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FINAL CLEANUP REVIEW TEAM REPORT EVALUATION OF REMEDY SELECTION AT THE EASTERN PLUME NAS BRUNSWICK ME

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NAVAL FACILITIES ENGINEERING COMMAND MID-ATLANTIC

Naval Facilities Engineering Command

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FINAL
Cleanup Review Team (CURT) Report

EVALUATION OF REMEDY SELECTION AT THE EASTERN PLUME, NAS BRUNSWICK

by

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EXECUTIVE SUMMARY

A Cleanup Review Team (CURT) evaluation was conducted for the Eastern Plume at Naval Air Station (NAS) Brunswick. The objectives of the review were to evaluate technologies and strategies for managing the Eastern Plume. The review process consisted of assembling a team of experts in 1,4-dioxane and chlorinated solvent groundwater remediation and management. Together with the BRAC project team, the CURT met to review the site data and assess potential remedial alternatives as well as to visit the site and meet with the regulators and the public to improve the Team's understanding of the Eastern Plume. This CURT report provides a recommended path forward regarding remedy selection by assessing the viability of technologies for final treatment. As part of the evaluation, the CURT took the following factors into account: complex hydrogeology of the site, feasibility of more aggressive remedies, multiple attenuation mechanisms already at work at the site, potential reduction of shallow groundwater discharge to surface water by phytoremediation, and absence of any unacceptable risk to potential groundwater and surface water receptors posed by the current plume. The CURT reviewed the applicability of all possible remediation technologies in several major categories including: refinements to the existing groundwater extraction and treatment system (GWETS), bioremediation, in-situ chemical oxidation, thermal treatment, permeable reactive barriers, reactive mats, phytoremediation, and monitored natural attenuation (MNA). After a careful review of all possible remediation options that could be applicable to the Eastern Plume, the CURT recommends a transition from the interim remedy (GWETS) to a final remedy consisting of MNA, supplemented by phytoremediation.

CONTENTS

EXECUTIVE SUMMARY ii
FIGURES iv
TABLES iv
APPENDICES iv

SECTION 1.0: INTRODUCTION 1
1.1 History of CERCLA Process at Brunswick 1
1.2 Cleanup Review Team (CURT) Overview 2

SECTION 2.0: CONCEPTUAL SITE MODEL REVIEW 5
2.1 CURT's Understanding of the CSM 5
2.1.1 Site Hydrogeology and Its Influence on the Evolution of the Eastern Plume 5
2.1.2 Potential Groundwater Uses 9
2.1.3 Nature and Extent of Contamination 12
2.1.4 Aquifer Geochemistry and Natural Attenuation Potential 15
2.1.5 Additional Investigations 16
2.1.5.1 Groundwater 16
2.1.5.2 Surface Water 19
2.1.5.3 Sediment Samples 20
2.1.5.4 Shallow Groundwater or "Pore Water" Samples 21
2.2 Risk Assessment and Management 22
2.2.1 Potential Human Receptors and Exposures 22
2.2.2 Potential Ecological Receptors and Exposures 26
2.2.3 Risk Summary 26
2.3 Summary of CSM Recommendations 29

SECTION 3.0: GROUNDWATER EXTRACTION AND TREATMENT SYSTEM (GWETS) 30
3.1 Remedy Performance 30
3.2 Present/Short-term Plans for GWETS 33
3.3 Long Term Plans for GWETS 33
3.4 Continued GWETS Operation from a Sustainability Perspective 35
3.5 GWETS Summary and Final Recommendations 35

SECTION 4.0: ALTERNATIVE REMEDIAL OPTION EVALUATIONS 37
4.1 Enhanced In Situ Bioremediation 37
4.1.1 Cometabolic Biodegradation 38
4.2 In Situ Chemical Oxidation (ISCO) 39
4.3 Thermal Treatment 40
4.4 Vertical Permeable Reactive Barriers 41
4.5 Sheet Pile/Slurry Walls 42
4.6 Reactive Mats (horizontal permeable barriers) 42
4.7 Phytoremediation 43
4.8 Monitored Natural Attenuation (MNA) 45

Section 5.0: TIGER TEAM REMEDY RECOMMENDATIONS 47
5.1 Basis of Recommendations 47
5.1.1 Complex Hydrogeology of the Site 47
5.1.2 Infeasibility of More Aggressive Remedies 48

5.1.3 Natural Attenuation Capacity at the Eastern Plume 49
5.1.4 Absence of Unacceptable Risk 50
5.2 Summary of Final Remedy Recommendations 50

SECTION 6.0: REFERENCES 52

FIGURES

Figure 1. CERCLA Status Timeline for Brunswick Eastern Groundwater Plume 2
Figure 2. Topographic Vicinity Map showing Harpswell Cove 7
Figure 3. General Area of the Eastern Plume 8
Figure 4A. Top of Bedrock Contour Map Eastern Plume 10
Figure 4B. Surface Drainage Map with Bedrock Ridges 10
Figure 4C. Shallow Groundwater Surface Contour Map 11
Figure 4D. Deep Groundwater Surface Contour Map 11
Figure 5. Impact of Back-Diffusion on Contaminant Concentrations Released from Transition Unit .. 13
Figure 6. Historical Plume Map Since 1991 18
Figure 7. Reduction of 1,1,1-TCA from 1995 to 2008 with the Contaminant Threshold of MEG/MCL... 19
Figure 8. Risk Assessment Conceptual Site Model for the Eastern Plume 24
Figure 9. VOC Removal over Time 31
Figure 10. Cost Increase over Time Due to Reduced VOC Concentrations 31

TABLES

Table 1. Contaminants of Concern Concentration Summary in Groundwater (µg/L) 16
Table 2. Contaminants of Concern Concentration Summary in Surface Water 20
Table 3. Contaminants of Concern Concentration Summary in Sediment 20
Table 4. Contaminants of Concern Concentration Summary in Shallow Groundwater or "Pore Water ... 21
Table 5. COPCs and Physicochemical Properties Associated with Bioaccumulation 25
Table 6. Comparison of Surface Water Concentrations to Water Quality Criteria 26
Table 7. Comparison of Surface Water Concentrations to Risk-Based Ecological Screening Values 28

APPENDICES

APPENDIX A: CURT Biosketches
APPENDIX B: Well Summary Tables
APPENDIX C: Trend Graphs
APPENDIX D: ECOSAR Model Results for 1,4-Dioxane
APPENDIX E: Analysis Details to Alternative 1,4-Dioxane Treatment with the Current GWETS
APPENDIX F: Phytoremediation Tables for ITRC

SECTION 1.0: INTRODUCTION

The Naval Air Station (NAS) Brunswick Eastern Groundwater Plume in Brunswick, Maine is a mixed chlorinated solvent plume that also contains 1,4-dioxane. Potential source areas for the Eastern Plume include Site 4 (Acid/Caustic Pit), Site 11 (former Fire Training Area), and Site 13 (Defense Reutilization and Marketing Office area). Chlorinated volatile organic compounds (VOCs) including tetrachloroethene (PCE), 1,1,1-trichloroethane (TCA), and trichloroethene (TCE) were first discovered during the Remedial Investigation (RI) and attributed to disposal activities at the aforementioned sites. Upon further investigation, the contaminants of concern (COCs) have expanded to include 1,1-dichlorethene (1,1-DCE), 1,1-dichloroethane (1,1-DCA), cis-1,2-dichloroethene (cis-1,2-DCE), trans-1,2-dichloroethene (trans-1,2-DCE), and 1,4-dioxane. In 1995, a pump and treat (P&T) system, using ultraviolet (UV) oxidation, was put in place to remove contamination and contain the plume by preventing its potential discharge into Mere Brook or Merriconeag Stream. Since installation, this Groundwater Extraction and Treatment System (GWETS) has removed over 90 gallons of chlorinated solvent mass from the plume. Much of the solvent recovery occurred in the early years of operation. In the last one year (2008), less than a gallon of solvent was recovered. GWETS system optimization over the years included discontinuing UV oxidation, adding air stripping, and adjusting the locations of the extraction wells. The UV oxidation unit was replaced with an air stripper and activated carbon unit prior to 2004 when 1,4-dioxane was first detected in the Eastern Plume. The GWETS currently consists of four groundwater extraction wells (EW-01, 02A, 04, and 05A) that are screened through the shallow and deep zones of the overburden aquifer. During the most recent extraction well optimization in 2008, 1,4-dioxane was measured in excess of 100 ppb in the new extraction well, EW-5B. At these levels, the groundwater exceeds Maine's promulgated value of 32 ppb for 1,4-dioxane.

1.1 History of CERCLA Process at Brunswick

The RI, completed by E.C. Jordan in 1990, summarized the history of the site investigations undertaken at the Eastern Plume from 1983 to 1990. As can be seen in Figure 1, an interim Record of Decision (ROD) was signed in 1992 that allowed the Navy to implement a pump-and-treat (P&T) system that included using UV oxidation of contaminants in order to remove contamination and prevent discharge into Mere Brook and Merricongeag Stream. In 1998, the final ROD was signed and No Further Action (NFA) was granted for Sites 4, 11, and 13. The 1998 ROD included the continuation of the GWETS operation, as well as the ability to discharge treated water into the publicly-owned treatment works, along with recognition of the need for long term monitoring (LTM) and five-year reviews at the Eastern Plume. A GWETS optimization review was conducted in January 2000 and suggested that the UV oxidation system be taken offline and replaced with an air stripping system with carbon polishing. The treatment system recommendations were completed in January 2001. In addition, the explanation of significant differences (ESD) was finalized for the Eastern Plume in 2000 and included Institutional Controls (ICs) for Sites 1 and 3 Landfills. Between 2000 and 2008, the GWETS continued operation while the LTM plan was updated several times. In 2004, 1,4-dioxane was detected at low concentrations and led to a series of investigations into the nature and extent of contamination in the Eastern Plume. These additional studies include but are not limited to the following: southern boundary of Eastern Plume investigations (2000-2003), bedrock investigations of Site 11 (2003-2005) and the Eastern Plume (2008-to present), Mere Brook and Merriconeag Stream investigations (2005-2007), monitored natural attenuation evaluation (MNA) of Eastern Plume (2003-2005), and the 1,4-dioxane RI at the Eastern Plume in Groundwater and Surface Water (2008-to present).

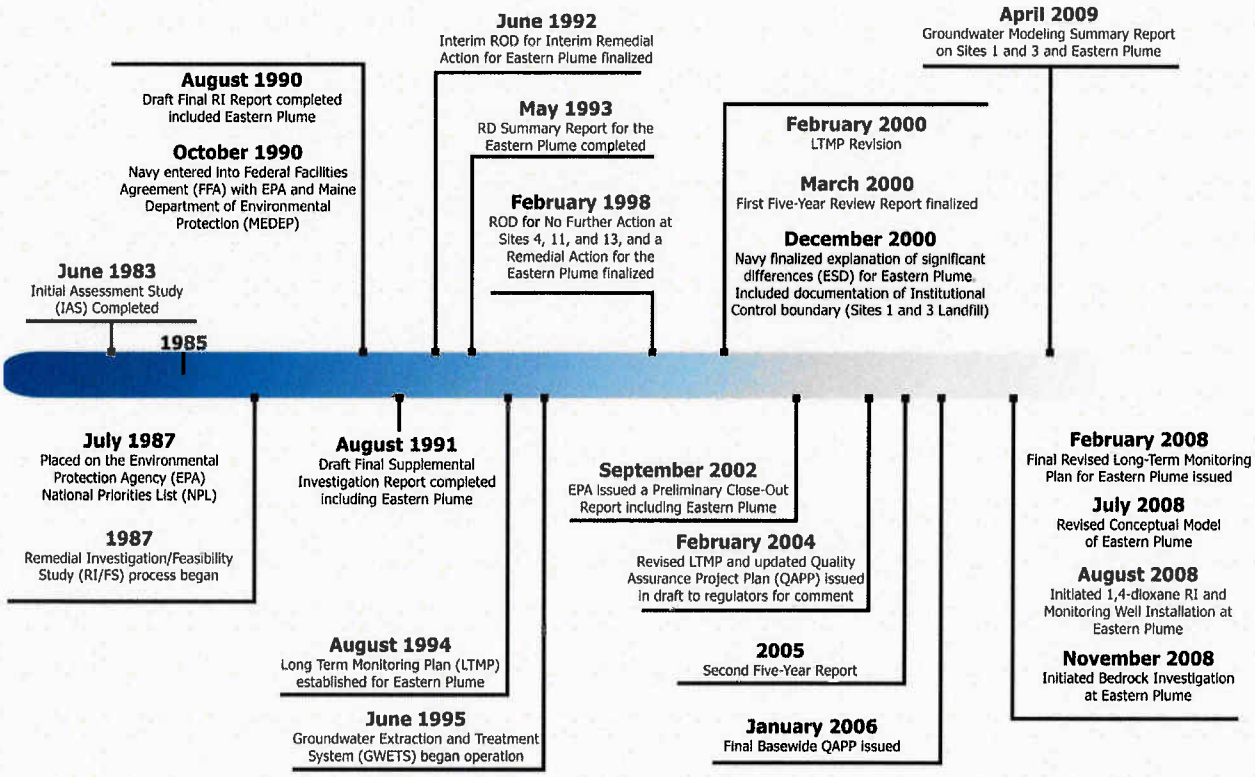

Figure 1. CERCLA Status Timeline for Brunswick Eastern Groundwater Plume

1.2 Cleanup Review Team (CURT) Overview

In March 2009, Base Realignment and Closure (BRAC) Northeast Region requested a CURT be formed to assist in evaluating treatment options to address 1,4-dioxane in the 100 ppb range as well as VOCs in the Eastern Groundwater Plume. The Naval Facilities Engineering Service Center (NAVFAC ESC) assembled a Team of recognized experts on chlorinated solvent groundwater remediation and 1,4-dioxane contamination (see **Appendix A** for team members and biosketches). Using available site data, the CURT was asked to assess the implementability, effectiveness, and cost of technologies for short-term and long-term remedies. Specifically, the Navy Remedial Project Manager (RPM) requested assistance to:

- Determine whether the current groundwater extraction/treatment system in its current configuration is still the best approach for the Eastern Plume site;
- Identify and conduct initial evaluation of all reasonable treatment options that are available for the 1,4-dioxane;
- Identify any recommendations for pilot studies based on the CURT assessment; and
- Recommend an integrated treatment approach for all contaminants of the Eastern Plume including chlorinated VOCs and 1,4-dioxane.

The CURT review was conducted in accordance with Chief of Naval Operations (CNO) policy (CNO, 2004) on optimization of soil and groundwater remediation at Navy and Marine Corps installations. The policy stresses the need to optimize remediation projects at every phase of the CERCLA process.

Implementation of the optimization policy requires that (1) appropriate remedies be selected, (2) remedies be protective of human health and the environment, (3) cleanup objectives be met in a cost-effective and timely manner, and 4) innovative technologies and risk-based approaches be considered during remedy selection and implementation.

In June 2009, as a first step, the CURT conducted a site visit with the BRAC project team. As part of the site visit, the team was introduced to the public and regulators and listened to their concerns. After the public meeting, the CURT reviewed site data, assessed potential remedial alternatives, and conducted a site walk. The areas visited included: the northern lobe of the plume at Picnic Pond and the southern lobe of the plume at the confluence of the Mere Brook and Merricongeag Stream. The following items of concern were noted by the CURT during the joint meeting with the regulators and members of the Restoration Advisory Board (RAB):

- General Concerns
  - The proposed long term remedy must ensure that all contaminants of concern, including TCE and TCA daughter products and 1,4-dioxane, are addressed.
  - The proposed long term remedy should recognize impacts of said remedy on the future land use and the potential future groundwater use.
  - The RAB members wanted better definition of the current state of the plume.
  - The RAB members want to increase the speed with which new approaches are implemented at the Eastern Plume.
- Risk Concerns
  - The RAB members asked for more information on the implementation of risk management strategies used at other BRAC sites.
  - The RAB members asked for more evaluation of the potential impacts of the plume on the surface water bodies. Specifically, it was requested to determine the ecological impacts, especially for 1,4-dioxane, on receiving water bodies and Harpswell Cove (i.e. shellfish and lobsters).

The items noted during the joint meeting were discussed further in a follow-on meeting by the CURT with regard to providing a path forward for remedy selection. Specifically, the request for more risk analysis was incorporated into the objectives and the CURT re-assessed the conceptual site model of the plume.

To assist in evaluating remedy options for the Eastern Plume as well as identify any Conceptual Site Model (CSM) data gaps that would impact remedy evaluation, this report is divided into four main evaluation sections. For each section, a general discussion of the topic is followed by specific recommendations for that topic. First, the report reviews the conceptual site model (CSM) and makes recommendations for additional data collection and analyses (Section 2). Secondly, the report summarizes remedy performance of the current groundwater extraction and treatment system and evaluates the short-term and long-term potential for the current remedial strategy (Section 3). Then, the report evaluates alternative remedial options potentially applicable for the Easter Plume (Section 4). Finally, the key recommendations are summarized in the conclusion of the report (Section 5).

It must be emphasized that the topics addressed by the CURT in this report are broad-based issues that the CURT believes will impact the remedy selection for this site. The conclusions of the CURT are based on the best collective judgment of the assembled experts who reviewed the available data and its recommendations are advisory in nature. Selected data from a multitude of investigations have been highlighted in this report and the CURT has made every effort in the time available to check the validity of the original data. However, some uncertainties in the data have been difficult to resolve and will have

to addressed through a concerted effort in the future to prepare consolidated and validated data sets for each of the media (soil, groundwater, sediment, pore water) associated with the Eastern Plume.

SECTION 2.0: CONCEPTUAL SITE MODEL REVIEW

Given the extremely complex nature of the site, considerable progress has been made by site representatives and stakeholders in delineating the hydrogeology and contaminant distribution associated with the Eastern Plume. The original CSM of the Eastern Plume was developed as part of the RI (E.C. Jordan, 1990) and supplemental RI (E.C. Jordan, 1991) processes. As new data were obtained through LTM and subsequent investigations, the CSM has been updated progressively to reflect the new data. The most recent update of the CSM for the Eastern Plume was issued in July 2008 (ECC, 2008). The large plume has shown relatively little movement to the east or south over the last several years. In order to better understand site conditions and prepare remedial recommendations for the Eastern Plume, the CURT conducted a detailed review of the existing 2008 CSM and available analytical data obtained since then. This section presents the CURT's interpretation of the Eastern Plume CSM, focusing on the understanding of the subsurface and hydrogeologic conditions. In general, the CURT's emerging understanding is that the Eastern Plume has evolved into its current relatively stable footprint due to the hydrogeologic containment afforded by Merriconeag Stream and Mere Brook to the east and by the discontinuities in the Lower Sand Unit to the south.

2.1 CURT's Understanding of the CSM

Much of the CURT's efforts were spent in understanding the details of a very complex site that contains the Eastern Plume.

2.1.1 Site Hydrogeology and Its Influence on the Evolution of the Eastern Plume. The site geology is complex with interbedded layers of sand, silt, and clay that overlie basal clay and bedrock units. Except in the few locations where the bedrock sub-crops, the clay represents a competent aquitard and a significant barrier to vertical migration of contamination. Thus, the plume appears to be hydraulically confined near its southern boundary through a combination of geological features. The major geologic layers as they are encountered are described below:

- Upper Sand Unit - The Upper Sand Unit is approximately 10- to 20-ft thick across the Eastern Plume area and consists of fine sand that readily transmits groundwater. The upper layers of fine sand are mostly silt-free and have the highest conductivity of the overburden units (E.C. Jordan, 1990).
- Transition Unit - The Transition Unit lies between the upper sand and the clay and is composed of interbedded sands, silts, and clays (E.C. Jordan, 1990). The Transition Unit ranges in thickness from zero to 80 feet (EA Engineering, 2000) and forms a wedge that increases in thickness from west to east across the Eastern Plume. The upper portions of the transition unit exhibit unconfined groundwater conditions while deeper intervals in the transition unit exhibit semi-confined to confined conditions due to the presence of low permeability zones within this unit. The majority of the transition unit is silt and clay. Sand stringers may be present sporadically within the Transition Unit and may facilitate some groundwater movement within this unit.
- Lower Sand Unit - The Lower Sand Unit is a mappable, discontinuous, sandy interval which was identified as a distinct unit within the base of the Transition Unit for the first time in the Supplemental RI (E.C. Jordan, 1991).
- Presumpscot Clay - The Presumpscot clay underlies the Transition Unit and the Lower Sand Unit and is draped over the bedrock or till surface in a nearly continuous layer. The clay thickness is as much as 80 feet in some areas (EA Engineering, 2000). In a few areas, the

clay appears to be very thin or absent. The remaining portions of the Eastern Plume appear to be underlain by several feet or tens of feet of clay. This clay forms the base of the overburden flow system and prevents significant groundwater flow between the overburden and bedrock or till.

- Bedrock - Within the boundaries of the Eastern Plume, bedrock underlying the Presumpscot clay consists of the Cape Elizabeth Formation and is characterized as thinly-bedded gray schist, composed primarily of quartz-plagioclase-biotite-muscovite, and characteristically interbedded with thin beds of quartzite schist. Bedding planes and schistosity of the formation characteristically strike to the north-northeast and dip steeply to the southeast (Lough, 2004). Overall, bedrock is overlain by relatively impermeable Presumpscot clay, creating confined, artesian conditions (E.C. Jordan, 1991). Bedrock sub-crops divide the Eastern Plume into a northern lobe and a southern lobe.

NAS Brunswick lies within the Mere Brook watershed and the majority of the runoff from the installation drains into Mere Brook and its largest tributary, Merriconeag Stream. Upon entering Mere Brook, surface water continues through fresh and saltwater wetlands for nearly a mile before draining into the tidally-influenced Harpswell Cove (see **Figure 2**). The hydrogeology of the Eastern Plume is controlled by Merriconeag Stream and Mere Brook as they are gaining streams. Specifically, the hydraulic gradients in the overburden aquifer are oriented towards the stream/brook in an eastward direction. The more permeable units including the Upper Sand Unit and Lower Sand Unit are migration pathways for groundwater and associated contaminants towards these surface water bodies. This migration towards the streams is assisted by the bowl-like geology of the clay and bedrock that dips eastward starting from potential source areas on the western side of the Eastern Plume as it reaches a topographic low along the edge of the streams. Groundwater flow within the Lower Sand Unit and the Transition Unit/top of Presumpscot Clay in the upland areas is found to be confined or semi-confined at some locations. The groundwater gauging data indicate artesian well conditions are present in the Lower Sand Unit in monitoring wells near the Mere Brook and Merriconeag confluence confirming the confined/semi-confined conditions. Along the southern boundary of the plume, the Lower Sand Unit is highly discontinuous, which restricts southward groundwater flow. As groundwater moves eastward, beyond the topographic low of the clay and bedrock, it is restricted by the geology including the upward trend of bedrock (and clay) to its eastern peak at Buttermilk Mountain and the Presumpscot Clay overburden. Based on potentiometric maps of the area, bedrock groundwater flow appears to generally track the overburden flow directions and converges towards the streams, both on the east (residential) and west (NAS Brunswick) sides of the streams.

Based on available hydrogeologic information, groundwater appears to upwell and discharge to the streams along the eastern and southern boundaries of the Eastern Plume. This hydrogeologic flow regime is the reason why the dilute Eastern Plume appears to have stabilized over the years into its current location and shape (**Figure 3**). At this time, advective flow beyond the southern boundary of the plume appears to be restricted by these hydrogeologic factors.

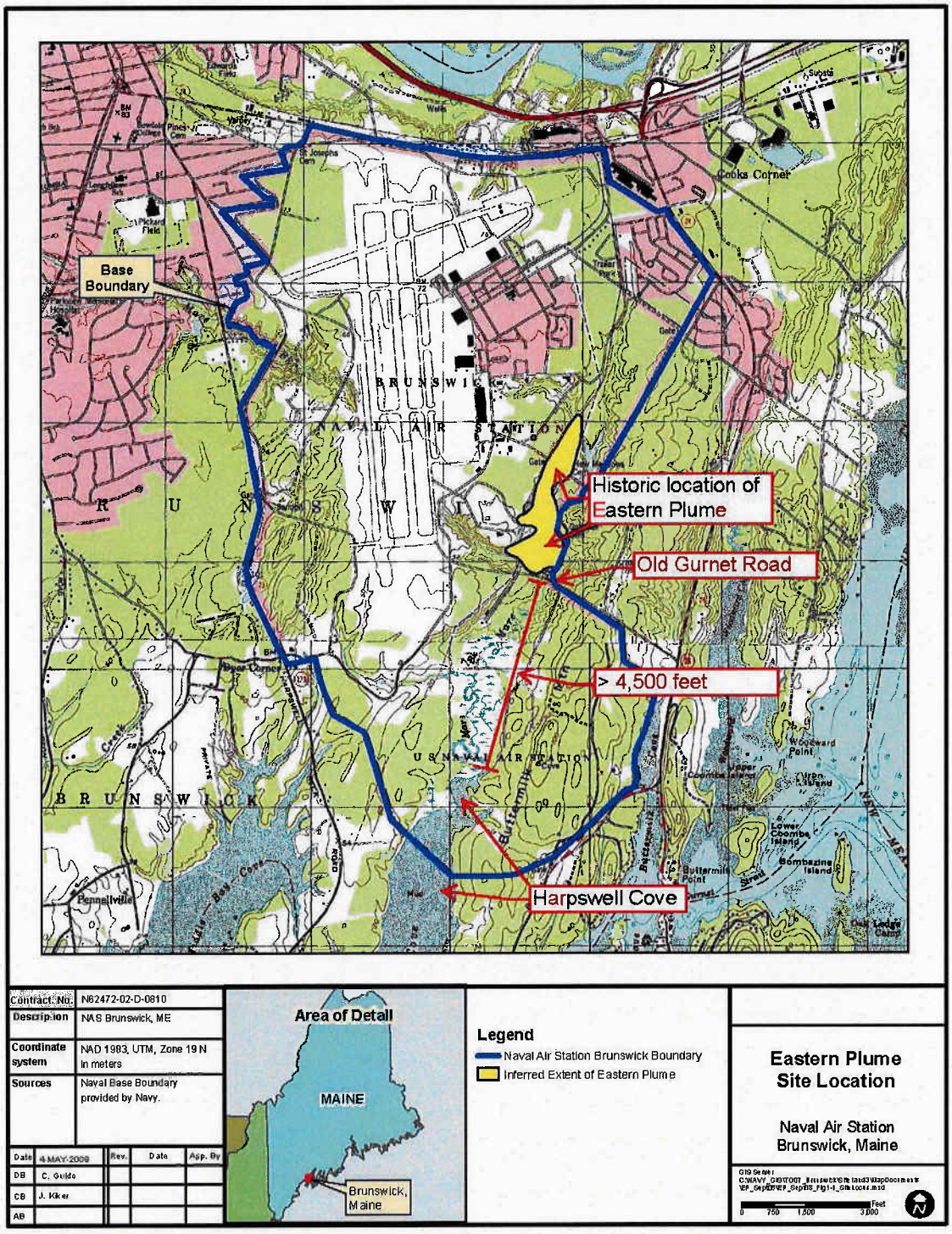

Figure 2. Topographic Vicinity Map showing Harpswell Cove (ECC, 2008)

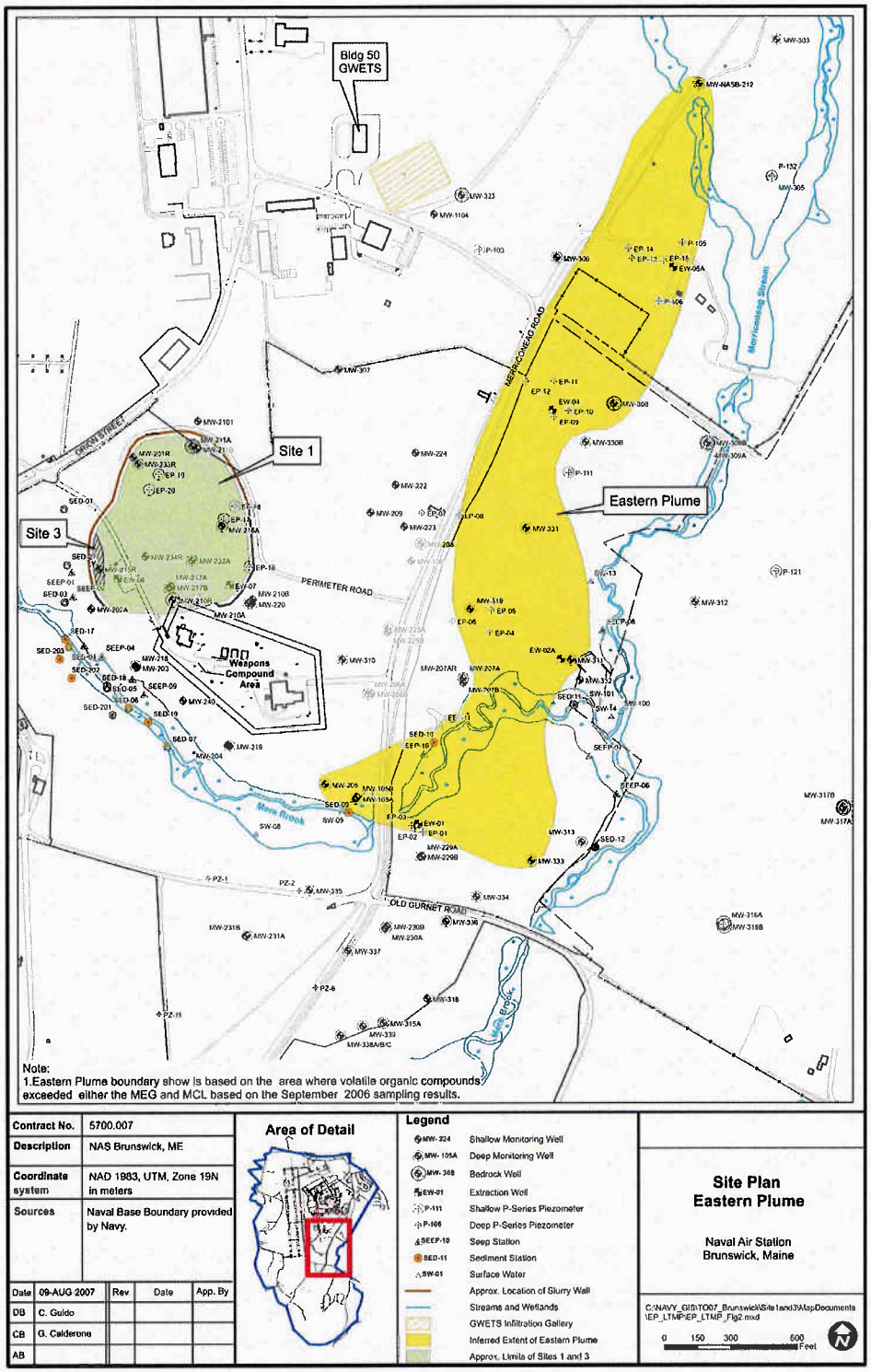

Figure 3. General Area of the Eastern Plume

The yellow area is the inferred extent of the Eastern Plume based on regulatory exceedances observed in September 2007 (ECC, 2009b)

The deep groundwater and shallow bedrock wells were gauged during the LTM report-Monitoring Event 33 (ECC, 2009b). The limited bedrock groundwater contour data show flow from the east and the west towards Mere Brook and Merriconeag Stream. The bedrock dips eastward to southeastward starting from potential source areas on the western side of the Eastern Plume and reaches a topographic low along the western edge of the streams. On the eastern side of the streams, the bedrock starts ascending to the topographic highs of Buttermilk Mountain. As a result, bedrock ridges located at topographic highs are located to the west and east of the Eastern Plume (which is located in a bedrock depression). A bedrock surface contour map is provided as **Figure 4A** and bedrock ridge locations are highlighted in **Figure 4B**. Based on groundwater contours in shallow bedrock, shallow bedrock groundwater mimics the overburden aquifer as shown in **Figure 4C**.

Recommendations. As described in more detail in Section 2.1.3, the CURT recommends better definition of the geology surrounding wells designated as the Lower Sand Unit by using slug tests to determine whether their screened intervals are in the Transition Unit or the Lower Sand Unit.

2.1.2 Potential Groundwater Uses. Groundwater occurring in the overburden or bedrock beneath the Eastern Plume is not used for drinking water or any other uses. The Base is connected to a public water supply administered by the Brunswick-Topsham Water District; with the exception of the golf course which is irrigated from a well that is located cross gradient to and far enough away from the Eastern Plume so it is not affected by groundwater flow from the Eastern Plume. ICs consisting of groundwater and land use restrictions have been applied to the entire Eastern Plume as part of the Explanation of Significant Differences (EA Engineering, 2000). The final land use restrictions are documented in the NAS Brunswick Operating Instruction 5090.1A, "Restriction on Excavation Activities" and placed in the Administrative Record for the Eastern Plume.

According to the Maine Geological Survey, the latest boundary of the Eastern Plume is west and outside the "Significant Sand and Gravel Aquifer" zone and within a moderate/low or no potential yield zone. Therefore, the Eastern Plume aquifer is not considered viable for drinking water wells and would not be developed as such. In accordance with the USEPA criteria presented in *Guidelines for Ground-Water Classification Under the EPA Ground-Water Protection Strategy* (USEPA, 1988), the aquifer is not a potential source of potable water and is of limited beneficial use. Therefore, by this classification, the overburden aquifer would be considered a Class III Groundwater Aquifer (not a viable drinking water source). As such, it is recommended to evaluate the applicability of alternate concentration limits for use in the overburden aquifer.

Recommendations. The CURT recommends including appropriate provisions (i.e., restrictive covenants or other land use restrictions) to address drinking water for future transfer or lease of the property including water well and construction restrictions within the footprint of the Eastern Plume. In addition, the potential use of alternate concentration limits should be evaluated given the pursuit of a Class III groundwater aquifer designation.

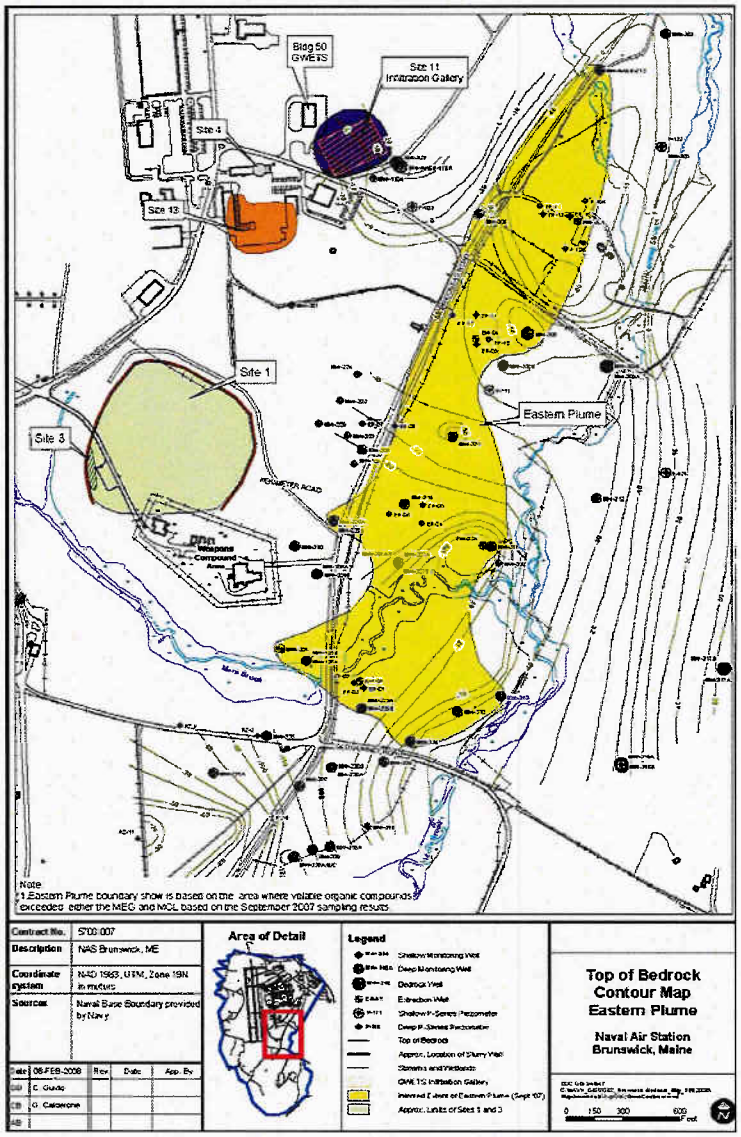

Figure 4A. Top of Bedrock Contour Map Eastern Plume (ECC, 2008)

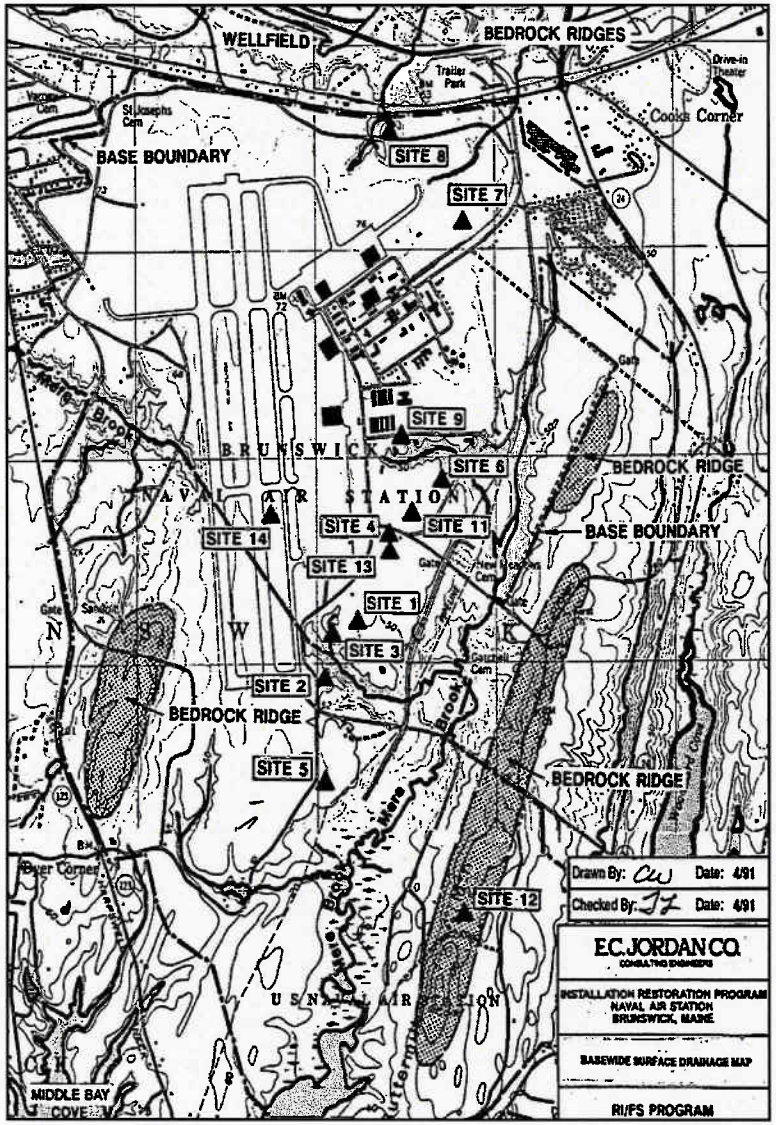

Figure 4B. Surface Drainage Map with Bedrock Ridges (E.C. Jordan, 1991)

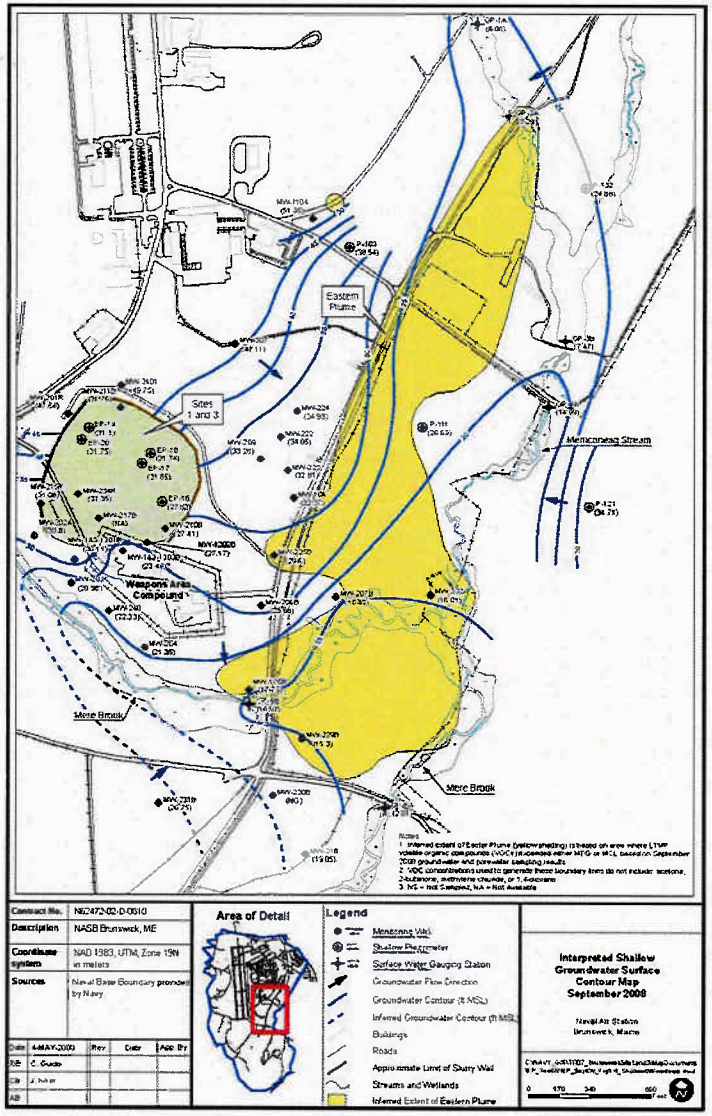

Figure 4C. Shallow Groundwater Surface Contour Map (ECC, 2008)

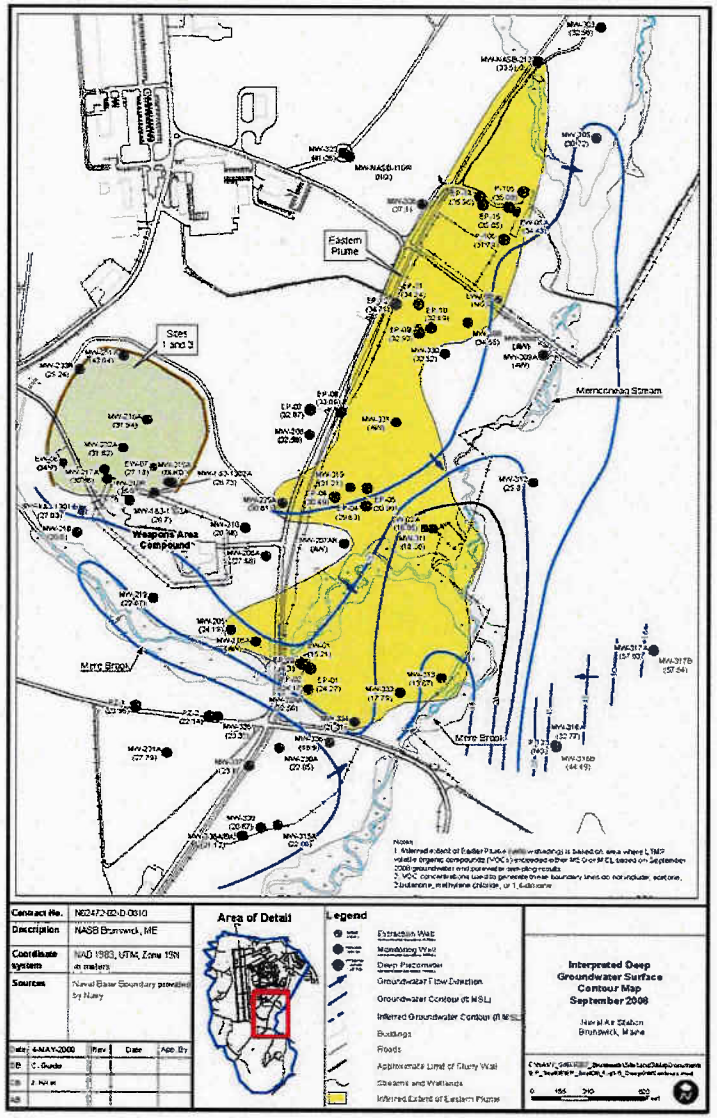

Figure 4D. Deep Groundwater Surface Contour Map (ECC, 2008)

2.1.3 Nature and Extent of Contamination. The Eastern Plume is spread in a relatively thin band of contamination that extends approximately one-half mile alongside Merriconeag Stream and Mere Brook. The primary COCs in the Eastern Plume are chlorinated VOCs (TCE, 1,1-DCE, TCA, 1,1-DCA, cis-1,2-DCE) and the emerging contaminant, 1,4-dioxane. Relatively low levels of biodegradation products, 1,1-DCA and cis-1,2-DCE, indicate that intrinsic biodegradation is fairly limited in the plume.

There are several contaminated sites on the west side of the Eastern Plume that could have served as sources for this plume (E.C. Jordan 1990; E.C. Jordan, 1991). Sites 4, 11, and 13 have been identified as potential source areas of the Eastern Plume and are located to the north-northwest of the current plume (**Figure 3**). These sites were investigated and source removal activities implemented in the early 1990s. These activities appear to have depleted much of the residual fuel and solvents in these source areas. Chlorinated solvents released from Sites 4, 11, and 13 are assumed to have entered the Upper Sand Unit, migrated around or through the upper Transition Unit, and eventually reached the Lower Sand Unit (ECC, 2008). In addition, utility lines, such as storm-water drains (depicted on older maps), could have acted as conduits for migration of contamination from the suspected source areas to the current boundaries of the Eastern Plume.

Various lines of evidence suggest that, in all likelihood, VOCs and 1,4-dioxane are trapped in the Transition Unit, not in the Lower Sand Unit as indicated in previous CSMs. Specifically, contamination is trapped in the Transition Unit along the entire historically affected boundary near the streams and is now serving as a continuing "source" of contamination for the Eastern Plume. This appears to be the case especially in the region where numerous geologic cross-sections show the Lower Sand Unit pinching out (ending) before reaching the streams. The resulting artesian conditions and hydraulic pressure near the streams may have caused the contamination in the Lower Sand Unit to migrate deeper into the Transition Unit above and to the east. The lines of evidence pointing towards this scenario include:

1. The peculiar arrangement of the stratigraphic layers near the streams (pinching out of the Lower Sand Unit);
2. The generation of artesian conditions that potentially push contamination from the Lower Sand Unit into the Transition Unit;
3. The continuing hydraulic gradient towards the streams through the intervening Transition Unit;
4. The persistence of elevated VOC and 1,4-dioxane levels in the plume footprint despite 14 years of pump and treat (even though concentrations have significantly decreased over time);
5. The fact that the highly water-soluble and less sorptive contaminant (1,4-dioxane) has not been washed away with the groundwater flow and continues to persist in the same historical plume footprint as the less soluble and more sorptive VOCs; and,
6. Slug test results that seem to show that the geology surrounding some of the monitoring wells with continuing elevated levels of contamination as being predominantly Transition Unit, not Lower Sand Unit.

To support the CURT's understanding of the contamination residing in the Transition Unit, the CURT briefly reviewed the designation of the monitoring wells. The review indicated some uncertainty in the current differentiation of monitoring wells between Transition and Lower Sand Units, especially at locations closer to Merriconeag Stream and Mere Brook, alongside the eastern boundary of the plume. **Appendix B** Table 1 summarizes the CURT's review of slug test data, boring logs, and geological cross-sections associated with the monitoring wells in the long-term monitoring program. Some wells designated as being in the Lower Sand Unit show slug test results (hydraulic conductivities of 10^{-4} cm/s

or lower) more characteristic of the Transition Unit (interbedded silts and clays). A review of the geologic cross-sections and the locations of wells near the streams also indicate that key eastern boundary wells, such as MW-313, MW-333, MW-334, MW-EP-345, MW-EP-347, MW-EP-354, MW-MB-06, MW-MB-04B, PZ-MB-B1, PZ-MB-B2, PZ-MB-B3, PZ-MB-C3, PZ-MB-C4, PZ-MB-01, PZ-MB-B4B, and PZ-MB-B6B, could possibly be screened in strata more akin to that of the Transition Unit than the Lower Sand Unit. If so, it would indicate that much of the remaining contamination in the Eastern Plume remains trapped in the Transition Unit, from where it could slowly be released to the Upper Sand Unit or Lower Sand Unit.

Figure 5 further explains how contamination that has historically migrated in sandy layers gets trapped in silty or clayey zones. In addition, the figure illustrates how these less permeable layers then act as "sources" themselves, with contamination diffusing slowly out over time. This often results in large dilute plumes that persist for many years or decades, after the bulk of the contamination in the sandy layers has been removed by natural advective flow or active treatment. This scenario has been encountered at several former Navy and BRAC sites including NIROP Fridley, former NAS Alameda Point, and NSA Mid-South. Residual contamination trapped in finer lower-permeability layers is very difficult to extract by pumping or treat by active injection of reagents.

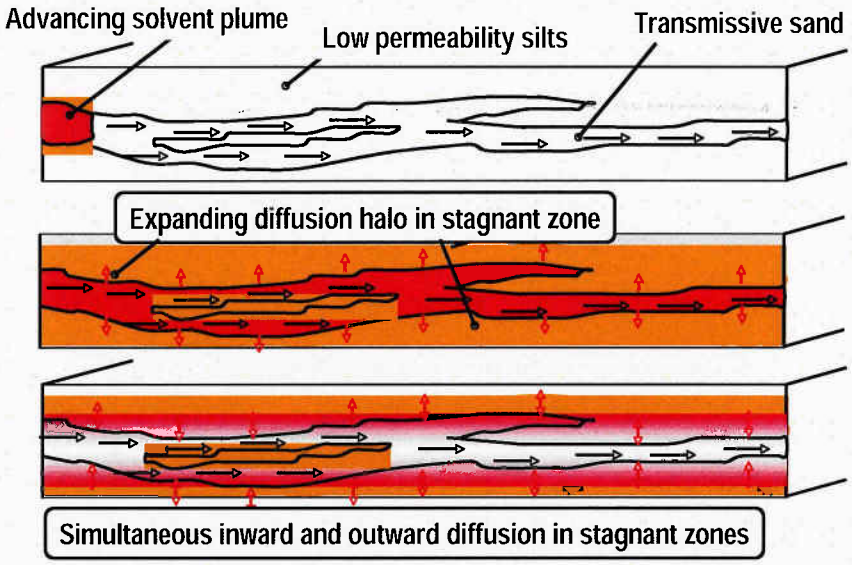

Figure 5. Impact of Back-Diffusion on Contaminant Concentrations Released from Transition Unit (RITS, 2008)

In the bedrock beneath the Eastern Plume, groundwater flow is primarily to the east and appears to have remained largely free of the contamination in the overburden (e.g., bedrock wells MW-210R and MW-210A). The clay layer overlying the bedrock is relatively continuous and is several feet thick in many places. This clay layer acts as a competent confining layer for downward migration. However, in two locations where the bedrock subcrops and the clay is very thin or absent, very low concentrations of VOCs have been found. It is unclear if these two locations are connected hydraulically in the bedrock. One location, MW-323 (near Site 11), is where low levels of 1,1-DCE (2 ppb), 1,1-DCA (5 ppb) and cis-1,2-DCE (0.9 ppb "J", or estimated) were found in October 2003. This location is far west of the plume's western boundary. The other location is near MW-308, where low levels of VOCs were first detected in 2006. In September 2008, LTM sampling showed groundwater contamination at MW-308 with concentrations of 1,1-DCE (7.4 ppb), 1,4-dioxane (10.8 ppb), TCE (14.4 ppb) and 1,1-DCA (3.4 ppb). Based on the results of the LTM, a bedrock investigation in the vicinity of MW-308 was initiated in

November 2008. The most recent round of LTM sampling at MW-308 (April 2009) detected two VOCs exceeding regulatory limits, 1,1-DCE (8.1 ppb) and TCE (17.1 ppb), with the 1,4-dioxane result similar to the last monitoring event (9.1 ppb), (final report forthcoming). **Appendix B** Table 2 presents the bedrock wells (including any sampled residential wells) in progression from west to east. This table includes the screened interval, stratigraphy, TCE concentration, and date sampled (TCE has been detected more consistently in the bedrock than the other VOCs or 1,4-dioxane). Sample results from the latest round of LTM (April 2009) were also included where applicable. As seen in this table, the only consistent detection of TCE concentration in bedrock wells is associated with only one well, MW-308.

The November 2008 bedrock investigation involving three bedrock well clusters at MW-340, MW-341, and MW-342 near MW-308 did not find any indication of widespread contamination in the bedrock. The bedrock well clusters, MW-340 and MW-341, installed north and upgradient of MW-308 did not have detectable concentrations of VOCs. The bedrock well cluster, MW-342, that was co-located with MW-308 had low levels of VOCs. At these locations, where the bedrock subcrops and the clay layer is absent, the Upper Sand Unit (the more conductive layer) also appears to be absent. Therefore, the bedrock is in direct contact with the Transition Unit, which is less conductive. It is possible that some contamination from the Transition Unit may have contacted the bedrock in these locations. There have been no detections above practical quantitation levels in bedrock monitoring wells for VOCs that are located east of the Merriconeag Stream (namely MW-309, MW-317 A and B, and MW-316 A and B).

In October 1990, the Navy sampled 23 off-site private wells for VOCs using drinking water sampling methods. TCE was tentatively detected at a very low level (0.5 ppb) in a shallower residential well (100 ft deep) close to Merriconeag Stream. This detection was interpreted in the Supplement RI (E.C. Jordan, 1991) as unlikely to be associated with the Eastern Plume and possibly a false positive. This well was re-sampled in February 1991 and no VOCs were detected during the second round of sampling. Another shallow residential well (47 ft deep) was sampled by MEDEP twice in January 2006 and showed low (0.4 J and 0.74 ppb) concentrations of TCE. Again, background interference cannot be ruled out at these low levels. This well is shallow enough to be screened in the Transition Unit rather than bedrock. Neither of these two shallow residential wells has been consistently sampled. The only residential well that has been consistently sampled from 2003 to 2009 (at a depth of 240 ft) has not showed any detection of VOCs or 1,4-dioxane. Therefore, there is no clear indication that the plume has migrated beyond Merriconeag Stream through the bedrock or is likely to do so in the future, in any significant measure. As seen in **Figure 4-D**, the hydraulic gradient in the bedrock on the east side of Merriconeag Stream appears to be towards the stream (or towards the west). Therefore, the geology (subcropping of the clay and bedrock) and hydrology (flow towards Merriconeag Stream) on the east side of the streams do not appear to support any substantial migration of the Eastern Plume eastward beyond Merriconeag Stream).

Recommendations. To better understand the hydrogeology governing the Eastern Plume, the CURT recommends the following (driven by data gaps identified both in Section 2.1.1 and Section 2.1.3).

- Conduct slug tests in as many wells as possible, especially along the eastern boundary of the plume near the streams. This will enable a better understanding of which wells are truly screened in the Lower Sand and which wells are more likely screened in a predominantly Transition type geology. This may provide a clearer picture of how accessible the remaining contamination in the plume is to pumping or treatment (injection of reagents).
- Add an additional bedrock well east of MW-309 to provide better delineation of bedrock gradient and flow east of the streams and to act as a sentinel for any potential plume migration in the horizon running through MW-323, MW-308, and MW-309.
- Continue annual monitoring of overburden wells along the western, eastern, and southern boundaries of the current plume footprint as well as the continued annual monitoring of sentinel

bedrock wells located on the east side of the streams for VOCs and 1,4-dioxane as added protection for the residential wells further east.

- Consider completing the residential well inventory to collect well depths, GPS locations and groundwater use (landscaping vs. drinking) for bedrock wells located east of the Eastern Plume. Upon completion of the inventory, site representatives may be in a better position to assess the need for any additional sentinel wells.

2.1.4 Aquifer Geochemistry and Natural Attenuation Potential. The objective of the MNA assessment in 2005-2006 was to determine the potential for biodegradation within the Lower Sand Unit of the Eastern Plume with regard to the chlorinated solvents. In order to determine the potential for biodegradation, MNA parameters were collected at 34 monitoring wells and included the following analytes:

- Dissolved Gases (methane, ethane, and ethene)
- Total Selected Metals (arsenic, iron, and manganese)
- General Chemistry (alkalinity, chloride, nitrate, nitrite, sulfate, ferrous iron, and total organic carbon)
- Field Parameters—Collected during the time of sampling at the selected well locations including temperature, pH, conductivity, dissolved oxygen, oxidation-reduction potential, turbidity, and color

In addition to the MNA parameters, VOCs were collected to look for the presence of biodegradation daughter products of the parent chlorinated solvents. The results of the MNA assessment showed sporadic evidence of chlorinated solvent degradation by reductive dechlorination in the Lower Sand Unit. Anaerobic biodegradation products, such as 1,2-DCE (from reductive dechlorination of PCE and TCE) and 1,1-DCA (from 1,1,1-TCA) appear in some wells, but not in others. In terms of geochemical parameters, the Lower Sand Unit appears to range from aerobic along the western edge of the Eastern Plume (e.g., MW-105A) to anaerobic in the middle of the plume (e.g., MW-207AR) to strongly anaerobic near the streams (e.g., MW-230A). This is evident from low dissolved oxygen and oxidation-reduction potential, higher iron, lower sulfate, and minor methane detections in wells nearer the streams. No lesser-chlorinated biodegradation products (such as vinyl chloride [VC], ethane, chloroethane) were reported in the Lower Sand Unit, but a subsequent investigation (ECC, 2008) of "pore water" or shallow groundwater in the Upper Sand Unit showed signs of vinyl chloride and chloroethane production. This indicates that anaerobic biodegradation potential improves as the groundwater enters the more carbon-rich (organic matter-rich) environment associated with the stream sediments and associated wetlands.

When assessing the natural attenuation processes at a site, consideration should also be given to potential contributions of plants to attenuate the contamination. Given the abundance of natural vegetation in the area near the confluence, the propensity of both VOCs and 1,4-dioxane to be uptaken by plants, and the upwelling of groundwater near the streams, the CURT sees good potential for attenuation of the target contaminants by plant uptake and discusses this further in Section 4.7.

Recommendations: The CURT recommends a concerted effort to better assess the geochemistry and natural attenuation potential of the aquifer, especially at the groundwater-surface water interface. The groundwater-to-surface water interface should be better evaluated for MNA potential, especially in the critical last several inches of sediment (pore water) before the upwelling groundwater discharges to surface water. LTM plan should include general chemistry and selected metal parameters in select wells

once every two years for proper monitoring of aquifer geochemistry. VOCs and 1,4-dioxane should be monitored at several depths in the sediment pore water to determine the degree of attenuation.

2.1.5 Additional Investigations. Several additional investigations and annual LTM over the past 15 to 20 years have evaluated the impacts of the Eastern Plume to shallow and bedrock groundwater, surface water, sediment, and pore water.

2.1.5.1 Groundwater. As a part of the LTM of the plume, groundwater VOC data have been collected since 1995. VOC concentrations in the plume have declined considerably over the years as shown in trend graphs compiled by the CURT (see **Appendix C**). The LTM reports have traditionally focused on total VOC concentrations rather than individual constituents. To better evaluate specific VOCs with respect to regulatory limits, the CURT generated VOC trend graphs for the selected COCs while comparing to associated Maine CDC Maximum Exposure Guidelines (MEGs) for drinking water and EPA Maximum Contaminant Levels (MCLs) for drinking water. Constituent specific figures enable the assessment for each contaminant of concern and more accurately represent the state of the plume. The CURT recommends reporting the VOC on a constituent specific basis. Furthermore, if total VOCs will still be calculated, the method for generating the total VOCs should be re-evaluated as the addition of all data, including flagged data, compounds statistical error.

Table 1 summarizes the findings from the CURT review of the results from recent investigations. Historical maximum concentrations are shown in the first data column. When the CURT review began, the LTM data from Event 33 (ECC, 2009b) were the most recent and are shown in the second data column. Subsequently, data from an April 2009 investigation became available and are summarized in the third data column. These data indicate that VOC concentrations have declined substantially in the plume, especially since 1995 when the GWETS was first installed. The operation of the GWETS has resulted in significant VOC mass removal from the plume. However, the recent persistence of VOCs at levels below 1 mg/L (or 1,000 µg/L) indicates that the GWETS may be reaching the limits of its ability to extract residual contamination, which may be sequestered in the lower permeability portions of the aquifer (i.e., in the Transition Unit).

Table 1. Contaminants of Concern Concentration Summary in Groundwater (µg/L)

Contaminant of Concern	MEG	MCL	Historical Maximum Concentration Long-Term Monitoring 1995 - 2008	Recent Maximum Concentration DRAFT LTM Event 34 (H&S, April 2009)	Current Maximum Concentration DRAFT 1,4-Dioxane Remedial Investigation Supplement, (TtNUS, 2009)*
1,1-Dichloroethene (DCE)	0.6	7	1810	79.0	430
1,1-Dichloroethane (DCA)	70	NC	130	60.8	210
cis-1,2-dichloroethene	70	70	340	6.1	72
trans-1,2-dichloroethene	140	100	1.2 J	ND	2
1,1,1-Trichloroethane (TCA)	200	200	14,000	251	500
Trichloroethene (TCE)	32	5	3,400	182	860
Tetrachloroethene (PCE)	7	5	150	22.8	15
Vinyl Chloride (VC)	0.2**	2	ND	ND	0.8 J
1,4-Dioxane	32	NC	180	102 J (101)	350

* New well location results (TtNUS report forthcoming)
** Interim (not final)
ND = Non-Detect
NC = No Criteria
J = Estimated value, below practical quantitation limit

The majority of the recent maximum concentrations from LTM Event 34 were detected in extraction well EW-5B. This extraction well is not connected to the GWETS at this time. The majority of the 2009 maximums from the Draft 1,4-Dioxane Remedial Investigation Supplement (TtNUS, 2009) were in the new monitoring well, MW-EP-347, which is just south of bedrock well MW-308, which separates the northern and southern lobes of the Eastern Plume. This new well is designated as a Lower Sand Unit well, but given the uncertainty of the stratigraphy at nearby points, it could be in a predominantly Transition Unit type geology. This newly identified location with elevated VOC and 1,4-dioxane levels illustrates the limitations of the GWETS. If much of the residual contamination is sequestered in the Transition Unit, more such localized zones of contamination could continue to be found. Such zones in the Transition Unit were probably inaccessible to efficient treatment during previous operation of the GWETS and could continue to be inaccessible to inefficient treatment during future pump-and-treat efforts. For example, the current maximum concentrations at MW-EP-347 appear to be in a location that may be inaccessible to the nearest planned pumping well EW-05B located across the bedrock sub-crop divide near MW-308.

Total VOC isoconcentration maps were produced for each ground water sampling event since 1995. **Figure 6** is a composite map showing the changes in the shape of the total VOC plume from 1991 to 2003. This figure is based on the detection of any VOC above laboratory reporting limit and not the associated MEG or MCL. The plume concentrations have significantly decreased over the past fourteen years due to the operation of the GWETS. However, the overall size and shape of the plume has remained relatively unchanged over time, especially at the eastern and southern boundaries. This indicates that although the GWETS has removed considerable VOC (and 1,4-dioxane) mass from the interior of the plume, containment of the plume has historically been brought about primarily by the peculiar geology and hydrology of the site (the bowl-like clay and bedrock geology, the streams to the east, and the discontinuous nature of the Lower Sand Unit to the south). Furthermore, the effectiveness of the GWETS in removing VOC mass from the interior of the plume is illustrated in **Figures 7A-D** for 1,1,1-TCA (from 1995 to 2008).

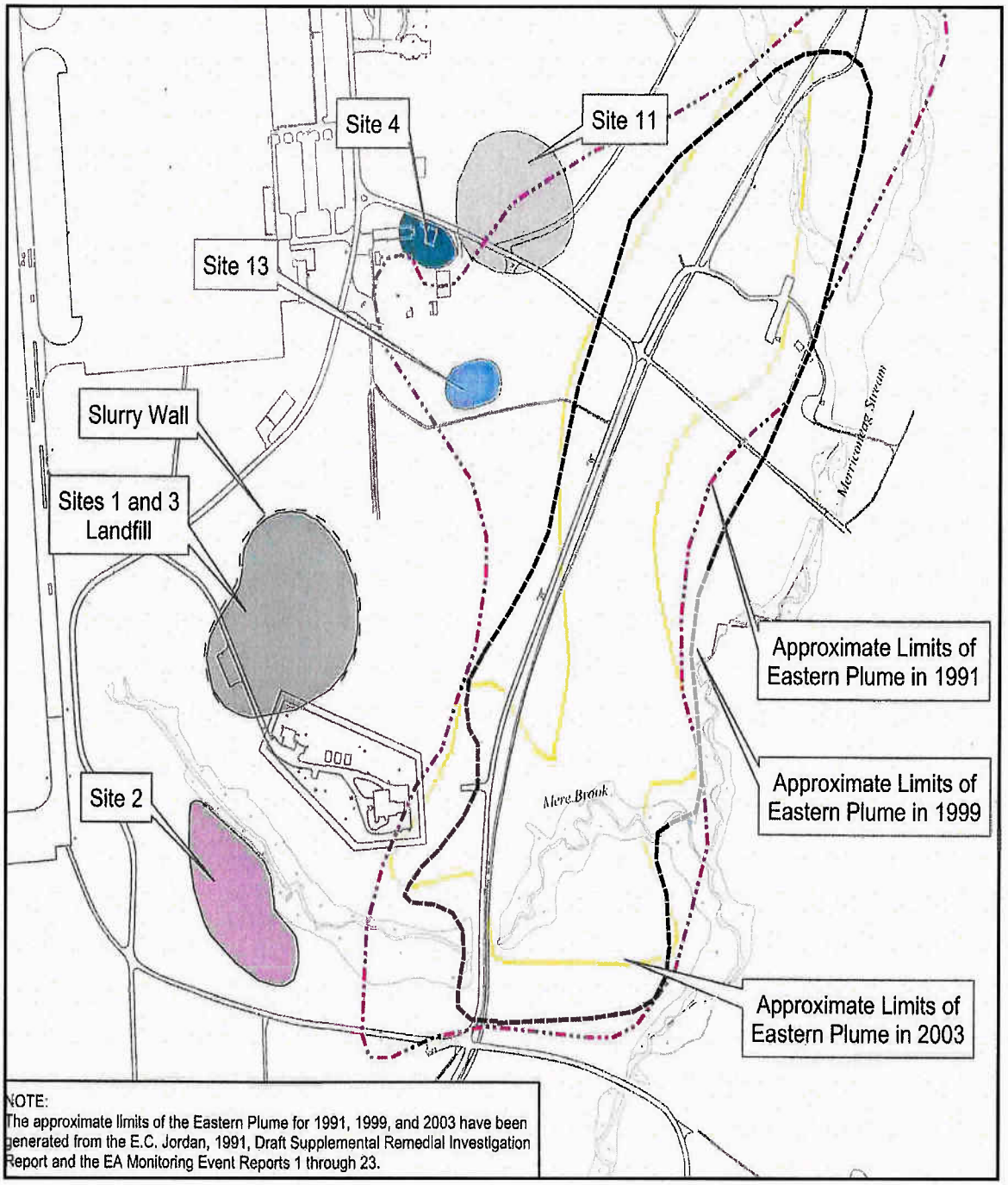

Figure 6. Historical Plume Map Since 1991
Showing that the Plume has Maintained the Same Shape

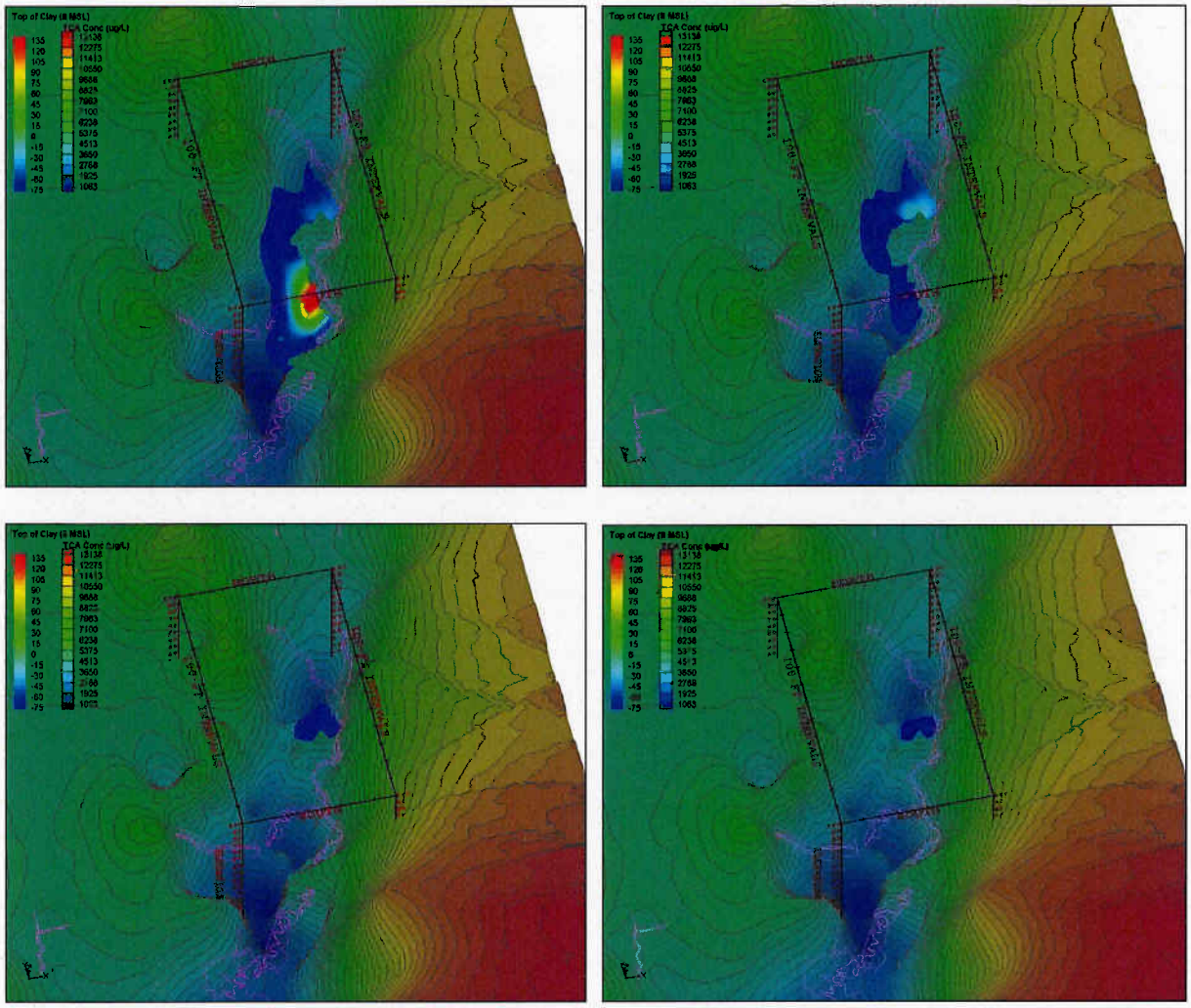

Figure 7. Reduction of 1,1,1-TCA from 1995 to 2008 with the Contaminant Threshold of MEG/MCL. Figure 7A is from 1998. Figure 7B is from 2000, Figure 7C is from 2004. Figure 7D is from 2008. (ECC, 2009a)

2.1.5.2 Surface Water. As stated previously, groundwater in the overburden region of the Eastern Plume appears to discharge primarily to the two streams, Merriconeag Stream and Mere Brook. These two streams and the associated hydrogeology (the tapering out of the Lower Sand Unit near the streams and the predominance of the low-permeability Transition Unit) have effectively confined the Eastern Plume along its current eastern boundary for several years. Surface water sampling of these streams, along the edge of the plume, during LTM has not indicated impact from COCs. There is no indication that COCs are migrating advectively in a southerly direction near the current southern boundary of the plume. The plume has shown relatively little movement to the south over the years and appears to be hydraulically confined near its southern boundary through a combination of two features. One is the hydraulic gradients that appear to direct flow towards Mere Brook. The other is the increasing discontinuity of the Lower Sand Unit south of the plume.

Surface water samples are collected as part of the LTM and have not shown any significant impact to the streams (**Table 2**). One COC (TCE) was detected in surface water during Fall 2001 and Spring 2003 with

low concentrations of 4 ppb and 5 ppb, respectively. No other VOC or 1,4-dioxane has been detected above practical quantitation levels in the surface water. In the most recent surface water sampling in April 2009, all the VOCs were non-detect, except PCE with an estimated value of 3.7J µg/L in a duplicate sample where the other sample was non-detect. As such, there has been no consistent detection of any of the VOCs in surface water. However, surface water has not yet been analyzed for 1,4-dioxane. Therefore, the CURT recommends adding 1,4-dioxane to the suite of compounds analyzed in surface water samples in the LTM.

Table 2. Contaminants of Concern Concentration Summary in Surface Water

Contaminant of Concern	Historical Maximum Concentration in Surface Water - LTM through April 2009 (ug/L)
1,1-Dichloroethene (DCE)	ND
1,1-Dichloroethane (DCA)	ND
cis-1,2-Dichloroethene	ND
Trans-1,2-Dichloroethene	ND
1,1,1-Trichloroethane (TCA)	ND
Trichloroethene (TCE)	5.0*
Tetrachloroethene (PCE)	ND, 3.7 J (Duplicate)**
Vinyl Chloride (VC)	ND
1,4-Dioxane	NA

*Detected in November 2001 & May 2003 only
**Detected in April 2009 only as J value
J = Estimated value, below practical quantitation limit
ND = Non-Detect
NA = Not Analyzed

2.1.5.3 Sediment Samples. Sediment sampling has been limited under the LTM program. Sediment samples from one location (SED-11) have been collected twice per year from 2004 to April 2009. However, the samples were not analyzed for VOCs until the April 2008 sampling event. **Table 3** presents the maximum detected sediment concentration data collected during the LTM program. The limited sediment data indicate that no substantial levels of contamination (including VOCs and 1,4-dioxane) is reaching the sediment-surface water interface from the groundwater below. The VOC detects are below practical quantitation limits and the 1,4-dioxane detect is similarly low and needs validation (appears to be below achievable method detection limits). Sorption and biodegradation in the sediment, as well as uptake by plants, may be possible mechanisms attenuating any contamination upwelling through the shallow groundwater.

Table 3. Contaminants of Concern Concentration Summary in Sediment

Contaminant of Concern	Sediment Sampling - LTM through April 2009 (mg/kg)
1,1-Dichloroethene (DCE)	ND
1,1-Dichloroethane (DCA)	ND
cis-1,2-Dichloroethene	ND
trans-1,2-Dichloroethene	ND
1,1,1-Trichloroethane (TCA)	0.02 J
Trichloroethene (TCE)	0.05 J
Tetrachloroethene (PCE)	0.17 J
Vinyl Chloride (VC)	ND
1,4-Dioxane	0.0039 J

*Limited data - one sediment station was sampled during April 2008 and 2009 LTM (SED-11)
ND = Non-Detect
J = Estimated value, below practical quantitation limit

2.1.5.4 Shallow Groundwater or "Pore Water" Samples. Two sediment "pore water" investigations have been conducted along Merriconeag Stream and Mere Brook and are documented by MEDEP in the "Pore Water Sampling Data from Mere Brook & Merriconeag Stream Area" (August & September 2005) and from the EPA New England Field and Fixed Laboratory (August 2008). For these studies, samples were collected every 20-50 feet for approximately 4,000 feet along Mere Brook and Merriconeag Stream, starting approximately 1,000 feet north of Picnic Pond, proceeding south to approximately 750 feet south of the confluence of the streams. In addition, there are "pore water" samples collected as part of the LTM. Some of these "pore water" samples were collected as much as three feet below the sediment-water interface using push point sampling (metal rods) and pumping of groundwater up through tubing for collection. Therefore, these samples are more representative of shallow groundwater rather than pore water within the sediment. A true pore water sample would be collected from the interstitial pore water which is the water adhering between near-surface sediment particles. There are several methods such as passive diffusion bags, centrifuged sediments, Passive Vapor Diffuser (PVD) samplers, or any suitable multi-level sampler available for collecting sediment pore water samples. At some point, true pore water samples for the Eastern Plume may be desirable to verify that attenuation of COCs is taking place in the upwelling water, as indicated by the surface water sample results.

"Pore water" sampling conducted along Mere Brook's eastern bank in the vicinity of MW-313 north of the confluence with Merriconeag Stream (triggered in part by the surface water detections) indicates that the COCs are upwelling in the shallow groundwater in the Mere Brook floodplain, with the highest measured concentrations found near the confluence within the vicinity of PW-51 in August 2005 (**Table 4**; ECC, 2008). Aside from the immediate area surrounding PW-51, the concentrations were significantly lower or undetected in the other "pore water" samples (> 100 samples collected as part of the studies). In addition to the parent VOCs, biodegradation daughter products such as VC were detected at the site for the first time in the "pore water" studies, ranging from 1.2 to 19 µg/L. The investigations found upwelling of contaminants in the southern lobe of the plume, but not in the northern lobe. Most importantly, the data show biodegradation occurring in the sediment, before the upwelling groundwater discharges to surface water. Many of the parent VOCs and the less-chlorinated degradation products, such as VC, would be very amenable to biodegradation in the changing redox environment of the sediment.

Table 4. Contaminants of Concern Concentration Summary in Shallow Groundwater or "Pore Water"

Contaminant of Concern	Maximum Shallow Groundwater Concentrations or "Pore Water" (LTM, DEP/EPA Studies from 2005 & 2008) (µg/L)	Depth of Sample Below Ground Surface (inches)
1,1-Dichloroethene (DCE)	40 / 130 D*	18
1,1-Dichloroethane (DCA)	130	30
cis-1,2-Dichloroethene	2.3	36
trans-1,2-Dichloroethene	NA	NA
1,1,1-Trichloroethane (TCA)	200 / 390 D*	18
Trichloroethene (TCE)	150 / 160 D*	18
Tetrachloroethene (PCE)	10 / 6.9*	18
Vinyl Chloride (VC)	19	18
1,4-Dioxane	180 / 490 D	18

*EPA mobile lab / fixed lab
ND = Non-Detect
NA = Not Analyzed
D = serial dilution

Recommendations: In summary of Section 2.1.5 on the additional investigations and annual LTM over the past 15 to 20 years, the CURT recommends the following:

- Present groundwater plume maps for key individual COCs instead of the total VOCs. The sum of the total VOC does not appropriately represent the state of the plume nor the potential risk from the plume as each COC has different regulatory limits. Furthermore, the many J flagged data and their use in data tables and plume maps needs to be studied closely. In some instances, J flagged data appear to be above reporting limits.
- Add 1,4-dioxane to the suite of compounds analyzed in surface water samples in the LTM.
- Collect true pore water samples from the sediment pore water (as opposed to shallow groundwater) for analysis of VOCs, 1,4-dioxane, and geochemistry/natural attenuation parameters. Pore water should be collected from multiple depths in the sediment, including water from near-surface sediment.

2.2 Risk Evaluation

The CURT conducted a preliminary risk evaluation of NAS Brunswick in order to be able to assess the feasibility of incorporating a risk management approach along with the selection of alternative actions for the groundwater plume. A risk management approach is the process of evaluating and selecting among alternative actions to reduce risk to human health and the environment, which is driven by an evaluation of the contaminated media, exposure pathways, and impact to current and future receptors. For the Eastern Plume, important factors such as land use, groundwater use, and potential exposures to COCs in the plume were examined by the CURT in order to help the BRAC team determine the remedial strategy for this site. Understanding contaminant properties and geologic/hydrogeologic conditions is important for determining whether human or environmental receptors could potentially be exposed to the COCs in the Eastern Plume, and ultimately aid in identifying appropriate treatment technologies or other risk management alternatives to render the exposure incomplete. There must be a complete exposure pathway from the source of chemicals in the environment to potential receptors for chemical intake to occur. If an exposure pathway is incomplete, no chemical intake occurs and no adverse effects are associated with site-related contaminants. Due to the mitigating effects of the hydrogeological containment of the Eastern plume within its current boundaries and of several years of groundwater remediation (GWETS) that have removed considerable contaminant mass from the plume, a preliminary evaluation of the human and ecological potential exposure evaluations (described below) shows exposure to COCs is insignificant or incomplete.

2.2.1 Potential Human Receptors and Exposures. Human receptors may be exposed to COCs either directly, through activities that result in contact with contaminated environmental media (e.g., ingestion of groundwater), or indirectly, as a result of contaminant migration to locations where contact with receptors can occur (e.g., vapor migration into buildings). Exposure to COCs in groundwater are currently prevented through the use of institutional controls (ICs) consisting of groundwater and land use restrictions that are in place. Evaluations of potential future human exposure situations were conducted based on the current re-use plans of the land overlying the Eastern Plume in conjunction with expressed risk concerns of the RAB members.

The current future use of the land overlying the Eastern Plume is designated as Recreation and Open Space or Natural Areas in the Reuse Master Plan for the base prepared for the Brunswick Local Redevelopment Authority by the Matrix Design Group (2007). Overseeing implementation of the reuse plan is the Midcoast Regional Redevelopment Authority (MRRA), a governmental agency established by the Maine Legislature. The intent of the Recreation and Open Space is to provide suitable areas for a

variety of active and passive outdoor recreational opportunities for the community, such as public parks, recreation fields, golf courses, public gardens, bicycle trails, and equestrian facilities. The intent of the Natural Areas is to preserve, maintain, and enhance existing natural areas for the long-term benefit of area residents and the natural environment. Thus, uses that would not significantly alter the environment and/or would provide opportunities to experience the environment would be considered, including pedestrian trails, nature and interpretive centers, environmental education, and other non-intrusive passive outdoor recreation and educational uses.

Based on the potential future use, exposure pathways were evaluated and are summarized in **Figure 8** and described below.

- **Possible groundwater and drinking water use on-site.** For on-site receptors, this exposure pathway is incomplete because groundwater within the overburden and bedrock beneath the Eastern Plume is not used for drinking water or any other uses and the area is already serviced by a public water supply. In addition, transfer or lease of the property in the future will include appropriate provisions (i.e., restrictive covenants or other use restrictions) to prevent the potential future use of and contact with the site groundwater without prior written approval from EPA and MEDEP.
- **Possible vapors in buildings above or near groundwater contamination.** For on-site receptors, this pathway is incomplete because future use of the site will be recreation/open space and no buildings are likely to be built overlying the groundwater plume.
- **Possible groundwater and drinking water use off-site**. For off-site receptors, this exposure pathway may be potentially complete in the future. Some residents living to the east of the Eastern Plume obtain their drinking water from private bedrock wells. These off-site private wells have been sampled periodically by the Navy or MEDEP between 1990 and 2006 (EC Jordan, 1991; ECC, 2008). TCE was detected below the regulatory limits in two residential wells – once in 1991 and once in 2006 (see Table 2 in **Appendix B**). Groundwater sampling results of some of the Eastern bedrock wells in the current plume footprint have indicated the presence of low level VOCs, therefore, there may be a potential concern of COCs impacting residential private wells in the future. However, concentrations of the COCs are expected to be less than concentrations observed within the Eastern Plume (i.e., below MEG and MCL) because of historical remediation efforts and various natural attenuation mechanisms (e.g., hydrogeologic containment); thus, the pathway is deemed to be insignificant.
- **Possible exposure to COCs in on-site or nearby surface water/sediment**. For on-site receptors, this exposure pathway might be complete. Because the future use of the site will be recreation/open space, individuals will have access to the streams. Although recreational activities such as swimming and boating will most likely not occur in these streams, it is feasible that an individual might wade in them. Therefore, exposure to surface water and sediment is a potentially complete pathway in the future; however, exposure to COCs in surface water and sediment is unknown at this time. Surface water sampling results have been non-detect for VOCs since 2001 (see Table 2). Surface water has not been analyzed for 1,4-dioxane yet, but given the relatively low levels of this compound in groundwater and various potential attenuating mechanisms (e.g., plant uptake) that are operative near the streams and associated wetland, this exposure pathway is likely to remain insignificant.

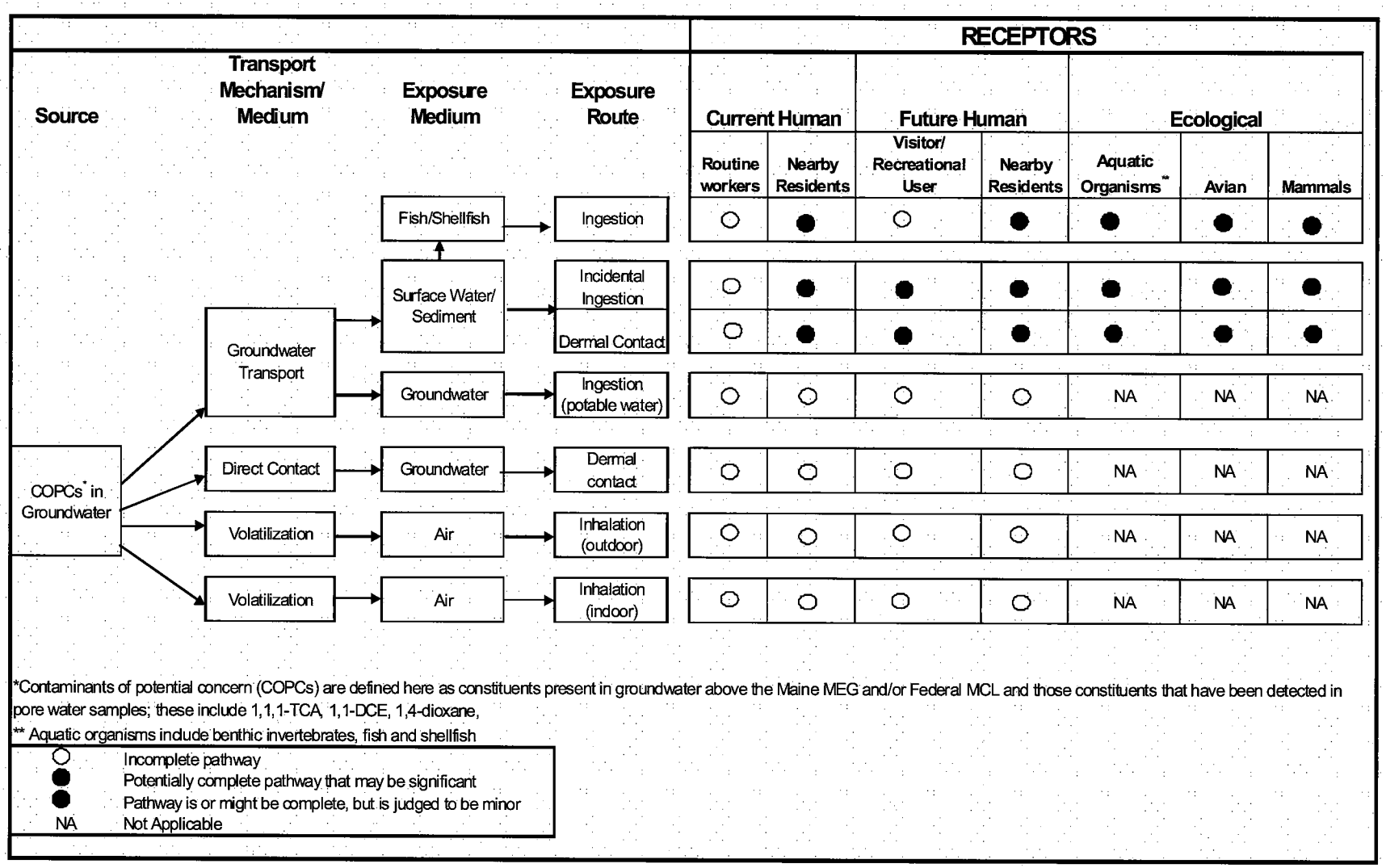

Figure 8. Risk Assessment Conceptual Site Model for the Eastern Plume

- **Possible ingestion of contaminated fish/shellfish.** For on-site and off-site receptors, ingestion of fish/shellfish has been assumed to be a potentially complete exposure pathway, but an insignificant route of exposure. This exposure route is complete because consumption of fish/shellfish caught from on-site streams may potentially occur in the future when the site is redeveloped as a recreation/open space area. However, COCs identified in the Eastern Plume are not bioaccumulative based on USEPA's definition, and therefore the fish/shellfish caught from on-site streams are not expected to contain concentrations of the COCs at levels that would be harmful if consumed. USEPA defines bioaccumulative chemicals as those displaying a half-life of greater than 30 days (i.e., are persistent), a bioconcentration factor (BCF) of greater than 1000, or a log K_{ow} value of greater than 4.2 (USEPA, 2000). COCs identified in the Eastern Plume are not bioaccumulative based on USEPA's definition (see **Table 5**).

To further evaluate the potential exposure associated with ingestion of fish/shellfish, maximum concentrations (as a conservative case) of COCs detected in surface water were compared to USEPA Water Quality Criteria (WQC) (**Table 6**). Once near-surface pore water is collected and analyzed, these data could be used for comparison to WQC as well. In order to prevent harmful exposures to chemicals in water through eating contaminated fish and shellfish, USEPA, as part of Section 304(a)(1) of the Clean Water Act, has derived water quality criteria for protecting human health that addresses chemical bioaccumulation in aquatic organisms. A human health criterion is the highest concentration of a pollutant in water that is not expected to pose a significant risk to human health. Because the COCs within the Eastern Plume are not bioaccumulative, WQC are expected to be high relative to other criteria, such as drinking water standards (i.e., MEG and MCL) where the constituent is directly consumed by the receptor.

Table 5. Contaminants of Concern and Physicochemical Properties Associated with Bioaccumulation

Contaminants of Concern	Volatilization Half-life from River Model[a]	BCF	Log Kow
1,1-Dichloroethene (DCE)	3 hours	2.5 - <13	2.13
1,1-Dichloroethane (DCA)	3 hours	5	1.79
cis-1,2-Dichloroethene	1.1 hours	5	1.86
trans-1,2-Dichloroethene	1.1 hours	8	2.06
1,1,1-Trichloroethane (TCA)	1 hour	0.7 – 4.9	2.49
Trichloroethene (TCE)	3.5 hours	4 - 39	2.61
Tetrachloroethene (PCE)	1 hour	26 - 77	3.4
Vinyl chloride (VC)	1 hour	<10	0.6[b]
1,4-Dioxane	5 days	0.2 - 0.7	-0.27

Source for all of the values: the Hazardous Substances Data Bank available at http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB, unless otherwise indicated.
BCF = bioconcentration factor
[a] Volatilization from water surfaces is expected based on the chemical-specific Henry's Law constant. Using the Henry's Law constant and an estimation method, volatilization half-lives for a model river [model river 1 m deep, flowing 1 m/sec, wind velocity of 3 m/sec (Lyman et al.. 1990. Handbook of Chemical Property Estimation Methods. Washington, DC: Amer Chem Soc pp. 4-9, 15-1 to 15-29] were calculated and provided in the Hazardous Substances Data Bank available at http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB.
[b] Log Kow for vinyl chloride was obtained from an USEPA fact sheet available here: http://www.epa.gov/ogwdw/pdfs/factsheets/voc/tech/vinylchl.pdf

Table 6. Comparison of Surface Water Concentrations to Water Quality Criteria

Contaminants of Concern	Maximum Concentration Detected in Surface Water[a] (µg/L)	USEPA National Recommended Water Quality Criteria for Consumption of Organism Only[c] (µg/L)
1,1-Dichloroethene (DCE)	0.05 (ND)	7100
1,1-Dichloroethane (DCA)	ND	NDT[d]
cis-1,2-Dichloroethene	ND	NDT[d]
trans-1,2-Dichloroethene	ND	10,000
1,1,1-Trichloroethane(TCA)	0.05 (ND)	NDT[d]
Trichloroethene (TCE)	5	30
Tetrachloroethene (PCE)	ND, 3.7 J (Duplicate)	3.3
Vinyl chloride (VC)	0.05 (ND)	2.4
1,4-Dioxane	NA	NDT[d]

*EPA mobile/fixed lab
J = Estimated value, below practical quantitation limit
NA- Not Analyzed
ND = Non Detect
NDT - Not Determined
[a] Data includes results from a total of four spring and fall events between April 2007 and September 2008 for sampling locations SW-10 through SW-14. All COCs were nondetect (i.e., <1 µg/L); the concentration shown here is 1/2 the detection limit.
[b] Data consists of pore water samples collected in August 2008 (MEDEP/Navy/USEPA) and September 2008, sampling locations PW-01 through PW-04, from Monitoring Event 33.
[c] USEPA. 2006. National Recommended Water Quality Criteria for Human Health Consumption of Organism Only (http://www.epa.gov/waterscience/criteria/wqctable/). Values for 1,1,1-TCA and 1,4-dioxane have not been developed by USEPA.
[d] Chemical will not build up in plants or animals (ATSDR ToxFAQs: http://www.atsdr.cdc.gov/tfacts20.html).

As previously discussed, swimming in the streams does not currently occur, nor is it likely to occur in the future based on the physical limitations of the streams themselves; thus, ingestion of surface water is not a complete exposure pathway. Therefore, the USEPA WQC for human health consumption of "organism only" and not "water + organism" is used in this comparison. As evidenced in **Table 6**, the maximum concentrations detected in surface water are less than the respective USEPA WQC for all COCs, except PCE, which showed a low estimated (i.e, "J" qualifier) detection of 3.7 µg/L in a duplicate sample. The PCE detection, however, is suspect given that the associated field sample was nondetect. Although a WQC does not exist for 1,1,1-TCA and 1,4-dioxane, published information available for these two COCs (ATSDR, 2006 and 2007) indicate that bioaccumulation does not occur in plants or animals.

The comparison showing surface water concentrations of COCs as being below WQC was based on COC concentrations within the current Eastern Plume boundaries. COC concentrations in the surface water outside the Eastern Plume boundaries, at locations downstream along Mere Brook, including Harpswell Cove, will be much lower (due to various attenuating mechanisms) and therefore will be below the WQC as well.

2.2.2 Potential Ecological Receptors and Exposures. Ecological receptors could potentially be exposed to COCs in groundwater via groundwater discharge to surface water. As discussed above (**Table 5**), the COCs identified for groundwater possess physicochemical properties that greatly affect their behavior (i.e., partitioning, bioaccumulation) in the environment. These properties are important considerations in exposure pathway analysis because they are a primary determinant of whether a contaminant detected in surface water is likely to be associated with adverse effects to ecological receptors. Because detected concentrations of VOCs in the surface water and pore water samples

associated with the Eastern Plume are generally low and these constituents do not bioaccumulate, VOC exposures to ecological receptors do not pose unacceptable risk.

In addition, maximum COC concentrations in surface water samples collected near the Eastern Plume area were compared to risk-based ecological screening values in **Table 7**. These values were developed by the Navy and agreed to by the USEPA and Maine as part of the long-term monitoring program for the Eastern Plume. Final approved values are provided in EA Engineering (2006) and supporting documentation for the 1,4-dioxane screening-values are provided in **Appendix D**. The screening values developed are for freshwater environments and are based on continuous chronic criteria for the protection of aquatic organisms. As shown in **Table 7**, all of the COC concentrations in surface water samples are below the surface water screening criteria.

The simple screening evaluation presented in **Table 7**, can also be used to assess the impact of contaminated groundwater through the groundwater-surface water transition zone, once near-surface pore water samples are collected. The transition zone represents an important ecosystem that exists between surface water and the underlying groundwater because it receives water from both of these sources, and as such, biota inhabiting or dependent on the transition zone may be adversely impacted by contaminated groundwater discharging through the transition zone into overlying surface-waters (USEPA, 2008). In accordance with the methodology provided by USEPA (2008), chemicals present at concentrations below the screening values are assumed to pose acceptable risks to the transition zone biota and no further evaluation of the transition zone is necessary.

2.2.3 Risk Summary. In summary, the CURT did not see any clear evidence of unacceptable risk associated with potential exposure to the Eastern Plume by human and ecological receptors, based on this preliminary evaluation. Although 1,4 dioxane has not been analyzed in surface water samples yet, none of the VOCs have been consistently detected in surface water. Distant surface water receptors, such as Harpswell Cove, are protected by the hydraulic containment afforded the plume along its southern boundary by discontinuities in the Lower Sand Unit and by the travel distance along Mere Brook. Residential wells on the eastern side of the streams appear to be counter-gradient to the direction of bedrock flow on the east side of Merriconeag Stream and no VOC has been consistently detected on the east side of the streams.

Table 7. Comparison of Surface Water Concentrations to Risk-Based Ecological Screening Values

Contaminants of Concern	Maximum Concentration Detected in Surface Water[a] (µg/L)	Risk-Based Ecological Screening Values[c] (µg/L)
1,1-Dichloroethene (DCE)	0.05 (ND)	25
1,1-Dichloroethane (DCA)	ND	47
cis-1,2-Dichloroethene	ND	590
trans-1,2-Dichloroethene	ND	590
1,1,1-Trichloroethane (TCA)	0.05	11
Trichloroethene (TCE)	5	47
Tetrachloroethene (PCE)	ND, 3.7 J (Duplicate)	98
Vinyl chloride (VC)	0.05	69
1,4-Dioxane	NA	121,000 (fish) 1,151,000 (Mysid shrimp)[d] 22,000[e] 200,000[f] 390,000[g]

NA- Not Analyzed
ND - Not Determined
[a] Data includes results from a total of four spring and fall events between April 2007 and September 2008 for sampling locations SW-10 through SW-14. All COCs were nondetect (i.e., <1 µg/L); the concentration shown here is 1/2 the detection limit.
[b] Data consists of pore water samples collected in August 2008 (MEDEP/Navy/USEPA) and September 2008, sampling locations PW-01 through PW-04, from Monitoring Event 33.
[c] EA Engineering. 2006. Revised Screening Values for Surface Water, Seep Water, and Sediment, Naval Air Station, Brunswick, Maine. January 31.
[d] Screening values for 1,4-dioxane derived using methodology in EA Engineering 2006, which utilized USEPA's ECOSAR model to estimate chronic aquatic toxicity values for fish and Mysid shrimp. As was conducted in the EA Engineering document, division of the modeled chronic value by 5 was used to approximate the No Observed Adverse Effect Level (NOAEL). Attachment D contains the ECOSAR output for 1,4-dioxane. Mysid shrimp are more similar to lobster with respect to life cycle, feeding habits, and biology than are fish; however, fish (which was the only receptor used in the EA Engineering document for ECOSAR values) provides a more conservative screening value.
[e] Value obtained from the Risk Assessment Information System (http://rais.ornl.gov/homepage/eco_foot.shtml#78) based on the U.S EPA Region 5 Ecological Screening Level for surface water and the Final Chronic Value provided in the Michigan Department of Environmental Quality Rule 57 Water Quality Values (http://www.michigan.gov/deq/0,1607,7-135-3313_3686_3728-11383--,00.html).
[f] Value is the Aquatic Maximum Value from the Michigan Department of Environmental Quality Rule 57 Water Quality Values (http://www.michigan.gov/deq/0,1607,7-135-3313_3686_3728-11383--,00.html).
[g] Value is the Final Acute Value from the Michigan Department of Environmental Quality Rule 57 Water Quality Values (http://www.michigan.gov/deq/0,1607,7-135-3313_3686_3728-11383--,00.html).

Recommendations: The CURT recommends the following to minimize exposure and prevent any future potential adverse effects to humans and the environment.

- Ensure appropriate provisions remain in place (i.e., restrictive covenants or other land use restrictions) to address drinking water and vapor intrusion for future transfer or lease of the property including water well and construction restrictions within the footprint of the Eastern Plume.
- Conduct annual sampling for VOCs and 1,4-dioxane in sentinel bedrock wells located to the east of Merriconeag Stream.

- Include analysis for 1,4-dioxane in the surface water at locations established as part of the LTM with one additional location near the southern boundary of NAS Brunswick.
- Analyze VOCs and 1,4-dioxane in pore water samples collected from near-surface sediment.

2.3 Summary of CSM Recommendations

In summary, the CURT recommends the following steps to fill data gaps and improve the Eastern Plume CSM:

- To improve the understanding of the geology and hydrogeology in the CSM as well as better understand the current location of the contamination, conduct a closer examination of the predominant geology surrounding monitoring wells, especially ones along the eastern and southern edges of the plume that show persistent low level contamination. Include a review of electrical conductivity logs, CPT logs, and slug test data in order to assist in stratigraphy determination.
- Depict individual VOCs in relation to individual MEGs/MCLs, instead of total VOCs, on isoconcentration plume maps to more accurately represent the contamination within the plume.
- Complete a residential well inventory to collect well depths, GPS locations and groundwater use (landscaping vs drinking) for bedrock wells located east of the Eastern Plume. Upon completion of the inventory, site representatives may be in a better position to assess the need for any additional sentinel wells. Set up a program to monitor sentinel bedrock wells on the east side of Merriconeag Stream on a consistent basis for both VOCs and 1,4-dioxane. For example, installing an additional bedrock well east of MW-309 will better evaluate bedrock gradients and serve as another sentinel for any potential eastward migration of the plume beyond the streams.
- Collect pore water samples at multiple depths in the sediment, including near the sediment-surface water interface. This will provide a better indication of the degree of attenuation occurring in the stream bed and associated wetland sediment, as the groundwater upwells through the Upper Sand Unit and sediment. These samples should be analyzed for VOCs, 1,4-dioxane, and geochemical/natural attenuation parameters.
- Analyze for 1,4-dioxane in the surface water locations established as part of the LTM with one additional location added near the southern boundary of NAS Brunswick.
- Ensure appropriate provisions remain in place (i.e., restrictive covenants or other land use restrictions) to address drinking water and vapor intrusion for future transfer or lease of the property including water well and construction restrictions within the footprint of the Eastern Plume.

SECTION 3.0: GROUNDWATER EXTRACTION AND TREATMENT SYSTEM (GWETS)

In 1995, the Navy installed the GWETS to capture and treat a portion of the Eastern Plume in known areas of higher concentration. Since then the GWETS has captured considerable VOC mass from the plume, most of it in the early years. In the last 3 to 5 years, VOC mass recovery has declined considerably, even though extraction well locations and aboveground treatment components have been changed several times to take advantage of incremental information from ongoing soil and groundwater investigations. This section describes the remedy performance and the recommended short-term and long-term plans of the GWETS.

3.1 Remedy Performance

The treatment system consists of extraction wells screened through the shallow and deep zones of the overburden aquifer, and a treatment plant to remove dissolved-phase VOCs from groundwater and provide hydraulic control of the plume.

The GWETS has been treating the Eastern Plume since June 1995 and has successfully removed over 90 gallons of chlorinated solvent from the aquifer during the 14 years of operation. The vast majority of the mass recovery was accomplished during the first five years of operation, with a maximum of approximately 22 gallons of chlorinated VOC recovered per year in the late 1990s. Since 1999, the contaminant mass removal rate progressively decreased, falling to asymptotic removal after 2003. The asymptotic removal rate is less than one gallon per year (ECC, 2009c). Currently, the extraction and treatment of almost 50,000 gallons of groundwater per day from the Eastern Plume is resulting in the removal of approximately 1½ teaspoons per day (ECC, 2009c). This decline in contaminant mass recovery has occurred despite continuing efforts to optimize the system, as understanding of the plume has developed with more monitoring each year. In this fashion, location of extraction wells and screened intervals have been changed or adjusted over the years, as understanding of the Eastern Plume has grown. In addition, the aboveground treatment system has been adjusted over the years to more efficiently treat and discharge the extracted groundwater. When first installed, the GWETS used UV Oxidation for treatment and the treated water was discharged to the publically owned treatment works (POTW). In 2001, the UV Oxidation was replaced by an air stripper and in 2002 the treated water was directed to an on-site infiltration gallery up gradient of the plume

The GWETS is responsible for considerable mass removal from the plume and has, therefore, been protective of the environment. **Figure 9** shows the monthly and cumulative mass removal attributable to the GWETS. Because of this mass removal, the plume has shrunk from its 1995 extent to its current size (Figure 6). **Figure 10** shows a summary of costs over time with respect to amount of VOCs removed. As the former "hot spots" of VOCs have been reduced, the cost has increased significantly over time. This trend indicates that the Eastern Plume is a large, low-level dilute plume and that VOC removal has become futile.

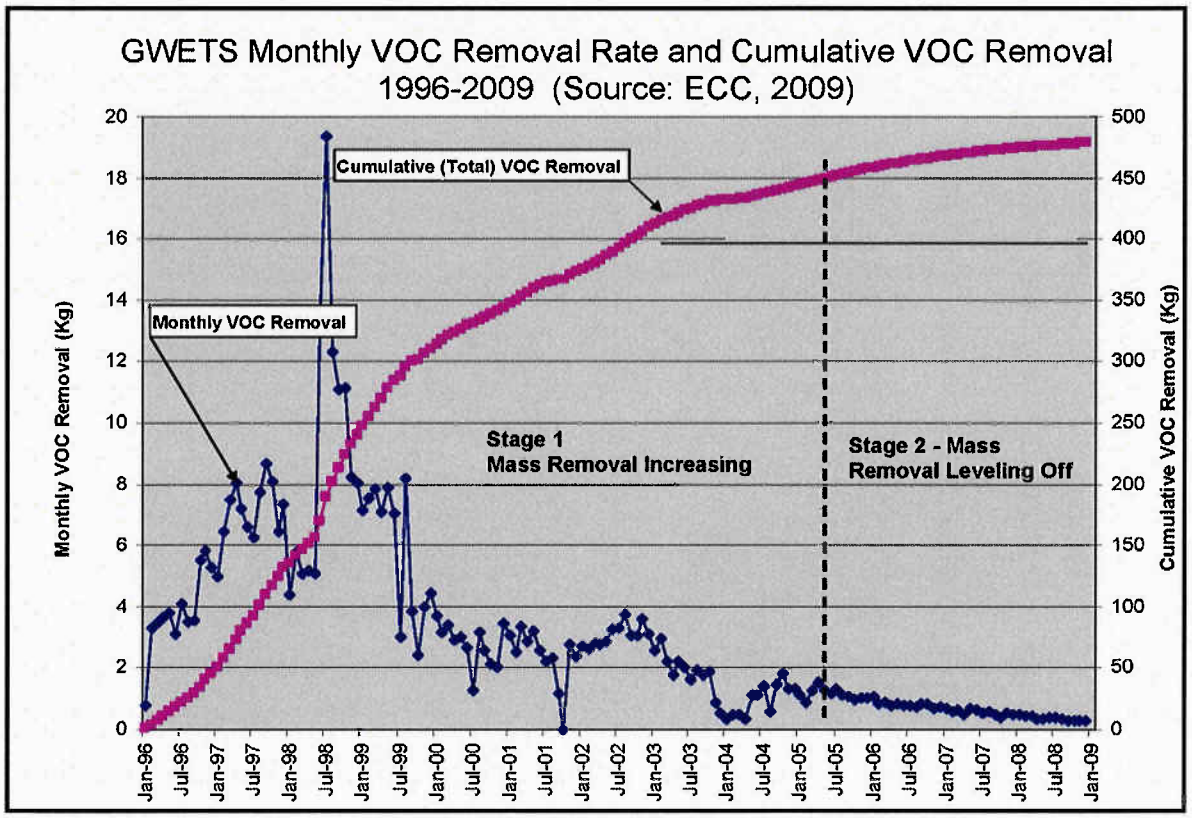

Figure 9. VOC Removal over Time (ECC, 2009c)

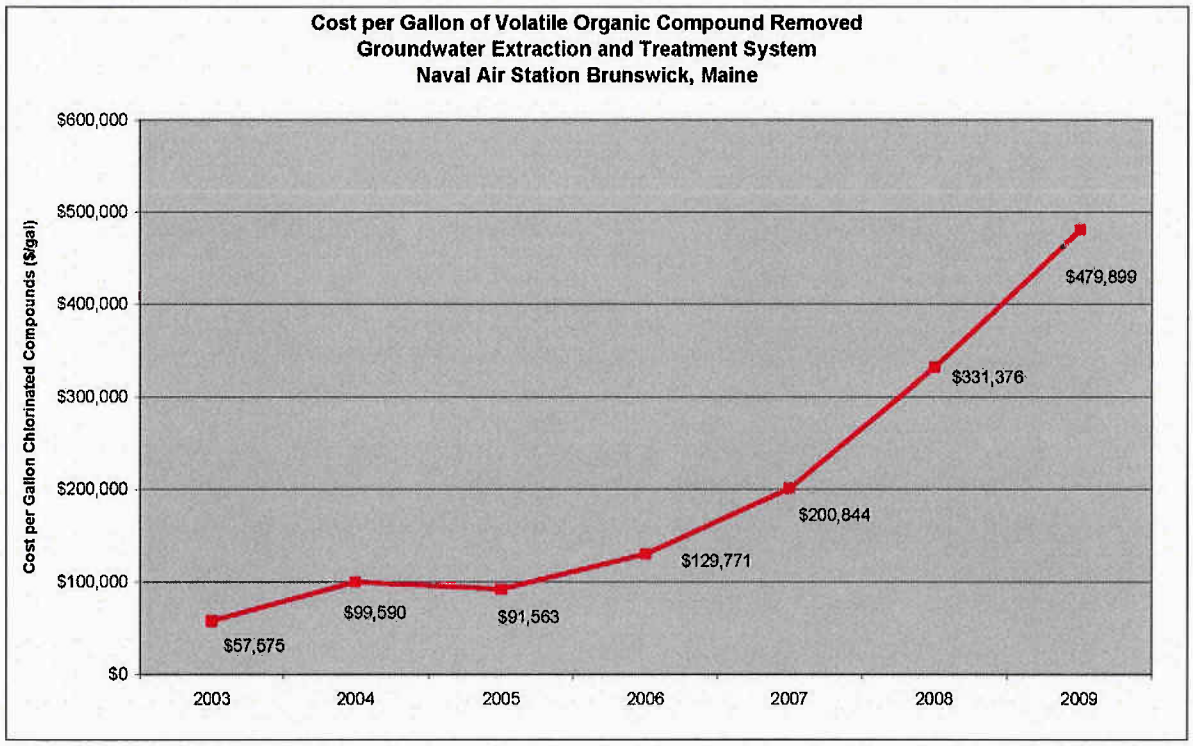

Figure 10. Cost Increase over Time Due to Reduced VOC Concentrations (ECC, 2009c)

In 2004, 1,4-dioxane was detected in the groundwater exceeding the MEGs of 32 ppb with the highest detected concentration at MW-313 of 93.8 ppb. Since 2004, 1,4-dioxane sampling has been performed during the LTM. Additional studies were conducted from 2005-2009 to delineate and address the 1,4-dioxane. Effluent concentrations of 1,4-dioxane have been below the MEG to date. The average 1,4-dioxane concentration at the GWETS influent was 6.79 μg/L during 2008, significantly less than the corresponding MEG of 32 μg/L (ECC, 2009c). Although 1,4-dioxane is recovered in the extraction well system, very little treatment is provided for this compound with the above ground treatment train currently implemented by the GWETS. During the early stages of the GWETS operation, prior to identification of 1,4-dioxane as a COC, 1,4-dioxane was being treated via UV oxidation unbeknownst to the Brunswick IR Team. Tracking of the 1,4-dioxane mass removed by the GWETS did not start until 2006. However, when the UV oxidation system was in operation at the GWETS, it is probable that a considerable amount of 1,4-dioxane mass was removed from the aquifer in the early years of the GWETS operation. This is a key advantage of the GWETS operation so far, since there is no other cost-effective system that is proven to remove 1,4-dioxane from an aquifer because it is recalcitrant to in-situ chemical or biological treatments.

In addition to mass removal, GWETS function as a plume containment system. Although the mass removal aspect of the GWETS is conclusively verified by the data, plume containment is not easily verified. Containment of the plume in its current location and shape appears to have occurred primarily due to a combination of geological and hydrologic factors as described in the CSM section (Section 2), including:

- Sub-cropping of the bedrock and clay layer along the eastern boundary of the plume.
- Hydraulic gradients that appear to push the plume towards the east, where it is bounded by the sub-cropping clay in the northern lobe and Merriconeag Stream and Mere Brook in the southern lobe, as shown in CSM.
- A northeastern gradient that appears to push the southern edge of the plume towards the confluence of the two streams.
- Discontinuous nature of the Lower Sand Unit (the major suspected migration stratum at the site) south of New Gurnett Road.
- Upward gradients and artesian conditions near the streams that appear to push portions of the plume upwards, instead of towards the south or east.

It is unclear as to how much of a role the GWETS has played in containing the plume within its current boundaries. It is likely that even without the GWETS the plume would have ultimately stabilized into its current configuration because of the geologic and hydrologic bounds on its migration, as described above. However, it is also probable that by removing considerable contaminant mass from the plume over the years, the GWETS has minimized the diffusion component of the plume along its southern boundary and may have minimized the contamination upwelling towards the two neighboring streams.

The GWETS, together with natural degradation, was designed for attainment of cleanup levels throughout the plume over a time period estimated to be between 13 and 71 years, as specified in the current ROD (ABB-ES 1998). With much of the extractable contaminant mass already removed from the plume (see CSM), the future plume containment potential of the GWETS appears to be limited. Achievement of cleanup levels is likely to be accomplished without continued operation of the GWETS in a similar time scale.

3.2 Present/Short-term Plans for GWETS

The discovery of 1,4-dioxane in 2004 and its subsequent delineation in 2005-2009 has imposed a new challenge on the aboveground treatment train of the GWETS. As mentioned previously, the current GWETS provides very little removal of dissolved-phase 1,4-dioxane, most of which passes through the system and is discharged to the infiltration gallery. Therefore, a HiPOx HCU advanced oxidation system is being installed to perform a pilot study for 1,4-dioxane and chlorinated ethene treatment. The HiPOx HCU (Hydraulic Control Unit) is a packaged system sold by Applied Process Technology, Inc. Three new extraction wells are proposed for this pilot study for VOC and 1,4-dioxane removal. EW-05A will be replaced by EW-05B and two additional extraction wells will be installed in target zones agreed upon by all stakeholders.

The HiPOx HCU is an advanced oxidation technology that combines ozone and hydrogen peroxide to destroy groundwater contaminants in a continuous flow reaction. During the HiPOx treatment, hydrogen peroxide and ozone react to form the very strong oxidizing agent, hydroxyl radical. The hydroxyl radical reacts rapidly with organic molecules and oxidizes them. Because the hydroxyl radical is short lived, the HiPOx treatment utilizes in-line mixers to ensure immediate contact between the target contaminants and the reactive radical. HiPOx treatment is one of the few technologies shown to destroy 1,4-dioxane, and it also can destroy chlorinated ethenes. It is not, however, effective against 1,1,1-TCA.

The proposed short-term plan is to incorporate the HiPOx HCU treatment unit into the existing GWETS facility location in Building 50 at NAS Brunswick. Specifically, the HiPOx HCU system would be installed after the sand filters and prior to the air stripper. The reagents and groundwater are mixed in pipes containing in-line mixers. Bench scale testing using site groundwater with a HiPOx unit confirmed the oxidization of 1,4-dioxane and chlorinated ethenes. The manufacturer has guaranteed reduction in 1,4-dioxane to a 10 ppb threshold. The remaining steps in the GWETS (e.g., liquid-phase GAC) will remove the remaining chlorinated ethanes.

The HiPOX technology has been proven effective for treating 1,4-dioxane levels from mg/L to < 10 ppb, but treatment costs are relatively high. Consequently, the CURT considered possible alternatives to the HiPOX system. Two options that warranted evaluation were 1) using the existing or modified air stripping system to remove the contaminants from recovered groundwater; and, 2) use of existing hydrogen peroxide and tanks at the facility to treat the contaminated groundwater with a Fenton's reagent oxidation approach. However, a preliminary analysis suggests that the existing air stripper will not have sufficient capacity to remove 1,4-dioxane from the pumped groundwater, even at relatively low flow rates. In addition, the use of the existing on-site hydrogen peroxide solution appears infeasible because of slow reaction rates and expected heat generation. Details on these analyses are provided in **Appendix E**.

In terms of system performance with the HiPOx unit and the additional wells, the CURT expects a slight increase in COC recovery after the new extraction wells are brought on line. However, within a short time, the CURT expects that contaminant recovery levels for both VOCs and 1,4-dioxane will become asymptotic again. When asymptotic recovery resumes, the system should be re-evaluated as the HiPOx HCU may be unnecessary for the treatment of 1,4-dioxane. Given the anticipated recovery results, exit strategies and goals for the HiPOx/GWETS should be agreed upon prior to system start up.

3.3 Long Term Plans for GWETS

P&T systems, such as the GWETS, were used extensively at many sites in the 1980s and 1990s for arresting the migration of plumes towards potential receptors. One key advantage of P&T systems was robustness. Once the aboveground treatment system was established, locations and screened intervals of extraction wells could be adjusted over time to optimize contaminant recovery. P&T systems also

allowed more control over how the extracted water was treated than most in situ remedies, which contributed to their popularity. However, in the late 1990s several landmark studies (e.g., National Research Council [NRC], 1994) by independent scientific bodies questioned the long-term effectiveness of pump-and-treat systems. Since then, there have been fewer applications of these systems. According to these studies (NRC, 1994), sites that may not be suitable for P&T include aquifers with dilute plumes, aquifers or water bearing zones with high silt or clay content, fractured bedrock with low connectivity, and portions of aquifers close to surface water bodies. In situations like these, effectiveness of P&T systems may be limited by inadequate capture of the plume or excessive intake of clean water (from a nearby stream).

Many sites throughout the nation with chlorinated organic contamination in groundwater have gone through extensive remedial evaluations and actions. The remedial alternatives for many of these sites include high-energy treatments such as P&T systems. After years of operation, the effectiveness of these high-energy processes has begun to diminish without remedial objectives being met. Other more effective remedial alternatives need to be implemented. How and when to transition these sites to lower-energy remedial alternatives and eventually to MNA is addressed in the ITRC Enhanced Attenuation: Chlorinated Organics (EACO), which includes a protocol to assist in a smooth transition (or a bridge) between aggressive remedial actions and MNA (ITRC, 2008).

Despite the past advantages of using P&T systems, the future usefulness of the GWETS system is questionable because the GWETS may have reached the limits of its effectiveness based on the following information:

- First, the cumulative VOC mass removed has nearly reached asymptotic levels (that is, the additional VOC mass removed every month has tapered off, as indicated by the monthly VOC mass removal line). This is also apparent from the fact that the general shape of the plume has not changed much over the life of the system, although there has been some retraction and expansion in a few places. Recovery of contamination by the GWETS has tapered off to an estimated mass of only 0.5 kg/month. As stated above, many different sites have identified this tendency of contaminant concentrations in extracted groundwater to taper off, as any residual contamination in the aquifer (after several years of pumping) are likely to either be sorbed on soil or to have diffused into relatively inaccessible pores. Once this point is reached, extracting additional mass of contaminants from the aquifer involves extraction of large volumes of relatively clean water and incurrence of extremely high monetary costs for every new pound of contaminants removed.
- Second, there are no obvious "hot spots" left in extractable locations where additional VOC mass could be effectively removed. In the past, extraction well locations were changed, as each previous "hot spot" area was either remediated to the extent practicable or to adjust screen locations and depths to other intervals where there was more contamination. However, over the years, the intensity of subsequent "hot spots" has been reduced, with the new wells planned (EW-X and EW-Y) targeting lower level "hot spots" that contain only a maximum of 860 ppb of TCE and 350 ppb of 1,4-dioxane in the Lower Sand Unit wells targeted. The Transition Unit and Upper Sand Unit probably contain somewhat higher levels of VOCs and 1,4-dioxane (as indicated by their trace level detection in the pore water samples), but these are not strata that are efficiently pumpable. The Transition Unit is not efficiently pumpable because it contains a higher proportion of less permeable soil (silt and clay). The Upper Sand Unit is not efficiently extractable because it is a relatively thin unit adjoining a surface water body. Any pumping in this Unit is likely to draw clean water from the streams, rather than from the aquifer.

Of course, in addition to its mass removal function, the GWETS may also have served to partially contain the plume. However, in terms of mass removal, the GWETS appears to have reached the natural limits of the aquifer to yield more contaminant mass from the currently known distribution of the plume.

3.4 Continued GWETS Operation from a Sustainability Perspective

In April 2008, the USEPA released *Green Remediation: Incorporating Sustainable Practices into Remediation of Contaminated Sites* (http://www.epa.gov/Sustainability/) as part of its mission to protect human health and the environmental through promoting cleanup while reducing negative impacts. "Green Remediation" considers all environmental effects of remedy implementation for contaminated sites and incorporates options to maximize the net environmental benefit of cleanup actions. Currently, the GWETS is treating 1.5 million gallons of groundwater per month (approximately 50,000 gallons per day). Since late 2007, the contaminant removal rate has been less than 0.5 kg of VOCs per month. Subsequently, the GWETS is removing very little contaminant mass per gallon of water extracted per month. According to the *Remediation System Evaluation* (ECC, 2009c), for every 8 lbs of VOC recovered by the GWETS, 548,584 pounds of CO_2 and 39 pounds of mercury are emitted per year. The team needs to determine whether its cost in terms of contribution to climate change is worth the incremental benefit to the environment from treatment of very low concentrations of groundwater.

3.5 GWETS Summary and Final Recommendations

In summary, the GWETS appears to have performed well over the years and recovered considerable VOC mass from the Eastern Plume. Both the subsurface extraction well locations and the aboveground system components of the GWETS have been changed and optimized as the NAS Brunswick team learned more about the plume from ongoing site investigations. However, over the last three to five years, VOC mass recovery has dropped considerably as the natural limits of the system imposed by the complex site geology and technology have been reached. This tendency of P&T systems to reach a plateau in terms of contaminant mass removal from aquifers was identified at several sites as far back as 1998 in a landmark study by the National Research Council (NRC, 1994). In the Eastern Plume, much of the VOC mass that was removable from sandy layers (where most of the flow occurs) has been removed. Much of the contamination that remains is either trapped in the silts and clays of the Transition Unit or in transit upwards into the Upper Sand Unit. Any effort to pump groundwater from the Transition Unit would only result in drawing water from the sandy layers above and below it. The Upper Sand Unit near the streams would be difficult to extract with P&T because it is a relatively thin layer that lies very close to the streams. Efforts to pump the Upper Sand Unit could lead to significant quantities of clean water being drawn into the extraction system from the streams. Therefore, the CURT sees very little net benefit from the continued operation of the GWETS, either in terms of human or ecological risk reduction or in terms of sustainability.

As with any P&T system, "rebound" of contaminants is expected after the cessation of pumping. Contaminant rebound refers to the increase in aqueous contaminant concentration after a period of no pumping. Rebound is a result of several factors: physical and chemical properties of the contaminants, subsurface environment, and groundwater. Heterogeneous aquifer properties produce residual non-aqueous phase liquid (NAPL) sorbed to the aquifer sediment. During pumping, the contaminant dissolution reaches equilibrium with the groundwater velocity. Once the pump is turned off, a new equilibrium is reached which produces a higher contaminant concentration in the groundwater as the groundwater velocity has decreased. Given that the bulk of the COC are NAPLs and the Transition Unit is comprised of intermittent layers of clay and sand, rebound tests should be performed at the Eastern Plume during the first year after the GWETS is turned off as part of LTM at the site.

To determine the potential rebound within the Eastern Plume, soil within the transition layer could be sampled and analyzed by a diffusion test to mimic conditions that would exist after the P&T has ceased operations. Another indicator of rebound at the site could be using former extraction wells for testing. Extraction wells, EW-02, EW-03 and EW-05, have historical data showing a significant reduction in contaminant concentrations due to P&T at these locations. These extraction wells were taken off-line several years ago and could possibly be used as indicators of rebound at the site using pots-pumping groundwater data.

Recommendations: In the long term management of the Eastern Plume, the CURT recommends that the diminished effectiveness of the GWETS be recognized and that other more effective lower-energy remedial alternatives be implemented. How and when to transition the Eastern Plume site to lower-energy remedial alternatives and eventually to MNA is addressed in the ITRC guidance (ITRC, 2008), which will be helpful for the stakeholders to develop a path forward and exit strategy.

SECTION 4.0: ALTERNATIVE REMEDIAL OPTION EVALUATIONS

Given the limitations of the GWETS discussed in Section 3, the CURT reviewed all possible groundwater technologies potentially applicable for the Eastern Plume. Based on the CSM and the CURT's understanding of the site conditions, the remediation technologies were evaluated in the context of the challenges described in the following paragraph.

Various lines of evidence suggest that the bulk of the remaining contaminant mass (VOCs and 1,4-dioxane) may be trapped in the Transition Unit, especially in the region where the Lower Sand Unit ends near the streams. The artesian conditions and the resulting hydraulic pressure in the Lower Sand Unit direct contaminated groundwater to flow up through the Transition Unit into the streams. It is likely that the easily accessible contamination in the Lower Sand Unit has already been remediated by the GWETS, leaving residual contamination tied up in the Transition Unit from where it may slowly release into the Upper Sand Unit (or into the Lower Sand Unit, as extraction wells continue to target this unit). Current data suggest that residual contamination in the Transition Unit is spread throughout the half-mile length of the Eastern Plume. These conditions pose a challenge for future remediation efforts because of the size of the area to be addressed and the less permeable soils in the Transition Unit are unlikely to be amenable to either extraction (e.g., GWETS) or to injection of reagents.

4.1 Enhanced In Situ Bioremediation

The CURT evaluated the potential of using enhanced anaerobic bioremediation for treating the Eastern Plume aquifer because it has become a preferred technology for treating many groundwater contaminants. Anaerobic bioremediation can be performed by naturally occurring indigenous bacteria that use the contaminants and available nutrients as growth substrates (McCarty, 1997). Because no additional nutrients are needed to support their activity, this process is a primary component of natural attenuation. In other cases, additional nutrients are needed to support the activity of the indigenous bacteria (i.e., biostimulation or enhanced in situ bioremediation), or exogenous bacteria are added to supplement the indigenous microbial population (i.e., bioaugmentation).

Contaminants present in the Eastern Plume aquifer include a mixture of chlorinated aliphatic hydrocarbons (VOCs; PCE, TCE, 1,1,1-TCA, etc.) and 1,4-dioxane. Although anaerobic biodegradation of chlorinated alkanes and chlorinated alkenes is well recognized, and bioaugmentation cultures capable of degrading these contaminants are commercially available if needed, 1,4-dioxane is not known to be degraded under anaerobic conditions (Steffan, 2007). Therefore, while anaerobic treatment of the Eastern Plume aquifer may reduce levels of VOCs present, anaerobic treatment is unlikely to reduce the levels of 1,4-dioxane.

Successful enhanced in situ bioremediation of the VOCs present within the plume also will likely be limited because of the site geochemistry and geophysical properties of the aquifer and an apparent lack of necessary degradative microorganisms as the prevailing redox potentials of the groundwater are fairly oxidizing and not sufficiently reducing (<-100 mV) to support deductive dehalogenation of the target chemicals. This is likely due to the relatively low levels of natural organic material (TOC) present at the site. In addition, the VOC concentrations at the site are very low and are likely insufficient to support a robust population of contaminant-degrading bacteria (Schaefer et al., 2009). The conclusion of a lack of an adequate natural microbial population and insufficiently reducing conditions at the site are supported by the relatively low levels of 1,1-DCA and cis-1,2-DCE, compounds indicative of intrinsic biodegradation, in the Eastern Plume groundwater.

Because the redox potential of the aquifer may not be suitable for effective in situ bioremediation and an adequate natural population of dechlorinating bacteria appears to be lacking, the CURT examined the potential for enhancing in situ biodegradation by adding electron donor compounds and dechlorinating bacteria. However, this approach was considered unlikely to be successful. Successful application of both biostimulation and bioaugmentation relies on adequately targeting and distributing the electron donor and bacterial culture within the aquifer. Because of the textural variability of the different layers of contaminated aquifer soils and apparent upward movement of groundwater in the Lower Sand Unit near the stream boundaries, care would be needed in determining the suitability and location of substrate and culture injection. Injection into the silty Transition Unit would likely result in poor distribution of the electron donor and culture. Slow groundwater movement would result in effective treatment only near injection points, and the use of a groundwater recirculation to improve distribution would be limited. Likewise, the termination of the Lower Sand Unit and the upward movement of groundwater through the Transition Unit near the streams would make distribution of the amendments challenging. Artesian conditions in the formation also would limit amendment injection. The fine grained sediments and slow groundwater movement would require the use of closely spaced injection points, resulting in high treatment costs that would be prohibitive, given the potentially large discharge areas around the streams. Furthermore, forced injection of additives into the Upper Sand Unit could lead to discharge of the additives to the nearby surface waters resulting in a reduction in surface water quality. If this approach were selected for further evaluation, pilot testing would be required to evaluate the distribution of amendments and effectiveness of the in situ treatment before consideration of augmented bioremediation as a viable remedy.

The relatively low VOC concentrations in the pore water, the sporadic discovery of vinyl chloride in the pore water, and the absence of VOC in surface water samples, do however, indicate that natural attenuation (via sorption and biodegradation) may be active in the organic-rich sediment of the two streams, into which the groundwater eventually discharges. Section 2.1.5.4 also noted those degradation product observations. The Maine Department of Environmental Protection in commenting on the results of the "Monitored Natural Attenuation Assessment of the Eastern Plume Naval Station, Brunswick, Maine" (ECC, 2006) concluded "The pore water data suggest that complete degradation/dechlorination does occur in the vicinity of the surface waters."

Recommendations:

- As noted in the CSM section, examine intrinsic bioremediation in stream bed sediments.
- Due to difficulties with efficient injection over large volumes of affected aquifer, enhanced in situ bioremediation is not a viable option in the groundwater at the Eastern Plume.

4.1.1 Cometabolic Biodegradation. Cometabolism is a process during which a bacterium that is utilizing one chemical compound as a growth substrate (i.e., the primary substrate) fortuitously oxidizes a second chemical (e.g., a pollutant) by using the same enzyme(s) involved in the utilization of the primary substrate. Consequently, application of this process for remedial activity requires balancing between the available concentrations of the primary substrate and the target chemical. If the concentration of the primary substrate is too high, it will competitively inhibit oxidation of the target chemical. An advantage of co-metabolic approaches is that the growth and activity of the degradative bacteria is supported by the primary substrate and the bacteria do not have to rely on low concentrations of contaminants, like those in the Eastern Plume aquifer, to support their survival and maintain optimum microbial populations in situ. Cometabolic biodegradation of chlorinated aliphatic chemicals like TCE and TCA has been widely studied and tested in several field-scale applications (Semprini, 1997). Chlorinated ethenes like TCE, DCE, and vinyl chloride are cometabolically degraded by aerobic bacteria that oxidize methane (Kang et al., 2001), propane/butane (Young et al., 2002), ammonia (Hommes et al., 1998), or toluene (Semprini, 1997), provided methane, propane/butane, ammonia, or toluene, respectively, are provided as a primary

substrate. PCE is generally considered to not be degraded by aerobic co-metabolism (Steffan et al., 1999). Fewer bacteria can co-metabolize chlorinated alkanes, but TCA, DCA, and chloroethane are known to be oxidized by bacteria that oxidize propane or butane (Jitnuyanont et al., 2001; Young et al., 2000). Likewise, 1,4-dioxane is oxidized by propane oxidizing bacteria (Mahendra and Alvarez-Cohen, 2006; Steffan, 2007; Vainberg et al., 2006). Thus, at NAS Brunswick, aerobic co-metabolism has the potential, if the proper microorganisms are present, to treat many of the target aquifer contaminants, but not PCE.

Because 1,4-dioxane and many VOCs are known to be biodegraded by aerobic co-metabolism mechanisms, the CURT considered the utility of this approach for treating the Eastern Plume aquifer. Despite the potential to degrade many of the Eastern Plume contaminants by co-metabolism, the fine-grained nature of the contaminated aquifer soils of the Transition Unit would make co-metabolic treatment impractical. Effective application of the technology requires dissolution of the gas substrates into groundwater and distribution of the dissolved gasses away from the injection points. The most common approach utilizes sparging technologies, but gas sparging would not distribute gasses through the silt and clay-laden contaminated Transition Unit sediments. Likewise, the use of direct gas diffusion technologies (e.g., ISOC™) would be limited by the low groundwater flow through the tight formation. The artesian nature of the groundwater in some areas also would make injection of gasses challenging and ineffective. Because of the mixture of contaminants present in the groundwater and the fine-grained nature of much of the contaminated aquifer soils, aerobic co-metabolism is unlikely to efficiently remediate the site.

Recommendation:

- Given the injection limitations with adding the necessary primary substrate over large tracts of aquifer, co-metabolism is not recommended as a treatment option at the Eastern Plume.

4.2 In Situ Chemical Oxidation (ISCO)

ISCO involves injecting chemical oxidants into the vadose zone and/or ground water to chemically oxidize organic contaminants. The most common oxidants used include permanganate, persulfate, ozone and Fenton's reagent (peroxide plus iron), or some variation of these chemicals. Oxidation chemically converts hazardous contaminants to non-hazardous or less toxic compounds that are more stable, less mobile, and/or inert. While ISCO is a widely used technology, its use is most commonly focused at treating high contaminant concentration source areas where ISCO becomes economical relative to other treatments. Typically, ISCO treats 1,1,1-TCA, 1,1-DCE, TCE and the associated daughter products. However, ISCO would be largely ineffective in treating PCE and 1,4-dioxane, which themselves are highly oxidized molecules. The use of alkaline-activated persulfate treatment has recently been reported to degrade 1,4-dioxane (XDD, LLC; http://www.xdd-llc.com/news040909.html), but few data were provided. The company reported that target chemicals were reduced to below 1 mg/L, a level substantially greater than those found at the Eastern Plume. Presumably, the initial concentration of 1,4-dioxane and other contaminants at the XDD test site were much greater than those at the Eastern Plume site.

Several site characteristics at the Eastern Plume are expected to preclude the use of ISCO at the site. First, the fine grained soils of the Transition Unit, which is the source of most of the remaining contamination, would prevent adequate distribution of the added chemical oxidant. Because of the proximity of the contaminant plume to the two streams on the site, injection of oxidants under pressure into the Transition Unit to promote distribution could result in oxidant contamination of the streams, if the oxidants found preferred flow paths leading to the streams. In addition, the extreme artesian pressures measured in some parts of the plume could result in discharge of injected oxidant leading to ground

surface environmental impacts and health risks to personnel working on the site. Furthermore, the primary cost driver for the ISCO technology is the soil oxidant demand (SOD). SOD is the amount of oxidant consumed by the soils themselves, and it is typically much greater than the oxidant consumed by oxidation of contaminants. SOD is typically greatest in fine-grained sediments. Therefore, even if oxidant distribution could be achieved, the consumption of oxidant by the soils themselves would reduce the effectiveness, and greatly increase the cost, of the ISCO treatment. Finally, the strongly oxidizing environment created by ISCO has the potential to cause release of native metals of environmental concern (e.g., chromium, lead, etc.) from the formation soils. These metals releases could potentially be of the same order as the residual concentrations of target contaminants. Given how close the treatment areas would be to the two streams, the potential for metals release creates uncertainty about the net environmental benefit that may accrue from ISCO treatment.

Recommendations:

- The CURT evaluated the potential of treating the Eastern Plume aquifer using ISCO and concluded that success of this technology at the site would be unlikely due to the limitations of ISCO for all COCs, as well as due to other limiting site conditions (such as, proximity to receiving streams, artesian conditions in the hot spots, large area, etc.).
- There are uncertainties about the effectiveness of the chemical reactions of 1,4-dioxane with several oxidants, without the use of UV light as a trigger (which is impracticable to do in situ).

4.3 Thermal Treatment

Thermal treatment is the injection of steam/hot air or the use of electrical resistance or radio frequency (RF) heating to drive contaminants into the vapor phase and facilitate extraction. Steam injection can be done using a fixed system of wells or a mobile system with augers that drill into the soil. In both cases, low-moisture-content steam is injected into the aquifer to heat the formation, vaporizing contaminants and mobilizing NAPL and the vapors removed by a vacuum extraction system. With electrical resistance heating (ERH), the application of an electric current through the subsurface heats the subsurface and volatilizes the contaminants. The technology is implemented by placing electrodes in the ground and applying sufficient voltage to produce an electric current utilizing the moisture in the soil to conduct the electricity. Increased rates of biodegradation of VOCs have been reported at moderately elevated temperatures prevalent in the plume during long heating and cooling cycles (and at the fringes). Therefore, thermal technologies can remediate contamination through multiple mechanisms – volatilization, boiling, steam stripping, and bioremediation. Unfortunately, the technology is extremely energy demanding and a mechanisms for removing the volatilized contaminants (e.g., air sparging and/or soil vapor extraction) are required to make the technology effective.

Thermal treatment has some advantages in the Eastern Plume in that all the VOCs are potentially amenable to thermal treatment. 1,4-Dioxane, however, does not appear to be the type of contaminant that would be suitable for thermal treatment as it does not volatilize, its boiling point is slightly above that of water, and it does not biodegrade. Nevertheless, 1,4-dioxane may be amenable to steam stripping although this possibility has not been tested yet. In testing of the application of thermal treatment of a related contaminant, MTBE, electrical resistance heating and air sparging were employed in a large experimental cell containing sand (http://mcmillan-mcgee.com/mcmillan-mcgee/papers/MTBE Remediation.pdf). Although MTBE was successfully removed, the soil had to be heated to >90 °C and vigorous air sparging was required. Energy requirements were 384 kWhr/m^3, and ~3,000 pore volumes of sparged air were required to make the technology successful. Because of the relatively large size and low porosity of the Eastern Plume area, this technology would not be feasible.

Recommendation:

- Thermal treatment was considered by the CURT to be an unlikely technology for the Eastern Plume site based on the following.
  - Although thermal treatment is a proven technology for VOCs, it is uncertain as to how effectively 1,4-dioxane would be removed by it.
  - For a half-mile long treatment zone, the cost of ensuring effective heating throughout the fine-grained and heterogeneous Transition Unit would be cost prohibitive.

4.4 Vertical Permeable Reactive Barriers

A vertical permeable reactive barrier (PRB) is an in situ groundwater treatment method that involves installing a vertical barrier containing a reactive media to intercept and remediate a contaminant plume. In general, a treatment barrier consists of a trench placed in the path of a dissolved contaminant plume that is filled with a reactive material, most commonly zero valent iron (ZVI) or emulsified vegetable oil (EVO), to degrade the contaminants of concern. As the groundwater passes through the treatment barrier, the contaminants react with the media. The main advantage of this system is that no pumping or aboveground treatment is required; the contaminated water passively moves through the barrier. Because there are no aboveground installed structures, the affected property can be put to productive use during remediation. In addition to installing the reactive media in a trench or barrier, emulsified ZVI or EVO can be injected into the subsurface through an injection well gallery or recirculation system to create a "biobarrier". This zone of activity degrades contaminants of concern (Air Force Center for Engineering and the Environment [AFCEE], 2007; Solutions-IES, 2006). Injection of the substrate often is done through direction push technology or dedicated injection/extraction wells depending on remedial design objectives.

There are several reasons why this treatment may not be appropriate in the Eastern Plume. First, ZVI effectively treats only the chlorinated VOCs (1,1,1,-TCA, 1,1-DCE, PCE, and TCE) but not the 1,4-dioxane. Furthermore, 1,2 DCA, which also has been found sporadically in the Eastern Plume, is resistant to treatment by ZVI. In regards to EVO, the limitations to anaerobic bioremediation have already been discussed in Section 4.1 and apply to the biobarrier concept. The potential release of trace metals as a result of the low redox environment for both ZVI and EVO would also need to be evaluated. Second, installation of a traditional PRB trench system would damage the wetlands and streams. The vertical movement of the groundwater due to the artesian conditions also makes proper placement of a traditional barrier difficult because groundwater is not traveling horizontally. Third, the expense of micro-scale ZVI particles suitable for injection is greater than trench barrier because the particles must be finer for injection. Fourth, injection of the solid product (ZVI) in silty or clayey soils is challenging and requires extraordinary measures (e.g., pneumatic fracturing of the soil medium) to accomplish. Coupled with the artesian conditions in the southern lobe, pneumatic fracturing or augering could also prove disruptive to the wetlands and streams environment. Therefore, ZVI injection typically has been applied to relatively small areas of higher-concentration contamination considerable distance from sensitive habitats. Given the target contamination in the Eastern Plume contains low levels and is dispersed over a half-mile long area, PRB is not considered cost-effective method to treat the COCs at the Eastern Plume.

Recommendation:

- Permeable reactive barriers are not recommended for the Eastern Plume for the following reasons:
  - Contaminant migration appears to be occurring vertically, not horizontally, and it would be difficult to intercept it with a conventional vertical barrier.

- None of the available reactive media are likely to be effective in removing 1,4-dioxane, either through degradation or sorption.
- The amount of reactive media and level of construction required to intercept the contamination along the entire length of the plume would be cost prohibitive.

4.5 Sheet Pile/Slurry Walls

Vertical barriers, in the form of slurry walls and sheet piling, constructed underground to stop, collect, and/or treat the flow of contaminated groundwater are a feature of many site remediation projects. Vertical barriers, typically used to control the horizontal migration of sources are: soil-bentonite, soil-cement-bentonite, cement-bentonite, sheet pile (steel or high density polyethylene [HDPE]), and clay barriers. Soil-bentonite barriers are the most widely used in the United States (USEPA, 1998), and are referred to herein as vertical barriers.

Many disadvantages exist with respect to the unique groundwater conditions at the site regarding the use of a vertical barrier. While installation would not only entail major construction/heavy equipment in environmentally sensitive areas, excavations that extend close to strata under artesian pressure may be severely damaged due to "blow outs" taking place in their floors (Bell, 2004). Since "blow outs" create a pathway for groundwater to upwell, aquifer drawdown with a well point system is typically used during vertical barrier construction. In addition, the proposed vertical barrier would not inhibit groundwater flow, due to artesian conditions that would potentially produce a vertical upward gradient along the barrier resulting in groundwater bypassing the barrier. To avoid upwelling, a cap and groundwater drawdown system would be required (similar to landfill slurry walls) which is not practical at this site given the sensitive habitat. The installation of a vertical barrier could potentially direct groundwater south causing advection of contaminants, pushing the plume to the south.

Recommendations:

- A vertical barrier is are not recommended for Eastern Plume for the following reasons:
  - The installation requires construction in environmentally sensitive area and has many complications when taking into account site conditions.
  - A vertical barrier will not inhibit the vertical upwelling of groundwater and could redirect groundwater flow, forcing groundwater towards the south.
  - An impermeable barrier is effective in the long term only if the contamination is completely surrounded by the barrier. Otherwise, the plume will eventually find a way around the barrier.

4.6 Reactive Mats (horizontal permeable barriers)

A reactive material mat typically is a geotextile fortified with a reactive or sorptive material designed to treat the COCs at the surface water interface. In practice, most applications tested have used mats fortified with activated carbon or similar sorptive material to treat or sequester organic contaminants and certain heavy metals (e.g., mercury).

However, there are issues with this approach that make it unsuitable for the Eastern Plume. First, activated carbon or other similar material will not capture 1,4-dioxane, the contaminant with the greatest potential for discharging to surface water. Secondly, there is no evidence that the VOCs are making their way through the groundwater to the sediment-water interface at concentrations of concern. Although an occasional sediment pore-water sample (namely, PW-51) has shown elevated levels of parent compounds TCA, TCE, and PCE), the broader group of detections included biodegradation byproducts, such as 1,1-DCA (e.g., PWTR1-02 AND PW-51), chloroethane (PW-81 and PW-50), and cis-1,2-DCE (PWTR1-02

and PW-51). As already discussed, this indicates that microbial communities are very active in the anaerobic organic-rich sediment associated with the two streams in comparison to the groundwater in the Eastern Plume. Therefore for the Eastern Plume, reactive mats placed on the sediment-water interface would serve to primarily remove very low levels (if any) of VOC degradation products, without addressing 1,4-dioxane. Unfortunately, this scenario does not address all the COCs and would allow continued migration of 1,4-dioxane. In addition, the area over which such mats would have to be placed is large enough that it might disrupt the large portions of the habitats of the benthic organisms in the streams and associated wetlands.

Recommendation:

- Reactive mats are not recommended for NAS Brunswick for the following reasons:
  - There is no good reactive medium that could be used in the mat that would capture or treat 1,4-dioxane.
  - Potential mat area is large and could impact sensitive habitat.

4.7 Phytoremediation

Phytoremediation is a remedial alternative that utilizes the natural process of transpiration of plants in concert with soil microorganisms to remove contamination from water and/or soil. The photosynthesis process creates favorable environmental conditions, starting in the root "ecosystem," for the degradation of various compounds, including VOCs and 1,4-dioxane. For example, hybrid poplars (Aitchison et al., 2000) and native tree species (Ferro and Tammi, 2009) have been effective in removing 1,4-dioxane from soil and water. The root zone, called the rhizosphere, offers an aerobic environment where plant roots exude nutrients and oxygen, providing energy for microbial growth, and in turn, microbial activity provides essential nutrients to the plants. http://distans.livstek.lth.se:2080/rootnodules.htmIn transpiration, water and nutrients are drawn up through the rhizosphere, transporting it through the plant to the leaf, and the evaporation of the water to the atmosphere. Transpiration creates negative pressure on water tables, acting as a pump to wick moisture out of the vadose zone. Plume treatment is not limited to shallow aquifers; some species of trees have been used to capture water as deep as 32 ft (Gatliff, 1994). Phreatophytes are plants with root systems that tolerate saturated conditions and can reach into shallow groundwater. For example, a mature willow tree may use as much as 50 gallons/day (ITRC, 2009) in the summer from transpiration and young poplars, from 10-53 gallons/day (ITRC, 2009). Aside from transpiration providing hydraulic control alone, contaminants are phytoremediated through several other mechanisms such as transformation, rhizodegradation, and volatilization. **Appendix F** contains tables from the ITRC 2009 document on phytotechnology that show various media with respect to phytoremediation applications and their attenuation mechanisms.

Phytoremediation offers many advantages to the property owners, site neighbors and regulatory community. It is an in situ process that can target shallow groundwater, soil and streams. Phytoremediation is a "Green Technology" because it is solar driven, with no concerns of fossil fuel consumption or by-products polluting the environment. Many field studies have proven that it is more affordable than traditional remedial practices and faster than natural attenuation alone. As in other technologies when properly applied, phytoremediation can reduce the potential for receptor exposure to contaminants and reduce soil erosion.

In relation to the contaminants in the Eastern Plume, remediation studies, both in the lab and the field indicate that phytoremediation is effective in uptake of both VOCs and 1,4-dioxane (Aitchison et al., 2000; Ferro and Tammi, 2009; Strycharz and Newman, 2009). Hybrid poplar trees have been successfully tested at other solvent phytoremediation sites due to their ability to reach deep groundwater and uptake VOCs, including 1,4-dioxane. Poplars (*Populus spp.*) are considered pioneer species because

they are the first to populate a new environment and grow at a fast pace to outcompete other species. Aitchison et al. (2000) documented the rapid uptake of 1,4-dioxane in the hybrid poplar, where the mean photovolatilization of 1,4-dioxane was 77%, with the remaining found in the stem. Also, the transpired 1,4-dioxane, according to Aitchison's study, does not pose an inhalation risk, with the highest recorded amount five orders of magnitude less than OSHA standards. After only eight days, the average 1,4-dioxane mass removed was 54%. In addition to greenhouse experiments, field study results (Ferro and Tammi, 2009; personal correspondence) show tissue uptake in the planted tree species with an average of 78% of 1,4-dioxane phytovolitalized from irrigation water. Willow species (*Salix spp.*) are in the same family (*Salicaceae*) as poplars and exhibit the same high evapotranspiration rates. Both poplar and willow species can be found in northern temperate climates and are deciduous. Willows also tolerate wet soils and could be an ideal riparian or floodplain candidate to support phytoremediation at NAS Brunswick.

The climate condition of NAS Brunswick is northern temperate and located in the Coastal Climatic Division. The frost free growing season ranges from 120-180 days, starting around late April to early May and lasting until late September to late October. One positive attribute of the existing climate at NAS Brunswick is that freezing ground conditions during non-evapotranspiration periods could in fact slow vertical upwelling of groundwater and freeze ephemeral seeps. Shallow groundwater containment during the winter season can be accomplished by the presence of evergreen species which have been reported to metabolize TCE (Strycharz and Newman, 2009) during the growing season. Conifers have a slower water uptake rate than poplars. However, evergreens have the advantage over deciduous trees to transpire water during the winter months and potentially continue to remediate COCs at a slower rate. Pine seedlings were documented taking up water at 14-38% less than during the growing season (Kramer, 1942). Other winter effects on plants that would ultimately promote phytoremediation at NAS Brunswick include: prevention of desiccation (wetlands offer soil "winter wetness" and layers of ice on exposed tissues), as well as maintaining microbial populations within these wetland plant communities. Two pine species exhibited increased productivity (*Pinus taeda* and *P. ellottii*) within wetlands as opposed to the same species upland, which was attributed to winter wetness (Haywood et al., 1990). Tiner (1999) states "the significance of winter wetness to many wetland species cannot be overlooked, nor can year-round soil microbial activity."

One disadvantage of phytoremediation includes the need to monitor for plant mortality and control herbivores, such as deer and beaver. The NAS Brunswick environmental office reported that three beavers have been removed from area recently due to damming of a Mere Brook culvert. This threat to planting trees close to the streams should be evaluated and addressed.

Recommendations:

The CURT recommends the following activities to support phytoremediation as a supplemental remedy at NAS Brunswick:

- Conduct quantitative sampling of existing plant tissues to determine if phytoremediation is currently occurring. Specifically, tree cores and stem/leaf samples should be collected and analyzed for COCs and 1,4-dioxane. Evergreen species would be targeted as well since they are prevalent at the site and to determine if they currently uptake the COCs. These data would need to be collected during peak photosynthesis period, such as May through August.
- Conduct pytoremediation pilot study in an area of concern, such as the confluence of the streams (based on CSM).

4.8 Monitored Natural Attenuation (MNA)

MNA takes advantage of the natural capacity of an aquifer to remediate itself through a variety of mechanisms, such as advection-dispersion, hydrogeologic containment, sorption, plant uptake, volatilization, abiotic reactions, and/or biodegradation. MNA has been applied to a broad variety of contaminants (e.g., chlorinated VOCs, petroleum hydrocarbons, and heavy metals) in a variety of site settings (e.g., unconsolidated aquifers, fractured bedrock aquifers, on-site plumes, off-site plumes, etc.). As a remedy, MNA has been applied at numerous sites either as a primary treatment or as a secondary polishing step following a primary treatment (such as, pump and treat or in-situ chemical oxidation). There are many reasons why MNA is a ubiquitous secondary treatment remedy at contaminated sites:

- More aggressive remedies have technical limitations that result in residual contamination remaining in clay lenses, even after several years or cycles of active application. Low levels of contamination continue to diffuse out of finer-grained lenses or from sorbed contamination long after the bulk of the aquifer has been remediated by aggressive treatment. At some point during remedy application, most sites look to MNA, after the primary aggressive treatment reaches asymptotic contaminant recovery.
- All aggressive remedies create some changes in the aquifer that may often be undesirable. When contamination levels are high, the tradeoff of target contamination removal often outweighs any side-effects due to the remedy itself. However, after aggressive treatment has removed the bulk of the contamination, the tradeoff may not be worthwhile for low remaining concentrations of the target contaminants. For example, ISCO causes (as a side-effect) releases of trace metals of environmental concern from the native soil. While elevated trace metals are a concern in the affected groundwater, the benefit from removal of high concentrations of the target contaminants often outweighs the concerns over trace metals. However when the target contaminant concentrations themselves are very low, it is harder to justify replacing low levels of target contaminants with comparable levels of hazardous byproducts.
- Almost all aquifers have some capacity for natural attenuation, although some are more suitable than others. Because attenuation involves multiple mechanisms (hydrogeologic, sorption, degradation), it makes it more likely that target contaminants will be treated or sequestered by one or other of these mechanisms. Even with contaminants that are relatively recalcitrant to many of these mechanisms, dilute plumes will eventually encounter one or other of these mechanisms. For example, most aquifers have a very low capacity to sorb, biodegrade, or volatilize 1,4-dioxane. However, the natural attenuation capacity is not zero as indigenous vegetation is probably sequestering 1,4-dioxane.
- With the focus on green remediation and sustainable remedies, there usually comes a time in the life of a plume when collateral impacts from continued aggressive treatment outweigh the benefits of the treatment. A good example is petroleum hydrocarbon sites that are undergoing free-product recovery. Once the recovery reaches asymptotic levels, then stakeholders (including site representatives, regulatory agencies, and public) have questioned the continued application of an aggressive remedy and advocated MNA for addressing the remaining contamination.
- MNA has proved effective at many sites, including MCAS Cherry Point, NC and Former Department of Defense Housing Facility Novato, CA in arresting the migration of dilute plumes and protecting potential receptors.

As discussed in Section 2.1.4, there is evidence in the Eastern plume data that natural attenuation and plant uptake (intrinsic phytoremediation) are already playing a role in capturing and treating VOCs and

1,4-dioxane and mitigating their potential impact on groundwater and surface water receptors. In fact, uptake by native vegetation appears to be the only viable in-situ remedy for 1,4-dioxane in shallow groundwater that is both technically feasible and economically applicable over large tracts of land along the streams.

The groundwater in the Eastern Plume already contains abiotic degradation products of 1,1,1-TCA (e.g., 1,1-DCE) and "pore water" samples contained biodegradation products of PCE and TCE (e.g., vinyl chloride). Although the anaerobic biodegradation potential in the aerobic portions of the aquifer appears limited, there is evidence of increasing reductive dechlorination occurring as the groundwater approaches the carbon-rich environment of the stream sediment and associated wetland. The groundwater associated with the eastern Plume itself turns more anaerobic as it approaches the streams. Both chloroethane and vinyl chloride have been detected in "pore water samples" and concentrations of VOCs in the "pore water" are much lower than the concentrations historically encountered in the groundwater. Recent studies at numerous sites have shown the tendency of stream bed sediments to bring about considerable attenuation of VOCs (Hamonts et al., 2009; Ellis and Rivett, 2007; Lorah and Voytek, 2004; Bradley et al., 1998). In addition, the current remedy at the site (GWETS) appears to have run its course and is not recovering much contaminant mass, despite several attempts over the years to optimize the location of the extraction wells or the configuration of the aboveground system components.

Recommendations:

- MNA is recommended as a final remedy for the Eastern Plume based on the specific nature of the site and the contamination.
- Conduct recommended data gap studies to document VOC attenuation in the stream bed sediment (see section 2.1.5).
- Incorporate MNA parameters at the appropriate locations into the LTM Plan.