# Unit 4 Source Area In-Situ Bioremediation Treatability Study Work Plan, Revision 1
## Nevada Environmental Response Trust Site
## Henderson, Nevada

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# LIST OF ACRONYMS/ABBREVIATIONS

| Acronyms/Abbreviations | Definition |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| AC | asphalt concrete |
| AFCEE | Air Force Center for Engineering and the Environment |
| Amsl | above mean sea level |
| AP | ammonium perchlorate |
| ASTM | American Society for Testing and Materials |
| AWF | Athens Road Well Field |
| Bgs | below ground surface |
| BMI | Black Mountain Industrial (Complex) |
| COPC | chemical of potential concern |
| COH | City of Henderson |
| cm/s | centimeter per second |
| CRB | Central Retention Basin |
| DO | dissolved oxygen |
| EC | electrical conductivity |
| EDD | electronic data deliverable |
| EVO | emulsified vegetable oil |
| FBR | fluidized bed reactor |
| Gpm | gallons per minute |
| GWETS | Groundwater Extraction and Treatment System |
| IDW | investigative-derived waste |
| ISB | in-situ bioremediation |
| ITRC | Interstate Technology & Regulatory Council |
| IWF | Interceptor Well Field |
| lbs/day | pounds per day |
| mVs | millivolts |
| mg/L | milligrams per liter |
| mg/kg | milligrams per kilogram |
| NAC | Nevada Administrative Code |
| NAVD | North American Vertical Datum |
| NDEP | Nevada Division of Environmental Protection |
| NDWR | Nevada Division of Water Resources |
| NERT or Trust | Nevada Environmental Response Trust |

| Acronyms/Abbreviations | Definition |
|---|---|
| NMR | nuclear magnetic resonance |
| NOM | natural organic carbon |
| ORP | oxidation-reduction potential |
| PDF | portable document format |
| PFLA | phospholipid fatty acids |
| Psi | pounds per square inch |
| PVC | polyvinyl chloride |
| Qal | Quaternary alluvium/Quaternary alluvial |
| RI | remedial investigation |
| ROI | radius of influence |
| Site | Nevada Environmental Response Trust Site |
| SLMW | Stabilized Lake Mead water |
| SPT | Standard Penetration Test |
| SWF | Seep Well Field |
| TDS | total dissolved solids |
| Tetra Tech | Tetra Tech, Inc. |
| TOC | total organic carbon |
| Tronox | Tronox LLC |
| TSS | total suspended solids |
| UIC | Underground Injection Control |
| UMCf | Upper Muddy Creek formation |
| UNLV | University of Nevada at Las Vegas |
| US EPA | United States Environmental Protection Agency |
| USCS | Unified Soil Classification System |
| VFA | volatile fatty acid |
| VOC | volatile organic compound |
| WBZ | water-bearing zone |
| Work Plan | Unit 4 Source Area In-Situ Bioremediation Treatability Study Work Plan |
| ZOI | zone of influence |

# CERTIFICATION

**Unit 4 Source Area In-Situ Bioremediation**
**Treatability Study Work Plan, Revision 1**

**Nevada Environmental Response Trust Site**
**(Former Tronox LLC Site)**
**Henderson, Nevada**

**Nevada Environmental Response Trust (NERT) Representative Certification**
I certify that this document and all attachments submitted to the Division were prepared at the request of, or under the direction or supervision of NERT. Based on my own involvement and/or my inquiry of the person or persons who manage the systems(s) or those directly responsible for gathering the information or preparing the document, or the immediate supervisor of such person(s), the information submitted and provided herein is, to the best of my knowledge and belief, true, accurate, and complete in all material respects.

Office of the Nevada Environmental Response Trust

Le Petomane XXVII, not individually, but solely in its representative capacity as the Nevada Environmental Response Trust Trustee

not individually, but solely as Pres. [illegible]

**Signature:** Jay A Steinberg, ______, not individually, but solely in his representative capacity as President of the Nevada Environmental Response Trust Trustee

**Name:** Jay A. Steinberg, not individually, but solely in his representative capacity as President of the Nevada Environmental Response Trust Trustee

**Title:** Solely as President and not individually

**Company:** Le Petomane XXVII, Inc., not individually, but solely in its representative capacity as the Nevada Environmental Response Trust Trustee

**Date:** 2/13/18

# CERTIFICATION

I hereby certify that I am responsible for the services described in this document and for the preparation of this document. The services described in this document have been prepared in a manner consistent with the current standards of the profession, and to the best of my knowledge, comply with all applicable federal, state, and local statutes, regulations, and ordinances.

***Description of Services Provided:*** Prepared Unit 4 Source Area In-Situ Bioremediation Treatability Study Work Plan, Revision 1, Nevada Environmental Response Trust Site, Henderson, Nevada.

Kyle S. Hansen ______________________ February 5, 2018

**Kyle Hansen, CEM** Date
Field Operations Manager/Geologist
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Nevada CEM Certificate Number: 2167
Nevada CEM Expiration Date: September 18, 2018

# 1.0 INTRODUCTION

On behalf of the Nevada Environmental Response Trust (NERT or Trust), Tetra Tech, Inc. (Tetra Tech) has prepared this Unit 4 Source Area In-Situ Bioremediation Treatability Study Work Plan (Work Plan) for the NERT site (Site), located in Clark County, Nevada (Figure 1). This Work Plan is being submitted to the Nevada Division of Environmental Protection (NDEP) as part of the Remedial Investigation (RI) consistent with the Interim Consent Agreement effective February 14, 2011. The Work Plan presents the technical approach and conceptual scope of work for implementation of a treatability study employing a hybrid in-situ bioremediation (ISB) / groundwater extraction / soil flushing approach at the former Unit 4 cell building (Unit 4) based on currently available data. The overall treatability study consists of bench-scale studies, pre-implementation activities, field application, and post study sampling and reporting. The technical approach and scope of work for bench-scale studies for the treatability study was presented in the Unit 4 Source Area In-Situ Bioremediation Bench-Scale Studies Work Plan and is currently underway. However, the objectives and rationale for performing bench-scale studies have been summarized in this Work Plan for information purposes.

## 1.1 PROJECT OBJECTIVES

This treatability study will build on the results of the previous soil flushing and ISB treatability studies performed at the Site and down-gradient of the Site to evaluate a hybrid application of these technologies to address Unit 4, an area containing amongst the highest and deepest contaminant concentrations found at the Site (Tetra Tech, Inc., 2017a). Tetra Tech has developed the following objectives for this treatability study:

- Evaluate the overall effectiveness of a hybrid ISB / groundwater extraction / soil flushing approach to achieve source reduction of chemicals of potential concern (COPCs);
- Evaluate the impact of water chemistry below the Unit 4 Building on the rate of degradation of COPCs in bench-scale studies and a field treatability study;
- Evaluate the use of groundwater extraction to facilitate distribution of substrate to enhance COPC reduction; and
- Collect key information needed to support the feasibility study to evaluate design, optimization/scale-up, and overall effectiveness of these technologies.

This treatability study is unique from the prior and ongoing treatability studies in that the proposed study will be evaluating the use of soil flushing and ISB to remediate very high concentrations of perchlorate in the vadose and saturated zones where very high concentrations of chlorate and total dissolved solids are also present. In addition, the proposed treatability study will also evaluate the ability to treat chloroform using an ISB approach. As such the proposed treatability study has a number of complexities that have not been addressed.

## 1.2 WORK PLAN ORGANIZATION

This Work Plan is organized as follows:

- **Introduction (Section 1.0):** Provides the primary objectives of the treatability study along with relevant background information, including regional and local geology and hydrogeology and extent of contamination.
- **Technology Description (Section 2.0):** Provides an overview and technology description of soil flushing, ISB, and groundwater extraction for remediation of perchlorate-contaminated soil and groundwater, as well as a summary of previous and on-going ISB and soil flushing treatability studies.

- **Evaluation of Methods (Section 3.0):** Summarizes the results of an evaluation of both engineering and cost components using available data to identify the preferred implementation method(s) that will be employed during the treatability study.
- **Pre-Implementation Laboratory and Field Activities (Section 4.0):** Provides a description of the field and laboratory (currently underway) activities to be completed prior to implementation of the treatability study to optimize and finalize the treatability study design.
- **Treatability Study Conceptual Design (Section 5.0):** Describes the conceptual design of the treatability study including objectives, conceptual layout(s) for both the soil flushing and groundwater remediation system design.
- **Effectiveness Monitoring Plan (Section 6.0):** Presents the conceptual effectiveness monitoring program for the treatability study for soil and groundwater, including field and analytical monitoring components, mass evaluations, and data validation requirements.
- **Health and Safety and Permitting Requireme**nts **(Section 7.0)**: Provides a description of how chemical and physical hazards associated with the field activities will be addressed.
- **Reporting and Data Validation (Section 8.0):** Summarizes reporting related to design and execution of the bench-scale testing, pre-implementation field and laboratory activities, treatability study, and evaluation of the treatability study data and technologies.
- **Schedule (Section 9.0):** Presents the schedule for conducting the bench-scale testing, pre-implementation field and laboratory activities, treatability study, and associated reporting.
- **References (Section 10.0):** Lists the documents referenced in this Work Plan.

## 1.3 BACKGROUND

### 1.3.1 General

This section provides a brief description of the location and history of the Site along with details regarding the Unit 4 Source Area In-Situ Bioremediation Treatability Study area (Study Area) derived from the *Remedial Investigation Data Evaluation* (Ramboll Environ, 2016a), the *Unit 4 and 5 Buildings Investigation First Mobilization Technical Memorandum* (Tetra Tech, Inc., 2016a) and *Unit 4 and 5 Buildings Investigation Second Mobilization Technical Memorandum* (Tetra Tech, Inc., 2017a). The Study Area is a portion of the Unit 4 and 5 Buildings Investigation Area and only includes the area where the Unit 4 Source Area In-Situ Bioremediation Treatability Study will occur.

The Site, which was formerly owned and operated by Tronox LLC (Tronox), comprises approximately 364 acres located within the Black Mountain Industrial (BMI) Complex in an unincorporated portion of Clark County that is surrounded by the City of Henderson, Nevada (Ramboll Environ, 2017a). The Site has been used for industrial operations since 1942, when it was developed by the U.S. government as a magnesium plant in support of World War II operations. Following the war, various industrial activities, including the production of perchlorates, boron, and manganese compounds, continued at the BMI Complex. Former industrial and waste management practices at the Site and adjacent properties have resulted in impacts to soil, groundwater, and surface water. Tronox formerly owned and operated a portion of the Site, including the Unit 4 and 5 Buildings. In conjunction with the settlement of Tronox's bankruptcy proceeding, ownership of the Site was transferred to NERT on February 14, 2011. Tronox currently leases an approximately 114-acre portion of the Site, which includes the Unit 4 and 5 Buildings, and continues to operate its manufacturing business (Ramboll Environ, 2016a).

There are a total of ten unit buildings (numbered 1 through 10) aligned in a row from west to east along the southern portion of the Site (Figure 1). Each unit building consists of three structures: a chlorinator building on the north side, a cell building in the center, and substation building on the south side. Tronox leasehold includes four of the unit buildings (Units 3, 4, 5, and 6). The roof, above grade walls, and floors of the Unit 1 and 2 cell buildings have been demolished, with the basement walls and slabs remaining intact. In addition, the eastern half of the Unit 3 cell building has been demolished. Unit buildings 7, 8, 9, and 10 are not located on property owned by the Trust. The Unit 4 cell building is no longer used, and its above-ground structures were demolished in the mid-2000s. In 2012, Tronox retrofitted the Unit 4 substation building to house an advanced battery manufacturing process. The Unit 4 chlorinator building is currently used by Tronox, primarily for storage. The Unit 4 cell building historically contained chlorinators (furnaces) that created molten magnesium chloride by reacting magnesium oxide/carbon pellets with chlorine gas at high temperatures. Magnesium metal was then produced in banks of electrolytic cells in the cell building by electrochemical reduction of magnesium chloride. From 1945 to 1989, sodium chlorate and sodium perchlorate were produced by electrolytic processes, which involved the use of sodium dichromate (hexavalent chromium) on the first floor of the Unit 4 and 5 cell buildings. The concrete basements reportedly served as sumps to collect process liquor, spillage, and wash water, and process chemicals may have leaked to the soil through cracks in the basements of the Unit 4 and 5 cell buildings (Tetra Tech, Inc., 2015a).

### 1.3.2 Regional Geology

The Site is located near the southeast end of the Las Vegas Valley, a northwest-southeast trending structural basin that extends approximately 55 miles and includes metropolitan areas of North Las Vegas, Las Vegas, and Henderson. Locally, the ground surface slopes to the north toward the Las Vegas Wash. The Las Vegas Valley is bounded on the west by the Spring Mountains, on the north by the southern ends of the Sheep and Las Vegas Ranges, on the east by Frenchman and Sunrise Mountains, and on the south by the River Mountains and McCullough Range (Plume, 1989). The structural basin that underlies Las Vegas Valley is comprised of Precambrian crystalline rocks; Precambrian and Paleozoic carbonate rocks; Permian, Triassic, and Jurassic clastic rocks; and Miocene igneous rocks. Gravity data indicate that the deeper portions of the basin are filled with 3,000 to 5,000 feet of clastic sedimentary deposits that range in age from Miocene through Holocene (Plume, 1989).

The clastic sedimentary valley-fill deposits of Las Vegas Valley are more than 4,000 feet thick beneath Henderson, Nevada (Plume, 1989), and consist of Quaternary alluvial (Qal) deposits, transitional Muddy Creek formation, and Pleistocene Upper Muddy Creek formation (UMCf). The alluvium is generally described as reddish-brown discontinuous layers of sand and gravel with minor amounts of silt, clay and caliche. The thickness of these alluvial deposits ranges from less than 1 foot to more than 50 feet beneath the Site (Ramboll Environ, 2016a).

### 1.3.3 Regional Hydrogeology

Surface water at the Site generally flows from south to north but is contained onsite within two retention basins. During the 2011 Interim Soil Removal Action (ENVIRON, 2012), many portions of the Site were graded such that storm water would be retained on the Site. Existing roads, utility berms, and other site features were created to prevent storm water from flowing off the Site. Two main storm water retention basins, the Central Retention Basin (CRB) and Northern Retention Basin, were constructed to control storm water flow and maintain storm water on the Site. The CRB collects surface runoff from the Tronox-leased area. The Northern Retention Basin collects surface runoff water from north of the former Beta Ditch (located near the center of the Site) and accepts overflow from the CRB.

According to previous work performed at the Site, the depth to groundwater ranges from approximately 27 to 80 feet below ground surface (bgs), is generally deepest in the southern portion of the Site, and becomes shallower to the north as it approaches the Las Vegas Wash. The average groundwater gradient ranges from 0.015 to 0.020 feet/foot south of Galleria Road, located approximately 2 miles north of the Site, decreasing to approximately 0.007 to 0.010 feet/foot to the north of the AWF. The direction of groundwater flow on the Site is generally north to north-northeast; north of the Site, the direction of groundwater flow is toward the northeast (Ramboll Environ, 2016a).

The NDEP has defined the following three water-bearing zones (WBZ) that occur within the BMI Complex:

- Shallow WBZ – The first occurrence of groundwater in the area occurs within either the alluvium or the UMCf. Groundwater in the Shallow WBZ occurs under unconfined to partially confined conditions and is considered the "water table aquifer." At the Site, the Shallow WBZ is comprised of the saturated portions of the alluvium and the uppermost portion of the UMCf to depths of approximately 90 feet bgs (Ramboll Environ, 2016b).
- Middle WBZ – Groundwater in the Middle WBZ generally occurs between 90 and 300 feet bgs. Water-bearing units in the Middle WBZ are confined (Ramboll Environ, 2016a). Groundwater in the Middle WBZ exhibits an upward vertical gradient (Ramboll Environ, 2016b).
- Deep WBZ – Groundwater in the Deep WBZ generally occurs between 300 and 400 feet bgs. Water-bearing units in Deep WBZ are confined. Groundwater in the Deep WBZ exhibits an upward vertical gradient (Ramboll Environ, 2016b).

Limited data is available in the Middle WBZ at the Site, as historical environmental investigations have primarily focused on the Shallow WBZ. However, investigations conducted by Northgate Environmental Management in 2009 included the installation of several monitoring wells in the Middle WBZ to characterize the vertical distribution of chemical constituents (Ramboll Environ, 2016a). In addition, the recent investigations conducted by Ramboll Environ and Tetra Tech have included borings and wells within the Middle WBZ. Specifically, Tetra Tech's investigation of the Unit 4 and 5 buildings included drilling over 60 soil borings and collecting discrete depth groundwater samples in multiple horizons within the Shallow and Middle WBZ (maximum depth 250 feet bgs) (Tetra Tech, Inc., 2017a). As discussed in Section 1.4.2, groundwater concentrations of COPCs within the Middle WBZ at the Unit 4 and 5 Buildings Investigation Area are significantly higher than the groundwater concentrations of COPCs within the Shallow WBZ.

### 1.3.4 Treatability Study Area Geology and Hydrogeology

As shown in Figure 2, the proposed Study Area is a subset of the Unit 4 and 5 Buildings Investigation Area. The footprint of the Study Area consists of an approximately 120 foot x 120 foot area within the basement of the former Unit 4 cell building where in-situ bioremediation will be implemented (In-situ Bioremediation Area) plus an area adjacent to the east side of the basement where soil flushing will be utilized to target very high perchlorate mass in the vadose zone (Soil Flushing Area). The Study Area was selected to evaluate the effectiveness of a hybrid soil flushing and ISB approach to achieve source reduction of COPCs within an area where some of the highest concentrations of perchlorate and hexavalent chromium in soil and groundwater have been identified at the Site, along with access considerations.

The geology and hydrogeology introduced in this section are based on data collected during the first and second mobilizations performed in the area of the Unit 4 and 5 buildings and as previously reported in the *Unit 4 and 5 Buildings Investigation First Mobilization Technical Memorandum* (Tetra Tech, Inc., 2016a) and *Unit 4 and 5 Buildings Investigation Second Mobilization Technical Memorandum* (Tetra Tech, Inc., 2017a). Additional data collected during the third mobilization will be used to refine Tetra Tech's understanding of the Study Area and to refine the treatability study design (Figure 3).

The Qal consists primarily of sand and silty sand while the UMCf, which underlies the alluvium within the Unit 4 and 5 Buildings Investigation Area, consists of interbedded coarse-grained and fine-grained sediments. The contact between the base of the sandy alluvium and the top of the UMCf in the Study Area is encountered at a depth of approximately 25 feet below the floor of the basement, which is approximately 8 feet below the surrounding ground surface. The upper 30 to 40 feet of the UMCf within the Unit 4 and 5 Buildings Investigation Area is characterized by a higher proportion of sandy interbeds which transition into predominately fine-grained materials, including silt, sandy silt, and clayey silt. Intervals of predominantly coarse-grained water-bearing sand and/or gravel and intervals of predominantly fine-grained silt and/or clay units were identified throughout the boreholes (Figures 4 through 6). Within the Unit 4 and 5 Buildings Investigation Area, first groundwater in the

Shallow WBZ was encountered during the second mobilization at depths ranging from approximately 30 to 47.5 feet bgs, and following installation of temporary wells, depth to groundwater stabilized between 37.5 and 43 feet bgs (Tetra Tech, Inc., 2017a). Using the latest available groundwater elevations from nearby monitoring wells, M-189, M-191, and M-192 (Figure 3), and wells recently installed as part of the third mobilization, the groundwater piezometric surface within the proposed Study Area is approximately 40 feet bgs, below the interface between the Qal and UMCf.

## 1.4 NATURE AND EXTENT OF CONTAMINATION

As discussed in the *Unit 4 and 5 Buildings Investigation Work Plan* (Tetra Tech, Inc., 2015a), the area associated with the Unit 4 and 5 buildings was identified as a potential perchlorate and hexavalent chromium source to the underlying soil and groundwater. In response, an environmental investigation to characterize the vertical and horizontal extent of impacted soil and shallow groundwater beneath the Unit 4 and 5 buildings (herein referred to as the Unit 4 and 5 Buildings Investigation Area) was proposed to be conducted over a series of three field mobilizations (Tetra Tech, Inc., 2015a). The first mobilization was conducted from October 2015 to December 2015, and the second mobilization was completed from June 2016 to January 2017. The third mobilization started in August 2017 and is expected to be completed by October 2017, concurrent with the submittal of this Work Plan. The results of the first and second mobilizations are summarized in the *Unit 4 and 5 Buildings Investigation First Mobilization Technical Memorandum* (Tetra Tech, Inc., 2016a) and *Unit 4 and 5 Buildings Investigation Second Mobilization Technical Memorandum* (Tetra Tech, Inc., 2017a), respectively.

Based on the soil and groundwater data collected during the first and second mobilizations, concentrations of perchlorate and hexavalent chromium in soil and groundwater beneath Unit 4 were among the highest concentrations identified at the Site. Based on soil data, the perchlorate mass in the Unit 4 and 5 Buildings Investigation Area was estimated to be 140,000 pounds in the vadose zone and 220,000 pounds in the saturated zone (Tetra Tech, Inc., 2017a). Because active operations inside the Unit 5 Building prohibit the completion of investigation activities inside the building, additional data gaps regarding soil and groundwater data below the Unit 5 building will be addressed as part of the third mobilization through the installation of angled borings. The footprint of the Unit 4 building is accessible, and sufficient soil and groundwater data have been collected to prepare a conceptual treatability study design for remediation of contaminated soil and groundwater in the vicinity of Unit 4.

The following sections provide a general summary of the nature and extent of perchlorate, chlorate, hexavalent chromium, and chloroform as these are the more relevant COPCs in terms of overall contaminant impacts and potential influence on the proposed hybrid ISB / groundwater extraction approaches. The presence and significance of elevated concentrations of total dissolved solids (TDS) in groundwater are also discussed. Information on other COPCs in the vicinity of the Unit 4 building can be found in *Unit 4 and 5 Buildings Investigation Second Mobilization Technical Memorandum* (Tetra Tech, Inc., 2017a).

The approach to developing the mass estimates presented in this work plan was generally consistent with the approach presented in the *RI Study Mass Estimate and Expanded Performance Metrics Technical Approach* (Ramboll Environ, 2017b), which was approved by NDEP on October 20, 2017. Variations to that approach were the use of a more refined grid using soil concentrations and an average bulk soil density value of 1.5 grams per cubic centimeter for both the Qal and UMCf. Refined mass estimates for the Unit 4 Source Area Treatability Study area for perchlorate, chlorate, hexavalent chromium, chloroform and nitrate will be performed prior to flushing, injection and extraction activities. The refined mass estimates will use the NDEP-approved methodology and incorporate the latest chemical and physical parameter data obtained during the Unit 4 and 5 Buildings Investigation third field mobilization. These refined mass estimates will be provided in a memorandum as an addendum to this work plan and submitted to NDEP for approval prior to field implementation of the flushing, injection, and extraction activities. The memorandum will also include any proposed modifications to the work plan based on the results obtained from the Unit 4 and 5 Buildings Investigation third field mobilization and the bench-scale studies.

## 1.4.1 Soil

### 1.4.1.1 Perchlorate

Based on available data from 92 soil borings, including 72 soil borings advanced as part of the Unit 4 and 5 Buildings Investigation, perchlorate is distributed throughout the Unit 4 and 5 Buildings Investigation Area (Figures 7 through 10). The proposed Study Area was selected to generally coincide with where the highest perchlorate mass was present in both the Qal and UMCf, taking into account site-specific constraints such as accessibility and existing infrastructure (further discussed in Section 3.1). The Study Area may be adjusted as additional investigation data becomes available and as Site-specific constraints allow.

Figure 11 shows the perchlorate masses in the Qal in 40 foot x 40 foot grids in and around the Unit 4 basement. The highest masses of perchlorate in the Qal are located near and outside the southeast corner of the Unit 4 basement. The proposed soil flushing area targets the grids where highest perchlorate masses are present in the unsaturated Qal. This area was selected to evaluate the ability of soil flushing/in-situ bioremediation to remediate very high concentrations of perchlorate in the vadose zone. This particular area is unique to previous soil flushing treatability study areas given the high concentrations of perchlorate, chlorate, and TDS. Figure 12 shows the perchlorate masses in the UMCf in 40 foot x 40 foot grids in and around the Unit 4 basement. The highest masses of perchlorate in the UMCf are located near the center and northeast corner of the Unit 4 basement.

As shown below in ***Table 1***, 84 percent of the perchlorate mass within the proposed In-situ Bioremediation Area is located in the UMCf in the depth intervals between 88 and 118 feet bgs, significantly below the groundwater piezometric surface of approximately 40 feet bgs. The depth intervals in ***Table 1*** are presented as feet below the surrounding ground surface, which takes into account that the floor of the basement is approximately 8 feet below the surrounding ground surface. The second largest accumulation of perchlorate mass (7 percent) is located in the vadose zone between 23 and 38 feet bgs. Relatively little of the perchlorate mass (4 percent) was located in the interval between 38 and 88 feet bgs, in the upper portion of the UMCf. Concentrations and mass of perchlorate drop off by orders of magnitude below 118 feet bgs.

***Table 1.*** Perchlorate Mass Estimate in Soil with Depth Beneath the In-Situ Bioremediation Area

| Depth Interval (feet bgs) | Estimated Perchlorate Mass (lbs) | Percent of Total Perchlorate Mass |
|---|---|---|
| 8 - 13 | 399 | 1% |
| 13 - 18 | 301 | 1% |
| 18 - 23 | 270 | 1% |
| 23 - 28 | 933 | 2% |
| 28 - 33 | 1,720 | 3% |
| 33 - 38 | 800 | 2% |
| 38 - 43 | 491 | 1% |
| 43 - 48 | 263 | 1% |
| 48 - 53 | 108 | 0% |
| 53 - 58 | 116 | 0% |
| 58 - 63 | 102 | 0% |
| 63 - 68 | 65 | 0% |
| 68 - 73 | 66 | 0% |
| 73 - 78 | 76 | 0% |

| Depth Interval (feet bgs) | Estimated Perchlorate Mass (lbs) | Percent of Total Perchlorate Mass |
|---|---|---|
| 78 - 83 | 174 | 0% |
| 83 - 88 | 973 | 2% |
| 88 - 93 | 3,435 | 6% |
| 93 - 98 | 6,801 | 13% |
| 98 - 103 | 11,902 | 22% |
| 103 - 108 | 12,544 | 23% |
| 108 - 113 | 7,705 | 14% |
| 113 - 118 | 3,288 | 6% |
| 118 - 123 | 1,059 | 2% |
| 123 - 128 | 109 | 0% |
| 128 - 133 | 12 | 0% |
| 133 - 138 | 1 | 0% |
| 138 - 143 | 0 | 0% |
| 143 - 148 | 0 | 0% |
| 148 - 153 | 1 | 0% |
| 153 - 158 | 1 | 0% |
| **Total** | 53,715 | 100% |

**Note:**

1. Mass estimates for the proposed 120 foot by 120 foot In-Situ Bioremediation Area were calculated using a geostatistical distribution of data collected.

### 1.4.1.2 Chlorate

Chlorate was analyzed in soil samples collected from two soil borings located within the footprint of the Unit 4 basement during the Unit 4 and 5 Buildings Investigation first and second mobilizations. Chlorate was analyzed in soil samples collected at 10 foot intervals from 30 feet bgs to 120 feet bgs in boring U4U5-64, located in the northeastern portion of the Unit 4 basement, and in soil samples collected at 130 feet bgs and 140 feet bgs in boring U4U5-65, located in the southwest portion of the Unit 4 basement. The Unit 4 and 5 Building investigation did not include the collection of soil samples for chlorate analysis. However, NERT collected samples from two borings to gain a general understanding of chlorate concentrations in soil. As such, there is not yet a sufficient data set to estimate mass within the proposed Study Area. However, the chlorate concentration profile with depth from the two borings is similar to that of perchlorate. In general, chlorate concentrations are approximately two to three times the concentrations of perchlorate at the same sampling depths. For example, the chlorate concentration in the one soil sample collected within the Qal at a depth of 30 feet bgs was 1,800 mg/kg while the perchlorate concentration was 910 mg/kg in the same sample. Within the UMCf, the highest chlorate concentrations in soil were detected between 80 and 100 feet bgs with a maximum concentration of 6,500 mg/kg at a depth of 90 feet bgs. Chlorate concentrations below 100 feet bgs were significantly less with a concentration of 49 mg/kg at 110 feet bgs, 0.41 mg/kg at 120 feet bgs, 0.13 mg/kg at 130 feet bgs, and 0.24 mg/kg at 140 feet bgs. Chlorate will be analyzed on samples obtained from the third mobilization of the Unit 4 and 5 Buildings Investigation. Chlorate is a COPC and it is important from a remediation standpoint because the in-situ biodegradation of perchlorate follows hexavalent chromium and chlorate.

### 1.4.1.3 Hexavalent Chromium

Hexavalent chromium concentrations in soil exhibit a distribution similar to the perchlorate concentrations. As shown below in ***Table 2***, 80 percent of the hexavalent chromium mass within the proposed Study Area is located in UMCf in the depth interval between 88 and 118 feet bgs, significantly below the groundwater piezometric surface of approximately 40 feet bgs. The second largest accumulation of hexavalent chromium mass (8 percent) is located in the vadose zone between 23 and 38 feet bgs. Relatively little of the hexavalent chromium mass (6 percent) was located in the interval between 38 and 88 feet bgs, in the upper portion of the UMCf. Concentrations and mass of hexavalent chromium drop off by orders of magnitude below 118 feet bgs.

***Table 2.*** Hexavalent Chromium Mass Estimate in Soil with Depth Beneath the In-Situ Bioremediation Area

| Depth Interval (feet bgs) | Estimated Hexavalent Chromium Mass (lbs) | Percent of Total Hexavalent Chromium Mass |
|---|---|---|
| 8 – 13 | 17 | 1% |
| 13 – 18 | 16 | 1% |
| 18 – 23 | 20 | 2% |
| 23 – 28 | 31 | 3% |
| 28 – 33 | 32 | 3% |
| 33 – 38 | 27 | 2% |
| 38 – 43 | 16 | 1% |
| 43 – 48 | 7 | 1% |
| 48 – 53 | 3 | 0% |
| 53 – 58 | 3 | 0% |
| 58 – 63 | 3 | 0% |
| 63 – 68 | 3 | 0% |
| 68 – 73 | 3 | 0% |
| 73 – 78 | 4 | 0% |
| 78 – 83 | 8 | 1% |
| 83 – 88 | 35 | 3% |
| 88 – 93 | 108 | 9% |
| 93 – 98 | 198 | 16% |
| 98 – 103 | 294 | 24% |
| 103 – 108 | 227 | 18% |
| 108 – 113 | 111 | 9% |
| 113 – 118 | 58 | 4% |
| 118 – 123 | 21 | 2% |
| 123 – 128 | 1 | 0% |
| 128 – 133 | 0 | 0% |
| 133 – 138 | 0 | 0% |
| 138 – 143 | 0 | 0% |
| 143 – 148 | 0 | 0% |
| 148 – 153 | 0 | 0% |
| 153 – 158 | 0 | 0% |
| **Total** | **1,246** | **100%** |

**Note:**

1. Mass estimates for the proposed 120 foot by 120 foot In-Situ Bioremediation Area were calculated using a geostatistical distribution of data collected.

### 1.4.1.4 Chloroform

Chloroform concentrations and corresponding mass in soil exhibit a distribution similar to the perchlorate concentrations. As shown below in ***Table 3***, 86 percent of the chloroform mass within the proposed Study Area is located in the UMCf in the depth interval between 88 and 118 feet bgs, significantly below the groundwater piezometric surface of approximately 40 feet bgs. The second largest accumulation of chloroform mass (7 percent) is located in the Qal and top of the UMCf between 28 and 43 feet bgs. Relatively little of the chloroform mass (5 percent) was located in the intervals between 43 and 88 feet bgs, in the upper portion of the UMCf. Concentrations and mass of chloroform drop off by orders of magnitude below 118 ft bgs.

***Table 3.*** Chloroform Mass Estimate in Soil with Depth Beneath the In-Situ Bioremediation Area

| Depth Interval (feet bgs) | Estimated Chloroform Mass (lbs) | Percent of Total Chloroform Mass |
|---|---|---|
| 8 - 13 | 0.0 | 0% |
| 13 - 18 | 0.1 | 0% |
| 18 - 23 | 0.2 | 0% |
| 23 - 28 | 0.5 | 1% |
| 28 - 33 | 1.3 | 2% |
| 33 - 38 | 1.8 | 3% |
| 38 - 43 | 1.2 | 2% |
| 43 - 48 | 0.4 | 1% |
| 48 - 53 | 0.1 | 0% |
| 53 - 58 | 0.1 | 0% |
| 58 - 63 | 0.1 | 0% |
| 63 - 68 | 0.1 | 0% |
| 68 - 73 | 0.1 | 0% |
| 73 - 78 | 0.1 | 0% |
| 78 - 83 | 0.3 | 1% |
| 83 - 88 | 2.2 | 3% |
| 88 - 93 | 7.1 | 11% |
| 93 - 98 | 11.4 | 18% |
| 98 - 103 | 17.3 | 28% |
| 103 - 108 | 11.1 | 18% |
| 108 - 113 | 4.7 | 8% |
| 113 - 118 | 1.8 | 3% |
| 118 - 123 | 0.5 | 1% |
| 123 - 128 | 0.0 | 0% |
| 128 - 133 | 0.0 | 0% |
| 133 - 138 | 0.0 | 0% |
| 138 - 143 | 0.0 | 0% |
| 143 - 148 | 0.0 | 0% |

| Depth Interval (feet bgs) | Estimated Chloroform Mass (lbs) | Percent of Total Chloroform Mass |
|---|---|---|
| 148 - 153 | 0.0 | 0% |
| 153 - 158 | 0.0 | 0% |
| **Total** | **62.5** | **100%** |

**Note:**

1. Mass estimates for the proposed 120 foot by 120 foot In-Situ Bioremediation Area were calculated using a geostatistical distribution of data collected.

## 1.4.2 Groundwater

During the second mobilization of the Unit 4 and 5 Buildings Investigation, depth-discrete groundwater samples were collected from boreholes following the construction of a temporary well. Within the 90-foot boreholes, the discrete-depth groundwater samples were collected at the top (groundwater first encountered), middle, and bottom of the Shallow WBZ. Within the 150-foot boreholes, discrete-depth sampling continued at 20-foot intervals below the Shallow WBZ at depths of 110, 130, and 150 feet bgs. Within the 250-foot borehole, discrete-depth sampling below 90 feet was conducted at 110, 150, 200, and 250 feet bgs. The following provides a summary of the analytical results from the depth-discrete groundwater samples in regards to the relevant COPCs.

### 1.4.2.1 Perchlorate

Perchlorate was detected in groundwater within the Qal at concentrations as high as 2,900 milligrams per liter (mg/L) at a depth of 38 feet bgs and in the upper saturated interval of the UMCf as high as 3,500 mg/L at a depth of 58.5 feet bgs. Perchlorate as high as 6,700 mg/L was detected in a groundwater sample collected in the lower saturated interval of the UMCf at 102 feet bgs. The highest perchlorate concentrations in groundwater were observed directly below and downgradient of the Unit 4 building in the UMCf (Figures 13 through 16).

### 1.4.2.2 Chlorate

Chlorate was detected in groundwater within the Qal at concentrations as high as 3,200 mg/L at a depth of 38 feet bgs and within the UMCf at concentrations as high as 22,000 mg/L at a depth of 102 feet bgs. Similar to the distribution of perchlorate in groundwater, the highest chlorate concentrations in groundwater were observed directly below and downgradient of the Unit 4 building in the UMCf.

### 1.4.2.3 Hexavalent Chromium

Hexavalent chromium concentrations in groundwater are similar to the perchlorate concentration distribution in groundwater in the Unit 4 and 5 Buildings Investigation Area. Within the Qal, the highest hexavalent chromium concentration of 12 mg/L was detected in groundwater at a depth of 38 feet bgs beneath the southeastern portion of the Unit 4 basement. The highest hexavalent chromium concentrations in groundwater were detected below and downgradient of the Unit 4 building within the UMCf between a depth of 100 and 110 feet bgs. The highest hexavalent chromium concentration in the UMCf was detected at 90 mg/L in groundwater collected at a depth of 102 feet bgs beneath the middle of the Unit 4 basement.

### 1.4.2.4 Chloroform

Similar to its distribution in soil, the highest chloroform concentrations in groundwater below the Unit 4 building were detected in the UMCf. Within the UMCf, the highest chloroform concentration in groundwater was detected was at 4.4 mg/L at a depth of 82 feet bgs beneath the northern portion of the Unit 4 basement. Within the Qal, the highest chloroform concentration detected in groundwater was 1.6 mg/L at a depth of 32.5 feet bgs beneath the western portion of the Unit 4 basement.

#### 1.4.2.5 Total Dissolved Solids

Elevated concentrations of TDS were detected in groundwater samples beneath Unit 4. Concentrations of TDS ranged as high as 43,000 mg/L in a groundwater sample collected from boring U4U5-31 at a depth of 110 feet bgs. Many groundwater samples contained TDS in excess of 10,000 mg/L. A groundwater sample collected from boring U4U5-63 at a depth of 110 feet bgs contained 39,000 mg/L of TDS, 22,000 mg/L of chlorate and 2,900 mg/L of perchlorate. This sample illustrates the pattern that chlorate concentrations exceed perchlorate concentrations and that, while TDS concentrations are high, much of the TDS is represented by chlorate and perchlorate. The high TDS and high chlorate concentrations pose special challenges for the implementation of ISB in the UMCf under Unit 4, which are discussed in this work plan.

# 2.0 TECHNOLOGY DESCRIPTION

The Unit 4 Source Area In-Situ Bioremediation Treatability Study will implement a hybrid ISB / groundwater extraction / soil flushing approach in an area containing amongst the highest and deepest contaminant concentrations found at the Site. The hybrid ISB / groundwater extraction approach will target the deep contamination in the UMCf and soil flushing will be applied to target contamination in the unsaturated Qal. This treatability study will build on the results of the previous soil flushing and ISB treatability studies performed at the Site and down-gradient of the Site to evaluate a hybrid application of these technologies to address Unit 4. The following sections provide an overview of the soil flushing and in-situ bioremediation technologies along with a summary of the results of previous and on-going soil flushing and ISB treatability studies associated with the Site. The lessons learned from the previous and on-going soil flushing and ISB treatability studies will be incorporated into the implementation of this treatability study.

## 2.1 SOIL FLUSHING

Soil flushing is a technology in which water and various additives are injected or infiltrated into the vadose zone. Contaminants are leached into the groundwater where they can be extracted and treated. Soil flushing can also be combined with in-situ bioremediation whereby the contaminants are treated in the groundwater and in the pore water of the vadose zone, which is the approach described in Section 3.1. Effectiveness of soil flushing is largely dependent on the permeability and subsurface heterogeneities in the vadose zone, the solubility of the contaminants present, maintenance of saturated conditions, and the number of pore volumes able to be flushed through the zone of contamination.

Perchlorate is the anionic component of ammonium and sodium perchlorate, the two highest production perchlorate salts formerly manufactured at the Site. Perchlorate salts are very soluble in water (solubility limit is approximately 200,000 mg/L for ammonium perchlorate and approximately 2,100,000 mg/L for sodium perchlorate) and do not adsorb very strongly to most soils. The high aqueous solubility of perchlorate compounds helps make flushing the vadose zone with water a viable means of removing perchlorate from vadose zone soils. Water infiltrated from the surface mobilizes and transports perchlorate compounds from the vadose zone to groundwater. Once in groundwater, the perchlorate can be treated in-situ or ex-situ via groundwater extraction and treatment. The addition of carbon substrate to the flush water helps induce in-situ biodegradation of perchlorate as it is flushed through the vadose zone and into groundwater.

### 2.1.1 Previous Soil Flushing Applications

A soil flushing treatability study was performed between December 2015 and August 2016 in the CRB at the Site, which is located upgradient of the Interceptor Well Field (IWF) and barrier wall. The primary objective of the study was to evaluate the feasibility of remediating contaminants, primarily perchlorate, in vadose zone soils using soil flushing. A treatability study results report, which summarized the laboratory bench-scale study, soil flushing design and details, and all results and findings, was submitted in July 2017 (Tetra Tech, Inc., 2017b). This section provides a brief summary of the findings of the treatability study.

Four test plots were constructed and operated during the treatability study. Each test plot was operated using a variation on water application rates and use of an added carbon substrate to enhance perchlorate biodegradation. During operation of the soil flushing test plots, the treatability study was monitored using several methods, including the following:

- Measuring flow to determine the water application rate;
- Measuring groundwater levels in nearby monitoring wells to evaluate groundwater mounding in response to water application;

- Collecting pore water samples from lysimeters installed in each test plot to monitor changes in the perchlorate and TDS concentrations of the infiltrating solution during the study; and
- Collecting groundwater samples from monitoring wells installed downgradient of the test plots to evaluate the effects of soil flushing on perchlorate and TDS concentrations in groundwater.

Treatment effectiveness was evaluated by collecting and analyzing soil samples before and after the treatability study. Five soil borings were drilled and sampled in each test plot prior to the start of the study to provide an estimate of baseline conditions. After treatment was completed, borings were drilled immediately adjacent to the baseline borings to evaluate changes in soil chemistry and perchlorate mass.

Baseline and post-treatment soil sampling data were used to estimate contaminant masses in the vadose zone before and after the treatability study. Perchlorate mass reduction was highest for Test Plot 2 (98 percent), where water was applied at the maximum rate and glycerol was added near the end of the test to induce biodegradation. A mass reduction of approximately 73 percent was observed in Test Plot 3, where water was applied at the maximum rate, but carbon substrate was not added. The difference in mass reduction between Test Plot 2 and Test Plot 3 may be due, at least in part, to in-situ biodegradation occurring in Test Plot 2. Mass reductions of 5 and 43 percent were observed in the two reduced-flow test plots, Test Plots 1 and 4, respectively. Carbon substrate was added to Test Plot 1 but not Test Plot 4. The relatively low mass reduction in these test plots was attributed to preferential flow through relatively narrow pathways in the vadose zone due to the reduced water application rates.

Based on the results of the soil flushing treatability study, the conclusions were as follows:

- The mass reductions observed in Test Plot 2 (98 percent) and Test Plot 3 (73 percent) during the treatability study indicate that soil flushing is a viable technology for treatment of perchlorate in the vadose zone.
- To optimize mass reduction, water application rates during soil flushing should be at or near the maximum allowed by the local soils. The effectiveness of soil flushing is reduced at lower water application rates, likely due to preferential flow through the vadose zone.
- Although the supporting data are equivocal, the large mass reduction observed in Test Plot 2 suggests that biodegradation of perchlorate can be induced by adding a carbon substrate to the water used for soil flushing.
- The results suggest that 90 percent mass reduction can be achieved with application of as little as 6 pore volumes of water. However, these results should be confirmed in a larger-scale field application.
- Further field study is needed to optimize water and carbon substrate application rates and application methods.
- Large-scale implementation of soil flushing could have effects on the groundwater extraction and treatment system (GWETS) that may require management. These potential effects include groundwater mounding, which could impact plume capture; leaching of soluble salts from the soil, which could have an inhibitory effect on biodegradation if salt buildup occurs; hydraulic and chemical loading effects on the GWETS and fluidized bed reactor (FBR) treatment plant; and effluent pipeline carrying capacity.

This study was the first soil flushing treatability completed by NERT and demonstrated the technology could remove perchlorate from the vadose zone where perchlorate was present as moderate concentrations.

### 2.1.2 On-Going Soil Flushing Applications

A soil flushing treatability study is currently being undertaken in the Ammonium Perchlorate (AP) Area at the Site. The objective of the treatability study is to build on the results of the soil flushing treatability study conducted in the CRB by applying a different water delivery system at a larger scale and to evaluate methods to maximize perchlorate removal. The CRB and AP Area soil flushing treatability studies utilize different methods to apply water to the soil flushing treatability study areas. In the CRB soil flushing treatability study, water was applied using infiltration galleries. For large-scale implementation, infiltration galleries are not an ideal water application method, as it is difficult to control water application rates over large areas with non-uniform infiltration rates. In the AP Area soil flushing treatability study, two 90 foot by 90 foot plots (Plots 1 and 2) are being flushed, which are substantially larger than in the CRB treatability study plots (8,100 vs. 900 square feet) and contain significantly higher perchlorate concentrations in soil within the vadose zone. To mitigate potential heterogeneity in infiltration rates across the two plots, micro-irrigation systems designed to apply water uniformly across the ground surface at a controllable rate are used to apply water at rates approaching the maximum infiltration rate. Operation of the soil flushing system at Plot 1 was completed; operation of the down-flushing system at Plot 2 was initiated in July 2017 and is anticipated to continue through December 2017. The purpose of this follow up treatability study is to evaluate the efficiency of soil flushing at source areas where perchlorate were manufactured (and where perchlorate concentrations are considerably higher in concentration within the vadose zone).

## 2.2 IN-SITU BIOREMEDIATION

### 2.2.1 Perchlorate

Perchlorate tends to be biologically stable under aerobic conditions or when there is a limited source of organic carbon. However, in the presence of a carbon substrate and after dissolved oxygen (DO) and nitrate have been depleted, perchlorate can act as an electron acceptor for anaerobic respiration. A variety of perchlorate-reducing bacteria have been isolated, with some of them being strict anaerobes, while others are facultative microbes. In the absence of more easily reduced constituents (e.g., nitrate), the first step in perchlorate biodegradation is carried out by the enzyme perchlorate reductase, wherein perchlorate is sequentially converted to chlorate and then to chlorite. A second enzyme, chlorite dismutase, further reduces the chlorite to chloride and oxygen (ITRC, 2008).

Perchlorate-reducing microorganisms are known to be ubiquitous in the subsurface and adaptable to a range of geochemical conditions. The key to successful groundwater treatment is developing an understanding of the chemical, geochemical, physical, geological, and hydrogeological conditions at a site and devising a prudent approach to engineer a successful remedial strategy. Certain environmental conditions, however, may make perchlorate biodegradation challenging at some locations. These conditions include high or low pH, high salinity, or the presence of other electron acceptors, such as chlorate and nitrate, that act as competitors for bacterial respiration.

Successful bioremediation of perchlorate relies on achieving and maintaining appropriate geochemical conditions that allow for sustainable biodegradation to occur. Favorable redox conditions appropriate for perchlorate biodegradation are less than 0 millivolts (mVs), preferably between 0 to -100 mVs. This range of redox is generally indicative of the following aquifer conditions: DO is depleted, nitrate is consumed, and perchlorate becomes the next preferred electron acceptor for microbial respiration (ITRC, 2008). For the Site, it has been demonstrated from previous bench-scale testing at the University of Nevada, Las Vegas (UNLV) that the sequence of degradation is:

chromium > nitrate > chlorate > perchlorate

In aquifers that are aerobic or have a limited supply of natural organic carbon (NOM), the key to successfully attaining and sustaining the appropriate redox range is to add a carbon electron donor/substrate to the subsurface. Numerous carbon donors are available that can be injected into the groundwater via a variety of engineering configurations, and the choice at a given site is based on several physical, chemical, geochemical, and economic factors.

### 2.2.2 Hexavalent Chromium

In-situ microbial reduction of Cr(VI) to Cr(III) can be enhanced by injecting a carbon substrate solution, such as a dilute molasses solution. The mechanisms for hexavalent chromium reduction are briefly summarized here and discussed in more detail in the *In-Situ Chromium Treatability Study Work Plan* (Tetra Tech, Inc., 2016b). Carbohydrates, primarily sucrose, are readily degraded by heterotrophic microorganisms present in the aquifer. This process depletes the available dissolved oxygen and causes reducing conditions within the aquifer. Various mechanisms of Cr(VI) to Cr(III) include: (1) the direct enzymatic reduction of Cr(VI) by numerous bacteria species, such as *Bacillus subtilis* (Tetra Tech, Inc., 2016b); (2) an extracellular reaction with by-products of sulfate reduction such as $H_2S$; and (3) abiotic oxidation of the organic compounds including soil organic matter such as humic and fulvic acids. Microbial reduction of Cr(VI) primarily occurs under anaerobic conditions. In addition, microbial reduction of Fe(III) and $SO4^{2-}$ creates chemical reductants, Fe(II) and sulfide respectively, which can reduce Cr(VI) to Cr(III) (Tetra Tech, Inc., 2016b).

As shown in the following chemical equation, the primary end product of hexavalent chromium reduction is chromic hydroxide [$Cr(OH)_3$], which readily precipitates out of solution under alkaline to moderately acidic and alkaline conditions:

$$\text{Carbon Substrate} + 4\ CrO_4^{2-} + 8\ H^+ \rightarrow 3\ CO_2 + 4\ Cr(OH)_3 + H_2$$

The chromium precipitates remain immobilized within the soil matrix of the aquifer, ensuring short-term and long-term effectiveness.

### 2.2.3 Chloroform

Under anaerobic conditions, chloroform is mainly degraded through cometabolic processes. The three main anaerobic biodegradation pathways are dehaolorespiration, cometabolic reductive dechlorination, and hydrolysis followed by oxidation to carbon dioxide. The products of chloroform degradation depend on the type of reducing environment, growth substrate, organisms present, chloroform concentration, and coenzymes. Intermediate degradation products of chloroform degradation can include dichloromethane, chloromethane, chlorocarbene, formaldehyde, and formic acid. End products of complete biodegradation include carbon dioxide and methane (Cappelletti et al., 2012). Some of the intermediate degradation products have more stringent water quality standards than chloroform, such as dichloromethane, which has a US EPA maximum contaminant level of 5 micrograms per liter. For reference, the US EPA maximum contaminant level for trihalomethanes, a class of chemicals that includes chloroform, is 80 micrograms per liter. In addition to being degraded under anaerobic conditions, dichloromethane has also been shown to be biodegraded under aerobic or microaerophilic conditions (La-Pat-Polasko, 1984). Chloroform is expected to degrade to the final end products by maintaining a strong reducing environment at the Site. The degradation of chloroform will be evaluated in bench-scale tests conducted by UNLV (Section 4.3.1).

### 2.2.4 Carbon Substrate

Carbon substrates that have been typically used for ISB can be broadly subdivided into three general groups that include: 1) water-soluble substrates such as glycerin or molasses, 2) slow-release substrates such as emulsified vegetable oil (EVO), and 3) solid substrates such as compost or wood chips. Combinations of these are also used in practice. Each has its own advantages and/or limitations for a given site-specific situation, which have been described in detail in the *Groundwater Bioremediation Pilot Test Work Plan* (Tetra Tech, Inc., 2015b) and are further evaluated in Section 3.2.1.

The addition of carbon substrate can be performed via a variety of engineering configurations. The selection of the optimal configuration at a particular site depends on several factors including the nature and extent of the perchlorate plume and whether the application is for source area treatment, large/long plumes, or plume containment/boundary treatment. Mechanisms and conduits for the addition of a carbon substrate can also vary in the form of permanent injection wells, direct push injection points, or continuous barriers. Another set-up that has been successfully employed is the creation of in-situ anaerobic bioreactors installed in strategic areas of the groundwater plume in a grid pattern to treat perchlorate contamination (AFCEE, 2008). In some cases, groundwater extraction and recirculation can optimize the distribution of the carbon substrate, enhance kinetics of perchlorate biodegradation, and decrease overall remedial timeframes. Three basic engineering approaches that are typically considered for bioremediation of perchlorate include the following:

- **Transect Systems:** Transect systems involve the installation of permanent injection wells that are installed along selected transects at a designed spacing perpendicular to the direction of groundwater flow. The injection of carbon substrate into the wells along the transect creates a downgradient biologically reducing zone, also known as biologically-active zone of enhancement (ESTCP, 2010). Transects in the form of direct push points, or if feasible, a continuous trench are alternatives to injection wells. The objective is to create a long-term biologically reducing zone to treat perchlorate in groundwater at strategic locations within groundwater plumes using one or more transects.
- **Grid Systems:** When specific areas of a plume require treatment, bioremediation can be performed in the form of injection points that are arranged in a grid within the targeted treatment area. This configuration could contain permanent injection wells, direct push points, or a combination of these two delivery methods. The design and spacing of a grid system depends on the zone of influence (ZOI) of the carbon substrate; the perchlorate treatment that can be achieved in the particular geological setting; and on other physical, geochemical, and economic factors.
- **Combination of Transects and Grid Patterns:** A combination of the transect and grid approaches can be used to achieve the desired objectives of targeting areas of higher contamination at strategic locations within the plume, as well as preventing further perchlorate migration beyond defined strategic locations or compliance points.

### 2.2.5 Previous In-Situ Bioremediation Applications

A groundwater bioremediation treatability study was performed between April 2015 and September 2016 within the vicinity of the City of Henderson (COH) Water Treatment Facility, which is immediately upgradient of the Bird Viewing Preserve and mid-way between the AWF and Seep Well Field (SWF). A treatability study results report, which summarized the laboratory bench-scale study, field carbon substrate injection design and details, and all results and findings, was submitted in November 2016 and approved by NDEP on June 26, 2017 (Tetra Tech, Inc., 2016c). This section provides a brief summary of the findings of the treatability study.

The main elements of the treatability study included the following:

- Single borehole dilution and slug tests to determine site hydrogeologic characteristics of hydraulic permeability and groundwater velocity;
- Bench batch microcosm and column testing at UNLV;
- Installation of field test injection and monitoring wells;
- Two carbon substrate injection events; and
- Periodic groundwater sampling, analyses, and evaluation of chemical, biochemical, and microbial parameters, which included a baseline sampling event followed by weekly, biweekly, and monthly groundwater sampling events.

As presented in the *Groundwater Bioremediation Treatability Study Results Report* (Tetra Tech, Inc., 2016c), groundwater in this area was amenable to enhanced biodegradation of perchlorate and other electron acceptors and co-contaminants, such as chlorate and nitrate. The addition of a carbon substrate in the form of a slow-release EVO product provided a sustained reducing environment over a six-month period, conducive to biodegrading perchlorate, in the subsurface within the targeted area downgradient of the injection. Bioremediation was shown to be a promising remedial process at this site and has strong potential to be a significant component of the overall remedy. The results, findings, and lessons learned from this study can be used to optimize the design and application of the technology for the Unit 4 Source Area In-Situ Bioremediation Treatability Study. Several of the key findings of the treatability study include the following:

- Although the test was implemented in an area with very high groundwater velocity (32 feet/day) that would result in short residence times, significant perchlorate reduction was observed during the six-month study.
- The carbon substrate that was selected for laboratory and field testing, EVO, proved to be effective in creating and sustaining reducing conditions in groundwater.
- During the course of the study, perchlorate concentrations decreased by over 90 percent in some of the monitoring wells. Non-detectable concentrations of perchlorate was achieved at one location during the study.
- Maximum first-order perchlorate biodegradation rates in the field were determined to range from -0.25 $day^{-1}$ to -0.51 $day^{-1}$. At these rates, perchlorate concentrations decreased very rapidly in groundwater. The estimate for mass removal ranged from 4.1 to 17.4 pounds per day (lbs/day) destruction of perchlorate through the Study Area.
- The higher TDS concentrations (greater than 5,000 mg/L) in the area did not have an observable impact on the development of a microbial consortium with the ability to biodegrade perchlorate, nor did it appear to have an impact on acclimation time for perchlorate biodegradation.
- In both the laboratory and field studies, denitrification (nitrate biodegradation) occurred very rapidly and preferentially compared to perchlorate biodegradation. Perchlorate biodegradation followed denitrification and, once initiated, the two reductive processes were observed to occur concurrently.
- Transient arsenic solubilization was observed but it did not appear to mobilize downgradient of the Study Area.
- An overall decrease in permeability with the bioremediation technology was observed from periodic slug tests performed during the study, which was more pronounced in the last two events toward the end of the study.
    - Plausible causes of the decrease in permeability include biomass buildup, oil adsorption, increase in alkalinity, and the formation of gas bubbles from biological activity.
    - Well redevelopment performed on the wells in the Study Area indicates that relatively simple techniques such as surging, jetting, or the addition of biocides can be adopted for permeability recovery that would enable periodic carbon substrate injections to be performed.

### 2.2.6 Current In-Situ Bioremediation Applications

Two ISB treatability studies are currently being conducted in association with the NERT Site; the In-Situ Chromium Treatability Study within the CRB (Tetra Tech, Inc., 2016b) and the Seep Well Field Area Bioremediation Treatability Study (Tetra Tech, Inc., 2016d).

The overall objective of the In-Situ Chromium Treatability Study is to evaluate the feasibility of, and the optimal approach for, achieving in-situ reduction of hexavalent chromium in groundwater at the Site. The treatability study is evaluating both biological and abiotic approaches to reduce hexavalent chromium. For the biological approach, carbon substrates and nutrients are injected into the Qal and UMCf through injection wells installed up to 50 feet bgs. In early 2017, UNLV performed bench-scale tests to evaluate the effectiveness and kinetics of chromium reduction using EVO, a fructose solution, and molasses. The bench-scale tests confirmed the following: 1) hexavalent chromium in the soil and groundwater collected from the Site could be reduced with the various carbon substrates; 2) a combination of soluble carbon substrates and EVO was able to achieve fast reduction rates and maintain reducing conditions for an extended duration; and 3) addition of nutrients is necessary to achieve perchlorate reduction. Based on the results of the UNLV tests, several carbon substrate injection events using EVO, a fructose solution, molasses, and nutrients were performed from April 2017 to August 2017. Injection rates of up to 8.6 gallons per minute (gpm) were able to be achieved in both the Qal and UMCf with maximum injection pressures of 20 pounds per square inch (psi). While the treatability study was primarily focused on reducing hexavalent chromium, the biological approach was also able to achieve sufficient reducing conditions to degrade perchlorate, as demonstrated in the bench-scale tests and based on preliminary performance groundwater monitoring results from the field test.

The overall objective of Seep Well Field Area Bioremediation Treatability Study is to demonstrate the effectiveness of using ISB to reduce the flux of perchlorate mass that is migrating off-Site and is not currently being captured by the existing extraction well network known as the SWF. Based on data from the fourth quarter of 2015, an estimated 4.5 lbs/day of perchlorate are being discharged into the Las Vegas Wash from within the boundary of the Off-Site NERT RI Study Area (Ramboll Environ, 2016b). The treatability study is building on the results and findings of the previous treatability study summarized in Section 2.2.5 and incorporates some of the findings and recommendations of this study, including the use of geophysical surveys, installation of a staggered injection well transect system, and construction of paired injection wells when the subsurface lithology suggests that this may improve injection coverage.

Pre-design activities have been completed and implementation of the treatability study is underway. As part of the pre-design, geophysical surveys, installation of soil borings and groundwater monitoring wells, groundwater sampling, aquifer testing, and basic bench-scale laboratory testing were completed between January and May 2017. Following the completion of the pre-design phase, 25 substrate injection wells (two transects, each of which are approximately 750 feet long) and an effectiveness monitoring network were installed in June 2017. Preliminary results from the on-going laboratory bench-scale studies currently being performed at UNLV have indicated that the addition of a slow-release carbon substrate, i.e., EVO, results in rapid bioremediation of nitrate and perchlorate in batch microcosms of site-specific media. One of the recommendations from a previous treatability study, namely an evaluation of the sorption/desorption characteristics to site soils, is currently being performed at UNLV. The first carbon substrate injection event was completed in September 2017.

Final results from the UNLV bench-scale testing, pre-design field activities, and effectiveness monitoring for both the In-Situ Chromium Treatability Study and the Seep Well Field Area Bioremediation Treatability Study will be evaluated and applied to the design of the Unit 4 Source Area In-Situ Bioremediation Treatability Study as appropriate. These include:

- Laboratory sorption/desorption test results from bench-scale studies;
- Usefulness and accuracy of geophysics and nuclear magnetic resonance (NMR) and their applicability;
- Injection well design;
- Injection rates and pressures;
- ZOI of the carbon substrate injection(s) and longevity of the carbon substrate; and
- Effectiveness of the application of a staggered configuration and paired injection well network, injection protocol and water distribution, downgradient influence of the injections, and any observed secondary geochemical impacts of the injections.

# 3.0 EVALUATION OF METHODS

Tetra Tech performed a preliminary evaluation of various methodologies that could be employed for soil flushing and ISB within the NERT RI Study Area. The goal of the preliminary evaluation was to select cost-effective methodologies for implementation that will have the highest likelihood of achieving the objectives given the physical constraints associated with this treatability study. Figure 17 provides a conceptual depiction of how soil flushing and ISB will work concurrently to address the COPC impacts within the vadose and saturated zones in the Study Area.

## 3.1 SOIL FLUSHING

Implementing soil flushing in the Unit 4 area will encounter special challenges and constraints that were not present for the previous soil flushing studies at the Site, which have been performed in open areas away from any permanent structures. Soil flushing in the Study Area presents several unique physical challenges. First, there are two adjacent buildings: the Unit 4 substation building to the south, which is used by Tronox and has a basement that shares a common wall with the Unit 4 basement, and the Unit 4 chlorinator building to the north, which is used by Tronox for storage and also has a common wall with the Unit 4 basement. Infiltrating relatively large volumes of water through the vadose zone has the potential to impact these structures from settlement and differential settlement due to consolidation of the soils and from reduction in the bearing capacity of the foundations due to saturation. Second, water applied during soil flushing has the potential to migrate through the area along a number of pathways, including the interface between the bottom of the basement slab and underlying soil as well as along underground utility corridors. Third, a concrete slab is present in the Unit 4 basement, which will need to be perforated to allow the underlying soil to be flushed. Fourth, the area outside of the southeast corner of the Unit 4 basement is paved with asphalt concrete (AC) and is used for access. Some of these challenges can be readily resolved, but potential issues such as consolidation and reduced bearing capacity require further detailed evaluation as part of this treatability study to determine appropriate methods, if necessary.

The following paragraphs present the preferred approach for soil flushing as part of the Unit 4 Source Area In-Situ Bioremediation Treatability Study. Additional investigation activities will be performed during the pre-implementation phase to determine whether adjustments to the preferred approach will be necessary. The preferred approach consists of the down-flushing approach successfully utilized in the Soil Flushing Treatability Study performed at the CRB, supplemented with vadose-zone injection wells.

The soil flushing will be focused in the southeast portion of the Unit 4 basement area and an area just to the east of the basement where some of the highest masses of perchlorate are present in the vadose zone as depicted in Figure 11. The rationale for this approach is: 1) the perchlorate mass in the vadose zone within the remainder of the basement area is more than an order of magnitude less than the perchlorate mass in the vadose zone within the southeast corner; 2) focusing the soil flushing on targeted areas helps reduce the amount of water that will be used, which helps reduce the eventual flow to the IWF downgradient; and 3) targeting soil flushing in the southeast area allows for monitoring/injection wells to be installed between the soil flushing area and the downgradient chlorinator building to help monitor and prevent flushed COPCs migrating downgradient.

The purpose of the vadose zone injection wells is to: 1) create a biologically reducing environment toward the bottom of the Qal prior to the commencement of down-flushing, 2) help avoid channelization of down-flushing water and fully saturate the vadose zone, and 3) overcome the potential hindrances to down-flushing of the Unit 4 basement slab and nearby AC pavement and the compacted soil subgrade immediately under the slab and pavement. It is anticipated that the vadose zone injection wells will be screened from approximately 15 to 25 feet bgs.

Three shallow monitoring/injection wells will be installed in the Qal down-gradient of the soil flushing area to monitor the groundwater mounding that is anticipated from the soil flushing operation and monitor whether COPCs migrate out of the Study Area through the Qal. If necessary, these monitoring wells can be used to inject carbon substrate near the bottom of the Qal in order to create a biologically reducing zone that will help reduce the potential for downgradient migration through the Qal of perchlorate and other COPCs flushed out of the vadose zone. The optimal spacing of the Qal monitoring/injection wells will be evaluated during the treatability study. It is anticipated that the Qal monitoring/injection wells will be screened from the top of the Qal/UMCf contact to approximately 10 feet above the contact.

It is anticipated that approximately six to ten pore volumes of water will be required for the down-flushing. The initial pore volumes of water will consist of SLMW or reclaimed water, without the addition of carbon substrate, in order to dilute the high COPC concentrations in the vadose zone and to avoid accumulation of biomass in the vadose zone which could reduce the rate of percolation of subsequent pore volumes of donor solution. After the initial pore volumes flush significant COPC mass out of the vadose zone, the later pore volumes will consist of a carbon substrate solution to act as a polishing phase. The selection of the carbon substrate to be used for the soil flushing will be part of the bench-scale tests described in Section 4.3.1. It is anticipated that it will consist of a soluble substrate, such as glycerol or molasses.

In preparation for soil flushing, portions of the Unit 4 building basement slab and the AC pavement will be perforated or removed to allow water to flow into the underlying soil targeted for flushing. Relatively small perforations (1-inch diameter or less) will likely be sufficient to allow flow of water to the underlying soil. Perforated distribution piping and berms will then be installed on top of the slab and AC pavement to create infiltration galleries and prevent flushing water from leaving the flushing area. SLMW or reclaimed water from a City of Henderson distribution line located in the general vicinity of the treatability study will be conveyed to the distribution piping. Water levels within the galleries will be controlled using mechanical float valves. Care will be taken to avoid the potential for migration of water into the basements of the Unit 4 substation building or chlorinator building. A series of infiltration tests performed at different depths will be performed to evaluate whether the soils immediately below the slab and AC pavement have reduced infiltration rates due to compaction or other factors along with a test to empirically evaluate the maximum perforation spacing necessary to achieve complete wetting of the soil underlying the slab and AC pavement.

After installation of wells, obtaining baseline data and preparing the soil flushing area, the anticipated sequence for implementing soil flushing will be as follows:

1. Inject carbon substrate solution into the vadose zone injection wells within the soil flushing area to create a biologically reducing environment toward the bottom of the Qal to help treat COPCs that will be flushed down out of the vadose zone.
2. Commence down-flushing with approximately three pore volumes of SLMW or reclaimed water to flush some of the highest concentrations of COPCs out of the vadose zone and toward the biologically reducing zone established in step 1.
3. Inject carbon substrate solution again into the vadose zone injection wells within the soil flushing area in order to help avoid channelization of down-flushing water, to help fully saturate the vadose zone, and to replenish the biologically reducing zone in the lower part of the Qal.
4. Continue down-flushing with approximately three additional pores volumes of carbon donor solution, as a polishing step.
5. The lysimeters and Qal monitoring wells will be monitored throughout the soil flushing to optimize the application.
6. At the end of the soil flushing program, confirmation soil samples will be obtained from the vadose zone.

## 3.2 HYBRID IN-SITU BIOREMEDIATION AND GROUNDWATER EXTRACTION

Tetra Tech has evaluated options for implementation of ISB in the UMCf using standard injection techniques, injection enhanced with hydraulic/pneumatic fracturing, and injection wells enhanced with groundwater extraction. The options were evaluated with respect to overall cost and likelihood of success. Due to the fact that the majority of the mass of COPCs in the UMCf is at significant depths of approximately 88 to 118 feet bgs, minimizing the number and cost of injection wells and accelerating mixing of COPCs and carbon substrates are key factors. It was determined that the cost of implementing a groundwater extraction system, in conjunction with ISB injection wells, will be more cost effective and have a higher likelihood of success than using standard injection techniques or injection enhanced with hydraulic/pneumatic fracturing. Preliminary modeling indicates that groundwater extraction helps to mix the COPCs and injected carbon substrates and reduces the number of injection wells needed. An additional benefit is that the groundwater extraction will remove substantial mass of COPCs such that they can be treated in the FBR portion of the GWETS. Groundwater extraction will likely also help reduce the concentrations of TDS in the high concentration depth interval of approximately 88 to 118 feet bgs where TDS was detected as high as 37,000 mg/L. Over time, the groundwater extracted will reduce the TDS concentration assuming there is not a continuing source of high TDS groundwater flowing into the capture zone of the extraction wells. Such high concentrations of TDS might retard the rate of ISB. The potential impact of very high concentrations of TDS on the rate of biodegradation will be evaluated as part of the bench scale portion of the treatability study as discussed in Section 4.3.1.

The analysis of options considered the overall cost effectiveness for not just the Unit 4 Source Area In-Situ Bioremediation Treatability Study, but also considered how the hybrid approach might be evaluated as part of the Feasibility Study for application to the UMCf elsewhere on the Site. The following subsections describe in more detail the evaluation of methods.

### 3.2.1 Substrate Selection

The carbon substrate selected for use during this treatability study is important both in terms of effectiveness within the Study Area, but also in terms of its applicability to be used elsewhere on the Site, if appropriate, as part of a viable remediation strategy. Organic carbon substrates that have been typically used to treat perchlorate in groundwater can be divided into three general groups:

- **Water-soluble substrates**: These materials dissolve completely in water, and are transported with groundwater in the subsurface. It is typically necessary to add these substrate types in designed amounts to the aquifer either continually or in bulk (slug) quantities over relatively short time intervals. Examples include alcohols, glycerin, sugars, and soluble salts. The advantage of soluble substrates is the ease of delivery, handling, and storage. However, they also typically have shorter half-lives and, over a longer timeframe, could cause biofouling in the aquifer.
- **Slow-release substrates:** These materials include a variety of relatively water-insoluble substances that are typically relatively slow moving in the subsurface. These materials remain in the area where injected for a longer period, and provide a controlled, slow release of organic carbon into the environment. The major advantages of these substrates are their longevity in the subsurface, less frequent injection intervals, and less likelihood of biofouling.
- **Solid substrates:** These materials include agricultural materials such as mulch, compost, or wood chips. These materials are commonly placed, along with gravel, within a designed continuous biowall or biobarrier. Natural solid substrates are often economical, available in many parts of the country, safe to handle, and generally last for longer time periods. However, such substrates are generally only applicable to continuous biowalls and cannot be directly added to conventional injection wells.

All three types of substrates discussed above have been successfully employed at major perchlorate sites across the country to treat groundwater (ITRC, 2008). The choice of a particular substrate depends on a host of physical, chemical, geochemical, and hydrogeological factors as well as the engineering configuration that has been selected for the particular site. A biowall would be cost-prohibitive and likely ineffective in remediating the impacts at Unit 4 due to the depth and extent of contamination as well as physical limitations. Therefore, the use of solid substrates was not as evaluated as part of this treatability studies.

Tetra Tech evaluated the use of numerous water-soluble and slow-release substrates in terms of ability to be injected, longevity, creation of donor-related by-products, handling, potential decrease in permeability, and overall cost-effectiveness. These include acetate, compost extract, corn syrup, ethanol, citric acid, EVO, fructose, sucrose, glycerol, Hydrogen Release Compound®, lactate, molasses, and soybean oil.

In support of other NERT treatability studies, UNLV has performed bench-scale tests to evaluate the biodegradation of perchlorate with soil and water from the Site using molasses, glycerol, compost extract, fructose, and EVO. Glycerol was used as an amendment for soil flushing as part of the Soil Flushing Treatability Study. Tetra Tech has injected molasses, sucrose, fructose, and emulsified vegetable oil at the Site in both the Qal and UMCf as part of the In Situ Chromium Treatability Study. EVO has been injected off-Site into the Qal as part of the previous Groundwater Bioremediation Treatability Study (described in Section 2.2.5) and on-going Seep Well Field Area Bioremediation Treatability Study (described in Section 2.2.6) (Tetra Tech, Inc., 2016d), and EVO injection is planned to be used for the Galleria Bioremediation Treatability Study and the Las Vegas Wash Bioremediation Treatability Study (Tetra Tech, Inc., 2017c). Ethanol and citric acid were injected off-Site at the AMPAC facility as part of a recirculation treatability study conducted by Geosyntec (Geosyntec Consultants, 2003).

Each substrate has its advantages and disadvantages. Highly soluble substrates such as acetate, lactate, sucrose, and ethanol are easier to handle, mix, and inject without requiring significant dilution. However, they generally have less reducing capacity on a pound-for-pound basis compared to the more viscous substrates such as corn syrup, molasses, EVO, and soybean oil, creating the need to inject significantly more volume. One of the benefits of using viscous substances such as EVO and soybean oil is their longevity, and therefore reduced need for frequent reinjections. As part of the bench-scale testing, UNLV is evaluating the effectiveness of both a soluble substrate and EVO to reduce perchlorate, chlorate, chromium, and chloroform concentrations in the groundwater collected from the UMCf at Unit 4. Based on the results of the bench-scale testing, Tetra Tech will evaluate and select the appropriate substrate and amount of substrate for use during the treatability study to achieve the overall objectives of the treatability study.

### 3.2.2 Substrate Delivery Methods

In order for ISB to be effective, the selected substrate needs to be adequately distributed through the target zone. Typically, at the depths and targeted treatment interval proposed for this treatability study, this distribution requires the installation of multiple injection wells screened at various depths throughout the treatment area. Because the UMCf consists primarily of fine-grained material, and based on injections performed in the UMCf during the In-Situ Chromium Treatability Study, the ZOI that can be achieved by injecting substrate through a typical injection well by injecting under pressure is anticipated to be limited to approximately 10 to 15 feet. If injection wells are the sole mechanism for introducing and distributing the carbon substrates of choice into the subsurface, this could result in the installation of a significant number of injection wells to ensure adequate coverage throughout the treatment area. However, several options exist, including hydraulic/pneumatic fracturing and groundwater extraction, to optimize substrate distribution and reduce the number of injection wells.

#### 3.2.2.1 Hydraulic/Pneumatic Fracturing

Hydraulic/pneumatic fracturing is a method of creating thin lenses of granular material in soil that are more permeable than the surrounding formation. This allows the substrate to be injected farther into the formation, increasing the ZOI and reducing the number of injection wells required. The fractures are created when enough fluid pressure is applied to the surrounding formation to cause the fracture to start. Once started, the fracture will continue to propagate until an obstruction is encountered or the rate of fluid loss from the fracture into the surrounding formation equals the rate of injection. The fracture can then be filled with a proppant[1] such as sand. After discussions with several companies that offer pneumatic fracturing services, the expected ZOI that could be achieved in the UMCf with an injection well installed within a boring that has been hydraulically/pneumatically fractured is approximately 20 to 30 feet. However, the cost of the hydraulic/pneumatic fracturing services is approximately three to ten times the cost of installing a traditional injection well. Additionally, hydraulic/pneumatic fracturing may create structural issues for the adjacent Unit 4 chlorinator and substation buildings. Therefore, hydraulic/pneumatic fracturing will not be considered for implementation for this treatability study.

#### 3.2.2.2 Injection and Extraction Process Methodology

Spreading and mixing of the substrate throughout the treatment area can be enhanced by an engineered injection and extraction system (Piscopo, Neupauer, & Mays, 2013). Depending on the subsurface conditions, extraction wells can be used to "pull" substrate through the formation, increasing the effective ZOI of an injection well and reducing the overall timeframe for the substrate to be distributed. To further promote mixing, a "push-pull" technique can be applied by alternating injection and extraction applications throughout the treatment zone. This concept involves alternating the use of injection and extraction wells to enhance spreading and mixing of the carbon substrate in the subsurface. Installed wells would be used for injections, extraction, and/or monitoring in order to continuously move substrate around and evaluate the amount of carbon substrate present across the treatment area. Preliminary groundwater modeling has indicated that injecting over a one month-long period followed by groundwater extraction in adjacent wells, which in turn is followed by switching the injection wells to extraction wells and vice versa would significantly enhance the substrate distribution over injections alone (Section 3.3). Additionally, pulsing or varying injection pressures during injection activities can help spread the substrate into the surrounding formation (Jones, 1988; Neupauer, 2014). Groundwater modeling also indicates that integrating groundwater extraction with the injection of carbon substrate solution also helps reduce the potential for downward migration of COPCs due to the injection of carbon substrate solution.

### 3.2.3 Well Installation Methodology

Injection, extraction, and monitoring wells will be required to implement the treatability study. Soil borings have generally been advanced utilizing sonic or hollow-stem auger technologies to install wells at the Site. Understanding that the cost of well installations is a large percentage of the cost of the treatability study and of any future remediation strategy, Tetra Tech has evaluated various drilling technologies in terms of cost-effectiveness and ability to achieve the technical objectives. The drilling technologies evaluated include direct-push, mud-rotary, air-rotary casing hammer, continuous stem augers, sonic, and hollow-stem auger. Hollow-stem auger and sonic were determined to be the most cost-effective drilling methods and provide the best data for the installation of wells at the depths planned for the Unit 4 Source Area In-Situ Bioremediation Treatability Study. Hollow-stem auger is preferred for collection of undisturbed soil samples for geotechnical evaluation. Based on discussions with drilling companies that have significant drilling experience at and in the immediate vicinity of the NERT Site, hollow-stem auger has been able to attain depths up to 180 feet bgs, significantly deeper than the planned depth wells to be installed as part of this treatability study. Sonic technology allows for faster drilling, continuous cores for logging, and generation of less soil cuttings compared to hollow-stem auger.

[1] A proppant is a solid media, typically sand, designed to keep an induced hydraulic fracture open, during or following the fracturing process.

### 3.2.4 Extracted Groundwater Management Methods

Groundwater extracted as part of the treatability study will need to be managed by on-Site treatment. Preliminary modeling suggests that the groundwater extraction rate could be approximately 17.5 gpm (Section 3.3), but this estimate could vary and will need to be further evaluated after more information is obtained from hydraulic testing performed in the initial extraction wells to be installed.

Extracted groundwater could potentially be re-injected within or upgradient of the treatment area, with or without treatment, depending on regulatory approvals. The benefits of re-injection include minimizing the handling of the extracted water and ability to potentially dilute the high TDS concentrations present in the treatment area by adding SLMW or reclaimed water to the extracted water prior to re-injection. However, preliminary groundwater modeling indicates that the amount of groundwater extracted will likely exceed the quantity that the Study Area can accept via reinjection. Given the estimated quantity of groundwater to be extracted, off-Site disposal of the extracted groundwater would be cost prohibitive. On-Site treatment is therefore the preferred method for handling the extracted groundwater. Based on data collected during the first and second mobilizations, hexavalent chromium is present at concentrations up to 110 mg/L in groundwater beneath Unit 4. The extracted groundwater will be conveyed via a double-containment pipeline to the existing GWTP where its chromium content will be treated, along with groundwater extracted from the IWF. After chromium treatment, the combined flow will then be treated by the GWETS FBR system. A conceptual layout for the double-containment pipeline is depicted in Figure 18.

The existing GWTP is currently operating close to its hydraulic capacity. In order to free up capacity in the GWTP to treat the expected 17.5 gpm from the Unit 4 Source Area In-Situ Bioremediation Treatability Study, a bypass will be evaluated whereby the western manifold of the IWF would bypass the GWTP. The western manifold of the IWF produces approximately 0.14 lbs/day of chromium from 13 gpm from the western-most nine IWF wells. Additional capacity will be realized when ceasing the current 12 gpm of extraction from the AP Area extraction wells following completion of soil flushing activities. The GWETS FBRs are currently treating approximately 0.7 lbs/day of chromium, mostly from the AWF and the effluent from the GWTP. In the past (November 2014), the FBRs have successfully treated as much as 1.6 lbs/day of chromium. Consequently, the addition of the 0.14 lbs/day of chromium from the bypassed western manifold to the current 0.7 lbs/day being treated by the FBRs will be within the demonstrated capacity of the FBRs to treat chromium. This bypass approach would free up approximately 25 gpm of hydraulic capacity in the GWTP to handle the flow from the Unit 4 Source Area In-Situ Bioremediation Treatability Study.

Preliminary analysis indicates that the GWTP will have sufficient capacity to handle not only the 17.5 gpm hydraulic loading from the Unit 4 Source Area In-Situ Bioremediation Treatability Study, but also the estimated 3.5 lbs/day of chromium loading. Preliminary analysis indicates that the GWETS hydraulic capacity and treatment capacity will need to be managed in order that the additional flow and loading from the Unit 4 Source Area In-Situ Bioremediation Treatability Study not exceed its capacities.

NERT will perform a more detailed analysis with both Tetra Tech and Envirogen Technologies, Inc., to further evaluate the impact the additional flow and mass loading the extracted groundwater from the treatability study would have on the GWETS operation following additional testing and modelling efforts.

## 3.3 PRELIMINARY GROUNDWATER MODELING

A simple 3-D groundwater flow model was constructed to evaluate different scenarios of injection and extraction at the Study Area and the effect of these activities on downgradient areas, such as the IWF. The modeling results were used to assist in the preliminary injection and extraction design for this study. This section discusses the preliminary modeling approach and results.

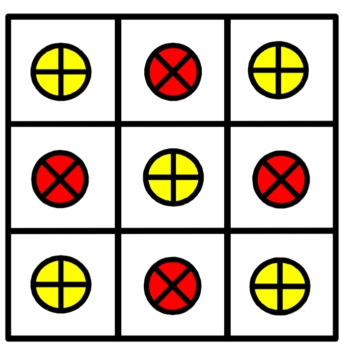
### 3.3.1 Model Setup

A numerical model grid was constructed that was centered on the Study Area, which included 136 rows, 61 columns, and 6 model layers. Horizontal grid spacing was a constant 5 feet. Model layer thicknesses are either 10 or 15 feet to correspond to the anticipated well screen intervals for the intermediate (88-103 feet bgs), and deep (103-118 feet bgs) zones. The top of the model is the contact of the Qal and UMCf, which is higher than the water table. The Qal is not included in this preliminary model.

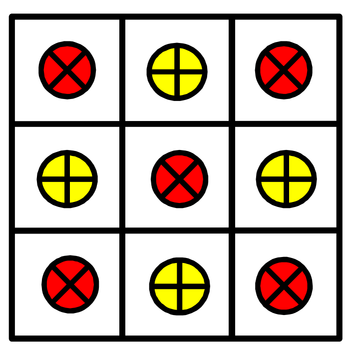
Hydraulic conductivity for the UMCf was set to constant values in all model layers. Horizontal hydraulic conductivity was assumed to be 1 foot/day or 3.53x10$^{-4}$ centimeter per second (cm/s) and 0.5 ft/day or 1.76x10$^{-4}$ cm/s in the intermediate and deep zones, respectively, based on data collected from the In-Situ Chromium Treatability Study and the AP Area Treatability Study. Vertical hydraulic conductivity is assumed to be 0.0283 foot/day or 1x10$^{-5}$ cm/s. These values are within the range of hydraulic conductivities observed from slug tests conducted within the UMCf for the AP Area Treatability Study and the In-Situ Chromium Treatability Study. For particle tracking simulations, an effective porosity of 30 percent was assumed based on the UMCf lithology and professional experience. The effective porosity value will be updated based on the results of analysis conducted during the Unit 4 and 5 Buildings Investigation and the Phase 2 Remedial Investigation.

Recharge is applied at the top of layer 1 to simulate soil flushing water reaching the UMCf. For these preliminary simulations, 50 gpm was assumed to be uniformly distributed across the approximately 10,000 square foot area southeast of the injection/extraction well clusters at the Study Area (Figures 19 and 20). No other recharge was applied in the model area. Groundwater contours from the 2016 Annual Report (Ramboll Environ, 2016b) were used to set constant heads along the northern (1,770 feet above mean sea level [amsl]) and southern boundaries (1,780 feet amsl) of the model grid.

Injection rates were assumed to be 1 gpm per well based on previous injection rates achieved within the UMCf. Extraction wells were assumed to be 2 gpm in the intermediate zone and 1.5 gpm in the deep zone. The nine injection/extraction wells were located in the intermediate and deep UMCf zones, 45 feet apart in a 3 x 3 pattern (three rows of three wells; Figures 19 and 20). To maximize the uniform distribution of substrate, the model duration was set up over six 30-day stress periods (stress periods 1 through 6). During the stress periods 1, 3, and 5, injection and extraction were occurring in all wells with five of the wells on the 3 x 3 grid alternating from injection to extraction and the other four wells alternating from extraction to injection. This scheme of alternating injection and extraction was used to spread the substrate over a wider area compared to injection alone or continued injections and extractions using the same wells. The following schematic illustrates the injection and extraction pattern used for the preliminary modelling, with the red circles indicating wells being used for extraction and the yellow circles indicating wells being used for injection:



Months 1, 3, and 5



Months 2, 4, and 6

### 3.3.2 Model Results

Figures 19 and 20 show the resulting water-level elevation contours at the end of month 6. The dashed lines depicted on Figures 19 and 20 represent areas where groundwater elevations would decrease due to extraction of groundwater. Model results indicate that applying 50 gpm of down-flushing water will produce water table mounding of approximately 5 feet in the Study Area. This additional saturated thickness allows the shallow extraction wells to pump more groundwater than under ambient groundwater conditions. Total extraction rate for all of the extraction wells in the two zones is 17.5 gpm. Note these extraction rates were not fully optimized to maximize pumping given the preliminary nature of this modeling.

A portion of the amount of water applied for the soil flushing is expected to flow down-gradient mostly through the Qal toward the IWF. To evaluate the travel time of the water from soil flushing at Unit 4 to reach the IWF, the Phase 5 groundwater model was used because it has the IWF pumping wells in the model domain (Ramboll Environ, 2016c). Using the model, the same amount of soil flushing water was applied to the Study Area to evaluate the travel times to the IWF. Travel times to the IWF ranged from approximately 2 to 4 years with an average of 3 years. By the time the flushing water reaches the IWF, it will be significantly diluted and dispersed to the point where there would be minimal effect on groundwater concentrations, elevations or the pumping rates of the IWF.

In order to further evaluate the migration of soil flushing water to the IWF, shallow monitoring wells will be installed downgradient of the Unit 4 Source Area In-Situ Bioremediation Treatability Study soil flushing area as shown in Figure 21. The number of wells, screen intervals, and well locations may be adjusted based on the area being flushed, hydraulic testing, groundwater modeling, and access considerations. These wells will be monitored on a regular basis to measure the quantity, COPC concentrations, and arrival time of water from soil flushing operations. If necessary, these wells could be used as injection wells to further treat the soil flushing water prior to reaching the IWF. Additional modeling will be performed during the treatability study using the latest version of the groundwater model to further evaluate the travel time to the IWF and the capture zone of the IWF based on updated hydrogeologic data collected across the Site as part of the Phase 2 Remedial Investigation and from this and other treatability studies.

The preliminary groundwater modeling also considered the potential that the anticipated hybrid ISB injection / groundwater extraction approach might induce downward migration of COPCs below the anticipated treatment zone of 88 feet to 118 feet bgs. The modeling indicates that there will likely be no net effect from the ISB injection / groundwater extraction program on downward migration of COPCs below the treatment zone. Monitoring well results from deeper monitoring wells, such as wells M-252, M-254 and M-257, will be used to confirm that there is no downward migration of COPCs due to the treatability study.

## 3.4 METHODS SELECTED FOR FURTHER EVALUATION

### 3.4.1 Soil Flushing

Additional assessment activities will be performed to refine the soil flushing approach presented in Section 3.1. Initially, a geotechnical and structural engineering assessment is needed to evaluate the effects of soil flushing on the adjacent structures, including the potential for settlement and differential settlement due consolidation of the soil and the potential for reduction in the bearing capacity of the building foundations due to saturation. Infiltration tests will be performed at multiple depths in the soil flushing area to evaluate whether compaction or other construction artifacts have affected soils immediately beneath the slab and AC pavement. Testing will be also be performed to estimate spacing for perforations in the slab/AC pavement and for vadose-zone injection wells.

### 3.4.2 In-Situ Bioremediation

Based on the preliminary evaluation conducted by Tetra Tech and summarized in Section 3.2, Tetra Tech recommends further evaluating a combination of injection and extraction wells throughout the Study Area to assist in distributing the carbon substrate. Based on results from previous and on-going treatability studies at the Site, there could be considerable heterogeneity in the lithology within relatively short distances, and soil properties and soil types may vary in all three dimensions in the saturated subsurface. Flow pathways and transport of organic carbon during injections may be non-uniform and bounded by the hydraulic properties of the UMCf. The proposed treatability study approach will utilize wells for both injection and extraction to enhance distribution of carbon substrate throughout the treatment zone and counter the impacts of heterogeneity and non-uniform flow.

# 4.0 PRE-IMPLEMENTATION LABORATORY AND FIELD ACTIVITIES

This section describes the pre-implementation activities to be completed prior to the conducting the treatability study, including various laboratory studies and field activities. Results from these pre-implementation activities will be used to finalize design details for the treatability study.

## 4.1 OBJECTIVES

The objectives of the pre-implementation activities for soil flushing and hybrid ISB / groundwater extraction include the following:

**Soil Flushing**

- Evaluate the potential impact the installation and operation of the soil flushing system may have on the structural integrity of the infrastructure;
- Supplement baseline concentrations of perchlorate and chlorate in the vadose zone soil;
- Determine optimal water infiltration and substrate amendment rates; and
- Determine optimal spacing between perforations and injection wells, pending the results of the geotechnical evaluation.

**Hybrid In-Situ Bioremediation / Groundwater Extraction**

- Determine the hydraulic properties of the UMCf in the Study Area;
- Investigate COPC degradation kinetics through bench-scale tests with soil and groundwater collected from the Study Area. This was addressed in the *Unit 4 Source Area In-Situ Bioremediation Treatability Study Bench-Scale Work Plan* (Tetra Tech, Inc., 2017d) and this evaluation is currently underway;
- Determine optimal well spacing and number of injection, extraction, and monitoring wells;
- Determine the injection flow rate and injection quantities;
- Determine the extraction flow rates and pulsing methodology;
- Determine the mixture of substrates and amendments to be injected;
- Determine well construction parameters for the injection, extraction, and monitoring wells, including screen intervals, filter pack, and total installation depth; and
- Install injection, extraction, and monitoring wells to be used during the treatability study.

## 4.2 PRE-IMPLEMENTATION ACTIVITIES OVERVIEW

The pre-implementation activities are proposed to be completed over the course of three phases to streamline the collection of critical data required to finalize the treatability study design. Field activities described herein will be conducted in general accordance with the existing Field Sampling Plan, Revision 1 (ENVIRON, 2014a). The pre-implementation activities associated with each phase are as follows:

- Pre-Implementation Phase 1
  - Bench-scale laboratory studies
  - Geotechnical and structural assessment
  - Utility clearance
- Pre-Implementation Phase 2
  - Infiltration tests
  - Collection of baseline soil samples

  - Well survey
  - Constant rate pumping test
  - Soil flushing perforation spacing test
  - Installation of select injection, extraction, and monitoring wells
  - Single-borehole dilution/slug tests
  - Step drawdown tests
  - Groundwater model verification and validation
  - Nuclear magnetic resonance logging
  - Well development
- Pre-Implementation Phase 3
  - Lysimeter installation
  - Well development
  - Baseline pore water sampling
  - Well survey
  - Installation of injection, extraction, and monitoring wells
  - Completion of additional aquifer testing GW sampling

Management of investigative-derived waste (IDW) will be conducted during each pre-implementation phase, as discussed in Section 4.6.

## 4.3 PRE-IMPLEMENTATION PHASE 1

### 4.3.1 Bench-Scale Laboratory Studies

Bench-scale laboratory studies performed in support of this treatability study are described in the Unit 4 Source Area In-Situ Bioremediation Bench-Scale Studies Work Plan submitted under a separate cover. The scope of the proposed bench-scale studies includes batch microcosm studies and completion of a column study based on the results of the batch microcosm studies. Soil and groundwater have been collected and transported to UNLV for use in the laboratory bench-scale tests during the Unit 4 and 5 Buildings Investigation third mobilization activities.

Specific objectives of the bench-scale studies are:

- Determine the impact of concentrations of high TDS on the biodegradation kinetics of the COPCs using groundwater and soil collected from the proposed Study Area;
- Evaluate the impact of VOC presence on the biodegradation of perchlorate, chlorate, and chromium; and
- Examine the impact of bioaugmentation, along with adding nutrients and vitamins, on the biodegradation of the COPCs.

### 4.3.2 Contingency Plan

In accordance with the *Site Management Plan, Revision* 3 (Ramboll Environ, 2017a), a contingency plan is required due to the proposed pre-implementation field activities being located within 50 feet of a GWETS component or monitoring well. As a result, Tetra Tech will prepare and submit a contingency plan to NDEP, after Trust review, prior to performing field activities. The contingency plan will outline the protection measures that will be implemented to prevent damage to GWETS components or monitoring wells and response actions to be taken if damage is caused to a GWETS component that causes a release.

### 4.3.3 Utility Clearance

Tetra Tech will contact USA North Utility Locating Services, review available utility maps, and retain the services of a geophysical locator to check for underground utility lines prior to conducting intrusive subsurface activities. This information will also be used to obtain Tronox groundbreaking permits, as discussed in Section 7.2. To streamline utility clearance activities, one utility mark out is assumed to be conducted to support pre-implementation activities for both soil flushing and hybrid ISB / groundwater extraction. With the exception of perforations in the Unit 4 basement slab and surrounding AC pavement (described in Section 4.4.1.2.), each borehole will be cleared for utilities to at least 5 feet bgs using a Hydrovac unit that will inject pressurized water through a handheld wand and extract the resulting slurry by a powerful vacuum. Boring locations may be adjusted in the field to avoid existing utilities, structures, or other site features.

### 4.3.4 Geotechnical and Structural Evaluation

Performing soil flushing in the Unit 4 basement presents a number of unique challenges. These challenges include potential impacts to on-going Tronox operations in the adjacent substation and chlorinator buildings. These issues will be evaluated and the findings addressed by performing a geotechnical engineering and structural assessment of the potential effects of soil flushing on the adjacent structures.

The geotechnical and structural assessment will include a field investigation, laboratory testing, analysis, and data evaluation. The field investigation will consist of drilling six soil borings to a short distance below the water table (up to approximately 55 feet deep) using a hollow-stem auger drill rig. The borings will be logged by an engineering geologist or geotechnical engineer using the Unified Soil Classification System (USCS). Disturbed soil samples will be collected continuously using a Standard Penetration Test (SPT) sampler. Undisturbed samples will be substituted for SPT samples at selected locations within fine-grained layers for physical property testing on an as-needed basis. Undisturbed samples will be collected using Shelby tubes, or with an Osterberg sampler if necessary due to soil conditions. Selected soil samples will be analyzed for moisture content (American Society for Testing and Materials [ASTM] Method D2216), grain size distribution (ASTM Method D422), Atterberg limits (ASTM Method 4318), direct shear strength (American Association of State Highway and Transportation Officials [AASHTO] Method T 236), and one-dimensional swell or collapse of soils (ASTM Method D4546).

The data will be evaluated by a team of geotechnical and structural engineers. The evaluation will consider the potential effects of soil flushing on soils and the adjacent structures including: 1) total and differential settlement due to consolidation of the unsaturated soil column upon wetting; and 2) the potential reduction in the soil bearing capacity below the building foundations due to saturation of the soils. The results of these analyses will be used to determine the potential monitoring and mitigation measures for performing soil flushing within and in the vicinity of the Unit 4 basement.

## 4.4 PRE-IMPLEMENTATION PHASE 2

### 4.4.1 Soil Flushing

#### 4.4.1.1 Injection Well Test

Tetra Tech will retain a licensed drilling contractor to install vadose zone injection wells using hollow-stem auger or sonic drilling technology. It is anticipated that up to three injection wells will be installed to perform the injection well test. The wells will be installed at approximately 15 to 25 feet bgs and constructed of 2-inch Schedule 40 polyvinyl chloride (PVC). The test would involve continuously injecting SLMW or reclaimed water into the injection wells over a period of 1 to 2 weeks. At the conclusion of injection activities, up to five soil borings will be drilled at various distances away from the injection wells for qualitative observations of moisture content of the soil and to determine the lateral and vertical influence for soil flushing. Injection flow rates and pressures will be adjusted to evaluate the optimal soil flushing conditions.

#### 4.4.1.2 Infiltration and Perforation Spacing Test

In order to optimize soil flushing, infiltration tests will be conducted using a double-ring infiltrometer apparatus to evaluate the maximum infiltration rate across the Unit 4 Source Area In-Situ Bioremediation Treatability Study soil flushing area. The tests will be conducted in accordance with ASTM Standard D3385-09 (Standard Test Method for Infiltration Rate of Soils in Field Using Double Ring Infiltrometer) (ASTM International, 2009).

The perforation spacing tests will consist of drilling several sets of four 1-inch holes in a square pattern through the concrete slab or AC pavement. The holes will be drilled using a carbide drill and using wet methods. Each set of holes will be drilled with a different hole spacing. The test area will then be bermed, and SLMW or reclaimed water will be infiltrated through the holes for a period of several days. When infiltration is completed, the concrete slab or AC pavement will be cored at the center point and at one of the application holes for each group. A hand auger or direct push boring will be drilled at each of the cored locations. The soil boring at the water application hole will be drilled first, and qualitative observations of moisture content during drilling will serve as an observation baseline. The boring at the center point of the array will then be drilled, and the moisture content observed in the center point boring cuttings will be qualitatively compared with the baseline boring. If large differences in moisture content are observed between the baseline and center point borings, then the spacing of the application holes may be too large. This process will be continued until the maximum spacing consistent with adequate wetting of the soil is determined.

### 4.4.2 In-Situ Bioremediation

#### 4.4.2.1 Installation of Injection, Extraction, and Monitoring Wells

Installation of injection, extraction, and monitoring wells to support the implementation of the hybrid ISB / groundwater extraction portion of the treatability study will be conducted over two or three separate mobilizations. Based on the preliminary groundwater modeling, up to 15 well clusters are planned be installed within the Study Area to depths of up to 118 feet bgs to support the implementation of the hybrid ISB / groundwater extraction in the UMCf (Figure 21). During the first mobilization, approximately one-third of the total number of wells will be installed to support the following objectives:

- Collect soil samples, supplementing the data available as part of the Unit 4 and 5 Buildings Investigation, to establish baseline soil conditions in the vadose zone prior to implementation of soil flushing; and
- Obtain aquifer testing data from a sufficient number of data points within the Study Area to update the groundwater model prior to the implementation of hybrid ISB / groundwater extraction.

The final well spacing, configuration, number of wells, and well design for the first mobilization will be determined based upon data collected during the ongoing Unit 4 and 5 Buildings Investigation and groundwater modeling simulations. The well locations and screen intervals will target zones where the highest mass of COPCs are present as well as high permeability zones. The remaining wells will be installed during Phase 3 of the pre-implementation field activities as described in Section 4.5.2.

The preliminary depth intervals for the monitoring, injection, and extraction wells within the Study Area are defined as follows:

- Intermediate UMCf interval (approximately 88 to 103 feet bgs); and
- Deep UMCf interval (approximately 103 to 118 feet bgs).

The selection of the depth intervals within the UMCf was based on the distribution of COPC mass within the treatment area and a maximum screen interval of 15 feet. The screen intervals listed above and the number of screen intervals will be updated based on the results of the Unit 4 and 5 Buildings Investigation, groundwater modeling, lithology, and results of pre-implementation activities (including hydraulic testing). The screen intervals will target the zone where the highest mass of COPCs are present. Based on the results of final modeling, the screen intervals for the injection/extraction wells might be staggered three-dimensionally to reduce the potential for short-circuiting.

Tetra Tech will retain a licensed drilling contractor to advance the soil boring using hollow-stem auger or sonic drilling technology, if deemed necessary, to permit the collection of continuous soil cores for accurate lithologic logging and sampling. Before the drill rig mobilizes to each soil boring location, downhole drilling equipment will be cleaned with a high-pressure, high-temperature water spray to avoid potential cross-contamination. The continuous soil cores will be logged by the field geologist from ground surface to total depth using the USCS.

Soil samples will be collected for chemical analysis at 5-foot intervals from a select number of boring locations from approximately 0 to 120 feet bgs to provide adequate characterization of baseline conditions. The drilling contractor will decontaminate soil sampling equipment between samples. Soil samples for laboratory analysis will be collected in laboratory-supplied containers, labeled, placed in plastic bags, and stored in a cooler on ice for transport to the project analytical laboratory. Baseline soil samples will be analyzed for a variety of physical properties (***Table 4***) and chemical parameters (***Table 5***).

***Table 4.*** Geotechnical Laboratory Testing Protocol

| Parameter | Analytical Method | Purpose |
|---|---|---|
| Moisture Content | ASTM D2216 | Assess soil properties and geotechnical parameters |
| Bulk Density, Dry | ASTM D2937 | |
| Specific Gravity | ASTM D854 | |
| Total Porosity | API RP40 | |
| Effective Porosity | Modified ASTM D425, D854, D2937 | |
| Air-Filled Porosity | API RP40 | |
| Hydraulic Conductivity | ASTM D5048 | |
| Soil pH | EPA 9045 | |
| Total Organic Carbon | Walkley-Black | |
| Fraction Organic Carbon | ASTM 2974 | |
| Grain Size Distribution, Sieve with Hydrometer/ Laser Light Scattering | ASTM D422 / ASTM 4464 | |
| Atterberg Limits | ASTM D4318 | |
| Consolidation | ASTM D2435 | |
| Direct Shear Strength | AASHTO T236 | |
| Water Soluble Sulfates | Various Methods | |
| Resistivity | ASTM G57 | |
| Corrosivity | Various Methods | |

**Acronyms and Abbreviations:**

AASHTO: American Association of State Highway and Transportation Officials
API: American Petroleum Institute
ASTM: American Society for Testing and Materials

***Table 5.*** Baseline and Post-Implementation Soil Sampling Protocol

| Parameter | Analytical Method | Purpose | Frequency |
|---|---|---|---|
| **Laboratory Analyses** | | | |
| Perchlorate | E314.1 | Estimate mass of perchlorate/ Assess treatment effectiveness | Baseline, Post-Implementation |
| Chlorate | E300.1 | Estimate mass of chlorate/ Assess treatment effectiveness | |
| Chlorite | E300.1 | Estimate mass of chlorite/ Assess treatment effectiveness | |
| Hexavalent Chromium | SW7199 | Estimate mass of hexavalent chromium/ Assess treatment effectiveness | |
| Total Chromium | SW6010B | Estimate mass of chromium/ Assess treatment effectiveness | |
| Total Organic Carbon | SM5310B | Estimate available natural organic carbon | |
| Soil pH | SW846 9045C | Assess geochemical conditions | |
| Soluble Cations and Anions [1,2] | Notes 1 and 2 | Assess salt loading | |
| Total Dissolved Solids [2] | SM2540C | Assess salt loading | |
| Metals [3] | SW 846 6010/6020 | Estimate mass of various metals in unsaturated soil | |
| Perchlorate Reductase and Chlorite Dismutase Genes | Microbial Insights Method | Assess microbial response to carbon substrate addition | |

**Notes:**

1. Soluble cations and anions via analysis of leachate [cations include calcium, magnesium, potassium, and sodium (Method SW6010B); anions include chloride, sulfate, and nitrate (Method 300.0), chlorate (Method E300.1), and carbonate alkalinity (Method SM2320B).
2. Analysis to be performed on water extract prepared per method SW9056.
3. Metals include boron, iron, manganese, and titanium (Method SW6010B); antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, molybdenum, nickel, selenium, silver, and zinc (Method 6020); and mercury (Method SW7471A).

Monitoring wells are anticipated to be installed as nested wells, although the configuration will have to be confirmed by final groundwater modeling. The monitoring wells will be constructed with 2-inch Schedule 40 or Schedule 80 PVC casing, and screened with 2-inch diameter slotted PVC well screen. Wells that will be used for injections and extraction will be clustered and constructed with 4-inch Schedule 80 PVC casing and screened with a 4-inch diameter slotted PVC or wire-wrapped stainless steel well screen. A washed sand filter pack will be installed in the annular space around the well screens and extended up to 2 feet above the top of each screen interval. The screen slot size and filter pack sand will be selected based on the results of grain size analyses. A minimum 5-foot hydrated bentonite seal will be placed above the filter pack. The remainder of the annular space will be backfilled with cement containing approximately 5 percent bentonite.

As previously discussed, the total well depth, slot size, filter pack, and length of the well screens will be determined after completion of the Unit 4 and 5 Buildings Investigation, groundwater modeling, and results of pre-implementation activities. Wells installed within the Study Area may be completed with above-grade monuments at an elevation approximately 3 feet above surrounding grade or with flush-mounted, tamper-resistant, traffic-rated well boxes, at an elevation approximately one-half inch above surrounding grade. Wells installed outside of the Study Area will be completed with flush-mounted, tamper-resistant, traffic-rated well boxes, at an elevation approximately one-half inch above surrounding grade.

### 4.4.2.2 Well Development

Following the completion of well construction, but no sooner than 24 hours after well construction is complete, Tetra Tech will develop each of the newly installed wells. A surge block and bailer will be used to swab and surge the filter pack and remove sediment from the well. This process will be followed by pumping with a submersible pump. Well development will be considered complete when 3 to 10 casing volumes of water have been removed from the well, and index parameters consisting of pH, specific conductivity, turbidity, and temperature are stable (pH within 0.1, turbidity less than 5 NTU or stable, and other parameters generally within 10 percent) over three consecutive measurements. All index parameter readings will be recorded by Tetra Tech on well development logs. Baseline groundwater sampling, discussed in Section 4.5.2.3, will not be conducted until at least 72 hours following the completion of the well development.

### 4.4.2.3 Well Survey

Following installation of the wells, a licensed land surveyor will survey the horizontal coordinates of each well relative to North American Datum 83 with an accuracy of 0.1 foot, and the elevation of the ground surface and top of well casing measuring point relative to North American Vertical Datum (NAVD) 88 with accuracies of 0.1 foot and 0.01 foot, respectively.

### 4.4.2.4 Single-Borehole Dilution Test

A single-borehole dilution test will be performed in select wells to evaluate volumetric flow in the UMCf within the field Study Area. Single-borehole dilution tests consist of mixing a tracer compound into the groundwater in a well, and then observing the decline in tracer concentration in the well as a function of time using downhole instruments (Pitrak, Mares, & Kobr, 2007). The decline in tracer concentration in the well is due to dilution by volumetric groundwater flow, and the results will be used to estimate groundwater velocity in the immediate vicinity of the well. Results of the single-borehole dilution tests will be used to determine appropriate flow rates for use in the Unit 4 Source Area In-Situ Bioremediation Treatability Study design.

### 4.4.2.5 Slug Tests

Slug tests will be performed in select newly installed wells to estimate location-specific aquifer hydraulic conductivity (pre-implementation) within the Study Area and to confirm the results of the borehole dilution tests described in Section 4.4.2.4. The slug tests will be performed in general accordance with ASTM Standard D4044-96 (ASTM International, 2008). Prior to conducting each slug test, the water level in the well will be measured manually with an electronic water level probe to determine the static groundwater level. An electronic pressure transducer/data logger will then be suspended in the well, and water levels will be monitored manually until static conditions are reestablished. A falling-head test will then be conducted by smoothly lowering a length of weighted and sealed PVC pipe (slug) into the well, securing it in place above the transducer, and recording the rate of water level decline. Once static conditions are reestablished, a rising-head test will be conducted by removing the slug and allowing the water level to again recover to static conditions while recording the rate of recovery. Barometric pressure changes during testing will be monitored and recorded using a pressure transducer placed above the water table.

At the end of each test, the pressure transducer will be removed from the well, and the water level displacement data will be downloaded to a laptop computer and corrected for barometric pressure effects. The corrected data will be interpreted using AQTESOLV for Windows (Duffield, 2014), or similar aquifer test analysis software. If possible, both the falling-head and rising-head data will be analyzed to cross-check the interpretation results.

#### 4.4.2.6 Step-Drawdown Test

The step-drawdown tests will be performed in select newly installed wells by pumping at three rates for approximately 2 hours each, similar to what was performed for the GWETS Optimization Project (ENVIRON, 2015). The rates will be confirmed during well development but may be 1 gpm, 3 gpm and 5 gpm. Flow rates will be monitored throughout the test with a direct reading rotameter-type flow meter and a totalizing flow meter. All flow rate changes and interruptions will be recorded, and the causes for such changes will be noted, if known. Flow rates will be adjusted to maintain the target rates through the duration of each step.

Electronic pressure transducer/data logger units will be used to record groundwater level changes over time in the extraction and observation wells. The pressure transducers will be set at least 1 day before aquifer performance testing begins to record barometric and diurnal effects on static water levels. Atmospheric pressure will be recorded throughout the test period to correct the pressure transducer data for barometric pressure fluctuations. Water levels will also be manually monitored and recorded on a periodic basis as a backup.

Water level recovery data will be collected from the time pumping is terminated until the end of the test, defined as when water levels have recovered to within 90 percent of initial static levels. The results of the step-drawdown tests will be evaluated to determine the pump size, well efficiency, and target extraction rate for the constant-rate pump tests.

#### 4.4.2.7 Constant-Rate Pumping Test

After water levels have recovered in the select wells where a step-drawdown test was performed, constant-rate pumping tests will be conducted. The flow rate for this test will be determined using the data obtained during the step-drawdown test. Flow rates, drawdown, and water level recovery data will be monitored as described in the step-drawdown test. In addition, at least one monitoring well outside the likely area of influence of the pumping test will be monitored. In order to obtain the ZOI of each well at steady state conditions, pumping will continue until water levels at proximal injection, monitoring, or extraction wells change less than 0.01 foot over the period of 30 minutes.

#### 4.4.2.8 Nuclear Magnetic Resonance Logging

NMR logging was used successfully at the SWF Area Study Area to identify higher-transmissivity zones within each well. NMR will be used on a select number of newly installed and existing monitoring wells within the vicinity of the Study Area to delineate localized preferential flow pathways. This technology can be used in wells to provide high-resolution downhole estimates of hydraulic conductivity, total water content, and relative pore-size distributions below the water table (Walsh et al., 2013). Above the water table, NMR provides volumetric water content measurements. The specific tool used will depend on the diameter of the well, because larger diameter wells require a larger tool that has a larger radius of investigation. All tools are expected to provide a measurement approximately every 1.5 to 2 feet of depth. The high-resolution estimates of hydraulic conductivity will be compared to the lithologic logs and aquifer testing results for each well to assess preferential flow pathways.

#### 4.4.2.9 Groundwater Model Verification and Validation

The preliminary groundwater model discussed in Section 3.3 will be updated using data collected during pre-implementation Phase 2. Additional modeling simulations will be performed to confirm and verify the appropriate well spacing and number of wells used for injection and extraction, and to evaluate placement of monitoring wells within and downgradient of the Study Area prior to completing the activities associated with Pre-Implementation Phase 3.

# 4.5 PRE-IMPLEMENTATON PHASE 3

## 4.5.1 Soil Flushing

### 4.5.1.1 Lysimeter Installation

Up to five pressure-vacuum lysimeters will be installed within the treatability study soil flushing area to allow sampling of pore water in the vadose zone during the treatability study. Lysimeters consist of a porous ceramic cup that allows collection of pore water samples from the surrounding unsaturated soil when a vacuum is applied from the ground surface. A sample chamber in the lysimeter is then pressurized to lift the sample to the surface.

Lysimeters will be installed in hollow-stem auger or sonic soil borings. Prior to installation, a lysimeter will be attached to a string of PVC well casing. The casing diameter and the system used to couple the lysimeter to the casing depend on the lysimeter design, and the manufacturer's specification for casing diameter and coupling type will be followed during installation. The lysimeter tubing will be placed inside the casing to prevent contact between the tubing and borehole wall, which could potentially create preferential vertical flow pathways. Centralizers will be placed on the lysimeter body, at least 2 feet above the top of the porous cup and at 20-foot intervals on the casing string, to ensure that the lysimeter and casing do not come in contact with the borehole wall. Approximately 1 foot of less than 200-mesh silica flour slurry (50 pounds of silica flour to 1 gallon of water) will be placed at the bottom of the borehole using a tremie pipe. The lysimeter and casing will be lowered into the borehole and gently pushed into the slurry. Additional slurry will be placed to approximately 1 to 1.5 feet above the top of the porous cup using a tremie pipe. A seal consisting of a minimum of 3 feet of bentonite will be placed above the silica flour slurry. The remainder of the borehole will be backfilled with hydrated bentonite or cement bentonite grout.

A minimum of 24 hours after installation, newly installed lysimeters will be purged to remove fluids introduced into the silica flour slurry and surrounding formation during installation. Purging will consist of evacuating and pressurizing the lysimeter to remove the accumulated water. Purging will continue until approximately 3 borehole volumes of water have been removed from the silica slurry, or until water samples can no longer be retrieved from the lysimeter.

### 4.5.1.2 Baseline Pore Water Sampling

Lysimeter sampling will be performed to collect baseline pore water samples. A pore water sample will be collected from each lysimeter a minimum of 2 weeks after installation. Prior to sampling, the sampling tube will be opened to the atmosphere and an air pump or compressed gas cylinder will be attached to the pressure-vacuum tube. The lysimeter will be pressurized to remove any water that may have accumulated in the lysimeter. The sampling tube will be closed to the atmosphere, and the pressure-vacuum line will be attached to a vacuum pump. The lysimeter will be placed under a vacuum of approximately 0.65 to 0.85 bars. The pressure-vacuum line will be closed, and the vacuum pump will be removed. The lysimeter will be left under vacuum to allow pore water to accumulate in the lysimeter body. When a sufficient volume of water has accumulated in the lysimeter, the sampling and pressure-vacuum tubes are opened to the atmosphere, and an air pump will be attached to the pressure-vacuum tube to pressurize the lysimeter and retrieve a sample to the surface through the sampling tube. Samples will be collected in either a decontaminated sampling jar and then transferred to containers appropriate for the analyses to be conducted, or will be collected directly into the appropriate containers.

Lysimeters typically yield relatively small volumes of water during sampling, and the number of analytes in the pore water sampling program is limited to critical constituents needed for evaluating technology performance. Samples for perchlorate, TDS, and TOC will be collected preferentially. If sufficient sample volume is available, additional parameters will also be analyzed in the pore water samples (***Table 6***).

***Table 6.*** Pore Water Sampling Protocol

| Parameter | Analytical Method | Purpose | Frequency |
|---|---|---|---|
| **Laboratory Analyses** | | | |
| Perchlorate | E314.1 | Estimate perchlorate mass in pore water | Baseline, Weekly [2] |
| Chlorate | E300.1 | Estimate chlorate mass in pore water and electron donor requirements | |
| TDS | SM2540C | Assess salt loading | |
| TOC | SM5310B | Estimate available natural organic carbon | |
| Hexavalent Chromium | SW7199 | Estimate hexavalent chromium mass in pore water | |
| Total Chromium | SW6010B | Estimate chromium mass in pore water | |
| Soluble Cations/Anions [1] | Note 1 | Assess salt loading | |

**Acronyms and Abbreviations:**

TDS: Total dissolved solids
TOC: Total organic carbon

**Notes:**

1. Soluble cations and anions via analysis of leachate [cations include calcium, magnesium, potassium, and sodium (Method SW6010B); anions include chloride, sulfate, and nitrate (Method 300.0), chlorate (Method E300.1), and bicarbonate, hydroxide, and carbonate alkalinity (Method SM2320B).
2. Lysimeters will be checked on weekly basis for the duration of system operation, plus a period of 4 weeks after operation is terminated.

## 4.5.2 In-Situ Bioremediation

### 4.5.2.1 Installation of Injection, Extraction, and Monitoring Wells

The remaining injection, extraction, and monitoring wells to support the implementation of the treatability study will be installed as part of Pre-Implementation Phase 3. The remaining wells may be installed in one or two separate mobilizations, depending on access restraints and the results of the previous mobilization. The total number of wells may be revised based on the results of groundwater modeling simulations and data collected during the first mobilization. The well installation procedures for the wells will be consistent with the procedures previously described in Section 4.4.2.1.

Following the completion of well construction, but no sooner than 24 hours after well construction is complete, Tetra Tech will develop each of the newly installed wells. The well development procedures for the wells installed during the second mobilization will be consistent with the procedures previously described in Section 4.4.2.2.

Following installation of the wells installed during the second mobilization, a land surveyor will survey the horizontal coordinates of each well relative to North American Datum 83 with an accuracy of 0.1 foot, and the elevation of the ground surface and top of well casing measuring point relative to NAVD 88 with accuracies of 0.1 foot and 0.01 foot, respectively.

### 4.5.2.2 Completion of Additional Aquifer Testing

Based on the results of the groundwater modeling simulations and/or to address potential data gaps, single-borehole dilution tests, slug tests, step-drawdown tests, or constant-rate pumping tests may be performed. The procedures for the aquifer tests will be consistent with the procedures previously described in Section 4.4.2.4 through 4.4.2.8.

#### 4.5.2.3 Baseline Groundwater Sampling

Baseline groundwater sampling activities will follow the guidance of the *Field Sampling Plan, Revision 1* (ENVIRON, 2014a). Prior to groundwater sample collection, groundwater levels will be gauged in wells located within and adjacent to the Study Area for use in potentiometric contouring. Groundwater samples will be collected from the newly installed injection and monitoring wells and may be collected from a subset of existing monitoring wells and newly installed extraction wells to establish baseline conditions prior to the injections (***Table 7***). This data will also serve as baseline data for the soil flushing component of the treatability study.

Groundwater samples will be collected using low-flow purging and sampling techniques. During low-flow purging of the wells, a pump capable of purging between approximately 0.1 to 0.13 gpm will be used to minimize drawdown and induce inflow of fresh groundwater. The pump discharge water will be passed through a flow-through cell field water analyzer for continuous monitoring of field parameters [temperature, pH, turbidity, electrical conductivity (EC), DO, and oxidation-reduction potential (ORP)]. Field parameters will be monitored and recorded on field sampling forms during purging. The wells will be sampled when purging is complete, which is when the field parameter readings and water levels have stabilized. Baseline groundwater samples will be analyzed for a variety of chemical and physical parameters (***Table 7***).

***Table 7.*** Baseline and Performance Monitoring Groundwater Sampling Protocol

| Parameter | Analytical Method | Purpose | Potential Frequency |
|---|---|---|---|
| EC | Field Meter | Assess geochemical conditions | Baseline, Weekly, Biweekly, Monthly |
| pH | Field Meter | | |
| DO | Field Meter | | |
| ORP | Field Meter | | |
| Temperature | Field Meter | | |
| Turbidity | Field Meter | | |
| Perchlorate | E314.1 | Establish baseline perchlorate concentrations / Assess treatment effectiveness | Baseline, Weekly, Biweekly, Monthly |
| Chlorate | E300.1 | Establish baseline chlorate concentrations / Assess treatment effectiveness | Baseline, Monthly |
| Chlorite | E300.1 | Establish baseline chlorite concentrations / Assess treatment effectiveness | Baseline, Monthly |
| Chloride | E300.0 | Establish baseline chloride concentrations / Assess treatment effectiveness | Baseline, Monthly |
| Hexavalent Chromium | SW7199 | Establish baseline hexavalent chromium concentrations / Assess treatment effectiveness | Baseline, Weekly, Biweekly, Monthly |
| Total Chromium | 200.7 or SW6010B | Assess treatment effectiveness | Baseline, Weekly, Biweekly, Monthly |
| VOCs | SW846 8260B | Assess treatment effectiveness | Baseline, Monthly |
| Nitrate | E300.0 | Assessment of competing electron acceptor and carbon substrate consumer | Baseline, Weekly, Biweekly, Monthly |
| Sulfate | E300.0 | Assessment of competing electron acceptor and carbon substrate consumer | Baseline, Weekly, Biweekly, Monthly |
| Sulfite | HACH Method 8216 | Examine secondary geochemical impacts | Baseline, Monthly |

| Parameter | Analytical Method | Purpose | Potential Frequency |
|---|---|---|---|
| Sulfide | HACH Method 8131 | Examine secondary geochemical impacts | Baseline, Monthly |
| Total Nitrogen | E351.2 | Examine the need for micronutrients | Baseline, Monthly |
| Total Phosphorous | E365.3 | Examine the need for micronutrients | Baseline, Monthly |
| Total Organic Carbon | SM5310B | Estimate available organic carbon | Baseline, Weekly, Biweekly, Monthly |
| Alkalinity | SM2320B | Assess geochemical conditions | Baseline, Monthly |
| Calcium | SW6010B | Assess geochemical conditions | Baseline, Monthly |
| Ferrous and Ferric Iron | HACH Method 8146/ Calculation | Assess effect of reducing conditions on iron | Baseline, Monthly |
| Hardness | SM 2340C | Assess geochemical conditions | Baseline, Monthly |
| Magnesium | SW6010B | Assess geochemical conditions | Baseline, Monthly |
| Manganese | SW6010B | Assess potential for biologically driven dissolution of manganese | Baseline, Monthly |
| Methane | EPA Method RSK175 | Examine secondary geochemical impacts | Baseline, Monthly |
| Potassium | SW6010B | Assess geochemical conditions | Baseline, Monthly |
| Sodium | SW6010B | Assess geochemical conditions | Baseline, Monthly |
| TDS | SM2540C | Assess salt loading | Baseline, Monthly |
| TSS | SM2540D | Assess geochemical conditions | Baseline, Monthly |
| Dissolved Metals[1] | SW 846 6010/6020 | Assess secondary impacts of treatment | Baseline, Monthly |
| VFAs | VFA-IC | Surrogate carbon substrate assessment | Baseline, Monthly |
| Phospholipid Fatty Acids | Microbial Insights Method | Examine microbial response to carbon substrate addition | Baseline, Monthly |
| Perchlorate Reductase and Chlorite Dismutase Genes | Microbial Insights Method | Examine microbial response to carbon substrate addition | Baseline, Monthly |

**Acronyms and Abbreviations:**

DO: Dissolved oxygen
EC: Electrical conductivity
ORP: Oxidation-reduction potential
TDS: Total dissolved solids
TSS: Total suspended solids
VFAs: Volatile Fatty Acids
VOCs: Volatile organic compounds

**Notes:**

1. Dissolved metals include aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, silver, thallium, uranium, vanadium, and zinc.

## 4.6 MANAGEMENT OF INVESTIGATION-DERIVED WASTE

IDW is anticipated to be generated during each of the pre-implementation phases, and the procedures to manage IDW will be consistent throughout each of these phases. Waste generated during the well installation and development activities will be managed according to applicable state, federal, and local regulations and as described in Field Guidance Document No. 001, Managing Investigation-Derived Waste (ENVIRON, 2014a). The anticipated waste generated includes soil cuttings, concrete debris, personal protective equipment, equipment decontamination water, and groundwater generated during depth-discrete groundwater sampling and well development. Soil cuttings will be stored in plastic-lined roll-off bins. Solids will be characterized by collecting representative samples, as necessary, to determine disposal options. Depending upon the size of the container and volume of material, one sample may be sufficient for characterization, or several samples may be composited in the field. Generally, a minimum of one composite sample will be collected for up to five roll-off bins, unless observations of the collected soil suggest non-uniformity or other factors which might warrant collection of additional samples for material characterization. Waste sample analysis will be determined in conjunction with the receiving waste facility's analysis requirements. Consistent with the management of purge water generated during groundwater sampling activities, waste water generated during purging or decontamination activities will be temporarily stored in 55-gallon drums or poly-totes and transferred into the GW-11 Pond. Containers used to store waste will be labeled with "pending analysis" labels, the date accumulation began, contents, source, and contact information, and stored in a designated area.

# 5.0 TREATABILITY STUDY CONCEPTUAL DESIGN

This section describes the conceptual design of the treatability study including objectives, conceptual layout(s), soil flushing system design, and preliminary substrate injection and groundwater extraction design. The field treatability study design, as well as the effectiveness monitoring program (described in Section 6.0), may be modified or refined based on the results of pre-implementation activities described in Section 4.0 and information obtained during the third mobilization of the Unit 4 and 5 Buildings Investigation.

## 5.1 TREATABILITY STUDY AREA

The proposed Study Area consists of the Unit 4 cell building basement area plus an area in the southeast corner of the basement and adjacent to the east of the basement where soil flushing will target the very high perchlorate mass present in the vadose zone (Figure 21). This location was selected to evaluate the ability and cost-effectiveness of a hybrid soil flushing and ISB approach to achieve source reduction of COPCs within an area where some of the highest concentrations of perchlorate and hexavalent chromium in soil and groundwater were identified at the Site, as well as due to accessibility considerations. Soil flushing and the hybrid ISB / groundwater extraction approach will target the areas within the proposed Study Area with the highest perchlorate masses in the vadose and saturated zones, respectively.

## 5.2 PRELIMINARY SOIL FLUSHING SYSTEM DESIGN

### 5.2.1 Unit 4 Basement Slab and AC Pavement Preparation

The Unit 4 basement slab and the nearby AC pavement will be prepared for the implementation of soil flushing assuming that the results of the geotechnical and structural evaluation indicate that soil flushing can be performed without impacting the surrounding structures and based on the results of the injection well spacing, infiltration, and perforation spacing testing described in Sections 4.4.1.1 through 4.4.1.2. The Unit 4 basement slab and nearby AC pavement will be prepared by a combination of perforating the slab and AC pavement, slab or AC pavement removal, and installing vadose zone injection wells within the treatability study soil flushing area shown on Figure 21, where some of the highest perchlorate masses are present in the vadose zone. Slab and AC pavement preparation will be performed using standard drilling or construction methods; engineering controls will be used as necessary, per Tetra Tech's site-specific Health and Safety Plan.

### 5.2.2 Conceptual Layout

#### 5.2.2.1 Lysimeters

As described in Subsection 4.5.1.1, up to five lysimeters will be installed within the soil flushing area to monitor pore water chemistry during soil flushing. The final locations of the lysimeters will be determined after the completion of the pre-implementation field and laboratory activities. The conceptual design of the lysimeters is based on the preliminary groundwater modeling, which predicts up to 5 feet of groundwater mounding during soil flushing. Based on this result, the lysimeters are designed to sample pore water approximately 10 feet above the water table, to ensure that the pore water sampled during the treatability study is not influenced by groundwater conditions.

#### 5.2.2.2 Groundwater Monitoring/Injection Wells

As described in Subsections 3.1 and 3.3.2, up to 3 monitoring/injection wells will be installed downgradient of the soil flushing area to monitor groundwater chemistry and groundwater levels during soil flushing (Figure 21). If elevated COPCs are found to be migrating out of the soil flushing area, the option of injecting donor into these downgradient Qal monitoring wells will be considered.

The conceptual design of the Qal monitoring/injection wells is based on the preliminary groundwater modeling described in Section 3.3, which predicts up to 5 feet of groundwater mounding during soil flushing. Based on this result, the Qal monitoring/injection wells are designed with screened intervals extending approximately 10 feet above the water table. This design will allow the wells to sample groundwater/flushing water across the full thickness any saturated zone that exists in the alluvium during the treatability study, while minimizing the length of well screen extending above the water table, to avoid creating a preferential vertical flow pathway at depth.

### 5.2.3 Preliminary Water Application Methodology

The following sections briefly describe the primary components of the proposed soil flushing system.

#### 5.2.3.1 Water Source

SLMW or reclaimed water will be used as the water source for soil flushing. The water will be obtained from one of several SLMW hydrants or connections to the City of Henderson reclaimed water distribution lines located in the general vicinity of the treatability study; selection of the specific connection point will be determined cooperatively with Tronox. Water pressure will be regulated with a pressure control valve.

#### 5.2.3.2 Water Conveyance

To the extent feasible, the injection and percolation water will be conveyed to the Study Area via high-density polyethylene piping, which will be sized based on the results of the tests described in Sections 4.4.1.1 and 4.4.1.2. A main water shutoff valve will be installed at the basement edge, and the piping will be transitioned to PVC. A conveyance piping header will be constructed to direct water to individual distribution piping risers in the basement.

#### 5.2.3.3 Instrumentation and Controls

Instrumentation and controls will be installed at each injection well or distribution piping riser, and will consist of mechanical pressure reducing valves or float valves, totalizing flowmeters, pressure gauges, and a shutoff valves. Level controls will stop injection prior to water levels approaching the tops of the berms. Periodic system flow readings will be manually collected at each well or distribution riser piping.

## 5.3 IN-SITU BIOREMEDIATION CONCEPTUAL LAYOUT

This section describes the conceptual well network that will be installed to implement the hybrid ISB / groundwater extraction portion of the treatability study in the UMCf. All wells will be drilled in accordance with the Nevada Division of Water Resources requirements. Drilling, well installation, and well development procedures are provided in the *Field Sampling Plan, Revision 1* (ENVIRON, 2014a).

### 5.3.1 Injection/Extraction Well Layout

Although the final number, location, and orientation of the injection/extraction wells will be determined after completion of the pre-implementation field and laboratory activities, the conceptual design of the injection/extraction wells within the Study Area is based upon preliminary groundwater modeling simulations described in Section 3.3. Approximately nine well clusters used for injection and extraction will be installed in the UMCf in a grid-pattern across the Study Area on approximately 40-foot centers (Figure 21). The well clusters will be screened in up to two zones within the UMCf. Data collected during the pre-implementation activities (Section 4.0) will be used to finalize the injection/extraction well network. Construction details of the wells are generally described in Section 4.4.2.1.

### 5.3.2 Monitoring Well Layout

A monitoring well network, consisting of wells located within and in the nearby vicinity of the Study Area, will be utilized to evaluate the effectiveness of the treatability study. Monitoring wells installed as part of the third mobilization of the Unit 4 and 5 Buildings Investigation and a subset of existing monitoring wells will be incorporated into the effectiveness monitoring program. Monitoring wells will be installed in the UMCf within or immediately downgradient the Study Area in approximately five locations (Figure 21). Each location will include wells screened in the intermediate and deep UMCf depth intervals. It is anticipated that these wells will be installed as nested wells, although this will be confirmed after final groundwater monitoring. The exact number and location of monitoring wells will be finalized after completion of the third mobilization of the Unit 4 and 5 Buildings Investigation and pre-implementation activities including final groundwater modeling. Preliminary well construction details for the monitoring wells within the Study Area are described in Section 4.4.2.1.

## 5.4 INJECTION AND EXTRACTION METHODOLOGY

This section presents the general methodology for performing injections and extracting groundwater at Unit 4. A more detailed injection and extraction system program will be developed based on the results of the bench-scale tests and other pre-implementation activities described in Section 4.0.

### 5.4.1 Carbon Substrate Injections

It is anticipated that all of the injections into the UMCf will consist of carbon donor solution. This differs from the soil flushing program where it is anticipated that initial soil flushing pore volumes will consist of SLMW or reclaimed water in order to dilute the high concentrations in the vadose zone and to avoid accumulation of biomass in the vadose zone which could reduce the rate of percolation of subsequent pore volumes of donor solution. In the vadose zone, the dissolution of perchlorate and chlorate salts by the initial soil flushing pore volumes might lead to aqueous concentrations of perchlorate and chlorate close to their saturation concentrations, which are one or two orders of magnitude greater than the elevated concentrations detected in the UMCf target zone, If dilution of the elevated concentrations in the UMCf is necessary, groundwater extraction will be used to draw in lower concentration groundwater from surrounding zones, with possible injection of SLMW as a fallback option.

Bench-scale tests, currently being conducted at UNLV, will be instrumental in determining the type and quantity of carbon substrate, nutrients, vitamins, and bioaugmentation cultures which may be introduced into the subsurface during the treatability study. Factors to be considered when determining the quantity of amendments for the Study Area include the results and findings of the pre-implementation activities, known chemistry and geochemistry of the groundwater, and stoichiometric requirements for the selected carbon substrate(s) based on the mass of perchlorate and other electron acceptors that will migrate through the transects in the treatability study timeframe. The methodology used to introduce amendments into the subsurface, recirculation or injection and extraction (pull or push-pull), will affect the rate and volume of quantities injected into the Study Area.

Injections into the UMCf and Qal, will be managed as two separate injection well network systems. The selected amendments will be injected via gravity flow or pressure injected using an injection system consisting of storage tanks, a mixing tank, a manifold piping system and hoses supplied with valves and regulators for control and monitoring rates of injection. Prior to each injection, the injection solution will be prepared in an above-ground mixing tank. A specified volume of SLMW or reclaimed water will be pumped into the on-site mixing tank along with a corresponding volume of carbon substrate, nutrients, vitamins, oxygen scavenger and/or bioaugmentation cultures to make the desired injection rate and concentration. The use of an oxygen scavenger, such as ascorbic acid or sodium metabisulfite decreases microbial acclimation time as well as reduces the potential for biofouling. The injection solution will be prepared by thoroughly mixing the carbon substrate and water using a mixer in the mixing tank. The injection solution will then be gravity fed or pumped with a transfer pump to the injection wells through a manifold with hoses equipped with quick disconnect fittings. The injection pressure will be monitored to ensure the maximum injection pressure specified in the Underground Injection Control (UIC) permit is not exceeded.

Preliminary groundwater modeling efforts, as described in Section 3.3, indicate that a repeating injection program consisting of alternating the use of wells for injection and extraction on a monthly basis will create sufficient distribution of the amendments throughout the Study Area. The final injection program will be developed based on updated groundwater modeling scenarios using information obtained from the bench-scale tests and other pre-implementation activities.

### 5.4.2 Distribution Water

Distribution water is a key component of the injection process to improve subsurface distribution of the amendments within the treatment area. This feature of the bioremediation design is important because it improves the distribution of the carbon donor laterally within the injection area and creates a more complete zone of treatment. As a result, a designated quantity of water (determined based on results from the pre-implementation field activities described in Section 4.0) will be injected into each injection well following injection of the amendments.

Based on a review of the available water sources, three choices for distribution water were identified: extracted groundwater from wells within the Study Area, SLMW obtained from an on-site hydrant, or reclaimed water obtained from a connection point to a City of Henderson water distribution line. Re-injection of extracted groundwater as part of a recirculation methodology would require concurrence with the Trust and NDEP. The use of extracted groundwater, whether treated or untreated, as part of a recirculation methodology may require a supplemental water source if the rate of extraction is less than the rate of re-injection.

### 5.4.3 Groundwater Extraction System

Tetra Tech will install a groundwater extraction system to assist in the distribution of the selected amendments and reduce the net volume of injected water in order to reduce groundwater mounding and the potential for downward migration of contaminants. The extraction system will include extraction well pumps, an electrical panel, switches, control contactors, and motor starters. Totalizing flow meters, flow control valves, and sample ports will be installed for each extraction well to monitor the extraction flow rate, total amount of water extracted, adjust extraction flow rates, and allow for sample collection. To the extent possible, equipment used at the AP Area Soil Flushing will be reused for the Unit 4 Source Area In-Situ Bioremediation Treatability Study. The determination of an injection and extraction methodology, recirculation or injection and extraction (pull or push-pull), will provide a framework for how extracted groundwater will be managed.

### 5.4.4 Well Maintenance

Based on previous treatability studies, it is anticipated that the wells used for injections and extraction will require more maintenance than if they were used for only injection or extraction, because bioaccumulation may result from the mixing of donor solution and COPCs in and around the wells. However, using wells for only injection or extraction would require more wells to achieve the same amount of mixing of donor solution and groundwater. It is anticipated that the cost savings of fewer multi-use wells will more than offset the cost of increased well maintenance. Tetra Tech will evaluate the amount of bioaccumulation in the wells by periodic monitoring of injection rates, injection pressures, extraction rates, and performing slug tests. This will also monitor for potential chemical precipitation. Wells that exhibit signs of bioaccumulation or chemical precipitation that inordinately restricts injection, extraction, or monitoring activities will be rehabilitated by mechanical scrubbing, surging, jetting, addition of anti-scalant or biocides, and/or the use of increased injection pressures.

# 6.0 EFFECTIVENESS MONITORING PLAN

This section presents the conceptual effectiveness monitoring program for the treatability study for soil and groundwater, including field and analytical monitoring components.

## 6.1 SOIL FLUSHING

This section describes the conceptual monitoring program associated with implementation, operation, and shut down of the soil flushing system to determine treatment effectiveness in the vadose zone of the Study Area. Performance monitoring will include the following:

- System parameter monitoring;
- Pore water sampling and analysis;
- Groundwater level gauging;
- Groundwater sampling and analysis; and
- Post-implementation soil sampling and analysis.

### 6.1.1 System Parameter Monitoring

System parameter monitoring will consist of recording flow meter readings and measuring fluid levels in tanks on a daily basis for the 3 to 5 days during system start-up, followed by measurements every other day for one additional week. Readings will be recorded on a weekly basis during regular system maintenance visits. This frequency may be increased or decreased based on the observed infiltration rates and the estimated time needed to infiltrate each pore volume of water through the Study Area.

Infiltration rates will be determined using totalizing flow meters installed in the process lines leading to the Study Area. Oxygen scavenger and substrate dosages will be estimated from the water flow and fluid level measurements.

### 6.1.2 Pore Water Sampling

The lysimeters installed in the Study Area will be will be evacuated and checked for water on a weekly basis. If the moisture content of the soil is high enough to allow sampling of the lysimeters, pore water samples will be collected on a weekly basis for the duration of system operation, plus a period of 4 weeks after operation is terminated. The sampling frequency may be increased or decreased based on the observed infiltration rates and the estimated time needed to infiltrate each pore volume of water through the Study Area.

As discussed in Section 4.5.1.2, lysimeters typically yield relatively small volumes of water during sampling, and the number of analytes in the pore water sampling program is reflective is limited to critical constituents needed for evaluating technology performance. Samples for perchlorate, TDS, and TOC will be collected preferentially. If sufficient sample volume is available, additional constituents will also be analyzed in the pore water samples (***Table 6***).

### 6.1.3 Groundwater Level Gauging

Potential hydraulic effects due to groundwater mounding during the treatability study will be evaluated by gauging groundwater levels on a daily basis during system startup and on a weekly basis during prolonged operation of the soil flushing system. The gauging frequency may be increased or decreased based on the observed infiltration rates and the estimated time needed to infiltrate each pore volume of water through the Study Area. The wells to be gauged will consist of a subset of the newly installed wells and existing monitoring wells within or adjacent to the Study Area to provide adequate coverage to contour the groundwater surface.

### 6.1.4 Groundwater Sampling

The groundwater sampling program to assess the impacts of the soil flushing system on groundwater concentrations within and adjacent to the Study Area will be integrated with the hybrid ISB / groundwater extraction performance monitoring program discussed in Section 6.2.2.

### 6.1.5 Post-Implementation Soil Sampling

Soil samples will be collected before and after soil flushing system operation to verify treatment effectiveness. Upon completion of the treatability study, soil borings will be drilled adjacent to the location of each of the baseline soil sampling locations to evaluate changes against baseline parameters in the subsurface (***Table 5***). The post-implementation borings will be sampled at the same depths as the baseline borings.

## 6.2 IN-SITU BIOREMEDIATION

This section describes the conceptual effectiveness program associated with implementation, operation, and shut down of the hybrid ISB / groundwater extraction program to determine treatment effectiveness in the saturated zone of the Study Area. The effectiveness monitoring program will include the following:

- Extraction system monitoring; and
- Performance groundwater monitoring.

### 6.2.1 Extraction System Monitoring

System parameter monitoring will consist of daily and weekly tasks. Extraction well flow rates and injection well flow rates will generally be recorded on a daily basis along with general system operation and maintenance activities. Water samples will be collected from select extraction wells and groundwater levels will be gauged generally on a weekly basis. At a minimum, the water samples will be analyzed for perchlorate, chlorate, hexavalent chromium, and chloroform. The flow rates and perchlorate concentrations from the extraction wells will be used as an estimate of how much perchlorate mass is being extracted from the Study Area.

### 6.2.2 Performance Groundwater Monitoring

Performance groundwater monitoring for hybrid ISB / groundwater extraction approach will be used to evaluate the effectiveness of the approach and to evaluate the mass removed during the treatability study. As discussed in Section 4.5.2.3., groundwater samples will be collected from the newly installed injection and monitoring wells, and may be collected from a subset of existing monitoring wells and newly installed extraction wells, to establish baseline conditions prior to the injections. After injections have occurred, groundwater samples will be periodically collected from a series of performance monitoring wells located within the Study Area. Similar to the baseline groundwater sampling event, performance monitoring wells will include newly installed monitoring wells and may include newly installed injection and extraction wells or existing monitoring wells. Deep monitoring wells in the vicinity of the Study Area (M-250, M-252, M-254, and M-255), screened from approximately 140 to 150 feet bgs, will be periodically monitored to evaluate the potential effects in the deeper UMCf from the implementation of the hybrid ISB / groundwater extraction approach. The actual frequency of sampling, selected wells, and specific parameters to be sampled during each individual performance monitoring event will be determined during the treatability study and based on the results from prior events. A variety of field, laboratory, and microbial parameters that may be evaluated during the treatability study are listed in

***Table 7***, which presents the parameters, associated methods, purpose, and potential sampling frequency. Specialized microbial analyses, namely, PFLA analyses and the presence of the perchlorate reductase and chlorite dismutase genes will be determined via the employment of Bio-Traps® in select wells during the treatability study.

Groundwater sampling activities will follow the guidance of the *Field Sampling Plan, Revision 1* (ENVIRON, 2014a). Prior to groundwater sample collection, groundwater levels will be gauged in all wells for use in potentiometric contouring. Groundwater samples will be collected using low-flow purging and sampling techniques. During low-flow purging of the wells, a pump capable of purging between approximately 0.1 to 0.13 gpm will be used to minimize drawdown and induce inflow of fresh groundwater. The pump discharge water will be passed through a flow-through cell field water analyzer for continuous monitoring of field parameters (temperature, pH, turbidity, EC, DO, and ORP). Field parameters will be monitored and recorded on field sampling forms during purging. The wells will be sampled when purging is complete, which is when the field parameter readings and water levels have stabilized.

In addition to the analytical testing program, slug tests will be performed periodically during the implementation of the treatability study and compared to the baseline results to evaluate any changes in hydraulic conductivity as a result of substrate injections and geochemical processes.

# 7.0 HEALTH AND SAFETY AND PERMITTING REQUIREMENTS

## 7.1 HEALTH AND SAFETY

Field work will be conducted in accordance with an Activity Hazard Analysis and other elements of the site-wide Health and Safety Plan, which will address potential chemical and physical hazards associated with the Unit 4 Source Area In-Situ Bioremediation Treatability Study Work Plan and associated tasks. It is anticipated that modified Level D personal protective equipment will be required for all field activities.

## 7.2 PERMITTING REQUIREMENTS

The Unit 4 pre-implementation and treatability study activities will require a Nevada Administrative Code (NAC) 534.441 Monitor Well Drilling Waiver and an NAC 534.320 Notice of Intent Card prior to installation of injection, extraction, and monitoring wells. The Monitoring Well Drilling Waiver also requires a completed, signed, and notarized Affidavit of Intent to Abandon a Well as an attachment. As required, the injection, extraction, and monitoring wells will be drilled by a licensed well driller pursuant to Nevada Revised Statutes 534.160 and will be constructed pursuant to NAC Chapter 534 – Underground Water and Wells. All injection, extraction, and monitoring wells associated with the Unit 4 Source Area In-Situ Bioremediation Treatability Study will be abandoned in accordance with the provisions contained in NAC 534.4365 and all other applicable rules and regulations for plugging wells in the State of Nevada upon completion of the treatability study.

The Unit 4 Source Area In-Situ Bioremediation Treatability Study will require a UIC permit for the injection of the carbon substrate and amendments into the saturated subsurface. Specifically, an application for a Class V General Permit for Long-Term Remediation UIC permit will be required. The UIC long-term general permit falls under NAC 445A. The permit application requires completion of UIC Form U200 – Permit Application and UIC Form U210 – Notice of Intent.

Pursuant to Nevada Revised Statutes 533.335 and 533.437, an application for a Permit to Appropriate the Public Waters of the State of Nevada for Environmental Purposes (Water Appropriation Permit) will be required to support the extraction operations from wells to be used as distribution water during injections. An application for a new Permit to Appropriate Water for Environmental Purposes will be submitted to the Nevada State Engineer, Nevada Department of Conservation and Natural Resources.

Per the Clark County Department of Air Quality, a dust control permit is required for activities that result in soil disturbance greater than 0.25 acres. If deemed necessary, Tetra Tech, on behalf of NERT, will prepare and submit the required dust control permitting application. No air permitting other than dust control is anticipated because there will be no air emissions associated with the wells or equipment needed for their installation and operation that would trigger minor source permitting.

Tetra Tech will obtain all other required permits and perform necessary notifications prior to implementing the treatability study including obtaining Tronox groundbreaking permits, permits for electrical work, submittal of a contingency plan, and applicable permits and notifications for modifications to the GWETS.

# 8.0 REPORTING AND DATA VALIDATION

## 8.1 REPORTING

Monthly status updates will be provided to the Trust and NDEP summarizing the progress and results of the pre-implementation field activities and treatability study. Following completion of the treatability study, a Final Unit 4 Source Area In-Situ Bioremediation Treatability Study Report will be prepared for NDEP review and comment. The report will include the following:

- A bench-scale testing report including the following:
  - Summary of baseline soil and groundwater samples;
  - Summary of microcosm results;
  - Summary of column test results;
  - Evaluation of the effects TDS, perchlorate, chromium, and chloroform have on perchlorate degradation kinetics;
  - Evaluation of the benefits or need to add nutrients, vitamins, or bioaugmentation cultures to enhance perchlorate degradation kinetics;
  - Estimation of perchlorate degradation kinetics that are attainable in the field; and
  - Evaluation of the technology's feasibility and effectiveness for scale-up to support the design of the treatability study.
- Summary of pre-implementation field activities for the soil flushing conceptual field program, including presentation of infiltration tests, perforation spacing tests, and lysimeter sampling;
- Summary of pre-implementation field activities for the ISB conceptual field program, including presentation of soil boring logs, well construction diagrams, cross sections, single borehole dilution tests, slug tests, step-drawdown tests, NMR, and pumping tests;
- Results of groundwater modeling simulations performed based on the results of the pre-implementation activities and treatability study activities;
- Analytical results summary of soil, groundwater, and pore water samples collected during the pre-implementation and treatability study field activities;
- Summary of field measurements, including groundwater elevation and groundwater quality parameters;
- Final treatability study design, including soil flushing system construction, injection, extraction, and monitoring well layout, targeted treatment depths and intervals in the Qal and UMCf, injection protocol for carbon donor and distribution water source, extracted groundwater treatment, soil flushing treatment volumes and water application rates, and finalized effectiveness monitoring program; and
- Comparative analysis of baseline groundwater concentrations to performance monitoring groundwater concentrations along with an estimate of the mass removed.

Tetra Tech will also prepare required documents and reports for the permits obtained.

## 8.2 DATA VALIDATION

Field sampling will be conducted in accordance with the existing *Site Management Plan, Revision 3* (Ramboll Environ, 2017a) and *Field Sampling Plan, Revision 1* (ENVIRON, 2014a). Sampling and analytical methods are selected to meet the project data quality objectives and quality control criteria. Analytical data collected during the completion of the Unit 4 Source Area In-Situ Bioremediation Treatability Study will be verified and validated in accordance with the US EPA National Functional Guidelines, NDEP Basic Management Incorporated (BMI)

Complex and Common Areas data validation guidance documents (collectively referred to herein as the validation protocols). Soil and groundwater samples will be sent to a qualified laboratory for analysis. Soil samples for geophysical properties, including porosity, hydraulic conductivity, and grain size, will be sent to a qualified geotechnical laboratory for analysis. Laboratories will provide data in portable document format (PDF) and in electronic data deliverables (EDD) that contain sufficient and appropriate data to allow verification and validation at the required levels. Validation will be based on quality control requirements found in the US EPA functional guidelines, analytical methods, the site-wide quality assurance project plan, NDEP documents, and laboratory standard operating procedures. Ninety percent of the soil and groundwater samples will undergo Stage 2A validation, and a Level III data package will be requested from the laboratory. For 10 percent of the soil and groundwater samples, a Level IV data package will be requested from the laboratory and Stage 4 data validation will be performed. The waste characterization samples, consisting of soil cuttings generated during the monitoring well installation activities, and soil samples for geophysical properties require a Stage 1 validation. At the completion of data validation, results will be uploaded to the NERT database, and a Data Validation Summary Report will be prepared and presented with the Unit 4 Source Area In-Situ Bioremediation Treatability Study Report.

# 9.0 SCHEDULE

***Table 8*** provides the general schedule for the primary deliverables and activities associated with implementing this Work Plan. This schedule is contingent upon Trust and NDEP approval of this Work Plan, Trust approval of funding and notice to proceed, and access to Tronox and Department of Homeland Security Restricted Area.

The schedule is designed around providing the Unit 4 Source Area In-Situ Bioremediation Treatability Study Report prior to the submittal of the Feasibility Study for Operable Unit 1. It is anticipated that the 12 months of operation of the treatability study will be sufficient to indicate trends regarding the effectiveness of the technologies studied.

The COPC destruction trends from the treatability study will be evaluated with respect to predicting the degree of future COPC destruction with greater time frames.

***Table 8.*** Preliminary Project Schedule

| Task/Milestone | Estimated Start Date | Estimated Completion Date |
|---|---|---|
| Laboratory Bench-Scale Testing | October 2017[1] | April 2018 |
| Pre-Implementation Field Activities | December 2017[1,] | May 2018 |
| Treatability Study Implementation | June 2018 | June 2019 |
| Treatability Study Final Report | July 2019 | November 2019 |

**Notes:**

1. UNLV started analyzing soil and groundwater samples in October 2017 and began microcosm testing on November 11, 2017.

# 10.0 REFERENCES

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# Figures

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**SITE LOCATION MAP**

| | |
|---|---|
| Project No: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | PK |
| Figure No. | 1 |


**Legend**

- NERT Site Boundary
- Unit 4 & 5 Building Investigation Area
- In-situ Bioremediation Area
- Soil Flushing Area
- Unit 4 Treatability Study Area
- Department of Homeland Security Restricted Area
- Existing Unit 4 Building

Notes:

1. All locations are approximate.
2. Imagery Source: Aerotech Mapping, August 2016.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**PROPOSED UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY LOCATION**

| | |
|---|---|
| Project No: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | PK |
| Figure No. | 2 |

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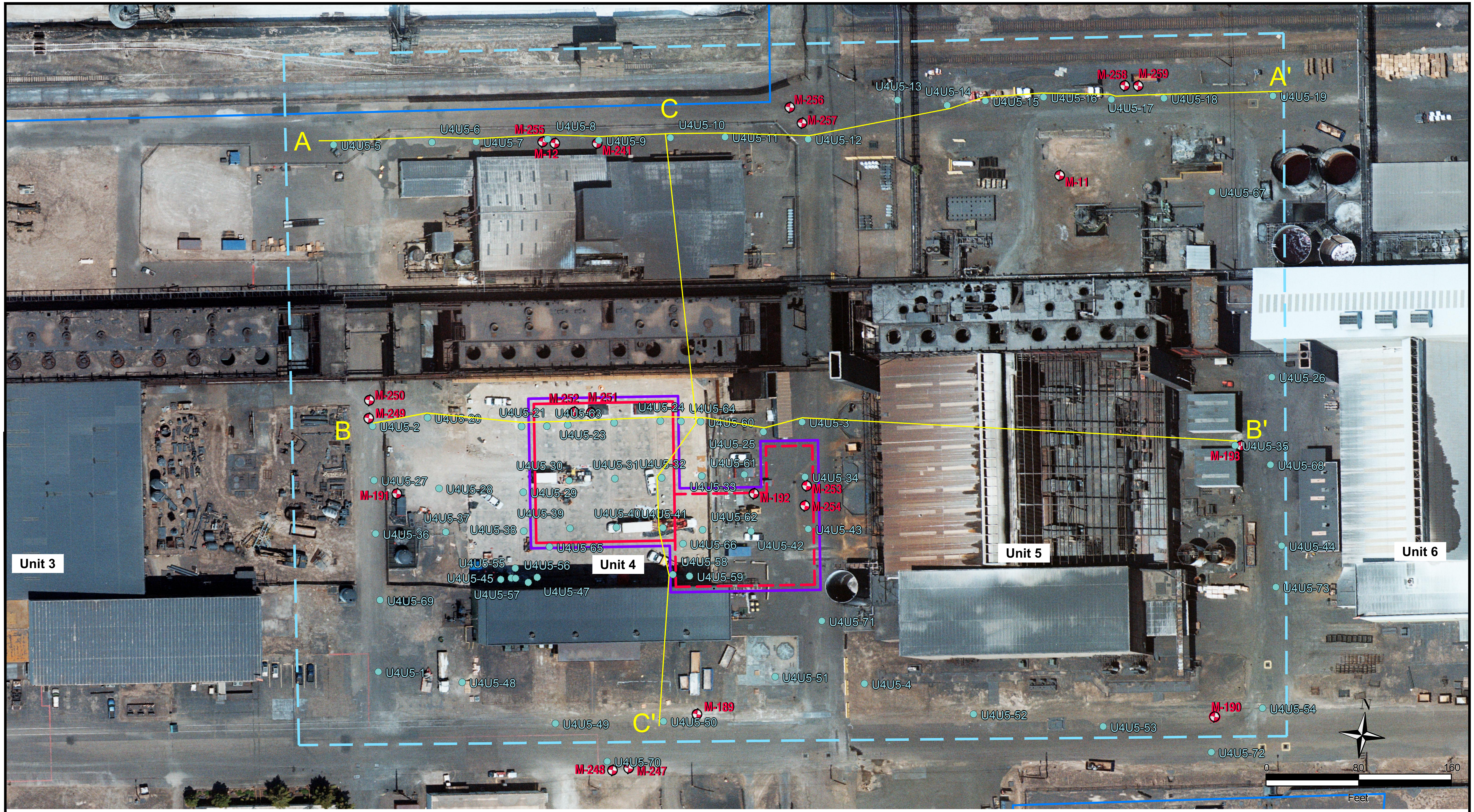


**Legend**

| | |
|---|---|
| Completed Borings | In-situ Bioremediation Area |
| Existing Well | Soil Flushing Area |
| NERT Site Boundary | Unit 4 Treatability Study Area |
| Unit 4 & 5 Building Investigation Area | |
| A — A' CROSS Section Location | |

Notes:

1. All locations are approximate.
2. Imagery Source: Aerotech Mapping, August 2016.

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UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**UNIT 4 AND 5 BUILDINGS INVESTIGATION LAYOUT**

| | |
|---|---|
| Project No: | 87600016 |
| Date: | NOVEMBER 21, 2017 |
| Designed By: | PK |
| Figure No. | 3 |

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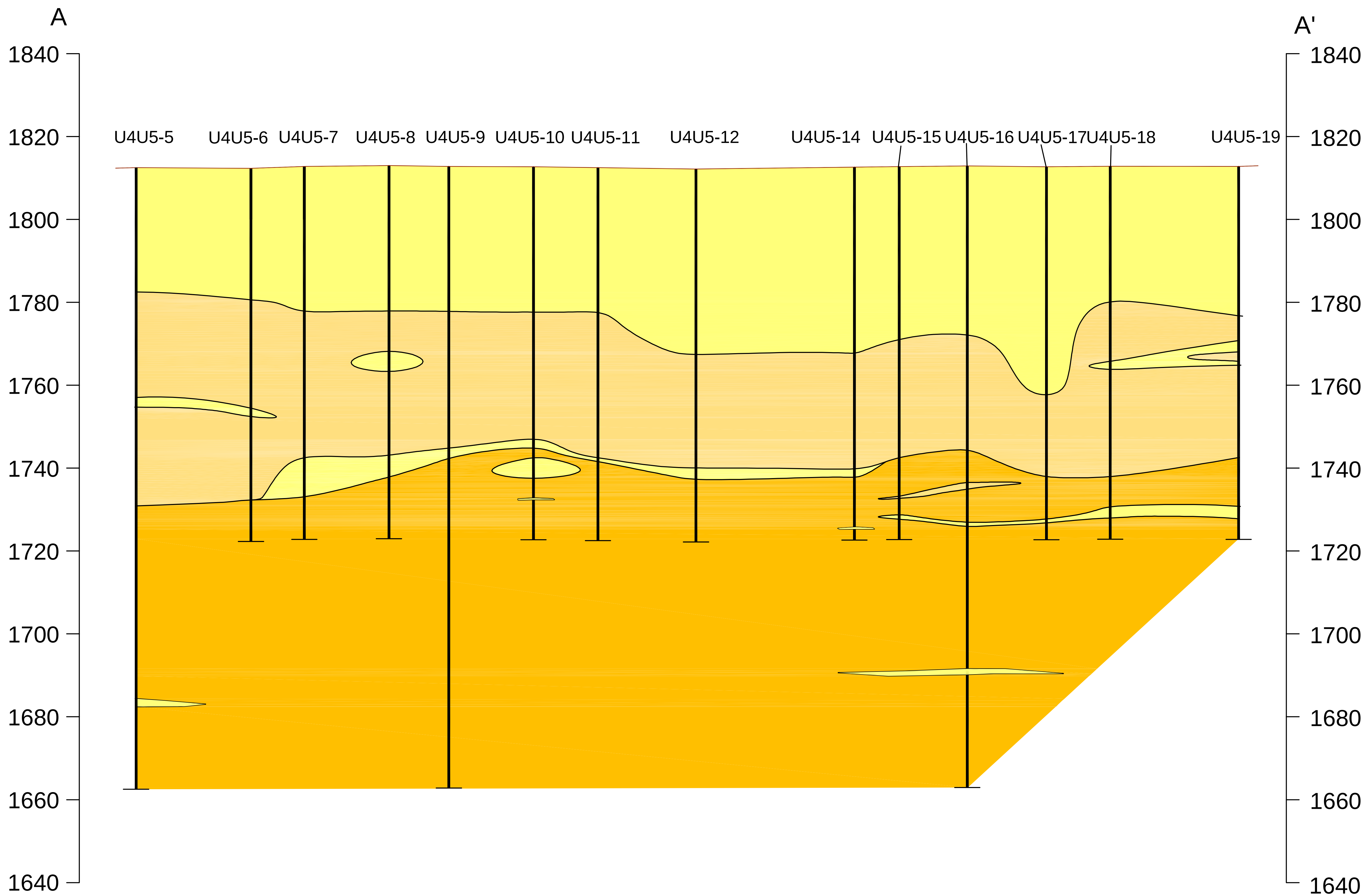


LEGEND

- Gravel, Sands, & Silty Sands
- Mostly Silt, Some Clay
- Mostly Clay, Some Silt

Note:
Cross-section generated from lithologic data obtained during Units 4 and 5 Building Investigation First and Second Mobilizations

0 75 150
HORIZONTAL SCALE IN FEET
VERTICAL EXAGGERATION: 3X

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UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**CROSS SECTION A-A'**

| | |
|---|---|
| Project No: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | JX |
| Figure No. | 4 |

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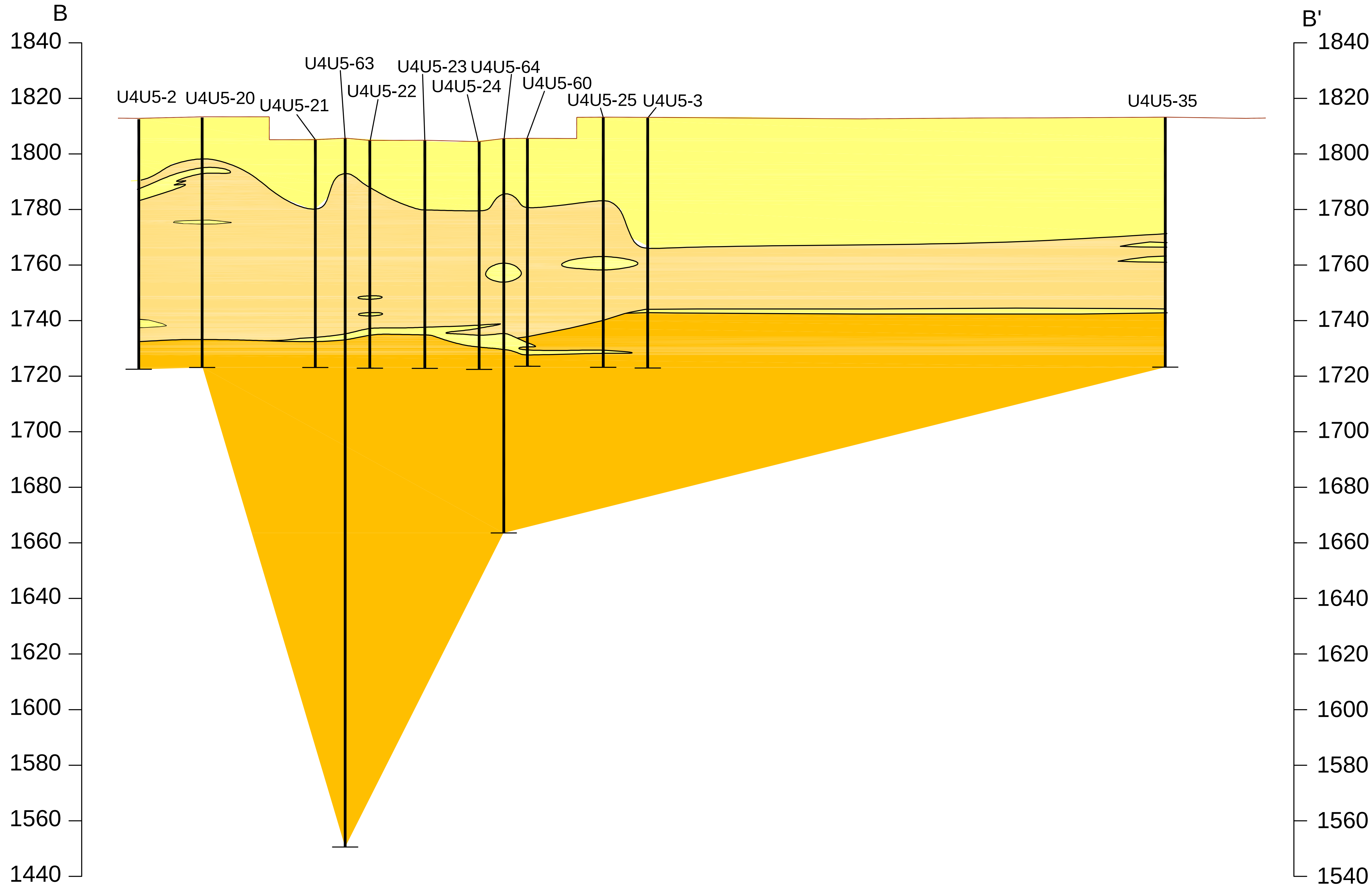


LEGEND

- Gravel, Sands, & Silty Sands
- Mostly Silt, Some Clay
- Mostly Clay, Some Silt

Note:
Cross–section generated from lithologic data obtained during Units 4 and 5 Building Investigation First and Second Mobilizations

0 75 150
HORIZONTAL SCALE IN FEET
VERTICAL EXAGGERATION: 2X

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UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

CROSS SECTION B-B'

| | |
|---|---|
| Project No: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | JX |
| Figure No. | 5 |

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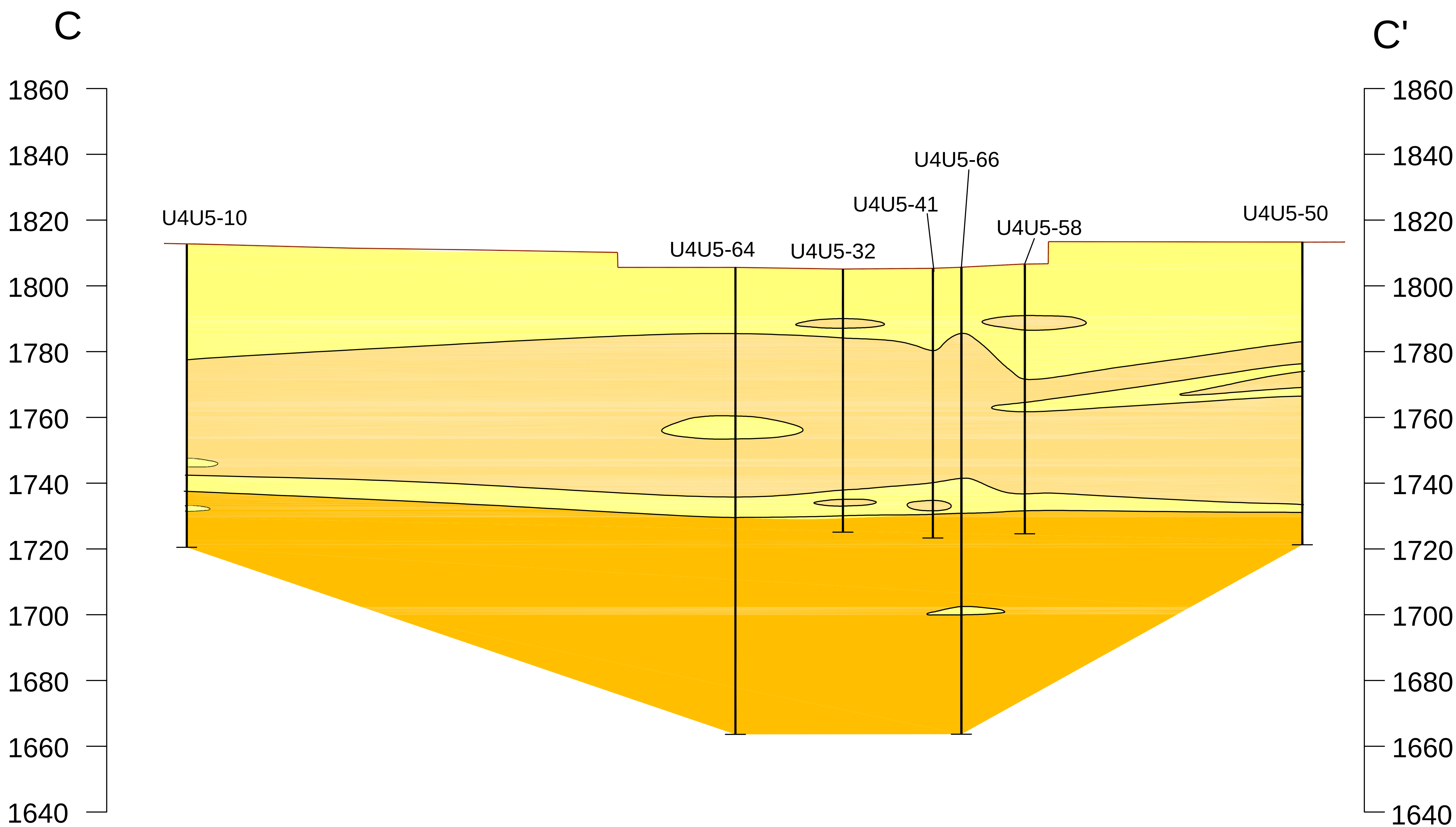


LEGEND

- Gravel, Sands, & Silty Sands
- Mostly Silt, Some Clay
- Mostly Clay, Some Silt

Note:
Cross–section generated from lithologic data obtained during Units 4 and 5 Building Investigation First and Second Mobilizations

0 50 100

HORIZONTAL SCALE IN FEET
VERTICAL EXAGGERATION: 3X

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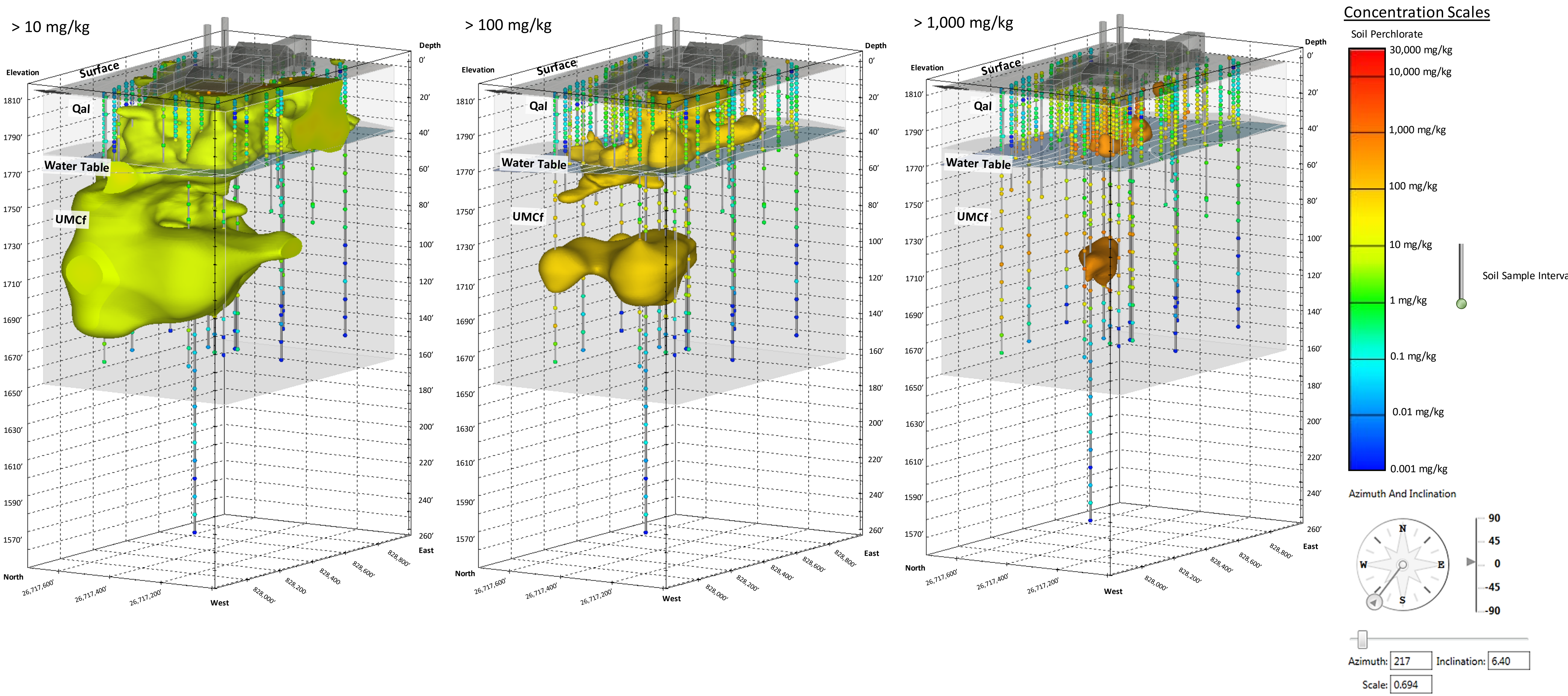
UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**CROSS SECTION C-C'**

| | |
|---|---|
| Project No: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | JX |
| Figure No. | 6 |




Notes:
1. Data interpolation truncated below 163 ft bgs due to insufficient data.
2. Water table surface based on June 2016 groundwater elevation data.
3. Colored spheres show soil perchlorate concentration.
4. Vertical Exaggeration: 6:1 Vertical:Horizontal(below ground).
5. mg/kg: milligrams per kilogram (soil).
6. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

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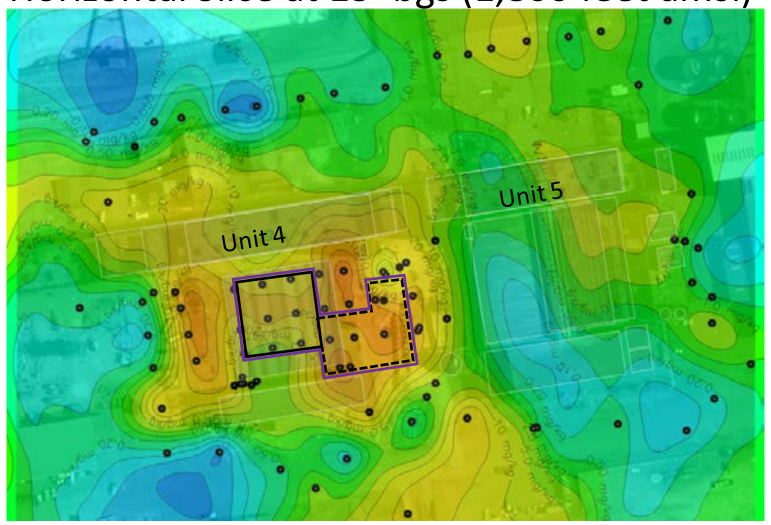
UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

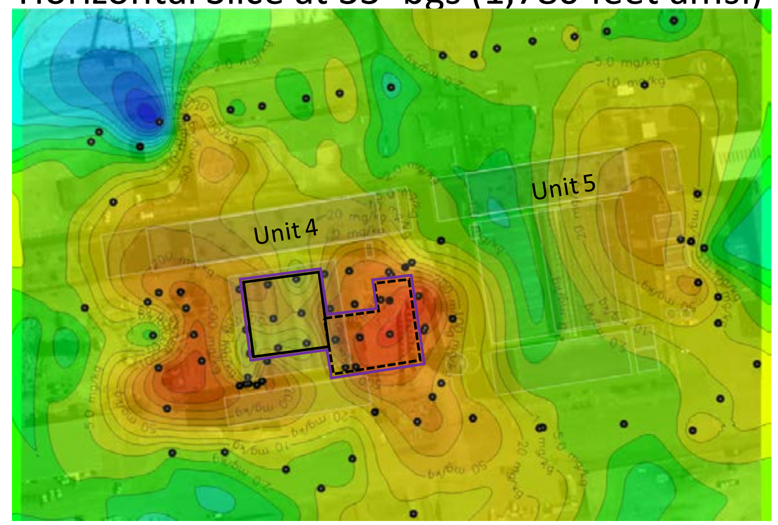
PERCHLORATE DISTRIBUTION IN SOIL

| | |
|---|---|
| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | MRB |
| Figure No. | 7 |

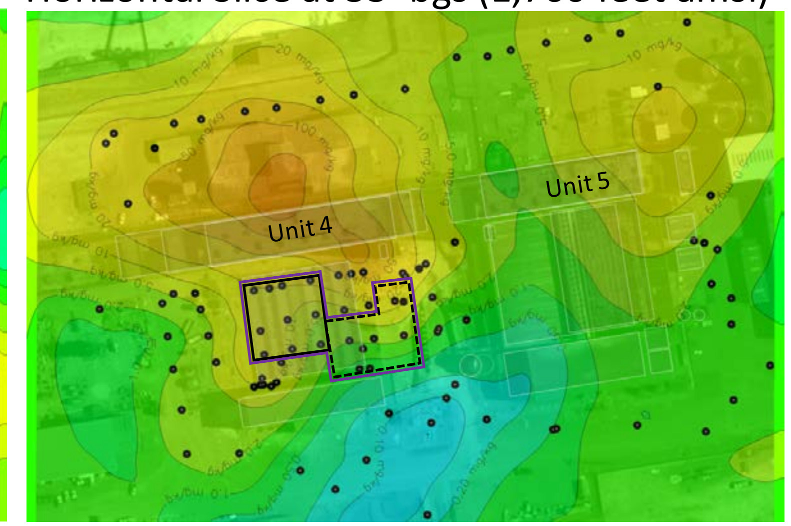
Horizontal Slice at 13’ bgs (1,800 feet amsl)



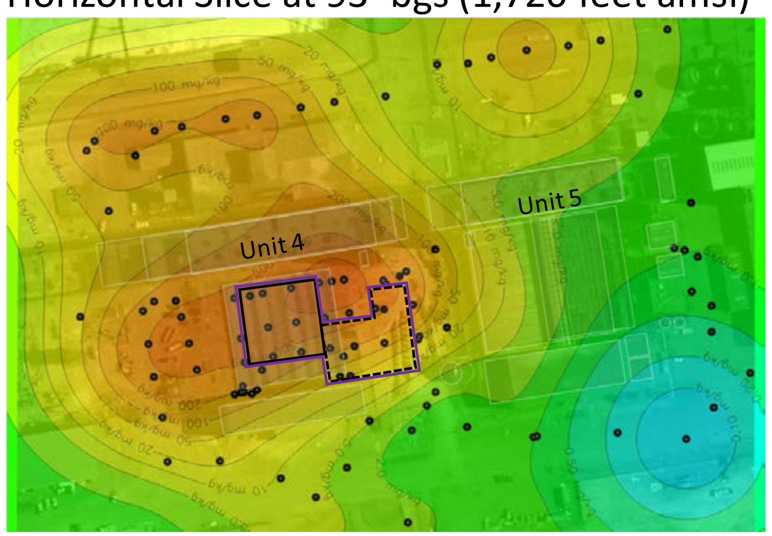

Horizontal Slice at 33’ bgs (1,780 feet amsl)



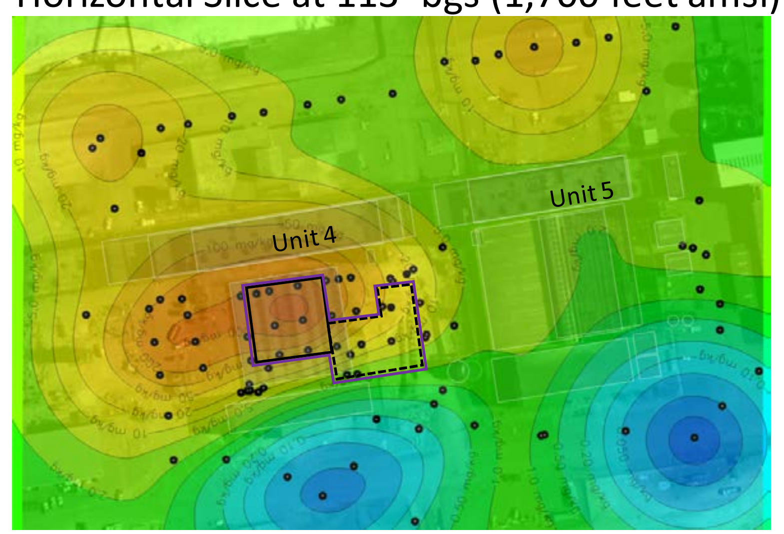

Horizontal Slice at 53’ bgs (1,760 feet amsl)



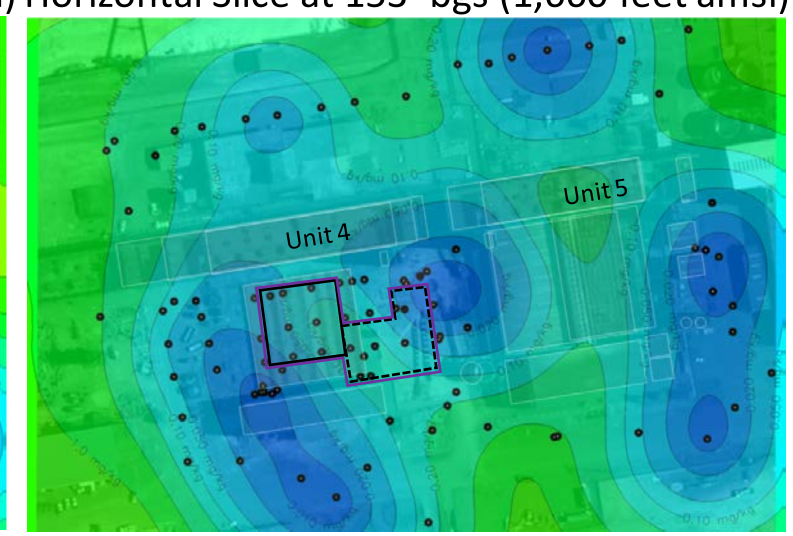

Horizontal Slice at 93’ bgs (1,720 feet amsl)



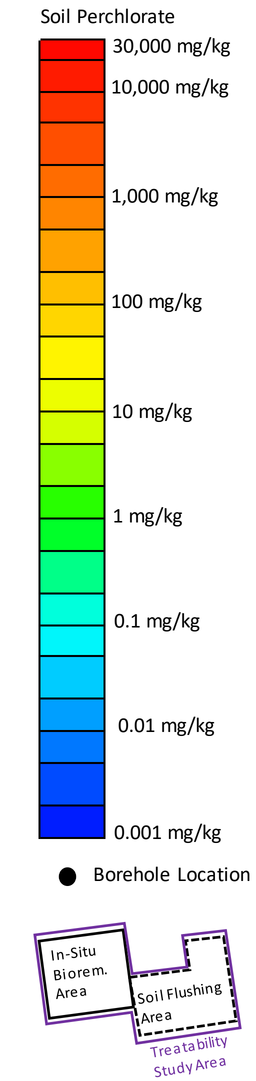

Horizontal Slice at 113’ bgs (1,700 feet amsl)




Horizontal Slice at 153’ bgs (1,660 feet amsl)




Concentration Scales





T:\NERT\M02\Pilot Test Treatment Area Graphic\Fig 8 - Perchlorate 2D Soil.pptx

Notes:
1. Ground surface elevation is assumed to be 1,813 ft amsl for the purposes of illustrated depth.
2. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

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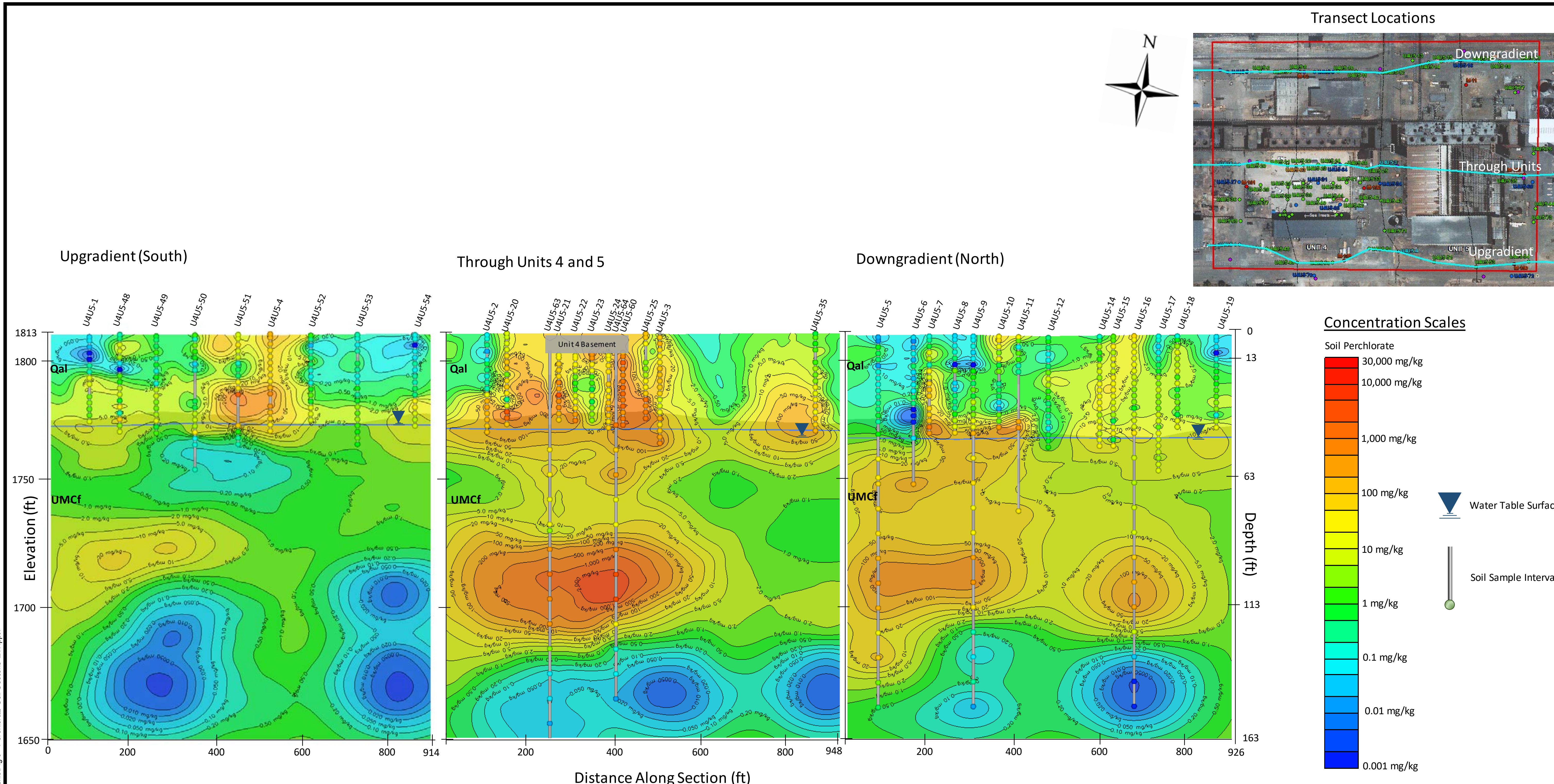
UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

2D VISUALIZATION PLAN VIEW OF PERCHLORATE DISTRIBUTION IN SOIL, UNITS 4 AND 5

| | |
|---|---|
| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | MRB |
| Figure No. | 8 |




T:\NERT\M02\Pilot Test Treatment Area Graphic\Fig 9 - Perchlorate Soil Sections EW.pptx

Notes:
1. Vertical exaggeration: 6:1.
2. Sections are shown looking North.
3. Colored spheres show soil perchlorate concentration.
4. Water table surface based on June 2016 groundwater elevation data.
5. Data interpolation truncated below 163 ft bgs due to insufficient data.
6. Ground surface elevation is assumed to be 1,813 ft amsl for the purposes of illustrated depth.
7. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

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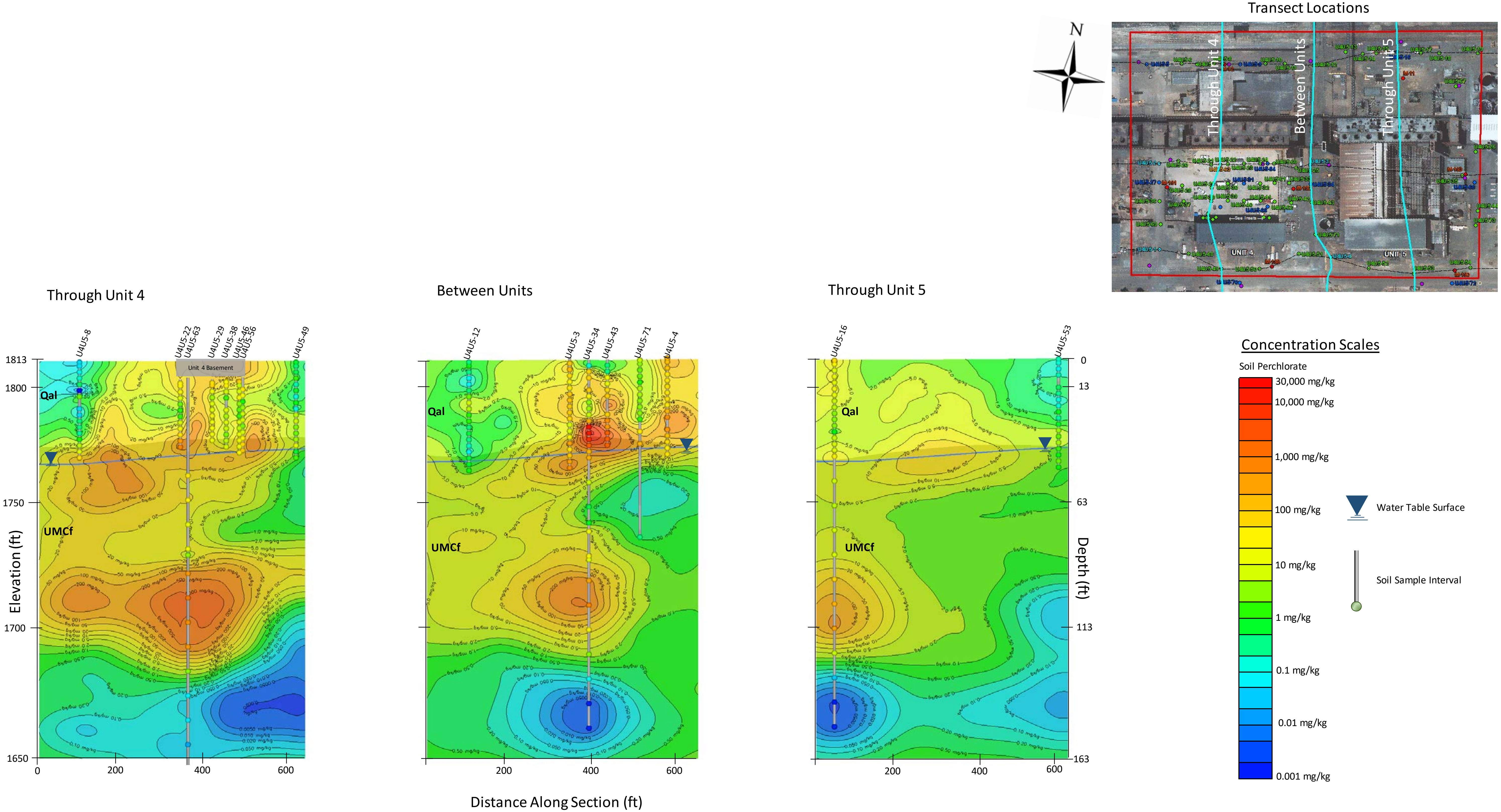
UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

2D VISUALIZATION EAST-WEST CROSS SECTIONS OF PERCHLORATE DISTRIBUTION IN SOIL, UNITS 4 AND 5

| | |
|---|---|
| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | MRB |
| Figure No. | 9 |




T:\NERT\M02\Pilot Test Treatment Area Graphic\Fig 10 - Perchlorate Soil Sections NS.pptx

Notes:

1. Vertical exaggeration: 6:1.
2. Sections are shown looking East.
3. Colored spheres show soil perchlorate concentration.
4. Water table surface based on June 2016 groundwater elevation data.
5. Data interpolation truncated below 163 ft bgs due to insufficient data.
6. Ground surface elevation is assumed to be 1,813 ft amsl for the purposes of illustrated depth.
7. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

2D VISUALIZATION NORTH-SOUTH CROSS SECTIONS OF PERCHLORATE DISTRIBUTION IN SOIL, UNITS 4 AND 5

| | |
|---|---|
| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | MRB |
| Figure No. | 10 |


**Legend**

| Perchlorate in Alluvium (lbs) | | |
|---|---|---|
| 9 - 100 | 501 - 1000 | Unit 4 & 5 Building Investigation Area |
| 101 - 200 | 1001 - 2000 | Unit 4 Treatability Study Area |
| 201 - 500 | 2001 - 5000 | Proposed Soil Flushing Area |
| | 5001 - 7773 | |

Notes:
1. All locations are approximate.
2. Imagery Source: Aerotech Mapping, August 2016


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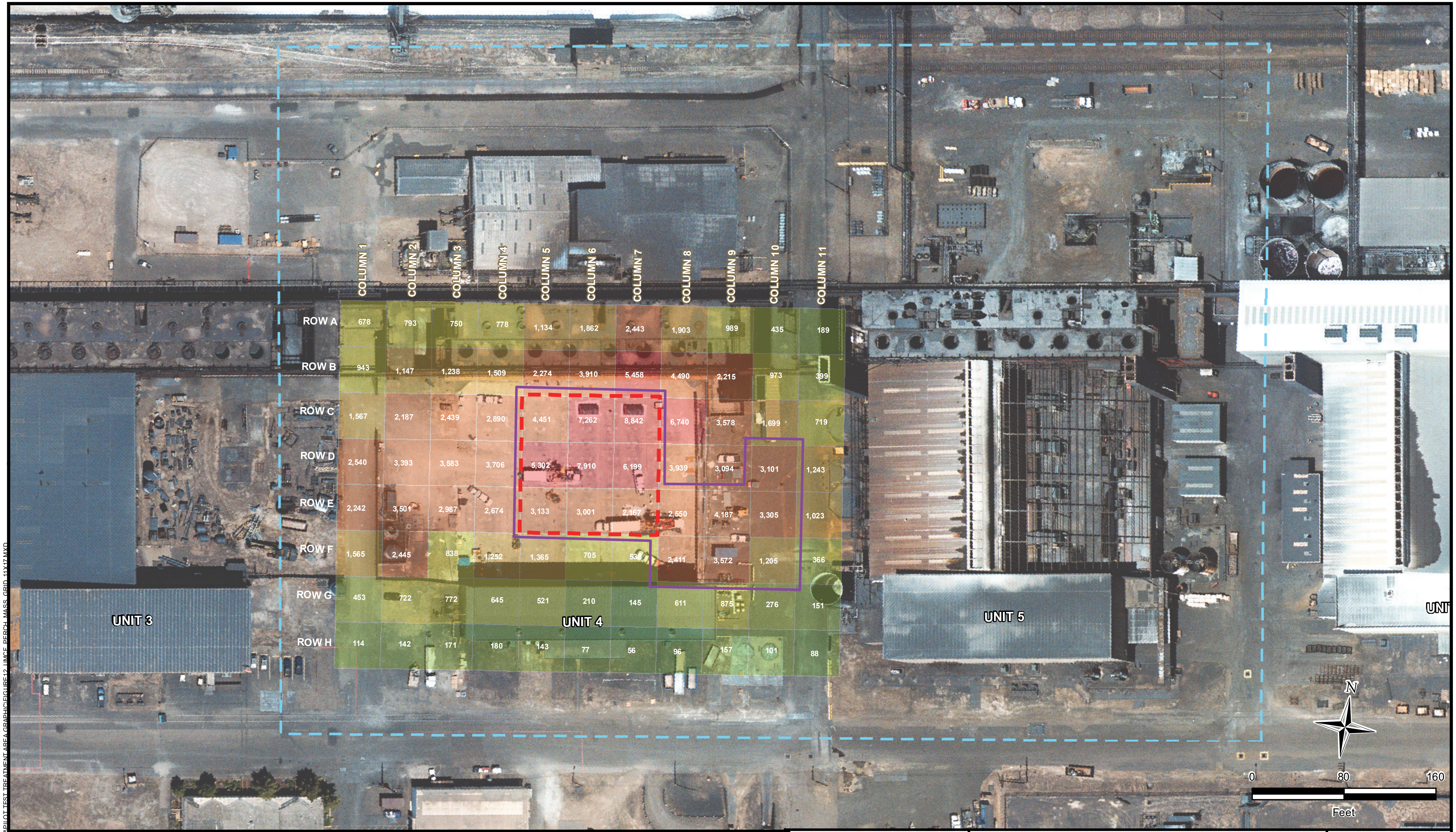
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**LATERAL DISTRIBUTION OF PERCHLORATE MASS IN THE QAL**

| | |
|---|---|
| Project No.: | 87600016 |
| Date: | OCT 27, 2017 |
| Designed By: | CKG |
| Figure No. | 11 |




**Legend**

Mass

Perchlorate Mass in UMCf (lbs)

- 56 - 100
- 101 - 200
- 201 - 500
- 501 - 1000
- 1001 - 2000
- 2001 - 5000
- 5001 - 8842

- Unit 4 & 5 Building Investigation Area
- Unit 4 Treatability Study Area
- Proposed In-Situ Soil Remediation Area

Notes:

1. All locations are approximate.
2. Imagery Source: Aerotech Mapping, August 2016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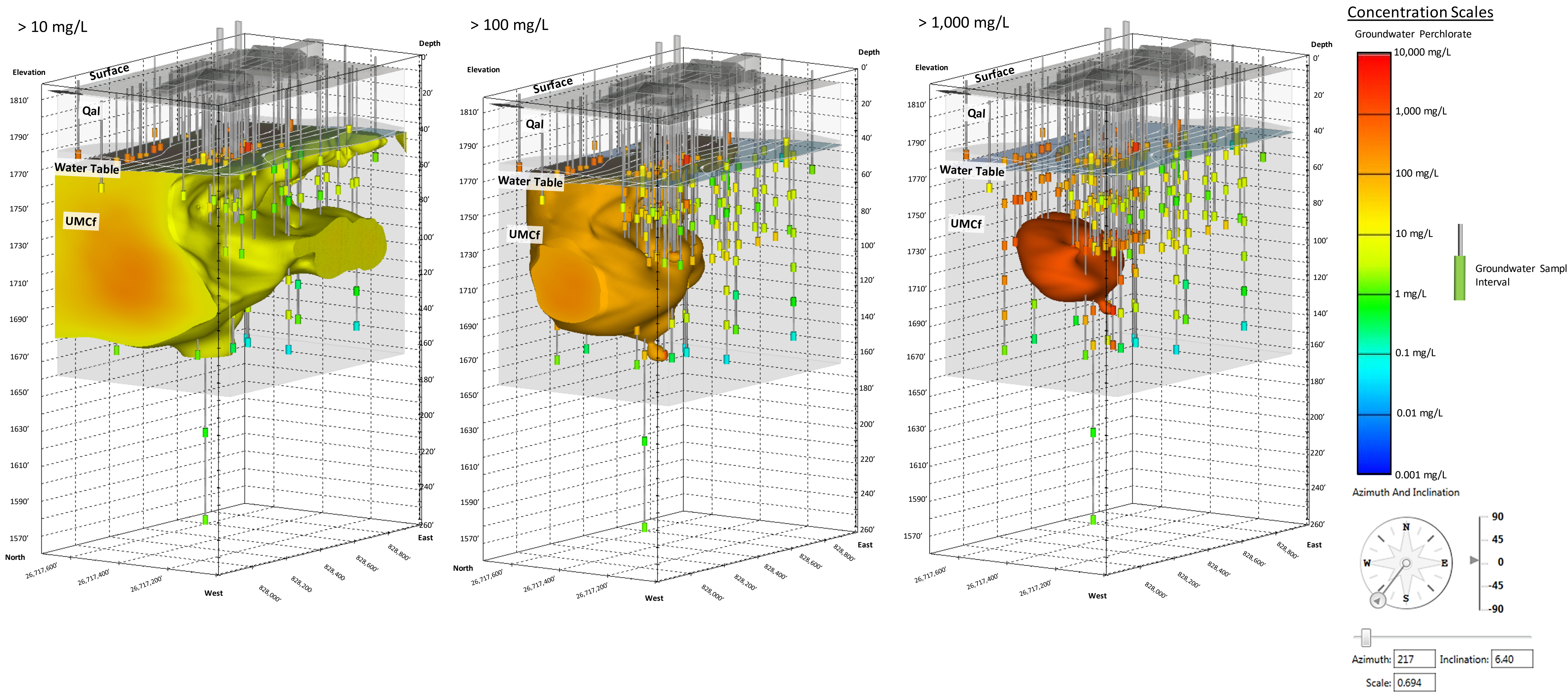
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**LATERAL DISTRIBUTION OF PERCHLORATE MASS IN THE UMCF**

| | |
|---|---|
| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | CKG |
| Figure No. | 12 |




Notes:

1. Data interpolation truncated below 163 ft bgs due to insufficient data.
2. Water table surface based on June 2016 groundwater elevation data.
3. Colored tubes show groundwater perchlorate concentration.
4. Vertical Exaggeration: 6:1 Vertical:Horizontal (below ground).
5. mg/L: milligrams per liter (groundwater).
6. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

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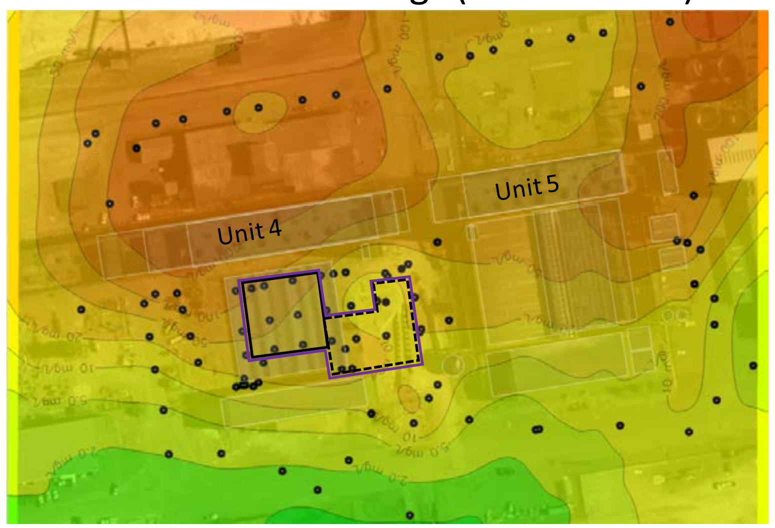
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

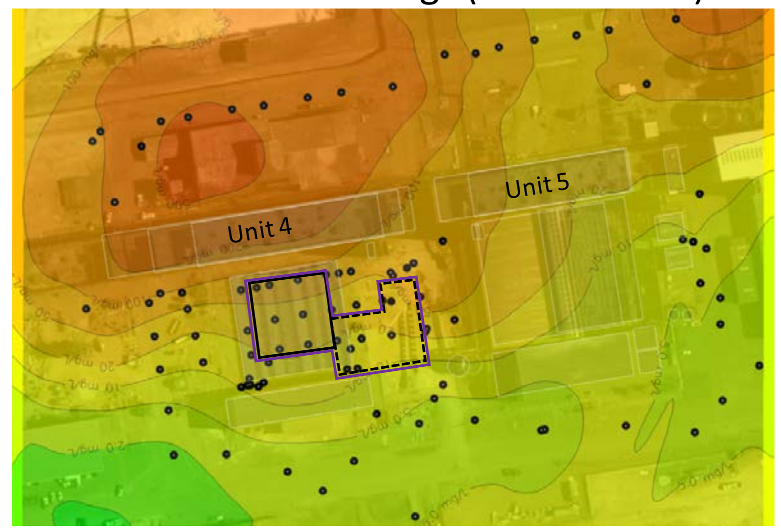
PERCHLORATE DISTRIBUTION IN GROUNDWATER

| | |
|---|---|
| Project No.: | 117-7502017 |
| Date: | October 27, 2017 |
| Designed By: | MRB |
| Figure No. | 13 |

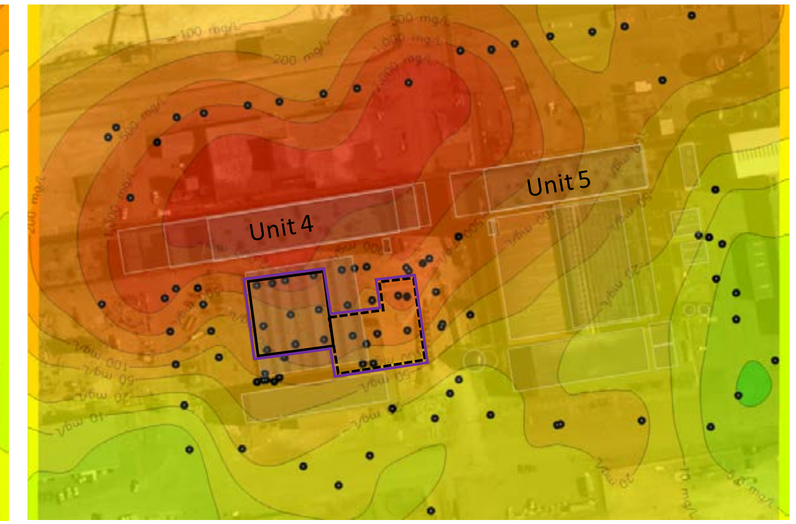
Horizontal Slice at 53’ bgs (1760 ft amsl)



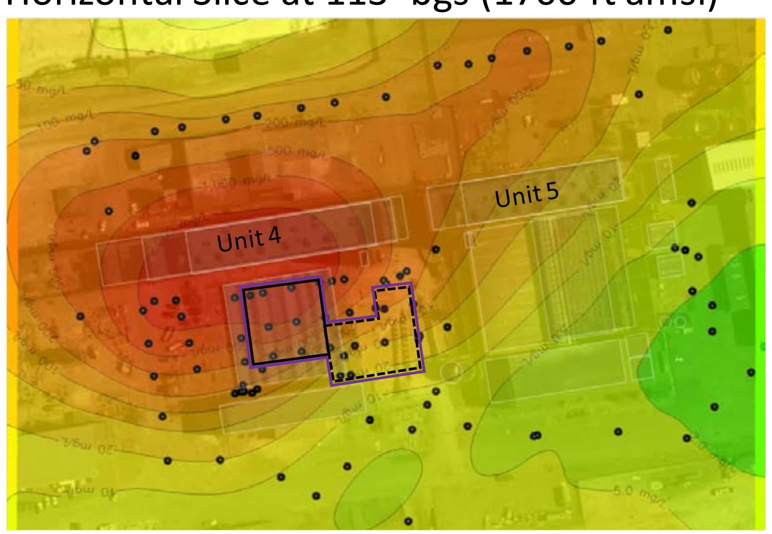

Horizontal Slice at 73’ bgs (1740 ft amsl)



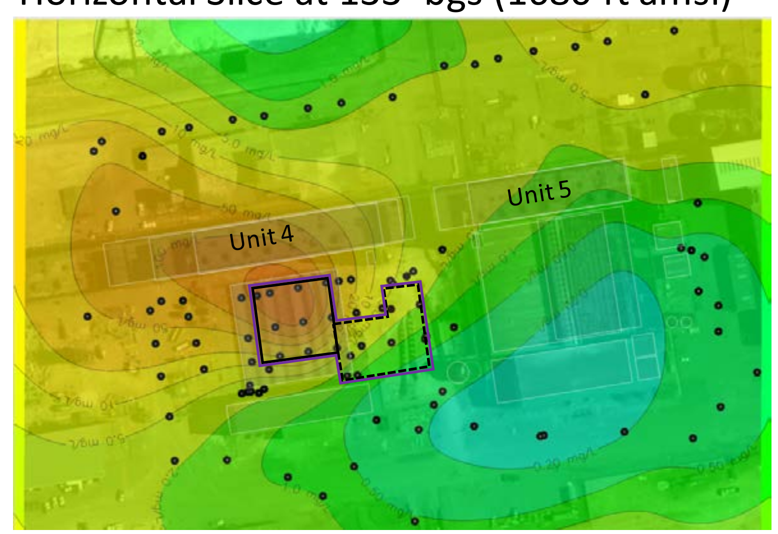

Horizontal Slice at 93’ bgs (1720 ft amsl)



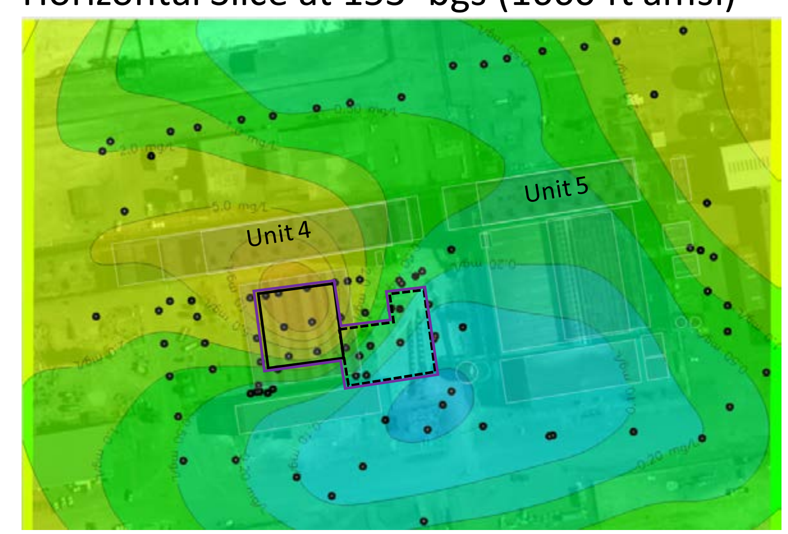

Horizontal Slice at 113’ bgs (1700 ft amsl)




Horizontal Slice at 133’ bgs (1680 ft amsl)

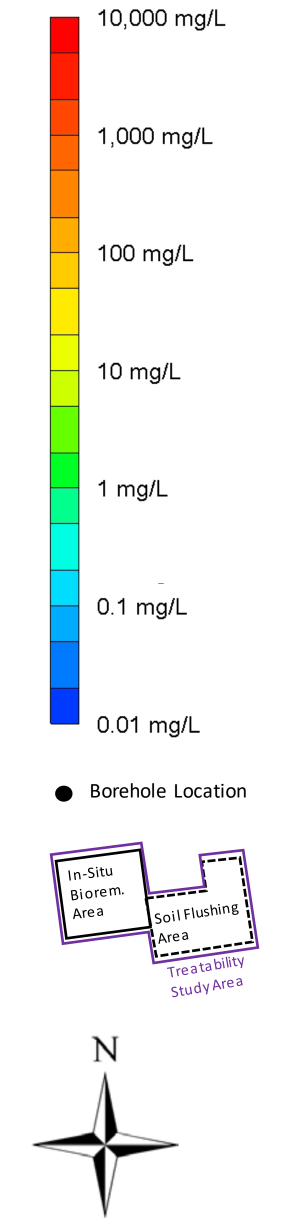



Horizontal Slice at 153’ bgs (1660 ft amsl)




Concentration Scales

Groundwater Perchlorate




T:\NERT\WM02\Pilot Test Treatment Area Graphic\Fig 14 - Perchlorate 2D GW_v2.pptx

Notes:
1. Ground surface elevation is assumed to be 1,813 ft amsl for the purposes of illustrated depth
2. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

2D VISUALIZATION PLAN VIEW OF PERCHLORATE DISTRIBUTION IN GROUNDWATER, UNITS 4 AND 5

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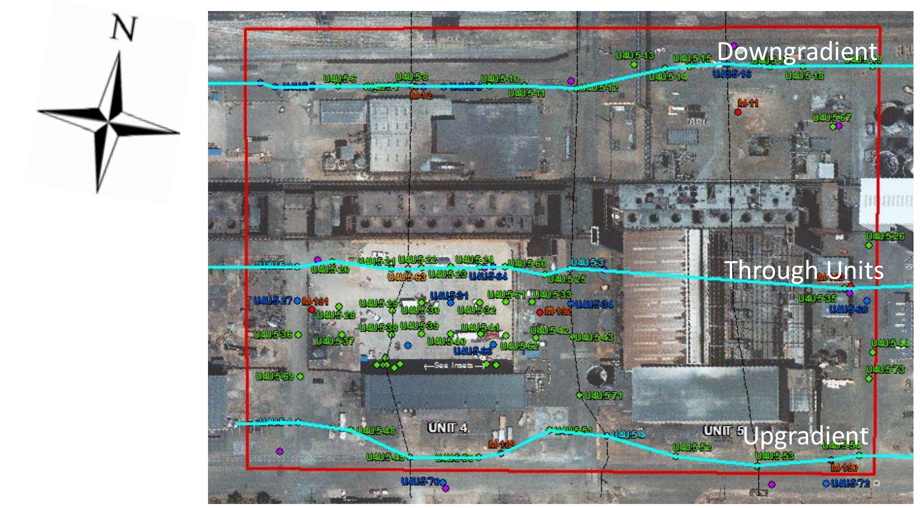
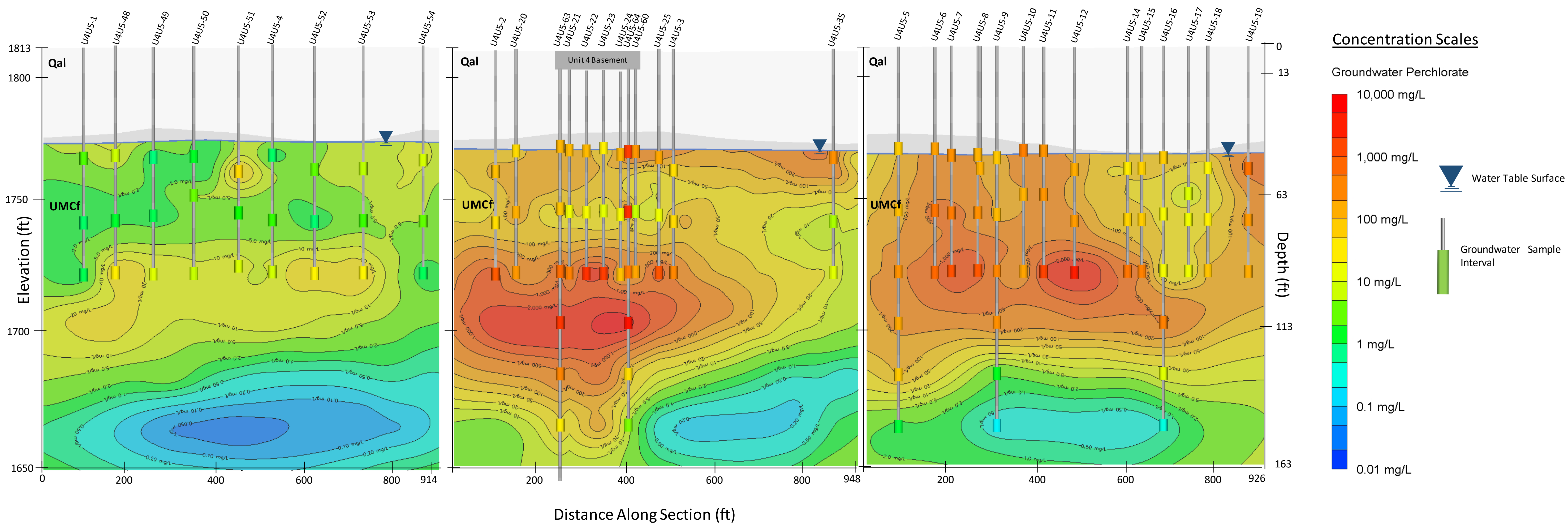
| Project No.: | 8700016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | MRB |
| Figure No. | 14 |

Transect Locations




Notes:

1. Vertical exaggeration: 6:1.
2. Sections are shown looking North.
3. Colored tubes show groundwater perchlorate concentration.
4. Water table surface based on June 2016 groundwater elevation data.
5. Data interpolation truncated below 163 ft bgs due to insufficient data.
6. Ground surface elevation is assumed to be 1,813 ft amsl for the purposes of illustrated depth.
7. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

T:\NERT\M 02\Pilot Test Treatment Area Graphic\Fig 15 - Perchlorate GW Sections EW.pptx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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

2D VISUALIZATION EAST-WEST CROSS SECTIONS OF PERCHLORATE DISTRIBUTION IN GROUNDWATER, UNITS 4 AND 5

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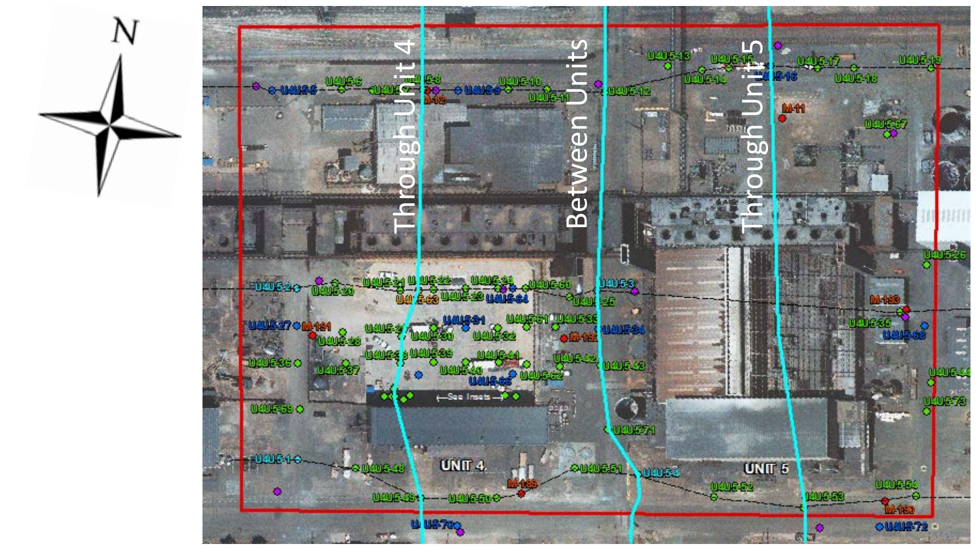
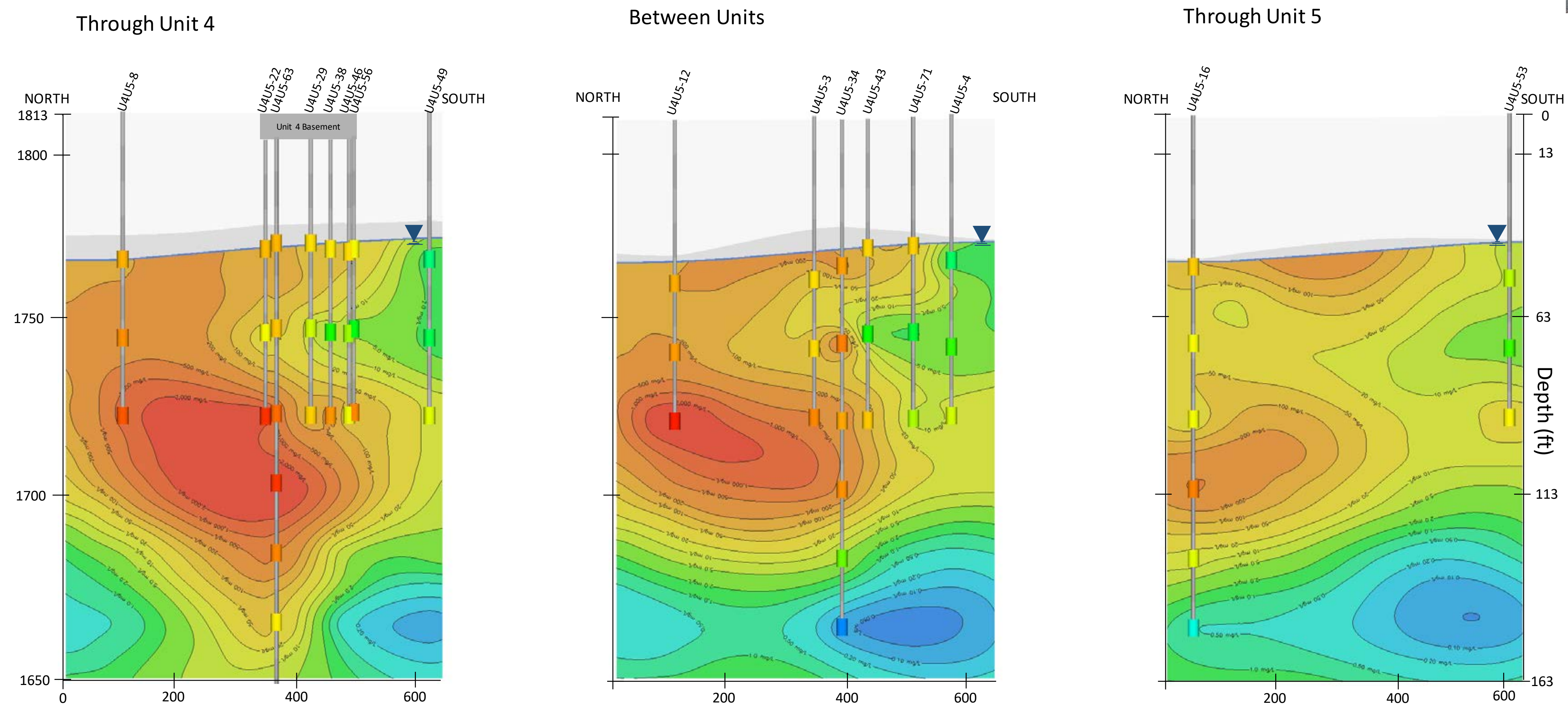
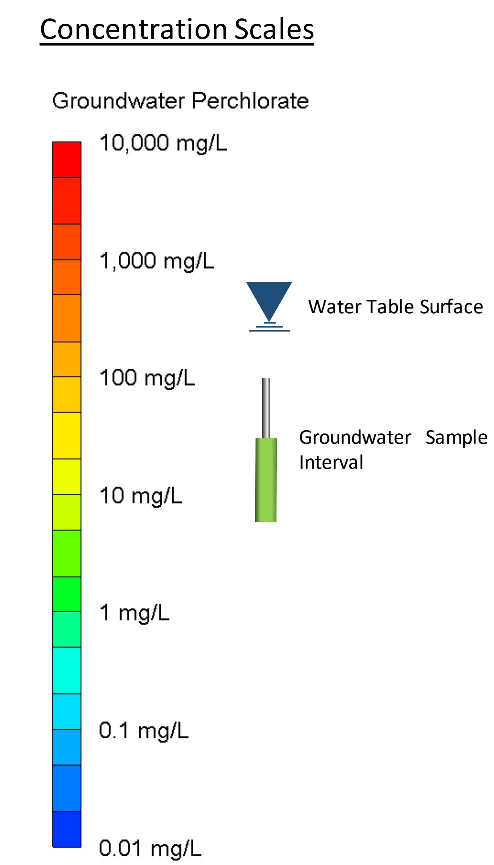
| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | MRB |
| Figure No. | 15 |




Notes:
1. Vertical exaggeration: 6:1.
2. Sections are shown looking East.
3. Colored tubes show groudnwater perchlorate concentration.
4. Water table surface based on June 2016 groundwater elevation data.
5. Data interpolation truncated below 163 ft bgs due to insufficient data.
6. Ground surface elevation is assumed to be 1,813 ft amsl for the purposes of illustrated depth.
7. Data gap present underneath the Unit 5 building; concentrations shown are interpolated by EVS using the closest available data.

T:\NERT\M 02\Pilot Test Treatment Area Graphic\Fig 16 - Perchlorate GW Sections NS.pptx

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE
UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

2D VISUALIZATION NORTH-SOUTH CROSS SECTIONS OF PERCHLORATE DISTRIBUTION IN GROUNDWATER, UNITS 4 AND 5

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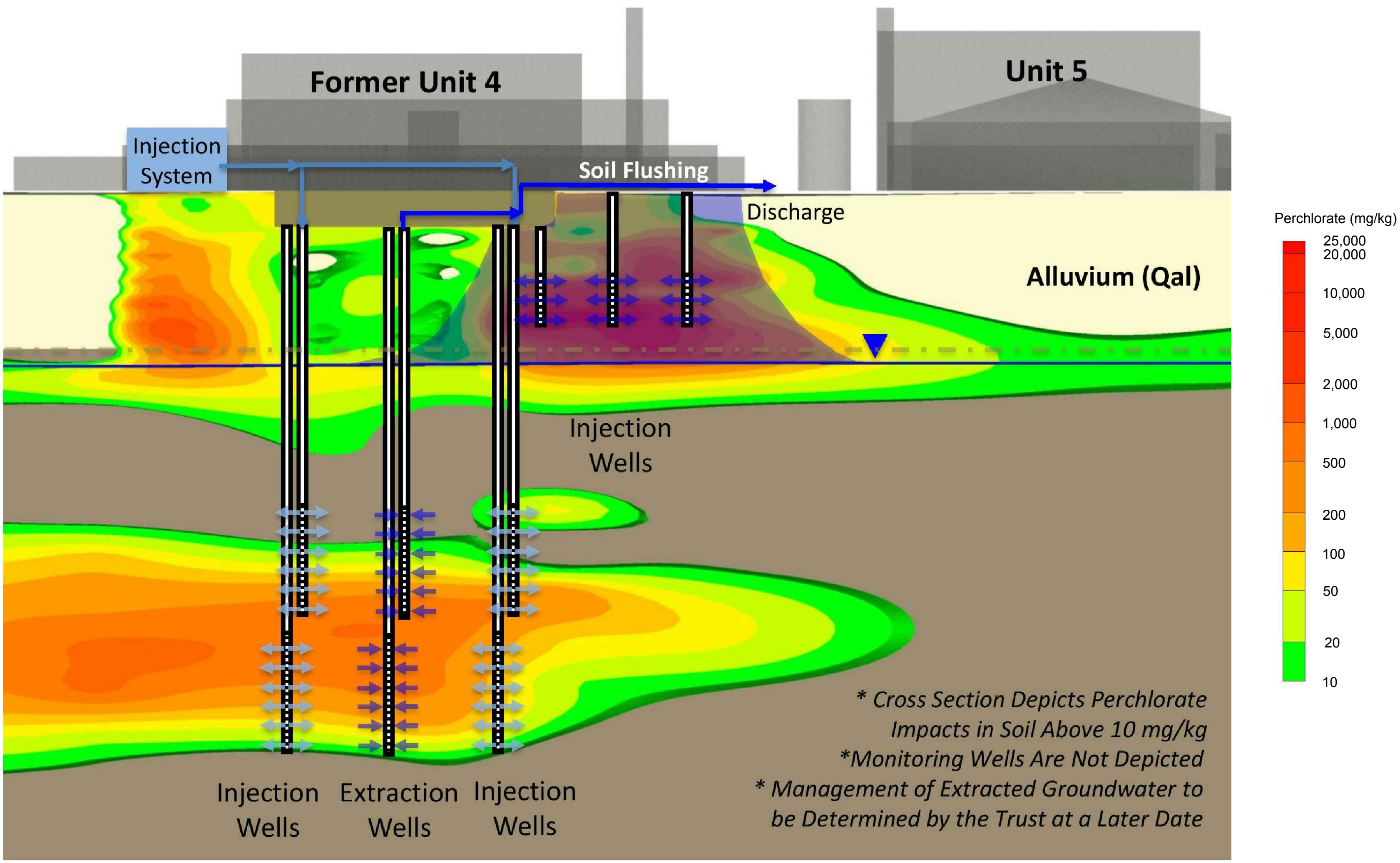
| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | MRB |
| Figure No. | 16 |




tts148fs1.tt.local\P: Figure 17 - Proposed Unit 4 Treatability Study Location 87600016.dwg

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**CONCEPTUAL TREATABILITY STUDY PROCESS FLOW DIAGRAM**

| | |
|---|---|
| Project No: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | PK |
| Figure No. | 17 |


tts148fs1.tt.local\P: Figure 18- Proposed Unit 4 Treatability Study Location 87600016.dwg

| | | |
|---|---|---|
| TETRA TECH<br>www.tetratech.com<br>150 S. 4th Street, Unit A<br>Henderson, Nevada 89015<br>PHONE: (702) 854-2293 | **NEVADA ENVIRONMENTAL RESPONSE TRUST SITE**<br>UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN<br>**CONCEPTUAL PIPELINE LAYOUT** | Project No: 87600016<br>Date: OCTOBER 27, 2017<br>Designed By: PK<br>Figure No.<br>**18** |


\\TTS134FS1\geosupvol1\PROJECTS\DATA\NERTL19\GIS\MXD\Figure 15 Intermediate UMCf.mxd


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**NEVADA ENVIRONMENTAL RESPONSE TRUST SITE**

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**PRELIMINARY GROUNDWATER MODELING RESULTS (INTERMEDIATE UMCf)**

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| Project No.: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | PLD |

Figure No.

**19**


\\TTS134FS1\geosupvol1\PROJECTS\DATA\NERT\L19\GIS\MXD\Figure 16 Deep UMCf.mxd


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**NEVADA ENVIRONMENTAL RESPONSE TRUST SITE**

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**PRELIMINARY GROUNDWATER MODELING RESULTS (DEEP UMCf)**

Project No.: 87600016

Date: OCTOBER 27, 2017

Designed By: PLD

Figure No.

**20**



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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

UNIT 4 SOURCE AREA IN-SITU BIOREMEDIATION TREATABILITY STUDY WORK PLAN

**TREATABILITY STUDY CONCEPTUAL LAYOUT**

| | |
|---|---|
| Project No: | 87600016 |
| Date: | OCTOBER 27, 2017 |
| Designed By: | PK |
| Figure No. | 21 |