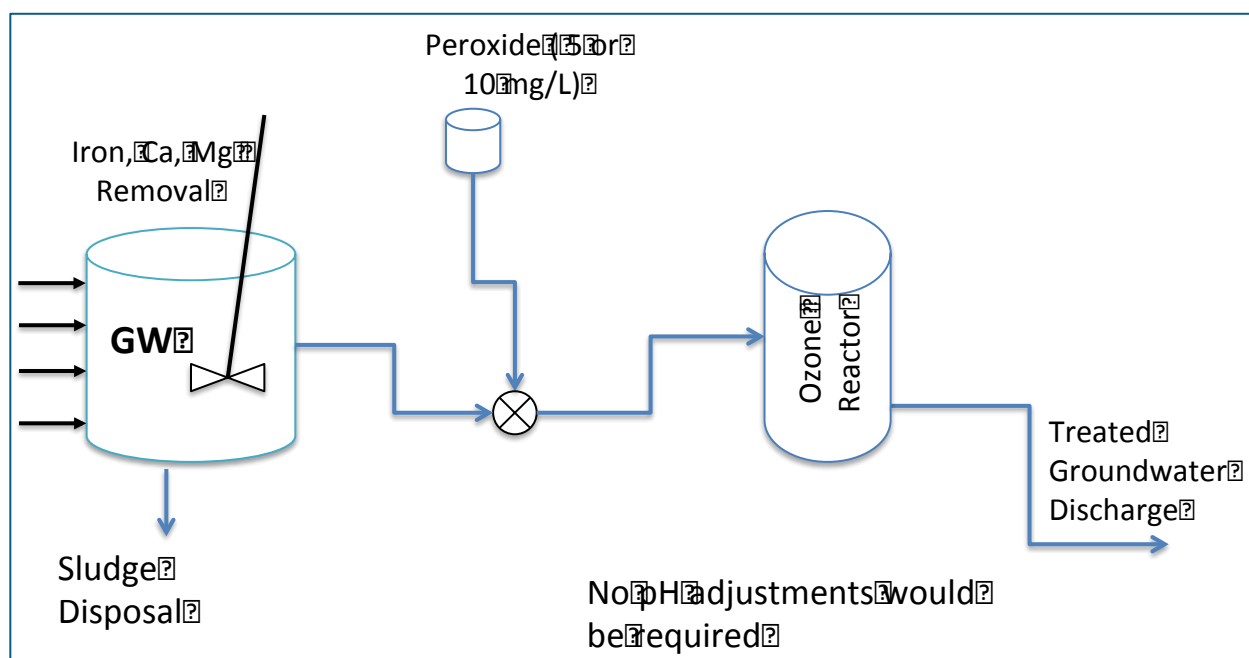


Figure 7: Treatment scheme 3

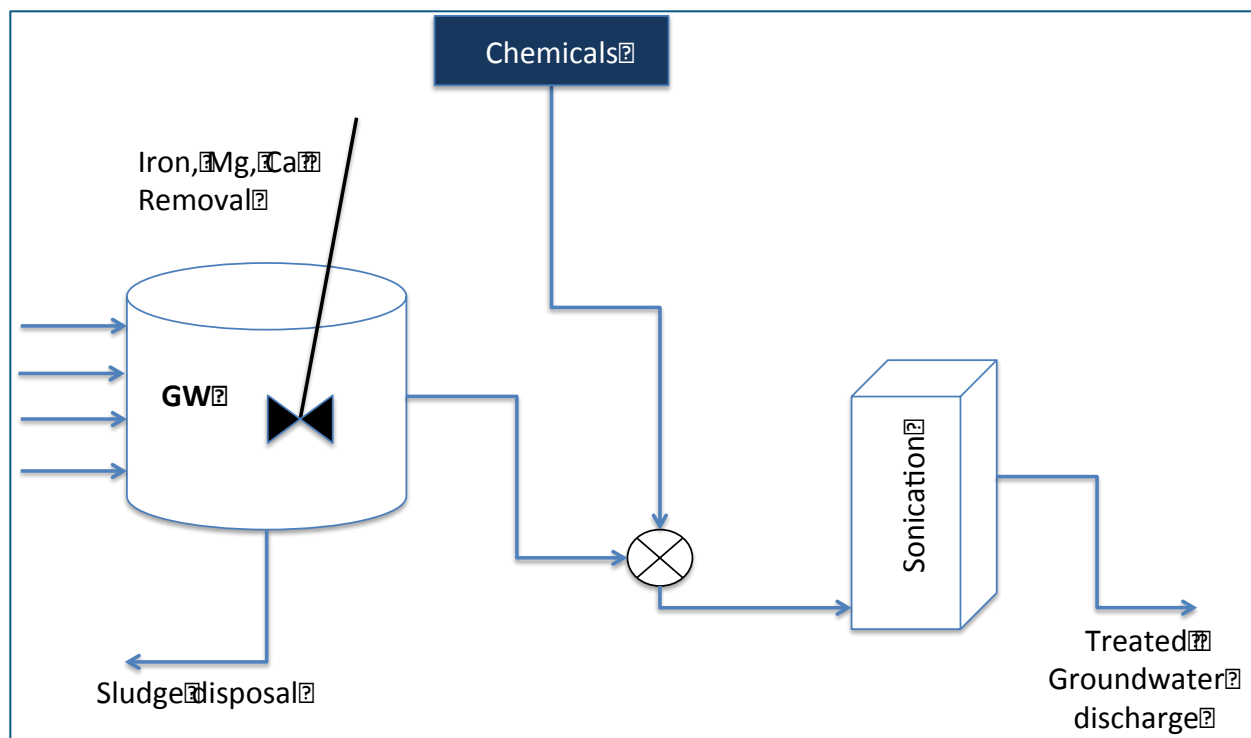


Figure 8: Treatment scheme 4

APPENDIX F
APTwater HiPOx Bench-Scale Treatability Report
November 6, 2017

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HiPOx[®] Bench-Scale Treatability Report

For Treatment of 1,4-Dioxane and TCE

Whidbey Island / NASWI AREA 6

Oak Harbor, WA

APT Proposal: P3518

Revision: 00

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TABLE OF CONTENTS

1. PROJECT SPECIFIC BENCH TEST INFORMATION.....	3
1.1 BACKGROUND INFORMATION	3
1.2 OBJECTIVE OF EVALUATION	3
1.3 PROCESS WATER INFORMATION	4
2. RESULTS.....	4
2.1 1,4-DIOXANE DESTRUCTION	5
2.2 DETECTED VOCs RESULTS.....	7
2.3 BROMATE FORMATION.....	9
3. DISCUSSION	11
3.1 CONCLUSIONS.....	11
3.2 RECOMMENDATIONS	11
4. ATTACHMENTS	13

ATTACHMENT 1	Bench Tests
ATTACHMENT 2	Bench Test Results
ATTACHMENT 3	Third Party Analytical Reports



1. PROJECT SPECIFIC BENCH TEST INFORMATION

1.1 Background Information

The HiPOx treatment system is being evaluated for use to reduce 1,4-Dioxane and other targeted compounds in groundwater from the Whidbey Island / NASWI AREA 6 site in Oak Harbor, WA (Site). A bench test was conducted because the efficacy and design of a pilot or full-scale HiPOx system is dependent on the specific chemistry of the water to be treated. The data will be used to determine the treatability of the stream by HiPOx and indicate if this technology can be used to effectively treat this groundwater for discharge.

The following is summary background information provided by AECOM regarding this project:

- The groundwater to be treated will be collected from monitoring well(s) reflecting a hydraulic control strategy;
- Two water samples are tested; water was drawn from specific monitoring wells;
- Bromate Control is not required by the Client at this stage;
- Compounds: 1,4-Dioxane, Trichloroethylene (TCE) and Trichloroethane (TCA) are well above clean-up levels and are expected to determine the oxidant dosage for this application.

- Discharge requirements are anticipated as follows:

	System A		System B	
Parameter	Influent	Effluent	Influent	Effluent
Flow (gpm)	200		100	
1,4-Dioxane (ug/L)	5	< 0.44	5	< 0.44
TCE (ug/L)	50	< 5	50	< 5

1.2 Objective of Evaluation

The bench test study was performed to evaluate the ozone and hydrogen peroxide dose required to treat 1,4-Dioxane and other targeted contaminants to stated discharge goals utilizing the HiPOx treatment system. The primary objectives of this evaluation were:

- To determine HiPOx ozone dose and hydrogen peroxide to ozone mole ratio (MR) required to reduce listed contaminants to below the discharge limits;
- Generate dose-response curves for 1,4-Dioxane and other targeted contaminants.



1.3 Process Water Information

Water sample was collected and composited by AECOM from the Site. The sample was received at the APTwater test facility in Pittsburg, California on June 23rd, 2017. The temperature and condition of the sample were acceptable and subsequently stored in refrigeration unit to prevent degradation.

The water sample from Well PW-5 received was relabeled P3518 SP-0. Treated samples are referred to as P3518-SP1 and P3518-SP2 in this report. The water sample from Well 6-S-43 received was relabeled P3518 SP-10. Treated samples are referred to as P3518-SP11 through P3518-SP14 in this report.

Two additional tests were run with Well PW-5 and Well 6-S-43 samples on 08/08/2017, labeled P3518-SP5 and P3518-SP15, respectively, to further confirm the best H_2O_2 : O_3 Mole Ratios for bromate control.

Processed Bromide and Bromate test samples were then sent to Eurofins Eaton Analytical, Inc. in South Bend, IN for analysis. VOCs, 1,4-Dioxane, and metals tested samples were sent to Eurofins Calscience, Inc. in Garden Grove for analysis.

2. RESULTS

Water sample SP-0 was drawn from monitor well PW-5 on Site, with 1,4-Dioxane concentration of 4 ug/L, 1,1,1-Trichloroethane level of 52 ug/L, Trichloroethene (TCE) level of 19 ug/L and other organic compounds with concentration higher than discharge requirements. In water sample SP-0, there are also dissolved metal contents, such as 56.4 ug/L of Magnesium and detected Iron and Manganese. In this HiPOx bench test, the selected test ozone doses for sample P3518-SP1 and P3518-SP2 were 4.0 and 9.0 (mg/L) respectively. Test runs P3518-SP1 and 2 HiPOx tests were all run with 2.0 and 1.5 H_2O_2 : O_3 Mole Ratios, respectively.

P3518-SP5 was run with 3.5 mg/L Ozone dose, 1.2 H_2O_2 : O_3 Mole Ratio and 5 injection points.

Water sample SP-10 was drawn from monitor well 6-S-43 on Site, with 1,4-Dioxane concentration of 8.4 ug/L, 1,1,1-Trichloroethane level of 41 ug/L, Dichlorodifluoromethane level of 12 ug/L and other organic compounds with concentration higher than discharge requirements. In water sample SP-10, there are also dissolved metal contents, such as 13 ug/L of Magnesium and detected Iron and Manganese. In this HiPOx bench test, the selected test ozone doses for sample P3518-SP11 through P3518-SP14 were 6.0, 10.0, 15.0 and 20.0 (mg/L) respectively. Test runs P3518-SP11 through SP14 HiPOx tests were all run with 2.0 H_2O_2 : O_3 Mole Ratios.



P3518-SP15 was run with 10.0 mg/L Ozone dose, 1.2 H₂O₂ : O₃ Mole Ratio and 6 injection points.

While destruction requirements of 1,4-Dioxane and VOCs were established, and the bromate concentration in all tested samples are equal to or lower than 1.5 ug/L, except P3518-SP15.

The rates of destruction of the 1-4 Dioxane was different between the PW-5 and 6-S-43. Alkalinity negatively effects the destruction rate as it is a hydroxyl radical scavenger. PW-5 alkalinity was 260 mg/L and 6-S-43 was 340 mg/L. PW-5 destruction rate was higher than 6-S-43 rate.

NOTE: Our bench test procedure allows us to reduce the ozone dose per injection by increasing the number of injection occurrences. This information can be incorporated into a commercial design by increasing the number of injection points, or by increasing the recycle rate in the design.

2.1 1,4-Dioxane Destruction

The ozone dose response curve for 1,4-Dioxane destruction in the water samples is presented in Figure 2.1.a and 2.1.b below. The 1,4-Dioxane results are listed in Table 2.1.a and 2.1.b below. The treatment series successfully reduced 1,4-Dioxane concentrations from 4 ug/L and 8.4 ug/L to below Method Detection Limit (< 0.1 ug/L) at the dose of 9.0 mg/L and 20.0 mg/L of ozone, respectively.

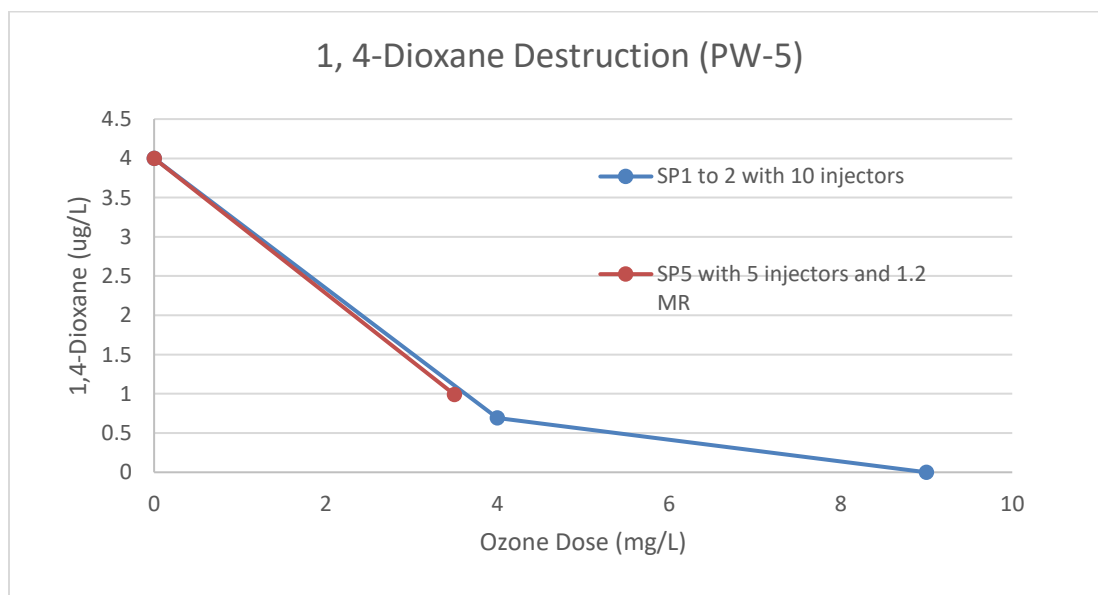


Figure 2.1.a: 1,4-Dioxane Destruction in water sample PW-5

Conditions	PW-5 Sample Matrix					
		Samples				
	Sample ID#	P3518-SP-0	P3518-SP-1	P3518-SP-2	P3518-SP-0a	P3518-SP-5
	Run#	0	1	2	0a	5
	Ozone Dose (mg/L)	0	4.0	9.0	0.0	3.5
	H2O2:O3 Mole Ratio	-	2.0	1.5	-	1.2
	# of injectors	-	10	10	-	5
Eurofins Calscience	1,4-Dioxane (ug/L)	4	0.69	<0.1	4	0.99

Table 2.1.a: Tabulated 1,4-Dioxane Results in water sample PW-5

Note: Sample SP-0a was for the condition of the the raw water sample PW-5 on 08/08/2017 when test SP-5 was conducted.

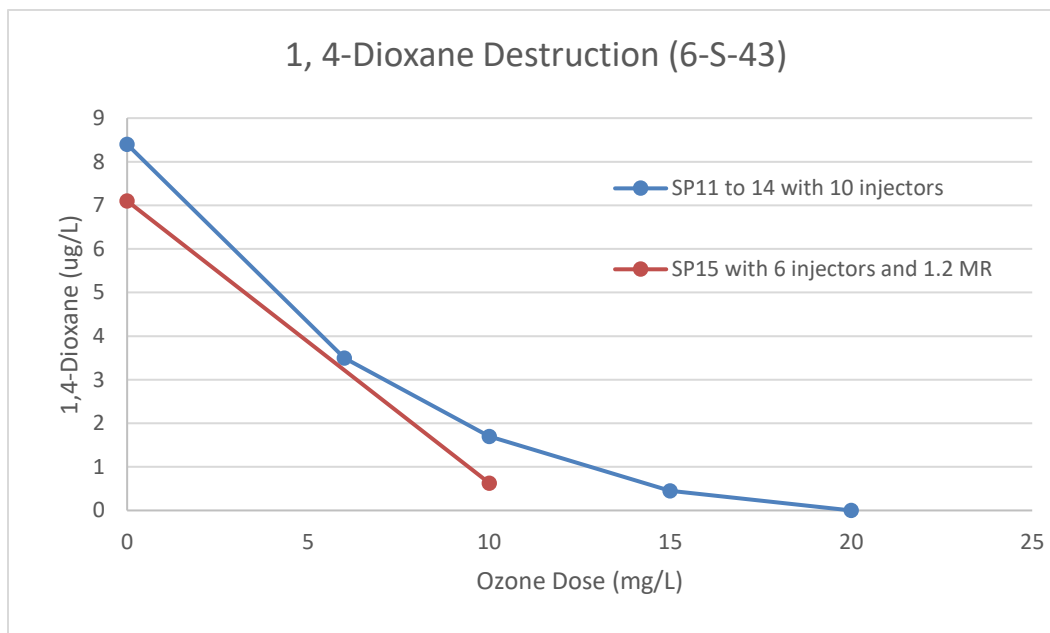


Figure 2.1.b: 1,4-Dioxane Destruction in water sample 6-S-43

6-S-43 Sample Matrix								
Conditions		Samples						
	Sample ID#	P3518-SP-10	P3518-SP-11	P3518-SP-12	P3518-SP-13	P3518-SP-14	P3518-SP-10a	P3518-SP-15
	Run#	10	11	12	13	14	10a	15
	Ozone Dose (mg/L)	0	6.0	10.0	15.0	20.0	0.0	10.0
	H2O2:O3 Mole Ratio	-	2.0	2.0	2.0	2.0	-	1.2
	# of injectors	-	10	10	10	10	-	6
Eurofins Calscience	1,4-Dioxane (ug/L)	8.4	3.5	1.7	0.45	<0.1	7.1	0.63

Table 2.1.b: Tabulated 1,4-Dioxane Results in water sample 6-S-43

Note: Sample SP-10a was for the condition of the the raw water sample 6-S-43 on 08/08/2017 when test SP-15 was conducted.

2.2 Detected VOCs Results

The ozone dose response curve for the destruction of other targeted VOCs compounds in the water sample is presented in Figure 2.2.a and 2.2.b below. The targeted VOCs results are listed in Table 2.2.a and 2.2.b below.

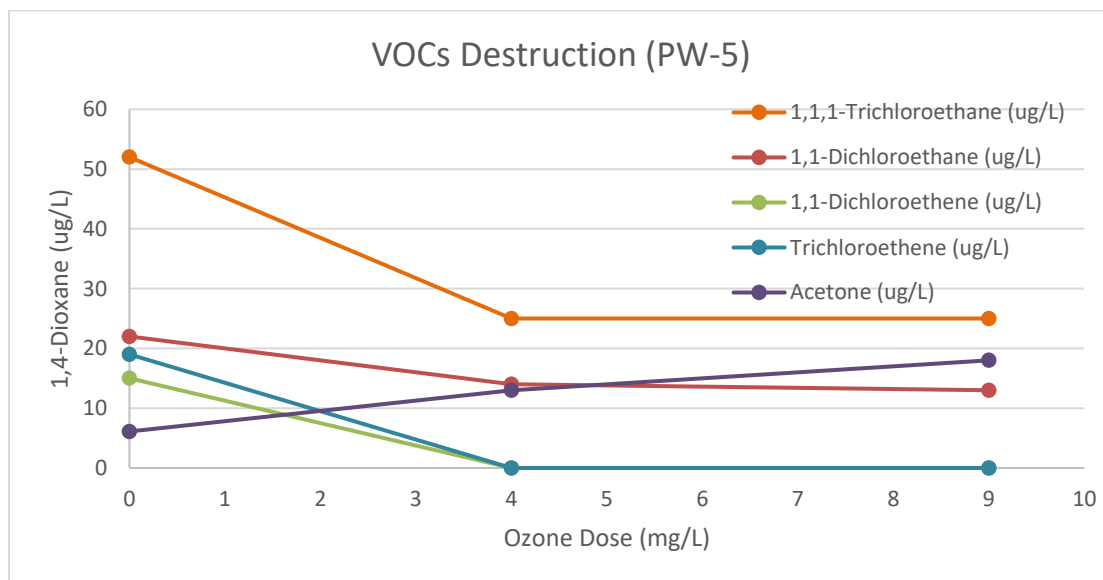


Figure 2.2.a: VOCs Destruction in water sample PW-5

Conditions	PW-5 Sample Matrix			
		Samples		
	Sample ID#	P3518-SP-0	P3518-SP-1	P3518-SP-2
	Run#	0	1	2
	Ozone Dose (mg/L)	0	4.0	9.0
	H2O2:O3 Mole Ratio	-	2.0	1.5
	# of injectors	-	10	10
Eurofins Calscience	1,1,1-Trichloroethane (ug/L)	52	25	25
	1,1-Dichloroethane (ug/L)	22	14	13
	1,1-Dichloroethene (ug/L)	15	<1	<1
	Trichloroethene (ug/L)	19	0.9J	<1
	Acetone (ug/L)	6.1	13	18

Table 2.2.a: VOCs Response in water sample PW-5

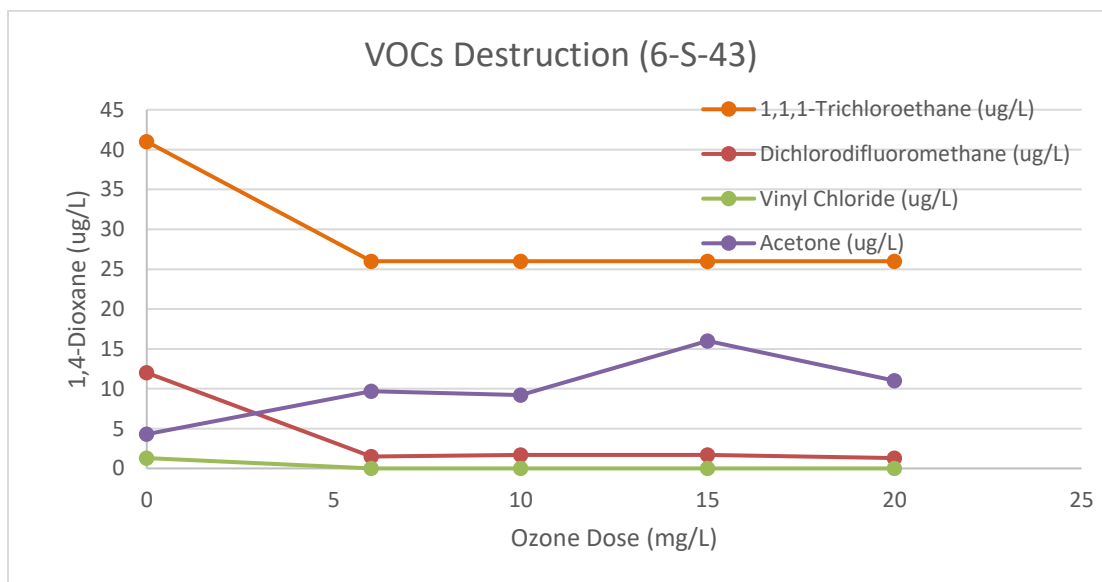


Figure 2.2.b: VOCs Destruction in water sample 6-S-43

Conditions	6-S-43 Sample Matrix					
		Samples				
	Sample ID#	P3518-SP-10	P3518-SP-11	P3518-SP-12	P3518-SP-13	P3518-SP-14
	Run#	10	11	12	13	14
	Ozone Dose (mg/L)	0	6.0	10.0	15.0	20.0
	H2O2:O3 Mole Ratio	-	2.0	2.0	2.0	2.0
	# of injectors	-	10	10	10	10

Eurofins Calscience	1,1,1-Trichloroethane (ug/L)	41	26	26	26	26
	Dichlorodifluoromethane (ug/L)	12	1.5	1.7	1.7	1.3
	Vinyl Chloride (ug/L)	1.3	<0.5	<0.5	<0.5	<0.5
	Acetone (ug/L)	4.3	9.7	9.2	16	11

Table 2.2.b: VOCs Response in water sample 6-S-43

From the tests in both water samples, we observed increases of Acetone concentrations in water, which were produced by the oxidation of organic compounds. Acetone at these low levels is typically not a concern for discharge requirements.

2.3 Bromate Formation

While bromate control is not required at this site, we ran conditions to control bromate if it should be required in the future. We designed 10 injectors for runs SP-1, SP-2 and runs SP-11 through SP-14. Bromide concentration were presented in the sample waters PW-5 and 6-S-43 at 0.14 mg/L and 0.36 mg/L, respectively. Each treated sample was analyzed for bromide and bromate, the bromate concentration in all tested samples are equal to or lower than 1.5 ug/L. The test results of which are shown in Table 2.3.a and 2.3.b below.

The ozone dose response curve for bromate formation in the water samples are presented in Figure 2.3.a and 2.3.b below.

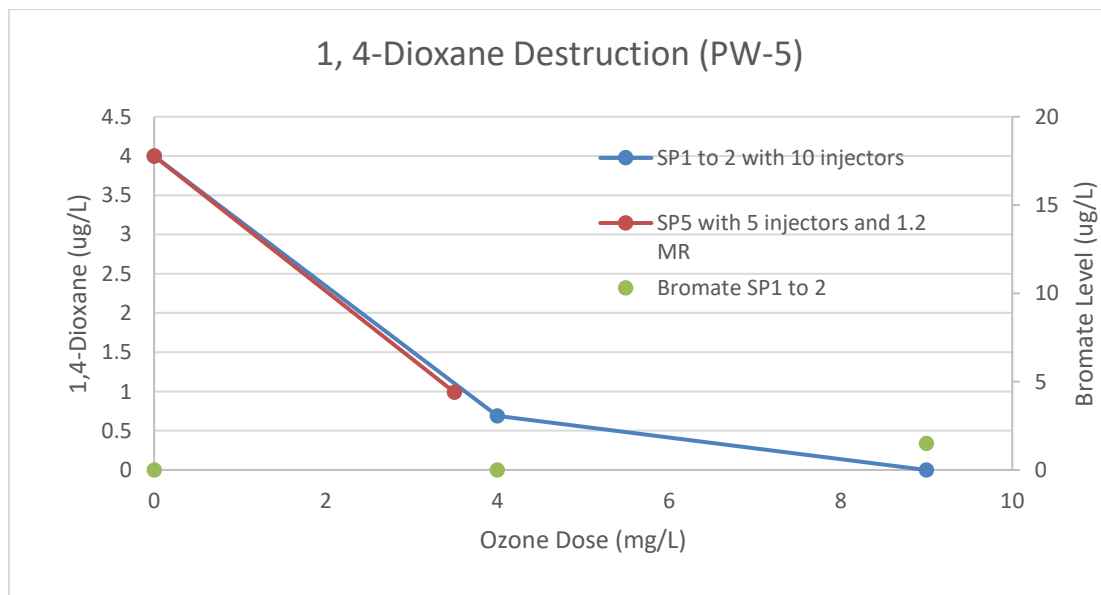


Figure 2.3.a: Bromate control vs. 1,4-Dioxane Destruction in sample PW-5

Conditions	PW-5 Sample Matrix				
		Samples			
	Sample ID#	P3518-SP-0	P3518-SP-1	P3518-SP-2	P3518-SP-5
	Run#	0	1	2	5
	Ozone Dose (mg/L)	0	4.0	9.0	3.5
	H2O2:O3 Mole Ratio	-	2.0	1.5	1.2
	# of injectors	-	10	10	5
Eurofins Eatons	Bromide (mg/L)	0.14	0.14	0.14	0.15
	Bromate (ug/L)	<1.0	<1.0	1.5	<1

Table 2.3.a: Bromate Formation in water sample PW-5

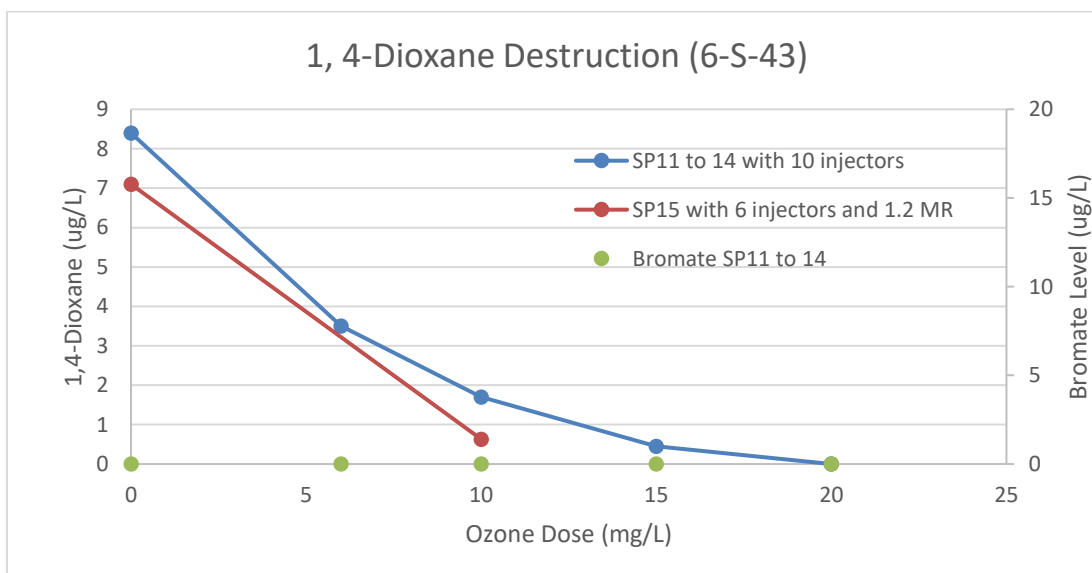


Table 2.3.b: Bromate Formation in water sample 6-S-43

Conditions	6-S-43 Sample Matrix						
		Samples					
	Sample ID#	P3518-SP-10	P3518-SP-11	P3518-SP-12	P3518-SP-13	P3518-SP-14	P3518-SP-15
	Run#	10	11	12	13	14	15
	Ozone Dose (mg/L)	0	6.0	10.0	15.0	20.0	10.0
	H2O2:O3 Mole Ratio	-	2.0	2.0	2.0	2.0	1.2
	# of injectors	-	10	10	10	10	6
Eurofins Eatons	Bromide (mg/L)	0.36	0.36	0.34	0.36	0.36	0.36*
	Bromate (ug/L)	<1.0	<1.0	<1.0	<1.0	<1.0	20

Table 2.3.b: Bromate Formation in water sample 6-S-43



Note: The second round of bench testing was aiming to find the best condition for reducing 1,4-Dioxane and other targeted VOCs to required level while optimizing the operation costs for bromate control. Even though the Bromate reading of SP15 is 20 ug/L, we have obtained sufficient information to design the full-scale system to achieve all the targets set forth.

3. DISCUSSION

3.1 Conclusions

The analytical results from the bench test support using HiPOx technology for the treatment of 1,4-Dioxane in the groundwater at the Whidbey Island / NASWI AREA 6 Site. 1,4-Dioxane concentration was successfully reduced to below the treatment objective of 0.44 ug/L.

Most of other VOC targeted contaminants (such as TCE) were reduced to less than 5 ug/L levels. However, once discharge limits are established, we'll need to discuss and select sequential process to further reduce TCA and DCA concentration if needed.

The bromate formation was controlled to < 2 ug/L at the designed ozone doses, H₂O₂ : O₃ mole ratios and numbers of ozone injection points. Runs SP5 and SP15 have been conducted for further analysis of the system configuration in order to optimize the full-scale operation costs.

3.2 Recommendations

Destruction models were generated within the limits of the data and it was necessary to extrapolate ozone and hydrogen peroxide dosing levels to meet the treatment objective using the current sample water constituent concentrations. The bench test clearly demonstrates that the HiPOx process can achieve the treatment goals of 1,4-Dioxane and other targeted VOCs, while controlling the bromate formation to below bromate MCL of 10 ppb.

Below are our recommendation for system design specifications based on the analytical results of the original tests (SP1 – 2 and SP11 – 14) and two optimization test runs (SP5 and SP15):

For System A (treating groundwater from Well PW-5)

Parameter (Units)	Influent	Effluent
Ozone (mg/L)	5.9	-
Hydrogen Peroxide (mg/L)	5.0	2.9
Mole Ratio	1.2	NA
Flow Rate (gpm)	200	200
1,4-Dioxane (ug/L)	4.0	< 0.44
TCE (ug/L)	50	<5

Table 3.2a: Recommended HiPOx Oxidant Dosing at Full Scale



For System B (treating groundwater from Well 6-S-43)

Parameter (Units)	Influent	Effluent
Ozone (mg/L)	15.6	-
Hydrogen Peroxide (mg/L)	19.9	14.4
Mole Ratio	1.8	NA
Flow Rate (gpm)	100	100
1,4-Dioxane (ug/L)	8.4	< 0.44
TCE (ug/L)	50	<5

Table 3.2b: Recommended HiPOx Oxidant Dosing at Full Scale



4. ATTACHMENTS

ATTACHMENT 1	Bench Tests
ATTACHMENT 2	Bench Test Results
ATTACHMENT 3	3 rd Party Analytical Reports



ATTACHMENT 1:
BENCH TESTS

P3518 Sample Details				
	<i>Lab</i>	<i>Method</i>	<i>Lab Bottle</i>	<i>Sample Volume (mL)</i>
pH	APT	Oakton Model pH Tester 3+	-	1800
Alkalinity (mg/L)	APT	Hach Model 5-EP Test Kit	-	
Turbidity (NTU)	APT	Hach Portable Turbidity Meter Model 2100Q	-	
Temperature (deg C)	APT	Therm	-	
UVT (%UVT)	APT	RealTech UVT monitor	-	
O3 Residual-DPD (mg/L)	APT	DPD method	-	
H2O2 Residual-Hach (mg/L)	APT	Hach Test Kit	-	
H2O2 Residual-Strips (mg/L)	APT	Test Strips	-	
COD (mg/L)	APT	Hach Test Kit	-	
VOC's (ug/L)	Calscience	EPA 8260B	(3) x 40 mL VOA's w/ HCl	120
1,4-Dioxane		EPA 522	(1) x 250 ml Amber w/Na2S2O3 + separate NaHSO4	250
Bromide	Eaton	EPA 300.0	(1) x 125 mL Poly w/EDA	125
Bromate		EPA 317.0		

ATTACHMENT 2: BENCH TEST RESULTS

Conditions	PW-5 Sample Matrix					
		Samples				
	Sample ID#	P3518-SP-0	P3518-SP-1	P3518-SP-2	P3518-SP-0a	P3518-SP-5
	Run#	0	1	2	0a	5
	Ozone Dose (mg/L)	0	4.0	9.0	0.0	3.5
	H2O2:O3 Mole Ratio	-	2.0	1.5	-	1.2
	# of injectors	-	10	10	-	5
APT Lab	pH	7.63	7.79	7.81		7.94
	ORP	222	343	339		265
	Alkalinity (mg/L)	260	240	240		180
	Turbidity (NTU)	1.98	1.76	1.91		0.55
	Temperature (deg F)	50	63	68		65.2
	UVT (cm-1)	85.9	90.5	91.4		92
	O3 Residual-DPD (mg/L)			0.03		0.05
	H2O2 Residual-Hach (mg/L)		4	5		2
	H2O2 Residual-Strips (mg/L)		>2	5		<2
	COD (mg/L)	7	12	4		7
Eurofins Calscience	1,1,1-Trichloroethane (ug/L)	52	25	25		
	1,1-Dichloroethane (ug/L)	22	14	13		
	1,1-Dichloroethene (ug/L)	15	<1	<1		
	Trichloroethene (ug/L)	19	0.9J	<1		
	Acetone (ug/L)	6.1	13	18		
	1,4-Dioxane (ug/L)	4	0.69	<0.1	4	0.99
	TOC (mg/l)	4.6		4.1		
	Iron (ug/L)	0.37				
	Magnesium (ug/L)	56.4				
	Manganese (ug/L)	0.344				
Eurofins Eaton	Bromide (mg/L)	0.14	0.14	0.14		0.15
	Bromate (ug/L)	<1.0	<1.0	1.5		<1

6-S-43 Sample Matrix								
Conditions		Samples						
	Sample ID#	P3518-SP-10	P3518-SP-11	P3518-SP-12	P3518-SP-13	P3518-SP-14	P3518-SP-10a	P3518-SP-15
	Run#	10	11	12	13	14	10a	15
	Ozone Dose (mg/L)	0	6.0	10.0	15.0	20.0	0.0	10.0
	H2O2:O3 Mole Ratio	-	2.0	2.0	2.0	2.0	-	1.2
	# of injectors	-	10	10	10	10	-	6
APT Lab	pH	7.07	7.36	7.37	7.4	7.41		7.66
	ORP	399	366	363	361	357		282
	Alkalinity (mg/L)	360	340	340	340	360		280
	Turbidity (NTU)	2.43	2.38	2.24	2.12	7.97		0.35
	Temperature (deg F)	55.5	63	63	63	65		67.8
	UVT (cm-1)	91.9	92	91.9	91.6	91.7		94.9
	O3 Residual-DPD (mg/L)		0	0.1	0	0.1		0
	H2O2 Residual-Hach (mg/L)		7	11	18	23		5
	H2O2 Residual-Strips (mg/L)		>5	>10	<25	25		<10
	COD (mg/L)	6	13	15	0	13		13
Eurofins Calscience	1,1,1-Trichloroethane (ug/L)	41	26	26	26	26		
	Dichlorodifluoromethane (ug/L)	12	1.5	1.7	1.7	1.3		
	Vinyl Chloride (ug/L)	1.3	<0.5	<0.5	<0.5	<0.5		
	Acetone (ug/L)	4.3	9.7	9.2	16	11		
	1,4-Dioxane (ug/L)	8.4	3.5	1.7	0.45	<0.1	7.1	0.63
	TOC (mg/l)	4.7			4.4			
	Iron (ug/L)	0.14						
	Magnesium (ug/L)	13						
	Manganese (ug/L)	0.0103						
Eurofins Eaton	Bromide (mg/L)	0.36	0.36	0.34	0.36	0.36		0.36*
	Bromate (ug/L)	<1.0	<1.0	<1.0	<1.0	<1.0		20

Note:

* suspected error in analytical data (Report < 0.010 mg/L).



ATTACHMENT 3:
3rd PARTY ANALYTICAL REPORTS

APPENDIX G

Alternatives Cost Estimates

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Table G-1
Comparison of Alternative Costs

Task	Alternative 1 No Action	Alternative 2 Two HiPOx Systems North System 9 Years South System 17 Years	Alternative 3 In-Situ Groundwater Treatment with ISCO using Base-Activated Persulfate	Alternative 4 In-Situ Groundwater Treatment with ISCO using Catalyzed Hydrogen Peroxide	Alternative 5 Expanded Groundwater Capture with all Untreated Effluent Discharged to Navy POTW at Ault Field
Implementation Costs					
Capital Direct Costs (Construction)	\$423,000	\$3,460,000	\$37,280,000	\$33,630,000	\$3,450,000
<i>Unlisted Items and Services Assumed (%)</i>	25	25	25	25	25
Capital Indirect Costs (Engineering)	\$118,000	\$508,000	\$1,190,000	\$1,110,000	\$492,000
<i>Unlisted Engineering Services Assumed (%)</i>	15	15	15	15	15
Total Capital Implementation Costs	\$541,000	\$3,970,000	\$38,470,000	\$34,740,000	\$3,940,000
Operational Costs (30 years)					
Annual O&M Costs (North System)	\$305,000	\$222,000	\$158,000	\$158,000	\$358,000
Years of O&M Assumed (North System)	30	9	5	5	9
Annual O&M Costs (South System)	NA	\$139,000.00	NA	NA	\$194,000.00
Years of O&M Assumed (South System)	NA	17	NA	NA	17
Annual Monitoring Costs	\$289,000	\$301,000	\$308,000	\$308,000	\$300,000
Years of Monitoring Assumed	30	30	15	15	30
Non-Routine O&M and Closure Costs	\$1,026,000	\$1,215,000	\$1,049,000	\$1,151,000	\$934,000
<i>Unlisted Operational Tasks Assumed (%)</i>	20	20	20	20	20
Total Operational Costs	\$18,850,000	\$14,610,000	\$6,460,000	\$6,570,000	\$16,460,000
TOTALS					
Total Capital and Operational Costs	\$19,391,000	\$18,580,000	\$44,930,000	\$41,310,000	\$20,400,000
Present-Worth Implementation Costs	\$483,000	\$3,870,000	\$35,740,000	\$32,450,000	\$3,840,000
Present-Worth Operational Costs	\$12,260,000	\$10,290,000	\$5,210,000	\$5,290,000	\$11,810,000
Site Inspection and Overhead	\$77,000	\$310,000	\$715,000	\$649,000	\$307,000
Agency Oversight	\$19,300	\$77,400	\$178,700	\$162,300	\$76,800
Total Project Present Worth ^a	\$12,800,000	\$14,500,000	\$41,800,000	\$38,600,000	\$16,000,000

^a Present worth costs were calculated using a 3% discount rate.

Notes:

Discount Rate (3%) = Interest Rate (6%) - Inflation (3%)

NA - Not Applicable

O&M - Operation and Maintenance

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Table G-2
ALTERNATIVE 1
No Action, Continued O&M of Existing Pump-and-Treat System

Alternative	1	The primary element of this Alt is to replace the existing tower air stripper after 5 years
Specific	2	Existing tower air stripper will be maintained and operated for 5 years
Assumptions	3	Existing tower air stripper will be demolished and disposed of off site after 5 years
	4	New shallow tray air stripper will be installed after 5 years and operated for 25 years
	5	Existing 10 pumping wells will be operated for 30 years

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
CONTRACTOR COSTS (CAPITAL DIRECT)						
Remedial Action Construction						
General \$28,000	1	Mobilization	1	LS	\$20,000	\$20,000
	2	Contractor Work Plans	80	HR	\$100	\$8,000
	3	Not Used	0	EA	\$0	\$0
Demo Tower Stripper \$85,000	1	Remove Existing Tower Air Stripper (after 5 years)	1	LS	\$80,000	\$80,000
	2	Off-site Disposal Costs for debris	1	LS	\$5,000	\$5,000
	3	Not Used	0	EA	\$0	\$0
Install New Stripper \$144,800	1	Modify concrete pad for new air stripper	1	LS	\$7,500	\$7,500
	2	Modify piping for new air stripper	1	LS	\$10,000	\$10,000
	3	Electrical connection for new air stripper	1	LS	\$5,000	\$5,000
	4	New Air Stripper (EZ-Tray 24.4, 15hp, 1,300 cfm)	1	LS	\$80,000	\$80,000
	5	Transportation of new Air Stripper to Site	1	LS	\$5,000	\$5,000
	6	Crane to unload new Air Stripper at the Site	1	LS	\$3,000	\$3,000
	7	Installation and connection of new Air Stripper	1	LS	\$7,500	\$7,500
	8	Integrate control system of new Air Stripper into well field	1	LS	\$5,000	\$5,000
	9	Startup and Training of O&M personnel (3 people for 3 days)	72	HR	\$100	\$7,200
	10	Commissioning and Initial Analytical Testing	1	LS	\$5,000	\$5,000
	11	Update O&M Manual for new air stripper	80	HR	\$120	\$9,600
Subtotal Contractor Costs						\$257,800
Unlisted Items and Services (%)			25	%	\$257,800	\$64,450
Contractor Overhead and Profit (%)			20	%	\$322,250	\$64,450
Washington State Sales Tax			9.5	%	\$386,700	\$36,737
TOTAL CONTRACTOR COST						\$423,000
PRESENT-WORTH CONTRACTOR COST			5	Year Implemented		\$365,000

Table G-2 (Continued)
ALTERNATIVE 1
No Action, Continued O&M of Existing Pump-and-Treat System

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
ENGINEERING COSTS (CAPITAL INDIRECT)						
	1	General Coordination, Meetings, and Planning	1	LS	\$25,000	\$25,000
	2	Regulatory Review, Coordination, and Meetings	1	LS	\$5,000	\$5,000
	3	Engineering Design Plans and Specs	200	HR	\$135	\$27,000
	4	Engineers Estimate	30	HR	\$135	\$4,050
	5	Bid & RFI Support	10	HR	\$135	\$1,350
	6	Permitting	40	HR	\$135	\$5,400
	7	Compliance Monitoring Plan	80	HR	\$135	\$10,800
	8	Construction Oversight and QA (% DCC)	3	%	\$365,000	\$10,950
	9	Documentation & Reporting	120	HR	\$110	\$13,200
Subtotal Engineering Costs						\$102,750
Unlisted Engineering Services (%)			15	%	\$102,750	\$15,413
Total Engineering Costs						\$118,000

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
O&M, MONITORING, AND CLOSURE COSTS						
Annual O&M Cost		<i>Years of Annual O&M</i>	<i>30</i>			
\$253,848	1	Common Elements - Existing 10 Pumping Well O&M	10	EA	\$3,000	\$30,000
<u>With Unlisted Costs</u>	2	Common Elements - Power for Ext 10 Pumping Wells (4hp)	10	EA	\$2,837	\$28,370
\$305,000	3	O&M of Either Existing or New Treatment System	1	LS	\$50,000	\$50,000
	4	O&M of existing tower Air Stripper for 5 years	1	LS	\$50,000	\$50,000
	5	Cleaning of pumps and pipeline for iron fixing bacterial	12	MO	\$6,000	\$72,000
	6	Power for Existing or New Air Stripper Blower (20hp)	1	LS	\$14,932	\$14,932
	7	Power for effluent discharge pump (5hp)	1	LS	\$3,546	\$3,546
	8	Intitutional Controls Implementation and Inspection	1	LS	\$5,000	\$5,000
Annual LTM Cost		<i>Years of Annual LTM</i>	<i>30</i>			
\$241,000	1	Common Elements - Treatment System Monitoring	1	LS	\$100,000	\$100,000
<u>With Unlisted Costs</u>	2	Common Elements - GW Sampling 35 wells (semi-annual)	70	EA	\$500	\$35,000
\$289,000	3	Common Elements - Analytical Testing (70 samples + QC)	80	EA	\$250	\$20,000
	4	Common Elements - GW Monitoring (semi-annual gauging)	2	Events	\$3,000	\$6,000
	5	Common Elements - Annual Reporting	1	LS	\$80,000	\$80,000
	6	Not Used	0	EA	\$0	\$0
	7	Not Used	0	EA	\$0	\$0
Subtotal Maximum Combined Annual Costs						\$494,848
Non-Routine O&M and Closure Costs						
\$855,000	1	Common Elements - 5 Year Reviews (6 total for 30 years)	6	EA	\$100,000	\$600,000
<u>With Unlisted Costs</u>	2	Common Elements - Pumping Well Rehab (2 every 5 years)	6	Events	\$25,000	\$150,000
\$1,026,000	3	New Air Stripper Cleaning and Minor Repair (at Year 10)	1	LS	\$15,000	\$15,000
	4	New Air Stripper Cleaning or MAJOR Repair (at Year 15)	1	LS	\$30,000	\$30,000
	5	New Air Stripper Cleaning and Minor Repair (at Year 20)	1	LS	\$15,000	\$15,000
	6	New Air Stripper Cleaning or MAJOR Repair (at Year 25)	1	LS	\$30,000	\$30,000
	7	New Air Stripper Cleaning and Minor Repair (at Year 30)	1	LS	\$15,000	\$15,000
Subtotal O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$15,700,440
Unlisted Operations Tasks (%)			20	%	\$15,700,440	\$3,140,088
Total O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$18,840,000
Annualized Operational Cost		<i>Years until project completion</i>	<i>30</i>			
Present-Worth Operational Cost						\$12,260,000
			<i>Presumed Inflation Rate</i>	<i>0.03</i>		

Table G-2 (Continued)
ALTERNATIVE 1
No Action, Continued O&M of Existing Pump-and-Treat System

ALTERNATIVE COST SUMMARY				Individual Total	Cumulative Total
PRESENT-WORTH TOTAL CAPITAL COSTS (DIRECT & INDIRECT)				\$483,000	\$483,000
TOTAL O&M COSTS (PRESENT WORTH)				\$12,260,000	\$12,743,000
SITE INSPECTION AND OVERHEAD (OWNER)	Percentage of Capital Costs	16.0%		\$77,000	\$12,820,000
AGENCY OVERSIGHT (EPA)	Percentage of Capital Costs	4.0%		\$19,300	\$12,839,300
TOTAL PRESENT-WORTH COST					\$12,800,000

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**Table G-3
 ALTERNATIVE 2**

Continued P&T with new Ex-Situ Groundwater Treatment using Advanced Oxidation Process and Install Additional Extraction Wells

Alternative Specific Assumptions	1	The primary element of this Alt is replacing the existing air stripper with a new AOP HiPOx Treatment System
	2	Additional extraction wells will be installed to expand the capture zone along the southern and western perimeters
	3	The main AOP HiPOx Treatment System will be rated at 200 gpm and treat 10 existing extraction wells plus 4 new ones
	4	Pumping rate from 4 new western extraction wells is assumed to be 20 gpm each
	5	Pumping rate from the existing and new western extraction wells is assumed to be 200 gpm
	6	The new southern extraction wells will be treated by an independent AOP HiPOx Treatment System rated at 100 gpm
	7	Each HiPOx system will have its only hydrogen peroxide AST with a minimum monthly supply of 1 month
	8	Pumping rate from 5 new southern extraction wells is assumed to be 20 gpm each
	9	A new underground pipeline will be installed offsite to connect the 5 new southern extraction wells
	10	The southern pipeline is assumed is dual-wall 6-inch HDPE (SDR 17)/10-inch HDPE (SDR 26)
	11	A new underground pipeline will be installed onsite to connect the 4 new western extraction wells
	12	The western pipeline is assumed is single-wall 6-inch HDPE (SDR 17)
	13	Sufficient electrical power is available at the site to power the main HiPOx treatment system
	14	A new electrical service will be needed to power the southern HiPOx treatment system
	15	Leak monitoring will be performed visually at leak monitoring stations, spaced 500 feet along the dual-walled pipeline
	16	Contaminated soils will not be encountered during construction of the new pipelines
	17	The Northern HiPOx system will run for 9 years and the Southern HiPOx system will run for 17 years

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
CONTRACTOR COSTS (CAPITAL DIRECT)						
Remedial Action Construction						
General \$133,600	1	Mobilization	7.50	%	\$927,900	\$69,600
	2	Contractor Work Plans	300	HR	\$100	\$30,000
	3	Bench Scale Testing of HiPOx with 4 samples by APTwater	1	LS	\$11,000	\$11,000
	4	Analytical Testing for Bench Scale Testing	1	LS	\$8,000	\$8,000
	5	Surveying and Utility Locates	1	LS	\$15,000	\$15,000
Main HiPOx System \$516,500	1	Modify Existing Concrete SC Treatment Pad	1	LS	\$10,000	\$10,000
	2	New Effluent Centrifugal Transfer Pump	1	LS	\$5,000	\$5,000
	3	Electrical connection for HiPOx System	1	LS	\$7,500	\$7,500
	4	New 200 gpm HiPOx AOP Treatment System	1	LS	\$425,000	\$425,000
	5	Transportation of HiPOx System to Site	1	LS	\$5,000	\$5,000
	6	Crane to unload new HiPOx System at the Site	1	LS	\$3,000	\$3,000
	7	Installation and connection of new HiPOx System	1	LS	\$10,000	\$10,000
	8	Integrate control system of HiPOx System with well field	1	LS	\$5,000	\$5,000
	9	Initial batch of Hydrogen Peroxide Chemical (3 month supply)	300	Gal	\$6	\$1,800
	10	Startup and Training of O&M personnel (3 people for 1 week)	120	HR	\$100	\$12,000
	11	Training by Manufacture Rep (1 person for 1 week)	50	HR	\$155	\$7,800
	12	Commissioning and Initial Analytical Testing	1	LS	\$10,000	\$10,000
	13	Update O&M Manual with HiPOx System information	120	HR	\$120	\$14,400
Southern HiPOx System \$490,300	1	Silt Fence	1,000	LF	\$2	\$2,400
	2	Clearing for new Secondary Containment (SC) Treatment Pad	1	AC	\$1,975	\$2,000
	3	Construct new Concrete SC Treatment Pad	1	LS	\$20,000	\$20,000
	4	New Effluent Batch Tank and Centrifugal Transfer Pump	1	LS	\$15,000	\$15,000
	5	New electrical service and connection for HiPOx System	1	LS	\$15,000	\$15,000
	6	New 100 gpm HiPOx AOP Treatment System	1	LS	\$367,000	\$367,000
	7	Transportation of HiPOx System to Site	1	LS	\$5,000	\$5,000
	8	Crane to unload new HiPOx System at the Site	1	LS	\$3,000	\$3,000
	9	Installation and connection of new HiPOx System	1	LS	\$10,000	\$10,000
	10	Integrate control system of HiPOx System with well field	1	LS	\$5,000	\$5,000
	11	Initial batch of Hydrogen Peroxide Chemical (3 month supply)	150	Gal	\$6	\$900
	12	Startup and Training of O&M personnel (2 people for 1 week)	80	HR	\$100	\$8,000
	13	Training by Manufacture Rep (1 person for 1 week)	50	HR	\$155	\$7,800
	14	Commissioning and Initial Analytical Testing	1	LS	\$10,000	\$10,000
	15	Write new O&M Manual for Southern HiPOx System	160	HR	\$120	\$19,200
Air Stripper Demo \$85,000	1	Remove Existing Tower Air Stripper	1	LS	\$80,000	\$80,000
	2	Off-site Disposal Costs for debris	1	LS	\$5,000	\$5,000
	3	Not Used	0	EA	\$0	\$0
New Western Pumps \$236,800	1	Install 4 new pumping wells to 120 ft Deep - 6-inch dia.	4	EA	\$13,000	\$52,000
	2	Logging of New Well Install by Geologist (1 well in 2 days)	8	DY	\$1,200	\$9,600
	3	Analytical Soil Samples (2 samples per well + QC)	9	EA	\$300	\$2,700
	4	Pumping Well Development and Water Disposal in System	4	EA	\$2,500	\$10,000
	5	Install 4 new pumps, vaults, and associated equipment	4	EA	\$10,000	\$40,000
	6	Install 6-inch pipeline - Single Wall on Navy Property	2,500	FT	\$49	\$122,500
New Southern Pumps \$643,300	1	Install 5 new pumping wells to 150 ft Deep - 6-inch dia.	5	EA	\$15,000	\$75,000
	2	Logging of New Well Install by Geologist (1 well in 2 days)	10	DY	\$1,200	\$12,000
	3	Analytical Soil Samples (2 samples per well + QC)	11	EA	\$300	\$3,300
	4	Pumping Well Development and Water Disposal in System	5	EA	\$2,500	\$12,500
	5	Install 5 new pumps, vaults, and associated equipment	5	EA	\$11,000	\$55,000
	6	Install 6-inch pipeline - Single Wall on Navy Property	4,500	FT	\$49	\$220,500
	7	Install 5hp booster pump station on Navy Property	1	LS	\$15,000	\$15,000
	8	City of Oak Harbor Franchise Agreement	1	LS	\$5,000	\$5,000
	9	Install 6-inch pipeline - Double Wall off Navy Property	2,500	FT	\$98	\$245,000
Subtotal Contractor Costs						\$2,105,500
Unlisted Items and Services (%)			25	%	\$2,105,500	\$526,375
Contractor Overhead and Profit (%)			20	%	\$2,631,875	\$526,375
Washington State Sales Tax			9.5	%	\$3,158,250	\$300,034
TOTAL CONTRACTOR COST						\$3,460,000
PRESENT-WORTH CONTRACTOR COST			1	Year Implemented	\$3,360,000	

Continued P&T with new Ex-Situ Groundwater Treatment using Advanced Oxidation Process and Install Additional Extraction Wells

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
O&M, MONITORING, AND CLOSURE COSTS						
Annual O&M Cost (North System)		<i>Years of Annual O&M</i>	<i>9</i>			
\$184,704	1	Common Elements - Existing 10 Pumping Well O&M	10	EA	\$3,000	\$30,000
<u>With Unlisted Costs</u>	2	Common Elements - Power for Ext 10 Pumping Wells (4hp)	10	EA	\$2,837	\$28,370
\$222,000	3	Routine Inspections for 2 HiPOx System (12 hours per week)	416	LS	\$100	\$41,600
	4	O&M for 2 HiPOx System (2 people 12 hours per month)	288	HR	\$100	\$28,800
	5	Power for 2 HiPOx System	1	LS	\$10,000	\$10,000
	6	Hydrogen Peroxide for 2 Systems (150 gal/month)	1,200	GAL	\$5.00	\$6,000
	7	Misc Supplies & Spare Parts for HiPOx Systems (3% of new)	1	LS	\$12,750	\$12,750
	8	New Pumping Well O&M (9 wells)	4	EA	\$2,500	\$10,000
	9	Power for pumping to North System (10hp)	0	LS	\$7,466	\$0
	10	Power for 9 new Pumping Wells (5hp each)	4	EA	\$3,546	\$14,184
	11	Power for Booster Pump for new Pumping Wells (5hp)	0	EA	\$3,546	\$0
	12	Intititutional Controls Implementation and Inspection	1	LS	\$3,000	\$3,000
Annual O&M Cost (South System)		<i>Years of Annual O&M</i>	<i>17</i>			
\$116,152	1	Common Elements - Existing 10 Pumping Well O&M	0	EA	\$3,000	\$0
<u>With Unlisted Costs</u>	2	Common Elements - Power for Ext 10 Pumping Wells (4hp)	0	EA	\$2,837	\$0
\$139,000	3	Routine Inspections for 5 HiPOx System (6 hours per week)	312	LS	\$100	\$31,200
	4	O&M for 2 HiPOx System (2 people 8 hours per month)	192	HR	\$100	\$19,200
	5	Power for South HiPOx System	1	LS	\$7,500	\$7,500
	6	Hydrogen Peroxide for South System (50 gal/month)	600	GAL	\$5.00	\$3,000
	7	Misc Supplies & Spare Parts for HiPOx Systems (3% of new)	1	LS	\$11,010	\$11,010
	8	New Pumping Well O&M (5 wells)	5	EA	\$2,500	\$12,500
	9	Power for pumping to North System (10hp)	1	LS	\$7,466	\$7,466
	10	Power for 5 new Pumping Wells (5hp each)	5	EA	\$3,546	\$17,730
	11	Power for Booster Pump for new Pumping Wells (5hp)	1	EA	\$3,546	\$3,546
	12	Intititutional Controls Implementation and Inspection (1/2)	1	LS	\$3,000	\$3,000
Annual LTM Cost		<i>Years of Annual LTM</i>	<i>30</i>			
\$251,000	1	Common Elements - Treatment System Monitoring	1	LS	\$80,000	\$80,000
<u>With Unlisted Costs</u>	2	Common Elements - GW Sampling 35 wells (semi-annual)	70	EA	\$500	\$35,000
\$301,000	3	Common Elements - Analytical Testing (70 samples + QC)	80	EA	\$250	\$20,000
	4	Common Elements - GW Monitoring (semi-annual gauging)	2	Events	\$3,000	\$6,000
	5	Common Elements - Annual Reporting	1	LS	\$80,000	\$80,000
	6	Treatment System Monitoring of 2nd HiPOx System	1	LS	\$20,000	\$20,000
	7	Visual Monitoring of Double Walled Pipeline for Leaks	4	Events	\$1,000	\$4,000
	8	HiPOx Specific Equipment Inspection	4	Events	\$1,500	\$6,000
Subtotal Maximum Combined Annual Costs						\$551,856
Non-Routine O&M and Closure Costs						
\$1,012,650	1	Common Elements - 5 Year Reviews (6 total for 30 years)	6	EA	\$100,000	\$600,000
<u>With Unlisted Costs</u>	2	Common Elements - Pumping Well Rehab (2 every 5 years)	3	Events	\$18,750	\$56,250
\$1,215,000	3	HiPOx System Repair Minor (at Year 5) - 5% of new	1	EA	\$39,600	\$39,600
	4	HiPOx System Repair Major (at Year 10) - 15% of new	1	EA	\$118,800	\$118,800
	5	HiPOx System Repair Minor (at Year 15) - 25% of new	1	EA	\$198,000	\$198,000
	6	HiPOx System Repair Major (at Year 20) - 5% of new	0	EA	\$39,600	\$0
	7	HiPOx System Repair Minor (at Year 25) - 15% of new	0	EA	\$118,800	\$0
	8	HiPOx System Repair Major (at Year 30) - 25% of new	0	EA	\$198,000	\$0
Subtotal O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$12,179,570
Unlisted Operationals Tasks (%)			20	%	\$12,179,570	\$2,435,914
Total O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$14,620,000
Annualized Operational Cost		<i>Years until project completion</i>	<i>30</i>			
						\$487,333.33
Present-Worth Operational Cost		<i>Presumed Inflation Rate</i>	<i>0.03</i>			
						\$10,290,000

Table G-3 (Continued)
ALTERNATIVE 2

Continued P&T with new Ex-Situ Groundwater Treatment using Advanced Oxidation Process and Install Additional Extraction Wells

ALTERNATIVE COST SUMMARY				Rounded Total	Cumulative Total
PRESENT-WORTH TOTAL CAPITAL COSTS (DIRECT & INDIRECT)				\$3,870,000	\$3,870,000
TOTAL O&M COSTS (PRESENT WORTH)				\$10,290,000	\$14,160,000
SITE INSPECTION AND OVERHEAD (OWNER)	Percentage of Capital Costs	8.0%		\$310,000	\$14,470,000
AGENCY OVERSIGHT (EPA)	Percentage of Capital Costs	2.0%		\$77,400	\$14,547,400
TOTAL PRESENT-WORTH COST					\$14,500,000

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Table G-4
ALTERNATIVE 3
In-Situ Groundwater Treatment using ISCO (Base-Activated Persulfate)

Alternative	1	The alternative consists of injecting base-activated persulfate on a ongoing basis for up to 7 years
Specific	2	245 reusable injection wells will be installed for continuous CHP injection over a 7 year period
Assumptions	3	135 new 2-inch PVC injection wells will be installed with 10 feet of screen to a depth of 120 feet along western perimeter
	4	110 new 2-inch PVC injection wells will be installed with 10 feet of screen to a depth of 150 feet along southern perimeter
	5	Each new well will have 2 soil samples and 1 baseline groundwater sample collected for analytical testing
	6	80% of soil cuttings generated during drilling are assumed to be clean and will be spread out on the surface of the site
	7	For the initial 4 year period 1 crew of 2 people each will inject 50 weeks per year during 4 day 10 hour work week
	8	For years 5 and 6, 1 crew of 2 people will inject 25 weeks per year during 4 day 10 hour work week
	9	During year 7, the final injection year, 1 crew of 2 people will inject CHP 12.5 weeks over the year
	10	One full time person will supervise injection activities and support activities from the site
	11	The injection crew can complete 8 wells per day and use 500 lbs of Kloszur oxidant and 1,500 lbs NaOH per well
	12	The Oxidizer (FMC Kloszur-Sodium Persulfate) will be shipped to the site dry in 55 lb bags or super sacks and mixed on site
	13	The base (sodium hydroxide) catalyst will be shipped to the site dry and used in a 3:1 ratio with Kloszur

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
CONTRACTOR COSTS (CAPITAL DIRECT)						
Remedial Action Construction						
General \$114,600	1	Mobilization	7.50	%	\$927,900	\$69,600
	2	Contractor Work Plans	300	HR	\$100	\$30,000
	3	Surveying and Utility Locates	1	LS	\$15,000	\$15,000
Injection System Install \$3,177,700	1	Install reusable injections wells along Southern Boundary (150ft)	110	EA	\$8,900	\$979,000
	2	Install reusable injections wells along Western Boundary (120ft)	135	EA	\$7,400	\$999,000
	3	Install new GW Monitoring wells (average 130ft)	8	EA	\$7,900	\$63,200
	4	Analytical Soil Samples during drilling (2 samples per well + QC)	557	EA	\$300	\$167,000
	5	Logging of New Well Install by Geologist (1 well per day)	245	DY	\$1,200	\$294,000
	6	New Well Development and Water Disposal in System	253	EA	\$850	\$215,100
	7	Baseline GW Analytical Testing of new Wells (338 wells + QC)	278	EA	\$250	\$69,600
	8	Drill Cutting Disposal (80% spread out on-site)	896	TN	\$10	\$9,000
	9	Drill Cutting Disposal (20% spread out on-site)	246	TN	\$60	\$14,800
	10	ISCO equipment Mob/Demob	2	EA	\$13,500	\$27,000
	11	ISCO mixing tanks and injection equipment	1	LS	\$100,000	\$100,000
	12	Dry Storage for base (Caustic Soda-Sodium Hydroxide)	1	LS	\$25,000	\$25,000
	13	Dry Storage for Persulfate	1	LS	\$25,000	\$25,000
	14	Water Storage Tanks	1	LS	\$10,000	\$10,000
	15	Mixing tanks to create liquid solutions from dry chemicals	1	LS	\$15,000	\$15,000
	16	Portable SC Pads for mixing operations	2	EA	\$7,500	\$15,000
	17	Tanker Truck for on-site chemical transfer	1	EA	\$150,000	\$150,000
Injection (Year 1) \$3,696,200 # of events per year 6.5 Cost Per Injection Event \$565,981	1	Injection Work Project Manager and Field Supervisor (Labor)	2,000	HR	\$100	\$200,000
	2	Labor for ongoing injection (1 crew, 2 people, 40 hrs per week)	50	WK	\$6,400	\$320,000
	3	Sodium Hydroxide Consumption (12,000 lbs per day @ \$0.50)	200	DY	\$8,160	\$1,632,000
	4	Persulfate Consumption (4,000 lbs per day @ \$1.65)	200	DY	\$6,600	\$1,320,000
	5	Water Consumption (6,000 gal per day @ \$0.01)	200	DY	\$60	\$12,000
	6	Chemical Shipments	200	DY	\$625	\$125,000
	7	Equipment useage and maintenance	1	LS	\$30,000	\$30,000
	8	Crew changeout Mob/Demob (monthly)	12	EA	\$600	\$7,200
	9	Injection Work Reporting	1	LS	\$50,000	\$50,000
Injection (Year 2-7) \$15,708,900	1	Year 2 Injection Work (100% of Year 1)	100	%	\$3,696,200	\$3,696,200
	2	Year 3 Injection Work (100% of Year 1)	100	%	\$3,696,200	\$3,696,200
	3	Year 4 Injection Work (100% of Year 1)	100	%	\$3,696,200	\$3,696,200
	4	Year 5 Injection Work (50% of Year 1)	50	%	\$3,696,200	\$1,848,100
	5	Year 6 Injection Work (50% of Year 1)	50	%	\$3,696,200	\$1,848,100
	6	Year 7 Injection Work (25% of Year 1)	25	%	\$3,696,200	\$924,100
Subtotal Contractor Costs						\$22,697,400
Unlisted Items and Services (%)			25	%	\$22,697,400	\$5,674,350
Contractor Overhead and Profit (%)			20	%	\$28,371,750	\$5,674,350
Washington State Sales Tax			9.5	%	\$34,046,100	\$3,234,380
TOTAL CONTRACTOR COST						\$37,280,000
PRESENT-WORTH CONTRACTOR COST			1	Year Implemented		\$34,550,000

Table G-4 (Continued)
ALTERNATIVE 3
In-Situ Groundwater Treatment using ISCO (Base-Activated Persulfate)

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
ENGINEERING COSTS (CAPITAL INDIRECT)						
	1	General Coordination, Meetings, and Planning	1	LS	\$80,000	\$80,000
	2	Regulatory Review, Coordination, and Meetings	1	LS	\$25,000	\$25,000
	3	Engineering Design Plans and Specs (% DCC)	1,000	HR	\$135	\$135,000
	4	Engineers Estimate	100	HR	\$135	\$13,500
	5	Bid & RFI Support	40	HR	\$135	\$5,400
	6	Permitting	120	HR	\$135	\$16,200
	7	Compliance Monitoring Plan	160	HR	\$135	\$21,600
	8	Construction Oversight and QA (% DCC)	2	%	\$34,550,000	\$691,000
	9	Closure Documentation & Reporting	400	HR	\$110	\$44,000
Subtotal Engineering Costs						\$1,031,700
Unlisted Engineering Services (%)			15	%	\$1,031,700	\$154,755
Total Engineering Costs						\$1,190,000

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
O&M, MONITORING, AND CLOSURE COSTS						
Annual O&M Cost		<i>Years of Annual O&M</i>	5			
\$131,848	1	Common Elements - Existing 10 Pumping Well O&M	10	EA	\$3,000	\$30,000
<u>With Unlisted Costs</u>	2	Common Elements - Power for Ext 10 Pumping Wells (4hp)	10	EA	\$2,837	\$28,370
\$158,000	3	O&M of Either Existing or New Treatment System	1	LS	\$50,000	\$50,000
	4	Power for Existing or New Air Stripper Blower (20hp)	1	LS	\$14,932	\$14,932
	5	Power for effluent discharge pump (5hp each)	1	LS	\$3,546	\$3,546
	6	Institutional Controls Implementation and Inspection	1	LS	\$5,000	\$5,000
	7	Not Used	0	EA	\$0	\$0
	8	Not Used	0	EA	\$0	\$0
	9	Not Used	0	EA	\$0	\$0
	10	Not Used	0	LS	\$0	\$0
	11	Not Used	0	EA	\$0	\$0
Annual LTM Cost		<i>Years of Annual LTM</i>	15			
\$257,000	1	Common Elements - Treatment System Monitoring	1	LS	\$100,000	\$100,000
<u>With Unlisted Costs</u>	2	Common Elements - GW Sampling 35 wells (semi-annual)	70	EA	\$500	\$35,000
\$308,000	3	Common Elements - Analytical Testing (70 samples + QC)	80	EA	\$250	\$20,000
	4	Common Elements - GW Monitoring (semi-annual gauging)	2	Events	\$3,000	\$6,000
	5	Common Elements - Annual Reporting	1	LS	\$80,000	\$80,000
	6	GW Monitoring and Analytical Testing of 8 New MWs	16	EA	\$1,000	\$16,000
	7	Not Used	0	EA	\$0	\$0
	8	Not Used	0	EA	\$0	\$0
Subtotal Maximum Combined Annual Costs						\$388,848
Non-Routine O&M and Closure Costs						
\$874,500	1	Common Elements - 5 Year Reviews (3 total for 15 years)	3	EA	\$100,000	\$300,000
<u>With Unlisted Costs</u>	2	Common Elements - Pumping Well Rehab (2 every 5 years)	2	Events	\$25,000	\$50,000
\$1,049,000	3	Additional Inj Well Install w/ Logging & Develop (at Year 5)	10	EA	\$10,950	\$109,500
	4	Abandon all Injection Wells (at Year 9)	245	EA	\$1,000	\$245,000
	5	Demo P&T System (at Year 10)	1	EA	\$120,000	\$120,000
	6	Abandon all Pumping Wells (at Year 10)	10	EA	\$5,000	\$50,000
	7		0	EA	\$0	\$0
	8		0	EA	\$0	\$0
Subtotal O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$5,388,740
Unlisted Operationals Tasks (%)			20	%	\$5,388,740	\$1,077,748
Total O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$6,470,000
Annualized Operational Cost		<i>Years until project completion</i>	15			\$431,333
Present-Worth Operational Cost		<i>Presumed Inflation Rate</i>	0.03			\$5,210,000

Table G-4 (Continued)
ALTERNATIVE 3
In-Situ Groundwater Treatment using ISCO (Base-Activated Persulfate)

ALTERNATIVE COST SUMMARY				Rounded Total	Cumulative Total
PRESENT-WORTH TOTAL CAPITAL COSTS (DIRECT & INDIRECT)				\$35,740,000	\$35,740,000
TOTAL O&M COSTS (PRESENT WORTH)				\$5,210,000	\$40,950,000
SITE INSPECTION AND OVERHEAD (OWNER)	Percentage of Capital Costs	2.0%		\$715,000	\$41,665,000
AGENCY OVERSIGHT (EPA)	Percentage of Capital Costs	0.5%		\$178,700	\$41,843,700
TOTAL PRESENT-WORTH COST					\$41,800,000

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Table G-5
ALTERNATIVE 4
In-Situ Groundwater Treatment using ISCO (Catalyzed Hydrogen Peroxide)

Alternative Specific Assumptions	1	The alternative consists of injecting CHP on a ongoing basis for up to 7 years
	2	330 reusable injection wells will be installed for continuous CHP injection over a 7 year period
	3	180 new 2-inch PVC injection wells will be installed with 10 feet of screen to a depth of 120 feet along western perimeter
	4	150 new 2-inch PVC injection wells will be installed with 10 feet of screen to a depth of 150 feet along southern perimeter
	5	Each new well will have 2 soil samples and 1 baseline groundwater sample collected for analytical testing
	6	80% of soil cuttings generated during drilling are assumed to be clean and will be spread out on the surface of the site
	7	For the initial 4 year period 1 crew of 2 people each will inject CHP 50 weeks per year during 4 day 10 hour work week
	8	For years 5 and 6, 1 crew of 2 people will inject CHP 25 weeks per year during 4 day 10 hour work week
	9	During Year 7, the final injection year, 1 crew of 2 people will inject CHP 12.5 weeks over the year
	10	One full time person will supervise injection activities and support activities from the site
	11	The injection crew can complete 12 wells per day and inject a total of 1,000 gallons of solution into each well
	12	The oxidizer (hydrogen peroxide) will be shipped to the site as a liquid at 30% concentration and diluted and stabilized on site
	13	Chelated-Iron Catalyst (ferrous sulfate and proprietary chelating agents) will be shipped to the site dry and mixed with water on site
	14	The catalyst and oxidizer will be used in a 1:1 ratio
	15	The existing P&T System will operate for 5 years and then be decommissioned

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
CONTRACTOR COSTS (CAPITAL DIRECT)						
Remedial Action Construction						
General \$114,600	1	Mobilization	7.50	%	\$927,900	\$69,600
	2	Contractor Work Plans	300	HR	\$100	\$30,000
	3	Surveying and Utility Locates	1	LS	\$15,000	\$15,000
Injection System Install \$4,108,400	1	Install reusable injections wells along Southern Boundary (150ft)	150	EA	\$8,900	\$1,335,000
	2	Install reusable injections wells along Western Boundary (120ft)	180	EA	\$7,400	\$1,332,000
	3	Install new GW Monitoring wells (average 130ft)	8	EA	\$7,900	\$63,200
	4	Analytical Soil Samples during drilling (2 samples per well + QC)	744	EA	\$300	\$223,100
	5	Logging of New Well Install by Geologist (1 well per day)	330	DY	\$1,200	\$396,000
	6	New Well Development and Water Disposal in System	338	EA	\$850	\$287,300
	7	Baseline GW Analytical Testing of new Wells (338 wells + QC)	372	EA	\$250	\$93,000
	8	Drill Cutting Disposal (80% spread out on-site)	1,197	TN	\$10	\$12,000
	9	Drill Cutting Disposal (20% spread out on-site)	329	TN	\$60	\$19,800
	10	ISCO equipment Mob/Demob	2	EA	\$13,500	\$27,000
	11	ISCO mixing tanks and injection equipment	1	LS	\$100,000	\$100,000
	12	Storage Tanks for proprietary iron chelate complex (20,000 gallon)	1	LS	\$25,000	\$25,000
	13	Storage Tanks for hydrogen peroxide (20,000 gallon)	1	LS	\$25,000	\$25,000
	14	Water Storage Tanks	1	LS	\$5,000	\$5,000
	15	Portable SC Pads for mixing operations	2	EA	\$7,500	\$15,000
	16	Tanker Truck for on-site chemical transfer	1	EA	\$150,000	\$150,000
CHP Injection (Year 1) \$3,096,000 # of events per year 7.3 Cost Per Injection Event \$425,700	1	Injection Work Project Manager and Field Supervisor (Labor)	2,000	HR	\$100	\$200,000
	2	Labor for ongoing injection (1 crew, 2 people, 40 hrs per week)	50	WK	\$8,000	\$400,000
	3	Proprietary iron chelate complex (5,000 gal per day @\$1.80)	200	DY	\$9,000	\$1,800,000
	4	12.5 percent Hydrogen Peroxide (5,000 gal per day @\$0.40)	200	DY	\$2,000	\$400,000
	5	Water Consumption (2,000 gal per day @ \$0.01)	200	DY	\$20	\$4,000
	6	Chemical Shipments	200	DY	\$1,000	\$200,000
	7	Equipment useage and maintenance	1	LS	\$30,000	\$30,000
	8	Crew Changeout Mob/Demob (monthly)	12	EA	\$1,000	\$12,000
	9	Injection Work Reporting	1	LS	\$50,000	\$50,000
Injection (Year 2-7) \$13,158,000	1	Year 2 Injection Work (100% of Year 1)	100	%	\$3,096,000	\$3,096,000
	2	Year 3 Injection Work (100% of Year 1)	100	%	\$3,096,000	\$3,096,000
	3	Year 4 Injection Work (100% of Year 1)	100	%	\$3,096,000	\$3,096,000
	4	Year 5 Injection Work (50% of Year 1)	50	%	\$3,096,000	\$1,548,000
	5	Year 6 Injection Work (50% of Year 1)	50	%	\$3,096,000	\$1,548,000
	6	Year 7 Injection Work (25% of Year 1)	25	%	\$3,096,000	\$774,000
Subtotal Contractor Costs						\$20,477,000
Unlisted Items and Services (%)			25	%	\$20,477,000	\$5,119,250
Contractor Overhead and Profit (%)			20	%	\$25,596,250	\$5,119,250
Washington State Sales Tax			9.5	%	\$30,715,500	\$2,917,973
TOTAL CONTRACTOR COST						\$33,630,000
PRESENT-WORTH CONTRACTOR COST			1	Year Implemented	\$31,340,000	

Table G-5 (Continued)
ALTERNATIVE 4
In-Situ Groundwater Treatment using ISCO (Catalyzed Hydrogen Peroxide)

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
ENGINEERING COSTS (CAPITAL INDIRECT)						
	1	General Coordination, Meetings, and Planning	1	LS	\$80,000	\$80,000
	2	Regulatory Review, Coordination, and Meetings	1	LS	\$25,000	\$25,000
	3	Engineering Design Plans and Specs (% DCC)	1,000	HR	\$135	\$135,000
	4	Engineers Estimate	100	HR	\$135	\$13,500
	5	Bid & RFI Support	40	HR	\$135	\$5,400
	6	Permitting	120	HR	\$135	\$16,200
	7	Compliance Monitoring Plan	160	HR	\$135	\$21,600
	8	Construction Oversight and QA (% DCC)	2	%	\$31,340,000	\$626,800
	9	Closure Documentation & Reporting	400	HR	\$110	\$44,000
Subtotal Engineering Costs						\$967,500
Unlisted Engineering Services (%)			15	%	\$967,500	\$145,125
Total Engineering Costs						\$1,110,000

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
O&M, MONITORING, AND CLOSURE COSTS						
Annual O&M Cost		<i>Years of Annual O&M</i>	5			
\$131,848	1	Common Elements - Existing 10 Pumping Well O&M	10	EA	\$3,000	\$30,000
<u>With Unlisted Costs</u>	2	Common Elements - Power for Ext 10 Pumping Wells (4hp)	10	EA	\$2,837	\$28,370
\$158,000	3	O&M of Either Existing or New Treatment System	1	LS	\$50,000	\$50,000
	4	Power for Existing or New Air Stripper Blower (20hp)	1	LS	\$14,932	\$14,932
	5	Power for effluent discharge pump (5hp each)	1	LS	\$3,546	\$3,546
	6	Institutional Controls Implementation and Inspection	1	LS	\$5,000	\$5,000
	7	Not Used	0	EA	\$0	\$0
	8	Not Used	0	EA	\$0	\$0
	9	Not Used	0	EA	\$0	\$0
	10	Not Used	0	EA	\$0	\$0
	11	Not Used	0	EA	\$0	\$0
Annual LTM Cost		<i>Years of Annual LTM</i>	15			
\$257,000	1	Common Elements - Treatment System Monitoring	1	LS	\$100,000	\$100,000
<u>With Unlisted Costs</u>	2	Common Elements - GW Sampling 35 wells (semi-annual)	70	EA	\$500	\$35,000
\$308,000	3	Common Elements - Analytical Testing (70 samples + QC)	80	EA	\$250	\$20,000
	4	Common Elements - GW Monitoring (semi-annual gauging)	2	Events	\$3,000	\$6,000
	5	Common Elements - Annual Reporting	1	LS	\$80,000	\$80,000
	6	GW Monitoring and Analytical Testing of 8 New MWs	16	EA	\$1,000	\$16,000
	7	Not Used	0	EA	\$0	\$0
	8	Not Used	0	EA	\$0	\$0
Subtotal Maximum Combined Annual Costs						\$388,848
Non-Routine O&M and Closure Costs						
\$959,500	1	Common Elements - 5 Year Reviews (3 total for 15 years)	3	EA	\$100,000	\$300,000
<u>With Unlisted Costs</u>	2	Common Elements - Pumping Well Rehab (2 every 5 years)	2	Events	\$25,000	\$50,000
\$1,151,000	3	Additional Inj Well Install w/ Logging & Develop (at Year 5)	10	EA	\$10,950	\$109,500
	4	Abandon all Injection Wells (at Year 9)	330	EA	\$1,000	\$330,000
	5	Demo P&T System (at Year 10)	1	EA	\$120,000	\$120,000
	6	Abandon all Pumping Wells (at Year 10)	10	EA	\$5,000	\$50,000
	7		0	EA	\$0	\$0
	8		0	EA	\$0	\$0
Subtotal O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$5,473,740
Unlisted Operationals Tasks (%)			20	%	\$5,473,740	\$1,094,748
Total O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$6,570,000
Annualized Operational Cost		<i>Years until project completion</i>	15			
Present-Worth Operational Cost						\$5,290,000
			<i>Presumed Inflation Rate</i>	0.03		

Table G-5 (Continued)
ALTERNATIVE 4
In-Situ Groundwater Treatment using ISCO (Catalyzed Hydrogen Peroxide)

ALTERNATIVE COST SUMMARY			Rounded Total	Cumulative Total
PRESENT-WORTH TOTAL CAPITAL COSTS (DIRECT & INDIRECT)			\$32,450,000	\$32,450,000
TOTAL O&M COSTS (PRESENT WORTH)			\$5,290,000	\$37,740,000
SITE INSPECTION AND OVERHEAD (OWNER)	Percentage of Capital Costs	2.0%	\$649,000	\$38,389,000
AGENCY OVERSIGHT (EPA)	Percentage of Capital Costs	0.5%	\$162,300	\$38,551,300
TOTAL PRESENT-WORTH COST				\$38,600,000

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Table G-6
ALTERNATIVE 5
Expanded Groundwater Capture with All Untreated Effluent Discharged to Navy POTW at Ault Field

Alternative Specific Assumptions	1	The primary element of this Alt is a new 8-IN forcemain 9,000 LF to route untreated water to the existing Sanitary Sewer Line
	2	This Alt also includes new infrastructure to expand GW capture including new pumping wells and pipelines as in Alt 2
	3	Treatment plant to connection point along N Charles Porter Ave (between Torpedo Rd and Prowler St)
	4	Pumping rate is 400 gpm. Pressure in pipe is estimated to be 22 psi (40.6 feet of head loss).
	5	Pumping will start at/from the existing tank at the treatment plant.
	6	Pipe assumed is dual-wall 8-inch HDPE (SDR 17)/12-inch HDPE (SDR 26)
	7	Trench dimensions: (ID+30")W x (36"+OD+6")H x (length of alignment)L and no shoring will be needed to perform the work
	8	Alignment is assumed to be off the paved shoulders, except at road crossings.
	9	Open cut is assumed along the entire alignment (no trenchless technology assumed).
	10	Location of connection point to existing sanitary sewer system is approximated at this time.
	11	Asphalt concrete pavement patch assumed to be 4-inches thick.
	12	Required electrical power is available at existing treatment plant.
	13	Pipe elevation from upgradient end to downgradient end is assumed equal (i.e., no static head).
	14	Leak monitoring will be performed visually at leak monitoring stations, spaced 500 feet along the pipe alignment.
	15	Contaminated soils will not be encountered during construction of the new forcemain pipeline
	16	MicroC will be injected at the WWTP as a biodegradable carbon source (electron donor) for nitrogen removal
	17	An aboveground storage tank, feed pumps, and control system will be used to inject MicroC at 250 gallons per day

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
CONTRACTOR COSTS (CAPITAL DIRECT)						
Remedial Action Construction						
General \$108,600	1	Mobilization	7.50	%	\$927,900	\$69,600
	2	Contractor Work Plans	240	HR	\$100	\$24,000
	3	Surveying and Utility Locates	1	LS	\$15,000	\$15,000
Ault Field Pipeline \$927,900	1	Silt Fence	9,000	LF	\$2	\$21,400
	2	Safety and Traffic Control Management	1	LS	\$24,400	\$24,400
	3	Clearing	5	AC	\$1,975	\$9,000
	4	Trench Excavation	5,290	CY	\$7	\$35,500
	5	Gravel Backfill for Pipe Zone Bedding	2,100	CY	\$15	\$31,200
	6	Trench Backfill (Native Fill)	2,900	CY	\$12	\$34,100
	7	Export Fill	2,390	CY	\$7	\$17,800
	8	8-inch HDPE Pipe(SDR 17)/12-inch HDPE Pipe (SDR 26)	9,000	FT	\$48	\$427,500
	9	Cleanout	8	EA	\$1,200	\$9,600
	10	Leak Detection Monitoring Station	18	EA	\$8,600	\$154,800
	11	HMA Patch	1	LS	\$17,700	\$17,700
	12	Pavement Striping	1	LS	\$1,000	\$1,000
	13	8-inch Centrifugal Pumps	1	LS	\$18,600	\$18,600
	14	Floats	1	LS	\$2,100	\$2,100
	15	Control Panel	1	LS	\$15,000	\$15,000
	16	Inline flow meter	1	EA	\$8,600	\$8,600
	17	Air Release Valve	2	EA	\$2,325	\$4,700
	18	8-inch Gate Valve	4	EA	\$10,450	\$41,800
	19	8-inch Check Valve	1	EA	\$10,075	\$10,100
	20	Electrical Service	1	LS	\$5,000	\$5,000
	21	48-inch Concrete Manhole	1	EA	\$3,700	\$3,700
	22	Pressure Testing	1	LS	\$34,250	\$34,300
Carbon Source Injection \$75,000	1	MicroC 6,000 gal Insulated Bulk Storage Tank and SC Pad	1	LS	\$35,000	\$35,000
	2	MicroC 500 gal Day Tank, Pumps, Controls, and Storage Shed	1	LS	\$25,000	\$25,000
	3	Installation of Carbon Injection system into existing WWTP	1	LS	\$15,000	\$15,000
Demo \$105,000	1	Remove Existing Tower Air Stripper	1	LS	\$80,000	\$80,000
	2	Grout and Cap existing Effluent pipe	1	LS	\$20,000	\$20,000
	3	Off-site Disposal Costs for debris	1	LS	\$5,000	\$5,000
New Western Pumps \$239,500	1	Install 4 new pumping wells to 120 ft Deep - 6-inch dia.	4	EA	\$13,000	\$52,000
	2	Logging of New Well Install by Geologist (1 well in 2 days)	8	DY	\$1,200	\$9,600
	3	Analytical Soil Samples (2 samples per well + QC)	18	EA	\$300	\$5,400
	4	Pumping Well Development and Water Disposal in System	4	EA	\$2,500	\$10,000
	5	Install 4 new pumps, vaults, and associated equipment	4	EA	\$10,000	\$40,000
	6	Install 6-inch pipeline - Single Wall on Navy Property	2,500	FT	\$49	\$122,500
New Southern Pumps \$646,600	1	Install 5 new pumping wells to 150 ft Deep - 6-inch dia.	5	EA	\$15,000	\$75,000
	2	Logging of New Well Install by Geologist (1 well in 2 days)	10	DY	\$1,200	\$12,000
	3	Analytical Soil Samples (2 samples per well + QC)	22	EA	\$300	\$6,600
	4	Pumping Well Development and Water Disposal in System	5	EA	\$2,500	\$12,500
	5	Install 5 new pumps, vaults, and associated equipment	5	EA	\$11,000	\$55,000
	6	Install 6-inch pipeline - Single Wall on Navy Property	4,500	FT	\$49	\$220,500
	7	Install 5hp booster pump station on Navy Property	1	LS	\$15,000	\$15,000
	8	City of Oak Harbor Franchise Agreement	1	LS	\$5,000	\$5,000
	9	Install 6-inch pipeline - Double Wall off Navy Property	2,500	FT	\$98	\$245,000
Subtotal Contractor Costs						\$2,102,600
Unlisted Items and Services (%)			25	%	\$2,102,600	\$525,650
Contractor Overhead and Profit (%)			20	%	\$2,628,250	\$525,650
Washington State Sales Tax			9.5	%	\$3,153,900	\$299,621
TOTAL CONTRACTOR COST						\$3,450,000
PRESENT-WORTH CONTRACTOR COST			1	Year Implemented	\$3,350,000	

Table G-6 (Continued)
ALTERNATIVE 5
Expanded Groundwater Capture with All Untreated Effluent Discharged to Navy POTW at Ault Field

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
ENGINEERING COSTS (CAPITAL INDIRECT)						
	1	General Coordination, Meetings, and Planning	1	LS	\$50,000	\$50,000
	2	Regulatory Review, Coordination, and Meetings	1	LS	\$25,000	\$25,000
	3	Engineering Design Plans and Specs (% DCC)	5	%	\$3,350,000	\$167,500
	4	Engineers Estimate	80	HR	\$135	\$10,800
	5	Bid & RFI Support	40	HR	\$135	\$5,400
	6	Permitting	60	HR	\$135	\$8,100
	7	Compliance Monitoring Plan	120	HR	\$135	\$16,200
	8	Construction Oversight and QA (% DCC)	3	%	\$3,350,000	\$100,500
	9	Closure Documentation & Reporting	400	HR	\$110	\$44,000
Subtotal Engineering Costs						\$427,500
Unlisted Engineering Services (%)			15	%	\$427,500	\$64,125
Total Engineering Costs						\$492,000

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
O&M, MONITORING, AND CLOSURE COSTS						
Annual O&M Cost (North System)		<i>Years of Annual O&M</i>	9			
\$298,645	1	Common Elements - Existing 10 Pumping Well O&M	10	EA	\$3,000	\$30,000
<u>With Unlisted Costs</u>	2	Common Elements - Power for Ext 10 Pumping Wells (4hp)	10	EA	\$2,837	\$28,370
\$358,000	3	New Pumping Well O&M (9 wells)	4	EA	\$2,500	\$10,000
	4	Power for pumping to Ault Field (10hp)	1	LS	\$7,466	\$7,466
	5	Annual supply of MicroC Carbon Substrate (250 gpd)	54,750	gal	\$3.50	\$191,625
	6	O&M for Carbon Substrate injection system	12	MO	\$1,000	\$12,000
	7	Power for 4 new Pumping Wells (5hp each)	4	EA	\$3,546	\$14,184
	9	Institutional Controls Implementation and Inspection	1	LS	\$5,000	\$5,000
Annual O&M Cost (Southern Area)		<i>Years of Annual O&M</i>	17			
\$162,026	1	New Pumping Well O&M (4 wells)	4	EA	\$2,500	\$10,000
<u>With Unlisted Costs</u>	2	Annual supply of MicroC Carbon Substrate (100 gpd)	36,500	gal	\$3.50	\$127,750
\$194,000	3	Power for 5 new Pumping Wells (5hp each)	5	EA	\$3,546	\$17,730
	4	Power for Booster Pump for new Pumping Wells (5hp)	1	EA	\$3,546	\$3,546
	5	Institutional Controls Implementation and Inspection (1/2)	1	LS	\$3,000	\$3,000
Subtotal Maximum Combined Annual Costs						
Annual LTM Cost		<i>Years of Annual LTM</i>	30			
\$250,000	1	Common Elements - Treatment System Monitoring	1	LS	\$100,000	\$100,000
<u>With Unlisted Costs</u>	2	Common Elements - GW Sampling 35 wells (semi-annual)	70	EA	\$500	\$35,000
\$300,000	3	Common Elements - Analytical Testing (70 samples + QC)	80	EA	\$250	\$20,000
	4	Common Elements - GW Monitoring (semi-annual gauging)	2	Events	\$3,000	\$6,000
	5	Common Elements - Annual Reporting	1	LS	\$80,000	\$80,000
	6	Visual Monitoring of Double Walled Pipeline for Leaks	4	Events	\$2,000	\$8,000
	7	Forcemain Pipeline Pump (2) and Equipment Inspection	2	Events	\$500	\$1,000
Subtotal Maximum Combined Annual Costs						\$710,671
Non-Routine O&M and Closure Costs						
\$778,000	1	Common Elements - 5 Year Reviews (6 total for 30 years)	6	EA	\$100,000	\$600,000
<u>With Unlisted Costs</u>	2	Common Elements - Pumping Well Rehab (2 every 5 years)	6	Events	\$25,000	\$150,000
\$934,000	3	Forcemain Pump Repair, Minor (at Year 5)	1	EA	\$3,400	\$3,400
	4	Forcemain Pump Repair, Major (at Year 10)	1	EA	\$5,300	\$5,300
	5	Forcemain Pump Repair, Minor (at Year 15)	1	EA	\$3,400	\$3,400
	6	Forcemain Pump Replacement (at Year 20)	1	EA	\$15,900	\$15,900
Total O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$13,720,000
Unlisted Operations Tasks (%)			20	%	\$13,720,000	\$2,744,000
Total O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$16,460,000
Annualized Operational Cost		<i>Years until project completion</i>	30			
Present-Worth Operational Cost						\$548,667
			<i>Presumed Inflation Rate</i>	0.03		
						\$11,810,000

ALTERNATIVE COST SUMMARY				Rounded Total	Cumulative Total
PRESENT-WORTH TOTAL CAPITAL COSTS (DIRECT & INDIRECT)				\$3,840,000	\$3,840,000
TOTAL O&M COSTS (PRESENT WORTH)				\$11,810,000	\$15,650,000
SITE INSPECTION AND OVERHEAD (OWNER)				Percentage of Capital Costs 8.0%	\$307,000
AGENCY OVERSIGHT (EPA)				Percentage of Capital Costs 2.0%	\$76,800
TOTAL PRESENT-WORTH COST					\$16,000,000

Table G-7
ALTERNATIVE - HiPOx for 13 Years North and 30 Years South
Continued P&T with new Ex-Situ Groundwater Treatment using Advanced Oxidation Process and Install Additional Pumping Wells

Alternative	1	The primary element of this Alt is replacing the existing air stripper with a new AOP HiPOx Treatment System
Specific	2	Additional extraction wells will be installed to expand the capture zone along the southern and western perimeters
Assumptions	3	The main AOP HiPOx Treatment System will be rated at 200 gpm and treat 14 pumping wells for 15 years
	4	Pumping rate from 4 new western extraction wells is assumed to be 20 gpm each
	5	Pumping rate from the existing and new western extraction wells is assumed to be 200 gpm
	6	The 5 southern pumping wells will be treated by a separate AOP HiPOx system rated at 100 gpm for 30 years
	7	Each HiPOx system will have its only hydrogen peroxide AST with a minimum monthly supply of 1 month
	8	Pumping rate from 5 new southern extraction wells is assumed to be 20 gpm each
	9	A new underground pipeline will be installed offsite to connect the 5 new southern extraction wells
	10	The southern pipeline is assumed is dual-wall 6-inch HDPE (SDR 17)/10-inch HDPE (SDR 26)
	11	A new underground pipeline will be installed onsite to connect the 4 new western extraction wells
	12	The western pipeline is assumed is single-wall 6-inch HDPE (SDR 17)
	13	Sufficient electrical power is available at the site to Power the main HiPOx treatment system
	14	A new electrical service will be needed to power the southern HiPOx treatment system
	15	Leak monitoring will be performed visually at leak monitoring stations, spaced 500 feet along the dual-walled pipeline
	16	Contaminated soils will not be encountered during construction of the new pipelines

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
CONTRACTOR COSTS (CAPITAL DIRECT)						
Remedial Action Construction						
General \$133,600	1	Mobilization	7.50	%	\$927,900	\$69,600
	2	Contractor Work Plans	300	HR	\$100	\$30,000
	3	Bench Scale Testing of HiPOx with 4 samples by APTwater	1	LS	\$11,000	\$11,000
	4	Analytical Testing for Bench Scale Testing	1	LS	\$8,000	\$8,000
	5	Surveying and Utility Locates	1	LS	\$15,000	\$15,000
Main HiPOx System \$516,500	1	Modify Existing Concrete SC Treatment Pad	1	LS	\$10,000	\$10,000
	2	New Effluent Centrifugal Transfer Pump	1	LS	\$5,000	\$5,000
	3	Electrical connection for HiPOx System	1	LS	\$7,500	\$7,500
	4	New 200 gpm HiPOx AOP Treatment System	1	LS	\$425,000	\$425,000
	5	Transportation of HiPOx System to Site	1	LS	\$5,000	\$5,000
	6	Crane to unload new HiPOx System at the Site	1	LS	\$3,000	\$3,000
	7	Installation and connection of new HiPOx System	1	LS	\$10,000	\$10,000
	8	Integrate control system of HiPOx System with well field	1	LS	\$5,000	\$5,000
	9	Initial batch of Hydrogen Peroxide Chemical (3 month supply)	300	Gal	\$6	\$1,800
	10	Startup and Training of O&M personnel (3 people for 1 week)	120	HR	\$100	\$12,000
	11	Training by Manufacture Rep (1 person for 1 week)	50	HR	\$155	\$7,800
	12	Commissioning and Initial Analytical Testing	1	LS	\$10,000	\$10,000
	13	Update O&M Manual with HiPOx System information	120	HR	\$120	\$14,400
Southern HiPOx System \$490,300	1	Silt Fence	1,000	LF	\$2	\$2,400
	2	Clearing for new Secondary Containment (SC) Treatment Pad	1	AC	\$1,975	\$2,000
	3	Construct new Concrete SC Treatment Pad	1	LS	\$20,000	\$20,000
	4	New Effluent Batch Tank and Centrifugal Transfer Pump	1	LS	\$15,000	\$15,000
	5	New electrical service and connection for HiPOx System	1	LS	\$15,000	\$15,000
	6	New 100 gpm HiPOx AOP Treatment System	1	LS	\$367,000	\$367,000
	7	Transportation of HiPOx System to Site	1	LS	\$5,000	\$5,000
	8	Crane to unload new HiPOx System at the Site	1	LS	\$3,000	\$3,000
	9	Installation and connection of new HiPOx System	1	LS	\$10,000	\$10,000
	10	Integrate control system of HiPOx System with well field	1	LS	\$5,000	\$5,000
	11	Initial batch of Hydrogen Peroxide Chemical (3 month supply)	150	Gal	\$6	\$900
	12	Startup and Training of O&M personnel (2 people for 1 week)	80	HR	\$100	\$8,000
	13	Training by Manufacture Rep (1 person for 1 week)	50	HR	\$155	\$7,800
	14	Commissioning and Initial Analytical Testing	1	LS	\$10,000	\$10,000
	15	Write new O&M Manual for Southern HiPOx System	160	HR	\$120	\$19,200
Air Stripper Demo \$85,000	1	Remove Existing Tower Air Stripper	1	LS	\$80,000	\$80,000
	2	Off-site Disposal Costs for debris	1	LS	\$5,000	\$5,000
	3	Not Used	0	EA	\$0	\$0
New Western Pumps \$236,800	1	Install 4 new pumping wells to 120 ft Deep - 6-inch dia.	4	EA	\$13,000	\$52,000
	2	Logging of New Well Install by Geologist (1 well in 2 days)	8	DY	\$1,200	\$9,600
	3	Analytical Soil Samples (2 samples per well + QC)	9	EA	\$300	\$2,700
	4	Pumping Well Development and Water Disposal in System	4	EA	\$2,500	\$10,000
	5	Install 4 new pumps, vaults, and associated equipment	4	EA	\$10,000	\$40,000
	6	Install 6-inch pipeline - Single Wall on Navy Property	2,500	FT	\$49	\$122,500
New Southern Pumps \$643,300	1	Install 5 new pumping wells to 150 ft Deep - 6-inch dia.	5	EA	\$15,000	\$75,000
	2	Logging of New Well Install by Geologist (1 well in 2 days)	10	DY	\$1,200	\$12,000
	3	Analytical Soil Samples (2 samples per well + QC)	11	EA	\$300	\$3,300
	4	Pumping Well Development and Water Disposal in System	5	EA	\$2,500	\$12,500
	5	Install 5 new pumps, vaults, and associated equipment	5	EA	\$11,000	\$55,000
	6	Install 6-inch pipeline - Single Wall on Navy Property	4,500	FT	\$49	\$220,500
	7	Install 5hp booster pump station on Navy Property	1	LS	\$15,000	\$15,000
	8	City of Oak Harbor Franchise Agreement	1	LS	\$5,000	\$5,000
	9	Install 6-inch pipeline - Double Wall off Navy Property	2,500	FT	\$98	\$245,000
Subtotal Contractor Costs						\$2,105,500
Unlisted Items and Services (%)			25	%	\$2,105,500	\$526,375
Contractor Overhead and Profit (%)			20	%	\$2,631,875	\$526,375
Washington State Sales Tax			9.5	%	\$3,158,250	\$300,034
TOTAL CONTRACTOR COST						\$3,460,000
PRESENT-WORTH CONTRACTOR COST			1	Year Implemented		\$3,360,000

Table G-7 (Continued)
ALTERNATIVE - HiPOx for 13 Years North and 30 Years South
Continued P&T with new Ex-Situ Groundwater Treatment using Advanced Oxidation Process and Install Additional Pumping Wells

ALTERNATIVE COST SUMMARY				Rounded Total	Cumulative Total
PRESENT-WORTH TOTAL CAPITAL COSTS (DIRECT & INDIRECT)				\$3,870,000	\$3,870,000
TOTAL O&M COSTS (PRESENT WORTH)				\$9,850,000	\$13,720,000
SITE INSPECTION AND OVERHEAD (OWNER)	Percentage of Capital Costs	8.0%		\$310,000	\$14,030,000
AGENCY OVERSIGHT (EPA)	Percentage of Capital Costs	2.0%		\$77,400	\$14,107,400
TOTAL PRESENT-WORTH COST					\$14,100,000

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Table G-8
ALTERNATIVE - CHP injections in 100 points in Source Area only
In-Situ Groundwater Treatment using ISCO (Catalyzed Hydrogen Peroxide)

Alternative	1	The alternative consists of injecting CHP on a ongoing basis for up to 7 years
Specific	2	100 new reusable 2-inch PVC injection wells will be installed for CHP injection over a 7 year period
Assumptions	3	Each well will be installed with 10 feet of screen to a depth of 120 feet near the central portion of the TCE plume
	4	No injection wells will be installed along southern or western perimeters
	5	Each new well will have 2 soil samples and 1 baseline groundwater sample collected for analytical testing
	6	80% of soil cuttings generated during drilling are assumed to be clean and will be spread out on the surface of the site
	7	For the initial 4 year period 1 crew of 2 people each will inject CHP 16 weeks per year during 4 day 10 hour work week
	8	For years 5 and 6, 1 crew of 2 people will inject CHP 8 weeks per year during 4 day 10 hour work week
	9	During Year 7, the final injection year, 1 crew of 2 people will inject CHP 4 weeks over the year
	10	One person will supervise injection activities and support activities from the site and will be spend 600 hours per year
	11	The injection crew can complete 12 wells per day and inject a total of 1,000 gallons of solution into each well
	12	The oxidizer (hydrogen peroxide) will be shipped to the site as a liquid at 30% concentration and diluted and stabilized on site
	13	Chelated-iron Catalyst (ferrous sulfate and proprietary chelating agents) will be shipped to the site dry and mixed with water
	14	The catalyst and Oxidizer will be used in a 1:1 ratio

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
CONTRACTOR COSTS (CAPITAL DIRECT)						
Remedial Action Construction						
General \$107,100	1	Mobilization	7.50	%	\$927,900	\$69,600
	2	Contractor Work Plans	300	HR	\$100	\$30,000
	3	Surveying and Utility Locates	1	LS	\$7,500	\$7,500
Injection System Install \$1,434,100	1	Install reusable injections wells along Southern Boundary (150ft)	0	EA	\$8,900	\$0
	2	Install reusable injections wells along Western Boundary (120ft)	100	EA	\$7,400	\$740,000
	3	Install new GW Monitoring wells (average 130ft)	4	EA	\$7,900	\$31,600
	4	Analytical Soil Samples during drilling (2 samples per well + QC)	229	EA	\$300	\$68,700
	5	Logging of New Well Install by Geologist (1 well per day)	100	DY	\$1,200	\$120,000
	6	New Well Development and Water Disposal in System	104	EA	\$850	\$88,400
	7	Baseline GW Analytical Testing of new Wells (104 wells + QC)	114	EA	\$250	\$28,600
	8	Drill Cutting Disposal (80% spread out on-site)	368	TN	\$10	\$3,700
	9	Drill Cutting Disposal (20% spread out on-site)	101	TN	\$60	\$6,100
	10	ISCO equipment Mob/Demob	2	EA	\$13,500	\$27,000
	11	ISCO mixing tanks and injection equipment	1	LS	\$100,000	\$100,000
	12	Storage Tanks for proprietary iron chelate complex (20,000 gallon)	1	LS	\$25,000	\$25,000
	13	Storage Tanks for hydrogen peroxide (20,000 gallon)	1	LS	\$25,000	\$25,000
	14	Water Storage Tanks	1	LS	\$5,000	\$5,000
	15	Portable SC Pads for mixing operations	2	EA	\$7,500	\$15,000
	16	Tanker Truck Purchase for on-site chemical transfer	1	LS	\$150,000	\$150,000
CHP Injection (Year 1) \$1,024,300 # of events per year 7.7 Cost Per Injection Event \$133,372	1	Injection Work Project Manager and Field Supervisor (Labor)	600	HR	\$100	\$60,000
	2	Labor for ongoing injection (1 crew, 2 people, 40 hrs per week)	16	WK	\$8,000	\$128,000
	3	Proprietary iron chelate complex (5,000 gal per day @\$1.80)	64	DY	\$9,000	\$576,000
	4	12.5 percent Hydrogen Peroxide (5,000 gal per day @\$0.40)	64	DY	\$2,000	\$128,000
	5	Water Consumption (2,000 gal per day @ \$0.01)	64	DY	\$20	\$1,300
	6	Chemical Shipments	64	DY	\$1,000	\$64,000
	7	Equipment useage and maintenance	1	LS	\$30,000	\$30,000
	8	Crew Changeout Mob/Demob (monthly)	12	EA	\$1,000	\$12,000
	9	Injection Work Reporting	1	LS	\$25,000	\$25,000
Injection (Year 2-7) \$4,353,400	1	Year 2 Injection Work (100% of Year 1)	100	%	\$1,024,300	\$1,024,300
	2	Year 3 Injection Work (100% of Year 1)	100	%	\$1,024,300	\$1,024,300
	3	Year 4 Injection Work (100% of Year 1)	100	%	\$1,024,300	\$1,024,300
	4	Year 5 Injection Work (50% of Year 1)	50	%	\$1,024,300	\$512,200
	5	Year 6 Injection Work (50% of Year 1)	50	%	\$1,024,300	\$512,200
	6	Year 7 Injection Work (25% of Year 1)	25	%	\$1,024,300	\$256,100
Subtotal Contractor Costs						\$6,918,900
Unlisted Items and Services (%)			25	%	\$6,918,900	\$1,729,725
Contractor Overhead and Profit (%)			20	%	\$8,648,625	\$1,729,725
Washington State Sales Tax			9.5	%	\$10,378,350	\$985,943
TOTAL CONTRACTOR COST						\$11,360,000
PRESENT-WORTH CONTRACTOR COST			1	Year Implemented		\$10,610,000

Table G-8 (Continued)
ALTERNATIVE - CHP injections in 100 points in Source Area only
In-Situ Groundwater Treatment using ISCO (Catalyzed Hydrogen Peroxide)

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
ENGINEERING COSTS (CAPITAL INDIRECT)						
	1	General Coordination, Meetings, and Planning	1	LS	\$80,000	\$80,000
	2	Regulatory Review, Coordination, and Meetings	1	LS	\$25,000	\$25,000
	3	Engineering Design Plans and Specs (% DCC)	1,000	HR	\$135	\$135,000
	4	Engineers Estimate	100	HR	\$135	\$13,500
	5	Bid & RFI Support	40	HR	\$135	\$5,400
	6	Permitting	120	HR	\$135	\$16,200
	7	Compliance Monitoring Plan	160	HR	\$135	\$21,600
	8	Construction Oversight and QA (% DCC)	2	%	\$10,610,000	\$212,200
	9	Closure Documentation & Reporting	400	HR	\$110	\$44,000
Subtotal Engineering Costs						\$552,900
Unlisted Engineering Services (%)			15	%	\$552,900	\$82,935
Total Engineering Costs						\$640,000

Category	Task #	Task Description	Quantity	Unit	Unit Cost	Total Cost
O&M, MONITORING, AND CLOSURE COSTS						
Annual O&M Cost		<i>Years of Annual O&M</i>	5			
\$0	1	Common Elements - Existing 10 Pumping Well O&M	0	EA	\$3,000	\$0
<u>With Unlisted Costs</u>	2	Common Elements - Power for Ext 10 Pumping Wells (4hp)	0	EA	\$2,837	\$0
\$0	3	O&M of Either Existing or New Treatment System	0	LS	\$50,000	\$0
	4	Power for Existing or New Air Stripper Blower (20hp)	0	LS	\$14,932	\$0
	5	Power for effluent discharge pump (5hp each)	0	LS	\$3,546	\$0
	6	Intitutional Controls Implementation and Inspection	0	LS	\$5,000	\$0
	7	Not Used	0	EA	\$0	\$0
	8	Not Used	0	EA	\$0	\$0
	9	Not Used	0	EA	\$0	\$0
	10	Not Used	0	EA	\$0	\$0
	11	Not Used	0	EA	\$0	\$0
Annual LTM Cost		<i>Years of Annual LTM</i>	15			
\$96,500	1	Common Elements - Treatment System Monitoring	0	LS	\$100,000	\$0
<u>With Unlisted Costs</u>	2	Common Elements - GW Sampling 20 wells (semi-annual)	40	EA	\$500	\$20,000
\$116,000	3	Common Elements - Analytical Testing (40 samples + QC)	50	EA	\$250	\$12,500
	4	Common Elements - GW Monitoring (semi-annual gauging)	2	Events	\$3,000	\$6,000
	5	Common Elements - Annual Reporting	1	LS	\$50,000	\$50,000
	6	GW Monitoring and Analytical Testing of 4 New MWs	8	EA	\$1,000	\$8,000
	7	Not Used	0	EA	\$0	\$0
	8	Not Used	0	EA	\$0	\$0
Subtotal Maximum Combined Annual Costs						\$96,500
Non-Routine O&M and Closure Costs						
\$279,500	1	Common Elements - 5 Year Reviews (3 total for 15 years)	0	EA	\$100,000	\$0
<u>With Unlisted Costs</u>	2	Common Elements - Pumping Well Rehab (2 every 5 years)	0	Events	\$25,000	\$0
\$335,000	3	Additional Inj Well Install w/ Logging & Develop (at Year 5)	10	EA	\$10,950	\$109,500
	4	Abandon all Injection Wells (at Year 9)	100	EA	\$1,000	\$100,000
	5	Demo P&T System (at Year 10)	0	EA	\$120,000	\$0
	6	Abandon all Pumping Wells (at Year 10)	14	EA	\$5,000	\$70,000
	7		0	EA	\$0	\$0
	8		0	EA	\$0	\$0
Subtotal O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$1,727,000
Unlisted Operations Tasks (%)			20	%	\$1,727,000	\$345,400
Total O&M, Monitoring, Non-Routine O&M, and Closure Costs						\$2,070,000
Annualized Operational Cost		<i>Years until project completion</i>	15			\$138,000
Present-Worth Operational Cost		<i>Presumed Inflation Rate</i>	0.03			\$1,970,000

Table G-8 (Continued)
ALTERNATIVE - CHP injections in 100 points in Source Area only
In-Situ Groundwater Treatment using ISCO (Catalyzed Hydrogen Peroxide)

ALTERNATIVE COST SUMMARY				Rounded Total	Cumulative Total
PRESENT-WORTH TOTAL CAPITAL COSTS (DIRECT & INDIRECT)				\$11,250,000	\$11,250,000
TOTAL O&M COSTS (PRESENT WORTH)				\$1,970,000	\$13,220,000
SITE INSPECTION AND OVERHEAD (OWNER)	Percentage of Capital Costs	2.0%		\$225,000	\$13,445,000
AGENCY OVERSIGHT (EPA)	Percentage of Capital Costs	0.5%		\$56,300	\$13,501,300
TOTAL PRESENT-WORTH COST					\$13,500,000

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Table G-9
Combined Alternative 2 and 4 (Tables F-7 and F-8) Costs

Task	Modified HiPOx Alt HiPOx North System 13 Years South System 30 Years	Modified CHP Alt ISCO using Catalyzed Hydrogen Peroxide 100 Points in Source Area	Combination HiPOX with CHP in Source Area
Implementation Costs			
Capital Direct Costs (Construction)	\$3,460,000	\$11,360,000	\$14,820,000
<i>Unlisted Items and Services Assumed (%)</i>	25	25	25
Capital Indirect Costs (Engineering)	\$508,000	\$640,000	\$1,148,000
<i>Unlisted Engineering Services Assumed (%)</i>	15	15	15
Total Capital Implementation Costs	\$3,970,000	\$12,000,000	\$15,970,000
Operational Costs (30 years)			
Annual O&M, Monitoring Costs, Western Plume	\$445,000	\$0	NA
Years of O&M Assumed	13	0	13
Annual O&M, Monitoring Costs, Southern Plume ^b	\$219,000	\$116,000	NA
Years of Monitoring Assumed	30	15	30
Non-Routine O&M and Closure Costs	\$1,353,000	\$335,000	\$1,688,000
<i>Unlisted Operational Tasks Assumed (%)</i>	20	20	20
Total Operational Costs	\$13,710,000	\$2,080,000	\$15,790,000
TOTALS			
Total Capital and Operational Costs	\$17,680,000	\$14,080,000	\$31,760,000
Present-Worth Implementation Costs	\$3,870,000	\$11,250,000	\$15,120,000
Present-Worth Operational Costs	\$9,850,000	\$1,970,000	\$11,820,000
Site Inspection and Overhead	\$310,000	\$225,000	\$535,000
Agency Oversight	\$77,400	\$56,300	\$133,700
Total Project Present Worth ^a	\$14,100,000	\$13,500,000	\$27,600,000

^a Present worth costs were calculated using a 3% discount rate.

^b Modified CHP O&M, monitoring costs for western plume only

Notes:

Discount Rate (3%) = Interest Rate (6%) - Inflation (3%)

NA - Not Applicable

O&M - Operation and Maintenance

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