



2021 Revised Final Focused Source Feasibility Study

**TUTU WELLS SUPERFUND SITE
OPERABLE UNIT 2**

**United States Environmental Protection
Agency**

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List of Acronyms and Abbreviations

AMSL	Above Mean Sea Level
ARAR	Applicable or Relevant and Appropriate Requirement
AS	Air sparging
bgs	Below ground surface
BTEX	Benzene, toluene, ethylbenzene, and xylene
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cis-1,2-DCE	Cis-1,2-dichloroethene
COC	Contaminant of Concern
COPC	Contaminant of Potential Concern
CPVC	Chlorinated polyvinyl chloride
CSM	Conceptual site model
CVI	Clean Venture, Inc.
CVOC	Chlorinated volatile organic compounds
CY	Cubic Yards
DCE	Dichloroethene
DNAPL	Dense non-aqueous phase liquid
DPE	Dual-phase extraction
DPNR	USVI Department of Planning and Natural Resources
DPVE	Dual phase vacuum extraction
DVI	Dual-valent iron
EAB	Enhanced anaerobic bioremediation
EFR	Enhanced fluid recovery
ELCR	Excess lifetime cancer risk
ERH	Electrical resistance heating
ERT	Environmental Response Team
ESD	Explanation of Significant Differences
ESSO	Esso Standard Oil, U.S.A., Inc.
EPA	United States Environmental Protection Agency
EPIC	Environmental Photographic Interpretation Center
FIT	Field Investigation Team
FS	Feasibility Study
FSRI	Focused source remedial investigation
FWQC	Federal water quality criteria
GAC	Granular Activated Carbon
gpm	Gallons per minute
GRA	General Response Action

GWTF	Groundwater Treatment Facility
GWQC	Groundwater Quality Criterion/Criteria
GWQS	Groundwater Quality Standard
HDR	Henningson, Durham and Richardson Architecture and Engineering, P.C., in association with HDR Engineering, Inc.
HHRA	Human Health Risk Assessment
HI	Hazard index
IC	Institutional Control
ISCO	In Situ Chemical Oxidation
ISCR	In Situ Chemical Reduction
ISTT	In-Situ Thermal Treatment
ITRC	Interstate Technology & Regulatory Council
LAGA	LAGA Industries, Ltd.
LEL	Lowest Effects Level
LNAPL	Light non-aqueous phase liquid
LTM	Long-term monitoring
LTRA	Long-term response action
MCL	Maximum Contaminant Level
µg/kg	Micrograms per kilogram
mg/kg	Milligrams per kilogram
µg/l	Micrograms per liter
MNA	Monitored Natural Attenuation
MNR	Monitored Natural Recovery
NAPL	Non-aqueous phase liquid
NCP	National Contingency Plan
NPDES	National Pollution Discharge Elimination System
NPL	National Priorities List
O&M	Operations and Maintenance
OIT	Operator Interface Terminal
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
OU	Operable Unit
PA	Preliminary Assessment
PCB	Polychlorinated Biphenyl
PCE	Tetrachloroethene
PDI	Pre-Design Investigation
%	Percent
PLC	Programmable logic controller
POTW	Publicly Owned Treatment Works
PPE	Personal protective equipment
PRB	Passive Reactive Barrier
PRG	Preliminary Remediation Goals

RAO	Remedial Action Objective
RAPR	RA Progress Report
RCRA	Resource Conservation and Recovery Act
RD	Remedial Design
RI	Remedial Investigation
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
ROI	Radius of Influence
SARA	Superfund Amendments and Reauthorization Act
scfm	Standard Cubic Feet per Minute
SEE	Steam enhanced extraction
Site	Tutu Wells Superfund Site
SLERA	Screening Level Ecological Risk Assessment
SSA	Sole Source Aquifer
SSL	Soil screening levels
SVE	Soil Vapor Extraction
TAL	Target analyte list
TBC	To Be Considered
TCA	1,1,1-trichloroethane
TCE	Trichloroethene
TCH	Thermal Conductive Heating
TCL	Target Compound List
Texaco	Texaco Caribbean, Inc.
TPDES	Territorial Discharge Pollutant Elimination System
UIC	Underground Injection Control
USVI	U.S. Virgin Islands
UV	Ultraviolet
VC	Vinyl chloride
VI	Vapor Intrusion
VIDE	USVI Department of Education
VIHA	Virgin Islands Housing Authority
VOC	Volatile Organic Compound
ZVI	Zero-valent Iron

1 INTRODUCTION

This Final Focused Source Feasibility Study (FS) for Operable Unit (OU) 2 of the Tutu Wells Superfund Site (the Site), located in St. Thomas, U.S. Virgin Islands (USVI), has been prepared by Henningson, Durham & Richardson Architecture and Engineering, P.C. (HDR) in association with HDR Engineering, Inc. under United States Environmental Protection Agency (EPA) Region 2 Contract Number EP-W-09-009, EPA Work Assignment Number 031-RICO-021D. This Final FS report was prepared in accordance with the Work Plan for the above assignment, dated October 2015 (HDR, 2015a).

The focus of this FS is the USVI Department of Education (VIDE) Curriculum Center property (i.e., OU2), located in the northern portion of the Tutu Site. A groundwater treatment system has been operating at the Curriculum Center since 2004, as part of OU1 (Site-wide groundwater). EPA created OU2 after the second 5-year review for OU1 indicated that the remedy for the Tutu Wells Site was not functioning as intended. The 5-year review concluded that the current system would not achieve the remedial action objective (RAO) of restoring the Tutu aquifer to drinking water standards (EPA, 2014). Of concern to EPA at the time was the potential presence of dense non-aqueous phase liquid (DNAPL) in the source area at the Curriculum Center. The purpose of the OU2 FS is to investigate the continuing source of contamination at the Curriculum Center, evaluate risks to human health, and identify and evaluate remedial alternatives in support of a Record of Decision (ROD) for OU2.

1.1 Purpose and Organization of the Report

This FS report has been prepared in accordance with EPA's Guidance for Conducting Remedial Investigations and Feasibility Studies under Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) (EPA, 1988) and other applicable guidance as included in the list of references.

In accordance with the National Oil and Hazardous Substances Pollution Contingency Plan, more commonly called the National Contingency Plan (NCP) (EPA 1992a), the relative performance of each alternative is evaluated using the nine criteria of the NCP as the basis for comparison. The purpose of the evaluation process is to determine which alternatives meet the threshold criteria of (1) overall protection of human health and the environment over both the long-term and short-term and (2) attainment of Applicable or Relevant and Appropriate Requirements (ARARs), unless a waiver is appropriate.

Section 121 of CERCLA requires that remedial actions completed under Section 104 or Section 106 of CERCLA be protective of human health and the environment and attain the levels or standards of control for hazardous substances, pollutants, or contaminants specified by ARARs (i.e., cleanup standards, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental, state environmental, or facility siting laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location,

or other circumstance at a National Priorities List [NPL] site) found in federal and state statutes, unless waivers are obtained. Non-promulgated “to be considered” (TBC) criteria or guidelines must also be considered.

Once the threshold criteria have been met, the remedial alternatives are evaluated in terms of their ability to provide the best balance with respect to the five NCP balancing criteria, including:

- Long-term effectiveness and permanence, to address how well a remedy protects human health and the environment after RAOs have been met, including an assessment of residual risk, and the adequacy and long-term reliability of management controls.
- Toxicity, mobility, or volume reduction, to assess the amounts of chemicals destroyed or treated and that remain at the site.
- Short-term effectiveness in the protection of human health and the environment during construction and remedial actions, including the length of time required to achieve protection, short-term reliability of remedial technologies, protection of workers and the community during construction, and disruption of neighboring areas.
- Implementability, considering the technical and administrative feasibility of each alternative, and availability of the products and services needed to execute the remedy. This also considers the ability to construct and operate remedial facilities, ease of undertaking additional remedial actions, ability to monitor remedial effectiveness, and ability to obtain approvals and Permit Equivalents.
- Cost evaluation of remedial alternatives, including both total long-term (operational) and short-term (construction) costs.

The modifying criteria, namely state and community acceptance of the remedial alternatives are evaluated based on formal comments received during the remedial project’s comment period. Issues and concerns presented by stakeholders (e.g., government agencies, property owners, and community groups) will be addressed after the public comment period concludes.

The development and screening of each alternative includes the following six general steps:

- Develop RAOs;
- Develop General Response Actions (GRAs);
- Identify volumes and areas where GRAs will be applied;
- Identify and screen technologies applicable to each GRA;
- Identify and evaluate technology process options to select representative process options for each technology; and
- Assemble combinations of selected process options into remedial alternatives.

Once the alternatives have been assembled, a detailed evaluation is completed. The purpose of the evaluation is to identify the advantages and disadvantages of each alternative as well as key trade-offs among the alternatives. The detailed evaluation of alternatives consists of an individual analysis of each alternative against the evaluation criteria and a comparative analysis among the alternatives to assess the relative performance of each alternative with respect to the evaluation criteria. This analysis is designed to provide decision makers with sufficient information to adequately compare the alternatives, select an appropriate remedy for a particular source area, and demonstrate satisfaction of the CERCLA remedy selection process in the ROD.

This report is comprised of ten sections, summarized below.

- **Section 1 – Introduction;** provides general information on the purpose and organization of the FS Report, and the criteria and process involved in evaluating and selecting the remedial alternative(s) to be implemented.
- **Section 2 – Site Description and History;** includes a summary of background information, description, history, and physical characteristics of the site and potential source areas used in the FS.
- **Section 3 – Summary of Remedial Investigations;** provides a summary of the OU2 remedial investigation (RI) sampling results; information on OU2 geology, hydrogeology, and the nature and extent of contamination; and results of human health risk assessment screening.
- **Section 4 – Remedial Goals and Remedial Action Objectives;** develops a list of RAOs and preliminary remediation goals (PRGs) that consider the contaminant characterization, results from the human health risk assessment screening, and compliance with ARARs and TBCs.
- **Section 5 – General Response Actions;** identifies the GRAs for each medium.
- **Section 6 – Identification and Screening of Remedial Technologies and Process Options;** provides an evaluation of the GRAs against the NCP criteria, based on what is most appropriate to the source area-specific conditions and contamination, and a description of which approaches are technically implementable and capable of achieving source area-specific RAOs. Screening of technologies and process options for the source areas are also included.
- **Section 7 – Evaluation of Process Options;** describes and evaluates the various groundwater remediation process options assembled from the remedial technologies retained after screening.
- **Section 8 – Development and Screening of Remedial Action Alternatives;** provides a detailed development and description of the individual remedial alternatives for the source

areas. This section also provides the preliminary design assumptions associated with the alternatives that were retained and that were used to develop costs for each alternative.

- **Section 9 – Detailed Evaluation of Remedial Action Alternatives;** provides a detailed description of the NCP criteria and evaluation of the individual remedial alternatives against the criteria. A comparison between the various remedial alternatives is also provided.
- **Section 10 – References;** provides a list of references used to prepare the FS.

2 SITE DESCRIPTION

2.1 Location and Description

The Tutu Wells Superfund Site (the Site) encompasses an area of approximately 1.5 square miles of the Tutu Valley in the Anna's Retreat section of St. Thomas, east of the city of Charlotte-Amalie (**Figure 2-1**). The Site is within the Upper Turpentine Run surface drainage basin, which covers approximately 2.3 square miles. The basin is oriented along a north-south axis and is bordered by steeply sloping hills. Turpentine Run is an intermittent stream that traverses the length of the basin from north to south.

The original RI (Geraghty & Miller, 1995) identified a plume of groundwater contaminated with chlorinated volatile organic compounds (CVOC) and two plumes of groundwater contaminated with gasoline components (the Texaco and Esso plumes) that co-mingled with the CVOC plume. The CVOC plume originated at or near the VIDE Curriculum Center and extended beyond the former O'Henry Dry Cleaners building (potential secondary source), following an eastward path towards the discharge area of Turpentine Run.

The CVOC and petroleum sources are briefly described below:

- **Curriculum Center** – The northernmost (upgradient) source of CVOC groundwater contamination is located on the Curriculum Center property and is currently owned and operated by the VIDE. The Curriculum Center building and property were previously occupied by LAGA Industries, Ltd. (LAGA). LAGA owned and operated a textile manufacturing plant at this location from 1971 to 1978. The plant included a dry-cleaning process that utilized tetrachloroethene (PCE) as the dry-cleaning solvent. The RI documented the presence of CVOC contaminants in the soils and groundwater at the Curriculum Center property. The Curriculum Center property is the focus of this OU2 FS.
- **Texaco Service Station (now Puma)** – The RI documented the presence of benzene, toluene, ethylbenzene and xylene (BTEX) and other petroleum constituents in soil and groundwater at the Texaco Caribbean, Inc., (Texaco) service station. The Texaco station is located approximately 90 feet downgradient (southwest) of the Curriculum Center property (beyond the adjoining Tutu fire station). Historically, an automotive service station was also operated at the Texaco facility. This facility overlies the CVOC plume originating at the Curriculum Center.
- **Esso Service Station (now Total Petroleum)** – The RI documented the presence of CVOC, BTEX, and other petroleum constituents in soil and groundwater at the Esso Standard Oil, U.S.A., Inc., (Esso) service station. The Esso station is located approximately 750 feet southwest (downgradient) of the Curriculum Center. An automotive service station also operated at the Esso facility.
- **O'Henry Dry Cleaners** – The RI documented the presence of CVOC contaminants in soils at the O'Henry dry cleaning facility located approximately 1,300 feet south/southwest

(downgradient) of the Curriculum Center. The O'Henry facility was in operation at the time of the original RI. Currently this facility does not overlie the current CVOC plume originating at the Curriculum Center but it is within the historical footprint of the plume.

The current land use surrounding the Tutu Wells Superfund Site and the Curriculum Center ranges from institutional and commercial to residential (**Figures 2-2 and 2-3**).

The focus of this OU2 FS is the Curriculum Center. The overall history and remedial progress of the Site is available in the following documents:

- Final Pre-Design Report (CDM, 2001a);
- Remediation System Evaluation Report (TetraTech GEO, 2011);
- EPA's Second 5-Year Review (EPA, 2014); and
- The most recent annual RA Progress Report (RAPR) for the groundwater treatment systems (Arrowhead, 2017).

VIDE Curriculum Center – OU2 Area

This OU2 FS focuses on characterizing the northernmost (upgradient) source of CVOC groundwater contamination of the Tutu Wells Superfund Site plume, at the VIDE Curriculum Center property. The Curriculum Center is located at 386 Smith Bay Road (Highway 38), Anna's Retreat, St. Thomas.

The Curriculum Center property is occupied by a single-story building, that formerly housed offices, maintenance shops, warehouse space and walk-in freezers that supported the school district cafeterias. A paved parking lot is on the south side of the building, facing Smith Bay Road. An unpaved parking area and loading docks are located on the west side of the building. Additional loading and parking areas are located on the north side of the building (**Figure 2-4**). The northern OU1 groundwater treatment system is also located on the north side of the building. The groundwater treatment system is described in detail in **Section 3.2**, Previous Remedial Actions. The Curriculum Center building was condemned after extensive damage sustained during Hurricane Irma/Maria in 2017.

Terrain at Curriculum Center generally slopes from east to west across the property, with approximately 15 feet of relief between the highest points in the east and northeast and the lowest point near the southwest corner. During the construction of Curriculum Center, the property was graded using imported fill. Fill material was observed during the OU2 drilling activities and reported by previous investigations (e.g., Geraghty & Miller, 1995).

2.2 Curriculum Center History

The Curriculum Center property is currently owned and occupied by VIDE. The property was originally owned by LAGA, who began operation of a textile manufacturing facility at the property in 1969. In 1970, LAGA was sold to the Duplan Corporation at which time Duplan reportedly

began dry cleaning operations at the property, with dry cleaning equipment using PCE as the dry-cleaning fluid. Duplan filed for bankruptcy in 1976 and ceased all operations at the property in late 1978. Panex Co. (a corporation formed by the former owners of LAGA) purchased the facility from Duplan's bankruptcy trustee in 1979 and sold it to VIDE in 1981 (Delaware Chancery Court, 2007). Information on property operations during Panex' ownership was not available. From 1982 to 2017, the building was used by VIDE as a book repository/library, warehouse with cold storage, maintenance shop and school district administrative offices (TetraTech GEO, 2011).

2.3 Geology and Hydrogeology

Bedrock geology at St. Thomas was formed by volcanism. Rock units that underlie the ridges of St. Thomas consist of lithified lava flows, flow breccias and tuffs, spilitic lava, andesitic breccia and tuff, and minor limestone beds intruded by Cretaceous and early Tertiary dikes and plugs. **Figure 2-5** shows the regional geology of the area (Renken et al, 2002). These rocks have been uplifted and faulted, forming northward-dipping volcanic bedding and bedding planes (Donnelly, 1966). Unconsolidated alluvial and coastal deposits were deposited within several small stream valleys near the shoreline.

Bedrock in the upper reach of Turpentine Run basin consists of two volcanic formations, the Water Island Formation and the younger Louisenhoj Formation, separated by a mild angular unconformity. The Water Island Formation consists of keratophyre flows and tuffs, spilite flows, and radiolarian tuffs. Erosional sediments are absent, and the entire volcanic sequence appears to have been extruded on the ocean floor. Overlying the Water Island Formation is the Louisenhoj Formation, which consists of augite andesite tuff and volcanic breccia layered with conglomerate (Capes Point Conglomerate lithofacies). The conglomerate contains pebbles and cobbles of Water Island Formation lithologies. The eruptive center during Louisenhoj time was probably located close to Pillsbury Sound, between St. Thomas and St. John. In western St. John and eastern St. Thomas this formation consists of coarse volcanic cone debris derived largely from a volcanic eruption at land surface (Donnelly, 1966).

Alluvium in St. Thomas consists largely of silt, clay, sand and gravel lenses that grade coastward to sandy carbonate beach sands. The thickest alluvial deposits are near the coast and lower reaches of stream valleys. A narrow 200-foot-wide band, no more than 40 feet in thickness is present in the lower reach of Turpentine Run in eastern St. Thomas.

Surficial deposits consist of unconsolidated, poorly sorted mixtures of clay, silt, sand, gravel, cobbles, and boulders of alluvial origin. The alluvium is generally only two to four feet in thickness but can locally reach thicknesses of 10-30 feet along the valley axes. Fill material has also been observed beneath paved roads and in the commercially developed central part of the valley (CDM, 2001a). Approximately 10 feet of fill, consisting of sand and angular gravel, was observed at boring location OU2-MW5 during the OU2 focused source remedial investigation (FSRI), while as little as two feet of fill or soil was observed at other boring locations.

Bedrock at Curriculum Center is comprised of the Louisenhoj Formation. It consists of moderately weathered, fractured and faulted andesitic tuff and breccia. Andesite was encountered at all of

the OU2 borings. Locally, the andesite is exposed on hills, steep slopes, and at road and other construction cuts. On gentle slopes of hills and along the valley axes, the bedrock is overlain by thin, unconsolidated alluvial deposits.

Bedrock fracture trace trends in the vicinity of OU2 (CDM Federal, 1992; Geraghty & Miller, 1992) were presented in the Phase II RI (Geraghty & Miller, 1995). The inferred fracture traces are shown on **Figure 2-6** along with the fracture traces identified in the Environmental Photographic Interpretation Center (EPIC) Site Analysis Report (EPIC, 1988). The predominant fracture trace orientations trend N68°E and N33°W in the vicinity of the Curriculum Center. An additional fracture, oriented N9°E, aligns with Turpentine Run. These three fracture trace orientations at and in close proximity to Curriculum Center are consistent with the three major regional fault trends discussed in literature.

The surface geophysical survey also identified local features that are consistent with regional fault trends. A northeast-southwest running fracture located on the north side of the Curriculum Center was identified from the GeoTrax Survey™ data. High-angle fractures, interpreted as a potential deformation zone, extended northwest-southeast along the bottom of the hill on the eastern side of Curriculum Center. A parallel fault runs northwest-southeast along the west side of the Curriculum Center.

The bedrock of St. Thomas has been described in literature as consisting of three separate hydrogeologic units; a thin soil zone and saprolite zone capable of absorbing large amounts of rainfall, a weathered bedrock zone (3 to 50 feet thick and rarely as much as 180 feet thick) and unweathered bedrock containing joints that are more numerous and more open at shallower depths (Cosner, 1972). Bedrock fractures and joint weakness are best expressed in valleys and provide the greatest opportunity for additional groundwater supplies, particularly in the lower part of the valley, where overlying alluvium often acts as a source of recharge. Drainage basins and minor valleys have formed by differential weathering along fault and fracture zones and generally function as conduits for groundwater flow in St. Thomas (Jordan, 1975).

Groundwater in both the alluvial and bedrock aquifers generally exists under unconfined or water table conditions. The water table depths have been reported as little as 5 feet to more than 100 feet bgs, with the greater depths occurring at higher land elevations. Groundwater is stored and transmitted in fractures in the bedrock. Since the groundwater is transmitted principally through fractures and the rock is more fractured along major lineaments, the bedrock aquifer demonstrates vertical, as well as horizontal anisotropy.

Recharge to the aquifers results from precipitation and is therefore dependent on the frequency and intensity/volume of rainfall. The bedrock aquifer is infrequently recharged and usually only after heavy rainfalls or a series of storms that generate two or more inches of rainfall (Jordan, 1975).

An alluvial aquifer does not exist at the Curriculum Center. The thin deposits of alluvium and fill material are unsaturated with respect to groundwater. The relatively coarse-grained deposits serve to transmit local recharge from rainfall to the underlying water table.

The water table is present at an approximate depth of 30 feet bgs at Curriculum Center. However, it ranges throughout the OU2 study area from approximately 65 feet bgs at higher elevations northeast of Curriculum Center to approximately 15 feet bgs in topographically lower areas to the west and south of the Curriculum Center.

The bedrock aquifer at Curriculum Center can be divided into two zones:

1. Shallow (<90 feet bgs) zone with water-bearing fractures with a moderate permeability extend in a west-southwest direction on the north side of Curriculum Center. A few low permeability fractures extend north-south in front and behind Curriculum Center and extend in a west-southwest direction in front of Curriculum Center.
2. Deep (90 to 140 feet bgs) zone with very few water-bearing bedrock fractures and low permeability.

The bedrock aquifer has both primary (matrix) and secondary (fracture) porosity. The primary or matrix porosity was estimated to be approximately two percent (%) during the matrix diffusion investigation. In general, it has limited interconnectivity and therefore groundwater movement through these pore spaces is minimal. Typical values for secondary or fracture porosity ranges between 0.001 and 0.1%. However, due to relatively high interconnectivity (high permeability), groundwater flow in fractured rock is largely through the secondary system of joints and fractures. Groundwater flow rates in the shallow zone are relatively higher than in the deep zone due to relatively higher fracture frequency and hydraulic conductivity. The degree and orientation of fracturing combined with heat pulse flow measurements and packer testing performed during the FSRI indicate that only limited groundwater flow is occurring in the deep water-bearing zone. However, water-bearing fractures exhibiting weak inflow were observed to depths approaching 200 feet bgs during the FSRI.

Borehole and surface geophysical surveys indicated the presence of numerous fractures, both high and low angle, and conductive, water-bearing features that provide hydraulic connection between monitoring well locations in the shallow zone of the bedrock aquifer. The high-angle fractures and water-bearing features also extended into the lower zone but with less frequency. The strike of these fractures generally trended to the northwest and northeast, consistent with regional trends. Fractures dipped to the northwest, southeast, and southwest. However, they most dipped to the northwest.

The surface geophysical survey identified the possible existence of bacterial weathering in the fracture zone on the north side of the Curriculum Center. Laboratory studies of the bacterial weathering of rock have been reported in the literature but environmental impacts are still being investigated. The presence of bacteria was associated with a stronger conductive (electrical) response in the fracture zone and may contribute to higher permeability of this fracture zone.

The transmissivity of the shallow and deep water-bearing zones was not characterized in the FSRI. Previous investigations indicated that the transmissivity of the shallow zone ranged from 1,662 to 2,991 square feet per day, based on a pumping test conducted at extraction well RW-7.

Although anticipated to be relatively lower, the transmissivity of the lower water-bearing zone has not been estimated.

Groundwater Flow

Shallow and deep zone groundwater flow contour maps were produced for two synoptic groundwater level monitoring events in February and June 2017 during the FSRI (**Figures 2-7 to 2-10**). Pumping activity, structural features (i.e., locations/trends of fracture zones/lineaments) and regional groundwater flow were considered when constructing the maps. Groundwater elevations for wells that were considered to be either significantly influenced by pumping at the Curriculum Center groundwater treatment facility (GWTF) (RD-11 for the June 2017 event, IW-1 for both events) and wells that do not appear to be representative of the groundwater zone (e.g., deep wells OU2-MW4, OU2-MW5, and RD-5) were not used to construct the contour maps. The low productivity of these wells demonstrates the non-homogenous nature of fractured rock and indicates that there are areas of the occurrence and movement of groundwater is minimal.

Shallow water-bearing zone groundwater elevations and flow directions for the February and June 2017 events were very similar (**Figures 2-7 and 2-8**). Because of limited well control, groundwater contours and flow direction beneath most of the Curriculum Center building and extending to Route 38 were inferred. The contour maps indicate that shallow groundwater flow is generally to the south-southwest at the Curriculum Center property. The contours also show a slight convergence of flow along an axis approximately centered on Turpentine Run valley. The flow convergence implies the presence of a more hydraulically conductive pathway. The general direction of groundwater flow shown by the contour maps is consistent with ground surface topography and the regional flow of groundwater identified in previous investigations.

The area covered by the deep zone monitoring wells during the OU2 investigation was not as extensive as in the shallow zone, due to limited well control, but was sufficient to evaluate groundwater flow at the Curriculum Center property (**Figures 2-9 and 2-10**). Groundwater flow in the lower zone during both events was generally to the southwest, towards the axis of the north-south running portion of the Tutu Valley. February contours showed a stronger southwestward flow and June contours showed a stronger southward trend. The difference is a result of lower groundwater levels at wells RD-11 and RD-9 located in the area of the extraction system during the June event. Because of limited well control in the lower water-bearing zone, groundwater contours and flow direction beneath most of the Curriculum Center building and extending to Route 38 were also inferred.

In addition to flow direction, the contour maps were used to estimate the magnitude of horizontal and vertical hydraulic gradients at OU2. Average horizontal gradients observed in the shallow zone were reasonably consistent between the February and June monitoring events. Average horizontal hydraulic gradients in the general direction of plume migration were 0.011 ft/ft for the February event and, 0.013 ft/ft for the June event.

Average horizontal hydraulic gradients for the deep zone were also relatively consistent between the February and June events and were slightly higher than the shallow zone; possibly a result of

the lower hydraulic conductivity in the deeper zone. Average deep zone horizontal hydraulic gradients in the general direction of plume migration were 0.019 ft/ft for the February event and, 0.016 ft/ft for the June event.

The shallow hydraulic gradients are relatively high and would be indicative of a low hydraulic conductivity in porous media. However, in fractured rock the calculated gradient is more reflective of the effective or net hydraulic conductivity in the direction of the hydraulic gradient. Groundwater flow is limited to the secondary system of joints and fractures. In general, this results in a longer pathway and a slower net velocity in the direction of the hydraulic gradient. Groundwater flow at the Curriculum Center can be expected to move most readily in a southwest direction because the conductive pathway and hydraulic gradient align reasonably well. In other areas of OU2, where conductive pathways are sub-parallel or perpendicular to the gradient, the longer pathway will result in a slower net movement in the direction of the hydraulic gradient.

Vertical hydraulic gradients were generally upward as was observed in previous investigations. Vertical gradients were calculated for the area of the treatment system and for the downgradient portion of OU2, in the area of monitoring well OU2-MW3. Upward gradients were generally stronger during the February event ranging from 0.08 ft/ft near the treatment system to 0.011 ft/ft near OU2-MW3. Upward gradients in June were estimated to be 0.025 ft/ft near the treatment system and 0.005 ft/ft in the downgradient area near OU2-MW3.

The difference in the magnitude of vertical gradients is largely due to the head differences in the lower water-bearing zone. Hydraulic head in the lower zone, in the area of the extraction system, was approximately 3.5 feet lower during the June event, when the system was in operation. Groundwater levels in the shallow zone were very similar between the February and June events.

The upward gradients are consistent with the results of previous investigations and with OU2's location in the discharge zone of the Turpentine Run drainage basin. Groundwater recharge zones in topographically high areas are present both to the west and east of OU2 and ground surface topography drops steeply to the valley in the area of OU2. Historical groundwater withdrawals from the more conductive shallow water-bearing zone for water supply may have contributed to the upward gradient.

Based on the direction of plume migration, the location of stream valleys and the general trend of faults in the area, the movement of groundwater within the Turpentine Run valley is expected to be controlled by a regional north-south trending fracture. Differential weathering has most likely increased the secondary fracture density and hydraulic conductivity along the valley. The plume migration pathway also indicates that a second northwest trending fault may be impacting groundwater flow in the area of the former O'Henry Dry Cleaners facility. Both fracture trends are consistent with regional fracture trends in the St. Thomas area.

3 SUMMARY OF REMEDIAL INVESTIGATIONS

3.1 Regulatory History and Previous Investigations

The following narrative summarizes investigations that have been performed at the Curriculum Center property.

1982 Groundwater Sampling of Virgin Islands Housing Authority (VIHA) Well No. 1

In 1982, Geraghty & Miller conducted an aquifer pumping test and water quality sampling of a supply well (VIHA #1) at the VIHA property to the northeast (upgradient) of the Curriculum Center (Geraghty & Miller 1995). A sample collected after five hours of pumping had concentrations of 12 micrograms per liter (µg/l) of cis-1,2-dichloroethene (cis-1,2-DCE), 55 µg/l of PCE, and 10 µg/l of trichloroethene (TCE). At the time, drinking water standards had not been established by EPA.

1987 EPA Well Sampling

Mr. Eric Tillett, owner of Tillett Gardens, contacted USVI Department of Planning and Natural Resources (DPNR) about an odor emanating from the water of his supply well, which is on the south side of Smith Bay Road, approximately 450 feet southwest of the Curriculum Center. DPNR requested help from the EPA and between July and October 1987, EPA collected groundwater samples from 26 wells and water samples from approximately 50 cisterns. Twenty-four wells and five cisterns were found to be contaminated. Elevated concentrations of petroleum hydrocarbons and CVOCs were detected in the Tillett supply well; VIHA Well No. 1, located approximately 120 feet northeast of the Curriculum Center building; and four other supply wells. The Tillett supply well had total volatile organic compound (VOC) concentrations above 1,000 µg/l. Both the Tillett well and VIHA Well No. 1 were taken out of service, along with other contaminated commercial, institutional, and private wells (Weston, 1988).

1989 Preliminary Assessment

The EPA Field Investigation Team (FIT) contractor, NUS Corporation, conducted a Preliminary Assessment (PA) of the LAGA building in 1989 (NUS, 1989). The PA identified a drum disposal area located less than 100 feet to the northwest of the LAGA building. Twenty-two drums were in an area of thick brush. Several drums were on their sides, some were corroded, and at least one drum contained an unknown liquid.

1995 Phase II RI

A Phase II Remedial Investigation/Feasibility Study (RI/FS) was completed from May 1994 to 1995 by Geraghty & Miller at the Curriculum Center property on behalf of the Tutu Environmental Investigation Committee (Geraghty & Miller, 1995). Prior investigations completed by Geraghty & Miller from December 1989 until May 1993 (e.g., preliminary reconnaissance activities and field activities for the Tutu Service Station investigation) were subsequently referred to as the Phase I

RI and were reported to the EPA in technical memoranda (Geraghty & Miller 1992a, 1992b, and 1993).

During the multi-phase Phase II RI, Geraghty & Miller collected groundwater samples from 51 monitoring wells and 15 supply wells in the Tutu Valley. The samples were analyzed for target compound list (TCL) organic compounds, target analyte list (TAL) inorganic substances, and various geochemical parameters.

The results showed a CVOC plume and two separate plumes of gasoline components (the Texaco and Esso plumes) that co-mingle with the northern portion of the CVOC plume. The CVOC plume starts at or near the VIDE Curriculum Center creating a $\frac{3}{4}$ -mile long plume. This plume is divided into a northern, central and southern portion. The data showed an additional CVOC source near the O'Henry Dry Cleaners building within the southern portion of the CVOC plume.

The CVOCs detected at Curriculum Center were cis-1,2-DCE, PCE, TCE, and vinyl chloride (VC). The highest concentrations detected were 2,100 µg/l of cis-1,2-DCE, 1,300 µg/l of VC, 360 µg/l of PCE, and 78 µg/l of TCE; all exceeded their respective Maximum Contaminant Levels (MCLs). Soil and groundwater at the former Texaco and Esso service stations were found to be impacted with BTEX and other petroleum hydrocarbon-related compounds). Historically, BTEX compounds have not exceeded MCLs in groundwater at the Curriculum Center (Geraghty & Miller, 1995).

In 1995, the northern portion of the CVOC plume (i.e., groundwater with concentrations above cleanup standards) extended 1,600 feet from the Curriculum Center to Four Winds Plaza. The plume was approximately 500 feet wide.

The highest concentrations of total CVOCs, were observed in shallow zone monitoring wells near the northern source area at Curriculum Center. Groundwater at the Curriculum Center below a depth of 50 feet was not investigated during the RI.

Monitoring well groundwater samples between Tillett Gardens and Four Winds Plaza contained 140 µg/l of PCE, 100 µg/l of cis-1,2-DCE, and 33 µg/l of TCE. VOC concentrations in the southern part of the plume were higher in deeper monitoring wells than in shallow wells.

1995 EPA and DPNR Investigation

In March of 1995, EPA and USVI DPNR discovered oil (containing 30% PCE) in subslab piping beneath the Curriculum Center building. The piping was traced from the floor drains to a room that apparently held a PCE reclamation still. There was no evidence of leakage in the section of pipe investigated; however, the full extent of the piping and its integrity remained unknown.

Soil samples contained from three to 180 micrograms per kilogram (µg/kg) of PCE at eight locations near the north-central side of the main building, in the vicinity of the former discharge pipe and former waste pit. TCE was detected in four soil samples at concentrations from one to 130 µg/kg. Although no samples were collected from beneath the building, it was suspected that higher concentrations of CVOCs might have been present in soil beneath the building or in the unsaturated bedrock.

BTEX and other petroleum-related compounds exceeded EPA's site-specific soil screening levels (SSLs) in two surface soil samples collected from the northern corner of Curriculum Center where a drain from the paint shop sink discharged to the ground. Benzene, toluene, total xylenes, and several naphthalenes and polycyclic aromatic hydrocarbons were present at high concentrations in these samples. Concentrations of both toluene and total xylenes exceeded their soil saturation limits of 289 milligrams per kilogram (mg/kg) and 168 mg/kg, indicating that residual saturation levels of non-aqueous phase liquid (NAPL) may have been present. One CVOC, 1,1,1-trichloroethane (TCA) also exceeded EPA SSLs in the sample that exhibited the highest toluene concentration.

The RI concluded that the elevated concentrations of CVOCs in groundwater adjacent to and immediately downgradient of the Curriculum Center indicated a high probability that PCE was present as DNAPL in the saturated or unsaturated bedrock.

1996 ROD

The ROD for the Tutu Wells Site was signed on August 5, 1996 (EPA 1996). A summary of the ROD requirements was included in the Final Interim Remedial Action (RA) Report (CDM 2004a) and is presented below.

a) Groundwater

Requirements in the ROD to address Site-wide groundwater impacted by CVOCs included the following:

- Installation of three recovery wells for hydraulic control of the northern and southern portions of the plume
- Installation of two recovery wells for hydraulic control of the CVOC contamination; one each at the Curriculum Center and the O'Henry Drycleaner location source areas.
- Construction of a groundwater treatment facility, with discharge water quality criteria to be determined during the design phase.
- Semi-annual groundwater sampling to monitor groundwater quality and contamination migration.
- Natural attenuation of low-concentration contaminants near the plume edges where groundwater contains less than 100 parts per billion (ppb) of total CVOCs.
- Implementation of institutional controls (ICs) to prohibit unauthorized use of groundwater and installation of new wells within the plume area.

Based upon the results of the pre-design investigation (PDI) and subsequent design analysis, a number of modifications were proposed and approved by EPA as part of the Final Remedial Design (RD). A summary of the approved modifications to the ROD was included in the Final Interim RA Report (CDM, 2004a). The modifications included:

- The configuration of the recovery wells at the Curriculum Center was changed from one well at the downgradient property boundary to three wells installed within the source area.
- The groundwater recovery well at the O'Henry Drycleaner location was eliminated based upon groundwater concentration trend analyses, which indicated that the southern portion of the groundwater plume was contracting with concentrations steadily decreasing in most wells.
- Monitored Natural Attenuation (MNA) was selected as an alternative to hydraulic control for the southern portion of the plume.
- Construction of two smaller groundwater treatment facilities instead of one centralized larger one for the northern and central portions of the plume.
- Investigation of enhanced anaerobic bioremediation (EAB) for its potential to reduce cleanup time.
- Determination by EPA, in consultation with DPNR, to discharge treated groundwater to Turpentine Run, with effluent water quality meeting the discharge requirements of the Territorial Discharge Pollutant Elimination System (TPDES) permit equivalency for the Site.

b) Soil

Requirements in the ROD to address Curriculum Center soils included the following:

- Excavation of impacted soils, followed by either off-site disposal, or ex-situ soil vapor extraction (SVE) and re-depositing of the treated soil on the property.
- In-situ SVE treatment in unsaturated bedrock areas and in soil areas not suitable for excavation.
- Thermal oxidation or off-gas treatment.

In the absence of promulgated federal or territorial regulatory standards for soils, EPA developed site-specific cleanup standards based on EPA soil screening levels (SSL) methodology for protection of groundwater (i.e., SSLs were developed based on residual concentrations remaining in soil such that the resulting groundwater concentrations would be at or below the MCLs).

Based upon the results of the PDI and subsequent design analysis, several modifications were proposed to the remedy for Curriculum Center soils. The modifications were approved by EPA as part of the Final RD and included:

- Excavation of impacted soil was not required because the PDI indicated that overburden soils did not contain CVOCs at concentrations above the site-specific soil cleanup standards.

- Activated carbon adsorption followed by potassium permanganate oxidation was determined to be more cost-effective than thermal oxidation for reducing CVOC concentrations in the off-gas effluent.
- The SSLs defined in the ROD were considered to be inappropriate for evaluation CVOC cleanup within fractured bedrock due to limitations associated with sample collection, analytical methods and representativeness of the sample results. Therefore, performance-based cleanup criteria for SVE treatment were developed during the RD (initial shut-down of the SVE system after asymptotic conditions are reached, followed by a pulse-operation period of the SVE system to confirm that significant rebound in soil vapor CVOC concentrations did not occur).

1998-1999 PDIs

Pre-design field investigations were performed by CDM to further define the extent of CVOCs in Curriculum Center soil and groundwater, and to collect hydrologic and geologic information for use in the RDs (CDM, 2001a). PDIs were performed from August 1998 through October 1999. CDM installed and/or collected soil samples from seven shallow interior building borings, nine shallow exterior building borings and seven deep borings. CDM collected groundwater from nine monitoring wells and two extraction wells. CDM collected soil gas from 26 vapor probes. CDM also conducted water level measurements, aquifer testing of extraction wells, packer testing of six supply wells, geophysical logging of 10 supply and two extraction wells, sediment and surface water sampling, and wetland delineation.

Subslab drain and pipe tracing was completed at the Curriculum Center using building architectural drawings, visual observation, hand augering, and concrete coring to identify unknown discharge points. Six core holes inside the building and three hand auger boreholes outside the building were advanced to confirm the presence of suspected pipes. Solvents encountered in the pipes were sampled and removed by wet vacuuming.

CVOC contamination existed at the Curriculum Center in the unconsolidated vadose zone. The existence of vadose-zone contamination was confirmed during the SVE pilot study completed from October to November 2000. Based upon data collected during this test, the extent of vadose-zone contamination was limited to the immediate area of the workshop behind the Curriculum Center. Approximately 40 pounds of CVOCs were removed during a 5-day SVE pilot test, with a mass removal rate of approximately four pounds per day (CDM, 2001b).

2004 EAB Pilot Study

In 2004, CDM performed a pilot study to assess the feasibility of enhancing the existing groundwater extraction and treatment system remedy at the Curriculum Center GWTF#1 using EAB (CDM, 2004b). EAB was considered to have potential for increasing mass removal of PCE. The pilot study was conducted in two phases: an EAB background groundwater monitoring phase to establish background conditions, and a tracer study/optimization phase to obtain more precise estimates of groundwater velocity and dilution.

During the EAB background groundwater monitoring phase, groundwater samples were collected and analyzed for CVOCs, dissolved gases, electron donors and electron acceptors to assess the nature and extent of EAB activity in the shallow and deep zones in the source area. Findings and conclusions for the background monitoring phase included:

- PCE, TCE, cis-1,2-DCE, and VC were detected in all monitoring wells, indicating that reductive dechlorination of PCE to VC was occurring;
- CVOc concentrations detected in the shallow zone were approximately two orders of magnitude lower than in the deep zone;
- Low concentrations of ethene/ethane, methane, and dissolved hydrogen in the shallow zone indicated that complete conversion of PCE to end products was occurring via reductive dechlorination; and
- Higher concentrations of ethene/ethane ($>10 \mu\text{g/l}$) and methane (up to $240 \mu\text{g/l}$) in the deep zone indicated that conversion of VC to the end products was occurring via reductive dechlorination at depth.

Based on these findings, CDM concluded that significant reductive dechlorination was not occurring within the shallow zone. The presence of the PCE daughter products appeared to be representative of historical reductive dechlorination activity (i.e., before the shallow groundwater in the source area was continually flushed with uncontaminated, oxygen-rich groundwater as the result of the operation of GWTF#1). CDM further concluded that reductive dechlorination was occurring within the deep zone but that it was limited by electron donor availability.

Separate tracer studies were completed for the shallow and deep zones EAB Pilot Study. Tracer was injected in wells IW-1S and IW-2S and samples were collected at extraction wells RW-7, BP-1, BP-2 and BP-3 for the shallow zone study. Tracer was injected in IW-2 and samples were collected at wells BP-1 through BP-3 for the deep zone study. Based on the results of the investigation, CDM reported the following findings:

- Multiple, well-defined flow paths exist between shallow zone wells IW-1S and IW-2S and extraction well RW-7, and deep zone well IW-2 and the extraction well;
- Well BP-2 is not in the shallow flow paths between IW-1S/IW-2S and extraction well RW-7 (based on detected tracer concentrations and the breakthrough curve for this well);
- When injecting into deeper well IW-2, upward flow into the shallow, more productive zone was observed with tracer detected at BP-3;
- Estimated average linear groundwater velocities were on the order of 45 feet per day for the shallow zone and 8 feet per day for the deep zone.

Conclusions for the EAB pilot study can be summarized as:

- Travel times between the upgradient edge of the study area and RW-7 are extremely short and indicative of rapid effective pore volume exchange (i.e., "flushing") for both the shallow

and deep zones. Rapid flushing was expected to decrease the dissolved-phase CVOC concentrations within the shallow, productive zone very quickly;

- The dissolved CVOC contamination present in the deep, less productive zone and in dead-end pore spaces within the shallow zone will not be flushed by remedial pumping. Such contamination will tend to persist and continue diffusing into the productive zone over the long term;
- EAB processes are occurring within the deep, less productive zone of study area. However, reductive dechlorination was not significant within the shallow, productive zone at the time of the pilot study;
- Estimated groundwater velocities within the shallow (45 ft/d) and deep zones (8 ft/d) were significantly greater than the targeted value of 1 ft/d under the controlled-gradient flow conditions associated with GWTF#1 operation.

2007 & 2011 Vapor Intrusion Investigations

EPA's Environmental Response Team (ERT) performed two investigations to characterize the potential for vapor intrusion into the Curriculum Center building. The investigations were performed in December 2007 and December 2011 (Lockheed Martin, 2008 and Lockheed Martin, 2012). Sub-slab vapor and indoor air samples were collected on both occasions.

In December 2007, the EPA ERT contractor installed 16 permanent sub-slab gas wells at the Curriculum Center building. Three wells were in the maintenance area, nine were located in the warehouse area, and four were located in the Curriculum/office area). A total of 32 air sampling locations, including three indoor air locations from the maintenance area, 12 indoor air locations from the warehouse area, 15 indoor air locations from the Curriculum/office area, and two ambient air samples were also selected. Sub-slab and air samples were collected over a period of 24 hours, using SUMMA® canisters, and were analyzed for PCE, TCE, cis-1,2-DCE, trans-1,2-dichloroethene (trans-1,2-DCE), 1,1-dichloroethene (1,1-DCE), and VC using EPA Method TO-15 with selective ion mode to achieve lower detection limits. The 2007 sampling event was replicated by ERT in December 2011 (Lockheed Martin 2012). One sub-slab vapor point was found to be compromised and was replaced at the time.

The extent of soil vapor with elevated concentrations of PCE and TCE did not change noticeably between the two sampling rounds. All but one sample exceeded the soil vapor action level for PCE. The area of the highest sub-slab concentrations was found in the warehouse area located in the central portion of the Curriculum Center building and extends into the adjoining maintenance and office areas. The extent of TCE concentrations that exceeded action levels in soil vapor falls within the area of highest PCE concentrations.

3.2 Previous Remedial Actions

This section provides a summary of previous remedial activities conducted at OU2.

Following extensive RI activities and completion of the RD during September 2001, the EPA constructed the GWTF at the Curriculum Center property to achieve hydraulic control of the northern portion of the plume and remove CVOC mass from the saturated zone. The system is referred to as GWTF #1 for the Curriculum Center property. GWTF#2 addresses downgradient central portions of the plume, north of the O’Henry drycleaner.

GWTF #1 became operational in 2004 and initially consisted of three groundwater extraction wells, an equalization tank and transfer pumping system, bag filters, a low-profile air stripper and an off-gas treatment system. Use of the off-gas treatment system was discontinued in April 2006 after CVOC concentrations dropped below the air pollution control Permit Equivalents limits. One GAC vessel and one potassium permanganate unit remain at the Curriculum Center on standby for emergency use. Chemical feed systems were also included for sequesterant/biocide injection and pH adjustment.

The groundwater extraction system at GWTF #1 consists of three wells; RW-6, RW-7, and RW-9. Extraction wells RW-7 and RW-9 are completed in the shallow, more productive portion of the aquifer, with open-hole sections from 30 to 80 feet below ground surface (bgs) and 40 to 60 feet bgs, respectively. Extraction well RW-6 is completed in the deeper, less productive portion of the aquifer with an open interval from 80 to 130 ft bgs. Extraction well RW-7 is operated on a continuous basis. Extraction well RW-9 operates as required to maintain the target groundwater elevation and is typically operated during and following heavy rain events. Extraction well RW-6 is operated approximately one hour per week, at a flow rate of approximately two gallons per minute (gpm), until the extraction well pump shuts down due to a low water level in the well (EPA, 2014 and Arrowhead, 2017). Treated water is discharged to Turpentine Run on the adjoining property to the northwest.

The treatment system was operated by EPA from 2004 to 2013. Operation and maintenance of the treatment system was transferred from EPA to the USVI government in April 2013. The system is currently operated by Arrowhead Contracting, Inc. (Arrowhead) under contract to the USVI.

As part of the long-term response action (LTRA) for the Tutu Wells Site, groundwater monitoring is routinely completed to assess RA progress. Groundwater monitoring was completed on a quarterly basis from system startup in 2004 until April 2007, and annually since 2007. A total of 30 monitoring and residential wells are monitored as part of the LTRA. Groundwater levels are measured on a monthly basis from 36 monitoring wells. Influent monitoring is performed monthly at two of the extraction wells (RW-6 and RW-7) using the GWTF influent sampling port.

RAPRs have been prepared by the operations and maintenance (O&M) contractor (Arrowhead) and submitted to DPNR annually to report the progress of the LTRA. Prior to 2014, the RAPRs were prepared by CDM and submitted to EPA under the RAC. The most recent available RAPR (Arrowhead 2018) documented O&M operations and sampling results for the period of May 1, 2017 through September 2, 2018. The treatment facilities were taken offline in September 2017, in preparation for hurricanes Irma and Maria, and have remained offline as of the preparation of this feasibility study, due to power-related factors (Arrowhead, 2018).

An SVE system was constructed in 2004 to remediate the unsaturated zone source of the CVOC groundwater contamination. The system included two SVE wells (SVE-1 and SVE-7), a moisture knockout tank and a blower, and discharge to the GWTF off-gas treatment system. The location of SVE-7 coincides with RW-7, which was constructed as a dual-phase extraction well. The SVE system was operated for approximately two years. The system was shut down in April 2006 due to a significant decrease in influent concentrations and achievement of asymptotic conditions. Based on these conditions, it was determined that the SVE system was no longer cost-effective (EPA, 2014).

A 2011 evaluation of the remediation system concluded that extraction well RW-7 was too far upgradient to effectively contain the Curriculum Center source area and recommended considering a new containment system with additional wells screened across the shallow and deep zones (EPA, 2011).

The second five-year review was completed in 2014 to determine if the current OU1 remedy was protective of human health and the environment, and whether it was anticipated to be protective in the future (EPA, 2014). The review concluded that the remedy for the Tutu Wells Site was not protective in the long-term and would not achieve the remedial objective of restoring the Tutu aquifer to drinking water standards. Of particular concern to EPA was the potential presence of DNAPL as an ongoing source of groundwater contamination for the deep aquifer in the northern portion of the Tutu groundwater plume. The review recommended installation of additional wells to further evaluate the presence of DNAPL, the evaluation of groundwater monitoring results and the development of a conceptual site model (CSM) to determine a strategy for addressing the ongoing sources of CVOCs at OU2. As part of the review, the 2014 document summarized findings and groundwater quality for the OU2 area as follows:

- Contaminant transport was believed to be controlled by advection. A discrete plume (with total CVOCs in excess of 1,000 µg/l) originated north of the Curriculum Center and extending approximately 500 feet downgradient to a location just north of the former Texaco service station (now Puma);
- Unexpectedly high concentrations of CVOCs were detected in several wells during the April 2009 annual sampling event. A follow-up sampling event was conducted in October 2009 at monitoring wells MW-2, MW-8, MW-15, RD-13, and TT-6. The October results did not confirm the concentrations detected in April 2009. The cause of the high results from April 2009 was not determined;
- Unexpectedly high concentrations of CVOCs were detected in several wells during the April 2009 annual sampling event. A follow-up sampling event was conducted in October 2009 at monitoring wells MW-2, MW-8, MW-15, RD-13, and TT-6. The October results did not confirm the concentrations detected in April 2009. The cause of the high results from April 2009 was not determined;
- A spike in concentrations was observed at well RD-9 in April 2011 with 478,500 µg/l total CVOCs. This represented the highest concentration observed at RD-9, including the 2004

baseline concentration (152,020 µg/l). The increase was attributed to nearby extraction wells RW-7 and RW-9 mobilizing contaminants in the vicinity of RD-9. Since RD-9 is screened in the deep zone that is suspected to contain free product, the spike was interpreted as an indicator of free product in the vicinity of RD-9;

- A comparison of total CVOC concentrations at three downgradient wells MW-1D, MW-14 and RD-13, located approximately 300 feet from RD-9, indicated that contaminant mass increased with depth downgradient of the source area. The lateral extent of the deep zone contamination could not be determined because deep monitoring wells did not exist further downgradient of RD-13;
- The 2011 remedial system evaluation indicated that hydraulic capture associated with GWTF #1 area was incomplete and recommended adding more extraction wells. The review concluded that the limits of hydraulic capture were difficult to ascertain due to the lack of monitoring points between the source area and downgradient monitoring wells MW-14, MW-1D and RD-13. It further noted that hydraulic capture in a fractured rock setting is complicated and complete capture could be difficult even with additional wells, especially considering the non-productive deep zone. The reviewers ultimately concluded that CVOC concentrations in the shallow zone had improved, but there might still be a concern for vertical migration from the deep highly contaminated zone to the shallow zone in response to pumping and lateral migration of the deep CVOC plume;
- The majority of contaminant mass remained at high concentrations in the source area near GWTF #1 (likely in the form of DNAPL) in deep fractured rock where hydraulic capture would be difficult. Although the deep zone has low permeability, it was likely to act as a slow and continuous source to downgradient areas and potentially to the shallow aquifer. Enhancing the extraction network could lead to the spreading of source material in the deep low-productive zone rather than improving the conditions in that zone, thus, other strategies might have to be assessed; and,
- The reviewers summarized their findings for the OU2 area groundwater as follows: “Of particular concern is the amount of mass that appears to be present in the source area of the northern portion of the plume. DNAPL remains in the fractured bedrock and although its presence is in a hydraulically low yielding zone, it has the potential to serve as a slow residual contaminant source to the dissolved-phase plume over time. Groundwater monitoring of the DNAPL is limited since the nearest downgradient wells are 300 feet from RD-9 and just one well is screened at a similar depth (RD-13). This well showed a decreasing trend in CVOC concentrations over the 2009-2014 review period, but the next downgradient well (RD-5) screened at a similar depth showed an increasing trend and there no additional monitoring wells exist at this depth further downgradient. The cause of the increasing trend was unclear, but may be related to downward vertical migration of the plume from shallow bedrock zones or lateral transport from the source area”; and, “Given the RAO to restore the groundwater to drinking water standards, the groundwater extraction remedy was considered to be ineffective at removing the DNAPL material from

the low-yielding fractured bedrock. If restoration was going to be achieved, alternative remediation technologies should be considered.”

The review further reported that vapor intrusion concerns had been addressed by sampling in 2007, because, although the sub-slab results exceeded screening values, the indoor air concentrations were negligible and well below risk-based concentrations. The five-year review did not discuss the 2011 sub-slab and indoor air sampling results.

3.2.1 LTRA Monitoring Results – Curriculum Center GWTF

Results of LTRA monitoring from 2004 through 2017 indicate that CVOC concentrations in most wells in the vicinity of the Curriculum Center have decreased since the startup of the groundwater extraction and treatment facility in 2004, but have remained relatively unchanged for the last five to eight years of monitoring. These trends indicate that the Curriculum Center treatment facility successfully removed contaminant mass and retarded the migration of a portion of the CVOC groundwater plume. However, the very high and stable CVOC concentrations over the past several years in the shallow zone just downgradient of the facility suggest that there is a continuing source of contamination at Curriculum Center that is not captured by the treatment facility.

Results of the 2018 LTRA monitoring event were generally consistent with data trends from the period before the treatment facilities were shut down as a result of the hurricanes. However, an order of magnitude increase in total CVOC was observed in the sample from RD-9 (237 µg/l in 2017 to 2,314 µg/l in 2018). Arrowhead concluded that the increase was likely due to treatment plant shutdown and loss of plume containment in the five-month period between sampling and shutdown on September 2, 2017(Arrowhead, 2018).

Based on the results of the most recent LTRA monitoring event, several wells in and near the OU2 investigation area have concentrations of one or more compounds exceeding the MCLs. Deep well RD-9, located near the source area, exceeded the MCLs for PCE, TCE, cis-1,2-DCE, and VC (12, 48, 110, and 48 µg/l, respectively) in 2017. In 2018, only cis-1,2-DCE, and VC exceeded MCLs (630, and 1,600 µg/l, respectively).

MW-1D (28 µg/l) and MW-14 (20 µg/l), located on Curriculum Center property south and southeast of the source area exceeded the MCL for PCE. MW-1D (7.1 µg/l) and MW-14 (6.1 µg/l) also exceeded the MCL for TCE. The MCLs for cis DCE and VC were exceeded at RD-13 (160 µg/l and 58 µg/l respectively) and RD-9 (630 µg/l and 1,600 µg/l respectively). Monitoring wells MW-6D, (6.7 µg/l), MW-15, (46 µg/l), RD-5 (22 µg/l), Tillett (6.4 µg/l), and TT-6 (15 µg/l), located on adjoining properties to the west and south of the Curriculum Center exceeded the MCL for PCE.. Monitoring results indicate that the core of the CVOC plume (total CVOCs greater than 100 µg/l) extends from the source area on the north side of the Curriculum Center building to the south and southwest in the direction of groundwater flow (**Figure 3-2**). Concentrations of total CVOCs of greater than 10 µg/l are present at adjoining properties to the west, southwest and south of the Curriculum Center. . The extent of contamination has not been defined to the southeast, towards Smith Bay Road (Highway 38), because of the lack of shallow wells in that area.

Treatment system monitoring indicates that concentrations of total CVOCs in the Curriculum Center GWTF influent and mass removal rates have significantly decreased since system startup. Total CVOC concentrations in the influent from extraction well RW-7 averaged 63 µg/l for the period of May through September 2017, prior to plant shut down, which represents a 97 percent reduction (Arrowhead, 2018).

Total CVOC concentrations for deep extraction well RW-6, which is pumped intermittently due to its low yield, generally ranged from less than 5,000 µg/l to 100,000 µg/l. Following a spike to almost 260,000 µg/l in early 2015, concentrations were below 50,000 µg/l for the subsequent 21 monthly sampling events until the plant was shut down in September 2017 (Arrowhead, 2018).

The concentrations of CVOCs in shallow zone wells just downgradient of the facility have remained constant over the last few years. Based on this observation, Arrowhead concluded that some contamination from the highly contaminated deeper zone of the aquifer may be migrating upward into the shallow zone (Arrowhead, 2017).

The historically high concentrations of PCE, greater than 20% of solubility at wells RD-9 and RW-6, indicate the potential presence of DNAPL. The location of the DNAPL is unknown, but previous investigations considered the area underneath the Curriculum Center to be the likely location (CDM, 2004a). An unexpectedly high total CVOCs concentration at RD-9 (14,860 µg/l) in April 2009 was considered to be an indication of the presence of DNAPL.

3.3 2016-2017 FSRI Summary

The OU2 FSRI was conducted by HDR between April 2016 and June 2017 to further investigate the source or sources of groundwater contamination in the northern portion of OU2, specifically the Curriculum Center. The FSRI activities were completed in four phases and included surface geophysical surveys, rock matrix diffusion borehole sampling and analysis, monitoring well installation, borehole geophysical investigation, packer testing and sampling at new monitoring well locations, groundwater sampling and elevation measurements, and DNAPL monitoring and removal. During the FSRI, two rock matrix boreholes (OU2-MD1 and OU2-MD2), two shallow monitoring wells (OU2-MW1 and OU2-MW2), and four deep monitoring wells (OU2-MW3 through OU2-MW6) were installed (**Figure 3-2**).

Details of the FSRI are provided in HDR's October 2017 Draft FSRI Report. The following is a summary of the FSRI findings which are most relevant to this FS:

1. The fractures in the andesitic tuff at Curriculum Center and Tutu Valley are the result of regional faulting that has resulted in structurally controlled erosion and weathering of bedrock forming river valleys such as Turpentine Run on St. Thomas. Most of the andesitic tuff at Curriculum Center contains few water-bearing fractures. Shallow (<90 feet bgs) water bearing fractures with a moderate permeability extend in a west-southwest direction on the north side of Curriculum Center. A few low permeability fractures extend north-south in front and behind Curriculum Center and extend in a west-southwest direction in front of Curriculum Center. The andesitic tuff between 90 and 140 feet bgs contains very

few water-bearing bedrock fractures and has a low permeability. The degree and orientation of fracturing observed below 140 feet bgs suggested limited potential for vertical contaminant migration below this depth.

2. Whole rock core samples were collected, processed, and analyzed to determine if CVOCs have diffused into pore water in the volcano-sedimentary andesitic tuff bedrock. The results show high concentrations of PCE in porewater that equate to 24% of the PCE solubility along one bedrock fracture (67 feet below ground surface) at OU2-MD2. Approximately one gallon of DNAPL migrated through this fracture and pooled at the bottom of OU2-MD2. Based on the strike and dip of the bedrock fracture, the DNAPL likely came from the top of bedrock at the former drum storage area. The drum storage area was reportedly located outside of the hydraulic containment system.
3. Some of the PCE released on the north side of Curriculum Center has been reductively dechlorinated to TCE, cis-1,2-DCE, trans-1,2-DCE, and vinyl chloride by biological activity associated with a co-located petroleum hydrocarbon release. PCE and its degradation by-products migrate to the west-southwest in bedrock fractures on the north side of Curriculum Center. Groundwater in these fractures connects and migrates down Tutu Valley contributing to the central and southern plumes. The concentration of total CVOCs in this zone reaches a historic maximum of 56,472 µg/l. Groundwater in the deeper (90-140 feet bgs), lower permeability zone north of Curriculum center also contains PCE and its degradation by-products. The concentration of total CVOCs in this zone reaches an historic maximum concentration of 321,702 µg/l.
4. Some of the PCE released on the north side of Curriculum Center or an unknown source of PCE DNAPL has not been reductively dechlorinated and migrates to the southeast through a bedrock deformation zone along the northeast side of Curriculum Center. Groundwater containing PCE migrates through the deformation zone into bedrock fractures that extend to the west-southwest on the southeast side of the Curriculum Center. Groundwater on the southeast side of Curriculum Center contains PCE at a concentration of 2,500 µg/l. A relatively small fraction of PCE degradation by-products were detected in groundwater in these fractures. This groundwater also migrates in a west-southwest direction down Tutu Valley.
5. A portion of the groundwater containing CVOCs defined during the OU2 FSRI is not hydraulically captured by the existing hydraulic containment system. The data collected during the OU2 FSRI show DNAPL likely exists in the former drum storage area and potentially under Curriculum Center. These locations are also outside of the current hydraulic containment system.
6. The contaminants of concern (COCs) at the Curriculum Center consist of PCE, TCE, 1,1-DCE, cis-1,2-DCE, trans-1,2-DCE, and VC.
7. Matrix diffusion data indicate that contamination of the rock matrix can be expected in areas where high levels of COCs are detected in groundwater and that compounds are

currently and will likely continue to back-diffuse from the rock matrix and impact groundwater in the OU2 area.

8. During Hurricane Irma/Maria in early September 2017, the electric grid on St. Thomas sustained widespread damage. The utility pole supplying power to the Curriculum Center GWTF broke and the pump and treat system became non-operational (a backup power generator was not available). A section of the Curriculum Center building sustained heavy damage when a portion of the roof was ripped away by the hurricane-force winds.

Based on the 2016-2017 FSRI findings, the following conclusions were made by HDR:

1. RW-7 is the primary shallow extraction well for groundwater remedy at Curriculum Center. RW-7 pumps at roughly 10 gpm on a continual basis at a constant head of 148 feet above mean sea level (amsl). The hydraulic influence of RW-7 extends tens of feet in an east-west direction (cross gradient) in the shallow monitoring zone. Comparing the hydraulic containment to the distribution of CVOCs groundwater shows that the full width of CVOCs in the shallow zone are not hydraulically captured by pumping in RW-7. RW-9 is also a shallow extraction well that only operates for short periods of time when the system is restarted after an alarm condition to increase the rate of drawdown and to maintain hydraulic control.
2. RW-6 is the deep extraction well at Curriculum center in the less productive zone. RW-6 is pumped once per week for 1-1.5 hours and removing approximately 1-1.5 gpm of groundwater. A total of 440 gallons were pumped from the well on a monthly basis during the 2016 to 2017 operating period. The influent concentration of CVOCs in RW-6 has decreased from 230,000 µg/l in 2005 to 15,000 µg/l in 2016. These data show the hydraulic influence of RW-6 in the deep zone is not capable of hydraulically capturing all of the CVOCs in the deep zone.
3. These data indicate incomplete hydraulic containment or an additional source of CVOCs outside of the hydraulic containment system.

3.4 2019 Supplemental Post-Hurricane Sampling

Supplemental rounds of post-hurricane sampling were performed by the U.S. Environmental Protection Agency, Region II (EPA) Superfund and Emergency Management Division (SEMD) with support from Weston Solutions, Inc., Superfund Technical Assessment Team V (START V) in June and October of 2019. Three residential wells were sampled in June, and a more comprehensive round of 36 monitoring wells and four residential wells were sampled in October. The October round represented Site-wide conditions approximately two years after the treatment plant was shut down. The October 2019 results for LTMP wells were generally consistent with pre-hurricane trends, including at RD-9 where a total CVOC concentration of 47.5 µg/l was recorded. The October round also included several OU2 RI monitoring wells. Results for these wells were generally lower than RI levels. Although low-flow methods were used in all cases, it is

not clear if the 2019 samples were collected at the same depth intervals as the previous samples, which may account for some variability in the analytical results.

PCE, TCE cis-1,2-DCE and VC MCLs were exceeded at shallow monitoring well OU2-MD-2 (300 µg/l, 42 µg/l, 290 µg/l and 110 µg/l, respectively) and PCE, TCE and VC MCLs were exceeded at shallow well OU2-MW-2 (63 µg/l, 16 µg/l and 1.6 µg/l, respectively) located near the source area. Deep well RD-9, also located near the source area, showed variable results. The MCLs for PCE, TCE, cis-1,2-DCE, and VC were exceeded at RD-9 in 2017 (12, 48, 110, and 48 µg/l, respectively). Total VOCs increased to 2,314 µg/l in 2018, but only cis-1,2-DCE, and VC exceeded MCLs (630, and 1,600 µg/l, respectively). In 2019, total CVOCs dropped to 47.5 µg/l, with only VC exceeding MCLs (24 µg/l). Although the concentrations are variable, the results show a stronger presence of PCE and TCE when the system is in operation while the metabolites cis-1,2-DCE, and VC predominate when the system is shut down.

Monitoring wells OU2-MW-3 (580 µg/l), OU2-MW-4 (810 µg/l), OU2-MW-5 (85 µg/l), MW-1D (25 µg/l) and MW-7 (5 µg/l), located on Curriculum Center property south and southwest of the source area, met or exceeded the MCL for PCE. OU2-MW-3 (27 µg/l), OU2-MW-4 (73 µg/l), OU2-MW-5 (190 µg/l), MW-1D (7.4 µg/l) also exceeded the MCL for TCE. The MCL for VC was exceeded at RD-13 (6 µg/l). Monitoring wells MW-15, (35 µg/l) RD-5 (44 µg/l), Tillett (20 µg/l), and TT-6 (15 µg/l), located on adjoining properties to the west and south of the Curriculum Center exceeded the MCL for PCE.

Monitoring results indicate that the core of the CVOC plume (total CVOCs greater than 100 µg/l) extends from the source area on the north side of the Curriculum Center building to the south and southwest in the direction of groundwater flow (**Figure 3-2**). Concentrations of total CVOCs of greater than 10 µg/l are present at adjoining properties to the west, southwest and south of the Curriculum Center. The extent of contamination has not been defined to the southeast, towards Smith Bay Road (Highway 38), because of the lack of shallow wells in that area.

3.5 Nature and Extent of Contamination

This section describes the nature and extent of CVOCs in groundwater collected from fractures of the bedrock. Groundwater samples were collected from conventional shallow bedrock wells and from open-hole wells during the FSRI.

Six CVOCs were identified as COCs during the OU2 FSRI, based on the site history, frequency of detection, and concentrations that exceeded cleanup standards: PCE, TCE, cis-1,2-DCE, trans-1,2-DCE, 1,1-DCE, and VC. **Table 3-1** provides the concentration range detected in groundwater during the FSRI.

COCs were detected in all groundwater samples collected from the 26 monitoring wells and three treatment system extraction wells during the February/March 2017 sampling event. Up to six COCs were detected, including, PCE, TCE, VC, cis-1,2-DCE, trans-1,2-DCE, and 1,1-DCE. The well locations with concentrations that exceeded the respective standards are shown on **Figure 3-1**.

The highest concentration of CVOCs in the shallow (<90 feet bgs) portion of bedrock was detected in groundwater collected from IW1-85. Groundwater collected from this well contained cis-1,2-DCE (33,000 µg/l), VC (12,000 µg/l), TCE (5,800 µg/l), PCE (4,100 µg/l), trans-1,2-DCE (1,400 µg/l) and 1,1-DCE (170 µg/l). These data show reductive dechlorination has degraded the PCE so that the highest concentrations are cis-1,2-DCE and VC. The reductive dechlorination is likely driven by co-located petroleum hydrocarbons and/or septic waste. Groundwater in the shallow water-bearing zone generally flows to the west-southwest to OU2-MW2 and then more to the southwest towards OU2-MW3.

PCE (2,500 µg/l) detected in OU2-MW4 with relatively low concentrations of TCE (130 µg/l), cis-1,2-DCE (140 µg/l) and VC (2.2 µg/l) shows that some PCE from the source area or an unknown location of DNAPL is contributing PCE to this well. These data show very little reductive dechlorination in this portion of bedrock. Groundwater containing mostly PCE migrates to the southwest OU2-MW4 towards OU2-MW5.

Very high concentrations of CVOCs were detected in groundwater collected from RD-9 (depth 97.5 feet bgs) located north of Curriculum Center near IW1-85. Groundwater collected from RD-9 contained; cis-1,2-DCE (160,000 µg/l), PCE (92,000 µg/l), VC (38,000 µg/l), TCE (29,000 µg/l), trans-1,2-DCE (2,300 µg/l) and 1,1-DCE (400 µg/l). The concentration of PCE (92,000 µg/l) detected in the sample from RD-9 was equivalent to 46% of its solubility limit, indicating the potential presence of DNAPL. Bedrock at these depths contain very few fractures and have a correspondingly low permeability. Groundwater containing high concentrations of CVOCs in the deep portion of bedrock is not migrating very fast or very far. However, the high concentrations of CVOCs could be diffusing into the porewater of the bedrock matrix creating a secondary source in this area. These data are shown on **Figure 3-1**. The distribution of CVOCs is consistent with groundwater flow.

These data show the heterogeneous nature of the groundwater flow system and the possibility that there are multiple source areas that may contain DNAPL.

Groundwater collected from four wells on the perimeter of Curriculum Center did not exceed potential cleanup standards. Two of the wells (MW-13 and OU2-MW1) are located upgradient of the Curriculum Center with total depths of 80.5 and 85 feet bgs, respectively and two (MW-14 and MW-17) are located to the west and cross-gradient to the plume. MW-14 and MW-17 are shallow wells with total depths of 45 and 13.5 feet bgs, respectively.

DNAPL was discovered at the bottom of rock matrix borehole OU2-MD2. Repeated measurements with an oil-water interface probe conducted between January and early March 2017, and again in June 2017, indicated that the depth to the top of the DNAPL did not significantly change, with measurements ranging between 198.05 feet to 198.10 feet bgs. DNAPL was pumped from the OU2-MD2 borehole on June 12, 2017.

The presence of DNAPL in the saturated or unsaturated portion of bedrock had been suspected in prior investigations, going back to the 1995 RI (Geraghty & Miller, 1995). In addition to the

physical presence of DNAPL, dissolved-phase concentrations of PCE, TCE, cis-1,2-DCE and VC were present at 1% or more of their aqueous solubility limits.

PCE detected in a sample and duplicate sample collected from RW-6 (8,800 µg/l and 12,000 µg/l respectively) indicate 3.4% and 9.5% of the PCE solubility limit. PCE detected in the sample from RD-9 (92,000 µg/l) indicates 46% of the PCE solubility limit. In addition to samples from these two wells, concentrations of cis-1,2-DCE and PCE either approached or slightly exceeded 1% of the respective solubility limits in samples from wells IW-1, IW-2, OU2-MW3, OU2-MW4 and RW-8. The completion depths of these wells were either in the deep monitoring zone or extended from lower elevations of the shallow zone into the deep zone.

Wells RW-6 and RD-9 are both completed in the deep monitoring zone. RD-9 is approximately 15 feet from the northern wall of the Curriculum Center and within close proximity of the original source areas. The presence of concentrations representing more than 1% of the solubility limits for PCE, TCE and VC in the deep monitoring zone indicates that a preferential pathway to depth, such as a high-angle joint, fracture or fault may exist in this area. The presence of this type of feature along the northern wall of the Curriculum Center is consistent with both the location of fracture traces identified in previous investigations and the lineament identified in the surface geophysical survey performed as part of the FSRI.

Wells IW-1, IW-2 and RW-6 are located to the north and northwest of both the source area and extraction well RW-7. The presence of high PCE concentrations at these locations indicates either the presence of a different source area local to these wells or that DNAPL has moved independent of both the extraction wells and the hydraulic head distribution at OU2. The location of a former drum storage area and the orientation of open fractures observed in the borehole geophysical investigation indicate that both scenarios are possible. Well RW-6 is located at the northwestern edge of the lineament, approximately 50 feet from the building. Wells IW-1 and IW-2 are located further to the north and approximately 70 feet from the building.

PCE, detected at approximately 1% of its solubility limit, in monitoring wells OU2-MW3 and OU2-MW-4, is not consistent with previously identified source areas. These wells are located near the northwestern and southeastern corners of the Curriculum Center. The presence of PCE at these levels could be explained by separate unknown sources, or they could indicate that these wells are located along fractures that directly connect them to locations where DNAPL has migrated to depth. The locations of these wells both appear to be hydraulically downgradient of known sources based on the current understanding of secondary porosity features and the distribution of hydraulic head in the area. The relative concentrations of individual compounds detected at OU2-MW-3 is generally consistent with results from OU2-MW-2 and the relative concentrations at OU2-MW-4 are consistent with OU2-MW-6 results providing further evidence of direct connections between these well locations.

3.6 Contaminant Fate and Transport

DNAPL is present on the surface of bedrock either beneath the building, at the suspected waste pit, or in the former drum storage area. DNAPL likely entered and migrated through bedrock

fractures such as the fracture bisected by boring OU2-MD2. This is evidenced by the high concentration of PCE (48,000 µg/l) in porewater at the face of a bedrock fracture at 66.9-67 feet bgs in rock matrix diffusion borehole OU2-MD2. DNAPL migrating through this fracture pooled at the bottom of OU2-MD2. DNAPL has not been confirmed in any other boring at the Curriculum Center. **Figure 3-3** provides a CSM for the Curriculum Center.

DNAPL dissolution produced a dissolved-phase plume in the andesitic tuff sedimentary bedrock at and downgradient of the Curriculum Center. The main transport mechanism of the aqueous COCs is advective groundwater flow through fractures. Some limited matrix diffusion is occurring that slightly retards the advective movement of COCs in fractured sedimentary bedrock. The amount of matrix diffusion is relatively small as the primary porosity of the andesitic tuff is 1-2% and the diffusive penetration of COCs into bedrock from the fracture faces is limited creating diffusion halos based on matrix diffusion sampling. For example, the concentration of PCE in porewater in bedrock at a fracture face at 66.9 feet bgs of OU2-MD2 is 48,000 µg/l which is about 24% of the solubility of PCE. A matrix diffusion sample collected at 67.5-67.6 feet (0.6 feet from the fracture face) was non-detect for PCE. Matrix diffusion of PCE into porewater was detected at four additional fractures at concentrations ranging from 100 to 2,700 µg/l. These data show that no other fracture likely contained DNAPL as the highest porewater sample was less than 2% (2,700 µg/l) the solubility of PCE. These data also show that the CVOCs only penetrated the bedrock by 0.6 feet.

Dissolved-phase CVOCs continue to migrate through bedrock fractures creating additional dissolved-phase plume. Dissolved-phase PCE is biologically transforming to TCE, cis-1,2-DCE, and VC through reductive dechlorination in only portions of the shallow and deep groundwater. This is likely due to either petroleum or septic waste locally driving the shallow portions of bedrock groundwater into an anaerobic condition which is supporting the reductive dechlorination of PCE. This is occurring in the shallow northwestern portion of the plume. Shallow groundwater is migrating into the deep portions of the bedrock aquifer in this area. The result is groundwater containing PCE, TCE, cis-1,2-DCE, and VC in both the shallow and deep portions of the aquifer on the north and northwestern portion of the Curriculum Center. The chlorinated compounds are used as an electron acceptor not as a source of carbon, and a chlorine atom is removed and replaced with a hydrogen atom generated through biological activity.

Groundwater on the eastern and southeastern portion of the Curriculum Center contains mostly PCE as the potential effects of the petroleum or septic waste is less and the aquifer remains mostly aerobic resulting in less reductive dechlorination. Groundwater contamination in this portion of the aquifer (both shallow and deep) is mainly PCE with much lower concentrations of TCE, cis-1,2-DCE, and VC than groundwater to the north-northwest.

3.7 Risk Assessment Screening Summary

This section provides a summary of the risk assessment prepared by HDR (February 2018) based on the FSRI findings for the Curriculum Center. The Human Health Risk Assessment (HHRA) was prepared to evaluate potential baseline health risks for future receptor exposure to contaminants of potential concern (COPCs) present in groundwater. The COPC screening of the

HHRA identified 13 COPCs. The potential exposure scenarios considered in the HHRA include drinking water ingestion, dermal contact and inhalation of groundwater by residents, drinking water ingestion and dermal contact by indoor and outdoor workers as well as incidental ingestion, contact and inhalation with groundwater by a construction worker in a trench.

The evaluation of potential cancer risks and noncancer hazards to future receptors on-site from exposure to COPCs in environmental media indicates that there are several primary COPCs, now identified as COCs, whose concentrations in environmental media contribute to the hazard and risk estimates, and exposure to these COCs may result in potential adverse health effects.

The evaluation for on-site future construction workers indicates that VC, TCE, PCE, cis-1,2-DCE and 1,1,2-trichloroethane have been identified as COCs for groundwater exposure, based on an excess lifetime cancer risk (ELCR) exceeding $1\text{E-}06$ or resulting in a hazard index (HI) greater than or equal to one.

The evaluation for on-site future workers indicates that VC, TCE, PCE and cis-1,2-DCE have been identified as COCs for groundwater exposure, based on an ELCR exceeding $1\text{E-}06$ or resulting in an HI greater than or equal to one. PCE and TCE volatilizing into buildings are also of potential concern to workers based on groundwater, indoor air and sub-slab soil gas data. Volatilizing of VC into buildings may be of potential concern based on groundwater concentrations; however, VC was non-detect in the sub-slab soil gas and indoor air during two sampling events in 2007 and 2011. The evaluation of potential cancer risks and noncancer hazards to future residents indicates VC, TCE, PCE, cis-1,2-DCE, trans-1,2-DCE, bromodichloromethane, 1,2-dichloroethane, 1,4-dichlorobenzene, 1,2,4-trichlorobenzene and 1,1,2-trichloroethane have been identified as COCs for groundwater exposure, based on an ELCR of $1\text{E-}06$ or resulting in an HI greater than or equal to one. PCE, TCE and other VOCs volatilizing into buildings are also of potential concern to future residents-based groundwater, indoor air and sub-slab soil gas data.

Note that bromodichloromethane, 1,2-dichloroethane, 1,1,2-trichloroethane, 1,2,4-trichlorobenzene, and 1,4-dichlorobenzene are included as COCs, as the calculated cancer risks for these constituents are in the $1\text{x}10^{-6}$ range, contributing to a cumulative ELCR greater than $1\text{x}10^{-4}$. 1,1,2-trichloroethane also contributes to noncancer hazards greater than one for the liver as a target organ. Review of the concentrations of these COCs in groundwater indicates that they do not exceed their respective MCLs, however, they are included in Section 4.5 to document their proposed PRGs for consideration in remedy selection. 1,1-DCE ELCR is less than $1\text{x}10^{-6}$, however, it exceeds its MCL, so it too is included as a COC.

The results of the HHRA indicate that site cleanup, engineering controls and/or ICs will be necessary to mitigate potential risks associated with existing contamination.

4 Remedial Goals and Remedial Action Objectives

4.1 Identification of ARARs

Section 121(d) of the CERCLA as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA), requires federal and state ARARs be met. Subpart E, Section 300.400(g) "Identification of applicable or relevant and appropriate requirements," of the NCP describes the process to attain ARARs. EPA last promulgated revisions to the NCP on September 15, 1994.

There are differences between the identification and analysis of applicable vs. relevant and appropriate requirements. Applicability is a legal and jurisdictional determination, while the determination of relevant and appropriate is based on professional judgment, considering the environmental and technical factors specific to a site.

To be applicable, a requirement must directly address the circumstances at the site. Applicable requirements are defined as "those cleanup or control standards, or other substantive environmental protection requirements, criteria, or limitations promulgated under Federal environmental or State environmental or facility siting law that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance found at a CERCLA site" (55 FR 8814). Jurisdictional prerequisites of the requirement must be met in order for the requirement to be applicable.

These jurisdictional prerequisites include:

- The party being subject to the law
- The substances or activities must be under the authority of the law
- The law must be in effect at the time activities occur
- The law requires, limits or protects the types of activity in question

A requirement that is relevant and appropriate may not meet one or more jurisdictional prerequisites for applicability but still make sense at the site, given the specific circumstances. In evaluating the relevance and appropriateness of a requirement, the eight comparison factors in CFR Title 40, 300.400(g) (2) should be carefully considered.

There is greater flexibility in determining relevant and appropriate requirements; i.e., it may be "relevant," in that it covers situations similar to those at the site, but may not be "appropriate" and, therefore, may not be well suited to conditions at the site. Portions of a requirement or regulation may be judged relevant and appropriate; however, if a requirement is deemed applicable, all substantive requirements must be met.

To be considered relevant and appropriate, a requirement must be considered in terms of whether the circumstances at the site are sufficiently similar to those regulated by the requirement.

“Relevant and appropriate” cleanup standards, or other substantive environmental protection requirements, criteria, or limitations promulgated under federal or state law, are those that while not considered applicable, address problems or situations similar to those at the CERCLA site, and whose use is suited to the site. The relevance and appropriateness is judged by comparing characteristics of the remedial action, physical circumstances of the site and other factors with those included in the requirement itself.

This is a two-step process, requiring a determination first of relevance, where the requirement pertains to the type of remedial action being taken, location of the action, or chemicals and related conditions at the site. Second, a determination of whether it is appropriate focuses on the nature of the items, in question, characteristics of the site, circumstances of the release, and proposed remedial action. The requirement is appropriate if suited to the particular site. The facility action must comply with requirements that are determined to be both relevant and appropriate. Once a requirement is determined to be relevant and appropriate, it must be complied with as if applicable.

EPA has classified both types - applicable or relevant and appropriate – of ARARs into three categories, depending on whether the requirement is triggered by the presence of a specific chemical, characteristics of a specific location, or a particular response action.

1. Chemical-specific ARARs are risk-based, numeric cleanup standards, e.g., MCLs established under the Safe Drinking Water Act, and federal water quality criteria (FWQC) established under the Clean Water Act.
2. Location-specific ARARs are restrictions on the concentration of hazardous substances or on activities in environmentally sensitive areas, e.g., restrictions within floodplains, wetlands.
3. Action-specific ARARs are technology- or activity-driven requirements, resulting largely from provisions of RCRA and the Clean Water Act.

ARARs are promulgated, legally enforceable federal and state requirements. In contrast, “TBC” values include non-promulgated, non-enforceable criteria, advisories, guidance and proposed standards generated by the federal or a state government. TBCs may assist in interpreting ARARs or determine preliminary remediation goals when ARARs do not exist. Once a TBC is identified and becomes part of a Superfund ROD, it is enforceable within the context of the remedial action that is the subject of the ROD.

Screening criteria consisting of ARARs (promulgated standards) and TBCs (screening criteria) were used as benchmarks to evaluate the nature and extent of contamination at OU2.

4.2 Chemical-Specific ARARs and TBCs for Groundwater

Groundwater at the Curriculum Center and within the area influenced by the contaminant plume currently is not being used as a source of drinking water. The USVI does not have drinking water source-based quality standards for organics in groundwater, as drinking water is taken from

rainwater cisterns or from pumped water supply using desalinated seawater. In the absence of any USVI regulations for CVOCs in groundwater, the Federal primary drinking water standards are considered to be relevant and appropriate.

- National Primary Drinking Water Standards (40 CFR 141). Drinking water standards MCLs are considered relevant and appropriate requirements and will be used as the primary basis for setting numerical criteria for groundwater cleanup. (CERCLA Section 300.430[e][2][i][b]).

4.3 Location Specific ARARs

No location specific ARARs were identified that are applicable or relevant and appropriate due to the location of the site or area to be remediated.

4.4 Action-specific ARARs and TBCs

Action-specific ARARs are requirements which set controls and restrictions to particular remedial actions, technologies, or process options. These regulations do not define site cleanup levels but do affect the implementation of specific remedial technologies. For example, although outdoor air has not been identified in the RI report as a contaminated medium of concern, air quality ARARs are listed below, because some potential remedial actions may result in air emissions of toxic or hazardous substances. These action specific ARARs are considered in the screening and evaluation of various technologies and process options in subsequent sections of this report.

4.4.1 Federal Standards and Guidelines

General - Site Remediation

- Occupational Safety and Health Administration (OSHA) Worker Protection (29 CFR 1904, 1910, 1926).
- Resource Conservation and Recovery Act (RCRA): Identification and Listing of Hazardous Waste (40 CFR 261); Standards Applicable to Generators of Hazardous Waste (40 CFR 262); Standards Applicable to Owners and Operators of Treatment, Storage, and Disposal Facilities (40 CFR 264)

Transportation of Hazardous Waste

- Hazardous Materials Transportation Regulations (49 CFR 107, 171, 172, 177, and 179)
- Federal Resource Conservation and Recovery Act - Standards Applicable to Transporters of Hazardous Waste (40 CFR 263).

Disposal of Hazardous Waste

- Federal Resource Conservation and Recovery Act - Land Disposal Restrictions (40 CFR 268).

Discharge of Groundwater

- Federal Clean Water Act - National Pollutant Discharge Elimination System (NPDES) (40 CFR 100 et seq.); Effluent Guidelines and Standards for the Point Source Category (40 CFR 414); Ambient Water Quality Criteria (40 CFR 131.36).
- Federal Safe Drinking Water Act - Underground Injection Control (UIC) Program (40 CFR 144, 146).

Off-Gas Management

- Federal Clean Air Act - National Ambient Air Quality Standards (40 CFR 50); National Emission Standards for Hazardous Air Pollutants (40 CFR 61).
- Federal Directive - Control of Air Emissions from Superfund Air Strippers (Office of Solid Waste and Emergency Response (OSWER) Directive 9355.0-28)

4.4.2 Local Standards and Guidelines

Solid and Hazardous Waste Management Regulations

- Title 19 Virgin Islands Code, Chapter 56
- DPNR- Division of Environmental Protection for waste storage, handling, and disposal, handling

Discharge of Groundwater

- Water Quality Standards for Waters of the Virgin Islands, Title 12, Chapter 7 (28 August 2015)

Off-Gas Management

- Virgin Islands Laws and Rules and Regulations on Air Pollution Control (Title 12, Chapter 9, Subchapters 201-204 and 206)

4.5 Preliminary Remediation Goals

Groundwater at the potential source areas is the contaminated media to be remediated under OU2. In the absence of local regulations or guidance values for organics in groundwater in the USVI, there are no chemical specific ARARs. Federal drinking water standards are relevant and appropriate requirements and were used to develop the PRGs, which are the cleanup goals. **Table 4-1** provides the PRGs for groundwater COCs.

Note that bromodichloromethane, 1,2-dichloroethane, 1,1,2-trichloroethane, 1,2,4-trichlorobenzene, 1,4-dichlorobenzene are included as COCs, as the calculated cancer risks for these constituents are in the 1×10^{-6} range, contributing to a cumulative ELCR greater than 1×10^{-4} . 1,1,2-trichloroethane also contributes to noncancer hazards greater than one for the liver as a target organ. Review of the concentrations of these COCs in groundwater indicates that they do not exceed their respective MCLs, however, they are included in **Table 4-1** to document their proposed PRGs for consideration in remedy selection. 1,1-DCE ELCR is less than 1×10^{-6} , however, it exceeds its MCL, so it too is included as a COC.

Even though PRGs are the ultimate concentration goals for site cleanup, site-specific situations and limitations may prevent the remedial action from achieving the PRGs in a reasonable time frame. These constraints are further discussed in Section 8.

4.6 Principal Threat Waste

The NCP establishes an expectation that EPA will use treatment to address the principal threats posed by a Site wherever practicable (NCP Section 300.430(a)(1)(iii)(A)). The "principal threat" concept is applied to the characterization of "source materials" at a Superfund Site. A source material is material that includes or contains hazardous substances, pollutants or contaminants that act as a reservoir for migration of contamination to groundwater, surface water or air, or acts as a source for direct exposure. Contaminated groundwater generally is not considered to be a source material; however, NAPL in groundwater may be viewed as source material. Principal threat wastes are those source materials considered to be highly toxic or highly mobile that generally cannot be reliably contained or would present a significant risk to human health or the environment should exposure occur. The decision to treat these wastes is made on a site-specific basis through a detailed analysis of the alternatives using the nine remedy selection criteria. This analysis provides a basis for making a statutory finding that the remedy employs treatment as a principal element.

4.7 Remedial Action Objectives

RAOs are media-specific goals for protecting human health and the environment. They serve as the basis for developing remedial action alternatives and specify what the cleanup action will accomplish. The process of identifying the RAOs follows the identification of affected media and contaminant characteristics; evaluation of exposure pathways, contaminant migration pathways and exposure limits to receptors. The RAOs are based on regulatory requirements and risk-based evaluation, which may apply to the various remedial alternatives being considered for a site.

The following presents RAOs that have been developed to address human health risks and environmental concerns based on the results of the OU2 FSRI and risk assessment screening:

- Decrease DNAPL mass in the bedrock aquifer;
- Restore the groundwater so that concentrations of site-related contaminants are below the Federal MCLs;

- Prevent the migration of groundwater contamination from OU2 to OU1; and
- Protect human health by preventing exposure to contaminated groundwater.

5 General Response Actions

GRAs are broad types of activities that will potentially satisfy the RAOs. Following the development of GRAs, one or more remedial technologies and process options are identified for each GRA category. The technologies and process options remaining after screening in Sections 6 and 7 will be assembled into alternatives that are discussed in Section 8. The alternatives will focus on containing and/or remediating groundwater.

The GRAs for impacted groundwater include:

- No Action – The no action option is included as a basis for comparison with the active groundwater remediation technologies. If no action is taken, the contaminants will remain in place and the RAOs will not be met.
- ICs – Restricting the property or resource use through ICs would not reduce the volume or eliminate the need for active remediation of groundwater to restore the impacted resource and meet RAOs. Long-term monitoring (LTM) would be required in conjunction with the maintenance of existing and /or implementation of additional institutional controls.
- MNA - MNA makes use of naturally occurring bioremediation processes where dilution, volatilization, biodegradation, adsorption, and/or chemical reactions with subsurface materials reduce contaminant concentrations to acceptable levels over time. In accordance with EPA guidance (EPA, 1998d), MNA is always to be used in combination with source control and LTM to assure the effectiveness and protectiveness of the process.
- Containment – Containment options are often implemented to prevent, or significantly reduce, the migration of contaminants in groundwater. They can be used in conjunction with treatment technologies where restoration of the resource has been identified as an objective, as is the case for the site. Containment solutions often require long-term groundwater monitoring. The AOCs are largely covered with asphalt and hard surfaces.
- Extraction – Groundwater extraction provides hydraulic control to prevent migration of dissolved contaminants. Groundwater extraction is typically combined with ex-situ treatment and discharge response actions to achieve the RAOs. Groundwater extraction response actions provide reduction in mobility and mass of contaminants by removing the contaminants from the subsurface using groundwater extraction wells.
- Treatment – Treatment of contaminants can be achieved either in-situ or ex-situ and includes several types of technologies that encompass biological, thermal, and physical/chemical treatment approaches.
- Biological – Bioremediation consists of stimulation of microorganisms to promote degradation of contaminants. Biological treatment is generally effective for organic contaminants.

- Thermal – Thermal treatment processes can be viable strategies to mobilize and remove or destroy contaminants in groundwater.
- Physical/Chemical – Physical/Chemical treatment processes can be used to destroy, separate or immobilize contaminants in groundwater.
- Discharge – Disposal options for extracted groundwater can include discharge to a publicly owned treatment works (POTW), surface or groundwater after treatment of the effluent to meet applicable discharge standards.

6 Identification and Screening of Remedial Technologies and Process Options

This section identifies and screens remedial technologies potentially capable of addressing groundwater contamination at OU2. As discussed in Section 3.0, DNAPL and the following contaminants have been detected at concentrations greater than PRGs in the groundwater at OU2 and/or present calculated cancer and noncancer risks:

PCE, TCE, 1,1-DCE, cis-1,2-DCE, trans-1,2-DCE, VC, bromodichloromethane, 1,2-dichloroethane, 1,1,2-trichloroethane, 1,2,4-trichlorobenzene, and 1,4-dichlorobenzene

This section identifies and screens remedial technologies and process options potentially capable of addressing groundwater contamination at OU2. The screening process serves to identify feasible technology categories and technology process options that have the potential to achieve the goal of the GRAs.

Remedial technologies are grouped by GRA (e.g., containment or treatment) and media. Specific technologies and process options for each of the GRAs, including No Action, ICs, MNA/LTM, Containment, Treatment, and Disposal/Discharge are initially screened to identify those that appear to be:

- Most effective in achieving area-specific RAOs and appropriate to the area-specific conditions and contamination;
- Technically implementable; and
- Cost-effective, providing the same level of protection to human health and the environment.

The initial screening considered effectiveness of the technologies for treating the contaminants present at OU2, implementability of the technology given site-specific conditions, and cost. Remedial technologies that were deemed to be impracticable or cost-prohibitive were removed from further consideration, in accordance with EPA guidance (EPA, 1988).

Table 6-1 summarizes the technology identification and screening process for groundwater. The table is grouped by the GRA (i.e., in situ treatment, ex situ treatment, containment). Technologies that may be appropriate for addressing the contaminants were retained for further evaluation and are identified on the last columns of **Table 6-1**. Technologies that were screened out and not retained for further analysis are designated as “no” in the last column of **Table 6-1**. Remedial technologies that were deemed to be impracticable or cost-prohibitive were removed from further consideration, in accordance with EPA guidance (EPA, 1988) and are not discussed further in this Section.

Site-specific conditions, including contamination type, concentration, location (areal extent and depth), and estimated quantity were incorporated into the analyses performed during the initial screening process.

Treatability studies and a PDI will be used when needed to refine the assumptions for design used in this document. The most promising technologies were combined into remedial alternatives designed to optimize the ability to achieve RAOs and are described in Section 8.0.

Remedy selection and/or design tier treatability studies will establish whether the technology can meet RAOs, and then determine the design and operating parameters to help optimize the effectiveness of the remedy. These types of studies are designed to quantify the extent of remediation that can be expected, and either estimate or refine the estimates of the remedial timeframe and associated costs. They supply the data necessary to assure, as best as can be predicted prior to implementation, that the remedy selected can satisfy the threshold and balancing criteria of the NCP (EPA, 1993a).

The most promising technologies were combined into remedial alternatives, which are described in the development of alternatives section of this report (Section 8).

Based on the OU2 RI data, the following assumptions were made for the FS:

- *Groundwater data from the 2017 FSRI indicate incomplete hydraulic containment or an additional source of CVOCs is outside of the OU1 hydraulic containment system. It is assumed that DNAPL likely exists in the former drum storage area and potentially under the northern portion of the Curriculum Center building. These locations are identified as potential source areas in this FS.*
- *Based on available data, it is assumed that there is little to no soil present below grade. The vertical zone of contamination of the fractured bedrock aquifer at OU2 is assumed to be from grade surface up to 140 feet bgs.*
- *It is assumed that these suspect areas will be further characterized / addressed during the PDI and RD phases in order to refine the treatment areas;*
- *It is assumed that dissolved groundwater contamination beyond OU2 will be captured by the OU1 remedy.*

6.1 No Action

The no action remedial option has been retained as a basis for comparison with other groundwater remediation technologies, as required by the NCP. This option includes no future activities to contain or remediate contaminants, provides no treatment for contaminants, or legal and administrative mechanisms for protection of human health and the environment beyond establishing cleanup criteria and recognizing those mechanisms that are in place (e.g., restrictions on well installation) under other state and/or federal environmental regulatory program (non-Superfund) authority. This option assumes that physical conditions at OU2 remain unchanged.

6.2 Institutional Controls

Institutional controls (ICs) are non-engineering measures, such as administrative and/or legal controls, that help minimize the potential for human exposure to contamination and/or protect the

integrity of a remedy by limiting site or resource use. EPA guidance on choosing and implementing ICs (EPA, 2000a) provides that:

- If the cleanup does not result in unrestricted use at a site, an IC may be appropriate.
- Consider life-cycle strengths, weaknesses, and costs for implementation, monitoring, and enforcement.
- Provide early coordination with state and local governments that may be responsible for ICs.
- ICs are to be assessed as carefully as any other remedial alternative.
- Place ICs in ways to increase their reliability.
- Clearly state IC objectives in decision documents.
- Obtain written assurances from those responsible for implementing, monitoring, and enforcing ICs; select the best ICs available to protect human health and the environment.

ICs are generally to be used in conjunction with, not in lieu of, engineering measures such as treatment or containment. ICs can be used during all stages of the cleanup process to accomplish remedial objectives, and they should be used or implemented in series to provide overlapping protection from contamination. Examples include easements, potable well drilling prohibitions, zoning restrictions, and building Permit Equivalents requirements. ICs could also include health and safety policies and procedures to limit exposure to groundwater contaminants during construction activities via local construction Permit Equivalents programs.

Performance monitoring would include a description of the ICs implemented or planned, verify IC implementation and discuss the IC's ability to meet performance objectives going forward. Actual or pending changes in land or resource use/ownership that may impact the effectiveness of the ICs should also be included in a performance monitoring report. ICs have been retained for further evaluation for use with another remedial technology, as site conditions make its use independent of another remedial action unlikely.

6.3 Monitored Natural Attenuation with Long-Term Monitoring

MNA refers to the remedial action that relies on naturally occurring attenuation processes to achieve site-specific RAOs within a reasonable time frame. Natural attenuation processes that reduce contaminant concentrations in groundwater over time include destructive (biodegradation and chemical reactions with other subsurface constituents) and nondestructive mechanisms (dilution, dispersion, volatilization, and adsorption). MNA is always used in combination with LTM to assess the effectiveness and protectiveness of the process.

The most important process for the natural biodegradation of the more highly chlorinated solvents is reductive dechlorination. During this process, the chlorinated compound is used as an electron acceptor, not as a source of carbon, and a chlorine atom is removed and replaced with a hydrogen atom. In general, reductive dechlorination of chlorinated ethenes occurs by sequential

dechlorination from PCE to TCE to DCE (primarily the cis-1,2-DCE isomer) to VC to ethene. Depending upon environmental conditions, these sequences may be interrupted by other processes such as aerobic or abiotic degradation. Reductive dechlorination of chlorinated solvents is associated with the accumulation of daughter products and an increase in metabolic byproducts such as chloride.

Reductive dechlorination affects chlorinated compounds differently. Of the ethenes, PCE is the most susceptible to reductive dechlorination because it is the most oxidized. Conversely, VC is the least susceptible to reductive dechlorination because it is the least oxidized of these compounds. In general, the rate of reductive dechlorination of chlorinated solvents has been observed to decrease as the degree of chlorination decreases. It has been postulated that this rate of decrease may explain the accumulation of VC and cis-1,2-DCE mass relative to PCE and TCE mass where reductive dechlorination is occurring.

In addition to being affected by the degree of chlorination of the compound, reductive dechlorination also can be affected by the redox conditions of the groundwater system. For example, dechlorination of PCE and TCE to DCE can proceed under mildly reducing conditions such as nitrate reduction or iron (III) reduction, while the transformation of DCE to VC, or the transformation of VC to ethene requires more strongly reducing conditions.

Based on the CSM for OU2, DNAPL from suspected source areas had likely collected on the surface of bedrock and migrated through fractures to the water table. DNAPL dissolution produced a dissolved-phase plume in bedrock at and downgradient of the Curriculum Center. Dissolved-phase CVOs continued to migrate through bedrock fractures thereby creating a dissolved-phase plume.

MNA is an effective remediation approach for sites where natural mechanisms can be demonstrated to minimize or prevent the further migration of groundwater contamination. Based on the review of the FSRI data, it appears that dissolved-phase PCE is biologically transforming to TCE, cis-1,2-DCE, and VC through reductive dechlorination in only portions of the shallow and deep groundwater. This is likely due to either petroleum or sewer waste locally driving the shallow portions of bedrock groundwater into an anaerobic condition which is supporting the reductive dechlorination of PCE. This is occurring in the shallow northwestern portion of the plume. Shallow groundwater is migrating into the deep portions of the bedrock aquifer in this area. The result is groundwater containing PCE, TCE, cis-1,2-DCE, and VC in both the shallow and deep portions of the aquifer on the north and northwestern portion of the Curriculum Center.

Groundwater on the eastern and southeastern portion of the Curriculum Center contains mostly PCE as the potential effects of the petroleum or sewer waste is less and the aquifer remains mostly aerobic resulting in less reductive dechlorination. Groundwater in this portion of the aquifer (both shallow and deep) is mainly PCE with much lower concentrations of TCE, cis-1,2-DCE, and VC than groundwater to the north-northwest.

Natural attenuation is considered to be easily implementable. Materials and services necessary to model and monitor the contaminant dynamics are readily available. Site restrictions and/or

institutional controls may be required as long-term control measures as part of the MNA alternative. MNA and associated modeling involves low capital cost and moderate O&M cost.

MNA is potentially effective at OU2; however, due to the presence of DNAPL and source area concentrations, MNA alone will not achieve RAOs in a reasonable timeframe and therefore will not be retained for further consideration.

LTM usually includes an inspection and maintenance program which involves periodic sampling and analysis of soils, inspection of engineering control systems, and performance of repairs, as necessary. LTM alone would not be effective in reducing contamination levels. LTM must be implemented in conjunction with other remedial technologies to confirm that contaminant degradation is proceeding at rates consistent with meeting cleanup objectives.

LTM has been retained for further evaluation for use with another remedial technology, as site conditions make its use independent of another remedial action unlikely.

6.4 Containment

Containment barriers are structures installed to reduce contaminant mobility but do not directly impact contaminant toxicity or volume. These barriers are filled with impermeable, semi-permeable or permeable materials, depending on the contaminants at a site.

Wastes can also be “contained” via their sequestration into a geological formation through deep well injection. Alternately, hydraulic containment, accomplished by installing a line of extraction wells and pumping out and then treating the groundwater can be employed to stop contaminated groundwater from migrating past a certain point in the subsurface. Once treated, the clean water can be put back in the subsurface, sent to a public sewer, or discharged to surface water.

6.4.1 Hydraulic Barrier - Groundwater Extraction and Treatment

Groundwater pumping from an aquifer to remove dissolved phase contaminants and/or achieve hydraulic containment of contaminated groundwater to prevent migration is a potentially applicable remedial technology. Groundwater extraction and treatment (or pump and treat) consists of wells pumping contaminated groundwater to the surface for treatment. The treatment train is typically a series of physical, chemical, or biological processes, with ultimate discharge or disposal of the treated water (FRTR, 2002; EPA, 1994).

Processes typically evaluated or used in pump and treat systems can include, but are not limited to:

- Air stripping
- Ion Exchange
- Precipitation/Coagulation/Flocculation
- Adsorption

- Separation

Treatment and monitoring of extracted groundwater is required in conjunction with a pump and treat option where restoration of the resource is a RAO, as is the case for this site. The pump and treat approach is an established technology with known design standards and performance. System design is straightforward, as extraction well positions and flow rates can be determined using groundwater modeling and field-testing methods. Water treatment requirements are also well-established.

The materials, maintenance and labor needed for water treatment system operation may be higher compared to other technologies. Contaminant mass removal may be slow due to the low solubility of organic compounds and slow desorption of contaminants; therefore, pump and treat may take longer to achieve remedial goals than other options. While a pump and treat system can help prevent plume migration and remove free product, costs for remediation of an entire plume can be prohibitive.

These systems can require long durations to reduce contamination, but there are techniques to increase their efficiency and to help in overcoming what is known as “tailing” or the gradual decrease in removal of contamination over time, with concentrations remaining above the target cleanup levels (EPA, 2002b).

Technologies such as in-situ flushing may be used in conjunction with a pump and treat system to enhance contaminant recovery. Chemical processes may also be used to overcome tailing. If physical processes contribute to tailing, chemical enhancement may be unsuccessful in improving efficiency of the system. Specific information about the chemical processes contributing to the tailing is needed to choose agents that can be used to improve the system's effectiveness. Other factors, such as delivery of the reactive agent where needed and ability of the agent to remove target contaminants must be considered carefully (EPA, 2002b).

Further site characterization beyond what is normally completed in a RI, treatability testing and pilot studies may be necessary. Additional capital and O&M costs for wells and treatment facilities can be incurred. Contingency and/or alternate remedies may need to be included in the decision documents to provide for the transition to other technologies, should residual contamination remain after use of pump and treat alone, or if tailing off occurs.

Groundwater pumping is normally most effective in aquifers with high hydraulic conductivities. Data related to the hydraulic conductivity, concentration and areal extent of contamination, contaminant and soil properties, depth and seasonal fluctuation of the water table, ground/surface water interaction, and the depth, location and pumping rates of any wells that are likely to be influenced by remedial activities at the site are required in designing the pump and treat system (EPA, 1996).

The existing OU1 groundwater pump and treat system at the Curriculum Center can be used with upgrades. Since hydraulic plume control is necessary at the site for source control and to prevent

further downgradient migration of the contamination, groundwater pump and treat has been retained for further analysis as a stand-alone remedy or in combination with other remedies.

6.4.2 Deep Well Injection

Deep well injection and sequestration is a liquid waste disposal technology that uses injection wells to place and sequester treated or untreated liquid waste into geologic formations that have little potential to allow migration of contaminants (FRTR, 2002).

Deep well injection would likely face regulatory hurdles under the UIC Program. Compliance with other environmental programs, including the Safe Drinking Water Act, Clean Water Act and RCRA may also be required, depending on the remedy chosen and waste characteristics. There are likely to be community acceptance issues related to implementing this remedy as well, due to location of OU2. Deep well injection has not been retained for further analysis.

6.5 Treatment

Available groundwater treatment technologies include in-situ biological treatment, including enhanced bioremediation, phytoremediation and natural attenuation. Natural attenuation is discussed separately, as it is not an active remedial technology and is included as part of MNA/LTM. Thermal and physical/chemical treatment options are also available.

6.5.1 In Situ Biological Treatment

Enhanced Bioremediation

Generally, in situ bioremediation technologies employ engineered systems to heighten the effects of naturally occurring degradation mechanisms. The engineered systems are designed to enhance bioremediation and accelerate the natural biodegradation process by introducing nutrients, electron acceptors, heat, and/or contaminant-degrading microorganisms to the subsurface. Various bioremediation technologies can be used in situ to treat groundwater without removing it from the ground. This approach reduces the cost of handling and associated environmental impacts. Ex situ processes require removal of contaminated groundwater to be treated (EPA, 2000a).

Depending on the COC and the media, bioremediation may work through aerobic or anaerobic metabolism. In selecting a bioremediation technology, the COC, media, biological pathways of degradation and site conditions must all be considered.

Technologies that involve the addition of supplemental microbes to the subsurface are referred to as bioaugmentation technologies. Microorganisms able to degrade specific contaminants (e.g., as *Dehalococcoides* bacteria can degrade chlorinated solvents) are added where their type or numbers are insufficient to remediate the contamination. Microorganisms may be “seeded” from populations already present or be introduced from cultivated strains of bacteria designed to degrade specific contaminants. The addition of key nutrients (e.g., nitrogen and phosphorus) is used to supplement other bioremediation methods, so the availability of nutrients does not limit

the effectiveness of the in-situ bioremediation. Supplemental electron donors are added as a reductant in the redox reaction used by the degrading microorganisms, for example, hydrogen-containing or generating compounds. Electron acceptors add oxygen (for aerobic processes) or an anaerobic oxidant (e.g., nitrate) to support microbial processes that degrade the contamination (EPA, 1996).

The components of in-situ bioremediation technologies can be implemented in different general configurations, including direct injection, groundwater recirculation, PRBs, thermal heating, and bioventing. The configurations include vertical and horizontal wells, and trenches for both injection and extraction of groundwater, or to inject amendments to support the biodegradation processes. Any of these systems is used to enhance degradation through the addition of microbes, nutrients, oxidants, or reductants into the aquifer or soil.

The rate of bioremediation can be enhanced by increasing the concentration of oxygen (creating an aerobic condition) or adding a carbon substrate (under anaerobic conditions) to the groundwater. Oxygen enhancement can be achieved by either sparging air below the water table or circulating chemically bound oxygen (i.e., hydrogen peroxide or other oxygen releasing compound) throughout the contaminated groundwater zone. Air sparging is typically used in conjunction with SVE or bioventing to introduce supplemental oxygen and enhance removal of the volatile component of the subsurface contamination (EPA, 1996).

Under anaerobic conditions, a carbon nutrient or electron source is circulated throughout the groundwater contamination zone to enhance the natural rate and process of bioremediation. In co-metabolism, the COC is degraded as a result of a side reaction. For example, microorganisms may be provided with a fuel source and just so happen to degrade other contaminants at the same time (e.g., TCE).

Because of the nature and extent of contamination and nature of the site, Enhanced bioremediation has not been retained for further evaluation.

6.5.2 In-Situ Physical/Chemical/Thermal Treatment

Physical treatment technologies are those that employ air, water or other means to oxygenate, agitate or flush contamination through the subsurface to enhance its removal. Chemical treatment options use various processes (e.g., ultraviolet [UV] radiation) to degrade contaminants. These physical and chemical treatment technologies are described below.

Air Sparging

Air sparging (AS) is a physical treatment that involves injecting air directly into the subsurface to volatilize contaminants from the liquid phase to the vapor phase for treatment or removal, and to enhance biodegradation of contaminants via the introduction of oxygen. It is effective in treating chlorinated solvent contamination.

Air sparging uses commercially available equipment and is a relatively simple, lower cost technology. The equipment can be readily installed and may require minimal oversight, as no

waste streams are generated and the technology is compatible with other technologies (e.g., SVE and bioventing). It does require careful design and operation and is best suited to sites with sandy soils and aquifer depths less than 50 feet bgs.

Injected air traverses horizontally and vertically in channels through the soil column, creating a subsurface “air stripper” effect that removes contaminants through volatilization. The injected air helps to flush, or sparge the contaminants upward into the unsaturated zone where an SVE system is usually implemented in conjunction with air sparging to remove the generated vapor phase contamination in soil. The injected air also helps mix contaminants or NAPLs and move them out of bedrock fractures to be collected by removal systems.

The lateral and vertical placement of the air injection wells, and screened intervals are determined to maximize operational efficiency. The homogeneity and coarseness of subsurface materials, length of screened interval and other factors are used to place wells, based on the radius of influence that can be expected as a result of the site and system characteristics (Marley, et al 1992).

Sites treated with air sparging technology have shown significant rebound of contaminants after treatment, possibly due to poor monitoring, and untreated residuals of the influence of preferential pathways in the subsurface. These result in the incorrect conclusion that contamination levels were truly trending downward when that may not be the case. It has been recommended that sites continue to be sampled for at least one year after air sparging is stopped.

Air sparging increases the rate of contaminant volatilization, and therefore may result in the potential for migration of VOC-impacted vapor to receptors at potential levels of concern. An SVE system can be used to reduce this problem, but proximity to buildings or other structures should be considered to avoid inducing vapor intrusion. This technology is not suitable for treating sites having significant geological stratification or heterogeneity, as these prevent uniform air flow and reduce effectiveness.

Air sparging has been retained for further evaluation because of its ability to mix the subsurface liquids and release NAPLs for recovery.

Bioslurping

Bioslurping is another physical treatment option that combines the two remedial approaches of bioventing and vacuum-enhanced free product recovery to address light non-aqueous phase liquid (LNAPL) contamination. Bioventing stimulates the aerobic bioremediation of hydrocarbon-contaminated groundwater. Vacuum-enhanced free-product recovery extracts LNAPL from the capillary fringe and the water table without extracting large quantities of groundwater.

A bioslurping system consists of a well with an adjustable length “slurp tube” that is connected to a vacuum pump lowered into the LNAPL and pumped to remove LNAPL and groundwater. The vacuum-induced negative pressure zone in the well moves LNAPL toward the well; when the LNAPL level declines in response to the pumping, the slurp tube draws and extracts vapors,

increasing air movement, increasing oxygen flow and thereby enhancing aerobic bioremediation. LNAPL and groundwater removed via the slurp tube are sent to an oil/water separator, and vapors to a liquid/vapor separator. Bioslurping can achieve greater recovery rates than either skimming or dual-pump methods. It can have lower costs and result in less aquifer “smearing”, where movement of contaminants (e.g., with water table fluctuations) increases the area of soil impacted, therefore increasing the volume of contaminated groundwater. However, it may induce biofouling of well screens due to active aeration (Ground-Water Remediation Technologies Analysis Center (GWRTAC), 1996).

Conditions that may limit the applicability of this technology include that it can be less effective in tight (low permeability) soils; aerobic biodegradation of chlorinated compounds may not be effective; and collected vapor and/or groundwater generally requires treatment.

Bioslurping is not practicable at this Site due to the presence of DNAPL and a chlorinated solvent plume in bedrock. Therefore, bioslurping has not been retained for further evaluation.

InSitu Chemical Oxidation/Reduction

In situ chemical oxidation (ISCO) chemically converts contaminants to less toxic compounds that are more stable, less mobile, and/or inert. It involves injecting a solution of oxidizing agent into the subsurface via an injection well to treat dissolved-phased contaminants. The oxidizing agents most commonly used are ozone, hydrogen peroxide, potassium permanganate, hypochlorites, zero valent iron (ZVI), chlorine, chlorine dioxide activated persulfate, and nanoscale ZVI. Matching the oxidant and in-situ delivery system to the COCs and the site conditions is a key factor in successful implementation and achieving performance goals.

ISCO can be a viable remediation technology as it is effective for mass reduction of organic compounds in groundwater, has a relatively rapid treatment time, and is implementable with commercially available equipment. There are safety requirements for handling and administering large quantities of hazardous oxidizing chemicals; a need to monitor the fate and transport of the chemicals in the aquifer; and naturally occurring organic material in the formation that can consume large quantities of oxidant.

The effective distribution of reagents in the treatment zone and the reactivity of a particular oxidant with the COCs are critical to the success of this technology. Robust site characterization, screening, and feasibility testing is required, particularly related to understanding subsurface heterogeneities or preferential flow paths. The reagents consume natural organic matter in the subsurface, some of it contaminated. As the organic matter is depleted, this contamination can be released to groundwater, especially in highly permeable soils. The amount of natural organic matter content and site-specific hydrogeology can impact this technology’s effectiveness, making it challenging to achieve mixing of groundwater and oxidants.

Advantages of ISCO include a faster remedial timeframe. However, both the concentration and distribution of contamination in the vapor, liquid, and sorbed phases can be disturbed and must be monitored (Adventus, 2007; Huling, 2006).

Chemical oxidation has been used for more than 50 years to treat wastewater ex-situ and is being applied to in-situ remediation of groundwater. The injected solution can have a tendency to displace groundwater, react with natural organic matter and only then react with contaminated groundwater. It also has potential to displace the plume, increasing chemical migration. There are certain safety hazards involved in the use of the reagents, particularly in a densely developed area, including heat generation from the exothermic reaction generated in the treatment process, and the resulting potential for damage due to fire and explosion if not carefully managed.

Chlorinated solvents can also be degraded via reductive processes. In-situ chemical reduction (ISCR) can utilize either ZVI or dual-valent iron (DVI) to facilitate the chemical reduction of these contaminants through the creation of low redox potential and production of hydrogen. ISCR can minimize the formation of “daughter products”, such as vinyl chloride and can overcome the “dichloroethene (DCE) stall”, where further dechlorination to ethane does not occur, or does so very slowly during solvent remediation.

In a hypoxic (low Eh; low oxygen) subsurface environment, ISCR is particularly advantageous. Before implementing the ISCR technology, analysis of the treatment area (e.g., use for source removal or plume control), contaminant characteristics, presence of NAPL, remedial timeframe, potential environmental impacts (i.e., secondary plumes) and health & safety issues is required (Adventus, 2007).

Chemical oxidation/reduction has been retained for further analysis as a remedial option and enhancement technology due to its effectiveness in treating CVOCs.

Dual Phase Extraction

Dual-phase extraction (DPE), also known as multi-phase extraction or vacuum-enhanced extraction, utilizes a vacuum system to physically remove various combinations of contaminated groundwater, separate-phase product, and soil vapor from the subsurface. Extracted liquids and vapor are treated and collected for disposal or discharge, under applicable State regulations.

DPE systems are utilized in low permeability or heterogeneous formations. The vacuum extraction well includes a screened section in the zone crossing contaminated soils and groundwater, removing contaminants from above and below the water table. The system lowers the water table around the well, exposing more of the impacted formation. Contaminants in the newly exposed vadose zone are then more amenable to vapor extraction. Once above ground, the extracted vapors or liquid-phase organics and groundwater are separated and treated (EPA, 2004d).

DPE has been retained for further analysis due to its effectiveness in mobilizing DNAPL in the shallow bedrock zone and removal of contaminants.

Thermal Treatment

In-situ thermal treatment (ISTT) methods mobilize chemicals through groundwater and bedrock by heating them. The chemicals then move through groundwater and bedrock toward wells to be

collected and transferred to the surface for treatment. The heat can destroy or vaporize certain chemicals.

Thermal methods can be used to separate contaminants from groundwater/bedrock matrices. They can be used in-situ and employ steam, hot air or hot water injection; electrical resistance and radio frequency heating that converts groundwater to steam. Ex-situ thermal desorption technologies include direct-fired methods, that apply flame to contaminated media (usually soil); indirect-fired, using heated air for desorption; and indirect-heated systems, using an externally fired heat source to desorb contaminants.

Thermal treatment can use steam forced into an aquifer through injection wells to vaporize volatile and semi-volatile organic contaminants. Injected steam condenses and raises the temperature of the rock and pore water, inducing a steam front in the subsurface. This process mobilizes both liquids and vapors towards recovery wells. The steam front is characterized by high contaminant concentrations in both the vapor and aqueous phase. Air may also be injected along with the steam. This approach promotes in-situ oxidation of contaminants.

A steam injection system consists of injection and extraction wells. For small areas, injection wells in a clean zone may surround a central extraction well near the middle of a source area to minimize the risk of spreading contaminants. In larger areas, multiple arrays of injection and extraction wells are used to heat and capture mobilized contaminants.

Thermal treatment has been retained for further analysis due to its effectiveness in treating source areas.

In-Well Air Stripping

With in-well air stripping, a physical treatment technology, air is injected into a vertical well that has been screened at two depths. The lower screen is set in the groundwater saturated zone, and the upper screen is set in the unsaturated zone. Pressurized air is injected into the well below the water table, aerating the water. The aerated water rises in the well and flows out of the system at the upper screen, inducing localized movement of groundwater into (and up) the well as contaminated groundwater is drawn into the system at the lower screen. VOCs vaporize within the well at the top of the water table, where the air bubbles are out of the water. The air injection removes volatiles and establishes a circulation pattern of oxygen-saturated water in the aquifer that may also enhance the biodegradation rate.

The contaminated vapors accumulating in the wells are collected via vapor extraction contained within the well. Vapor phase treatment typically occurs above grade. The partially treated groundwater is never brought to the surface; it is forced into the unsaturated zone, and the process is repeated as water follows a hydraulic circulation pattern or cell that allows continuous cycling of groundwater. As groundwater circulates through the treatment system in-situ, and vapor is extracted and treated, contaminant concentrations are reduced.

For effective in-well treatment, the contaminants must be adequately soluble and mobile so they can be transported by the circulating groundwater. In general, in-well air strippers are more effective at sites containing high concentrations of dissolved contaminants with high Henry's Law constants. The radius of influence and groundwater flow regime around the well require careful consideration in design and operation of the system (FRTR, 2002). Site and system characteristics to be considered are similar to those for air sparging, described above.

In-well air stripping is effective for the removal of organics in aquifers with relatively high permeability as opposed to the OU2 source area. In-well air stripping has not been retained for further evaluation.

Passive/Reactive Treatment Barriers

These are treatment barriers that combine physical and chemical treatment. They allow the passage of impacted groundwater while causing the degradation or removal of contaminants. One example, a passive reactive barrier (PRB) is a passive in-situ treatment zone that degrades contaminants as groundwater flows through it. The reactions within the PRB are dependent on pH, redox potential, contaminant concentrations, and other factors. The hydrogeology must be conductive, and a relatively shallow confining layer is needed to “key” into and thereby contain the system. Most PRBs are installed as either a funnel-and-gate or continuous trench.

A PRB is installed across the flow path of a contaminant plume, allowing the water portion of the plume to passively move through the wall. PRBs may combine a passive chemical or biological treatment zone with subsurface fluid flow management. Treatment media may include ZVI, nanoscale ZVI, chelators, sorbents, or microbes. The contaminants will either be degraded or retained in a concentrated form by the barrier material. The barrier could provide permanent containment for relatively benign residues or provide a decrease volume of the more toxic contaminants for subsequent treatment.

The passive/reactive treatment technology will not be efficient for addressing groundwater contaminants given the source area bedrock geology, concentrations and configuration of the groundwater plume at OU2.

PRB technology has not been retained for further analysis.

In-situ Flushing

The process involves the injection of an aqueous solution, commonly through vertical wells, into a contaminated zone. This may be within the vadose zone (the rock above the water table), the saturated zone, or both. The solution then flows through the contaminated zone and the resulting effluent is extracted downgradient where it is treated and discharged or re-injected. The aqueous solution injected may contain surfactants or co-solvents.

In-situ flushing has been used with conventional pump and treat and other methods of remediation to enhance the solubility or mobility of the contaminants, thus accelerating the remediation process. This technology was developed to treat chemicals with low solubility, such as DNAPL,

that can remain in the vadose zone for decades, slowly dissolving into the groundwater plume. By increasing the solubility or mobility of these contaminants at the source, in-situ flushing can provide a faster, more efficient method for groundwater remediation (GWRTAC, 1997).

In-situ flushing with water (which is effective as the flushing agent for dissolved PCE/TCE in groundwater) or co-solvents will be considered as an enhancement to be used in concert with another technology to increase contaminant mobilization and recovery from the bedrock aquifer at OU2.

In-situ flushing technology has been retained for further analysis.

6.5.3 Ex-Situ Biological Treatment

The following ex-situ treatment technologies assume the pumping of impacted groundwater at the site, prior to treatment.

Bioreactors

Contaminants in extracted groundwater are put into contact with microorganisms in attached or suspended growth biological reactors. Contaminated groundwater is circulated in suspended media, such as activated sludge, within an aeration basin. In attached systems, such as rotating biological contractors and trickling filters, microorganisms are established on an inert support matrix.

Because of the nature and extent of contamination at OU2, bioreactors have been screened out and will not be evaluated further.

6.5.4 Ex-Situ Physical / Chemical Treatment

The following ex-situ treatment technologies are considered in conjunction with pump and treat technology, as they require the pumping of impacted groundwater to the surface prior to treatment. The technologies discussed below are assumed to be implemented in conjunction with air stripping and groundwater pump and treat.

Adsorption

The adsorption process consists of passing contaminated air through a sorbent media. Contaminants are adsorbed onto the media, reducing their concentration in the bulk liquid phase. Adsorption mechanisms are generally categorized as physical, chemical, or electrostatic adsorption. The most common adsorbent used is GAC.

Vapor phase GAC adsorption is a process where vapor/air stream from a treatment process like air stripping, SVE, and in-situ thermal treatment (FRTR, 2002) is sent through a series of canisters or columns containing activated carbon to which organic contaminants adsorb. When the concentration of contaminants in the effluent from the bed exceeds a certain level, the carbon can be removed and regenerated at an off-site facility; or removed and disposed of off-site.

Since VC concentrations cannot be handled by adsorption, alternate methods to handle VC (e.g., oxidation using permanganate) would be employed as an adjunct technology to GAC adsorption.

Adsorption is a viable technology for VOC treatment of extracted vapors. Therefore, adsorption via GAC has been retained for further evaluation for vapor treatment in conjunction with air stripping and groundwater pump & treat.

Advanced Oxidation Processes

Advanced oxidation processes, including the use of UV radiation, catalytic oxidation, ozone, potassium permanganate, and/or hydrogen peroxide can destroy organic contaminants in groundwater and/or air. Chlorinated hydrocarbons (e.g., TCE, PCE, and VC) are rapidly destroyed in UV/oxidation processes. However, pretreatment of the vapor/air stream may be needed to minimize maintenance requirements of the oxidation treatment component.

If ozone is used as the oxidizer, an ozone destruction unit(s) may be required to treat off-gases resulting from treatment and where ozone gas may accumulate or escape, to avoid a safety hazard. Advanced oxidation technology is also associated with high energy requirements (FRTR, 2002). Advanced oxidation using potassium permanganate has been retained for further evaluation for vapor treatment in conjunction with air stripping and groundwater pump & treat.

Air Stripping

Ex-situ air stripping has been used in conjunction with pump and treat systems to enhance performance; it separates volatile organics from groundwater by increasing the surface area of the contaminated water exposed to air. Methods include packed towers, diffused, tray and spray aeration. The process as conducted in a packed tower involves spraying contaminated water over the packing in the column, with a fan moving air against the water flow, with a sump under the tower to collect decontaminated water. Modifying packing configurations can increase VOC removal efficiency. For example, a low-profile air stripper packs a number of trays in a very small chamber to maximize air to water contact while minimizing space. Because of the significant space saved, these units enhance the practicability of ex situ air stripping.

It can take decades to reach RAOs using pump and treat with an air stripping system. Successful implementation of this technology is largely dependent on the capture of the entire plume. Issues limiting the practicability and effectiveness of ex situ air stripping include: biological fouling, requirements for pumping and treatment of large volumes of water; moderate to high energy demands; and off-gases that require collection and treatment.

Ex situ air stripping has been retained for further evaluation as an enhancement to pump and treat technology.

Groundwater Pump & Treat

Groundwater pump and treat to remove dissolved phase contaminants from the aquifer and bring them to the surface for treatment is a potentially applicable remedial technology. Treatment is

typically a series of physical, chemical, or biological processes, with ultimate discharge or disposal of the treated water to surface water, groundwater or a POTW.

Treatment and monitoring of extracted groundwater is required where restoration of the resource is an RAO, as it is here. The pump and treat approach is an established technology at the site with known design standards and performance. System design is straightforward; water treatment requirements are also well-established. Although this is an established technology, due to the high CVOC concentrations in the groundwater, the presence of DNAPL, and a bedrock aquifer, it is anticipated that this technology will take a relatively long period of time to reach RAOs at the source areas.

Pump and treat technology has been retained for further evaluation.

6.6 Discharge

Discharge technology options address the means of disposal and/or discharge of groundwater that has undergone some sort of remedial processing and is either safe to discharge to the environment as is, or requires further treatment to protect human health and the environment prior to release to the air, water or a sewer system. There is specific guidance and numerous regulatory requirements related to the disposal or discharge of CERCLA wastes or emissions

The CERCLA Compliance with Other Laws Manual, Parts I and II (EPA 1988, 1989) provides an analysis of ARARs for Superfund Site discharges, including those related to compliance with the Clean Water Act and NPDES program, for surface water and POTW discharges; the Safe Drinking Water Act and its drinking water (i.e., MCLs), UIC and Sole Source Aquifer (SSA) programs, as well as RCRA and air quality programs. These may all relate directly to the RAOs for the AOCs.

6.6.1 On-Site Discharge

Surface Water

This option consists of discharging extracted and treated groundwater to surface water. The existing OU1 GWTF discharges treated water under a TPDES permit equivalency via an existing outfall to Turpentine Run. This approach can be an effective and implementable discharge method where surface water standards can be met. On-site discharge has been retained for further evaluation.

Groundwater

This on-site discharge technology involves injection of treated groundwater into the aquifer using a series of wells in combination with groundwater extraction technologies to maintain hydraulic control over the contaminated area. On-site injection used as a groundwater disposal measure would require that the groundwater be treated to meet applicable groundwater standards prior to disposal to the subsurface, and it is usually operated for a long time. This can be an effective and implementable discharge method where UIC and other regulatory requirements can be met. This

method can be used to act as a hydraulic barrier when injected downgradient from the recovery wells. On-site discharge has been retained for further evaluation.

6.6.2 Off-Site Discharge to POTW

Off-site discharge to a POTW consists of discharging treated groundwater directly to a sanitary sewer line or transporting the water to an off-site POTW via tanker trucks. This approach can be an effective and implementable discharge method, where CERCLA aqueous waste discharge requirements can be met (EPA, 1990b; EPA 1991). In evaluating the potential discharge to a POTW, the waste stream proposed must be characterized qualitatively and quantitatively, to assure the ability to treat the waste stream and maintain compliance with the candidate POTW's Permit Equivalents requirements, and that treatment capacity is available. The POTW's compliance status, whether the conveyance to be used is a combined or separate sanitary sewer system and other factors are also to be considered. There is one POTW in use on St. Thomas. Due to insufficient capacity, off-site discharge to the POTW has not been retained for further evaluation.

6.6.3 Enhancement Technology

6.6.3.1 Hydraulic Fracturing

Fracturing is an enhancement technology designed to increase the efficiency of other in situ technologies in certain types of subsurface conditions (i.e., very low permeability rock). Hydraulic fracturing can be used to dilate and activate existing fractures or to create altogether new fractures from existing boreholes. Fractures are created by pumping large quantities of fluids at high pressure down a borehole and into the target rock formation. Hydraulic fracturing fluids generally consist of water, proppants (sand, or ceramic pellets), or chemical additives that open and enlarge fractures within the rock formation.

Hydraulic fracturing should be limited to deep zone wells or the deep zone sections of wells. It may be beneficial for both extraction and injection wells as the objective is to increase the head in both shallow and deep zones during injection. Proppants are typically not needed to enhance the yield of water wells. Treated water from the existing treatment plant can be used under high pressure or non-potable water may be brought on site to serve as the injection fluid.

Hydraulic fracturing can also help mobilize DNAPL and contaminants, thereby increasing the volumes recovered during groundwater extraction and treatment. The extracted water is then treated above ground before discharge.

Hydraulic fracturing has not been retained at this time since there are no guarantees in controlling the distance a fracture can travel. However, this might be a promising technology in the future with more advancements and applications in the field.

6.7 Retained Remedial Technologies

The retained remedial technologies for groundwater include:

- No Action
- ICs
- LTM
- Hydraulic Barrier
- In Situ Physical/Chemical Treatment
- Ex Situ Physical/Chemical Treatment
- On-Site Discharge

7 Evaluation of Process Options

Groundwater remedial technologies were screened in Section 6 for potential applicability, effectiveness, reduction in toxicity, mobility, or volume of contaminants, and implementation at OU2 (**Table 6-1**). Technologies that successfully passed the screening process in Section 6 were assembled into process options, which were then evaluated based on effectiveness, reduction of toxicity, mobility, or volume of contamination through treatment, implementability, and general cost. Process options were evaluated based on effectiveness to treat both dissolved phase concentrations in groundwater and DNAPL in potential source areas. Process options that cannot be effectively implemented due to site characteristics or other restrictions were eliminated from further consideration. An evaluation of the remedial technology process options conducted for groundwater is presented in **Table 7-1**.

The following technologies and process options have been incorporated in the remedial alternatives and will be further evaluated based on their applicability to Site conditions and potential effectiveness in meeting the RAOs in Section 8.

- No Action
- ICs
- LTM
- Hydraulic Barrier
 - o Groundwater Pump & Treat
- In Situ Physical/Chemical Treatment
 - o Air Sparging
 - o In Situ Chemical Oxidation
 - o Dual Phase Recovery/Enhanced Fluid Recovery
 - o In Situ Thermal Treatment
 - o In Situ Flushing
- Ex Situ Physical/Chemical Treatment
 - o Adsorption
 - o Ex Situ Air Stripping
 - o Groundwater Pump & Treat
- On-Site Discharge
 - o Surface Water
 - o Groundwater Injections

7.1 Groundwater Process Options

The groundwater process options retained for detailed analysis include LTM/ICs (to be considered for use with other remedial technologies), hydraulic containment with groundwater extraction and treatment with disposal/discharge options, and in-situ/ex-situ treatment options.

The no action and ICs were included for evaluation, with ICs being recognized as an integral component of any remedy option. ICs are a critical component of the remedy, as the results of the HHRA indicate that risks from groundwater (via ingestion, dermal contact, and inhalation exposure routes) exceed acceptable levels for carcinogenic and non-carcinogenic effects in a future scenario that assumes exposure to impacted groundwater (i.e., if the engineering and ICs are no longer in-place). ICs under OU1 will also be applicable for OU2.

The options are described in the subsections below.

7.1.1 No Action

The no action option will not meet the RAOs and will not be acceptable to the local community or the USVI. There is no cost associated with this option. The no action option has been retained only to provide a basis for comparison with other active remedial process options, as required under CERCLA.

7.1.2 Long-Term Monitoring and Institutional Controls

LTM and ICs such as deed restrictions and well drilling restrictions can be combined as a strategy for remediation of the groundwater plume. This remedial option is considered in concert with other technologies, as Site conditions make its independent use unlikely. The use of this option relies on future enforcement of groundwater restrictions and implementation of a long-term groundwater monitoring program. This option is also dependent on natural attenuation of the plume through dispersion, diffusion, and degradation.

Deed restrictions will not reduce the mass of contamination at OU2 but are effective in protecting human health by restricting future site uses or activities that may result in direct contact with contamination. Future land use must be restricted via legal restrictions that require continued implementation to remain effective. LTM, including site inspections, is generally required. These measures, however, would not reduce the toxicity and migration of contaminants or the extent of environmental impacts and would not reduce site contaminant concentrations to protective levels. The implementation cost is generally low. Deed restrictions can be used in conjunction with other remedial process options and have been retained for further consideration.

Well drilling restrictions may effectively meet RAOs from a human health standpoint through restriction of future site uses or activities which may result in direct contact with contaminated groundwater. The migration and environmental impact of the contaminated groundwater will not be reduced. Implementation would be easy via the existing permitting process. The cost to

implement is low. Well drilling restrictions can be used in conjunction with other remedial process options and have been retained for further consideration.

LTM includes periodic sampling and analysis of groundwater. An LTM program provides an indication of the movement of contaminants and/or of progress of remedial activities. LTM alone would not be effective in meeting the RAOs. It would not alter the effects of contamination on human health and the environment. However, it may be implemented in conjunction with, as an enhancement to, or as a potential contingency/alternative remedy to other remedial technologies. LTM could be easily implemented, particularly given the existing monitoring well network that exists. Costs are limited to those associated with sampling and analysis required for LTM. Therefore, LTM has been retained for further analysis.

7.1.3 Air Sparging

AS is a technique in which air is injected into the groundwater for the purpose of removing organic contaminants by volatilization. It is typically used in conjunction with SVE to eliminate offsite migration of vapors. As air moves up through the groundwater, VOCs partition into the gas phase and are transported to the vadose zone. The VOCs stripped from the groundwater would rise along with the air into the unsaturated zone where they would be captured by the SVE system. AS/SVE has been shown to be effective in removing VOCs from the groundwater. This process is dependent upon how well the injected air permeates into the groundwater from the injection point.

Pulsed air sparging with SVE at source areas can help mobilize and recover residual DNAPL within the zone influenced by air sparging. Most components of the system are fairly easy to implement. Increasing the sparge rate and pulsing the air injection can lead to improved mass recovery, as the pulsing can induce water circulation thereby increasing the DNAPL dissolution rate. Dissolved PCE concentrations both within and outside the zone of air sparging will also be affected by the pulsing. It is anticipated that dissolved concentrations inside the sparge zone will decrease while outside the sparge zone, the dissolved concentrations will increase because highly contaminated water is being pushed away from the air injection point. In order to prevent off-site migration of the contaminated water, hydraulic control will be necessary.

Air sparging in the potential source areas may increase the average mass removal rate, thus reducing the treatment time of a pump and treat system alone. Moderate capital and moderate O&M costs are involved. This process option has been retained as a remedial enhancement to groundwater extraction and treatment.

7.1.4 SVE

SVE is used to eliminate offsite migration of vapors in conjunction with groundwater air sparging. SVE wells would be installed above the water table and a vacuum would be applied to mobilize soil gas and remove VOCs in the vadose zone (bedrock) by vaporization and volatilization. The VOCs stripped from the groundwater via air sparging would rise along with air into the unsaturated zone where they would be captured by the SVE wells. An off-gas treatment system using vapor

phase granular activated carbon (GAC) adsorption may be necessary to limit the release of contaminants to the atmosphere. The ability of the SVE wells to capture the contaminants forced into the unsaturated zone is an important component due to the potential risk of VOC migration into buildings located within the area of contaminated groundwater. Most components of the system are easy to implement. Moderate capital and moderate O&M costs are involved. This process option is retained in conjunction with air sparging as a remedial enhancement to groundwater extraction and treatment.

7.1.5 Groundwater Extraction and Treatment

Groundwater extraction and treatment can be effective in contaminant mass removal over a long timeframe as well as establishing hydraulic control of the aquifer, which can reduce or prevent further migration of contaminants beyond the OU2 boundary.

The existing OU1 GWTF at the Curriculum Center consists of three extraction wells; RW-6, RW-7, and RW-9. Extraction well RW-6 is completed in the deeper, less productive portion of the aquifer with an open interval from 80 to 130 ft bgs. Extraction wells RW-7 and RW-9 are completed in the shallow, more productive portion of the aquifer, with open-hole sections from 30 to 80 feet bgs and 40 to 60 feet bgs, respectively. Extraction well RW-6 is operated approximately one hour per week, at a flow rate of approximately two gpm, until the extraction well pump shuts down due to a low water level in the well (EPA, 2014; Arrowhead, 2017). Extraction well RW-7 is the primary extraction well and is operated on a continuous basis. Extraction well RW-9 operates as required to maintain the target groundwater elevation and is typically operated during and following heavy rain events. Treated water is discharged to Turpentine Run on the adjoining property to the northwest.

The influence of the existing pump and treat system extends tens of feet cross gradient in an east-west direction and potentially hundreds of feet up and down gradient in the northeast-southwest direction in the shallow monitoring zone. Drawdown is limited to bedrock features and faults with a direct connection to pumping well RW-7. The current system does not capture the full width of aqueous CVOC's in the shallow zone. Although extraction well RW-6 is completed in the deep, less productive zone, limited yield reduces its effectiveness in capturing contaminated groundwater that migrates into the deep zone. There has been no evidence to date that the influence of the extraction system extends measurably into the deep zone below 90 ft bgs. Therefore, contaminants that migrate to the deep zone are unlikely to be captured by the current extraction system. DNAPL is also outside the capture zone of the current system at the Curriculum Center. Refer to Section 9.0 for uncertainties regarding the capture zone.

Extraction wells are effective in providing hydraulic control for sites where the hydrogeology is well understood and the pumping rate necessary to maintain hydraulic control is sustainable. Due to the presence of DNAPL and high source area concentrations, it is necessary to maintain hydraulic control at the Curriculum Center during active treatment in any of the OU2 groundwater remedies developed in this FS. This hydraulic containment will limit or prevent the downgradient migration of contaminants from the Curriculum Center. It is estimated that operating the system at a total flow rate of 100 gpm instead of the current design flow rate of 60 gpm will establish

better hydraulic control and capture the deep bedrock groundwater at OU2. Additionally, lowering the water table by an increased flow may mobilize the DNAPL.

All of the OU2 groundwater remedies (excluding no action and in situ thermal treatment) developed in this FS will have limited success unless the current extraction and treatment system is upgraded and optimized. Therefore, all groundwater remedies (excluding no action) will include at a minimum, increasing the capacity of the treatment system and system upgrades to accommodate additional flow and improve system efficiency.

Extraction wells are implementable, and the equipment and materials are readily available. Installation of new extraction wells would involve high capital costs. Groundwater extraction and treatment has been retained for further analysis.

7.1.5.1 Dual Phase Recovery/EFR

One of the treatment options retained for OU2 include in situ treatment of groundwater using a modified dual phase vacuum extraction (DPVE) known as enhanced fluid recovery (EFR). EFR events are essentially portable DPVE units that are used to periodically remove organic mass from the subsurface. The following is a summary of the EFR technology based on the literature provided by vendors of the multi-phase dual phase extraction technology.

The EFR treatment is a relatively new technology. EFR events are performed to recover constituents released into the groundwater, and to reduce the dissolved phase constituent concentrations. EFR is a mobile form of high-vacuum, multi-phase extraction that simultaneously extracts groundwater and soil vapor from designated wells. The recovered groundwater and vapor are treated and discharged. By applying high suction, EFR can be effective in mobilizing DNAPL from fractures and potentially removing DNAPL from select source area wells.

EFR multi-phase extraction performs dual phase extraction and removes multiple phases of hydrocarbons (liquid and vapor phase) simultaneously by extracting the vapors and contaminated groundwater from multiple monitoring or recovery wells which have been drilled to define the extent of contamination in the subsurface. The technology employs high vacuum (with vacuum pumps rated at a maximum of 27 inches of mercury) and high flow rates simultaneously connected to as many as eight monitoring or recovery wells. The vacuum forcefully induces contaminant liquids and vapors to be pulled into the extraction wells from both the vadose zone above the water table and the saturated zone below simultaneously. Extracted contaminant liquids are containerized above ground and volatile vapor emissions are treated by the integrated vapor treatment or destruction system. EFR multi-phase extraction has become an accepted technology at both the State and Federal levels and has been replicated in many areas.

EFR is an innovative and cost-effective alternative for the removal of VOCs from the subsurface. The technology is also unique in that it can treat adsorbed phase VOCs existing within the bedrock fractures that act as a continuing source for dissolved phase VOCs. The process dewateres and exposes the fractures to the effects of "high rate" soil vapor extraction. The technology has also been well documented to be effective in the reduction in dissolved phase concentrations and

increases in flow rates achievable from low-yielding aquifers. Importantly, EFR technology also introduces oxygen to the aquifer, thereby enhancing aerobic biodegradation.

EFR would be effective in reducing source area concentrations and the removal of DNAPL. EFR is implemented for several hours on a set schedule. This will not be effective on its own to provide hydraulic control of any off-site groundwater plume. EFR is easily implementable and generally involves low capital cost and low to moderate O&M costs. EFR has been retained as a remedial enhancement to groundwater extraction and treatment

7.1.6 In Situ Treatment

In situ treatment technologies were evaluated for use at OU2 to potentially be applied in conjunction with a groundwater extraction and treatment system for hydraulic control. In situ treatment has the potential to significantly reduce the contaminant mass within source areas and significantly reduce the remedial timeframe to achieve the OU2 RAOs. Hydraulic control during in situ treatment is necessary to prevent off site migration of contaminants and to maximize treatment effectiveness.

7.1.6.1 In Situ Thermal Treatment

Thermal treatment transfers heat into the subsurface, causing groundwater and the contaminants to vaporize or evaporate, increasing the diffusion rate and solubility of contaminants, and potentially enhancing abiotic degradation or even biological degradation of contaminants. Heat can be delivered by direct conduction of heat away from heaters in wells (thermal conductive heating [TCH]); by passing electrical currents through the subsurface (electrical resistance heating [ERH]); and by steam injection. Contaminants transferred into the vapor phase rise to the unsaturated zone where they are captured by vacuum extraction and then treated above ground. ISTT has been retained for its ability to penetrate the fractured rock matrix, and to treat DNAPL and CVOCs in the saturated zone.

Due to the evaporation of groundwater, water levels within the treatment zone decrease, thus creating a hydraulic gradient toward the treatment zone and acting as a hydraulic control. The contaminant vapor can be effectively captured in the vadose zone using vertical or horizontal SVE system and treated above ground.

Toxicity, mobility, and/or volume of contaminants are reduced by thermal processes. Because heat can be generated and conducted through rock regardless of permeability, thermal treatment using TCH or ERH may be more effective than technologies that depend on flow pathways for removal of contaminants.

ISTT is implementable and would be applied to groundwater beneath the potential source areas and the northern portion of the building which continues to be the most significant source of CVOCs and DNAPL at the Curriculum Center based on RI results. ISTT using TCH will address mass in bedrock fractures and the bedrock matrix.

High capital and low to moderate O&M costs (over a relatively short timeframe) are typically associated with thermal treatment systems. This process option has been retained for further evaluation.

7.1.6.2 Steam Injection

Steam injection, e.g. steam enhanced extraction (SEE), involves introducing steam into the bedrock aquifer via injection wells and extracting the groundwater, contaminants, and vapors from recovery wells. The steam mobilizes contaminants by creating a pressure and temperature gradient, which propagates from the injection well and displaces the contaminated groundwater. NAPL displacement is aided by a viscosity reduction due to the rise in ambient groundwater temperatures from the steam injections. Some compounds will volatilize when the steam is introduced and will be transported to the leading edge of the steam zone before condensing back into the liquid phase. Contaminant removal occurs by several mechanisms. Vaporization, displacement and viscosity reductions, are the important mechanisms to understand and will drive the source area cleanup. Properly designing the injection and the recovery system will be critical to the success of this process option and to ensure that the system does not drive the contamination deeper into the subsurface.

A steam injection system would be installed at the most significant source of CVOCs and DNAPL at the Curriculum Center based on RI results. Steam injections may mobilize DNAPL which will be captured by recovery wells. The effectiveness of steam injection relies on its ability to contact, heat, and physically displace contaminants. It should be noted that SEE will heat bedrock fractures and not the bedrock matrix if the fractures are far apart.

High capital and low to moderate O&M costs are typical. This process option has been retained for further evaluation.

7.1.6.3 In Situ Chemical Oxidation

ISCO is a chemical process that involves introducing oxidizing compounds into the bedrock aquifer to convert contaminants into less toxic constituents. It is effective at treating the chlorinated solvent contamination found at OU2 and can be successfully delivered to the contaminated mass within the fractured bedrock aquifer using the existing monitoring well network. It is a passive treatment method and is less expensive when compared with other treatment methods.

ISCO, using slow-release cylinders (candles) that are constructed with oxidant compounds (e.g. potassium permanganate and sodium persulfate) and wax, is particularly advantageous for use at OU2. The slow, sustained, delivery of oxidant to the bedrock aquifer with minimal field oversight or injection/ installation, makes it a more attractive option over traditional ISCO injections.

Low capital and low to moderate O&M costs (mostly with LTM) are typically associated with ISCO. Based on OU2-specific conditions and potential benefits of this technology, ISCO using slow-

release cylinders (or comparable delivery method) has been retained for further evaluation as a remedial enhancement to groundwater extraction and treatment.

7.1.6.4 In Situ Flushing

In situ flushing is an aggressive technique that involves introducing a surfactant or co-solvent solution into the bedrock aquifer to remove contaminants. The contaminants are mobilized by solubilization, formation of emulsions, or a chemical reaction with the flushing solution. The contaminant bearing liquid is then extracted by recovery wells and brought to the surface for disposal, recirculation, or on site treatment and reinjection. Traditional flushing techniques rely on the ability to deliver, control the flow, and recover the flushing fluid (EPA, 2006) via a pump and treat system.

Surfactant flushing is used primarily to target the removal of source area concentrations and for DNAPL mass removal and is less effective for the remediation of dissolved plumes. Also, surfactants are only effective if there is contact; therefore, they need to be injected in sufficient volume and in the right location to flow through the contaminated zone. Surfactant solution can be introduced into the bedrock through injection wells, injection probes or even monitoring wells. Repeat injections may be necessary. Hydraulic control during injection and recovery is necessary to assure that the surfactant solution is delivered to the contaminated zone and can be fully recovered.

There are several challenges with surfactant flushing in bedrock. The ability of the formation to accept surfactant injection across a large vertical zone such as at OU2 is unknown. There has to be good hydraulic connections between proposed injection wells and recovery wells and the ability to maintain hydraulic control between the injection and recovery wells is essential.

Furthermore, the challenges of working in fractured bedrock in terms of predicting and managing subsurface distribution and recovery of injected fluids are many. As with all in situ injections, for treatment to be effective, the injected surfactant slurry needs to make contact with COCs.

High capital costs (associated with shipping to the USVI) and moderate O&M costs are anticipated. Surfactant flushing has been retained for further evaluation as a remedial enhancement to groundwater extraction and treatment.

7.1.7 Ex Situ Treatment

7.1.7.1 Vapor Phase Activated Carbon Adsorption

Carbon adsorption can be used to treat vapor phase contamination. The contaminated effluent from an SVE, air stripper vapor discharge or thermal treatment system is drawn through vessel(s) containing GAC to which contaminants are adsorbed and are, thereby, removed from the waste stream. When the concentration of contaminants in the effluent exceeds a breakthrough concentration, the GAC is removed for regeneration or disposal. Carbon adsorption can effectively treat TCE and PCE. Since carbon adsorption is not effective in removing vinyl chloride, potassium permanganate will be used as a polisher before off gas discharge. Activated carbon

adsorption is implementable and a proven technology. The equipment and materials are readily available. This technology involves moderate capital and moderate O&M costs. This process option has been retained for further analysis.

7.1.7.2 Air Stripping

Air stripping is a physical mass transfer process that uses clean air to remove dissolved VOCs from water by increasing the surface area of the groundwater exposed to air. Commonly used systems include the countercurrent packed column, multiple chamber fine bubble aeration systems, venturi systems, and low-profile sieve tray air strippers. In a countercurrent packed column, contaminated groundwater is sprayed through nozzles at the top of the column, flowing downward through packing materials. In a low-profile sieve tray air stripper, contaminated groundwater flows across the surface of a series of perforated trays. In both systems, clean air is forced into the system by a blower in a direction opposite to groundwater flow (e.g., from the bottom, flowing upward). In a multiple chamber fine bubble aeration system, contaminated groundwater flows through aeration tank chambers, and air is introduced at the bottom of each chamber through diffusers forming thousands of fine bubbles. As the fine air bubbles travel upward through the water, mass transfer occurs at the bubble/water interface. System efficiency increases with decreasing bubble diameters.

Air stripping would be effective in removing volatile contaminants from water. Air stripping is proven to successfully remove TCE and PCE from water, because of its high Henry's law constant. Most other contaminants have a moderate to high ease of stripping. Contaminants extracted from the treatment areas could be effectively treated.

Air stripping is implementable. Vendors and equipment are readily available to provide air strippers for groundwater VOC removal. It would be implemented as a treatment method with groundwater extraction and discharge. Air stripping has low capital and low O&M costs. This process option has been retained for further consideration.

7.1.8 Discharge/Disposal

Once groundwater has been treated, it will be discharged on site or off site. Potential on site and off-site discharge options for groundwater are evaluated below.

7.1.8.1 On Site Injection

This on-site discharge technology involves injecting treated groundwater to the subsurface using a series of wells. Injection requires that the groundwater be treated to meet applicable groundwater standards prior to disposal to the subsurface.

The effectiveness of this option relies on proper injection well design and construction, including adequate pipe sizing, proper placement of the wells, and reliable construction materials.

To discharge treated effluent to a series of injection wells will be easily and readily implementable, given that standard construction methods and materials will be utilized. Installation of injection

wells downgradient from the Curriculum Center property will raise the water table thereby creating a hydraulic barrier as a means of containment, and will also increase the yield of the aquifer, and potentially maintain water balance. Some implementability problems can arise during long term operation of injection wells, such as clogging of screen packs with precipitates or microbial fouling, particularly in high iron conditions. These can be overcome by proper removal of suspended solids and excess iron from the treated water, periodic chlorination of the injected water, and redevelopment and cycling on/off of wells.

This process option involves moderate capital and moderate O&M costs. This process option has been retained for further consideration.

7.1.8.2 Surface Water Discharge

Treated groundwater can be discharged to a surface water body such as a nearby pond or stream. Disposal to an off-site surface water body requires that the extracted groundwater be treated to meet applicable surface water discharge standards.

Discharge to an off-site surface water body will be an effective method for disposal of treated groundwater. This technology will be implemented at Turpentine Run via the existing outfall. A discharge monitoring program will be required to verify compliance with DPNR.

Discharge involves low capital and low O&M costs. Surface water discharge of treated groundwater has been retained for further consideration.

8 Development of Remedial Action Alternatives

8.1 Description of Groundwater Alternatives

Preliminary groundwater remedial alternatives for OU2 have been developed by combining the remedial technologies and process options that have successfully passed the screening stage into a range of alternatives. Each alternative presented below considers the effectiveness, implementability, and cost. The costs presented in this 2021 Revised Final Feasibility Study Report have been updated to reflect increased prices from the 2018 Final Feasibility Study submission. Detailed alternative evaluation, cost analysis, and comparison will be provided in Section 9.

Groundwater remedial treatment technologies were screened according to applicability, effectiveness, reduction in toxicity, mobility, or volume of contaminants and implementability in the deep fractured bedrock aquifer at OU2. Remedial alternatives for OU2 were developed based on the retained technologies and site-specific conditions as described above.

The technologies and groundwater process options retained for further analyses include:

- No Action
- Groundwater Pump and Treat with Discharge
 - o Adsorption
 - o Air Stripping
 - o ReInjection
- Enhancements:
 - Air Sparging and Soil Vapor Extraction
 - In Situ Chemical Oxidation
 - Dual Phase Extraction
 - In Situ Co-solvent/Surfactant Flushing
- In Situ Thermal Treatment
- In Situ Steam Injection

Although not retained as a separate process option, LTM/ICs will be included for use in conjunction with, or as enhancements, contingency remedies, or alternative remedies to the other remedial process options. In addition to the various process options, alternatives were assembled to address the most significant source area and provide containment to mitigate further migration of contaminated groundwater.

The range of process options that meet the RAOs based on the screening results are summarized in **Table 7-1**. Based on the screening of remedial technologies and process options in Sections 6

and 7, the following remedial alternatives have been developed and are described in detail in the following subsections:

- 1 - No Action
- 2 - Expand Existing Pump and Treat System
 - 2A - Reinjection
 - 2B - AS/SVE
 - 2C - In Situ Chemical Oxidation
 - 2D - In Situ Surfactant Flushing
- 3 - In Situ Thermal Treatment and Pump and Treat
- 4 - In Situ Steam Injection and Pump and Treat

8.1.1 Alternative 1 – No Action

The No Action alternative is required by the NCP to be carried through the screening process. Under this alternative, no action will be taken to remediate the contaminated groundwater. This alternative will also not involve ICs. Contaminants present in the groundwater will remain in place.

The No Action alternative provides a baseline for comparison with other active remedial alternatives. Because no remedial activities would be implemented under the No Action alternative, long term human health and environmental risks would remain the same as those identified in the HHRA except for any changes due to incidental natural attenuation. There are no capital, operations/maintenance, or monitoring costs, no permitting or institutional legal restrictions needed, but this alternative will not meet any of the RAOs for groundwater.

8.1.2 Common Components of Alternatives 2 through 4

Alternatives 2 through 4 each include an active remedy, followed by the use of ICs and LTM. Alternatives 2 through 4 each include upgrades to the existing pump and treat system at the Curriculum Center. The current pump and treat system will need to be evaluated for such upgrades prior to implementing any other technology for each of the Alternatives 2 through 4. The alternatives are discussed in greater detail below.

8.1.2.1 ICs/LTM

Modeling was performed to simulate the fate and transport of PCE in fractured bedrock where matrix diffusion plays a role in attenuating the contaminants life in the system after the source has been removed. Although the concentration of cis-1,2 DCE was higher than the PCE concentration in the sample from RD-9, PCE was the more conservative choice to estimate cleanup timeframe for the following reasons:

1. PCE degrades more slowly and is present at a higher concentration than cis-1,2-DCE at the property boundary. Using OU2-MW3 to approximate concentrations at the property boundary, cis-1,2-DCE is 1,700 µg/l and PCE is 3,500 µg/l. The higher PCE concentration at the property boundary (the point we are modeling to) makes PCE the more conservative analyte for the analysis.
2. PCE is the parent compound and no new mass is added as it migrates downgradient. Therefore, its degradation is consistent with the first-order decay constant used in the model. As a daughter product, cis-1,2-DCE mass is generated by the degradation of TCE as the plume migrates downgradient. Its mass is in a state of flux that is not approximated by a first-order decay constant. Simulating the decay of a daughter product such as cis-1,2 DCE would require a more sophisticated modeling effort than the parent, PCE.

A summary of the matrix back-diffusion findings is provided in Appendix B. Results of the matrix diffusion modeling indicate concentrations at the property boundary are predicted to drop below the MCL within about 25 years after complete source removal.

The groundwater at OU2 is not used as a source of drinking water.

Because of contaminated groundwater, well drilling restrictions would be placed on OU2 to restrict future intrusive activities that would expose users to contaminants at levels that may pose human health risk. These controls do not reduce the subsurface contamination or promote restoration of the resource, but instead provide notice to future residents and workers of current conditions and provide safeguards against accidental exposure. In accordance with Title 12, Chapter 5, Virgin Islands Code, the DPNR requires any well other than a public water supply well (which are regulated by DPNR) to obtain a groundwater appropriation permit equivalent/ well drilling permit equivalent before withdrawing water from anywhere in the Virgin Islands.

LTM involves monitoring over time for OU2 COCs to confirm progress in contaminant reduction to achieve RAOs. It may also be considered for implementation in areas of existing lower-level contamination that cannot be cost-effectively remediated with the selected active remediation technology and where doing so maintains the protectiveness of the remedy.

Groundwater monitoring will consist of a network of wells located within and downgradient of OU2. It is assumed that the existing monitoring well network at OU2 will be sufficient for LTM purposes. The selection of specific wells will depend on the selected alternative for OU2; the well selection will be made during the RD phase of the project and as determined necessary during implementation, based on reviews of the remedy's effectiveness.

The effectiveness of both ICs and LTM will be assessed over the course of the site remedial activity. Performance monitoring of the ICs and natural attenuation will support decisions regarding: continuation and/or revisions to the monitoring program or ICs; the need to implement contingency/alternative remedy options; and/or verification that remedial goals have been met, followed by termination of performance monitoring. Site-specific criteria are to be developed to define triggers for these decisions.

Monitoring program changes will be considered should contaminant concentrations increase or spread to new locations (e.g., via mobilization of contaminants in a different direction or along preferential flow paths in the deep bedrock aquifer). Once OU2 remedial goals are met, the necessary duration of verification monitoring will be decided.

The FS evaluation of alternatives assumes land and groundwater use in the OU2 area remains the same over the foreseeable future. Should LTM be less effective than needed to protect public health and the environment, remedies relying upon LTM outside of the active remediation area may incorporate a contingency remedy. Alternative remedies will be considered if the current remedy fails to perform as anticipated. Criteria for determining when a contingency or alternative remedy is invoked are part of the remedial decision process; specific criteria based on OU2's RAOs will trigger implementation of a contingency or alternative remedy (EPA, 1998d).

Five Year Review

The primary goal of Alternatives 2 through 4 is to decrease DNAPL mass and dissolved phase contamination at OU2. A review of site conditions would be conducted every five years using data collected through the long-term inspection and maintenance program to determine the effectiveness of the remedy.

8.1.2.2 Pre-Design Investigation

Assumptions have been made in the FS for areas that were not fully investigated during the RI, specifically, beneath the northern portion of the Curriculum Center building. Additional borings will be required to verify FS assumptions, address data gaps and obtain design parameters for the completion of an RD at OU2. All the alternatives except for Alternative 1 will include a PDI. A PDI would typically include groundwater screening, well installation and sampling. As feasible, additional sampling beneath the Curriculum Center building is recommended. Sample results from the PDI will be compared to PRGs to better define the extents of remediation and volumes needing treatment. The below paragraphs provide a conceptual framework of PDI work that may be conducted.

A total of five temporary 2-inch PVC groundwater monitoring points are assumed to be installed inside the Curriculum Center building during the PDI to varying depths from surface up to 140 feet bgs, and groundwater samples will be collected at depths for which analytical data is currently not available. For purposes of this FS, it was estimated that groundwater screening samples will be collected at five ft intervals for a total of 140 groundwater samples and sent for laboratory analysis during the PDI. It is assumed that the current monitoring well network at OU2 will be sufficient to monitor remedial progress. For purposes of this FS, it was estimated that groundwater samples will be collected from 30 monitoring wells during the PDI to serve as a baseline. The actual number of samples and monitoring wells will be determined during the RD.

A more detailed groundwater investigation may be required to refine the hydrogeologic understanding of OU2 based on current data. Additional testing including pump tests is recommended during the PDI to estimate the capture zone of the extraction system at full capacity

of the treatment facility. It is assumed that pump tests will include at a minimum, a video survey followed by step-drawdown testing. Except for Alternative 3, for costing purposes, it is assumed that all three existing extraction wells (RW-6, RW-7, and RW-9) will be redeveloped using a combination of mechanical methods and chemical treatment to return the wells as close to the original operating conditions as possible. An evaluation of the existing treatment system will be conducted during the PDI to determine the necessary improvements to upgrade the treatment capacity as described in Alternatives 2 through 4.

8.1.3 Alternative 2 – Expand Existing Pump and Treat System

The existing OU1 pump and treat system at the Curriculum Center consists of three 6-inch diameter extraction wells; RW-6, RW-7, and RW-9. The system is running on “Constant Head” mode that allows the programmable logic controller (PLC) to adjust the pumping rates and maintain a pre-set water level in the area. Following storm events, the system operates at a higher rate to maintain the set water level and during dry periods runs at lower rates. The flow rate fluctuates from 10 to 12 gpm and the average is 11 gpm (Arrowhead 2017).

Alternative 2 includes expanding the current system by the addition of new extraction wells downgradient from the Curriculum Center. The addition of extraction wells downgradient will allow for more flexibility in containing the plume as it moves away from the source area. Alternative 2 also includes upgrading the current system designed for a maximum flow rate of 60 gpm to a capacity of 100 gpm. It is estimated that operating the system at a “Flow Control” mode of a total flow rate of 100 gpm will establish hydraulic control and capture the deep bedrock groundwater at OU2. “Flow Control” mode allows the system to run continuously at a steady flow which will lower the water table and expand the hydraulic containment. This hydraulic containment will limit or prevent the downgradient migration of contaminants from the Curriculum Center.

The following design details are for FS cost estimating purposes and will be refined further during the PDI and RD phases. For cost estimating purposes, it is assumed that two new extraction wells will be installed. Additional testing including pump tests will be performed during the PDI to estimate capture zone of the extraction system at full capacity of the treatment facility. The actual remedial pumping rates for the extraction wells will be optimized based on the results of the pump test and a comprehensive groundwater flow calculation of OU2.

- A minimum of two bedrock extraction wells (RW-10 and RW-11) are assumed to be installed downgradient from the existing recovery wells (as shown on **Figure 8-1**).
 - o The new extraction wells will be installed in the vicinity of MW-1D to a target depth of approximately 140 ft bgs and will be open borehole construction from surface to 140 ft bgs. The extraction well depth is estimated based on the geophysical and hydrogeological data collected during the RI and will be further refined as part of the PDI.
 - o The extraction wells will be open across both the shallow and deep zones to combine the objectives of hydraulic capture and remediation of contamination that

has migrated into the deep zone. Pumping from the more conductive shallow zone also needs to be included to have a chance of achieving plume capture in this area.

- o It is assumed that at least three of the five (three existing plus two new) extraction wells will be operating at a given time in order to achieve complete plume control.
- All existing treatment equipment will be replaced with newer, more efficient equipment to accommodate the additional flow. It is assumed that equipment such as and not limited to the recovery well pumps, transfer pumps, the air stripper and blower, chemical feed metering and tank, flow meters, bag filters, heat exchanger, granular activated carbon vessels, and potassium permanganate vessels will be replaced. A process flow diagram of the treatment process is provided in **Figure 8-2**.
- The main control panel which includes the PLC, a flat-screen display Operator Interface Terminal (OIT), pump controllers, and an auto dialer will be upgraded.
- The above ground conveyance system including piping, valves, and flowmeters, within the facility from each of the extraction wells will be upgraded on as needed basis to accommodate the higher capacity.
- The current 1,000-gallon equalization tank will be replaced with a similar capacity tank that is designed for flow equalization in addition to DNAPL recovery and removal. The DNAPL that is collected at the bottom of the recovery tank will be removed and disposed at a licensed waste disposal facility.

Alternate Pumping

Alternative 2 will include alternate pumping from existing monitoring wells with high contaminant concentrations. It is assumed that the source area wells will include OU2-MW3, RD-9, OU2-MW6, OU2-MW2, IW-1, IW-2, and OU2-MD1. The well selection will be made during the RD phase. It is assumed that a small pump connected to a flexible HDPE line will be placed inside each of these monitoring wells and groundwater will be pumped into the DNAPL recovery tank, treated through the existing treatment system as described above, and then discharged at the existing outfall in accordance with the TPDES permit equivalency. For cost estimating purposes, it is assumed that this will be done in sequence at each well for a total estimated duration of one week per event.

DPE/EFR

Alternative 2 will include DPE/EFR from existing monitoring wells with high contaminant concentrations.

A pilot study will be conducted to obtain design parameters for the EFR including but not limited to, radius of influence (ROI), number of wells, wellhead vacuum, extraction flow rate, discharge limitations and off gas treatment requirements, if any.

The details of the DPE/EFR alternative described below are preliminary, for cost estimating purposes, and are subject to change based on the pilot study results. The DPE/EFR is a portable system that will extract groundwater from designated monitoring wells that are present in source areas at the Curriculum Center (**Figure 8-1**). It is assumed that the source area wells will include OU2-MW3, RD-9, OU2-MW6, OU2-MW2, IW-1, IW-2, and OU2-MD1. The actual number of EFR wells will be better determined during the design and remedial action phases.

Since the EFR is a portable system, no above ground piping will need to be installed. If the pilot study results indicate that the EFR is successful at the site, a cover will be installed in the vicinity of the wells that are outside the Curriculum Center building footprint. For cost estimating purposes, it is assumed that a 15-mil geomembrane liner with soil cover on top will be installed. The purpose of such a cover is to prevent surface water infiltration that can reduce air flow rates, reduce emissions of fugitive vapors, and prevent vertical short-circuiting of air flow. It is also assumed that OU2 would be inspected during each EFR event to evaluate the integrity of the cover. If damage in the cover is observed, repairs will be performed. These costs are considered as operational costs and are included as such in the cost estimates.

The well head of each extraction point/monitoring well will be sealed, and a DPE mobile system will be used to apply a high vacuum to each well in order to remove contaminated groundwater/DNAPL from source areas. The recovered contaminated liquid will be treated through the existing pump and treat system and then discharged at the outfall in accordance with the TPDES permit equivalency. At a minimum, the DPE system will include a vacuum blower, knockout tank, air filters and silencers, flow meters, transfer pump and a control panel. For cost estimating purposes, it is assumed that DPE/EFR events will be twice a year at each well, for a period of five years. The frequency of the events will be refined during the RD. For cost estimating purposes, it is assumed that vapor and liquid samples will be collected from each EFR well twice a year for five years and analyzed for VOCs to monitor off-gas concentrations and the effectiveness of the EFR.

LTM and ICs

To confirm that the groundwater pump and treat system is achieving remedial objectives, groundwater samples will be collected from OU2 monitoring wells and analyzed for VOCs. The results of these analyses will be used to determine whether remedial action objectives are being satisfied, and whether changes in the system design, configuration, and operation are required. The monitoring wells will be selected during the RD phase.

Based on calculations, it is estimated that clean up time for OU2 using groundwater pump and treat will be in excess of 30 years. For cost estimating purposes, it is assumed that groundwater pump and treat will be active for a period of 30 years. The success of the remedy in meeting the RAOs will be evaluated with the 5-Year reviews.

LTM and ICs will be required because contamination greater than the Federal MCLs may remain within the OU2 plume under this alternative due to the presence of DNAPL. LTM will be conducted

on a periodic basis to determine if remedial objectives are being met. For cost estimating, it was assumed that LTM will be conducted annually for 30 years.

8.1.3.1 Alternative Enhancement 2A – Reinjection

Alternative Enhancement 2A - Reinjection includes enhancing the existing pump and treat system as described earlier in Alternative 2 with reinjection of the treated groundwater downgradient from the Curriculum Center. This section includes only the description and assumptions for adding the reinjection option to alternative 2.

Under Alternative Enhancement 2A, the treated effluent from the GWTF will be reinjected downgradient from the Curriculum Center to potentially act as a hydraulic barrier to off-site migration of the contamination.

For cost estimating purposes, it is assumed that two injection wells (IW-3 and IW-4) will be installed as shown on **(Figure 8-3)**. Each borehole will be open hole. These preliminary locations were selected because they are downgradient of existing and proposed extraction wells and along major fracture/weathered zone trends identified during the FSRI. There appears to be approximately 30 feet of freeboard between the groundwater table and the ground surface in the area of the proposed injection wells. The increase in head associated with the injection of groundwater will be greater than the corresponding drawdown resulting from the extraction of groundwater because it is more difficult to displace water in the aquifer than to remove it. Both head increase and short circuiting will need to be considered during the PDI in the fractured rock setting at OU2. Injection wells will undergo separate injection tests to determine the actual degree of head increase at the injection well and in surrounding monitoring wells. The number and location of the injection wells will be refined during the PDI.

For cost estimating purposes, it is assumed that the pump and treat system with reinjection will be active for a period of 30 years. Alternative Enhancement 2A using reinjection will not reduce the remedial timeframe; however, reinjection of groundwater downgradient will help maintain water balance.

8.1.3.2 Alternative Enhancement 2B –AS/SVE

Alternative Enhancement 2B includes enhancing the existing pump and treat system as described earlier in Alternative 2 with air sparging/SVE in source areas. This section includes only the description and assumptions for adding AS/SVE option to Alternative 2.

Alternative Enhancement 2B will include air sparging in combination with SVE at the potential source areas, including the area beneath the northern portion of the building in order to help mobilize residual DNAPL within the zone influenced by air sparging and thereby reduce the remedial timeframe of the groundwater extraction and treatment system.

A PDI will be conducted as discussed in Section 8.1.2 to address data gaps that are necessary to complete the RD and to obtain design parameters (power needs, air flow rates, and vacuum pressures) for a full-scale application.

The AS/SVE system will consist of a network of air injection or sparging wells installed into the groundwater and a network of vapor extraction wells installed into the vadose zone (comprised primarily of fractured bedrock). An air compressor or blower will be used to deliver a stream of air under pressure to the subsurface via the sparging well, and vacuum pumps or blowers will be utilized for the removal of contaminants in the vapor phase through the vacuum extraction well. VOCs in the vapor phase are collected from each vacuum extraction well and pumped via a vacuum extraction blower to a treatment system. It is assumed that the upgraded off-gas treatment system that is part of the groundwater treatment facility will be utilized to treat the vapor phase. For the purposes of evaluation, comparison, and costing in the FS, vertical extraction wells are used as the representative process option.

The potential source areas include a portion of the contaminated plume in the rear of the Curriculum Center which is unpaved and a portion of the contaminated plume underneath a slab on-grade building which acts as a cap. The existing building cap will improve the effectiveness of the SVE system under the building by minimizing short circuiting of air flow from the ground surface. For areas outside the building footprint, it is assumed that a new cover will be installed. For cost estimating purposes, it is assumed that a 15-mil geomembrane liner with soil cover on top will be installed in the rear of the Curriculum Center property. The purpose of such a cover is to prevent surface water infiltration that can reduce air flow rates, reduce emissions of fugitive vapors, and prevent vertical short-circuiting of air flow. It is also assumed that OU2 will be inspected annually to evaluate the integrity of the cover. If damage in the cover is observed, repairs will be made. These costs are considered as operational costs and are included as such in the cost estimates.

For the purpose of this FS, a preliminary assessment of the AS/SVE system configuration, ROI, and air flow rates have been made based on a typical application and available site geology and hydrogeology data.

The SVE system will be sized to maintain a vacuum over the approximately 56,960 square feet of area which includes the potential source areas and the northern portion of the Curriculum Center building as shown on **Figure 8-4**. As shown in **Figure 8-4**, approximately 25 vacuum extraction wells will be installed at the Curriculum Center. Each vacuum extraction well will be flush mounted with the existing ground surface. Based on the RI data, depth to water is expected from 15 to 30 feet bgs. For FS costing purposes, an average depth to water of 23 feet bgs has been assumed. Each SVE well will be installed to a depth of approximately 15 feet bgs. The extraction wells will be screened from surface to 15 feet bgs. Based on historical SVE data for the Curriculum Center, each well is expected to have an ROI of approximately 80 feet. However, pilot testing and field measurements in the pre-design phase of the work will determine the number of vacuum extraction points, placement, and depth of each well. All conveyance piping will be installed below grade and used to connect the wells to a centrally located blower/treatment

system. A vacuum will be generated by a blower and collected vapor will be treated via GAC and potassium permanganate units.

A conceptual design includes approximately 30 AS wells at the Curriculum Center as shown in **Figure 8-4**. The AS wells will be placed in the saturated zone to a depth of approximately 140 feet bgs. The total number of AS wells was determined based on an assumed ROI of approximately 50 feet in each sparge well. However, pilot testing and field measurements in the pre-design phase of the work will determine the number of air sparge wells, placement, and depth of each well.

For cost estimating purposes, GAC and potassium permanganate is assumed as the vapor phase treatment option for the treatment system. At the treatment area, the collected vapors containing VOCs are passed through the treatment media, adsorbed, and the clean air is vented to the atmosphere. Air emissions must meet local emission requirements. High relative humidity of the treated vapor (i.e., above about 50%) reduces the adsorption efficiency of the treatment media. In addition, moisture and condensate can accumulate within the vapor extraction piping. To address these issues, vacuum extraction blowers will be specified so that sufficient heat is imparted to the vapor stream and the relative humidity is maintained within satisfactory limits. When the media is spent (i.e., saturated with VOCs), it will be transported off-site and replaced with fresh material. For cost estimating purposes, it is assumed that replacement of the treatment media will be required once a year depending on actual mass removal rates achieved. The ultimate configuration of the entire vapor recovery/treatment system, including treatment media usage rates over time, will be based on the results from the pilot study. Air monitoring and inspection of the vapor treatment system after startup may also determine system requirements.

A typical AS/SVE Process Schematic is shown on **Figure 8-5**. The treatment facility at the Curriculum Center will house the blowers, air compressors, moisture separators, controls, and vapor treatment units. It is assumed that the GAC/permanganate vapor treatment vessels that are part of the groundwater extraction and treatment system will be utilized to treat the SVE offgas. O&M costs are assumed to include electricity to operate the system; periodic repair and replacement of system parts and components; routine inspection; system monitoring; replacement of treatment media; and performance and compliance sampling. These assumptions will be refined further during the RD.

It is estimated that trenching will be required for the installation of the AS/SVE piping system. It is assumed that the AS and SVE piping will be placed within the same trench. It is estimated that soil will be excavated for trenching and require off-site disposal from the installation of the AS/SVE system. It is assumed that any nonhazardous soil that is excavated from within the trench will be reused as backfill.

An initial five years of AS/SVE is proposed. Based on calculations, it is estimated that clean up time for OU2 after complete source removal concentrations, will be within about 25 years. For cost estimating purposes, it is therefore assumed that the remedial system will be active for a period of 30 years.

8.1.3.3 Alternative Enhancement 2C –In Situ Chemical Oxidation

Alternative Enhancement 2C includes enhancing the existing pump and treat system as described earlier in Alternative 2 with ISCO treatment at the potential source areas as an enhancement. This section includes only the description and assumptions for adding ISCO option to Alternative 2.

Strong oxidizing agents will be delivered to existing monitoring wells within the potential source areas via slow-release cylinders or comparable delivery method. ISCO cylinders composed of 38% potassium permanganate and 38% sodium persulfate and 24% paraffin wax, or comparable oxidants would be used to reduce the source area concentrations in select monitoring wells. For the purposes of this FS, it is assumed that the cylinders will be stacked vertically within the monitoring well. Stacking the cylinders within the borehole helps ensure that the oxidant is covering the transmissive fractures where the contaminated mass is located.

Contaminants and oxidants will tend to migrate from injection wells toward extraction wells associated with the pump and treat system. This process could potentially enhance the distribution of oxidants across the source zone. The pump and treat system will maintain hydraulic control of the dissolved-phase plume emanating from the source.

For cost estimating purposes, it is assumed that approximately 64 cylinders will be deployed in a total of 12 monitoring wells in the potential source areas as shown on **Figure 8-6**. The ROI for each monitoring well is dependent on the groundwater velocity in each well and will be estimated during the PDI. However, since the ISCO component is being used as an enhancement to groundwater extraction and treatment, and no new wells injection wells are being installed, the determining the actual ROI is less critical than in other ISCO applications. A pilot study would be conducted prior to RD to confirm a suitable site-specific oxidant and to obtain site-specific engineering parameters, such as effective porosity, ROI, and dosage. A typical ISCO Cylinder Schematic is shown on **Figure 8-7**

The slow-release cylinders will provide sustained oxidant delivery to the treatment area over an estimated 6 to 9-month time frame before the oxidant is completely exhausted. The cylinders will be removed and replaced after twelve months and annual site-wide groundwater samples will be collected to evaluate the effectiveness of the treatment.

For cost estimating purposes, an initial five years of ISCO treatment is proposed before evaluating if further source area treatment is necessary. Based on calculations, it is estimated that clean up time for OU2 after complete source removal concentrations, will be within about 25 years. For cost estimating purposes, it is assumed that the remedial system will be active for a period of 30 years in order to capture contaminated groundwater beyond the active treatment source areas.

8.1.3.4 Alternative Enhancement 2D –Surfactant Flushing

Alternative Enhancement 2D includes enhancing the existing pump and treat system as described earlier in Alternative 2 with in situ flushing of fractures with surfactants at the potential source

areas as an enhancement. This section includes only the description and assumptions for adding surfactant flushing option to Alternative 2.

For purposes of this FS, it is assumed that a 4% surfactant solution will be injected in the vicinity of select monitoring wells within the potential source areas via injection wells as shown on **Figure 8-8**. Groundwater will be extracted by the recovery wells, treated and then discharged via the existing outfall. Since the treatment system at the GWTF consists of an air stripper, anti-foaming agents will also be introduced with the recovered water to prevent foaming the air stripper during the stripping process.

A PDI would be conducted as described in Section 8.1.1 to address data gaps that are necessary to complete the RD. The final remedial action implementation strategy will be developed during the design. The ROI for each injection well is dependent on the groundwater velocity in each well and will be estimated during the PDI. A pilot study would be conducted prior to RD to confirm a suitable site-specific amendment and to obtain site-specific engineering parameters, such as effective porosity, ROI, dosage, and frequency of injections.

Injection wells would be considered for delivery of surfactant into the treatment area. The thickness of the treatment zone is assumed to be from surface to 140 feet bgs. For cost estimating purposes, injections will be performed to target the shallow (<90 feet bgs) and deep zones (90 to 140 feet bgs).

A total of seven injection wells are estimated to be installed at OU2 as shown on **Figure 8-8**. It is assumed that injection wells will be installed in the vicinity of monitoring wells with high source area concentrations. For cost estimating purposes, it is assumed that a total of two deep injection wells will be installed; one in the vicinity of OU2-MW3 and the other in the vicinity of RD-9. It is estimated that approximately 4,500 gallons of surfactant solution will be injected per injection point. For cost estimating purposes, it is assumed that a total of five shallow injection wells will be installed in the vicinity of monitoring wells IW-1, IW-2, OU2-MW2, OU2-MW6, and OU2-MD2. It is estimated that approximately 8,500 gallons of surfactant solution will be injected per injection point. Based on the PDI results, the injection point layout and quantities will be adjusted to bias high in areas with high contaminant concentrations.

Extraction wells are required to maintain hydraulic control, bring emulsified/dissolved DNAPL to the surface for treatment and to clear the aquifer of surfactant solution. It is assumed that the upgraded pump and treat system with source area recovery wells and downgradient recovery wells will be used.

Site-specific hydrogeological parameters will be collected during the PDI. A permanent monitoring well network described in Section 8.2.1 would be used to monitor remedial progress. The actual selection of the surfactant(s) and layout of the pilot study would be developed during the design stage. It should be noted that selection of the surfactant should also include the use of an anti-foaming agent to avoid foaming when the extracted groundwater is treated in the air stripper. The final recommended surfactant(s) for the remedial action would be selected during the RD.

Due to challenges associated with surfactant flushing in a bedrock aquifer, it is assumed that surfactant flushing will be performed in source areas for one year. For cost estimating purposes two rounds of injections are assumed. It is assumed that an equivalent volume of treated water will be injected after the second event in order to clear the area immediately around the well of surfactant, pushing the solution into the formation where it can be used for flushing. Based on the results of the LTM, it will be determined if additional rounds are required and if the remedy is deemed to be effective, additional treatment areas may also be considered.

Based on calculations, it is estimated that clean up time for OU2 after complete source removal concentrations, will be within about 25 years. For cost estimating purposes, it is assumed that the remedial system will be active for a period of 26 years in order to capture contaminated groundwater beyond the active treatment source areas.

8.1.4 Alternative 3 – In-Situ Thermal Treatment and Pump and Treat

Alternative 3 primarily includes in situ thermal treatment in source areas with downgradient pump and treat for hydraulic control and includes the following individual components:

- In situ thermal treatment at source areas;
- Install new extraction wells downgradient and connect to the existing system;
 - o Increase the capacity of the treatment system to ensure full capture and operate the pump and treat system with downgradient extraction wells for hydraulic control during treatment;
 - o Perform system upgrades as discussed in Alternative 2-Replace all existing treatment equipment and conveyance piping.

In Situ Thermal Treatment

Alternative 3 will include ISTT to target the DNAPL in potential source areas at OU2 and thereby reduce the high dissolved contaminant concentrations in the groundwater. Alternative 3 also includes operating the extraction and treatment system with downgradient extraction wells to maintain hydraulic control of the dissolved outside the immediate source area that will be thermally treated. For purposes of this FS, TCH is assumed as the representative process option and is likely to be more effective in a bedrock aquifer.

The ISTT proposed for OU2 consists of in situ bedrock heating to provide significant mass reduction (>99%) of CVOCs and DNAPL in groundwater within the fractured bedrock of the potential source areas with a time frame of approximately two years. ISTT produces uniform heating of the rock matrix and has demonstrable success remediating CVOCs and DNAPL in fractured bedrock. The ISTT will essentially be a combination of two processes: thermal conductive heating and vacuum extraction (i.e., SVE). A PDI would be conducted as described in Section 8.1.1 to address data gaps that are necessary to complete the RD.

Heat causes the underground contaminants, DNAPL and water to boil, creating in situ steam and vapor. Contaminated vapor and steam are extracted using vacuum recovery wells and treated above ground. The heater wells will be co-located with the recovery wells. Each recovery well is connected to the conveyance pipe that routes the steam and vapors to the condenser. All conveyance piping and cable will be above grade.

For the purpose of this FS, an estimated 260 to 270 heater wells, co-located with 260 to 270 vacuum extraction points are proposed to treat groundwater within approximately 56,960 square feet area at OU2. This includes the area beneath the northern portion of the Curriculum Center building and the potential source areas. PDI results will be used to further refine the treatment boundary and optimize the number and location of the heater wells. A conceptual layout of the heating and recovery wells for the TCH system is shown on **Figure 8-9**.

Each heater well boring is assumed to be installed vertically from 1 to 140 feet bgs within the bedrock. The final method of installation will be determined during the PDI and RD phases. The conduction heating elements will be installed within a metal casing inside each boring. Vapor recovery wells will be co-located with the heater wells to recover vapors within the portion of the vadose zone that is not bedrock. The average distance between heater wells will be approximately 17 feet. Temperature monitoring points (TMPs) are installed to monitor the subsurface temperature data continuously. For cost estimating purposes, a total of 15 TMPs will be installed to monitor the temperature. Pilot testing during the PDI phase of the work will determine the exact number, placement, and depth of each heating and vacuum extraction well.

Surface piping will connect the recovery wells to a centrally located treatment system. It is estimated that two vacuum recovery blowers will operate and collected vapor will be treated via the offgas treatment system. Steam would be collected, condensed and treated. A schematic of a typical TCH system with vacuum extraction is shown in **Figure 8-10**.

A temporary building or treatment trailer will be constructed to house the treatment equipment. It is currently assumed that the treatment building/trailer will be constructed in the vicinity of the GWTF at the Curriculum Center. The exact location of the treatment building will be confirmed during the design stage.

System monitoring can be performed remotely. O&M costs are assumed to include electricity to operate the system, repair and replacement of system parts/components, routine inspection, performance monitoring, compliance sampling and replacement of GAC units.

It is anticipated that active thermal treatment will be on the order of two years. During this time, the pump and treat system will remain operational in order to maintain hydraulic control of the downgradient dissolved plume.

Operation of the Treatment System

Alternative 3 includes the addition of new extraction wells downgradient from the Curriculum Center to provide hydraulic control. Under this alternative, only the downgradient extraction wells

will be operating in order to maintain hydraulic control during in situ thermal treatment at the source areas. The addition of extraction wells downgradient will allow for more flexibility in controlling the plume as it moves away from the source area. Alternative 3 also includes upgrading the current system to a capacity of 100 gpm. It is estimated that operating the system at a total flow rate of 100 gpm will establish hydraulic control and capture the deep bedrock groundwater at OU2. This hydraulic containment will limit or prevent the downgradient migration of contaminants from the Curriculum Center.

Under Alternative 3, a minimum of two bedrock extraction wells (RW-10 and RW-11) are assumed to be installed downgradient from the existing recovery wells (as shown on **Figure 8-9**). The new extraction wells will be installed in the vicinity of MW-1D to a target depth of approximately 140 ft. bgs and will be open borehole construction from surface to 140 ft. bgs. The extraction well depth is estimated based on the geophysical and hydrogeological data collected during the RI and will be further refined as part of the PDI.

Additional testing including pump tests will be performed during the PDI to estimate capture zone of the extraction system with the downgradient wells operating at full system capacity. The actual remedial pumping rates for the extraction wells will be optimized based on the results of the pump test and a comprehensive groundwater flow calculation of OU2.

The contaminated groundwater from each new extraction well will be pumped to the on-Site groundwater treatment system. For the purposes of this FS, it has been assumed that upgrades will be made to accommodate the additional flow rate from the new extraction wells. All treatment system upgrades will be the same as described earlier in Alternative 2.

It is estimated that contamination outside of the thermal treatment area will take 10 years to reach the perimeter pump and treat system. For cost estimating purposes, it is assumed that the remedial system will be active for a period of 12 years in order to capture contaminated groundwater beyond the active treatment source areas.

LTM and ICs

To confirm that the ISTT is achieving remedial objectives, groundwater samples will be collected from site-wide monitoring wells and analyzed for VOCs. The results of these analyses will be used to determine whether RAOs are being satisfied. The monitoring wells will be selected during the RD phase.

For cost estimating purposes, it is assumed that thermal treatment will be for a period of 2 years and the pump and treat system with the downgradient wells will be operational for a period of 12 years to capture any off-site contamination outside the footprint of the thermal treatment.

Because contamination greater than the Federal MCLs may remain within the OU2 plume outside the ISTT footprint, LTM, and ICs will be required. LTM will be conducted on a periodic basis to determine if remedial objectives are being met. For cost estimating, it was assumed that LTM will

be conducted annually for 12 years and the success of the remedy will be evaluated with 5-Year reviews.

8.1.5 Alternative 4 –In Situ Steam Injection and Pump and Treat

Alternative 4 includes in situ steam injection in potential source areas with pump and treat for collecting contaminated groundwater and steam and for hydraulic control. The major components of Alternative 4 are:

- In situ steam injection and extraction at source areas;
- Install new extraction wells downgradient and connect to the existing system;
 - o Increase the capacity of the treatment system to ensure full capture and operate the pump and treat system with downgradient extraction wells for hydraulic control during treatment;
 - o Perform system upgrades as discussed in Alternative 2; replace all existing treatment equipment and conveyance piping.

Steam Injection

Alternative 4 will include steam injection at the potential source areas to mobilize the DNAPL in bedrock fractures and to cause destruction of contaminants in potential source areas. Mobilized DNAPL will be captured by the pump and treat system at the Curriculum Center.

A PDI would be conducted as described in Section 8.1.1 to address data gaps that are necessary to complete the RD.

Steam injection could be implemented either as a batch or continuous process. For a batch process, a grid of individual/paired wells would be installed across the source area. Each well system would be used for both steam injection and dual-phase extraction. The steam injection and dual-phase extraction cycles would alternate such that steam would be injected and recovered as vapor/condensate from the same location, along with associated contaminants and displaced groundwater. For a continuous system, a grid of individual steam injection wells would be installed across the source area, and dual-phase extraction wells would be installed along its perimeter. This configuration is intended to facilitate outward, horizontal advancement of the steam front from the steam injection wells toward the dual-phased extraction wells.

For purposes of this FS, it is assumed that a continuous system will be installed. The injection wells would be screened across the low-productive zone of the aquifer (approximately 80 to 140 feet bgs). The pressure of steam injection would also mobilize, and transport contaminants vertically based upon the higher permeability of the overlying shallow zone and the enhanced upward gradient imposed on the aquifer by shallow-zone remedial pumping associated with the pump and treat system.

For the purpose of this FS, an estimated 60 steam injection wells using 45 feet well spacing are proposed to treat groundwater within approximately 56,960 square feet area at OU2. This includes the area beneath the northern portion of the Curriculum Center building and the potential source areas. For cost estimating purposes, it is assumed that approximately 10 TMPs will be installed to monitor the subsurface temperature data continuously. For the purpose of this FS, it is estimated that approximately 30 multi-phase extraction wells will be required in the source area. The existing extraction wells and some of the existing monitoring wells may be converted into steam extraction wells to reduce construction costs. A conceptual layout for the SEE system is shown on **Figure 8-11**. Pilot testing during the PDI phase of the work will determine the exact number, placement, and depth of each steam injection well and recovery well. A schematic of a typical SEE system is shown in **Figure 8-12**.

A temporary building or treatment trailer will be constructed to house the steam generation and treatment equipment. It is currently assumed that the treatment building/trailer will be constructed in the vicinity of the GWTF at the Curriculum Center. The exact location of the treatment building will be confirmed during the design stage.

System monitoring can be performed remotely. O&M costs are assumed to include heating water for production of steam, repair and replacement of system parts/components, routine inspection, performance monitoring, compliance sampling and replacement of GAC units.

It is anticipated that steam injections will be on the order of two years. During this time, the pump and treat system will remain operational in order to maintain hydraulic control of the downgradient dissolved plume.

Operation of the Treatment System

Alternative 4 includes the addition of new extraction wells downgradient from the Curriculum Center to provide hydraulic control. Under this alternative, it is assumed that the downgradient extraction wells will be operating in order to maintain hydraulic control during steam injections at the source areas. Alternative 4 also includes upgrading the current system to a capacity of 100 gpm. It is estimated that operating the system at a total flow rate of 100 gpm will establish hydraulic control and capture the deep bedrock groundwater at OU2. This hydraulic containment will limit or prevent the downgradient migration of contaminants from the Curriculum Center.

Under Alternative 4, a minimum of two bedrock extraction wells (RW-10 and RW-11) are assumed to be installed downgradient from the source areas (as shown on **Figure 8-11**). The new extraction wells will be installed in the vicinity of MW-1D to a target depth of approximately 140 ft. bgs and will be open borehole construction from surface to 140 ft. bgs. The extraction well depth is estimated based on the geophysical and hydrogeological data collected during the RI and will be further refined as part of the PDI.

Additional testing including pump tests will be performed during the PDI to estimate capture zone of the extraction system with the downgradient wells operating at full system capacity. The actual

remedial pumping rates for the extraction wells will be optimized based on the results of the pump test and a comprehensive groundwater flow calculation of OU2.

The contaminated groundwater from each new extraction well will be pumped to the on-Site groundwater treatment system. For the purposes of this FS, it has been assumed that upgrades will be made to the treatment plant to accommodate the additional flow rate from the new extraction wells. All treatment system upgrades will be the same as described earlier in Alternative 2.

Based on calculations, it is estimated that clean up time for OU2 after complete source removal concentrations, will be within about 25 years. For cost estimating purposes, it is assumed that the remedial system will be active for a period of 27 years in order to capture contaminated groundwater beyond the active treatment source areas.

LTM and ICs

To confirm that the remedy is achieving remedial objectives, groundwater samples will be collected from site-wide monitoring wells and analyzed for VOCs. The results of these analyses will be used to determine whether RAOs are being satisfied, and whether changes in the system design, configuration, and operation are required. The monitoring wells will be selected during the RD phase.

The objective of the remedy will be to attempt removal of DNAPL from the bedrock aquifer to the extent possible. The success of the remedy in removing DNAPL will be evaluated with the 5-Year reviews.

For cost estimating purposes, it is assumed that steam injections (including construction and operation) will be over a period of 2 years and the remedial system will be active for a period of 27 years to achieve RAOs.

LTM will be conducted on a periodic basis to determine if remedial objectives are being met. For cost estimating, it was assumed that LTM will be conducted annually for 27 years and the success of the remedy will be evaluated with 5-Year reviews.

9 DETAILED EVALUATION OF REMEDIAL ACTION ALTERNATIVES

This section presents the detailed evaluation of the remedial alternatives described in Section 8.0. The purpose of the evaluation is to identify the advantages and disadvantages of each alternative as well as key trade-offs among the alternatives. The detailed evaluation of alternatives consists of an individual analysis of each alternative against the evaluation criteria and a comparative analysis among the alternatives to assess the relative performance of each alternative with respect to the evaluation criteria.

9.1 Evaluation Criteria

The evaluation was based on criteria established under Interim Final Guidance for Conducting Remedial Investigations and Feasibility Studies Under CERCLA (EPA 1988b). The nine evaluation criteria have been developed to address CERCLA requirements and to address the additional technical and policy considerations that have proven to be important for selecting among remedial alternatives. The evaluation criteria are as follows:

Overall Protection of Human Health and the Environment: This criterion is an evaluation of the alternative's ability to protect public health and the environment, assessing how risks posed through each existing or potential pathway of exposure identified in the human health risk assessment are eliminated, reduced or controlled through removal, treatment, engineering controls or institutional controls. The alternative's ability to achieve each of the RAOs is evaluated.

Compliance with ARARs: This criterion evaluates how the alternative complies with the ARARs, if an ARAR waiver is required and the justification for a waiver, if needed.

Long Term Effectiveness and Permanence: Each alternative is evaluated for its long-term effectiveness after implementation. If contamination or treated residuals remain after the selected remedy has been implemented, the following items are evaluated:

- The magnitude of the remaining risks (i.e., will there be any significant threats, exposure pathways, or risks to the community and environment remaining);
- The adequacy of the engineering and institutional controls intended to mitigate the risk;
- The reliability of these controls, and
- The ability of the remedy to continue to meet RAOs in the future.

Should the results of this evaluation indicate concerns with the risks or reliability of the remedy, the utilization of technological enhancement, contingency and/or alternative remedies may need to be considered.

Reduction of Toxicity, Mobility, or Volume of Contamination through Treatment: The alternative's ability to reduce the toxicity, mobility and/or volume of site contamination is evaluated. Preference

should be given to remedies that permanently and significantly reduce the toxicity, mobility, or volume of the contamination at the site.

Short Term Impacts and Effectiveness: The potential short-term adverse impacts and risks of the remedy upon the community, workers, and the environment during the construction and/or implementation are evaluated. A discussion of how the identified potential adverse impacts to the community or workers at the site will be controlled, and the effectiveness of the controls, should be presented. A discussion of engineering controls that could be used to mitigate short term impacts (e.g., dust control measures) is provided. The length of time needed to achieve the remedial objectives is also estimated.

Implementability: The technical and administrative feasibility of implementing each alternative is evaluated for this criterion. Technical feasibility includes such things as the difficulties associated with construction and the ability to monitor the effectiveness of the remedy. For administrative feasibility, the availability of the necessary personnel and material is evaluated along with potential difficulties in for example, obtaining specific operating approvals or access for construction and implementation of the remedy.

Relative Cost: This criterion evaluates the estimated capital, operations, maintenance, and monitoring costs for each alternative. Relative costs are estimated and presented on a present worth basis.

State Acceptance: USVI/DPNR's comments, concerns and overall perception of the remedy are evaluated in a format that responds to all questions that are raised (i.e., a responsiveness summary).

Community Acceptance: The public's comments, concerns and overall perception of the remedy are evaluated in a responsiveness summary.

The eighth and ninth criteria, State and Community acceptance, will be evaluated following comment on the RI/FS report and the proposed plan and will be addressed in preparing the ROD.

9.2 Individual Analysis of Remedial Alternatives

The individual analysis of the remedial alternatives with respect to the first seven criteria is presented below. A comparative analysis of the remedial alternatives is provided within **Table 9-1**.

9.2.1 Alternative 1 - No Action

Overall Protection of Human Health and the Environment – Alternative 1 provides no control of exposure to contaminated groundwater and no reduction in risk to human health and environmental impacts. The alternative allows for the potential continued migration of contaminated groundwater downgradient and further degradation of the groundwater quality at OU2.

Compliance with ARARs – Because no action is being taken, ARARs (federal MCLs for groundwater) will not be met. Under the No Action alternative, chemical-specific ARARs would continue to be exceeded in the area being considered for active groundwater remediation.

Long Term Effectiveness and Permanence – No long-term management or controls for exposure are included in Alternative 1. Long term potential risks would remain unchanged under this alternative.

Reduction of Toxicity, Mobility, or Volume of Contamination through Treatment – Alternative 1 will provide no reduction in toxicity, mobility, or volume of the contaminated groundwater.

Short Term Impacts and Effectiveness – Alternative 1 does not result in disruption of OU2 and therefore no additional risks are posed to the community, workers, or the environment as no remedial actions will occur at OU2.

Implementability – There are no implementability concerns posed by this remedy as no remedial actions are being implemented.

Relative Cost – Because this is a no action alternative, the capital, O&M, and net present worth costs are estimated to be \$0. The estimated cost for Alternative 1 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 1 are provided in Appendix A1.

9.2.2 **Alternative 2 – Expand Existing Extraction and Treatment System**

Overall Protection of Human Health and the Environment – This alternative will be protective of human health and eventually the environment. It would also meet RAOs by preventing human exposure pathways to contaminants, minimizing the migration of contaminated groundwater, and restoring groundwater quality eventually.

The pump and treat system will capture and treat the contaminants at and downgradient from the potential source areas. Expanding the pump and treat system by installing extraction wells downgradient from the Curriculum Center will prevent groundwater from migrating further downgradient and reduce the contaminant concentrations in the area. Operating at a higher capacity will allow for complete plume capture in the horizontal direction and would remove contamination from within the existing plume. The long-term monitoring program will be used to assess the groundwater quality and the operational time frame required for the pump and treat system(s).

Compliance with ARARs – Alternative 2 is expected to achieve compliance with ARARs over time. Remedial activities for Alternative 2 will be continued until the PRGs are met. Upgrading the existing pump and treat system will enable full capture of the plume and contaminant concentrations in the groundwater are expected to decrease over time. The time frame for groundwater quality to meet PRGs at the Curriculum Center is difficult to predict due to the possibly unknown quantity of DNAPL contamination in bedrock and underneath the building. The groundwater extraction remedy on its own might be ineffective at removing DNAPL from the low-

yielding fractured bedrock. Enhancements associated with Alternative 2 will likely be effective in reducing source area concentrations and mobilizing the DNAPL if implemented in conjunction with the pump and treat system. Long-term groundwater monitoring will be conducted to assess the degree of compliance achieved over time.

Through the operation of the treatment system, this alternative will meet action-specific ARARs for discharge of treated groundwater into the subsurface or a surface water body, and discharge of off-gas into ambient air.

Long Term Effectiveness and Permanence – This alternative will have long-term effectiveness and permanence. Extraction and treatment of contaminated groundwater will limit downgradient migration of the contaminants and reduce groundwater contamination. Long-term groundwater monitoring will be implemented to monitor the groundwater quality during the remediation period. This alternative will provide adequate control of risks to human health.

Pump and treat systems are a proven technology. During the RD, detailed groundwater calculations will be done to determine the exact locations of extraction screen intervals and pumping rates necessary to capture the downgradient plume. ICs, if properly enforced, will be considered reasonably adequate and reliable for protection of human health.

The long-term effectiveness of this alternative will be assessed through routine groundwater monitoring and five-year reviews to verify that human health is not at risk and the restoration of the environment.

Reduction of Toxicity, Mobility, or Volume of Contamination through Treatment – The pump and treat system will reduce the toxicity and volume of the contaminants in groundwater and potentially increase the mobility of contaminants in groundwater at the Curriculum Center. This increased mobility will increase the removal of contaminants in the subsurface.

Short Term Impacts and Effectiveness – Site work and installation of the downgradient extraction wells and upgrading the groundwater treatment system will be performed without significant risk to the community. Through required training, site workers will wear appropriate personal protective equipment (PPE) to minimize exposure to contamination and as protection from physical hazards.

The OU2 area is developed with buildings and parking areas and no adverse impacts to habitats or vegetation are anticipated from activities associated with implementation of this alternative.

The estimated period for the construction of new extraction wells and upgrading the treatment system is one year. Based on calculations, it is estimated that clean up time for OU2 using groundwater pump and treat will be in excess of 30 years. For cost estimating purposes, it is assumed that groundwater pump and treat will be active for a period of 30 years. **Implementability** – This alternative is technically implementable using conventional construction methods and equipment. No technical difficulties are anticipated for installation of wells and upgrading the groundwater extraction and treatment system equipment. Services and materials for

implementation of this alternative are not readily in the USVI but are available in the United States and will be transported to OU2. It is anticipated that equipment will also need to be shipped to the USVI if not locally available. High freight rates associated with shipping are anticipated. Competitive bids can be obtained from a number of equipment vendors and remediation contractors. No major problems are foreseen for the implementation and enforcement of the institutional controls. Local authorities are implementing regulatory systems to improve control of local work. Permit Equivalents from DPNR and/or USVI are anticipated for installation of extraction wells, discharge of treated groundwater and off-gas treatment.

PDI and pilot testing would be necessary to demonstrate effectiveness and to establish the site-specific design parameters. The pilot testing results will be used to determine the optimal well placement, flow rates and additional treatment that may be necessary.

Relative Cost – The present worth cost of Alternative 2 is estimated to be \$13,340,565. The capital cost is estimated to be \$4,802,538, the periodic cost is estimated to be \$56,350 and the total present value of O&M costs is estimated to be \$8,481,677. The capital cost is primarily the cost of system construction. The estimated cost for Alternative 2 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 2 are provided in Appendix A2.

9.2.2.1 Alternative Enhancement 2A – Reinjection

Reinjection of treated water downgradient from the Curriculum Center will raise the water table which will create a hydraulic barrier as a means of containment. Reinjection will not reduce the timeframe of the pump and treat Alternative 2; however, it will help in maintaining a water balance. Since, the reinjection option is an enhancement to the primary remedy, which is Alternative 2, individual analysis has not been performed.

For purposes of this FS, the pump and treat system with reinjection is assumed to operate for 30 years.

Relative Cost – The present worth cost of Alternative 2A is estimated to be \$488,417. The capital cost is estimated to be \$437,053 and the total present value of O&M costs for operations only is estimated to be \$51,364. The O&M costs and present worth costs are additive to Alternative 2. The estimated cost for Alternative 2 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 2 are provided in Appendix A2A.

9.2.2.2 Alternative Enhancement 2B – AS/SVE

Implementing AS/SVE at the potential source areas will help mobilize residual DNAPL within the zone influenced by air sparging. AS/SVE system will reduce the volume of contamination present by injecting air into sparging wells, volatilizing VOCs from the groundwater to the unsaturated zone, and extracting the volatilized contaminants for vapor phase GAC treatment. Extraction of VOCs from the contaminated groundwater will effectively reduce their toxicity and volume in the underlying aquifer.

Successful implementation of this technology at OU2 depends on an adequate understanding of site geology and its effects on system design. Air sparging is dependent upon how well the injected air permeates into the groundwater from the injection point. In order to prevent off-site migration of the contaminated water, hydraulic control will be necessary.

For purposes of this FS, AS/SVE is assumed to be implemented at the source areas for 5 years. During this time, it is assumed that source material in the fractures will be removed and hydraulic control will be maintained by the pump and treat system. Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will be active for a total of 30 years.

Relative Cost – The present worth cost of Alternative 2B is estimated to be \$1,945,206. The capital cost is estimated to be \$1,739,745 and the total present value of O&M costs is estimated to be \$205,461. The O&M costs and present worth costs are additive to Alternative 2. The estimated cost for Alternative 2 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 2 are provided in Appendix A2B.

9.2.2.3 Alternative Enhancement 2C – ISCO

Under Alternative Enhancement 2C, implementation of ISCO to treat the potential source areas would improve contaminant mass destruction and minimize contaminant migration from the Curriculum Center. This technology would reduce the contaminant mass and shorten the time required to remediate subsurface contamination at the Curriculum Center. The advantage of this option is that it is a relatively inexpensive passive treatment method.

This technology has been demonstrated on a full-scale basis to be effective for removing VOCs from groundwater, however, its effectiveness is highly dependent on the hydrogeology at the site. In addition, this technology has not been tested extensively for saturated-zone DNAPL remediation in a fractured-bedrock setting.

With regard to the contaminants at OU2, VC could be formed as an intermediate by-product if complete oxidation is not achieved. VC is more hazardous than PCE and its other daughter products, and it is difficult to treat at the surface. In addition, high concentrations of natural organic carbon and dissolved inorganics, could increase the amount of oxidant product required for effective treatment. Oxidation of inorganics could also result in the fouling of fractures and injection wells as a result of precipitation.

For purposes of this FS, ISCO is assumed to be implemented at the source areas for 5 years. During this time, it is assumed that source material in the fractures will be removed and hydraulic control will be maintained by the pump and treat system. Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will be active for a total of 30 years.

Relative Cost – The present worth cost of Alternative 2C is estimated to be \$216,474. The capital cost is estimated to be \$99,364 and the total present value of O&M costs is estimated to be \$117,110. The O&M costs and present worth costs are additive to Alternative 2. The estimated cost for Alternative 2 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 2 are provided in Appendix A2C.

9.2.2.4 Alternative Enhancement 2D – Surfactant Flushing

In situ surfactant flushing of fractures in potential source areas will be implemented to release contaminants from the formation. This technology would significantly reduce the contaminant mass and shorten the time required to remediate subsurface contamination at the Curriculum Center.

There are a number of unknowns in the fractured bedrock aquifer that can significantly impact surfactant flushing. At a minimum, these include the ability of the formation to accept the surfactant solution across a large vertical zone, and the ability to maintain hydraulic control between surfactant injection wells and the recovery wells.

For purposes of this FS, surfactant flushing is assumed to be implemented at the source areas for 1 year. During this time, it is assumed that source material in the fractures will be removed and hydraulic control will be maintained by the pump and treat system. Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will be active for a total of 26 years.

Relative Cost – The present worth cost of Alternative 2D is estimated to be \$1,265,756, which is the same as the capital cost. The capital cost is primarily the cost of system construction and the cost of two rounds of injections. The O&M costs and present worth costs are additive to Alternative 2. The estimated cost for Alternative 2 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 2 are provided in Appendix A2D.

9.2.3 Alternative 3 – In Situ Thermal Treatment and Pump and Treat

Overall Protection of Human Health and the Environment – Alternative 3 provides overall protection of human health and the environment by actively reducing VOC contaminant levels in OU2 groundwater through in-situ thermal treatment. Also, Alternative 3 will prevent impact to groundwater because it will remove the DNAPL and dissolved VOC contamination from the bedrock aquifer and will prevent further downward migration of VOC contamination to groundwater by operating the downgradient extraction wells.

ICs and LTM would be implemented inside and outside of the active remediation areas and if needed after the thermal treatment is no longer active. Alternative 3 will control further spread of the contaminant plume.

Compliance with ARARs – Alternative 3 will achieve compliance with chemical specific ARARs for VOCs. Thermal treatment for VOC contaminated groundwater will continue until the PRGs are met. This alternative is expected to meet the ARARs at OU2, within 12 years.

Long Term Effectiveness and Permanence – Alternative 3 provides a high degree of long-term effectiveness and permanence. Remedial activities for VOC contaminated groundwater will continue until PRGs are met. Long term potential risks will be removed.

Reduction of Toxicity, Mobility, or Volume of Contamination through Treatment – Alternative 3 will provide reduction in toxicity, mobility, and volume of VOC contamination in groundwater. Contamination migrating to the surface will be collected via a vapor recovery system and treated with commonly used media. Spent media will be regenerated resulting in destruction of the contamination.

Short Term Impacts and Effectiveness – Implementation of Alternative 3 will result in significant disruption of the Curriculum Center property and construction related risks will be imposed to the construction workers, and Curriculum Center employees. The additional risks will be generated from drilling activities to install the heating /vacuum extraction wells and construction of the treatment system. These risks will be mitigated by the development and implementation of a Remedial Action Work Plan including a Health and Safety Plan and Community Air Monitoring Plan. These plans will provide measures to prevent exposure of workers and Curriculum Center employees to the contamination, air sampling to protect the workers and the surrounding community, protection of workers from construction activities, create exclusion zones to protect the public from entering work areas and noise mitigation to prevent impacting the surrounding community. Also, standard industry protocols will be used to prevent dust generation during intrusive work and to provide for traffic control for all equipment on-site and off-site.

The presence and locations of underground utilities needs to be further investigated during PDI work and heating needs to be evaluated for short term impacts to subsurface utilities or structures because the temperature will reach about 100°C. Temperature rise near utilities will be monitored during remediation.

For purposes of this FS, thermal treatment is assumed to be implemented at the source areas for 2 years. During this time, it is assumed that source material in the fractures will be removed and hydraulic control will be maintained by the pump and treat system. It is estimated that contamination outside of the thermal treatment area will take 10 years to reach the perimeter pump and treat system. Therefore, the remedial system will be active for a total of 12 years.

Implementability – Alternative 3 is implementable with available equipment and material. Services and materials for implementation of this alternative are readily available in the United States. It is anticipated that equipment will be shipped to the USVI. High freight rates associated with shipping are anticipated. Power consumption for this technology is very high and there is an uncertainty at this time if the current local power grid system can provide the required power. The grid system was severely damaged from Hurricane Irma/Maria in 2017 and is undergoing reconstruction. If

power is not available from the local power authority, generators will be provided. Competitive bids can be obtained from a number of equipment vendors and remediation contractors. No problems are foreseen for the implementation and enforcement of the institutional controls. Permit Equivalents from DPNR and/or USVI are anticipated prior to any thermal treatment. In-situ thermal treatment is implemented on a number of field remediation projects; however, additional measures will need to be implemented while installing heating wells near the building and underground utilities. Heating sensors will be installed near the utilities to monitor the temperature rise near the utilities which can automatically shut off the heating input for the wells nearby. The vapor extraction system components of the in-situ thermal technology are more widely used and there is sufficient trained staff to perform the installation, and O&M.

Cost – The present worth cost of Alternative 3 is estimated to be \$94,309,778. The capital cost is estimated to be \$89,628,605 and the total present value of O&M costs is estimated to be \$4,569,283. The capital cost is primarily the cost of system construction. The estimated cost for Alternative 3 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 3 are provided in Appendix A3.

9.2.4 **Alternative 4 – In Situ Steam Injection and Pump and Treat**

Overall Protection of Human Health and the Environment – Alternative 4 provides overall protection of human health and the environment by actively reducing VOC contaminant levels in OU2 groundwater through in-situ steam injection treatment. Also, Alternative 4 will prevent impact to groundwater because it will remove the DNAPL and dissolved VOC contamination from the bedrock aquifer and will prevent further downward migration of VOC contamination to groundwater by operating the downgradient extraction wells.

ICs and LTM would be implemented inside and outside of the active remediation areas and if needed after the thermal treatment is no longer active. Alternative 4 will control further spread of the contaminant plume.

Compliance with ARARs – Alternative 4 will achieve compliance with chemical specific ARARs for VOCs. Treatment for VOC contaminated groundwater will continue until the PRGs are met. This alternative is expected to meet the ARARs at OU2, within 27 years.

Long Term Effectiveness and Permanence – Alternative 4 provides long-term effectiveness and permanence. Remedial activities for VOC contaminated groundwater will continue until PRGs are met. Long term potential risks will be removed.

Reduction of Toxicity, Mobility, or Volume of Contamination through Treatment – Alternative 4 will provide reduction in toxicity, mobility, and volume of VOC contamination in groundwater. Injection of steam in potential source areas will mobilize the residual DNAPL present in fractures which will be captured by the extraction wells.

Short Term Impacts and Effectiveness – Implementation of Alternative 4 will have construction related risks to the workers. These risks will be generated from drilling activities to install the steam injection wells and during steam injections. These risks will be mitigated by the development and implementation of a Remedial Action Work Plan including a Health and Safety Plan and Community Air Monitoring Plan. These plans will provide measures to prevent exposure of workers to the contamination, air sampling to protect the workers and the surrounding community, protection of workers from construction activities, create exclusion zones to protect the public from entering work areas and noise mitigation to prevent impacting the surrounding community. Also, standard industry protocols will be used to prevent dust generation during intrusive work and to provide for traffic control for all equipment on-site and off-site.

With regard to heating methods, steam injection would be most effective based upon its ability to be injected as a high temperature, high-pressure vapor, which could potentially: 1) penetrate and efficiently heat the fractured zones to enhance mass transfer and 2) physically displace contaminated groundwater and NAPL. Steam injection could, however, result in fouling of fractures and injection wells due to the introduction of oxygenated water into an oxygen-deficient environment.

For purposes of this FS, steam injection is assumed to be implemented at the source areas for 2 years. During this time, it is assumed that source material in the fractures will be removed and hydraulic control will be maintained by the pump and treat system. Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will be active for a total of 27 years.

Implementability – Alternative 4 is implementable with available equipment and material. Services and materials for implementation of this alternative are readily available in the United States. It is anticipated that equipment will be shipped to the USVI. High freight rates associated with shipping are anticipated. Power consumption for this technology is high and there is an uncertainty at this time if the current local power grid system can provide the required power. The grid system was severely damaged from hurricanes in 2017 and is undergoing reconstruction. If power is not available from the local power authority, generators will be provided. Competitive bids can be obtained from a number of equipment vendors and remediation contractors. No problems are foreseen for the implementation and enforcement of the institutional controls. Permits from DPNR and/or USVI are anticipated prior to any steam injections.

Cost – The present worth cost of Alternative 4 is estimated to be \$34,171,200. The capital cost is estimated to be \$25,568,569 and the total present value of O&M costs is estimated to be \$8,539,451. The capital cost is primarily the cost of system construction. The estimated cost for Alternative 4 is summarized in **Table 9-1** and Appendix A. Details of the cost estimate for Alternative 4 are provided in Appendix A4.

9.3 Comparative Analysis of Alternatives

Table 9-1 summarizes the comparison of the four alternatives against the seven criteria. Alternatives 2A through 2D are enhancements to Alternative 2 and are therefore not discussed in this Section.

Overall Protection of Human Health and the Environment

Alternative 1 would not meet RAOs and would not be protective of human health and the environment since no action will be taken. Contamination would remain in the groundwater for a long time in the future, while no mechanisms would be implemented to prevent exposure to contaminated groundwater, or to reduce the Toxicity, Mobility, or Volume of contamination except through natural processes, which would not be monitored to assess the effectiveness to predict the duration of this alternative.

Alternatives 2 through 4 would meet RAOs over time and would provide similar degrees of protection to human health and the environment through in-situ treatment processes, ICs, and LTM.

Compliance with ARARs

Alternative 1 would not achieve chemical-specific ARARs established for groundwater. Action-specific ARARs do not apply to this alternative since no remedial action would be conducted.

Alternatives 2, 3, and 4 would meet the PRGs within the active treatment areas over the long term. Alternatives 2 and 4 would meet the PRGs by extraction and treatment of contaminants to eliminate the exposure pathways to human receptors and as a continued source to the groundwater plume. Implementation of in-situ treatment processes would significantly reduce contaminant concentrations in the saturated treatment area. The contamination in areas outside the active treatment area would gradually reduce to meet PRGs through the operation of the hydraulic control system. Alternatives 2, 3, and 4 would meet the action specific ARARs by following the health and safety regulations and waste handling and disposal regulations, as applicable. Also, operations of these alternatives will require compliance with local permit equivalents.

There are no location specific ARARs associated with OU2.

Long-Term Effectiveness and Permanence

Alternative 1 would not be effective or permanent since there would be no mechanisms to prevent exposure to contaminated groundwater.

Alternatives 2 through 4 would provide long-term effectiveness and permanence by using in-situ treatment processes to reduce the contaminant mass in the treatment area. Remaining low concentration contaminants outside the active remediation area would be further degraded

through operation of the hydraulic control system. Alternatives 2 through 4 would provide hydraulic control to prevent off-site migration of the contaminated plume. Additionally, ICs would ensure continued protection of human health receptors in the long-term under Alternatives 2, 3, and 4.

Among Alternatives 2 through 4, Alternative 3 using in-situ thermal remediation would provide the highest mass reduction of groundwater contamination at the potential source areas in the shortest period of time, followed by Alternative 4 using steam injections. Alternative 2 using groundwater pump and treat would enhance degradation of contaminants but over a longer remedial timeframe when compared to Alternative 3 and 4.

Alternatives 2 through 4 would provide adequate control of risk to human health by implementing ICs and engineering controls until the aquifer is restored to PRGs. Alternative 3 using in-situ thermal remediation would be the most reliable mass reduction technology followed by, Alternative 4 using in-situ steam injections followed by Alternative 2 using groundwater pump-and-treat.

Reduction of Toxicity, Mobility, and Volume through Treatment

Alternative 1 would not provide any reduction of toxicity, mobility or volume of contaminants since no remedial action would be conducted. The total volume of contaminated groundwater might increase if natural processes are unable to contain the plume.

Alternatives 2, 3, and 4 would provide reduction of toxicity, mobility, and volume through treatment and removal of contaminants. Alternative 3 using in-situ thermal remediation would be the most effective in reducing toxicity and volume of contamination in groundwater through treatment, followed by Alternative 4 using in-situ steam injections, and finally Alternative 2 using pump and treat system.

Short-Term Effectiveness

Alternative 1 would not have short-term impacts since no action would be implemented.

There would be significant short-term impacts to the local community and workers for Alternatives 2 through 4, due to the active remedial actions undertaken and associated construction, operation and/or treatment activities. Efforts will be made to minimize noise and impact from construction activities to the operations of the Curriculum Center if applicable. Currently, the building is closed due to damage from the 2017 hurricanes. The future of the building and previous operations is unknown.

Coordination and access would be required from DPNR and Department of Education for staging or remedial action purposes. Noise and Community Air monitoring plans will be developed during the design and discussed with owners and local authorities. Engineering controls and appropriate PPE would be used to protect the community and workers for Alternatives 2 through 4.

Implementability

All four alternatives are implementable. Alternative 1 would be easiest both technically and administratively to implement as no additional work would be performed at OU2. Alternatives 2 through 4 would be equally implementable; more difficult to implement than Alternative 1. Services, materials and experienced vendors are readily available in the continental USA. Shipping equipment to the USVI from the United States would be required for majority of the equipment since local supplies are scarce. Pilot studies would be implemented to obtain site-specific design parameters for Alternatives 2 through 4. A permit equivalent would be required for in situ treatment technologies into the subsurface and/or to discharge treated vapor to the atmosphere under Alternatives 2 through 4.

The success rate of Alternatives 2 through 4 depends on site specific conditions. Based on the conditions at this site, with high levels of contamination and DNAPL in bedrock fractures, Alternative 3, using in-situ thermal remediation, will have the highest success rate followed by Alternative 4, using in-situ steam injections, and then Alternative 2, using an expanded pump and treat system.

Cost

A comparative summary of the cost estimates for each alternative is presented in Table 9-1, and Appendix A. In summary, Alternative 1 has no cost. Alternative 3 using in situ thermal treatment has the highest cost followed by Alternative 4 using in situ steam injections, and Alternative 2 using an expanded pump and treat system.

Amongst the enhancements for Alternative 2, the enhancement using ISCO is the lowest.

9.4 Uncertainties

Development of remedial alternatives for the restoration of groundwater at the Tutu Wellfield Site in Section 8 required a number of reasonable assumptions to be made based on available information. There is a degree of uncertainty associated with several of the key factors that serve as the basis for the alternatives. These factors include a range of source constraints (extent of DNAPL, mass under the Curriculum Center, range of cleanup times), hydrogeological constraints (long term response to pumping, heterogeneous nature of fractured bedrock, seasonal fluctuations in recharge), and site constraints (adequacy of the VI power grid, future plans for the Curriculum Center).

9.4.1 Source Constraints

The extent and distribution of contaminant mass could not be fully defined during the RI due to access and scope limitations and will require further delineation during the PDI. Assumptions have been made in the FS to include areas beneath the northern portion of the Curriculum Center building, the drum disposal area and areas where high dissolved phase concentrations indicated the presence of DNAPL as potential source areas. It is assumed that partially mobile DNAPL,

desorption and/or matrix back diffusion in these areas will act as ongoing sources of groundwater contamination. Additional investigation of these areas will be required to verify FS assumptions and address data gaps. The treatment area may be adjusted based on the PDI results.

The potential presence of DNAPL, highly contaminated pore water in isolated fractures and contamination within the rock matrix make most treatment technologies ineffective. Under these conditions, contaminant concentrations can rebound after treatment due to DNAPL or plume movement from isolated fractures, desorption and back diffusion from the rock matrix. There is also uncertainty associated with the location of contaminant transport pathways, due to the complexity of the groundwater flow system in the fractured bedrock aquifer.

Matrix diffusion modeling was performed to estimate cleanup times. The model predicted that concentrations at the property boundary would drop below the MCL approximately 25 years after complete source removal. However, remedial action can result in changes to the input parameters used in modeling and impact the estimated cleanup time. For purposes of the FS, it is assumed that the effectiveness of the chosen remedy would need to be re-evaluated in a minimum 5-year period.

9.4.2 Hydrogeological Constraints

The current system is configured to pump at a constant head. The elevation target limits extraction rates to preserve groundwater in the aquifer. For the proposed system, the constant head drawdown restriction will be removed, and the system will be modified to run on a constant rate basis to increase the yield at the existing wells. The underlying assumption is that additional yield can be obtained with greater drawdown and that the wells are capable of yielding higher rates.

There is uncertainty associated with yield and drawdown of the existing wells. Historical aquifer testing during the pre-design testing and system startup for the OU1 remedy resulted in different values for aquifer hydraulic parameters. Estimates of the extraction rate for the FS were conservatively based on the higher end of the range in historical data. Several factors may have contributed to the uncertainty, including seasonal variations, different lengths of the aquifer tests, fracture dewatering and degradation of well's efficiency.

The proposed system also includes two additional extraction wells located at the downgradient end of OU2. Because of the heterogeneous nature of fractured rock, there is uncertainty associated with the assumption that conditions measured at the existing wells are representative of those at the two proposed downgradient locations. The capacity of the proposed treatment facility includes yield from all three locations. It is recommended that test wells be installed at the two new locations and that the actual yield and response to pumping be characterized at all three locations as part of pre-design investigations. This will allow more accurate estimates of the influent rate for the treatment system to be made.

Capture zones in fractured rock aquifers are difficult to estimate because of the inherent heterogeneity and anisotropy in these systems. Estimates of capture zones for the FS were made

using analytical methods, an average value for hydraulic gradient, the high end of transmissivity estimates and the assumption of equivalent porous media. Estimates indicated that the plume width could be captured by the existing system operating at a rate of 50 gpm. However, at this rate capture would not extend downgradient to the drum disposal area or to the area of monitoring well OU2-MW3.

Capture zone estimates using the current average extraction rate resulted in a more limited capture zone that does not include many wells where DNAPL has been either directly observed or indicated by dissolved phase concentrations. Under current pumping conditions, it is likely that the plume and source area is not fully within the capture zone of the remediation system. It is expected that the actual response will vary from these estimates due to the heterogeneous and anisotropic nature of bedrock, but these estimates should be a reasonable approximation for purposes of the FS. The actual response should be established in a PDI.

9.4.3 Site Constraints

There is an uncertainty at this time as to whether or not the current local power grid system can provide the power required for the proposed power demanding remediation systems. The grid system was severely damaged from hurricanes in 2017 and is undergoing reconstruction. If power is not available from the local power authority, generators will have to be provided and costs will be affected.

Access to suspected source areas beneath the Curriculum Center building is uncertain. The building is currently condemned due to Hurricane Irma/Maria; future plans for the property are unknown. For purposes of the FS, it is assumed that the building will be demolished by others and access will be available during the PDI. Building demolition costs were not included in the cost estimates. The inability to access the groundwater contamination plume under the Curriculum Center building will limit the effectiveness of the remedial alternatives. Remedial timeframes may also be impacted if no data can be obtained beneath the Curriculum Center building to confirm the assumptions that source material is outside of the current capture zone.

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TABLES

Table 3-1
Contaminants of Concern
Tutu OU2, St. Thomas, USVI

Contaminant of Concern	Concentration Range (µg/l)*	Location and Depth (ft bgs)
Tetrachloroethene	5.4 – 92,000	MW13D-110 / RD9-97.5
Trichloroethene	5 – 29,000	IW2S-50.3/ RD9-97.5
1,1-Dichloroethene	37 – 400	RW6-125/ RD9-97.5
cis-1,2-Dichloroethene	94 – 160,000	IW2S-50.3/ RD9-97.5
trans-1,2-Dichloroethene	190 – 2,300	RW6-125/ RD9-97.5
Vinyl Chloride	2.2 – 38,000	OU2-MW4-95/ RD9-97.5
Bromodichloromethane**	1.2 – 2.7	OU2-MW4-95/ BP2-50
1,2-Dichloroethane**	0.65 – 0.8	IW1-85/ RD9-97.5
1,1,2-Trichloroethane**	0.76 – 1.6	RW6-125/ IW1-85
1,2,4-Trichlorobenzene**	0.63 – 4.1	RW8-80/ RD9-97.5
1,4-Dichlorobenzene**	0.53 – 2.8	RD11-97.5/ IW1-85

Notes:

*- Concentrations detected during the 2016-2017 focused source remedial investigation activities by HDR

** - included in this table based on HHRA (HDR 2018); calculated cancer risks for these constituents are in the 1×10^{-6} range, contributing to a cumulative ELCR greater than 1×10^{-4} . 1,1,2-trichloroethane also contributes to noncancer hazards greater than one for the liver as a target organ.

Highest concentration and corresponding location is highlighted in red

Acronyms:

µg/l - microgram per liter

ft - feet

bgs - below ground surface

HHRA- Human Health Risk Assessment



Table 4-1
Preliminary Remediation Goals For Groundwater
Tutu OU2, St. Thomas, USVI

Contaminants of Concern	EPA National Primary Drinking Water Standards¹ MCLs (µg/l)	PRGs² (µg/l)	Maximum Detected Concentrations³ (µg/l)
Tetrachloroethene	5	5	92,000
Trichloroethene	5	5	29,000
1,1-Dichloroethene	7	7	400
cis-1,2-Dichloroethene	70	70	160,000
trans-1,2-Dichloroethene	100	100	2,300
Vinyl Chloride	2	2	38,000
Bromodichloromethane**	80	80	2.7
1,2-Dichloroethane**	5	5	0.8
1,1,2-Trichloroethane**	5	5	1.6
1,2,4-Trichlorobenzene**	70	70	4.1
1,4-Dichlorobenzene**	75	75	2.8

Notes:

1. EPA National Primary Drinking Water Standards (web page), <http://www.epa.gov/safewater/consumer/pdf/mcl.pdf>.
2. In the absence of local guidance values and regulations, EPA MCLs will be the PRGs.
3. The maximum concentrations detected during the focused source remedial investigation by HDR in 2016-2017.

** - included in this table based on HHRA (HDR 2018); calculated cancer risks for these constituents are in the 1×10^{-6} range, contributing to a cumulative ELCR greater than 1×10^{-4} . 1,1,2-trichloroethane also contributes to noncancer hazards greater than one for the liver as a target organ.

Acronyms:

EPA - United States Environmental Protection Agency
MCLs - Maximum Contaminant Levels
PRGs - Preliminary Remediation Goals
µg/l - microgram per liter
HHRA- Human Health Risk Assessment



Table 6-1
Groundwater Technology Screening
Tutu OU2, St. Thomas, USVI

General Response Action	Remedial Technology	Process Option	Description	Screening Comments
No Action	No Action	Not Applicable	No remedial action.	Retained - No Action is required for consideration by NCP.
Institutional Controls (ICs)	Not Applicable	ICs - Non-Engineering (Administrative/ Legal) Controls	ICs are non-engineering measures that help minimize the potential for human exposure to contamination and/ or protect the integrity of a remedy by limiting site or resource use.	Retained - ICs will be considered and developed in conjunction with all active remedial alternatives.
Monitored Natural Attenuation with Long Term Monitoring	Not Applicable	Not Applicable	Natural subsurface processes (e.g., dilution, volatilization, biodegradation, adsorption, and chemical reactions) with subsurface materials reduce contaminant concentrations to acceptable levels. Monitoring to assess performance and risk mitigation. Does not reduce contamination.	Retained - MNA and LTM will be considered and developed in conjunction with active remedial alternatives as contingency/alternative remedy.
Containment	Physical Barriers	~~Slurry Wall~~	Trench around areas of contamination is filled with a soil (or cement) bentonite slurry.	Not Retained - This technology is difficult to implement in bedrock. Additionally, construction in urban area limits the practicability of this technology.
		~~Grout Curtain~~	Pressure injection of grout in a regular pattern of drilled holes.	Not Retained - This technology is difficult to implement in bedrock. Additionally, construction in urban area limits the practicability of this technology.
		~~Funnel & Gate~~	Sheet piles with injection of slurry as beam is withdrawn. Impermeable sheet pile wall (funnel) to direct water to a permeable reactive barrier (gate) for treatment.	Not Retained - This technology is difficult to implement in bedrock. Additionally, construction in urban area limits the practicability of this technology.
		~~Block Displacement~~	In conjunction with vertical barriers, injection of slurry in notched injection holes.	Not Retained - This technology is difficult to implement in bedrock. Additionally, construction in urban area limits the practicability of this technology.
	Hydraulic Barrier	Groundwater Pump & Treat	Consists of pumping groundwater from an aquifer to remove dissolved phase contaminants and/or achieve hydraulic containment of contaminated groundwater to prevent migration, with subsequent treatment and disposal/discharge.	Retained - Groundwater extraction and treatment will be developed as a remedial alternative for OU2.
	Deep Well Injection	~~Geologic Sequestration~~	Waste disposal technology using injection wells to place treated or untreated liquid waste into geologic formations that have little potential to allow migration of contaminants.	Not Retained - Regulatory hurdles under the Underground Injection Control (UIC) and other environmental programs, community acceptance issues, not practicable for OU2.

Table 6-1
Groundwater Technology Screening
Tutu OU2, St. Thomas, USVI

General Response Action	Remedial Technology	Process Option	Description	Screening Comments
Treatment	In Situ Biological Treatment	~~Enhanced Bioremediation~~	Process to accelerate the natural biodegradation process by introducing nutrients, electron acceptors, and/or competent contaminant-degrading microorganisms to the subsurface.	Not Retained - Enhanced bioremediation is not suitable for use due to the nature and extent of contamination at OU2.
		~~Phytoremediation~~	Set of processes that use plants to remove, transfer, stabilize and / or destroy contamination in groundwater.	Not Retained - Phytoremediation is generally limited to treating shallow groundwater with lower contaminant concentrations and requires a large area of land for remediation. Therefore, phytoremediation is not applicable for treating groundwater at OU2.
	In-Situ Physical/ Chemical/ Thermal Treatment	Air Sparging	Injected air traverses horizontally and vertically in channels through the soil column, creating a subsurface “air stripper” that removes contaminants by volatilization.	Retained - Air Sparging is effective at treating contaminants of concern, can be implemented at OU2.
		~~Bioslurping~~	Combines the two remedial approaches of bioventing and vacuum-enhanced free-product recovery.	Not Retained - Bioslurping is traditionally used to remediate contamination by petroleum products with a LNAPL layer, which is not present at OU2.
		ISCO	Chemically converts contaminants to less toxic compounds that are more stable, less mobile, and/or inert.	Retained - ISCO is effective at treating contaminants of concern, can be implemented at the OU2.
		Dual Phase Extraction	Technology that utilizes a high vacuum system to remove various combinations of contaminated groundwater, separate-phase product (NAPL), and soil vapor from the subsurface.	Retained - Dual Phase Extraction is effective at treating contaminants of concern, can be implemented at OU2.
		Thermal Treatment	Thermal treatment technologies such as steam enhanced extraction (SEE), thermal conductive heating (TCH), and electrical resistivity heating (ERH) work by introducing heat into the aquifer/ formation to destroy the organic contaminants present.	Retained - Thermal Treatment has been retained for further evaluation at OU2.

Table 6-1
Groundwater Technology Screening
Tutu OU2, St. Thomas, USVI

General Response Action	Remedial Technology	Process Option	Description	Screening Comments
Treatment (Continued)	In-Situ Physical/ Chemical/ Thermal Treatment	~~In Well Air Stripping~~	Air is injected into a vertical well that has been screened at two depths.	Not Retained - In Well Air Stripping is not applicable for use at OU2 due to the specific geology (groundwater contamination in fractured bedrock aquifer).
		~~Passive/ Reactive Treatment Barriers~~	Use of PRBs consisting of iron with a bulking agent to treat groundwater contaminated with chlorinated solvents. A PRB is installed across the flow path of a contaminant plume, allowing the water portion of the plume to passively move through the wall. Use of horizontal wells could also deliver reagents to contaminated areas.	Not Retained - PRBs are not applicable for use at OU2 due to the depth of groundwater contamination and site-specific geology (groundwater contamination in fractured bedrock aquifer).
		In Situ Flushing	In situ flushing involves the injection of chemicals like surfactants into a subsurface contaminated zone. The solution then flows through the contaminated zone and the resulting effluent is extracted downgradient where it is treated and discharged.	Retained - In situ flushing is potentially applicable as an enhancement to other remedy (such as pump and treat or in-well air stripping)
	Ex-Situ Biological Treatment	~~Bioreactors~~	Contaminants in extracted groundwater are put into contact with microorganisms in attached or suspended growth biological reactors.	Not Retained - Bioreactors are not applicable because of the nature and extent of contamination in the groundwater at OU2.
		~~Constructed Wetlands~~	The constructed wetlands-based treatment technology uses natural geochemical and biological processes inherent in an artificial wetland ecosystem to accumulate and fixate / remove metals and other contaminants from influent waters.	Not Retained - Constructed wetlands requires a large area of land for remediation.
	Ex-Situ Physical/ Chemical Treatment	Adsorption (Vapor-phase)	Organic contaminants are adsorbed onto treatment media, reducing their concentration.	Retained - Adsorption using carbon has been retained for vapor-phase treatment at OU2.
		Oxidation (Vapor-phase)	Strong oxidizing chemicals or processes are used to destroy organic contaminants.	Retained - Oxidation has been retained for vapor-phase treatment at OU2.
		Ex Situ Air Stripping	Mass transfer of volatile contaminants from water to air.	Retained - Ex situ air stripping has been retained for use at OU2.
		Groundwater Pump & Treat	Consists of pumping groundwater from an aquifer to remove dissolved phase contaminants and/or achieve hydraulic containment of contaminated groundwater to prevent migration, with subsequent treatment and disposal/discharge.	Retained - Groundwater pump & treat has been retained for use at OU2.

Table 6-1
Groundwater Technology Screening
Tutu OU2, St. Thomas, USVI

General Response Action	Remedial Technology	Process Option	Description	Screening Comments
Discharge/ Disposal	On-Site Discharge	Surface Water	Extracted water discharged to surface water	Retained - Surface water discharge has been retained for use at OU2.
		Groundwater	Extracted water treated and/or discharged into injection well or infiltration basin.	Retained - Groundwater discharge has been retained for use at OU2.
	Off-Site Discharge	POTW	Extracted water pre-treated and/or discharged to POTW.	Not Retained - POTW has not been retained for use at OU2.
Enhancements (To Be Considered)	Enhancements	~~Hydraulic Fracturing~~	Pressurized fluid and proppant (e.g. water and sand) is injected into the borehole at discreet intervals to induce fracturing of the bedrock formation. The newly created fractures enhance the hydraulic connection of the bedrock well.	Not Retained - Hydraulic fracturing has not been retained for use at OU2. May be considered at a later time.



Table 7-1
Groundwater Process Options Evaluation
Tutu OU2, St. Thomas, USVI

General Response Actions	Remedial Technology	Process Options	Description	Effectiveness (RAOs, COCs, Impacts to HHE, Reliability)	Implementability (Technical & Administrative)	Relative Cost	Screening Comment
No Action	No Action	No Action	COCs in groundwater are left untreated.	Poor. Not effective, because no active measures are taken to address the COCs.	Poor. Technically implementable; however, No Action can't be selected under CERCLA.	None.	Retained per NCP.
Institutional Control (ICs)	Not Applicable	ICs - Non-Engineering (Administrative/ Legal) Controls	Exposure pathways are controlled by administrative controls.	Moderate. Requires administrative measures to limit exposure to contaminated groundwater. Institutional Controls are an effective supplement to engineering controls.	Moderate. Readily implementable under EPA guidance (EPA 540-F-00-005), but requires homeowners concurrence.	Low.	Retained in conjunction with other remedies to treat the groundwater.
Long Term Monitoring (LTM)	Not Applicable	LTM	LTM evaluates the groundwater conditions	High. LTM is used to evaluate the effectiveness of other remedial actions at the Site and to understand how the conditions are changing over time.	High. Implementing an LTM programs is technically and administratively achievable.	Low.	Retained in conjunction with other remedies to treat the groundwater.
Containment	Hydraulic Containment	Groundwater extraction, treatment, and discharge.	Hydraulic containment is the process of prohibiting further migration of contaminants beyond the source area, by installing a series of perimeter bedrock wells and capturing the bedrock groundwater flow.	Moderate. Hydraulic containment is a widely accepted and implementable remedy; however, containment in fractured rock conditions can be challenging.	Moderate. The OU-1 treatment infrastructure is in place; a retrofit and upgrade to the system is required.	Moderate. Capital costs include down gradient recovery wells and upgraded treatment plant equipment. O&M costs for hydraulic containment would be similar to current OU-1 treatment operations.	Retained for groundwater source control.
Treatment	In Situ Physical/ Chemical/ Thermal Treatment	ISCO	Chemically converts contaminants to less toxic compounds that are more stable, less mobile, and/or inert.	Moderate. ISCO can be effective in treating the Site COCs; however, successful delivery to the contaminant mass will be a challenge in fractured bedrock. Safety precautions should be used when handling the ISCO cylinders, but proper handling procedures, are generally safe for use.	High. This technology is technically and administratively implementable.	Low. Low costs, compared to other technologies being considered, are associated with this technology.	Retained for further evaluation in conjunction with other remedies to treat the groundwater.
		Dual Phase Extraction	Technology that utilizes a high vacuum system to remove various combinations of contaminated groundwater, separate-phase product (NAPL), and soil vapor from the subsurface.	Moderate. Dual Phase Extraction can be very effective at removing NAPL from wells; however it is limited to the production of the particular wells it is applied to.	High. This technology is technically and administratively implementable.	Moderate. Moderate costs, compared to other technologies being considered, are associated with this technology.	Retained for further evaluation in conjunction with other remedies to treat the groundwater.
		Thermal Treatment	Thermal treatment technologies such as steam enhanced extraction (SEE), thermal conductive heating (TCH), and electrical resistivity heating (ERH) work by introducing heat into the aquifer/ formation to destroy the organic contaminants present.	High. Thermal treatment is highly effective at destroying organic contaminants present at the Site.	High. This technology is technically and administratively implementable.	High. Very high capital and operation costs; however short remedial timeframe.	Retained for further evaluation in conjunction with other remedies to treat the groundwater.
		In Situ Flushing	In situ flushing involves the injection of chemicals like surfactants into a subsurface contaminated zone. The solution then flows through the contaminated zone and the resulting effluent is extracted downgradient where it is treated and discharged.	Moderate. In situ flushing can be very effective at mobilizing NAPL; however it is limited to the production of the particular wells it is applied to.	High. This technology is technically and administratively implementable.	Moderate. Moderate costs, compared to other technologies being considered, are associated with this technology.	Retained for further evaluation in conjunction with other remedies to treat the groundwater.
	Ex Situ Physical/ Chemical/ Thermal Treatment	Air Stripping	Mass transfer of volatile contaminants from water to air.	High. Ex situ air stripping is a highly effective, safe and reliable means for treating the dissolved phase organics present in the Site groundwater. Additional treatment technologies will be required to treat the vapor-phase contaminants resulting from the air stripper.	High. This technology is technically and administratively implementable.	Low. Low capital and O&M costs are associated with this technology.	Retained as the primary ex situ groundwater treatment alternative.
		Adsorption (Vapor-Phase Treatment)	Organic contaminants are adsorbed onto treatment media, reducing their concentration.	High. Adsorption using GAC to treat the vapor-phase contaminants is highly effective at destroying the organic contaminants resultant from the ex situ air stripping operations at the Site.	High. This technology is technically and administratively implementable.	High. High capital and O&M costs are associated with this technology.	Retained for vapor-phase treatment of the air stripper off gas.
		Chemical Oxidation (Vapor-Phase Treatment)	Organic contaminants, particularly vinyl chloride, are chemical destroyed.	High. Chemical Oxidation is very effective at treating the vapor phase contaminants, particular vinyl chloride, that are resultant from the ex situ air stripping operation at the Site.	High. This technology is technically and administratively implementable.	High. High capital and O&M costs are associated with this technology.	Retained for vapor-phase treatment of vinyl chloride from the air stripper off gas.

Table 9-1
Comparative Analysis of Remedial Alternatives
Tutu OU2, St. Thomas, USVI

Alt. No.	Alternative Name	Overall Protection of Public Health and the Environment	Compliance with ARARs	Long Term Effectiveness and Permanence	Reduction of Toxicity, mobility or Volume of Contamination thru Treatment	Short Term Impacts and Effectiveness	Implementability	Cost Effectiveness	
1	No Action	- Will not meet any of the RAOs.	- Will not comply.	- Contaminants remain in the environment and may transform into other compounds. - Magnitude of potential risks will be unchanged.	- Does not reduce toxicity, mobility or volume of contamination present in the contaminated soils.	- Does not result in disruption of operations or pose a short term threat to public health or the environment. - No remedial timeframe is associated with this alternative.	- No technical or administrative difficulties or constraints.	Capital Cost:	\$ -
								Annual O&M:	\$ -
								Total Present Value Cost:	\$ -
2	Expand Existing Pump and Treat System	-This alternative is protective of the public health and the environment. -Expanding the pump and treat system would prevent groundwater from migrating further downgradient and reduce the contaminant concentrations at the source area.	-Will comply with ARARs and PRGs will be achieved.	-Permanent reduction in groundwater contamination from active groundwater remediation.	-This alternative will reduce the toxicity and volume of the contaminants in groundwater and potentially increase the mobility of contaminants in groundwater at the Curriculum Center. The increased mobility would increase the removal of contaminants in the subsurface.	-No adverse impacts to habitats or vegetation would be anticipated from this alternative. -The estimated period for the construction of the new extraction wells and upgrading the treatment system is one year. -The remedial timeframe for this alternative is 30 years.	-This alternative is technically implementable using conventional construction methods and equipment. -No technical difficulties are anticipated for installation of wells and upgrading the groundwater extraction and treatment system equipment. -Services and materials for implementation of this alternative are readily available in the United States. It is anticipated that equipment may need to be shipped to the USVI if not locally available.	Capital Cost:	\$ 4,802,538
								Annual O&M:	\$ 8,481,677
								Periodic Costs:	\$ 56,350
								Total Present Value Cost:	\$ 13,340,565

Table 9-1
Comparative Analysis of Remedial Alternatives
Tutu OU2, St. Thomas, USVI

Alt. No.	Alternative Name	Overall Protection of Public Health and the Environment	Compliance with ARARs	Long Term Effectiveness and Permanence	Reduction of Toxicity, mobility or Volume of Contamination thru Treatment	Short Term Impacts and Effectiveness	Implementability	Cost Effectiveness	
3	In Situ Thermal Treatment and Pump and Treat System	-This alternative is protective of the public health and the environment. This alternative will prevent impact to groundwater because it will remove the DNAPL and dissolved VOC contamination from the bedrock aquifer and will prevent further downgradient migration of groundwater by operating the downgradient extraction wells.	-Will comply with ARARs and remedial activities will continue until PRGs are achieved.	-Permanent reduction in groundwater contamination from active groundwater remediation.	-This alternative will provide a reduction in toxicity and volume of VOC contamination in groundwater. Contamination migrating to the surface will be collected via a vapor recovery system and treated with GAC. Spent GAC will be regenerated resulting in destruction of the contamination.	-This alternative will result in some disruption of the Curriculum Center property and construction related risks will be imposed to the workers, and the environment. The additional risks will be generated from drilling activities to install the heating /vacuum extraction wells and construction of the treatment system. -These risks will be mitigated by the development and implementation of a Remedial Action Work Plan including a Health and Safety Plan and Community Air Monitoring Plan. -This alternative is effective. Thermal treatment is assumed to be implemented in source areas for 2 years. Pump and treat will be active for a total of 12 years	-This alternative is technically implementable using conventional construction methods and equipment. -Administrative difficulties associated with shipping are anticipated.	Capital Cost:	\$ 89,628,605
								Annual O&M:	\$ 4,569,283
								Periodic Costs:	\$ 111,890
								Total Present Value Cost:	\$ 94,309,778

Table 9-1
Comparative Analysis of Remedial Alternatives
Tutu OU2, St. Thomas, USVI

Alt. No.	Alternative Name	Overall Protection of Public Health and the Environment	Compliance with ARARs	Long Term Effectiveness and Permanence	Reduction of Toxicity, mobility or Volume of Contamination thru Treatment	Short Term Impacts and Effectiveness	Implementability	Cost Effectiveness	
4	In Situ Steam Injection and Pump and Treat System	-This alternative is protective of the public health and the environment. This alternative will prevent impact to groundwater because it will remove the DNAPL and dissolved VOC contamination from the bedrock aquifer and will prevent further downgradient migration of groundwater by operating the downgradient extraction wells.	-Will comply with ARARs and PRGs will be achieved. -Steam treatment for VOC contaminated groundwater will continue until the PRGs are met. This alternative is expected to meet the ARARs at OU2, within 5 years.	-Permanent reduction in groundwater contamination from active groundwater remediation.	-This alternative will provide reduction in toxicity, and volume of VOC contamination in groundwater. Injection of steam in potential source areas will mobilize the residual DNAPL present in fractures which will be captured by the extraction wells.	-This alternative will have construction related risks to the workers. These risks will be generated from drilling activities to install the steam injection wells and during steam injections. -These risks will be mitigated by the development and implementation of a Remedial Action Work Plan including a Health and Safety Plan and Community Air Monitoring Plan. -Steam injection is assumed to be implemented in source areas for 2 years. Pump and treat will be active for a total of 27 years.	-This alternative is implementable with available equipment and material. Services and materials for implementation of this alternative are readily available in the United States. -It is anticipated that equipment will be shipped to the USVI. -Administrative difficulties associated with shipping are anticipated.	Capital Cost:	\$ 25,568,569
								Annual O&M:	\$ 8,539,451
								Periodic Costs:	\$ 63,180
								Total Present Value Cost:	\$ 34,171,200

FIGURES



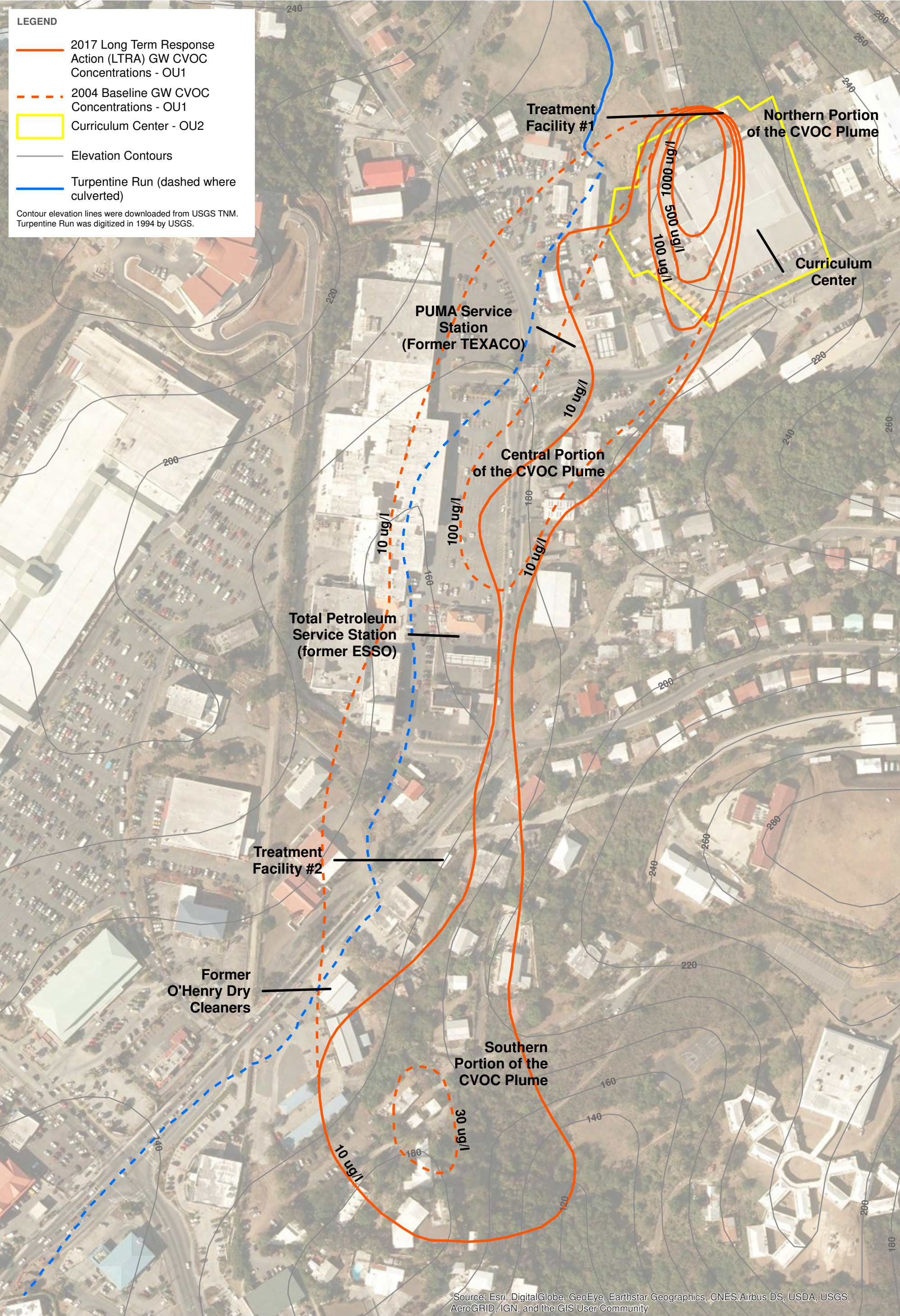
Service Layer Credits: Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community
 Source: US National Park Service

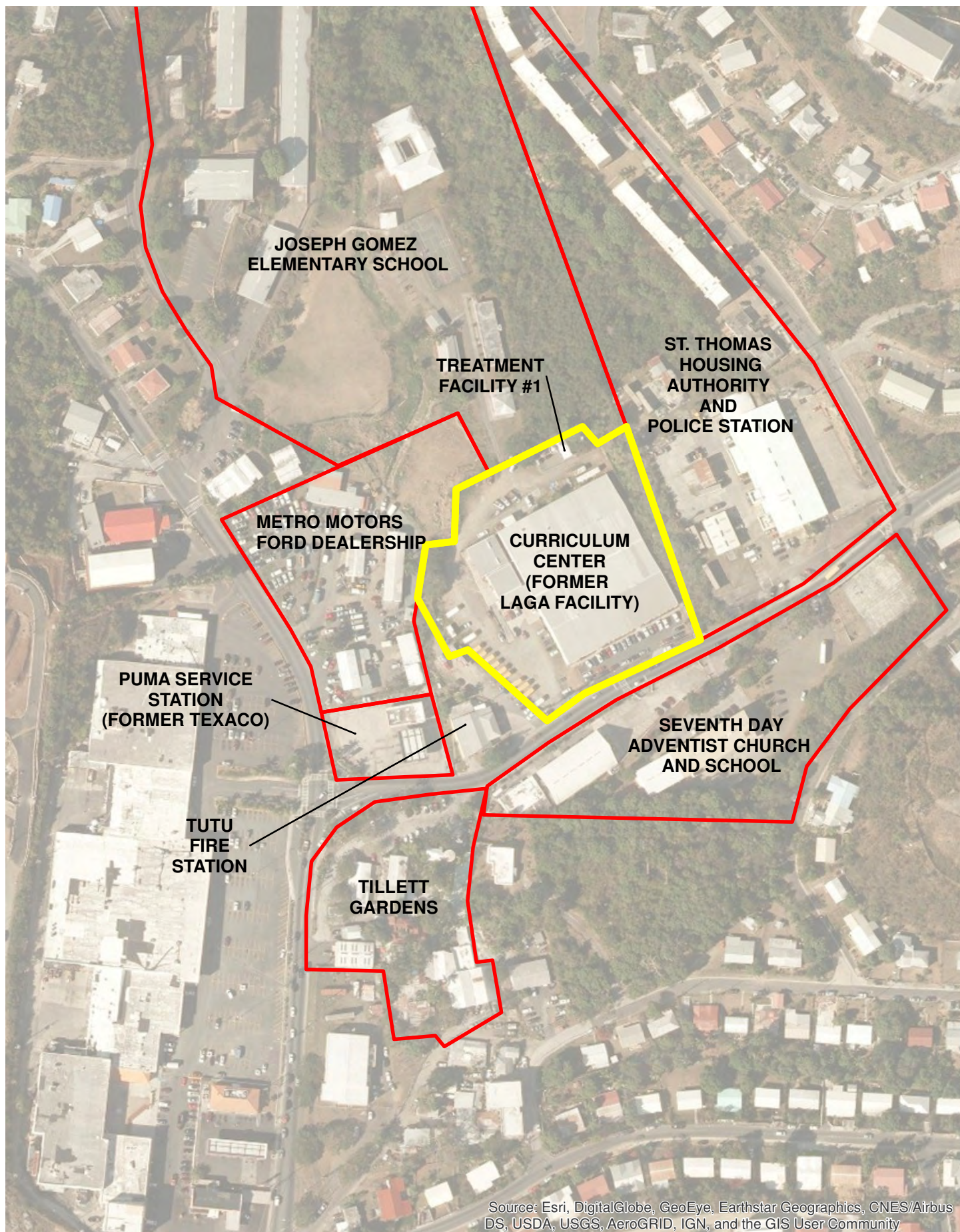
SITE LOCATION MAP
ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 2-1

TUTU WELLS SUPERFUND SITE FOCUSED SOURCE RI/FS OU2

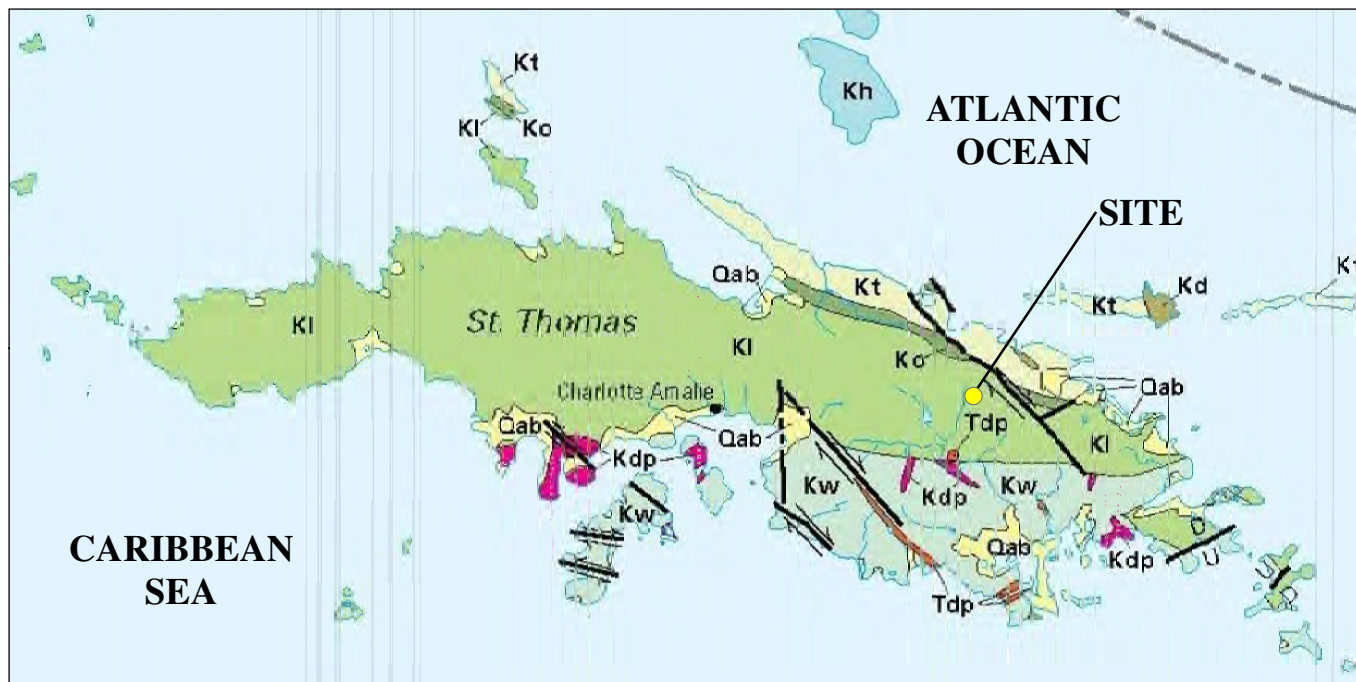






OU2 SITE VICINITY MAP ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 2-3



Base Modified from U.S. Geological Survey
 Western St. Thomas, Eastern St. Thomas
 Western St. John, Eastern St. John, 1:24,000

EXPLANATION

Quaternary deposits		Kt	Tutu Formation
Qab	Alluvium, minor beach deposits	Ko	Outer Brass Limestone
Early Tertiary to Cretaceous rocks		Kl	Louisenhoj Formation
Tdp	Dikes and plugs	Kdp	Dikes and plugs
Cretaceous rocks		Kw	Water Island Formation
Kd	Dioritic rocks	U	Fault - Arrows show relative horizontal movement, dashed where inferred. U, upthrown side; D downthrown side
Kh	Hans Lollik Formation	D	



REGIONAL GEOLOGY ST. THOMAS, U.S. VIRGIN ISLANDS

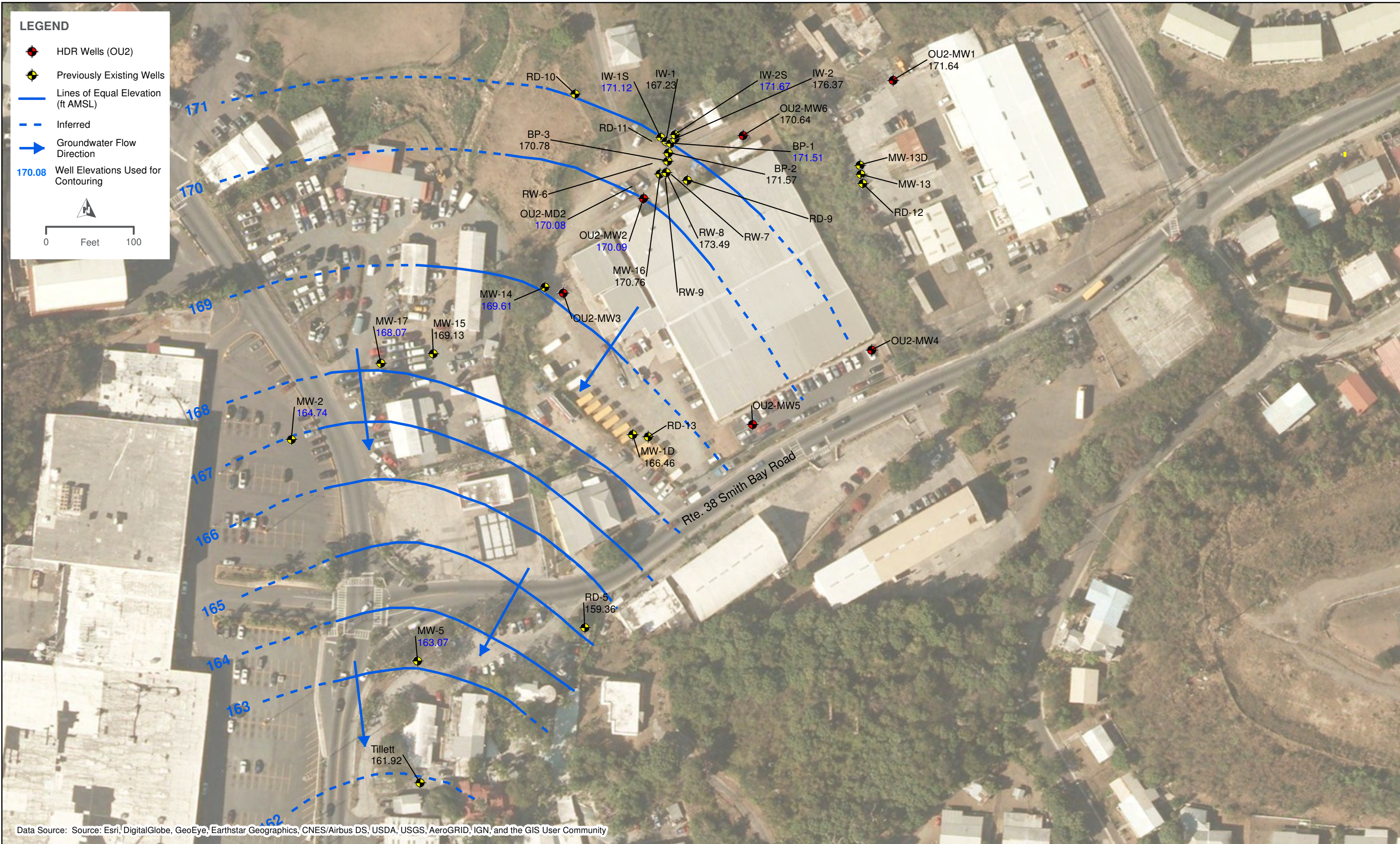
FIGURE 2-5



Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



OU2 SITE GEOLOGY
ST. THOMAS, U.S. VIRGIN ISLANDS
FIGURE 2-6



Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

SHALLOW GROUNDWATER ELEVATION MAP - FEBRUARY 2017

ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 2-7



United States
Environmental Protection
Agency



Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

SHALLOW GROUNDWATER ELEVATION MAP - JUNE 2017

ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 2-8





Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

DEEP GROUNDWATER ELEVATION MAP - FEBRUARY 2017

ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 2-9





Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

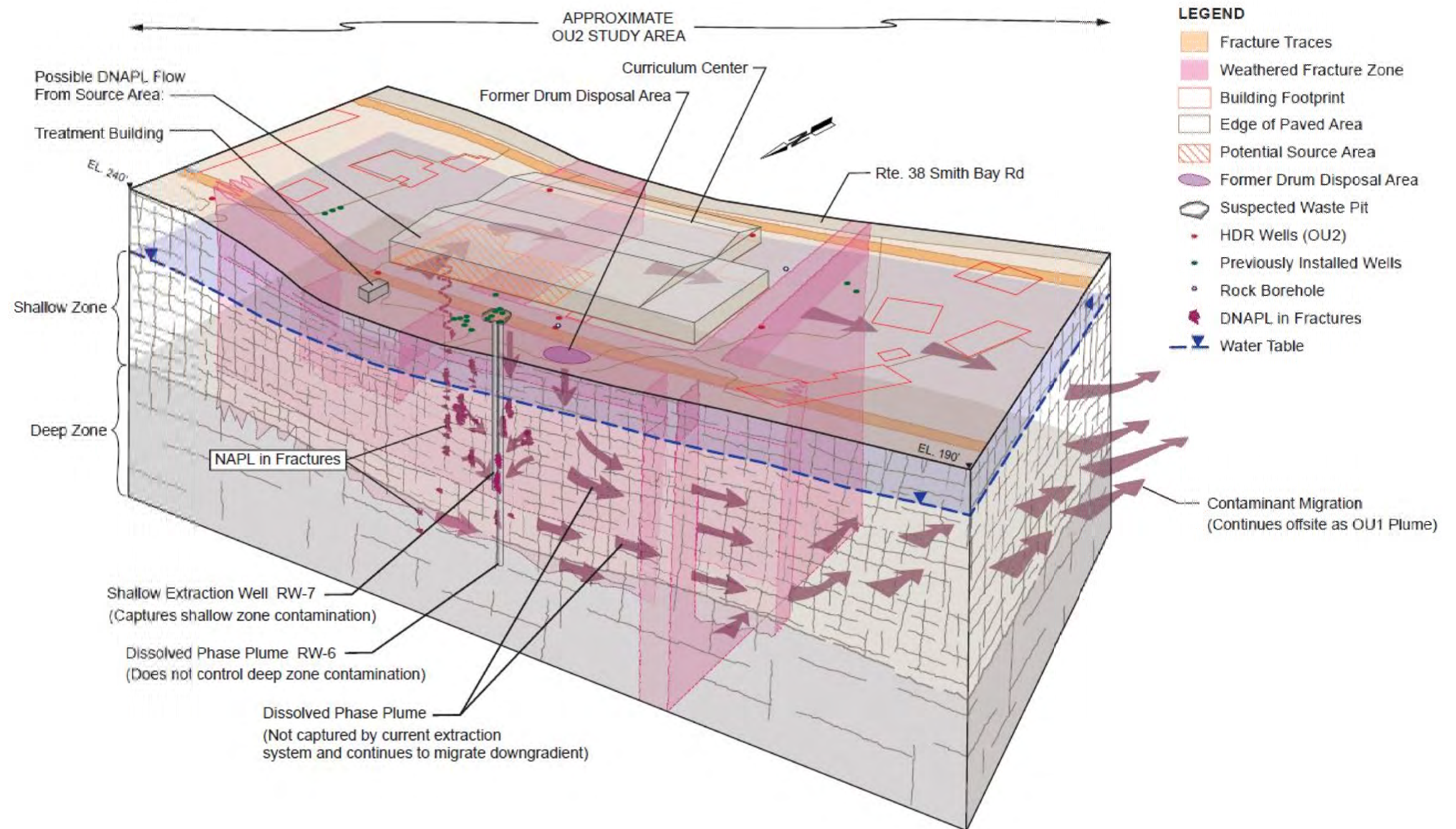
DEEP GROUNDWATER ELEVATION MAP - JUNE 2017

ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 2-10



United States
Environmental Protection
Agency



CONCEPTUAL SITE MODEL
TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 3-3



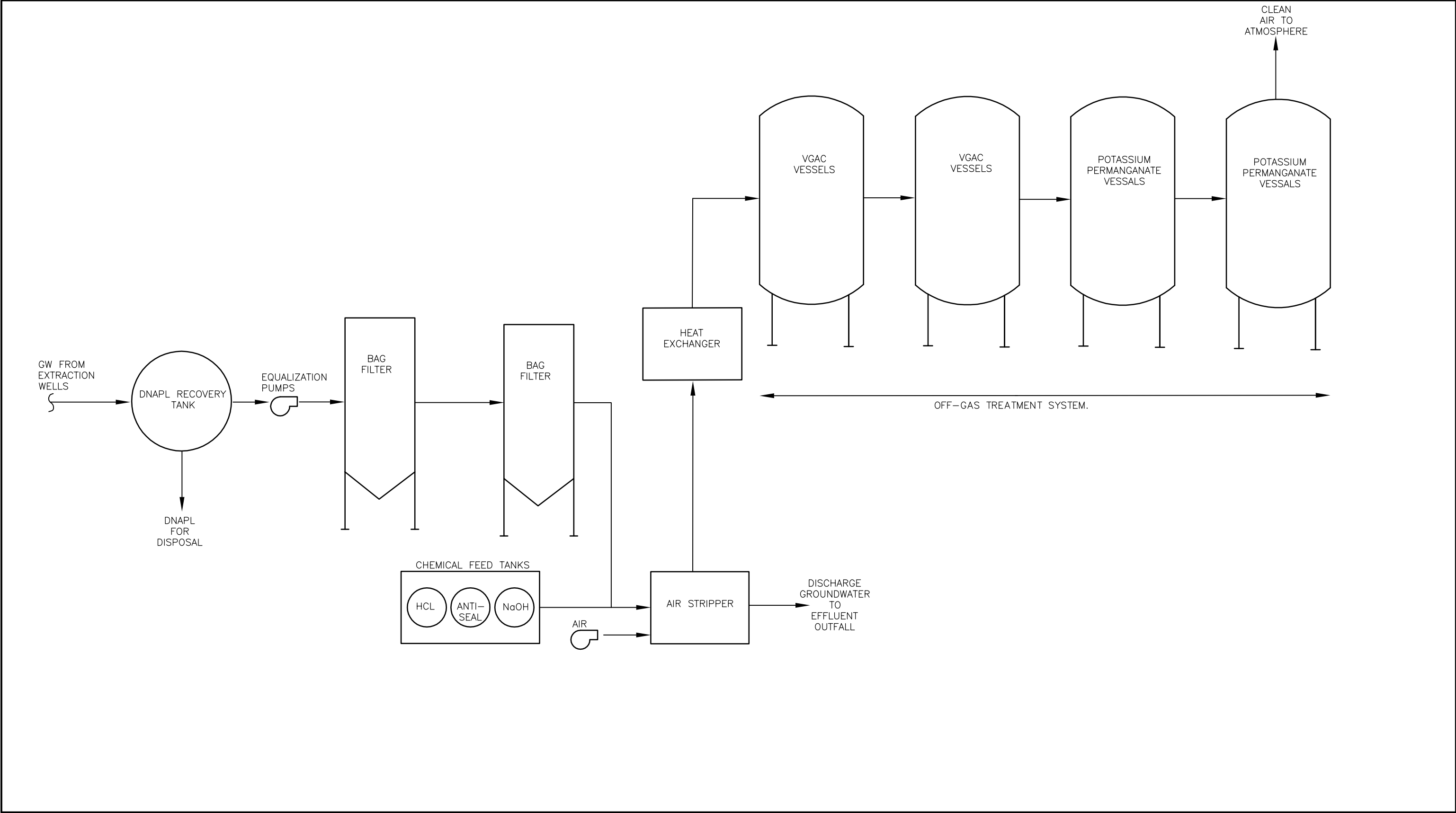
Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

ALTERNATIVE 2 - EXPANSION OF PUMP AND TREAT SYSTEM
TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 8-1



United States
Environmental Protection
Agency



PROJECT TITLE

TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS
TUTU WELLS SUPERFUND SITE FOCUSED SOURCE RI/FS OU2

PROJECT NUMBER

REFERENCE SHEET

SHEET TITLE

ALTERNATIVE 2
PUMP AND TREAT SYSTEM
PROCESS FLOW DIAGRAM

PROJECT MANAGER

SCALE

DATE

FIGURE

8-2



ALTERNATIVE 2A - EXPANSION OF PUMP AND TREAT SYSTEM AND REINJECTION

TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 8-3





LEGEND

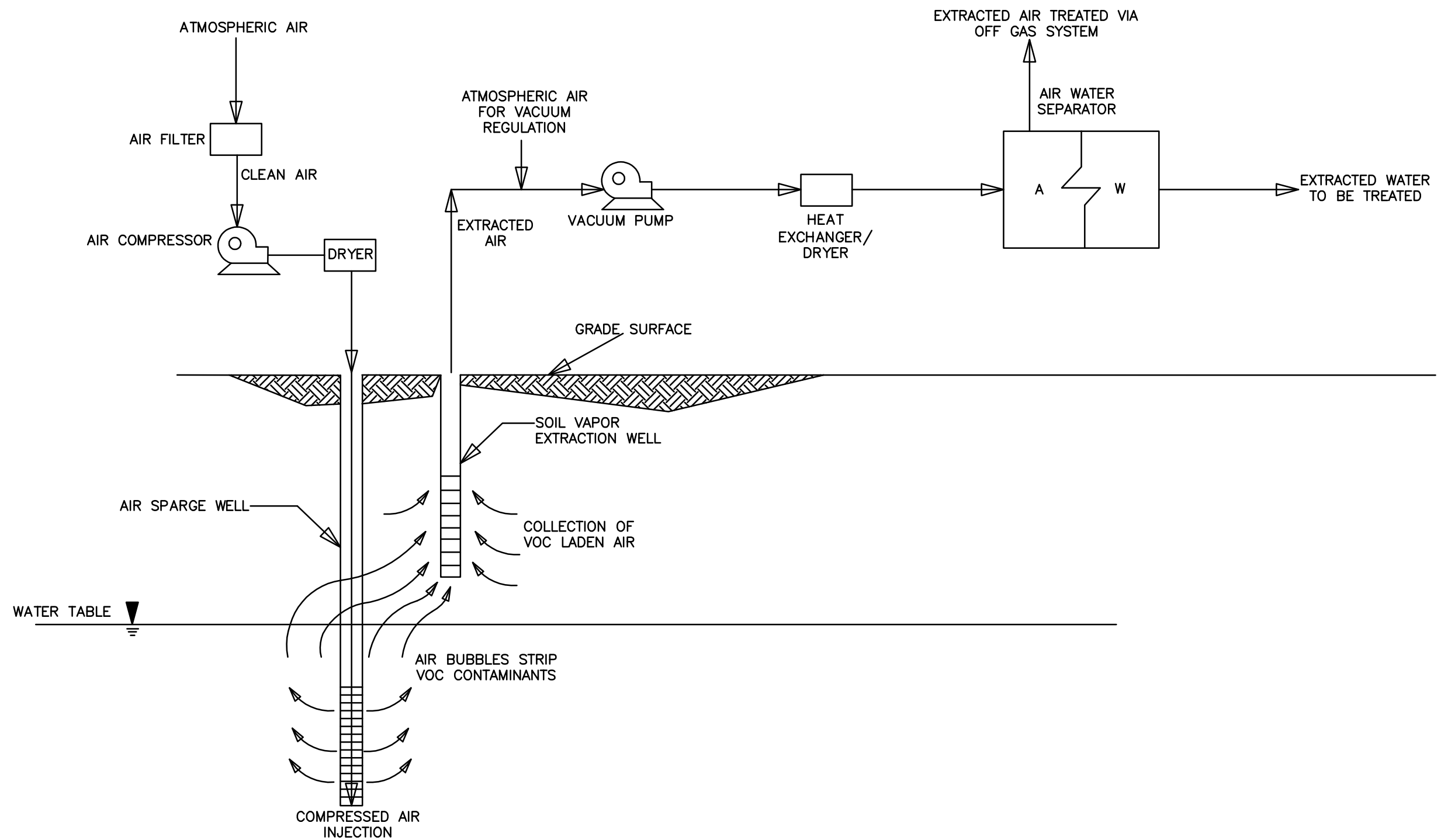
- Air Sparge (AS) Well
- Soil Vapor Extraction (SVE) Well
- Treatment System Wells (New)
- Vacuum Piping
- - - Air Sparging Piping
- ▭ Potential Source

NOTES:

1. Approximately 24 to 30 AS wells assumed to be installed to a depth of 140 feet bgs, assumed 50 feet radius of influence.
2. Approximately 20 to 25 SVE wells assumed to be installed to a depth of 15 to 20 feet bgs, assumed 80 feet radius of influence.
3. Water table encountered from 15 to 30 feet bgs.

0 Feet 50

Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



PROJECT TITLE

TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS
TUTU WELLS SUPERFUND SITE FOCUSED SOURCE RI/FS OU2

SHEET TITLE

ALTERNATIVE 2B
AIR SPARGING/SOIL VAPOR EXTRACTION
PROCESS FLOW DIAGRAM

PROJECT NUMBER

PROJECT MANAGER

DATE

REFERENCE SHEET

SCALE

FIGURE

8-5



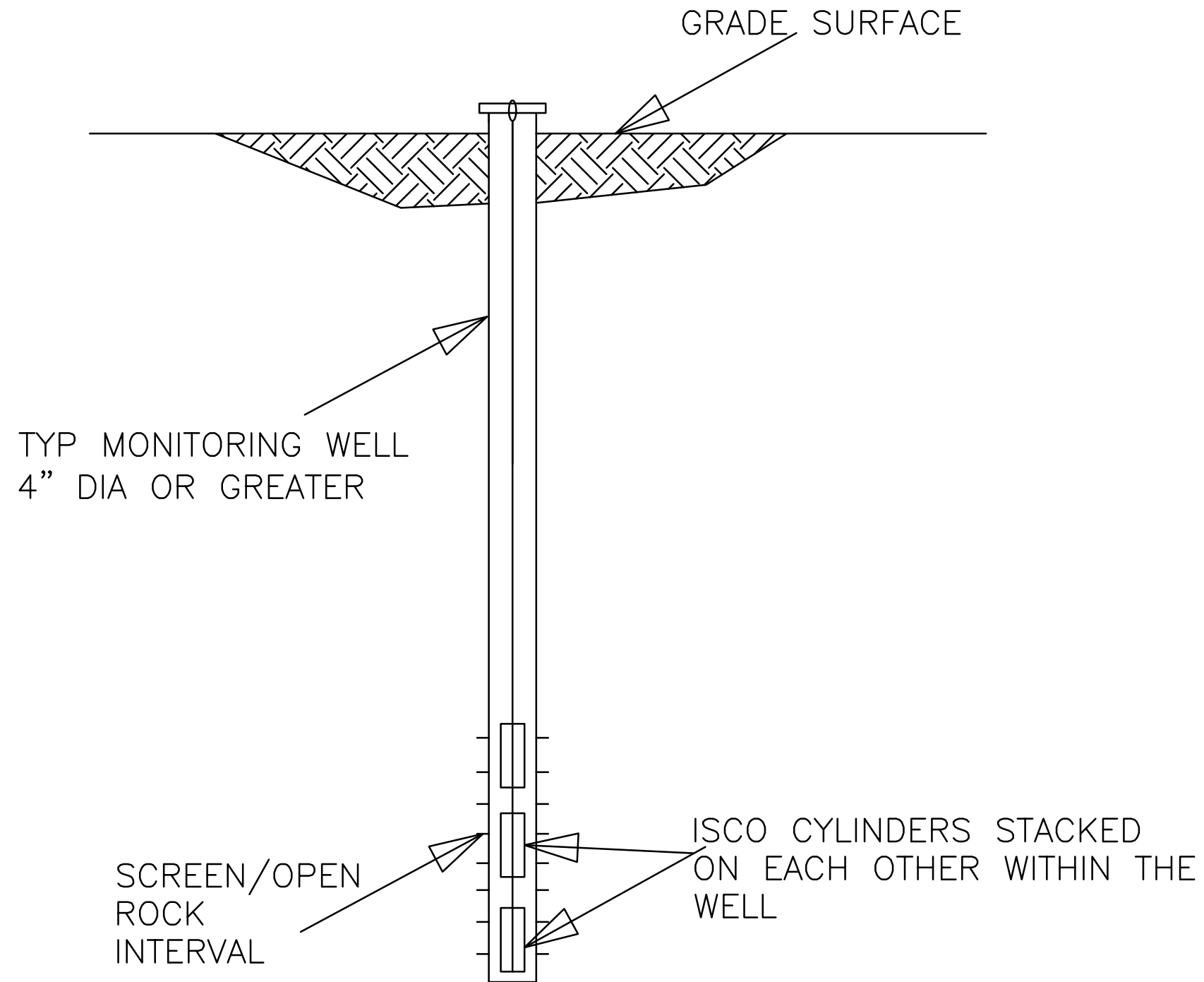
ALTERNATIVE 2C- EXPANSION OF PUMP AND TREAT SYSTEM AND ISCO CYLINDERS

ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 8-6



United States
Environmental Protection
Agency



PROJECT TITLE

TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS
TUTU WELLS SUPERFUND SITE FOCUSED SOURCE RI/FS OU2

SHEET TITLE

ALTERNATIVE 2C
ISCO CYLINDER SCHEMATIC

PROJECT NUMBER

PROJECT MANAGER

DATE

REFERENCE SHEET

SCALE

FIGURE

8-7



Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

ALTERNATIVE 2D - EXPANSION OF PUMP AND TREAT SYSTEM AND SURFACTANT FLUSHING
TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 8-8



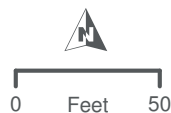


LEGEND

- Treatment System Wells (New)
- Approximate Extent of Thermal Treatment Area

NOTES:

1. Approximately 260 to 270 heater wells installed to an approximate depth of 140 ft bgs are assumed to be installed in a grid layout. Distance between wells assumed approximately 13 ft.
2. Approximately 260 to 270 co-located vapor recovery wells estimated.



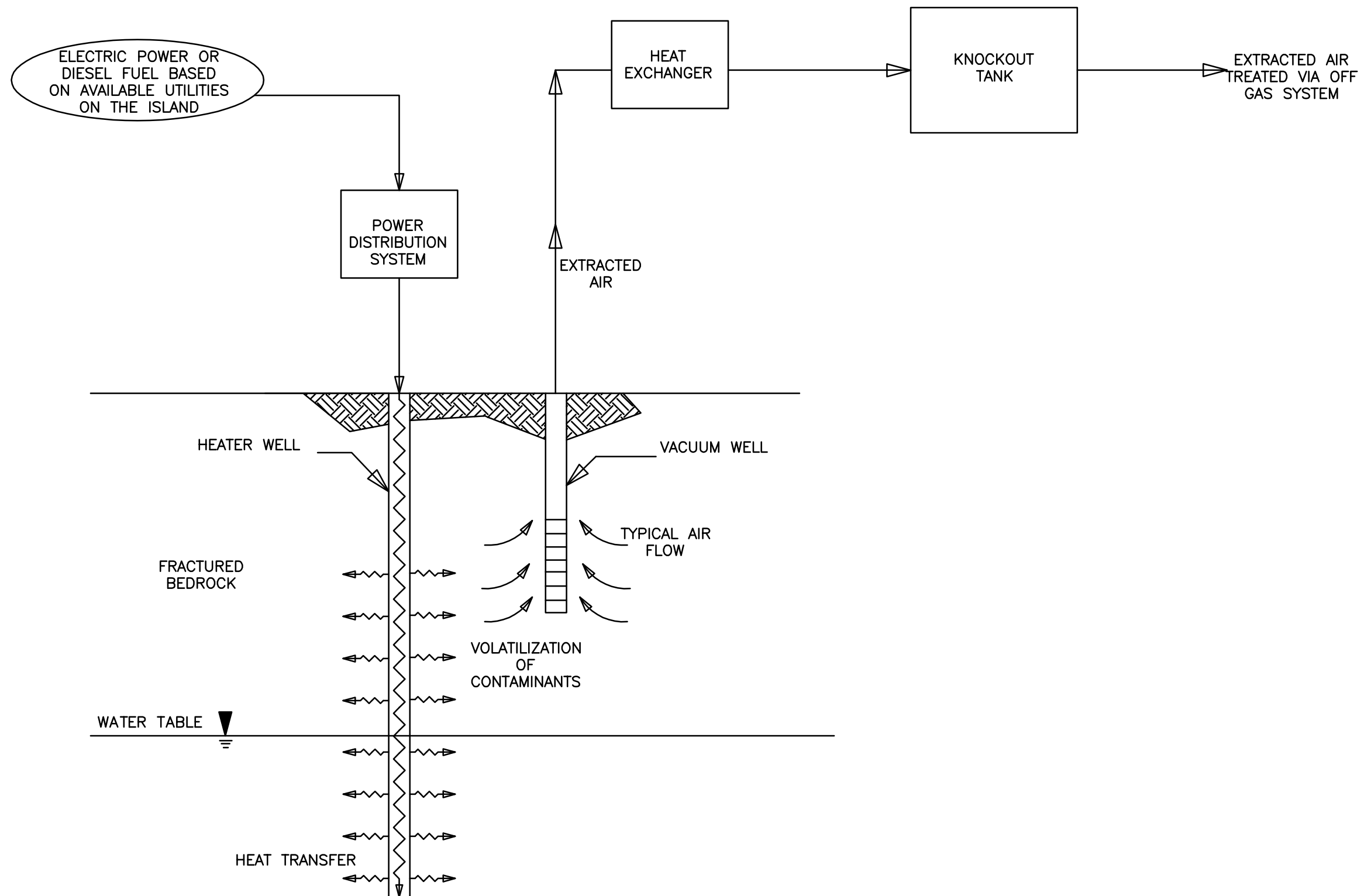
Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

ALTERNATIVE 3 - IN SITU THERMAL TREATMENT AND PUMP AND TREAT
TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 8-9



United States
Environmental Protection
Agency



PROJECT TITLE

TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS
TUTU WELLS SUPERFUND SITE FOCUSED SOURCE RI/FS OU2

PROJECT NUMBER

REFERENCE SHEET

SHEET TITLE

ALTERNATIVE 3
IN-SITU THERMAL TREATMENT
PROCESS FLOW DIAGRAM

PROJECT MANAGER

SCALE

DATE

FIGURE

8-10

LEGEND

-  Treatment System Wells (New)
-  Approximate Extent of Steam Treatment Area

NOTES:

1. Approximately 30 multiphase extraction wells installed to an approximate depth of 140 ft bgs. Distance between wells assumed approximately 45 ft.
2. Approximately 60 steam injection wells.
3. Approximately 10 temperature monitoring wells.

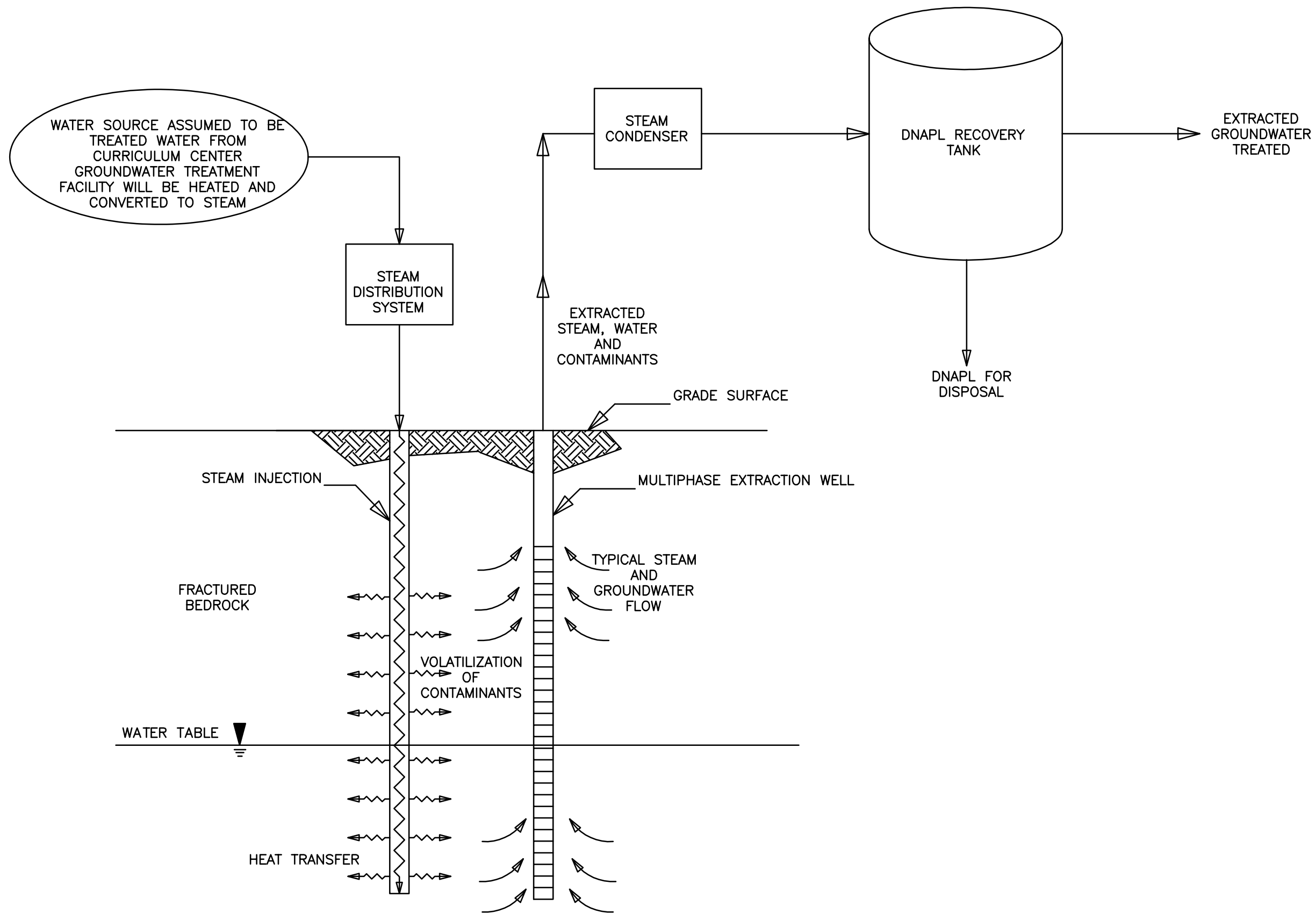


Data Source: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



ALTERNATIVE 4 - STEAM INJECTION AND PUMP AND TREAT TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS

FIGURE 8-11



PROJECT TITLE

TUTU OU2, ST. THOMAS, U.S. VIRGIN ISLANDS
TUTU WELLS SUPERFUND SITE FOCUSED SOURCE RI/FS OU2

PROJECT NUMBER

REFERENCE SHEET

SHEET TITLE

ALTERNATIVE 4
STEAM INJECTION
PROCESS FLOW DIAGRAM

PROJECT MANAGER

SCALE

DATE

FIGURE

8-12

APPENDIX A

COST ESTIMATE BACKUP SUMMARY

Appendix A Summary of Total Cost of Remedial Alternatives

Site: Tutu Wells Superfund Site Operable Unit 2	Base Year: 2021
Location: St. Thomas, USVI	Date: January 13, 2021
Phase: Feasibility Study (-30% - +50%)	

	Alternative 1	Alternative 2	Enhancements to Alternative 2 ¹				Alternative 3	Alternative 4
			Alternative 2A	Alternative 2B	Alternative 2C	Alternative 2D		
Description	No Action	Expand Existing Pump and Treat System	Reinjection	AS/SVE	In Situ Chemical Oxidation	Surfactant Flushing	In Situ Thermal Treatment and Pump and Treat	In Situ Steam Injection and Pump and Treat
Estimated Duration for Source Area Treatment (Years)	-	-	-	The AS/SVE system at the source area is assumed to be implemented for 5 years. During this time it is assumed that source material in the fractures will be removed. Hydraulic control will be maintained by the pump and treat system.	ISCO at the source area is assumed to be implemented for 5 years. During this time it is assumed that source material in the fractures will be removed. Hydraulic control will be maintained by the pump and treat system.	Surfactant flushing is assumed to be implemented for a period of 1 year. During this time it is assumed that source material in the fractures will be removed. Hydraulic control will be maintained by the pump and treat system.	Thermal treatment is assumed to be implemented for a period of 2 years. During this time it is assumed that source material in the fractures and rock matrix will be removed. Hydraulic control will be maintained by the pump and treat system.	Steam injections is assumed to be implemented for a period of 2 years. During this time it is assumed that source material in the fractures will be removed. Hydraulic control will be maintained by the pump and treat system.
Estimated Duration for Pump and Treat/Remedial System (Years)		>30; for cost estimating purposes the pump and treat system is assumed to be active for 30 years	>30; for cost estimating purposes the pump and treat system is assumed to be active for 30 years	Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will be active for a total of 30 years.	Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will be active for a total of 30 years.	Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will be active for a total of 26 years.	It is estimated that contamination outside of the thermal treatment area will take 10 years to reach the perimeter pump and treat system. Therefore, the remedial system will be active for a total of 12 years.	Based on calculations, upon removal of the source, concentrations downgradient from the source will reach PRGs in 25 years, during which time hydraulic control will continue to be maintained. The remedial system will therefore be active for a total of 27 years.
Estimated Long Term Monitoring (Years)	-	30	30	30	30	26	12	27
Total Capital Cost	\$ -	\$ 4,802,538	\$ 437,053	\$ 1,739,745	\$ 99,364	\$ 1,265,756	\$ 89,628,605	\$ 25,568,569
Annual O&M Cost	\$ -	\$ 8,481,677	\$ 51,364	\$ 205,461	\$ 117,110	Same as Alt 2	\$ 4,569,283	\$ 8,539,451
Periodic Cost	\$ -	\$ 56,350	Same as Alt 2	Same as Alt 2	Same as Alt 2	Same as Alt 2	\$ 111,890	\$ 63,180
Total Present Value of Alternatives	\$ -	\$ 13,340,565	\$ 488,417	\$ 1,945,206	\$ 216,474	\$ 1,265,756	\$ 94,309,778	\$ 34,171,200

Notes:

1. Cost shown for enhancements to Alternative 2 are additive to the cost for Alternative 2. Enhancement Alternative 2A, 2B, 2C, 2D-Annual O&M cost if applicable is for operations only. LTM costs are included in Alternative 2

Appendix A1 - Cost Estimate for Alternative 1

Alternative 1

No Action

COST ESTIMATE SUMMARY

Site: Tutu Wells Superfund Site Operable Unit 2 **Description:** Alternative 1 consists of no action.
Location: St. Thomas, USVI
Phase: Feasibility Study (-30% - +50%)
Base Year: 2021
Date: January 13, 2021

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	Capital Costs					
1.1	No Capital Costs	0	LS	\$ -	0	
	Sub-Total				0	
2	Institutional Controls					
2.1	No Institutional Controls	0	LS	\$ -	0	
	Sub-Total				0	
	TOTAL CAPITAL COST				0	

ANNUAL O&M COST:						
Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
1	Annual O&M Costs					
1.1	No Annual O&M Costs	0	LS	\$ -	0	
	Sub-Total				0	
2	Maintenance					
2.1	No Maintenance Costs	0	LS	\$ -	0	
	Sub-Total				0	
	Sub-Total				0	
	Contingency	15%			0	
	Sub-Total				0	
	Project Management				0	
	Technical Support				0	

PERIODIC COSTS:						
Item No.	Description	Year	Quantity	Unit	Unit Cost	Total
1	Periodic Costs					
1.1	No Periodic Costs		0	LS	\$ -	0
	Sub-Total					0

PRESENT VALUE ANALYSIS:						
		Rate of Return: 7%		Interest Rate: 3%		
Item No.	Cost Type	Year	Total Cost		Present Value	Notes
1	Capital Cost	0			0	
2	Annual O&M Cost		0		0	
3	Periodic Costs		0		0	
	TOTAL PRESENT VALUE OF ALTERNATIVE				0	

Appendix A2 - Cost Estimate for Alternative 2

Alternative 2

COST ESTIMATE SUMMARY

Expand Existing Pump and Treat System

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 2 consists of:	
Location:	St. Thomas, USVI		i.) Expansion of existing system with addition of new extraction wells downgradient;	ii)
Phase:	Feasibility Study (-30% - +50%)		Operate at higher capacity with combination of extraction wells;	
Base Year:	2021		iii) Replace all existing treatment equipment and conveyance piping, upgrade existing PLC system, and replace EQ tank for DNAPL separator;	
Date:	January 13, 2021		iv) Alternate pumping from existing monitoring wells with high contaminant concentrations; and	
			v) Dual phase extraction/EFR from source area wells	

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	Site Survey and Utility Clearance					
1.1	Survey	1	LS	\$ 15,000	\$ 15,000	
1.2	Utility Clearance	1	LS	\$ 15,000	\$ 15,000	
	Sub-Total				\$ 30,000	
2	Pre-Design Investigation					
2.1	Investigation Work Plan	1	LS	\$ 100,000	\$ 100,000	Sampling Plan, QAPP, HASP
2.2	Mobilization/ Demobilization	1	LS	\$ 100,000	\$ 100,000	Mobilize all equipment and personnel to USVI
2.3	Site Preparation	1	LS	\$ 18,500	\$ 18,500	Clearing/ Grubbing drilling locations
2.4	Permits	1	LS	\$ 10,000	\$ 10,000	Local Permits
2.5	Bedrock Drilling	700	LF	\$ 75	\$ 52,500	Five, 2-inch diameter MWs installed to 140 ft bgs.
2.6	Grouting Open Boreholes	100	LF	\$ 20	\$ 2,000	Back grouting boreholes as necessary. Assume 20 ft/ MW
2.7	Flush-mount curb box with inner locking cap	5	EA	\$ 300	\$ 1,500	For monitoring wells
2.8	Monitoring Well Redevelopment	40	hr	\$ 350	\$ 14,000	Assume 8 hrs per MW
2.9	Groundwater Sampling and Data Evaluation	1	LS	\$ 50,000	\$ 50,000	Assume 30 wells for baseline
2.10	Surface Repair	1	LS	\$ 6,000	\$ 6,000	
2.11	Water Level Measurements	1	LS	\$ 1,500	\$ 1,500	
2.12	Hydrogeologic Assessment - Pumping Test	1	LS	\$ 100,000	\$ 100,000	
2.13	Extraction Well Redevelopment	1	LS	\$ 100,000	\$ 100,000	
2.14	Hydrogeologic Evaluation	1	LS	\$ 75,000	\$ 75,000	
2.15	IDW Characterization and Disposal	1	LS	\$ 30,000	\$ 30,000	Sleeves, decon water, misc. used items, groundwater waste from well installation and redevelopment.
2.16	PDI Report	1	LS	\$ 50,000	\$ 50,000	
	Sub-Total				\$ 711,000	
3	Site Mobilization/Demobilization					
3.1	Remedial Action Work plan/Permitting	1	LS	\$ 100,000	\$ 100,000	Permit equivalents, access agreements, RAWP, Construction HASP, Subcontractor procurement
3.2	Submittals/Implementation Plans	1	LS	\$ 100,000	\$ 100,000	Remedial Design reports
3.3	Post Construction Submittals	1	LS	\$ 75,000	\$ 75,000	Bi-weekly reports, monthly progress reports
3.4	Decontamination Station	1	LS	\$ 5,000	\$ 5,000	
	Sub-Total				\$ 280,000	
4	Health and Safety					
4.1	PPE and Field Supplies	1	LS	\$ 5,000	\$ 5,000	
	Sub-Total				\$ 5,000	
5	Site Preparation					
5.1	Temporary Security Fence	1,000	LF	\$ 30	\$ 30,000	
	Sub-Total				\$ 30,000	
6	Treatment Plant Upgrades					
6.1	Demolition and Replacement of Existing Equipment	1	LS	\$ 1,000,000	\$ 1,000,000	Includes the demolition and replacement of treatment equipment such as EW pumps, transfer pumps, air stripper, air stripper blower, bag filters, EQ tank for DNAPL recovery tank, piping, PLC, chemical feed metering pumps and tank, heat exchanger, 2 GAC vessels, 2 permanganate vessels. Also includes cost for alternate pumping labor and equipment.
	Sub-Total				\$ 1,000,000	

Appendix A2 - Cost Estimate for Alternative 2

Alternative 2

Expand Existing Pump and Treat System

COST ESTIMATE SUMMARY

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 2 consists of:	
Location:	St. Thomas, USVI		i.) Expansion of existing system with addition of new extraction wells downgradient;	ii)
Phase:	Feasibility Study (-30% - +50%)		Operate at higher capacity with combination of extraction wells;	
Base Year:	2021		iii) Replace all existing treatment equipment and conveyance piping, upgrade existing PLC system, and replace EQ tank for DNAPL separator;	
Date:	January 13, 2021		iv) Alternate pumping from existing monitoring wells with high contaminant concentrations; and	
			v) Dual phase extraction/EFR from source area wells	

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
7	New Extraction Well Drilling					
7.1	Mobilization/ Demobilization	1	LS	\$ 50,000	\$ 50,000	
7.2	Per Diem (Per working crew day)	20	Crew-day	\$ 750	\$ 15,000	Estimate 10 days per well
7.3	Standby	8	HR	\$ 450	\$ 3,600	
7.4	Grouting Open Boreholes	100	LF	\$ 20	\$ 2,000	
7.5	Bedrock Drilling	280	LF	\$ 75	\$ 21,000	Assume each well is 140 ft bgs
7.6	Steel Casing	100	LF	\$ 50	\$ 5,000	Assume casing goes to 50 ft bgs for each well
7.7	Extraction Well Vault	2	EA	\$ 5,000	\$ 10,000	
7.8	Borehole/ Well Development	20	HR	\$ 375	\$ 7,500	
7.9	Dual Packer Testing	16	HR	\$ 525	\$ 8,400	
7.10	Site Access, Set-up, Breakdown and Restoration	1	LS	\$ 20,000	\$ 20,000	
7.11	Drums	100	EA	\$ 150	\$ 15,000	
7.12	Manage IDW	20	HR	\$ 350	\$ 7,000	
7.13	Decon	20	HR	\$ 250	\$ 5,000	
	Sub-Total				\$ 169,500	
8	Conveyance Piping					
8.1	Mobilization	1	LS	\$ 30,000	\$ 30,000	
8.2	Soil Erosion and Sediment Control	1,000	LF	\$ 5	\$ 5,000	
8.3	Trenching	593	CY	\$ 50	\$ 29,630	
8.4	Pipe (HDPE double walled)	1,000	LF	\$ 30	\$ 30,000	Piping from the extraction wells to the treatment plant.
8.5	Utility Marking Tape	1,000	LF	\$ 0.30	\$ 300	
8.6	Bedding	593	CY	\$ 20	\$ 11,852	
8.7	Backfill and Compaction	4,000	SF	\$ 5	\$ 20,000	
8.8	Vaults and Junctions	4	EA	\$ 6,500	\$ 26,000	Assume 2 vaults and 2 cleanouts
	Sub-Total				\$ 152,781	
9	DPE/EFR Events					
9.1	Pilot Study	1	LS	\$ 50,000	\$ 50,000	includes reporting
9.2	15-mil geomembrane liner with soil cover	60,000	SF	\$ 1.00	\$ 60,000	Vendor estimate
9.3	EFR Events at Source Area Wells	10	Each	\$ 60,000	\$ 600,000	Assume twice a year for 5 years
9.4	Vapor and Liquid sampling	140	Each	\$ 1,500	\$ 18,000	Assume a vapor and liquid sample at each EFR well (7) twice a year for 5 years
	Sub-Total				\$ 728,000	
10	Reporting and Institutional Controls					
10.1	Remedial Action Report	1	LS	\$ 50,000	\$ 50,000	
10.2	Institutional Controls & Site Management Plan	1	LS	\$ 20,000	\$ 20,000	
	Sub-Total				\$ 70,000	
	Sub-Total				\$ 3,176,281	Sub-Total All Construction Costs.
	Contingency	20%			\$ 635,256	10% scope + 10% bid
	Sub-Total				\$ 3,811,538	
	Project Management	6%			\$ 228,692	
	Remedial Design	12%			\$ 457,385	
	Construction Management	8%			\$ 304,923	
	TOTAL CAPITAL COST				\$ 4,802,538	

Appendix A2 - Cost Estimate for Alternative 2

Alternative 2

Expand Existing Pump and Treat System

COST ESTIMATE SUMMARY

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 2 consists of:	
Location:	St. Thomas, USVI		i.) Expansion of existing system with addition of new extraction wells downgradient;	ii)
Phase:	Feasibility Study (-30% - +50%)		Operate at higher capacity with combination of extraction wells;	
Base Year:	2021		iii) Replace all existing treatment equipment and conveyance piping, upgrade existing PLC system, and replace EQ tank for DNAPL separator;	
Date:	January 13, 2021		iv) Alternate pumping from existing monitoring wells with high contaminant concentrations; and	
			v) Dual phase extraction/EFR from source area wells	

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes	
ANNUAL O&M COST							
Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Operations Costs - Year 1 to 30	1 to 30					Every year through year 30.
1.1	Electrical Usage		150,000	KW-Hr	\$ 0.47	\$ 69,810	P&T system operates for 30 years
1.2	Vapor Carbon Usage		10,000	LB	\$ 4.00	\$ 40,000	Change out both units once per year, estimate 5,000 lbs ea
1.3	Vapor Carbon Disposal		10,000	lb	\$ 1.00	\$ 10,000	
1.4	Potassium Permanganate Usage		14,000	LB	\$ 4.00	\$ 56,000	
1.5	Potassium Permanganate Disposal		1	EA	\$ 3,000.00	\$ 3,000	
1.6	Weekly Inspections		52	EA	\$ 600.00	\$ 31,200	1x per week
1.7	Effluent Sampling		12	EA	\$ 1,500	\$ 18,000	Monthly Influent, Effluent Air Sampling and between GAC vessels for VOCs; includes labor
1.8	DNAPL Shipping and Disposal		3	EA	\$ 12,500	\$ 37,500	Assume 3, 55 gallon drums of DNAPL are generated annually and need to be disposed offsite.
1.9	Reporting		12	Month	\$ 5,000	\$ 60,000	Monthly
	Sub-Total					\$ 325,510	
	Contingency	15%				\$ 48,827	
	ANNUAL OPERATIONS COST (Year 1 to 30)					\$ 374,337	
2	LTM - Year 1 to 30	1 to 30					Every year through year 30.
2.1	Groundwater Sampling		30	EA	\$ 750	\$ 22,500	30 wells annually; includes labor
2.2	Groundwater Sample Laboratory Analysis		36	EA	\$ 550	\$ 19,800	Total VOCs analysis + 20% QC samples.
2.3	Data Reduction, Evaluation and Reporting		1	EA	\$ 20,000	\$ 20,000	
2.4	Annual Report		1	EA	\$ 24,000	\$ 24,000	Includes periodic report
	Sub-Total					\$ 86,300	
	Contingency	15%				\$ 12,945	
	ANNUAL LTM COST (Year 1 to 30)					\$ 99,245	
	Project Management					\$ 5,000	
	Technical Support					\$ 5,000	

Appendix A2 - Cost Estimate for Alternative 2

Alternative 2

Expand Existing Pump and Treat System

COST ESTIMATE SUMMARY

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 2 consists of:	
Location:	St. Thomas, USVI		i.) Expansion of existing system with addition of new extraction wells downgradient;	ii)
Phase:	Feasibility Study (-30% - +50%)		Operate at higher capacity with combination of extraction wells;	
Base Year:	2021		iii) Replace all existing treatment equipment and conveyance piping, upgrade existing PLC system, and replace EQ tank for DNAPL separator;	
Date:	January 13, 2021		iv) Alternate pumping from existing monitoring wells with high contaminant concentrations; and	
			v) Dual phase extraction/EFR from source area wells	

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes	
PERIODIC COSTS							
Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Decommission System and Site Close Out	30					At the end of Year 30
1.1	Decommission System		1	LS	\$ 50,000	\$ 50,000	
1.2	Monitoring Well Abandonment		30	EA	\$ 1,500	\$ 45,000	Drilling subcontractor, abandonment of monitoring wells
1.3	Final Closure Report		1	LS	\$ 50,000	\$ 50,000	
	Sub-Total					\$ 145,000	
	Contingency		15%			\$ 21,750	
	Project Management					\$ 5,000	
	Technical Support					\$ 5,000	
	PERIODIC COSTS (Year 30)					\$ 176,750	

PRESENT VALUE ANALYSIS:		Rate of Return: 7%		Inflation Rate 3%		
Item No.	Cost Type	Year	Total Cost	Present Value		Notes
1	Capital Cost	0		\$ 4,802,538		
2	Annual O&M Cost					
2.1	Year 1 to 30	1 to 30	483,582	\$8,481,677		Operations and LTM
3	Periodic Costs					
3.1	Year 30	30	176,750	\$56,350		Decommission System and Site Close Out
	Sub-Total			\$ 56,350		
	TOTAL PRESENT VALUE OF ALTERNATIVE			\$ 13,340,565		

Appendix A2A - Cost Estimate for Alternative 2A

Alternative 2A Reinjection

COST ESTIMATE SUMMARY

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 2A consists of :
Location:	St. Thomas, USVI		i) Includes additional components and cost to Alternative 2 for reinjection of treated water downgradient via injection wells.
Phase:	Feasibility Study (-30% - +50%)		
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	Injection Wells					Drilling and Piping
1.1	Mobilization/ Demobilization	1	LS	\$ 50,000	\$ 50,000	
1.2	Per Diem (Per working crew day)	20	Crew-day	\$ 750	\$ 15,000	Assume 2 injection wells, estimate 10 days per well
1.3	Standby	8	HR	\$ 450	\$ 3,600	
1.4	Grouting Open Boreholes	40	LF	\$ 20	\$ 800	
1.5	Bedrock Drilling	280	LF	\$ 75	\$ 21,000	
1.6	Steel Casing	40	LF	\$ 50	\$ 2,000	Assume 10ft of casing per injection well
1.7	Injection Well Vault	2	EA	\$ 5,000	\$ 10,000	
1.8	Borehole/ Well Development	20	HR	\$ 375	\$ 7,500	Assume 10hr per well
1.9	Site Access, Set-up, Breakdown and Restoration	1	LS	\$ 20,000	\$ 20,000	
1.10	Drums	100	EA	\$ 150	\$ 15,000	
1.11	Manage IDW	20	HR	\$ 350	\$ 7,000	
1.12	Decon	20	HR	\$ 250	\$ 5,000	
1.13	Soil Erosion and Sediment Control	1,000	LF	\$ 5	\$ 5,000	Injection well water conveyance estimate
1.14	Trenching	593	CY	\$ 50	\$ 29,630	
1.15	Pipe (HDPE)	1,000	LF	\$ 30	\$ 30,000	Includes labor and material
1.17	Utility Marking Tape	1,000	LF	\$ 0.30	\$ 300	
1.18	Bedding	593	CY	\$ 20	\$ 11,852	
1.19	Backfill and Compaction	4,000	SF	\$ 5	\$ 20,000	
1.20	Asphalt/ concrete repair	1,000	SF	\$ 5	\$ 5,000	
1.21	Asphalt/ concrete disposal	35	Ton	\$ 125	\$ 4,375	
1.22	Vaults and Junctions	4	EA	\$ 6,500	\$ 26,000	Assume 2 vaults, 2 cleanouts
	Sub-Total				\$ 289,056	
	Contingency	20%			\$ 57,811	10% scope + 10% bid
	Sub-Total				\$ 346,868	
	Project Management	6%			\$ 20,812	
	Remedial Design	12%			\$ 41,624	
	Construction Management	8%			\$ 27,749	
	TOTAL CAPITAL COST				\$ 437,053	

ANNUAL O&M COST

Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Operations Costs - Year 1 to 30	1 to 30					Every year through year 30.
1.1	Well Redevelopment		1	LS	\$ 10,000	\$ 10,000	Assumed once per year, 2 wells
	Sub-Total					\$ 10,000	
	Contingency	15%				\$ 1,500	
	ANNUAL OPERATIONS COST (Year 1 to 30)					\$ 11,500	
2	ANNUAL LTM COSTS ARE INCLUDED IN ALTERNATIVE 2						

PERIODIC COSTS ARE INCLUDED IN ALTERNATIVE 2

PRESENT VALUE ANALYSIS:

Item No.	Cost Type	Rate of Return: 7%		Inflation Rate 3%		Notes
		Year	Total Cost		Present Value	
1	Capital Cost	0			\$ 437,053	
2	Annual O&M Cost					
2.1	Year 1 to 30	1 to 30	11,500		\$ 51,364	Operations only. LTM, Project Management and Tech support costs included in Alternative 2
3	Periodic Costs	30			-	Included in Alternative 2
	TOTAL PRESENT VALUE OF ALTERNATIVE				\$ 488,417	In addition to costs under Alternative 2

Appendix A2B - Cost Estimate for Alternative 2B

Alternative 2B

Air Sparging/Soil Vapor Extraction

COST ESTIMATE SUMMARY

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 2B consists of :
Location:	St. Thomas, USVI		i) Includes additional components and cost to Alternative 2 for pulsed air sparging with SVE at source areas.
Phase:	Feasibility Study (-30% - +50%)		
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	Air Sparge/ Soil Vapor Extraction System					
1.1	Air Sparging Well Drilling	4,200	LF	\$ 75	\$ 315,000	
1.2	Soil Vapor Extraction Well Drilling	375	LF	\$ 75	\$ 28,125	
1.3	Air Sparge Well Install	30	EA	\$ 2,000	\$ 60,000	
1.4	SVE Well Install	25	EA	\$ 2,000	\$ 50,000	
1.5	Air Sparging/SVE Equipment/Components	1	LS	\$ 250,000	\$ 250,000	
1.6	Process Equipment Enclosure	400	SF	\$ 100	\$ 40,000	Includes foundation, electric, construction, site work, HVAC
1.7	Power Service	1	LS	\$ 50,000	\$ 50,000	Includes transformer
1.8	Trenching	2,000	LF	\$ 50	\$ 100,000	
1.9	15-mil geomembrane liner with soil cover	60,000	SF	\$ 1	\$ 60,000	
1.10	Vapor Phase GAC Vessels	10,000	EA	\$ 4	\$ 40,000	
1.11	IDW Characterization and Disposal	1	LS	\$ 100,000	\$ 100,000	
1.12	Well Survey	5	DAY	\$ 1,500	\$ 7,500	
1.13	Pilot Study	1	LS	\$ 50,000	\$ 50,000	Pilot Study to determine radius of influence and blower capacity needed
	Sub-Total				\$ 1,150,625	
	Contingency	20%			\$ 230,125	10% scope + 10% bid
	Sub-Total				\$ 1,380,750	
	Project Management	6%			\$ 82,845	
	Remedial Design	12%			\$ 165,690	
	Construction Management	8%			\$ 110,460	
	TOTAL CAPITAL COST				\$ 1,739,745	

ANNUAL O&M COST

Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Operations Costs - Year 1 to 5	1 to 5					Every year through year 5.
1.1	Vapor Carbon Usage		10,000	LB	\$ 4.00	\$ 40,000	Change out both units once per year, estimate 5,000 lbs ea
1.2	Vapor Carbon Disposal		1	EA	\$ 1.00	\$ 1	
	Sub-Total					\$ 40,001	
	Contingency		15%			\$ 6,000	
	ANNUAL OPERATIONS COST (Year 1 to 5)					\$ 46,001	

2 ANNUAL LTM COSTS ARE INCLUDED IN ALTERNATIVE 2

PERIODIC COSTS ARE INCLUDED IN ALTERNATIVE 2

PRESENT VALUE ANALYSIS:

Item No.	Cost Type	Rate of Return: 7%		Inflation Rate 3%		Notes
		Year	Total Cost	Present Value		
1	Capital Cost	0		\$ 1,739,745		
2	Annual O&M Cost					
2.1	Year 1 to 5	1 to 5	46,001	\$ 205,461		Operations only. LTM costs included in Alternative 2
3	Periodic Costs	30	-	-		Included in Alternative 2
	TOTAL PRESENT VALUE OF ALTERNATIVE			\$ 1,945,206		In addition to costs under Alternative 2

Appendix A2C - Cost Estimate for Alternative 2C

Alternative 2C

COST ESTIMATE SUMMARY

In Situ Chemical Oxidation

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 2C consists of:
Location:	St. Thomas, USVI		i) Includes additional components and cost to Alternative 2 for installing ISCO cylinders in select source wells.
Phase:	Feasibility Study (-30% - +50%)		
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	In Situ Chemical Oxidation					
1.1	ISCO Cylinders	12	Well	\$ 1,900	\$ 22,800	Includes material and shipping
1.2	Installation	1	LS	\$ 1,500	\$ 1,500	Labor
1.3	Pilot Study	1	LS	\$ 50,000	\$ 50,000	Pilot study to determine oxidant and engineering parameters
	Sub-Total				\$ 74,300	
	Contingency	20%			\$ 4,560	10% scope + 10% bid
	Sub-Total				\$ 78,860	
	Project Management	6%			\$ 4,732	
	Remedial Design	12%			\$ 9,463	
	Construction Management	8%			\$ 6,309	
	TOTAL CAPITAL COST				\$ 99,364	

ANNUAL O&M COST

Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Operations Costs - Year 1 to 5	1 to 5					Every year through year 5.
1.1	Replacement of cylinders		12	Well	\$ 1,900	\$ 22,800	
	Sub-Total					\$ 22,800	
	Contingency	15%				\$ 3,420	
	ANNUAL OPERATIONS COST (Year 1 to 5)					\$ 26,220	
2	ANNUAL LTM COSTS ARE INCLUDED IN ALTERNATIVE 2						

PERIODIC COSTS ARE INCLUDED IN ALTERNATIVE 2

PRESENT VALUE ANALYSIS:

Item No.	Cost Type	Rate of Return: 7%		Inflation Rate 3%		Notes
		Year	Total Cost	Present Value		
1	Capital Cost	0		\$ 99,364		
2	Annual O&M Cost					
2.1	Year 1 to 5	1 to 5	26,220	\$ 117,110		Operations only. LTM costs included in Alternative 2
3	Periodic Costs	30	-	-		Included in Alternative 2
	TOTAL PRESENT VALUE OF ALTERNATIVE			\$ 216,474		In addition to costs under Alternative 2

Appendix A2D - Cost Estimate for Alternative 2D

Alternative 2D Surfactant Flushing

COST ESTIMATE SUMMARY

Site: Tutu Wells Superfund Site Operable Unit 2	Description: Alternative 2D consists of :	i) Includes additional components and cost to Alternative 2 for surfactant flushing of fractures in potential source area wells.
Location: St. Thomas, USVI		
Phase: Feasibility Study (-30% - +50%)		
Base Year: 2021		
Date: January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	Pilot Study					
1.1	Mob/Demob- Drilling subcontractor	1	LS	\$ 6,000	\$ 6,000	Drill rig, decon pad
1.2	Mob/Demob- Injection subcontractor	1	LS	\$ 6,000	\$ 6,000	Equipment for pilot test
1.3	Injection Well Installation-Deep	2	EA	\$ 4,500	\$ 9,000	Approximately 140 ft deep Vendor estimate 4,500 gallons of 4% solution per deep injection point per event, water from treatment plant will be used for solution
1.4	Injection Substrate Material-Deep	7	Drum	\$ 2,000	\$ 14,000	Vendor estimate, assumed 4 drums per pallet
1.5	Freight costs to USVI	2	Pallet	\$ 1,000	\$ 2,000	Vendor estimate
1.6	Defoaming agent	1	Drum	\$ 1,000	\$ 1,000	Labor and equipment for 1, 3man crew + per diem
1.7	Injection Labor and Equipment	10	DAY	\$ 6,000	\$ 60,000	2 hr / injection well
1.8	Well Development	4	HR	\$ 350	\$ 1,400	Includes rock cuttings from installation and water disposal from development of injection wells and decon water
1.9	IDW characterization and disposal	1	LS	\$ 10,000	\$ 10,000	Sampling one round at 30 MWs, includes sample and VOCs analysis, 20% QC samples
1.1	Pilot Study Sampling	36	EA	\$ 1,500	\$ 54,000	
1.11	Data Reduction, Evaluation, Reporting	1	LS	\$ 30,000	\$ 30,000	
1.12	Flush-mount curb box with inner locking cap	2	EA	\$ 500	\$ 1,000	For injection wells
	Sub-Total				\$ 194,400	
2	Full Scale Injection Well Installation					
2.1	Mob/Demob- Drilling subcontractor	1	LS	\$ 100,000	\$ 100,000	Drill rig, decon pad, injection equipment for full scale
2.2	Injection Well Installation-Shallow	5	EA	\$ 4,500	\$ 22,500	Approximately 90 ft deep
2.3	Well Development	10	HR	\$ 350	\$ 3,500	2 hr / injection well
2.4	IDW characterization and disposal	1	LS	\$ 30,000	\$ 30,000	Includes rock cuttings from installation and water disposal from development of injection wells and decon water
2.5	Flush-mount curb box with inner locking cap	5	EA	\$ 500	\$ 2,500	For injection wells
2.6	Waste characterization testing	1	EA	\$ 1,000	\$ 1,000	
	Sub-Total				\$ 159,500	
3	Round 1 Injection Event					
3.1	Mob/Demob- Injection subcontractor	1	LS	\$ 16,000	\$ 16,000	Vendor estimate 8,500 gallons of 4% solution per shallow injection point per event, water from treatment plant will be used for solution.
3.2	Injection Substrate Material-Shallow	31	Drum	\$ 1,879	\$ 58,084	Vendor estimate 4,500 gallons of 4% solution per deep injection point per event, water from treatment plant will be used for solution
3.3	Injection Substrate Material-Deep	7	Drum	\$ 1,879	\$ 12,300	Vendor estimate, assumed 4 drums per pallet
3.4	Freight costs to USVI	9	Pallet	\$ 1,000	\$ 9,364	Vendor estimate, assumed 30 days of operation for flushing
3.5	Defoaming agent	10	Drum	\$ 1,000	\$ 10,000	Labor and equipment for 1 crew + per diem
3.6	Injection Labor and Equipment	35	DAY	\$ 3,500	\$ 122,500	Sampling for VOCs, labor, mobilization, data management and sample analysis at 30 monitoring wells + 20% QC samples
3.7	Performance Sampling	36	EA	\$ 550	\$ 19,800	
	Sub-Total				\$ 248,048	

Appendix A2D - Cost Estimate for Alternative 2D

Alternative 2D Surfactant Flushing

COST ESTIMATE SUMMARY

Site: Tutu Wells Superfund Site Operable Unit 2	Description: Alternative 2D consists of :	i) Includes additional components and cost to Alternative 2 for surfactant flushing of fractures in potential source area wells.
Location: St. Thomas, USVI		
Phase: Feasibility Study (-30% - +50%)		
Base Year: 2021		
Date: January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
4	Round 2 Injection Event					
4.1	Mob/Demob- Injection subcontractor	1	LS	\$ 16,000	\$ 16,000	
4.2	Injection Substrate Material-Shallow	31	Drum	\$ 1,863	\$ 57,584	Vendor estimate 8,500 gallons of 4% solution per shallow injection point per event, water from treatment plant will be used for solution.
4.3	Injection Substrate Material-Deep	7	Drum	\$ 1,863	\$ 12,194	Vendor estimate 4,500 gallons of 4% solution per deep injection point per event, water from treatment plant will be used for solution
4.4	Freight costs to USVI	9	Pallet	\$ 1,000	\$ 9,364	Vendor estimate, assumed 4 drums per pallet
4.5	Defoaming agent	10	Drum	\$ 1,000	\$ 10,000	Vendor estimate, assumed 30 days of operation for flushing
4.6	Injection Labor and Equipment	32	DAY	\$ 3,500	\$ 110,250	Labor and equipment for 1 crew + per diem
4.7	Performance Sampling	36	EA	\$ 550	\$ 19,800	Sampling for VOCs, labor, mobilization, data management and sample analysis at 15 monitoring wells + 20% QC samples
	Sub-Total				\$ 235,191	
	Sub-Total Capital costs				\$ 837,140	
	Contingency	20%			\$ 167,428	10% scope + 10% bid
	Sub-Total				\$ 1,004,568	
	Project Management	6%			\$ 60,274	
	Remedial Design	12%			\$ 120,548	
	Construction Management	8%			\$ 80,365	
	TOTAL CAPITAL COST				\$ 1,265,756	

ANNUAL O&M COSTS ARE INCLUDED IN ALTERNATIVE 2

PERIODIC COSTS ARE INCLUDED IN ALTERNATIVE 2

PRESENT VALUE ANALYSIS:		Rate of Return: 7%		Inflation Rate 3%		Notes
Item No.	Cost Type	Year	Total Cost	Present Value		
1	Capital Cost	0		\$ 1,265,756		
2	Annual O&M Cost					
2.1	Year 1 to 26	1 to 26	-	-		Included in Alternative 2
3	Periodic Costs					
3.1	Year 26	26	-	-		Included in Alternative 2
	TOTAL PRESENT VALUE OF ALTERNATIVE			\$ 1,265,756	In addition to costs under Alternative 2	

Appendix A3 - Cost Estimate for Alternative 3

Alternative 3

COST ESTIMATE SUMMARY

In Situ Thermal Treatment and Pump and Treat

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 3 consists of :
Location:	St. Thomas, USVI		i) In situ thermal treatment at source areas
Phase:	Feasibility Study (-30% - +50%)		ii) Install new extraction wells downgradient; increase system capacity; perform system upgrades as discussed in Alternative 2
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	Site Survey and Utility Clearance					
1.1	Survey	1	LS	\$ 15,000	\$ 15,000	
1.2	Utility Clearance	1	LS	\$ 15,000	\$ 15,000	
	Sub-Total				\$ 30,000	
2	Pre-Design Investigation					
2.1	Investigation Work Plan	1	LS	\$ 100,000	\$ 100,000	Sampling Plan, QAPP, HASP
2.2	Mobilization/ Demobilization	1	LS	\$ 100,000	\$ 100,000	Mobilize all equipment and personnel to USVI
2.3	Site Preparation	1	LS	\$ 18,500	\$ 18,500	Clearing/ Grubbing drilling locations
2.4	Permits	1	LS	\$ 10,000	\$ 10,000	Local Permits
2.5	Bedrock Drilling	700	LF	\$ 75	\$ 52,500	Five, 2-inch diameter MWs installed to 140 ft bgs.
2.6	Grouting Open Boreholes	100	LF	\$ 20	\$ 2,000	Back grouting boreholes as necessary. Assume 20 ft/ MW
2.7	Flush-mount curb box with inner locking cap	5	EA	\$ 300	\$ 1,500	For monitoring wells
2.8	Monitoring Well Redevelopment	40	hr	\$ 350	\$ 14,000	Assume 8 hrs per MW
2.9	Groundwater Sampling and Data Evaluation	1	LS	\$ 50,000	\$ 50,000	Assume 30 wells for baseline
2.10	Surface Repair	1	LS	\$ 6,000	\$ 6,000	
2.11	Water Level Measurements	1	LS	\$ 1,500	\$ 1,500	
2.12	Hydrogeologic Assessment - Pumping Test	1	LS	\$ 100,000	\$ 100,000	
2.13	Extraction Well Redevelopment	1	LS	\$ 100,000	\$ 100,000	
2.14	Hydrogeologic Evaluation	1	LS	\$ 75,000	\$ 75,000	
2.15	IDW Characterization and Disposal	1	LS	\$ 30,000	\$ 30,000	Sleeves, decon water, misc. used items, groundwater waste from well installation and redevelopment.
2.16	PDI Report	1	LS	\$ 50,000	\$ 50,000	
	Sub-Total				\$ 711,000	
3	Site Mobilization/Demobilization					
3.1	Remedial Action Work plan/Permitting					Permit equivalents, access agreements, RAWP, Construction HASP, Subcontractor procurement
		1	LS	\$ 100,000	\$ 100,000	
3.2	Submittals/Implementation Plans	1	LS	\$ 100,000	\$ 100,000	Remedial Design reports
3.3	Post Construction Submittals	1	LS	\$ 75,000	\$ 75,000	Bi-weekly reports, monthly progress reports
3.4	Decontamination Station	1	LS	\$ 5,000	\$ 5,000	
	Sub-Total				\$ 280,000	
4	Health and Safety					
4.1	PPE and Field Supplies	1	LS	\$ 5,000	\$ 5,000	
	Sub-Total				\$ 5,000	
5	Site Preparation					
5.1	Temporary Security Fence	1,000	LF	\$ 30	\$ 30,000	
	Sub-Total				\$ 30,000	
6	Treatment Plant Upgrades					
6.1	Demolition and Replacement of Existing Equipment	1	LS	\$ 1,000,000	\$ 1,000,000	Includes the demolition and replacement of treatment equipment such as EW pumps, transfer pumps, air stripper, air stripper blower, bag filters, EQ tank for DNAPL recovery tank, piping, PLC, chemical feed metering pumps and tank, heat exchanger, 2 GAC vessels, 2 permanganate vessels.
	Sub-Total				\$ 1,000,000	

Appendix A3 - Cost Estimate for Alternative 3

Alternative 3

COST ESTIMATE SUMMARY

In Situ Thermal Treatment and Pump and Treat

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 3 consists of :
Location:	St. Thomas, USVI		i) In situ thermal treatment at source areas
Phase:	Feasibility Study (-30% - +50%)		ii) Install new extraction wells downgradient; increase system capacity; perform system upgrades as discussed in Alternative 2
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
7	New Extraction Well Drilling					
7.1	Mobilization/ Demobilization	1	LS	\$ 50,000	\$ 50,000	
7.2	Per Diem (Per working crew day)	20	Crew-day	\$ 750	\$ 15,000	Estimate 10 days per well
7.3	Standby	8	HR	\$ 450	\$ 3,600	
7.4	Grouting Open Boreholes	100	LF	\$ 20	\$ 2,000	
7.5	Bedrock Drilling	280	LF	\$ 75	\$ 21,000	Assume each well is 140 ft bgs
7.6	Steel Casing	100	LF	\$ 50	\$ 5,000	Assume casing goes to 50 ft bgs for each well
7.7	Extraction Well Vault	2	EA	\$ 5,000	\$ 10,000	
7.8	Borehole/ Well Development	20	HR	\$ 375	\$ 7,500	
7.9	Dual Packer Testing	16	HR	\$ 525	\$ 8,400	
7.10	Site Access, Set-up, Breakdown and Restoration	1	LS	\$ 20,000	\$ 20,000	
7.11	Drums	100	EA	\$ 150	\$ 15,000	
7.12	Manage IDW	20	HR	\$ 350	\$ 7,000	
7.13	Decon	20	HR	\$ 250	\$ 5,000	
	Sub-Total				\$ 169,500	
8	Conveyance Piping					
8.1	Mobilization	1	LS	\$ 30,000	\$ 30,000	
8.2	Soil Erosion and Sediment Control	1,000	LF	\$ 5	\$ 5,000	
8.3	Trenching	593	CY	\$ 50	\$ 29,630	
8.4	Pipe (HDPE double walled)	1,000	LF	\$ 30	\$ 30,000	Piping from the extraction wells to the treatment plant.
8.5	Utility Marking Tape	1,000	LF	\$ 0.30	\$ 300	
8.6	Bedding	593	CY	\$ 20	\$ 11,852	
8.7	Backfill and Compaction	4,000	SF	\$ 5	\$ 20,000	
8.8	Vaults and Junctions	4	EA	\$ 6,500	\$ 26,000	Assume 2 vaults and 2 cleanouts
	Sub-Total				\$ 152,781	
9	In Situ Thermal Treatment					Vendor Estimate
9.1	Design, Work Plans, Permits	1	LS	\$ 299,980	\$299,980	
9.2	Materials Mobilization	1	LS	\$ 5,411,300	\$5,411,300	
9.3	Subsurface Installation	1	LS	\$ 10,576,680	\$10,576,680	
9.4	Surface Installation and Start-up	1	LS	\$ 2,348,960	\$2,348,960	
9.5	Remediation System Operation	1	LS	\$ 8,434,420	\$8,434,420	
9.6	Demobilization and Final Report	1	LS	\$ 1,085,440	\$1,085,440	
9.7	Drill Cuttings and Waste Disposal	1	LS	\$ 225,780	\$225,780	
9.8	Electrical Permit and Utility Connection	1	LS	\$ 50,000	\$50,000	
9.9	Electrical Energy Use	63,321,053	kWh	\$ 0.47	\$29,469,618	
9.10	Carbon Usage, Transportation & Regeneration	1	LS	\$ 75,000	\$75,000	
9.11	Condensate Disposal	1	LS	\$ -	\$0	
9.12	Other, Operational Costs	1	LS	\$ 175,000	\$175,000	
	Sub-Total				\$ 58,152,178	

Appendix A3 - Cost Estimate for Alternative 3

Alternative 3

COST ESTIMATE SUMMARY

In Situ Thermal Treatment and Pump and Treat

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 3 consists of :
Location:	St. Thomas, USVI		i) In situ thermal treatment at source areas
Phase:	Feasibility Study (-30% - +50%)		ii) Install new extraction wells downgradient; increase system capacity; perform system upgrades as discussed in Alternative 2
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
10	Reporting and Institutional Controls					
10.1	Remedial Action Report	1	LS	\$ 50,000	\$ 50,000	
10.2	Institutional Controls & Site Management Plan	1	LS	\$ 20,000	\$ 20,000	
	Sub-Total				\$ 70,000	
	Sub-Total				\$ 59,278,178	Sub-Total All Construction Costs.
	Contingency	20%			\$ 11,855,636	10% scope + 10% bid
	Sub-Total				\$ 71,133,814	
	Project Management	6%			\$ 4,268,029	
	Remedial Design	12%			\$ 8,536,058	
	Construction Management	8%			\$ 5,690,705	
	TOTAL CAPITAL COST				\$ 89,628,605	

ANNUAL O&M COST

Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Operations Costs - Year 1 to 12	1 to 12					Every year through year 12.
1.1	Electrical Usage		150,000	KW-Hr	\$ 0.47	\$ 69,810	Remedial system operates for 12 years
1.2	Vapor Carbon Usage		10,000	LB	\$ 4.00	\$ 40,000	Change out both units 2x per year, estimate 5,000 lbs ea
1.3	Vapor Carbon Disposal		10,000	EA	\$ 1.00	\$ 10,000	
1.4	Potassium Permanganate Usage		14,000	LB	\$ 4.00	\$ 56,000	
1.5	Potassium Permanganate Disposal		1	EA	\$ 3,000.00	\$ 3,000	
1.6	Weekly Inspections		52	EA	\$ 600	\$ 31,200	1x per week
1.7	Effluent Sampling		12	EA	\$ 1,500	\$ 18,000	Monthly Influent, Effluent Air Sampling and between GAC vessels for VOCs; includes labor
1.8	DNAPL Shipping and Disposal		3	EA	\$ 12,500	\$ 37,500	Assume 3, 55 gallon drums of DNAPL are generated annually and need to be disposed offsite.
1.9	Reporting		12	Month	\$ 5,000	\$ 60,000	Monthly
	Sub-Total					\$ 325,510	
	Contingency		15%			\$ 48,827	
	ANNUAL OPERATIONS COST (Year 1 to 12)					\$ 374,337	
2	LTM and Institutional Controls - Year 1 to 12	1 to 12					Every year through year 12.
2.1	Groundwater Sampling		30	EA	\$ 750	\$ 22,500	30 wells annually; includes labor
2.2	Groundwater Sample Laboratory Analysis		36	EA	\$ 550	\$ 19,800	Total VOCs analysis + 20% QC samples.
2.3	Data Reduction, Evaluation and Reporting		1	EA	\$ 20,000	\$ 20,000	
2.4	Annual Report		1	EA	\$ 24,000	\$ 24,000	Includes periodic report
	Sub-Total					\$ 86,300	
	Contingency		15%			\$ 12,945	
	ANNUAL LTM COST (Year 1 to 12)					\$ 99,245	
	Project Management					\$ 5,000	
	Technical Support					\$ 5,000	

Appendix A3 - Cost Estimate for Alternative 3

Alternative 3

COST ESTIMATE SUMMARY

In Situ Thermal Treatment and Pump and Treat

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 3 consists of :
Location:	St. Thomas, USVI		i) In situ thermal treatment at source areas
Phase:	Feasibility Study (-30% - +50%)		ii) Install new extraction wells downgradient; increase system capacity; perform system upgrades as discussed in Alternative 2
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes	
PERIODIC COSTS							
Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Decommission System	12					At the end of Year 12
1.1	Decommission System		1	LS	\$ 50,000	\$ 50,000	
1.2	Monitoring Well Abandonment		30	EA	\$ 1,500	\$ 45,000	
1.3	Final Closure Report		1	LS	\$ 50,000	\$ 50,000	
	Sub-Total					\$ 145,000	
	Contingency		15%			\$ 21,750	
	Project Management					\$ 5,000	
	Technical Support					\$ 5,000	
	PERIODIC COSTS (Year 12)					\$ 176,750	

PRESENT VALUE ANALYSIS:

Item No.	Cost Type	Rate of Return: 7%		Inflation Rate 3%		Notes
		Year	Total Cost		Present Value	
1	Capital Cost	0			\$ 89,628,605	
2	Annual O&M Cost					
2.1	Year 1 to 12	1 to 12	483,582		\$ 4,569,283	Operations and LTM
3	Periodic Costs					
3.1	Year 12	12	176,750		\$ 111,890	Decommission System and Site Close Out
	TOTAL PRESENT VALUE OF ALTERNATIVE				\$ 94,309,778	

Appendix A4 - Cost Estimate for Alternative 4

Alternative 4

COST ESTIMATE SUMMARY

In Situ Steam Injection and Pump and Treat

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 4 consists of:
Location:	St. Thomas, USVI		i) In situ steam injection and extraction at source areas
Phase:	Feasibility Study (-30% - +50%)		ii) Install new extraction wells downgradient; increase system capacity; perform system upgrades as discussed in Alternative 2
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
CAPITAL COSTS:						
1	Site Survey and Utility Clearance					
1.1	Survey	1	LS	\$ 15,000	\$ 15,000	
1.2	Utility Clearance	1	LS	\$ 15,000	\$ 15,000	
	Sub-Total				\$ 30,000	
2	Pre-Design Investigation					
2.1	Investigation Work Plan	1	LS	\$ 100,000	\$ 100,000	Sampling Plan, QAPP, HASP
2.2	Mobilization/ Demobilization	1	LS	\$ 100,000	\$ 100,000	Mobilize all equipment and personnel to USVI
2.3	Site Preparation	1	LS	\$ 18,500	\$ 18,500	Clearing/ Grubbing drilling locations
2.4	Permits	1	LS	\$ 10,000	\$ 10,000	Local Permits
2.5	Bedrock Drilling	700	LF	\$ 75	\$ 52,500	Five, 2-inch diameter MWs installed to 140 ft bgs.
2.6	Grouting Open Boreholes	100	LF	\$ 20	\$ 2,000	Back grouting boreholes as necessary. Assume 20 ft/ MW
2.7	Flush-mount curb box with inner locking cap	5	EA	\$ 300	\$ 1,500	For monitoring wells
2.8	Monitoring Well Redevelopment	40	hr	\$ 350	\$ 14,000	Assume 8 hrs per MW
2.9	Groundwater Sampling and Data Evaluation	1	LS	\$ 50,000	\$ 50,000	Assume 30 wells for baseline
2.10	Surface Repair	1	LS	\$ 6,000	\$ 6,000	
2.11	Water Level Measurements	1	LS	\$ 1,500	\$ 1,500	
2.12	Hydrogeologic Assessment - Pumping Test	1	LS	\$ 100,000	\$ 100,000	
2.13	Extraction Well Redevelopment	1	LS	\$ 100,000	\$ 100,000	
2.14	Hydrogeologic Evaluation	1	LS	\$ 75,000	\$ 75,000	
2.15	IDW Characterization and Disposal	1	LS	\$ 30,000	\$ 30,000	Sleeves, decon water, misc used items, groundwater waste from well installation and redevelopment.
2.16	PDI Report	1	LS	\$ 50,000	\$ 50,000	
	Sub-Total				\$ 711,000	
3	Site Mobilization/Demobilization					
3.1	Remedial Action Workplan/Permitting	1	LS	\$ 100,000	\$ 100,000	Permit equivalents, access agreements, RAWP, Construction HASP, Subcontractor procurement
3.2	Submittals/Implementation Plans	1	LS	\$ 100,000	\$ 100,000	Remedial Design reports
3.3	Post Construction Submittals	1	LS	\$ 75,000	\$ 75,000	Bi-weekly reports, monthly progress reports
3.4	Decontamination Station	1	LS	\$ 5,000	\$ 5,000	
	Sub-Total				\$ 280,000	
4	Health and Safety					
4.1	PPE and Field Supplies	1	LS	\$ 5,000	\$ 5,000	
	Sub-Total				\$ 5,000	
5	Site Preparation					
5.1	Temporary Security Fence	1,000	LF	\$ 30	\$ 30,000	
	Sub-Total				\$ 30,000	
6	Treatment Plant Upgrades					
6.1	Demolition and Replacement of Existing Equipment	1	LS	\$ 1,000,000	\$ 1,000,000	Includes the demolition and replacement of treatment equipment such as EW pumps, transfer pumps, air stripper, air stripper blower, bag filters, EQ tank for DNAPL recovery tank, piping, PLC, chemical feed metering pumps and tank, heat exchanger, 2 GAC vessels, 2 permanganate vessels.
	Sub-Total				\$ 1,000,000	

Appendix A4 - Cost Estimate for Alternative 4

Alternative 4

In Situ Steam Injection and Pump and Treat

COST ESTIMATE SUMMARY

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 4 consists of:
Location:	St. Thomas, USVI		i) In situ steam injection and extraction at source areas
Phase:	Feasibility Study (-30% - +50%)		ii) Install new extraction wells downgradient; increase system capacity; perform system upgrades as discussed in Alternative 2
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description	Quantity	Unit	Unit Cost	Total	Notes
7	New Extraction Well Drilling					
7.1	Mobilization/ Demobilization	1	LS	\$ 50,000	\$ 50,000	
7.2	Per Diem (Per working crew day)	20	Crew-day	\$ 750	\$ 15,000	Estimate 10 days per well
7.3	Standby	8	HR	\$ 450	\$ 3,600	
7.4	Grouting Open Boreholes	100	LF	\$ 20	\$ 2,000	
7.5	Bedrock Drilling	280	LF	\$ 75	\$ 21,000	Assume each well is 140 ft bgs
7.6	Steel Casing	100	LF	\$ 50	\$ 5,000	Assume casing goes to 50 ft bgs for each well
7.7	Extraction Well Vault	2	EA	\$ 5,000	\$ 10,000	
7.8	Borehole/ Well Development	20	HR	\$ 375	\$ 7,500	
7.9	Dual Packer Testing	16	HR	\$ 525	\$ 8,400	
7.10	Site Access, Set-up, Breakdown and Restoration	1	LS	\$ 20,000	\$ 20,000	
7.11	Drums	100	EA	\$ 150	\$ 15,000	
7.12	Manage IDW	20	HR	\$ 350	\$ 7,000	
7.13	Decon	20	HR	\$ 250	\$ 5,000	
	Sub-Total				\$ 169,500	
8	Conveyance Piping					
8.1	Mobilization	1	LS	\$ 30,000	\$ 30,000	
8.2	Soil Erosion and Sediment Control	1,000	LF	\$ 5	\$ 5,000	
8.3	Trenching	593	CY	\$ 50	\$ 29,630	
8.4	Pipe (HDPE double walled)	1,000	LF	\$ 30	\$ 30,000	Piping from the extraction wells to the treatment plant.
8.5	Utility Marking Tape	1,000	LF	\$ 0.30	\$ 300	
8.6	Bedding	593	CY	\$ 20	\$ 11,852	
8.7	Backfill and Compaction	4,000	SF	\$ 5	\$ 20,000	
8.8	Vaults and Junctions	4	EA	\$ 6,500	\$ 26,000	Assume 2 vaults and 2 cleanouts
	Sub-Total				\$ 152,781	
9	Steam Injection					
9.1	Design and Procurement	1	LS	\$ 296,800	\$ 296,800	Vendor estimate
9.2	Construction and Operation	1	LS	\$ 10,197,200	\$ 10,197,200	Vendor estimate
9.3	Power Usage	8,526,316	kWh	\$ 0.47	\$ 3,968,147	Vendor estimate
	Sub-Total				\$ 14,462,147	
10	Reporting and Institutional Controls					
10.1	Remedial Action Report	1	LS	\$ 50,000	\$ 50,000	
10.2	Institutional Controls & Site Management Plan	1	LS	\$ 20,000	\$ 20,000	
	Sub-Total				\$ 70,000	
	Sub-Total				\$ 16,910,429	Sub-Total All Construction Costs.
	Contingency	20%			\$ 3,382,086	10% scope + 10% bid
	Sub-Total				\$ 20,292,515	
	Project Management	6%			\$ 1,217,551	
	Remedial Design	12%			\$ 2,435,102	
	Construction Management	8%			\$ 1,623,401	
	TOTAL CAPITAL COST				\$ 25,568,569	

Appendix A4 - Cost Estimate for Alternative 4

Alternative 4

In Situ Steam Injection and Pump and Treat

COST ESTIMATE SUMMARY

Site:	Tutu Wells Superfund Site Operable Unit 2	Description:	Alternative 4 consists of:
Location:	St. Thomas, USVI		i) In situ steam injection and extraction at source areas
Phase:	Feasibility Study (-30% - +50%)		ii) Install new extraction wells downgradient; increase system capacity; perform system upgrades as discussed in Alternative 2
Base Year:	2021		
Date:	January 13, 2021		

Item No.	Description		Quantity	Unit	Unit Cost	Total	Notes
ANNUAL O&M COST							
Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Operations Costs - Year 1 to 27	1 to 27					Every year through year 27.
1.1	Electrical Usage		150,000	KW-Hr	\$ 0.47	\$ 69,810	Remedial system operates for 27 years
1.2	Vapor Carbon Usage		10,000	LB	\$ 4.00	\$ 40,000	Change out both units 2x per year, estimate 5,000 lbs ea
1.3	Vapor Carbon Disposal		10,000	EA	\$ 1.00	\$ 10,000	
1.4	Potassium Permanganate Usage		14,000	LB	\$ 4.00	\$ 56,000	
1.5	Potassium Permanganate Disposal		1	EA	\$ 3,000.00	\$ 3,000	
1.6	Weekly Inspections		52	EA	\$ 600	\$ 31,200	1x per week
1.7	Effluent Sampling		12	EA	\$ 1,500	\$ 18,000	Monthly Influent, Effluent Air Sampling and between GAC vessels for VOCs; includes labor
1.8	DNAPL Shipping and Disposal		3	EA	\$ 12,500	\$ 37,500	Assume 3, 55 gallon drums of DNAPL are generated annually and need to be disposed offsite.
1.9	Reporting		12	Month	\$ 5,000	\$ 60,000	Monthly
	Sub-Total					\$ 325,510	
	Contingency		25%			\$ 81,378	
ANNUAL OPERATIONS COST (Year 1 to 27)						\$ 406,888	
2	LTM - Year 1 to 27	1 to 27					Every year through year 27.
2.1	Groundwater Sampling		30	EA	\$ 750	\$ 22,500	30 wells annually; includes labor
2.2	Groundwater Sample Laboratory Analysis		36	EA	\$ 550	\$ 19,800	Total VOCs analysis + 20% QC samples.
2.3	Data Reduction, Evaluation and Reporting		1	EA	\$ 20,000	\$ 20,000	
2.4	Annual Report		1	EA	\$ 24,000	\$ 24,000	Includes periodic report
	Sub-Total					\$ 86,300	
	Contingency		15%			\$ 12,945	
ANNUAL LTM COST (Year 1 to 27)						\$ 99,245	
Project Management						\$ 5,000	
Technical Support						\$ 5,000	

PERIODIC COSTS

Item No.	Description	Year	Quantity	Unit	Unit Cost	Total	Notes
1	Decommission System	27					At the end of Year 27
1.1	Decommission System		1	LS	\$ 50,000	\$ 50,000	
1.2	Monitoring Well Abandonment		30	EA	\$ 1,500	\$ 45,000	
1.3	Final Closure Report		1	LS	\$ 50,000	\$ 50,000	
	Sub-Total					\$ 145,000	
	Contingency		15%			\$ 21,750	
	Project Management					\$ 5,000	
	Technical Support					\$ 5,000	
	PERIODIC COSTS (Year 27)					\$ 176,750	

PRESENT VALUE ANALYSIS:

		Rate of Return: 7%		Inflation Rate 3%		
Item No.	Cost Type	Year	Total Cost	Present Value		Notes
1	Capital Cost	0		\$ 25,568,569		
2	Annual O&M Cost					
2.1	Year 1 to 27	1 to 27	516,133	\$ 8,539,451		Operations and LTM
3	Periodic Costs					
3.1	Year 27	27	176,750	\$ 63,180		Decommission System and Site Close Out
	TOTAL PRESENT VALUE OF ALTERNATIVE			\$ 34,171,200		

APPENDIX B
MATRIX DIFFUSION STUDY

PCE fate and transport simulation in fractured rock, Tutu Wells Superfund Site, St. Thomas USVI

January 26, 2018

A basic/simplified modeling effort has been completed to evaluate the fate and transport of tetrachloroethylene (PCE) in the fractured rock aquifer at the Tutu Wells Superfund Site in St. Thomas, US Virgin Islands. The fundamental question being addressed is:

Once the source of PCE has been removed, how long will it take for PCE concentrations at the property boundary to fall below 5 mg/l (the MCL for PCE)?

Two 1-dimensional modeling programs were used to simulate the fate and transport of PCE in fractured bedrock where matrix diffusion plays a role in attenuating the contaminants life in the system after the source has been removed. The first is CRAFLUSH, an analytical model first developed at the University of Waterloo by Dr. Ed Sudicky and Dr. Emil Frind in the 1980's and then modified by Dr. Chris Neville (Sudicky and Frind, 1982; Neville, 2002). The second model is the Matrix Diffusion Toolkit (MDT) developed for ESTCP by GSI Environmental Inc. and Colorado State University (Farhat et. al., 2012). CRAFLUSH is a Fortran-based model that simulates fate and transport of specific chemicals through a single fracture or multiple parallel fracture. CRAFLUSH was run in the Windows environment using a DOS-emulator. The MDT is an Excel-based model that simulates transport and exchange between a more transmissive zone and a less transmissive zone along a specified plume geometry of a specified chemical to specified distance from the source area. Doubling the output concentrations (and mass flux) lets MDT emulate transport in a fracture. Both models can be used to estimate the reduction of concentrations at down-gradient locations after the source input has been removed.

There are several simplifying conditions that are assumed by both models and that must be considered when evaluating the modeling results. The most important of these assumed condition is that the source is completely removed at a specified time. In practicality, source removal will take some unknown amount of time to complete and may be less than perfect in its removal. Both aspects of actual source removal will lengthen the amount of time necessary for the concentrations to drop below the MCL at the property boundary. The simulations completed with MDT include uncertainty and provides a "most likely" and an "upper bound" for the timing.

Conceptual Site Model

A relatively simple conceptual site model (CSM) was used to constrain the simulations: chlorinated solvents (PCE) were released to a fractured andesitic tuff fractured rock aquifer, groundwater flow through the fracture and carries the PCE toward and past the property boundary about 300 feet from the source area. As the PCE is transported down gradient (advection in the fracture, controlled by the groundwater velocity in the fracture, V , the fracture aperture width, b , and dispersivity, α), diffusion causes PCE to enter the matrix pore space (matrix diffusion, controlled by the porosity, θ , and tortuosity, τ , of the pore spaces of the matrix, and the free water diffusion coefficient, D_o , of PCE in this environment). This causes PCE mass to accumulate in the rock matrix. A second co-process that occurs during transport/interaction with the rock matrix is PCE is adsorbed by organic carbon in the rock matrix furthering the accumulation PCE mass in the matrix. The sorption process associated with the organic carbon in the matrix also retards the movement of PCE relative to the movement of water (organic

carbon sorption, calculated from the bulk density of the matrix, ρ_b , the organic carbon content, f_{oc} , and the organic carbon-water partitioning coefficient of PCE, K_{oc} , resulting in two controlling terms: adsorption-desorption distribution coefficient, K_d , and retardation factor, R). These factors cause the PCE to exchange between the rock matrix and fracture water, resulting in a reservoir of PCE in the matrix which will back-diffuse into the fracture water after the source has been removed (using the same constraining parameters). An additional process that occurs is biological agents in the subsurface degrade the PCE to other compounds, effectively removing it from the system (controlled by the first order decay constant, λ). These factors and their mathematical relationships are described in Sudicky and Frind, 1982.

For the Tutu site, PCE was loaded to the subsurface approximately 320 feet up-gradient of the property boundary. The site has had some remedial measures, but the source has been largely in place for about 50 years. The bedrock aquifer matrix is comprised of fractured andesitic tuff. Rock properties including matrix porosity, bulk density, and organic carbon content were measured from 14 rock core samples by HDR subcontractor, Cascade Technical Services (Cascade, 2017). Monitoring and recovery wells near the source area have concentrations of PCE in groundwater of up to 92,000 $\mu\text{g/l}$. PCE at the property boundary have an estimated concentration of between 15 and 3,500 $\mu\text{g/l}$ based on concentrations in three wells (OU2-MW3-140, RD-13 and MW-1D). The presence of PCE biodegradation daughter products such as vinyl chloride suggest that significant biodegradation is occurring and the concentration gradient between the source area and the property boundary could be the result of this degradation. Several parameters were either derived from literature values (e.g., PCE K_{oc} , free solution diffusion) or based on values needed to match the concentration gradient (dispersivity, matrix tortuosity, first-order decay). Fracture velocity was calculated using estimates of hydraulic conductivity, site hydraulic gradient, and estimates of effective porosity.

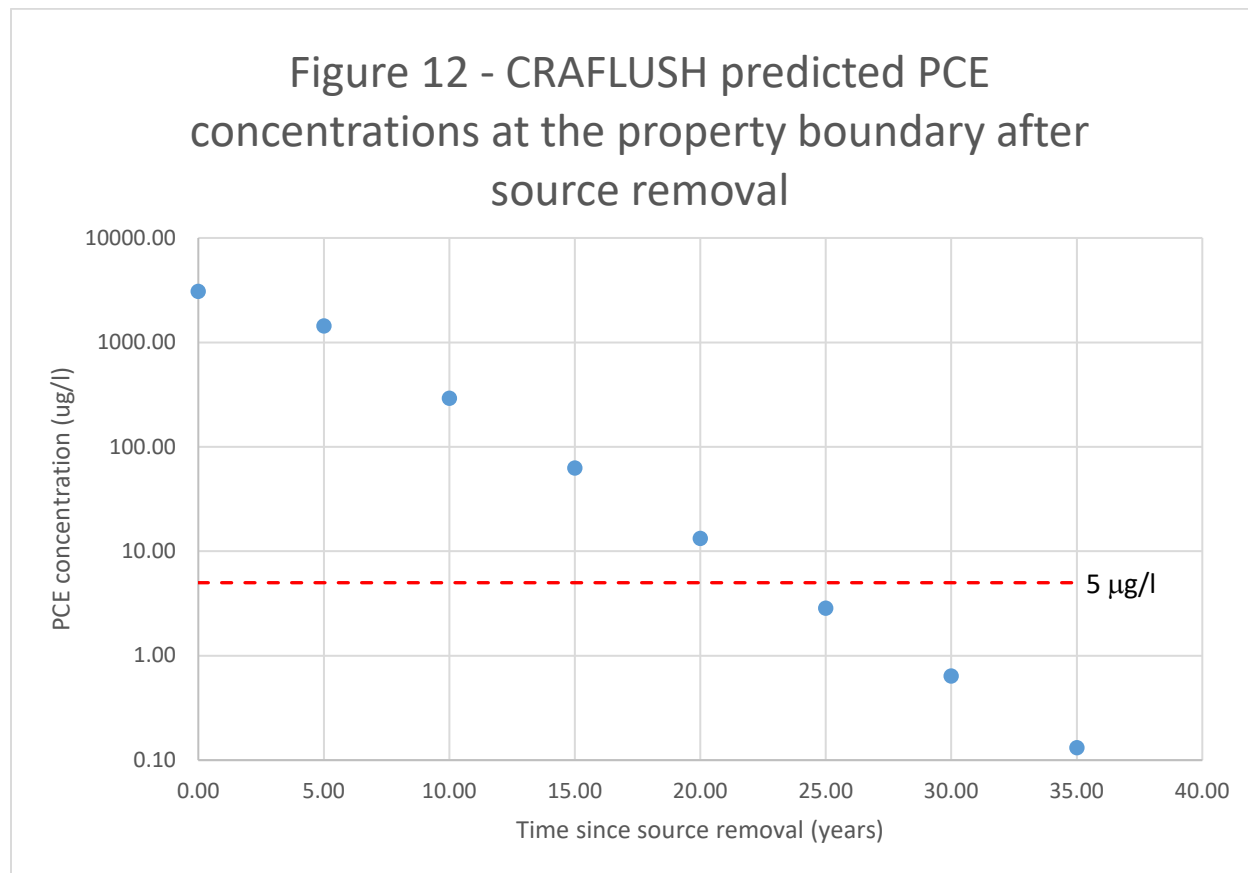
CRAFLUSH Simulation

The CRAFLUSH model was set to simulate a “fracture” that extends from immediately down gradient of the source area to 100 meters (320 feet) down-gradient to the property boundary. Loading is simulated for 50 years, with groundwater with high PCE concentrations simulated to enter the fracture. At 50 years the source is simulated to be removed (loading goes to 0) and the down gradient concentrations at 10 meter intervals are predicted at five year intervals for 75 years (total simulation time of 125 years). The ASCII text input and output files are attached (Tutu.inp and Tutu.out).

The final input values used in the CRAFLUSH model were:

Fracture Velocity	0.1786 m/d	Estimated
Fracture Dispersivity	10.0 m	Estimated
Fracture Aperture	0.00012 m	Literature value
Fracture Spacing	1.6 m	Median from site data
Matrix Tortuosity	0.100	Literature value
Matrix Porosity	0.03	Median measured from rock core
Matrix Bulk Density	2.830 g/cm^3	Median measured from rock core
First-order Decay Coefficient	0.0025/d	Estimated from site data
Matrix Sorption Coefficient	3.400 $\mu\text{g/m}^3$	Measured values and literature K_{oc}
Free Solution Diffusion Coefficient	9.0x10 ⁻⁰⁹ m^2/d	Literature value

The first output (50 years) was compared to the concentration gradient observed at the site and parameters, especially first order decay¹, were adjusted until a reasonable concentration gradient was predicted (loosely based on the concentrations of PCE found in OU3-MW3, RD-13 and MW-1D). For this run, source area PCE concentrations are predicted to be 92,000 µg/l and property boundary PCE concentrations are estimated to be 3,100 µg/l. The predicted down gradient concentrations were then plotted over the 75 years of simulation to estimate when the concentration at the property boundary (100m) over time. Figure 1 is a plot of the property boundary concentrations over time the 35 years after source removal. Based on the output from the final run, CRAFLUSH predicts that PCE concentrations will fall below 5 µg/l at the property boundary within about 23 years.



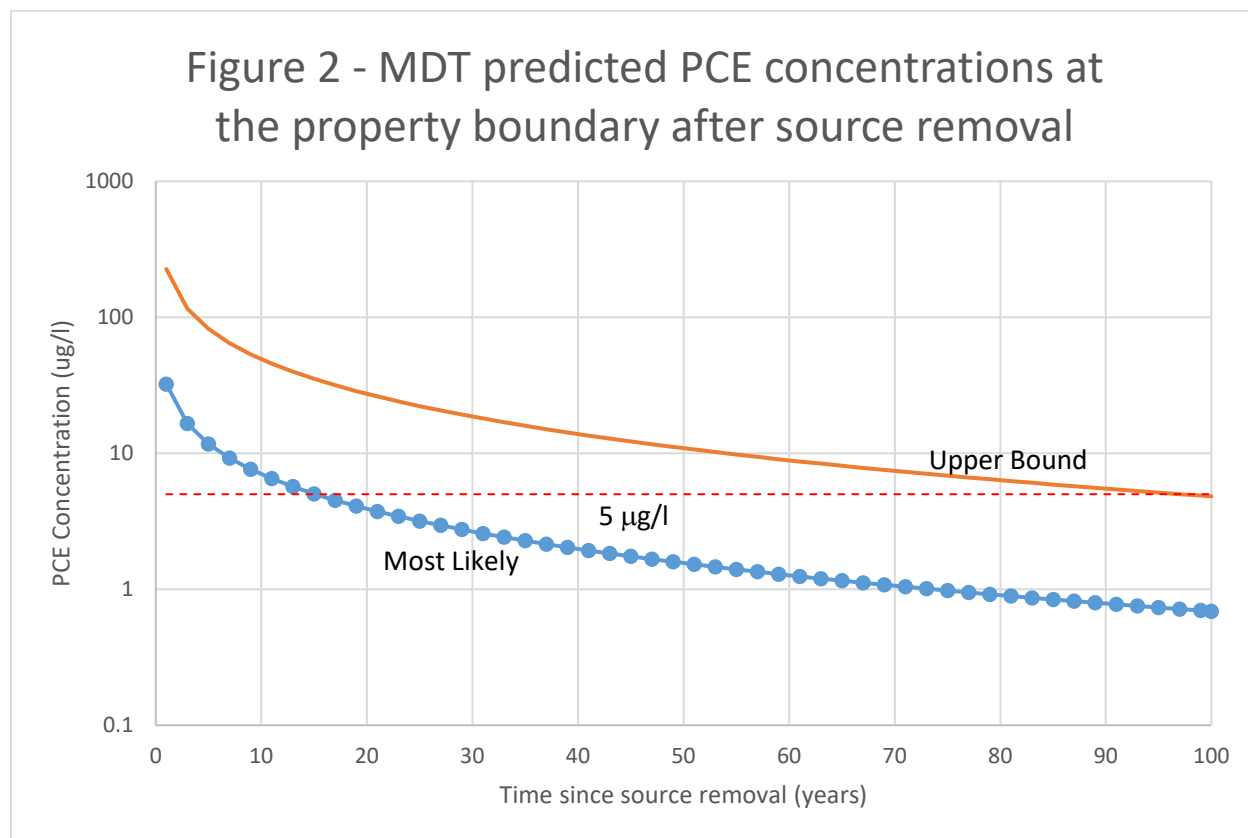
MDT Simulation

The MDT simulation² used similar input parameters as the CRAFLUSH model, however instead of using the concentrations seen in monitoring and recovery wells specifically, concentrations of total

¹ When the first order decay constant was set to 0, the concentration gradient across the site was orders of magnitude less than observed. Adding a first order decay constant 0.0025/day resulted in a closer approximation of the gradient observed at the site. The need for a first order decay constant and the presence of daughter product compounds in the groundwater are in line with robust biodegradation occurring in the aquifer.

² The MDT offers two methods of simulation, the Square Root Model and a more complex Dandy-Sale Model. The simpler Square Root Model was used for these simulations.

chlorinated ethenes were taken from the plume map (Arrowhead Contracting, 2017) along with the geometry of the plume (width and length). An uncertainty factor of 7 around the concentrations was also used for the uncertainty analysis. The results of the MDT simulation indicate that under the “most likely” scenario, the concentrations (note these are total chlorinated ethenes using PCE transport parameters) will fall below 5 µg/l in about 17 years, with the upper bound being about 97 years. Figure 2 is a plot of the MDT predicted property boundary concentration in the 100 years after source removal.



The MDT spreadsheet is attached.

Limitations

Many simplifying assumptions went into this modeling effort. Besides the assumption noted earlier that the source is quickly and completely removed, other assumptions include:

1. Groundwater concentrations seen in monitoring wells are representative of concentrations in a fracture. In reality, the groundwater concentrations are an amalgam of the water contributed to the monitoring well from potentially several fractures. Introduction of clean water from a particular fracture could result in underestimating the PCE concentration. A conservative down gradient concentration (greater than observed) was used in the CRAFLUSH simulations as the target concentration for just before the source was removed.
2. Monitoring wells on the down gradient property boundary are representative of the highest concentrations of PCE that are leaving the site. In reality, it is possible that at a different location or different time, a property boundary monitoring well would encounter a higher concentration of PCE. A conservative down gradient concentration (greater than observed) was

used in the CRAFLUSH simulations as the target concentration for just before the source was removed.

3. Many of the transport and matrix diffusion parameters were derived from either literature values or through 'calibration' of the model to fit observed values. *This is particularly true of the first order decay coefficient.* It is possible (and entirely likely) that a different combination of the parameters used would result in the same calibration fit, but would also result in different prediction of concentration reduction rates. Without site specific parameters to constrain the simulations, there is an unknown level of uncertainty caused by generalized parameters.
4. Remedial efforts to remove the source will not be instantaneous and may change the aquifer conditions (especially first order decay). Also, interim measures and hydraulic control pumping at the property boundary will change groundwater movement and gradients to condition other than were simulated here.

These and other simplifying assumptions result in a level of uncertainty in the modeled predictions. More sophisticated modeling that simulates highly detailed geometry of known fractures, contaminant concentrations, and transport and matrix diffusion parameters mapped through extensive field investigations and potential remedial efforts could result in more precise and less uncertain predictions, however, such efforts should only be contemplated if the level of uncertainty presented here is not suitable for the decisions that need the modeling support.

Conclusion

Based on the results of the two models, after complete source removal concentrations at the property boundary are predicted to drop below the MCL in as little as 17 years, but more likely within about 25 years. Given the upper limit of about 99 years, very large time frames (many decades or centuries) are unlikely as an outcome if the source can truly be removed.

References

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- Farhat, S.K., C.J. Newell, T.C. Sale, D.S. Dandy, J.J. Wahlberg, M.A. Seyedabbasi, J.M. McDade, and N.T. Mahler, 2012. Matrix Diffusion Toolkit, developed for the Environmental Security Technology Certification Program (ESTCP) by GSI Environmental Inc., Houston, Texas.
- Neville, C. J., 2002. CRA2 Documentation (unpublished, provided by C. Neville).
- Sudicky, E.A., and E.O. Frind, 1982. Contaminant transport in fractured porous media: Analytical solutions for a system of parallel fractures, *Water Resources Research*, 18(6), pp. 1634-1642.

Attachment 1 – Tutu CRAFLUSH files

Tutu.inp

Tutu

1.786D-1		V : FRACTURE VELOCITY
1.000D+1		aL : FRACTURE DISPERSIVITY
1.200D-4		2b : FRACTURE APERTURE
1.600		2B : FRACTURE SPACING
0.100		TAUm : MATRIX TORTUOSITY
0.03		THETA : MATRIX POROSITY
2.830		RHOb : MATRIX BULK DENSITY
7.500D-4		LAMDA : FIRST-ORDER DECAY COEFF.
0.000		Kf : FRACTURE SORPTION COEFF.
3.400		Km : MATRIX SORPTION COEFF.
9.000D-09		D0 : FREE SOL'N DIFFUSION COEFF.
0.000D+00		CIN : INITIAL CONCENTRATION
3		NP : NUMBER OF POINTS FOR C(0,T)
0.00E+00	9.20E+04	
3.65E+04	0.00E+00	
5.48E+04	0.00E+00	
0.00,100.0,5.0		ZMIN,ZMAX,ZSTEP
0.00,0.00,0.01		XMIN,XMAX,XSTEP
16		NUMBER OF TIMES
1.82E+04		
2.00E+04		
2.19E+04		
2.37E+04		
2.55E+04		
2.73E+04		
2.91E+04		
3.10E+04		
3.28E+04		
3.46E+04		
3.64E+04		
3.82E+04		
4.01E+04		
4.19E+04		
4.37E+04		
4.55E+04		TIMES

Tutu.out

CRAFLUSH V.2

=====

ANALYTICAL SOLUTION FOR TRANSPORT ALONG A SYSTEM
OF PARALLEL FRACTURES
D > 0 CASE

Tutu 1/2 Lamda

INPUT PARAMETERS

=====

FRACTURE TRANSPORT PARAMETERS

FRACTURE VELOCITY V = 1.786000E-01
LONGITUDINAL DISPERSIVITY aL = 1.000000E+01
FRACTURE APERTURE 2b = 1.200000E-04
SPACING BETWEEN FRACTURES 2B = 1.600000E+00

MATRIX TRANSPORT PARAMETERS

TORTUOSITY TAUm = 1.000000E-01
POROSITY THETA = 3.000000E-02
BULK DENSITY RHOb = 2.830000E+00

SOLUTE PROPERTIES

FIRST-ORDER DECAY COEFF. LAMDA = 7.500000E-04
FRACTURE SORPTION ISOTHERM Kf = 0.000000E+00
MATRIX SORPTION ISOTHERM Km = 3.400000E+00
FREE-SOLUTION DIFFUSION COEFF. D0 = 9.000000E-09

INITIAL AND BOUNDARY CONDITIONS

INITIAL CONCENTRATIONS CIN = 0.000000E+00

CONSTRUCTED INFLOW CONCENTRATION HISTOGRAM

TIME INTERVAL CONCENTRATION

0.000000E+00 - 1.825000E+04 9.200000E+04
1.825000E+04 - 4.565000E+04 0.000000E+00
4.565000E+04 --> INFINITY 0.000000E+00

COMPUTED CONCENTRATIONS...

TIME	Z	X	C(Z,X,t)
1.820000E+04	0.000000E+00	0.000000E+00	9.200920E+04
1.820000E+04	5.000000E+00	0.000000E+00	7.764909E+04
1.820000E+04	1.000000E+01	0.000000E+00	6.553020E+04
1.820000E+04	1.500000E+01	0.000000E+00	5.530273E+04
1.820000E+04	2.000000E+01	0.000000E+00	4.667150E+04
1.820000E+04	2.500000E+01	0.000000E+00	3.938736E+04
1.820000E+04	3.000000E+01	0.000000E+00	3.324007E+04
1.820000E+04	3.500000E+01	0.000000E+00	2.805221E+04
1.820000E+04	4.000000E+01	0.000000E+00	2.367403E+04
1.820000E+04	4.500000E+01	0.000000E+00	1.997916E+04
1.820000E+04	5.000000E+01	0.000000E+00	1.686096E+04
1.820000E+04	5.500000E+01	0.000000E+00	1.422943E+04
1.820000E+04	6.000000E+01	0.000000E+00	1.200861E+04
1.820000E+04	6.500000E+01	0.000000E+00	1.013439E+04
1.820000E+04	7.000000E+01	0.000000E+00	8.552692E+03
1.820000E+04	7.500000E+01	0.000000E+00	7.217851E+03
1.820000E+04	8.000000E+01	0.000000E+00	6.091342E+03
1.820000E+04	8.500000E+01	0.000000E+00	5.140651E+03
1.820000E+04	9.000000E+01	0.000000E+00	4.338336E+03
1.820000E+04	9.500000E+01	0.000000E+00	3.661241E+03
1.820000E+04	1.000000E+02	0.000000E+00	3.089821E+03
2.000000E+04	0.000000E+00	0.000000E+00	1.859153E+02
2.000000E+04	5.000000E+00	0.000000E+00	6.397967E+02
2.000000E+04	1.000000E+01	0.000000E+00	1.048727E+03
2.000000E+04	1.500000E+01	0.000000E+00	1.408073E+03
2.000000E+04	2.000000E+01	0.000000E+00	1.714874E+03
2.000000E+04	2.500000E+01	0.000000E+00	1.967843E+03
2.000000E+04	3.000000E+01	0.000000E+00	2.167265E+03
2.000000E+04	3.500000E+01	0.000000E+00	2.314825E+03
2.000000E+04	4.000000E+01	0.000000E+00	2.413390E+03
2.000000E+04	4.500000E+01	0.000000E+00	2.466766E+03
2.000000E+04	5.000000E+01	0.000000E+00	2.479449E+03
2.000000E+04	5.500000E+01	0.000000E+00	2.456387E+03
2.000000E+04	6.000000E+01	0.000000E+00	2.402753E+03
2.000000E+04	6.500000E+01	0.000000E+00	2.323749E+03
2.000000E+04	7.000000E+01	0.000000E+00	2.224437E+03
2.000000E+04	7.500000E+01	0.000000E+00	2.109605E+03
2.000000E+04	8.000000E+01	0.000000E+00	1.983667E+03

2.000000E+04	8.500000E+01	0.000000E+00	1.850590E+03
2.000000E+04	9.000000E+01	0.000000E+00	1.713858E+03
2.000000E+04	9.500000E+01	0.000000E+00	1.576451E+03
2.000000E+04	1.000000E+02	0.000000E+00	1.440857E+03
2.190000E+04	0.000000E+00	0.000000E+00	3.893118E+01
2.190000E+04	5.000000E+00	0.000000E+00	7.235204E+01
2.190000E+04	1.000000E+01	0.000000E+00	1.068168E+02
2.190000E+04	1.500000E+01	0.000000E+00	1.410980E+02
2.190000E+04	2.000000E+01	0.000000E+00	1.741943E+02
2.190000E+04	2.500000E+01	0.000000E+00	2.053028E+02
2.190000E+04	3.000000E+01	0.000000E+00	2.337975E+02
2.190000E+04	3.500000E+01	0.000000E+00	2.592116E+02
2.190000E+04	4.000000E+01	0.000000E+00	2.812209E+02
2.190000E+04	4.500000E+01	0.000000E+00	2.996287E+02
2.190000E+04	5.000000E+01	0.000000E+00	3.143506E+02
2.190000E+04	5.500000E+01	0.000000E+00	3.253999E+02
2.190000E+04	6.000000E+01	0.000000E+00	3.328724E+02
2.190000E+04	6.500000E+01	0.000000E+00	3.369322E+02
2.190000E+04	7.000000E+01	0.000000E+00	3.377976E+02
2.190000E+04	7.500000E+01	0.000000E+00	3.357277E+02
2.190000E+04	8.000000E+01	0.000000E+00	3.310109E+02
2.190000E+04	8.500000E+01	0.000000E+00	3.239533E+02
2.190000E+04	9.000000E+01	0.000000E+00	3.148698E+02
2.190000E+04	9.500000E+01	0.000000E+00	3.040751E+02
2.190000E+04	1.000000E+02	0.000000E+00	2.918769E+02
2.370000E+04	0.000000E+00	0.000000E+00	-1.477939E+00
2.370000E+04	5.000000E+00	0.000000E+00	7.619724E+00
2.370000E+04	1.000000E+01	0.000000E+00	1.599373E+01
2.370000E+04	1.500000E+01	0.000000E+00	2.367185E+01
2.370000E+04	2.000000E+01	0.000000E+00	3.067168E+01
2.370000E+04	2.500000E+01	0.000000E+00	3.700508E+01
2.370000E+04	3.000000E+01	0.000000E+00	4.268135E+01
2.370000E+04	3.500000E+01	0.000000E+00	4.770949E+01
2.370000E+04	4.000000E+01	0.000000E+00	5.209967E+01
2.370000E+04	4.500000E+01	0.000000E+00	5.586435E+01
2.370000E+04	5.000000E+01	0.000000E+00	5.901890E+01
2.370000E+04	5.500000E+01	0.000000E+00	6.158192E+01
2.370000E+04	6.000000E+01	0.000000E+00	6.357541E+01
2.370000E+04	6.500000E+01	0.000000E+00	6.502468E+01
2.370000E+04	7.000000E+01	0.000000E+00	6.595819E+01
2.370000E+04	7.500000E+01	0.000000E+00	6.640720E+01
2.370000E+04	8.000000E+01	0.000000E+00	6.640540E+01
2.370000E+04	8.500000E+01	0.000000E+00	6.598843E+01
2.370000E+04	9.000000E+01	0.000000E+00	6.519343E+01

2.370000E+04	9.500000E+01	0.000000E+00	6.405846E+01
2.370000E+04	1.000000E+02	0.000000E+00	6.262202E+01
2.550000E+04	0.000000E+00	0.000000E+00	-4.254845E+00
2.550000E+04	5.000000E+00	0.000000E+00	-2.134514E+00
2.550000E+04	1.000000E+01	0.000000E+00	-1.738710E-01
2.550000E+04	1.500000E+01	0.000000E+00	1.634451E+00
2.550000E+04	2.000000E+01	0.000000E+00	3.296026E+00
2.550000E+04	2.500000E+01	0.000000E+00	4.815269E+00
2.550000E+04	3.000000E+01	0.000000E+00	6.195927E+00
2.550000E+04	3.500000E+01	0.000000E+00	7.441457E+00
2.550000E+04	4.000000E+01	0.000000E+00	8.555289E+00
2.550000E+04	4.500000E+01	0.000000E+00	9.541010E+00
2.550000E+04	5.000000E+01	0.000000E+00	1.040248E+01
2.550000E+04	5.500000E+01	0.000000E+00	1.114387E+01
2.550000E+04	6.000000E+01	0.000000E+00	1.176974E+01
2.550000E+04	6.500000E+01	0.000000E+00	1.228497E+01
2.550000E+04	7.000000E+01	0.000000E+00	1.269479E+01
2.550000E+04	7.500000E+01	0.000000E+00	1.300473E+01
2.550000E+04	8.000000E+01	0.000000E+00	1.322056E+01
2.550000E+04	8.500000E+01	0.000000E+00	1.334829E+01
2.550000E+04	9.000000E+01	0.000000E+00	1.339408E+01
2.550000E+04	9.500000E+01	0.000000E+00	1.336423E+01
2.550000E+04	1.000000E+02	0.000000E+00	1.326508E+01
2.730000E+04	0.000000E+00	0.000000E+00	-4.052258E-01
2.730000E+04	5.000000E+00	0.000000E+00	-1.217184E-01
2.730000E+04	1.000000E+01	0.000000E+00	1.622769E-01
2.730000E+04	1.500000E+01	0.000000E+00	4.422994E-01
2.730000E+04	2.000000E+01	0.000000E+00	7.147142E-01
2.730000E+04	2.500000E+01	0.000000E+00	9.765483E-01
2.730000E+04	3.000000E+01	0.000000E+00	1.225380E+00
2.730000E+04	3.500000E+01	0.000000E+00	1.459265E+00
2.730000E+04	4.000000E+01	0.000000E+00	1.676677E+00
2.730000E+04	4.500000E+01	0.000000E+00	1.876475E+00
2.730000E+04	5.000000E+01	0.000000E+00	2.057861E+00
2.730000E+04	5.500000E+01	0.000000E+00	2.220347E+00
2.730000E+04	6.000000E+01	0.000000E+00	2.363727E+00
2.730000E+04	6.500000E+01	0.000000E+00	2.488038E+00
2.730000E+04	7.000000E+01	0.000000E+00	2.593533E+00
2.730000E+04	7.500000E+01	0.000000E+00	2.680649E+00
2.730000E+04	8.000000E+01	0.000000E+00	2.749976E+00
2.730000E+04	8.500000E+01	0.000000E+00	2.802229E+00
2.730000E+04	9.000000E+01	0.000000E+00	2.838227E+00
2.730000E+04	9.500000E+01	0.000000E+00	2.858868E+00
2.730000E+04	1.000000E+02	0.000000E+00	2.865107E+00

2.910000E+04	0.000000E+00	0.000000E+00	2.439289E-01
2.910000E+04	5.000000E+00	0.000000E+00	2.380145E-01
2.910000E+04	1.000000E+01	0.000000E+00	2.438273E-01
2.910000E+04	1.500000E+01	0.000000E+00	2.585284E-01
2.910000E+04	2.000000E+01	0.000000E+00	2.798149E-01
2.910000E+04	2.500000E+01	0.000000E+00	3.058025E-01
2.910000E+04	3.000000E+01	0.000000E+00	3.349364E-01
2.910000E+04	3.500000E+01	0.000000E+00	3.659247E-01
2.910000E+04	4.000000E+01	0.000000E+00	3.976904E-01
2.910000E+04	4.500000E+01	0.000000E+00	4.293374E-01
2.910000E+04	5.000000E+01	0.000000E+00	4.601248E-01
2.910000E+04	5.500000E+01	0.000000E+00	4.894479E-01
2.910000E+04	6.000000E+01	0.000000E+00	5.168233E-01
2.910000E+04	6.500000E+01	0.000000E+00	5.418752E-01
2.910000E+04	7.000000E+01	0.000000E+00	5.643242E-01
2.910000E+04	7.500000E+01	0.000000E+00	5.839755E-01
2.910000E+04	8.000000E+01	0.000000E+00	6.007086E-01
2.910000E+04	8.500000E+01	0.000000E+00	6.144674E-01
2.910000E+04	9.000000E+01	0.000000E+00	6.252502E-01
2.910000E+04	9.500000E+01	0.000000E+00	6.331013E-01
2.910000E+04	1.000000E+02	0.000000E+00	6.381025E-01
3.100000E+04	0.000000E+00	0.000000E+00	1.568633E-01
3.100000E+04	5.000000E+00	0.000000E+00	1.374258E-01
3.100000E+04	1.000000E+01	0.000000E+00	1.229613E-01
3.100000E+04	1.500000E+01	0.000000E+00	1.125291E-01
3.100000E+04	2.000000E+01	0.000000E+00	1.053664E-01
3.100000E+04	2.500000E+01	0.000000E+00	1.008519E-01
3.100000E+04	3.000000E+01	0.000000E+00	9.847460E-02
3.100000E+04	3.500000E+01	0.000000E+00	9.780836E-02
3.100000E+04	4.000000E+01	0.000000E+00	9.849245E-02
3.100000E+04	4.500000E+01	0.000000E+00	1.002173E-01
3.100000E+04	5.000000E+01	0.000000E+00	1.027147E-01
3.100000E+04	5.500000E+01	0.000000E+00	1.057512E-01
3.100000E+04	6.000000E+01	0.000000E+00	1.091236E-01
3.100000E+04	6.500000E+01	0.000000E+00	1.126567E-01
3.100000E+04	7.000000E+01	0.000000E+00	1.162006E-01
3.100000E+04	7.500000E+01	0.000000E+00	1.196297E-01
3.100000E+04	8.000000E+01	0.000000E+00	1.228403E-01
3.100000E+04	8.500000E+01	0.000000E+00	1.257497E-01
3.100000E+04	9.000000E+01	0.000000E+00	1.282942E-01
3.100000E+04	9.500000E+01	0.000000E+00	1.304269E-01
3.100000E+04	1.000000E+02	0.000000E+00	1.321161E-01
3.280000E+04	0.000000E+00	0.000000E+00	6.040937E-02
3.280000E+04	5.000000E+00	0.000000E+00	5.301134E-02

3.280000E+04	1.000000E+01	0.000000E+00	4.692297E-02
3.280000E+04	1.500000E+01	0.000000E+00	4.192524E-02
3.280000E+04	2.000000E+01	0.000000E+00	3.784094E-02
3.280000E+04	2.500000E+01	0.000000E+00	3.452901E-02
3.280000E+04	3.000000E+01	0.000000E+00	3.187756E-02
3.280000E+04	3.500000E+01	0.000000E+00	2.979664E-02
3.280000E+04	4.000000E+01	0.000000E+00	2.821175E-02
3.280000E+04	4.500000E+01	0.000000E+00	2.705854E-02
3.280000E+04	5.000000E+01	0.000000E+00	2.627900E-02
3.280000E+04	5.500000E+01	0.000000E+00	2.581909E-02
3.280000E+04	6.000000E+01	0.000000E+00	2.562748E-02
3.280000E+04	6.500000E+01	0.000000E+00	2.565523E-02
3.280000E+04	7.000000E+01	0.000000E+00	2.585595E-02
3.280000E+04	7.500000E+01	0.000000E+00	2.618621E-02
3.280000E+04	8.000000E+01	0.000000E+00	2.660608E-02
3.280000E+04	8.500000E+01	0.000000E+00	2.707956E-02
3.280000E+04	9.000000E+01	0.000000E+00	2.757488E-02
3.280000E+04	9.500000E+01	0.000000E+00	2.806467E-02
3.280000E+04	1.000000E+02	0.000000E+00	2.852596E-02
3.460000E+04	0.000000E+00	0.000000E+00	1.665773E-02
3.460000E+04	5.000000E+00	0.000000E+00	1.558995E-02
3.460000E+04	1.000000E+01	0.000000E+00	1.457379E-02
3.460000E+04	1.500000E+01	0.000000E+00	1.360271E-02
3.460000E+04	2.000000E+01	0.000000E+00	1.267121E-02
3.460000E+04	2.500000E+01	0.000000E+00	1.177771E-02
3.460000E+04	3.000000E+01	0.000000E+00	1.092535E-02
3.460000E+04	3.500000E+01	0.000000E+00	1.012118E-02
3.460000E+04	4.000000E+01	0.000000E+00	9.374464E-03
3.460000E+04	4.500000E+01	0.000000E+00	8.694812E-03
3.460000E+04	5.000000E+01	0.000000E+00	8.090487E-03
3.460000E+04	5.500000E+01	0.000000E+00	7.567225E-03
3.460000E+04	6.000000E+01	0.000000E+00	7.127610E-03
3.460000E+04	6.500000E+01	0.000000E+00	6.770975E-03
3.460000E+04	7.000000E+01	0.000000E+00	6.493686E-03
3.460000E+04	7.500000E+01	0.000000E+00	6.289669E-03
3.460000E+04	8.000000E+01	0.000000E+00	6.151060E-03
3.460000E+04	8.500000E+01	0.000000E+00	6.068856E-03
3.460000E+04	9.000000E+01	0.000000E+00	6.033521E-03
3.460000E+04	9.500000E+01	0.000000E+00	6.035487E-03
3.460000E+04	1.000000E+02	0.000000E+00	6.065554E-03
3.640000E+04	0.000000E+00	0.000000E+00	1.775501E-03
3.640000E+04	5.000000E+00	0.000000E+00	2.649343E-03
3.640000E+04	1.000000E+01	0.000000E+00	3.301479E-03
3.640000E+04	1.500000E+01	0.000000E+00	3.764688E-03

3.640000E+04	2.000000E+01	0.000000E+00	4.064311E-03
3.640000E+04	2.500000E+01	0.000000E+00	4.222322E-03
3.640000E+04	3.000000E+01	0.000000E+00	4.259839E-03
3.640000E+04	3.500000E+01	0.000000E+00	4.198222E-03
3.640000E+04	4.000000E+01	0.000000E+00	4.059050E-03
3.640000E+04	4.500000E+01	0.000000E+00	3.863440E-03
3.640000E+04	5.000000E+01	0.000000E+00	3.631117E-03
3.640000E+04	5.500000E+01	0.000000E+00	3.379563E-03
3.640000E+04	6.000000E+01	0.000000E+00	3.123423E-03
3.640000E+04	6.500000E+01	0.000000E+00	2.874246E-03
3.640000E+04	7.000000E+01	0.000000E+00	2.640512E-03
3.640000E+04	7.500000E+01	0.000000E+00	2.427890E-03
3.640000E+04	8.000000E+01	0.000000E+00	2.239630E-03
3.640000E+04	8.500000E+01	0.000000E+00	2.077015E-03
3.640000E+04	9.000000E+01	0.000000E+00	1.939814E-03
3.640000E+04	9.500000E+01	0.000000E+00	1.826698E-03
3.640000E+04	1.000000E+02	0.000000E+00	1.735604E-03
3.820000E+04	0.000000E+00	0.000000E+00	-1.927885E-03
3.820000E+04	5.000000E+00	0.000000E+00	-8.851693E-04
3.820000E+04	1.000000E+01	0.000000E+00	-3.831418E-05
3.820000E+04	1.500000E+01	0.000000E+00	6.399284E-04
3.820000E+04	2.000000E+01	0.000000E+00	1.169438E-03
3.820000E+04	2.500000E+01	0.000000E+00	1.566138E-03
3.820000E+04	3.000000E+01	0.000000E+00	1.844539E-03
3.820000E+04	3.500000E+01	0.000000E+00	2.019278E-03
3.820000E+04	4.000000E+01	0.000000E+00	2.105651E-03
3.820000E+04	4.500000E+01	0.000000E+00	2.119414E-03
3.820000E+04	5.000000E+01	0.000000E+00	2.076163E-03
3.820000E+04	5.500000E+01	0.000000E+00	1.990607E-03
3.820000E+04	6.000000E+01	0.000000E+00	1.875952E-03
3.820000E+04	6.500000E+01	0.000000E+00	1.743499E-03
3.820000E+04	7.000000E+01	0.000000E+00	1.602484E-03
3.820000E+04	7.500000E+01	0.000000E+00	1.460107E-03
3.820000E+04	8.000000E+01	0.000000E+00	1.321707E-03
3.820000E+04	8.500000E+01	0.000000E+00	1.191008E-03
3.820000E+04	9.000000E+01	0.000000E+00	1.070401E-03
3.820000E+04	9.500000E+01	0.000000E+00	9.612109E-04
3.820000E+04	1.000000E+02	0.000000E+00	8.639520E-04
4.010000E+04	0.000000E+00	0.000000E+00	-2.108555E-03
4.010000E+04	5.000000E+00	0.000000E+00	-1.405906E-03
4.010000E+04	1.000000E+01	0.000000E+00	-8.133941E-04
4.010000E+04	1.500000E+01	0.000000E+00	-3.156715E-04
4.010000E+04	2.000000E+01	0.000000E+00	9.675780E-05
4.010000E+04	2.500000E+01	0.000000E+00	4.300376E-04

4.010000E+04	3.000000E+01	0.000000E+00	6.891993E-04
4.010000E+04	3.500000E+01	0.000000E+00	8.797340E-04
4.010000E+04	4.000000E+01	0.000000E+00	1.008369E-03
4.010000E+04	4.500000E+01	0.000000E+00	1.083113E-03
4.010000E+04	5.000000E+01	0.000000E+00	1.112813E-03
4.010000E+04	5.500000E+01	0.000000E+00	1.106518E-03
4.010000E+04	6.000000E+01	0.000000E+00	1.072865E-03
4.010000E+04	6.500000E+01	0.000000E+00	1.019632E-03
4.010000E+04	7.000000E+01	0.000000E+00	9.534780E-04
4.010000E+04	7.500000E+01	0.000000E+00	8.798575E-04
4.010000E+04	8.000000E+01	0.000000E+00	8.030608E-04
4.010000E+04	8.500000E+01	0.000000E+00	7.263283E-04
4.010000E+04	9.000000E+01	0.000000E+00	6.520026E-04
4.010000E+04	9.500000E+01	0.000000E+00	5.816878E-04
4.010000E+04	1.000000E+02	0.000000E+00	5.163998E-04
4.190000E+04	0.000000E+00	0.000000E+00	-1.516482E-03
4.190000E+04	5.000000E+00	0.000000E+00	-1.148498E-03
4.190000E+04	1.000000E+01	0.000000E+00	-8.243462E-04
4.190000E+04	1.500000E+01	0.000000E+00	-5.367198E-04
4.190000E+04	2.000000E+01	0.000000E+00	-2.830734E-04
4.190000E+04	2.500000E+01	0.000000E+00	-6.378078E-05
4.190000E+04	3.000000E+01	0.000000E+00	1.198133E-04
4.190000E+04	3.500000E+01	0.000000E+00	2.669827E-04
4.190000E+04	4.000000E+01	0.000000E+00	3.785245E-04
4.190000E+04	4.500000E+01	0.000000E+00	4.569459E-04
4.190000E+04	5.000000E+01	0.000000E+00	5.061220E-04
4.190000E+04	5.500000E+01	0.000000E+00	5.307198E-04
4.190000E+04	6.000000E+01	0.000000E+00	5.356178E-04
4.190000E+04	6.500000E+01	0.000000E+00	5.254575E-04
4.190000E+04	7.000000E+01	0.000000E+00	5.043678E-04
4.190000E+04	7.500000E+01	0.000000E+00	4.758344E-04
4.190000E+04	8.000000E+01	0.000000E+00	4.426826E-04
4.190000E+04	8.500000E+01	0.000000E+00	4.071217E-04
4.190000E+04	9.000000E+01	0.000000E+00	3.708237E-04
4.190000E+04	9.500000E+01	0.000000E+00	3.350123E-04
4.190000E+04	1.000000E+02	0.000000E+00	3.005485E-04
4.370000E+04	0.000000E+00	0.000000E+00	-9.531032E-04
4.370000E+04	5.000000E+00	0.000000E+00	-8.144546E-04
4.370000E+04	1.000000E+01	0.000000E+00	-6.788246E-04
4.370000E+04	1.500000E+01	0.000000E+00	-5.433892E-04
4.370000E+04	2.000000E+01	0.000000E+00	-4.094015E-04
4.370000E+04	2.500000E+01	0.000000E+00	-2.808701E-04
4.370000E+04	3.000000E+01	0.000000E+00	-1.627791E-04
4.370000E+04	3.500000E+01	0.000000E+00	-5.946530E-05

4.370000E+04	4.000000E+01	0.000000E+00	2.638798E-05
4.370000E+04	4.500000E+01	0.000000E+00	9.401234E-05
4.370000E+04	5.000000E+01	0.000000E+00	1.442561E-04
4.370000E+04	5.500000E+01	0.000000E+00	1.790343E-04
4.370000E+04	6.000000E+01	0.000000E+00	2.007802E-04
4.370000E+04	6.500000E+01	0.000000E+00	2.120251E-04
4.370000E+04	7.000000E+01	0.000000E+00	2.151312E-04
4.370000E+04	7.500000E+01	0.000000E+00	2.121585E-04
4.370000E+04	8.000000E+01	0.000000E+00	2.048232E-04
4.370000E+04	8.500000E+01	0.000000E+00	1.945057E-04
4.370000E+04	9.000000E+01	0.000000E+00	1.822886E-04
4.370000E+04	9.500000E+01	0.000000E+00	1.690023E-04
4.370000E+04	1.000000E+02	0.000000E+00	1.552704E-04
4.550000E+04	0.000000E+00	0.000000E+00	-5.599540E-04
4.550000E+04	5.000000E+00	0.000000E+00	-5.480959E-04
4.550000E+04	1.000000E+01	0.000000E+00	-5.195094E-04
4.550000E+04	1.500000E+01	0.000000E+00	-4.732584E-04
4.550000E+04	2.000000E+01	0.000000E+00	-4.120659E-04
4.550000E+04	2.500000E+01	0.000000E+00	-3.414033E-04
4.550000E+04	3.000000E+01	0.000000E+00	-2.678186E-04
4.550000E+04	3.500000E+01	0.000000E+00	-1.972362E-04
4.550000E+04	4.000000E+01	0.000000E+00	-1.338787E-04
4.550000E+04	4.500000E+01	0.000000E+00	-7.999785E-05
4.550000E+04	5.000000E+01	0.000000E+00	-3.619218E-05
4.550000E+04	5.500000E+01	0.000000E+00	-1.942443E-06
4.550000E+04	6.000000E+01	0.000000E+00	2.386637E-05
4.550000E+04	6.500000E+01	0.000000E+00	4.257068E-05
4.550000E+04	7.000000E+01	0.000000E+00	5.549545E-05
4.550000E+04	7.500000E+01	0.000000E+00	6.383660E-05
4.550000E+04	8.000000E+01	0.000000E+00	6.861504E-05
4.550000E+04	8.500000E+01	0.000000E+00	7.067388E-05
4.550000E+04	9.000000E+01	0.000000E+00	7.069314E-05
4.550000E+04	9.500000E+01	0.000000E+00	6.921367E-05
4.550000E+04	1.000000E+02	0.000000E+00	6.666110E-05

Attachment 2 – Matrix Diffusion Toolkit Spreadsheets

SRM Data Input Screen

Matrix Diffusion Toolkit

Version 1.0

Site Location and ID: Industrial Site

1. SYSTEM UNITS

SI Units English Units

3. HYDROGEOLOGY

Low-k Zone Description
Low-k Zone Total Porosity
Transmissive Zone Darcy Velocity

4. TRANSPORT - Low-k Zone

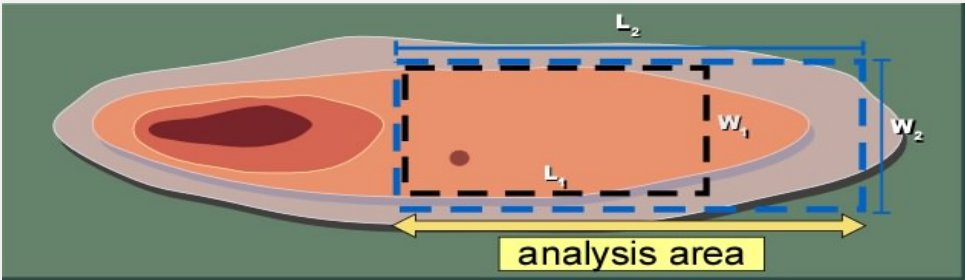
Key Constituent
Molecular Diffusion Coefficient in Free Water
Apparent Tortuosity Factor Exponent
Retardation Factor

2. ANALYSIS TYPE

Source Zone Analysis Plume Analysis PRB Analysis

Andesitic Tuff User Input
 ϕ 0.025 (-)
 V_d 0.178 (m/d) Calculate Vd

PCE PCE
 D_o 8.20E-10 (m2/sec)
 ρ 8.00E-02 (-)
 R 17.48 (-) Calculate R



High Concentration Zone (Black Box in Picture)

Approximate Length (Length of Black Box)
Approximate Width (Width of Black Box)
Highest Historical Concentration in Black Box
Concentration of Contour Line in Black Box
Representative Concentration (OK to Override)

Next Highest Concentration Zone (Blue Box in Picture)

Approximate Length (Length of Blue Box)
Approximate Width (Width of Blue Box)

L_1 7.00E+01 (m)
 W_1 3.00E+01 (m)
9.20E+04 (ug/L)
1.00E+03 (ug/L)
 C_{s1} 9.59E+03 (ug/L) Restore
 L_2 1.15E+02 (m)
 W_2 5.00E+01 (m)

DATA INPUT INSTRUCTIONS

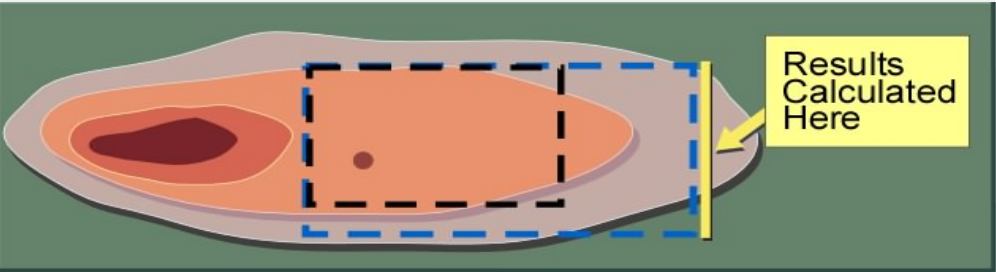
Enter value directly.
Value calculated by Toolkit. Do not enter data.

5. PLUME CHARACTERISTICS CONT'D

Concentration of Contour Line in Blue Box
Representative Concentration (OK to Override) C_{s2} 5.00E+02 (ug/L) 7.07E+02 (ug/L) Restore
Uncertainty in Plume Concentration Estimations $\pm$ factor of 7

6. GENERAL

Source Loading Starts in Year 1970 (format: yyyy)
Source Removed in Year 2020 (format: yyyy)



See Release Period Results
from Year 1995 (format: yyyy)
to Year 2120 (format: yyyy)
in Intervals of 2 (yrs)

7. FIELD DATA FOR COMPARISON

Year							
Concentration (ug/L)							
Mass Discharge (g/day)							
Mass (kg)							

Next Step:
Show Graph

New Site/Clear Data

Paste Example

Save Data

Load Data

HELP

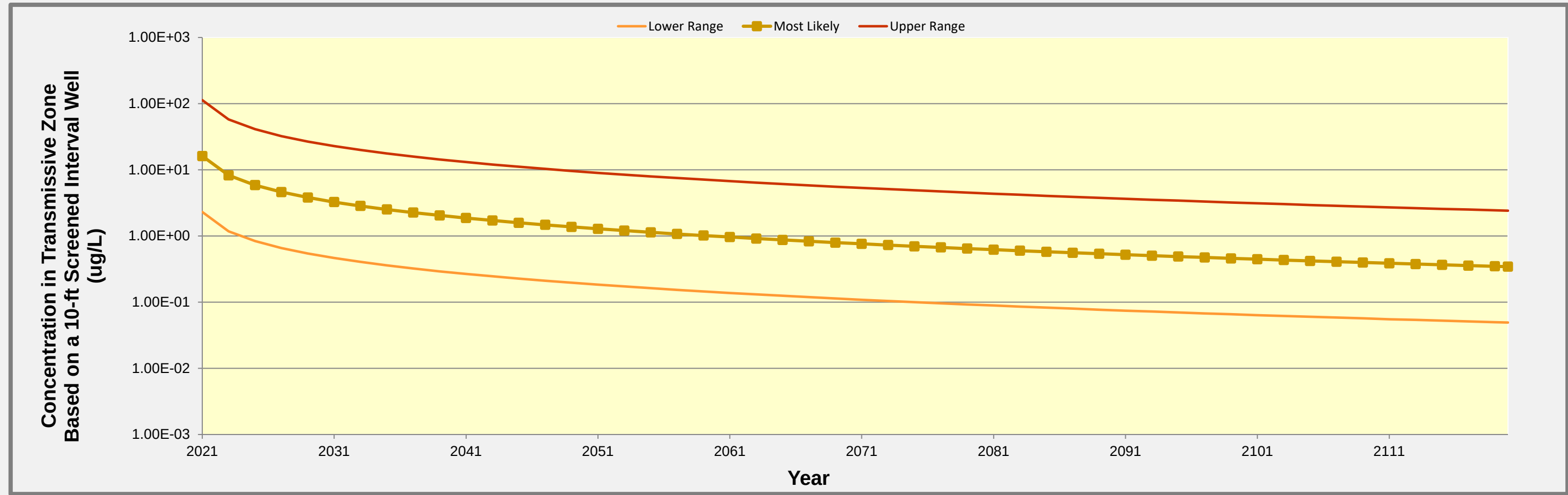
Return to Model Selection Screen

Return to Main Screen

Time (yr)	1995	1997	1999	2001	2003	2005	2007	2009	2011	2013	2015	2017	2019	2020	2021	2023	2025	2027	2029	2031
Mass Discharge (g/day)	-1.02E-01	-9.80E-02	-9.46E-02	-9.15E-02	-8.87E-02	-8.61E-02	-8.37E-02	-8.16E-02	-7.96E-02	-7.77E-02	-7.59E-02	-7.43E-02	-7.28E-02	-7.20E-02	4.38E-01	2.24E-01	1.59E-01	1.25E-01	1.03E-01	8.84E-02
Mass (kg)	1.86E+00	1.93E+00	2.00E+00	2.07E+00	2.14E+00	2.20E+00	2.26E+00	2.32E+00	2.38E+00	2.44E+00	2.49E+00	2.55E+00	2.60E+00	2.63E+00	2.28E+00	2.06E+00	1.93E+00	1.82E+00	1.74E+00	1.67E+00
Concentration (ug/L)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.61E+01	8.26E+00	5.87E+00	4.61E+00	3.81E+00	3.26E+00
Plume Magnitude	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Mag 4	Mag 4	Mag 4	Mag 4	Mag 4	Mag 3

Note: Negative mass discharge values represent diffusion into the low-k zone from the transmissive zone. Positive values represent diffusion from the low-k zone into the transmissive zone.

What's up with the gap?



Log↔Linear

Re-Plot Graph from Year to Year
(format: yyyy) (format: yyyy)

Update Graph

Restore Original IntervalRestore Original Graph

Next Step: Save Data

Run Advanced Uncertainty Analysis

See Mass Discharge ResultsSee Mass Results

Return to SRM Data InputExport/Print Data Table

Return to Main ScreenHELP

Note that in the analyses concentrations are doubled from what is presented here to emulate a fracture.