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Nevada Environmental Response Trust
Henderson, Nevada

Prepared by
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Emeryville, California

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GALLERIA ROAD ZVI-ENHANCED BIOREMEDIATION TREATABILITY STUDY WORK PLAN

NEVADA ENVIRONMENTAL RESPONSE TRUST SITE
HENDERSON, NEVADA

RAMBOLL ENVIRON

Galleria Road ZVI-Enhanced Bioremediation Treatability Study Work Plan

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 system(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, Inc., not individually, but solely in its representative capacity as the Nevada Environmental Response Trust Trustee

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Date: 9/29/17

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Responsible Certified Environmental Manager (CEM) for this project

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 provided 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.

__________________________________ 9/29/17 ______________________________

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Date	**September 29, 2017**
Prepared by	**Ramboll Environ**
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ACRONYMS AND ABBREVIATIONS

AWF	Athens Road Well Field
bgs	below ground surface
BMI	Black Mountain Industrial
BRC	Basic Remediation Company LLC
CEM	Certified Environmental Manager
Combined Metals	Combined Metals Reduction Company
CRC	Colorado River Commission
ENVIRON	ENVIRON International Corporation
ft	feet
ITRC	Interstate Technology and Regulatory Council
lbs	pounds
lbs/day	pounds per day
mg/L	milligrams per liter
NDEP	Nevada Division of Environmental Protection
NERT	Nevada Environmental Response Trust
NFA	No Further Action
OU	Operable Unit
Qal	Quaternary alluvium
Ramboll Environ	Ramboll Environ US Corporation
RAO	Remedial Action Objective
RI	Remedial Investigation
RI/FS	Remedial Investigation and Feasibility Study
Site	Nevada Environmental Response Trust Site
Stauffer	Stauffer Chemical Company
Tetra Tech	Tetra Tech, Inc.
TIMET	Titanium Metals Corporation of America
Trust	Nevada Environmental Response Trust
ug/L	micrograms per liter
UMCf	Upper Muddy Creek Formation
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

VOC	volatile organic compound
WECCO	Western Electric Chemical Company
WBZ	water-bearing zone
xMCf	Transitional Muddy Creek Formation
ZVI	Zero-Valent Iron

1. INTRODUCTION

On behalf of the Nevada Environmental Response Trust (NERT or "the Trust"), Ramboll Environ US Corporation (Ramboll Environ) has prepared this Galleria Road Zero-Valent Iron (ZVI)-Enhanced Bioremediation Treatability Study Work Plan (Work Plan). This Work Plan is being submitted to the Nevada Division of Environmental Protection (NDEP) in accordance with the Interim Consent Agreement effective February 14, 2011. This Work Plan presents the technical approach and scope of work for conducting laboratory and field testing to evaluate the use of granular ZVI—a sand-size material composed of iron metal—to stimulate naturally-occurring biological perchlorate and chlorate reduction in groundwater under site-specific conditions in the Eastside Study Area in the vicinity of Galleria Road.

This Work Plan is being conducted to support remedy selection as part of the Remedial Investigation and Feasibility Study (RI/FS). Currently, the Remedial Investigation (RI) is being conducted in four investigation study areas: the NERT Site; the NERT Off-Site Study Area; the Downgradient Study Area; and the Eastside Study Area (see Figure 1). These investigation areas are now collectively referred to as the NERT RI Study Area. The Eastside Study Area encompasses two subareas: the Eastside Sub-Area and the Northeast Sub-Area.

The Trust has determined that additional technical evaluation of location-specific remedial options is necessary to support remedy selection in the Eastside Study Area. This Work Plan describes one of two coordinated treatability studies currently planned for the northern portion of the Eastside Sub-Area located along Galleria Drive. The companion treatability study is being conducted by Tetra Tech and involves groundwater bioremediation using emulsified oil.

With the proposed revision to the Remedial Action Objectives (RAOs) and related development of Operable Units (OUs), as described in the *RI/FS Work Plan Addendum: Phase 3 Remedial Investigation, Revision 1* (Ramboll Environ 2017b), the northern portion of the Eastside Sub-Area located along Galleria Drive has become an important mid-plume boundary. As shown on Figure 2, the northern boundary of the Eastside Sub-Area is also the boundary between proposed OU-2 and OU-3. The revised RAOs call for mitigation of migration of contaminants north (downgradient) of this boundary. The Athens Road Well Field (AWF) is an effective control measure to mitigate migration of the highest perchlorate concentrations downgradient of the mid-plume boundary; however, the capture zone of the AWF does not extend into the Eastside Sub-Area (Ramboll Environ 2017a). Currently, there are no control measures in place to mitigate migration of contaminants downgradient of the Eastside Sub-Area. These companion treatability studies would be the first step in developing remedial options in this area.

1.1 Treatability Study Approach

The goal of the treatability study is to design, construct, and monitor a field test comprised of chiefly of ZVI that is to be operated as a passive flow-through groundwater treatment system. Other amendments that may support the performance of ZVI (or assist in pre-treating groundwater to remove deleterious compounds that could reduce ZVI effectiveness) may also be applied following the results of bench-scale testing. Designing an effective system such as this requires understanding the site-specific hydrogeology and geochemistry, nature and extent of contamination, chemical properties, and specific performance characteristics of the reactive media to be employed.

A phased approach is proposed for the treatability study such that knowledge gained in preceding steps may be used to inform subsequent steps; however, where appropriate to do so, steps will be performed in parallel to reduce, to the extent practicable, the duration of the study. The treatability study consists of the following primary steps:

1. **Evaluation of existing site-specific field data** to identify data gaps and help design the pre-design field investigation and bench-scale testing program.
2. **Pre-design field investigation** activities will be performed to address geochemical and hydrogeological data needs and provide information important for executing bench-scale testing and designing the field testing program.
3. **Bench-scale testing** will be performed using soil and groundwater collected during the pre-design investigation and will provide critical information for designing the field testing program. The evaluation and analysis of the bench-scale testing will be supported by numerical modeling to assess reactive transport processes important to overall design and performance of an eventual remedy.
4. **Field testing and performance monitoring** will be performed using information collected during the pre-design investigation and bench-scale testing program to evaluate technology effectiveness and provide key design parameters for a potential full-scale system. Field testing may be supported by numerical modeling and hydraulic testing methods to confirm and evaluate the treatment process.

1.2 Treatability Study Objectives

The overall objectives of the this treatability study are to 1) determine whether ZVI alone can promote the biological reduction of perchlorate, chlorate, and other co-contaminants (e.g., nitrate and hexavalent chromium) contained in the groundwater in the Eastside Sub-Area; 2) evaluate whether other amendments would be necessary to either enhance ZVI performance or reduce the potential deleterious effects of site-specific groundwater conditions (e.g., the presence of nitrate) on ZVI treatment performance; and 3) provide important information for the design of a full-scale remedial system intended to mitigate migration of contaminants at the mid-plume boundary.

ZVI is a commercially and readily available granular material that has been used for more than 25 years as an in-situ treatment material for remediating groundwater contaminated with a variety of industrial chemicals, including both organic and inorganic compounds. Granular ZVI is produced from the grinding and baking of recycled iron products and, when introduced to the subsurface aqueous environment can establish geochemically reducing conditions and promote sustained (shown to last decades based on existing project experience) release of dissolved hydrogen from the natural iron corrosion process in water. The combination of sustained dissolved hydrogen release and establishment of a reducing environment enhance the biological activity that promotes perchlorate reduction.

The bacteria capable of biologically reducing perchlorate require a food source, which provides electrons that drive the perchlorate reduction process. This is often referred to as an electron donor. The electron donor can be an organic source (e.g. acetate, ethanol, etc.) or it can be dissolved hydrogen. The bacteria also require some source of carbon for bacterial cell growth, particularly at the start of the process. When organic carbon is used for bacterial cell growth, the process is termed heterotrophic. In such a case, the organic carbon source acts as both electron donor and as the source of carbon to support bacterial growth. Conversely, when hydrogen is used as the electron donor, the process is termed autotrophic and carbon dioxide (typically present as alkalinity in water) or some other inorganic carbon is used as the source of carbon. The corrosion of ZVI produces dissolved hydrogen that can be used as an electron donor for perchlorate reduction. By comparison, emulsified oil, which has been used at NERT to support other bioremediation treatability studies, is not directly used for biological perchlorate reduction. When oil is degraded, it generates hydrogen, acetate, and other short-chain fatty acids, which can be subsequently used as electron donors for biological perchlorate reduction.

A potential major benefit of ZVI is that it is anticipated to be a long-lasting source of dissolved hydrogen. ZVI corrosion in a groundwater system is slow, with decades typically needed to completely oxidize a granule of iron metal. This natural condition allows ZVI systems to be designed and operated passively with low operation and maintenance (O&M) costs and no significant aboveground infrastructure. Therefore, if demonstrated effective in this application, ZVI-enhanced bioremediation could provide a highly cost-effective long-term treatment for perchlorate and chlorate in groundwater with negligible impact to future development by others within the Eastside Study Area.

Because of the varying concentrations of perchlorate and co-contaminants (e.g. chlorate, nitrate, hexavalent chromium), all of which will consume electron donor, as well as the varying hydrologic and geochemical conditions throughout the perchlorate plume, the use of ZVI may not be appropriate in all areas. However, the conditions at the mid-plume boundary area are expected to be suitable to test the application of ZVI to support biological perchlorate reduction. While ZVI can support biological perchlorate reduction on its own, conditions may warrant the use of other ancillary amendments, such as relatively small additions of organic carbon to achieve the desired performance and reduce the impact of conditions that would limit or reduce the effectiveness ZVI corrosion on the treatment process.

This study will rely on bench-scale tests, field investigation, field tests, and local-scale reactive transport and flow modeling to achieve the following specific technical objectives:

1. Evaluate the efficacy of ZVI as a treatment matrix to promote the reduction of perchlorate and chlorate in groundwater within the UMCf (and alluvium, if saturated) in the treatability test area by:
    a. Performing bench-scale tests to confirm the treatment process using site-specific groundwater and soil;
    b. Evaluating the potential interference of other constituents in the study area (e.g., nitrate).
    c. Selecting, through bench-scale testing, the type and approximate compositions of ZVI and ancillary amendments that may be necessary to negate site-specific conditions that could limit ZVI effectiveness and would thus promote anticipated treatment under site conditions; and

2. Assess contaminant (e.g., perchlorate and chlorate) degradation rates, as well as the potential for passivation and/or clogging (via secondary mineral precipitation and/or biofouling) by performing bench-scale column tests and reactive transport modeling.
3. Characterize the treatability test area for geochemical, hydrogeological, and geotechnical characteristics necessary for designing and implementing a field test.
4. Assess different implementation (i.e., alignment and methodology) approaches for effectiveness and constructability considering the site-specific data collected during the field investigation.

1.3 Work Plan Organization

This work plan is organized as follows:

- **Section 1** presents the objectives and organization of the work plan.
- **Section 2** provides relevant background information and an evaluation of existing data and recognized data gaps.
- **Section 3** provides a description of the proposed technology.
- **Section 4** provides a summary of the proposed pre-design field investigation activities.
- **Section 5** presents proposed bench-scale testing objectives and approach.
- **Section 6** provides a proposed field test conceptual design.
- **Section 7** describes property access and permitting requirements.
- **Section 8** describes data management, verification, and validation procedures.
- **Section 9** describes the proposed reporting to be performed.
- **Section 10** provides a proposed schedule for the treatability study.
- **Section 11** lists citations for key documents referenced in this work plan.

2. BACKGROUND

This section provides a summary of relevant background information for the NERT site and the Eastside Study Area with emphasis on the area in proximity to the mid-plume boundary. The information presented in this section was considered during the development of this Work Plan. Additional background information is available in the following documents:

- RI/FS Work Plan Addendum: Phase 3 Remedial Investigation, Revision 1, prepared by Ramboll Environ (Ramboll Environ 2017b), the "Phase 3 RI Work Plan"; and
- Remedial Investigation and Feasibility Study Work Plan, Revision 2 prepared by ENVIRON International Corporation (ENVIRON) (ENVIRON 2014), the "RI/FS Work Plan".

This section focuses on the Eastside Study Area because the treatability study is planned to be conducted there; however, the NERT site is discussed as necessary to provide additional relevant context.

2.1 Site Description and Use

The Eastside Study Area covers approximately 2,527 acres and is located approximately 14 miles southeast of the City of Las Vegas and within the city limits of Henderson. It is located between Pabco Road and Lake Mead Parkway, northeast of the active industrial operations at the Black Mountain Industrial (BMI)[1] Complex and adjacent to primarily residential properties.

The Eastside Study Area encompasses two subareas: the Eastside Sub-Area and the Northeast Sub-Area.

- The Eastside Sub-Area is approximately 1,983 acres and located east of Pabco Road, west of Lake Mead Parkway, and south of Galleria Drive. It was historically part of the BMI Common Area. Portions of the Eastside Sub-Area were historically used for the disposal of process wastewater generated at the neighboring BMI Complex.
- The Northeast Sub-Area is approximately 544 acres and is located north of Galleria Drive and encompasses much of the area currently occupied by the Chimera Golf Club, Tuscany Village, and other residential communities.

The BMI Complex, including the NERT site, was initially developed by the United States Government during World War II, under the Defense Plant Corporation, as a magnesium production facility. Facility construction began in 1941 under a contract with Basic Magnesium Incorporated (BMI) and the plant was operated from August 31, 1942 to November 15, 1944 in support of the war effort.

Starting in 1945, several companies began leasing portions of the complex from the U.S. Government. In 1949, ownership of a majority of the overall industrial complex was transferred to the State of Nevada's Colorado River Commission (CRC). In 1952, the five principal operating companies at the time (Western Electric Chemical Company

[1] The acronym "BMI" has been applied to several entities over the years. From 1941 until 1951 it referred to Basic Magnesium Incorporated; in 1951, a syndicate of tenants formed under the name of Basic Management, Inc. to provide utilities and other services at the complex; the group has also been known as Basic Metals, Inc., and at the present is called the Black Mountain Industrial complex.

[WECCO], Stauffer Chemical Company [Stauffer], U.S. Lime, Titanium Metals Corporation of America [TIMET], and Combined Metals Reduction Company [Combined Metals]) purchased operational facilities from the CRC. The CRC conveyed most of its remaining property to Basic Management Incorporated (Basic Management) as a new organization, which was owned by the five principal operating companies.

Basic Management was established to manage facilities and utilities common to all tenants at the complex, including water, power, sanitary sewers, and transportation. Areas used by Basic Management for general facility and utility operations are often referred to as the BMI Common Area.

The Eastside Sub-Area, which makes up the southern portion of the Eastside Study Area, was part of the BMI Common Area and was used for a variety of functions including industrial wastewater collection. Although much of the Eastside Sub-Area is currently vacant, portions of the area have been developed with residential, commercial, and public spaces, which is anticipated to expand throughout much of the Eastside Study Area within the next decade. Much of the Northeast Sub-Area was vacant prior to the construction of residential housing and a golf course in the late 1990s and early 2000s.

Process wastewaters generated by industrial operations within the BMI Complex were conveyed to the Upper BMI Ponds (located in the northern portion of the Eastside Sub-Area) via the Beta Ditch, which was an unlined ditch constructed circa 1941 or 1942. The Beta Ditch historically received a variety of wastes in addition to receiving storm water and non-contact cooling water. The Beta Ditch extended east of the NERT site to a siphon inlet/pond location on what is now TIMET property. The siphon inlet then transmitted flows from the western section of Beta Ditch under Boulder Highway to the eastern section of the Beta Ditch and subsequently to the Upper BMI Ponds (located within the Eastside Sub-Area) and Lower BMI ponds (located in the Downgradient Study Area to the northwest of the Eastside Sub-Area).

The Alpha Ditch was constructed in approximately 1943 to convey non-contact cooling water to the Las Vegas Wash and, possibly, the Lower BMI Ponds. Collection segments on the TIMET property directed flow north and northwest, joined, and then routed the combined flow northeast under Boulder Highway to the main segment of the Alpha Ditch.

2.2 Regulatory Background

Large portions of the Eastside Study Area have been the subject of numerous regulatory actions and environmental investigations (Ramboll Environ 2017b). In 2006, Basic Remediation Company LLC (BRC) and other companies within the BMI complex executed a settlement agreement defining the framework for characterization and remediation of the BMI Common Areas and defined steps by which the remedial actions should be performed (NDEP 2006). BRC conducted soil and groundwater investigations and remediation activity (completed in 2014), which served as the basis for NDEP granting No Further Action (NFA) determinations on parcels comprising the Eastside Sub-Area. NDEP's NFA determinations were restricted to the upper 10 feet of the soil horizon and were consistent with proposed future land uses (BRC 2014). NDEP has directed the Trust to investigate the Eastside Sub-Area in order to evaluate the nature and extent of COPCs (i.e., perchlorate and chlorate) impacts to the subsurface as a result of migration from the NERT site, particularly in soil and the underlying groundwater (Ramboll Environ 2017b).

2.3 Physical Setting

Topographic elevation within the Eastside Study Area ranges from approximately 1820 to 1530 feet above mean sea level (amsl). The land surface across the Eastside Study Area generally slopes toward the north at a gradient of approximately 0.02 feet per foot (ft/ft). The developed portions of the Eastside Study Area have been modified by grading to accommodate structures, access roads, recreational spaces, and historical ponds and ditches.

2.4 Regional Geology

The Eastside Study Area is located within the Las Vegas Valley, which occupies a topographic and structural basin trending northwest-southeast and extending approximately 55 miles from near Indian Springs on the north to Railroad Pass on the south. The mountain ranges bounding the east, north, and west sides of the valley consist primarily of Paleozoic and Mesozoic sedimentary rocks, whereas the mountains on the south and southeast consist primarily of Tertiary volcanic rocks that overlie Precambrian metamorphic and granitic basement. The valley floor consists of deposits surrounded by more steeply sloping alluvial fan aprons derived from erosion of the surrounding mountains. Generally, the deposits grade finer with increasing distance from their source and with decreasing elevation.

2.5 Local Geology and Hydrogeology

The local geology and hydrogeology are currently defined by data collected from more than 1,100 borings and wells that have been installed by BMI/BRC and other neighboring parties over approximately the last 30 years in the Eastside Study Area. The following descriptions are summarized from BRC's Conceptual Site Model (BRC CSM) report (BRC 2007) as presented in the Phase 3 RI Work Plan (Ramboll Environ 2017b). Additional hydrogeological investigation of the Eastside Study Area is planned as part of the Phase 3 RI Work Plan and additional focused investigation will be conducted as part of this treatability study (as described in Section 4). These investigations will further inform the understanding of the local geology and hydrogeology necessary to implement this treatability study.

2.5.1 Alluvium

The Eastside Study Area is located on Quaternary alluvial deposits (Qal or "alluvium") that slope north toward Las Vegas Wash. The alluvium consists of a reddish-brown heterogeneous mixture of well-graded sand and gravel with lesser amounts of silt, clay, and caliche. Clasts within the alluvium are primarily composed of volcanic material. Boulders and cobbles are common.

A major feature of the alluvial deposits is the stream-deposited sands and gravels that were laid down within paleochannels eroded into the surface of the Muddy Creek Formation during infrequent flood runoff periods. These deposits vary in thickness and are narrow and generally linear. These sand and gravel deposits exhibit higher hydraulic conductivity than the adjacent, well-graded deposits. In general, these paleochannels trend northeastward toward the Las Vegas Wash.

The thickness of the alluvial deposits ranges from approximately 20 feet to more than 50 feet beneath the Eastside Study Area. The alluvial soils identified in on-site borings include poorly sorted gravel, silty gravel, poorly sorted sand, well sorted sand, and silty sand. The thickness of the alluvium, as well as the top of the underlying Muddy Creek Formation, was mapped to locate these paleochannels.

2.5.2 Transitional (or Reworked) Muddy Creek Formation

Where present, Transitional Muddy Creek Formation (xMCf) is encountered at the base of the alluvium. The xMCf consists of reworked sediments derived from the Muddy Creek Formation, which is described below. Therefore, the xMCf appears similar to the Muddy Creek Formation but consists of reworked, less consolidated and indurated sediments.

2.5.3 Muddy Creek Formation

The Upper Muddy Creek Formation (UMCf) in the Las Vegas Valley consists of valley-fill deposits that are coarse-grained near mountain fronts and progressively finer-grained moving toward the center of the valley. Stratigraphic logs from historical borings indicate that, where encountered beneath the Eastside Study Area, the UMCf comprises fine-grained sediment composed of clay and silt interbedded with occasional thin layers of coarse-grained sediments of sand, silt, and gravel.

The contact between the alluvium and the UMCf is typically marked by the appearance of a well-compacted, moderate brown silt-to-sandy silt or stiff clay-to-sandy clay, except near the Las Vegas Wash where the contact is marked by gray-green to yellow-green gypsiferous clays and silts.

2.5.4 Hydrogeology

Depth to groundwater in the Eastside Study Area ranges from about 20 to 70 feet below ground surface (ft bgs) with the depth generally greatest in the southernmost portion of the Eastside Study Area, becoming shallower to the north (Ramboll Environ 2017b). The presumed direction of groundwater flow is generally toward the north-northwest on the east side of the Eastside Study Area and generally toward the north-northeast on the west side. These regional groundwater flow patterns may be influenced locally by lateral zones of coarser and more transmissive material (otherwise referred to as paleochannels) eroded into the underlying UMCf and/or hydraulic depressions created by pumping at the AWF located east of the Eastside Study Area along Galleria Drive.

NDEP has defined three water-bearing zones (WBZs) that are of interest in the BMI Complex[2]: the Shallow WBZ, which is defined by the first occurrence of groundwater in either the Qal, xMCf, or the UMCf where the xMCf is missing, is unconfined to partially confined, and is considered the “water table aquifer”; the Middle WBZ, which extends from approximately 90 to 300 feet bgs; and the Deep WBZ, which is defined as the contiguous WBZ that is generally encountered between 300 to 400 feet bgs (NDEP 2009).

During previous investigations in the Eastside Sub-Area, the base of the Middle WBZ was considered to be 270 feet bgs (MWH 2004). Within the Eastside Study Area, 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. Beneath the southern portion of the Eastside Sub-Area, the first groundwater encountered occurs at depths of approximately

[2] BRC reports have historically used two groundwater zones, a shallow unconfined WBZ (first encountered between 8 and 65 feet bgs) and a deeper confined WBZ (first encountered between 335 and 395 feet bgs) (BRC 2007). This Work Plan refers to WBZ using NDEP-defined nomenclature rather than the shallow and deep groundwater aquifers referenced in BRC’s reports.

40 feet bgs or more and shallows northward, occurring near the ground surface at Las Vegas Wash within the Northeast Sub-Area (BRC 2016). The water table occurs in the alluvium in the western part of the Eastside Sub-Area and predominantly in the UMCf near the northern boundary and eastern portion of the Eastside Sub-Area where the alluvium has become dewatered.

Based on the results of single-well hydraulic tests, implemented as rising head slug tests conducted at ten wells located within the Eastside Sub-Area in 2007, calculated hydraulic conductivity values ranged from approximately 0.8 to 60 feet per day (feet/day) in wells screened within the alluvium, and from approximately 0.06 to 0.5 feet/day in wells screened within the UMCf (Kleinfelder 2007). A 48-hour constant discharge pumping test conducted in 1998 in test wells located along Galleria Road, approximately 1,700 feet due west of Pabco Road (near current extraction well ART-8A), concluded that permeabilities of the “channel-fill alluvium” ranged from 1,072-1,698 gallons per day per square foot (gpd/ft^2), transmissivities ranged from 39,666-66,000 gpd/ft, and storage coefficients ranged from 0.03 to 0.11 (Kerr-McGee 1998). The field investigation presented in Section 4 is intended to provide location-specific hydrogeologic information to add to the understanding of hydraulic conductivities and groundwater velocities in the area of the proposed treatability study.

Investigations of the Middle WBZ within the Eastside Study Area and surrounding areas indicate that, with a few exceptions, a vertically upward hydraulic gradient exists between the Middle and Shallow WBZs with the magnitude of the vertical head difference generally increasing as depth increases. Additional data on vertical gradients within the Eastside Study Area and the proposed treatability study location will be collected as part of the Phase 3 RI and this Work Plan (as described in Section 4), respectively.

2.6 Existing Data Evaluation at the Mid-Plume Boundary

This section provides an evaluation of the current data in the vicinity of the mid-plume boundary, specifically along Galleria Road in the Eastside Study Area, and discusses known data gaps along Galleria Road. Figure 3 shows a detailed view of the area in the vicinity of the mid-plume boundary along Galleria Road, along with recently sampled well locations. Data for recently sampled locations along Galleria Road are listed Appendix A in Table A-1, while data for additional wells in the vicinity of the mid-plume boundary are listed in Appendix A in Table A-2.

2.6.1 Hydrogeology

Along Galleria Road, recently sampled wells are either cross-screened between the alluvium and the UMCf or screened in the UMCf. The depth to the UMCf along Galleria Road generally ranges from 30 to 40 feet bgs (Table A-1). However, local variations in UMCf contact topography may range from 25 to 60 feet bgs.

Depth to groundwater in the vicinity of the mid-plume boundary is generally consistent with the range for the entire Eastside Sub-Area, though the range of depth to groundwater along Galleria Road is narrower, from about 26 to 59 feet bgs (Table A-1). Available shallow groundwater elevation data from 2015 and 2016 in the vicinity of the mid-plume boundary are shown on Figure 4. 2016 data were collected by the Trust and TIMET, and 2015 data were collected by BRC. Additional 2016 data were also collected by AECOM in support of the Downgradient Study Area investigation. These data were used in conjunction with the NERT Phase 5 Transient Groundwater Flow Model (the Phase

5 model) interpretation of the Qal-UMCf contact (Ramboll Environ 2016) to estimate the approximate saturated thickness of alluvium in the vicinity of the mid-plume boundary. As discussed in the Phase 3 RI Work Plan, the alluvium has generally become dewatered near the northern boundary of the Eastside Sub-Area. Therefore, in many locations the first encountered groundwater exists within the UMCf (Ramboll Environ 2017b).

2.6.2 Soil

In 2009, BRC conducted an extensive soil investigation in the Eastside Study Area. Along Galleria Road, approximately 210 locations were sampled at multiple depths up to 20 feet below ground surface. While these data can be used to characterize the vadose zone in the area, the soil samples were not deep enough to characterize the saturated alluvium and the UMCf. Between 2004 and 2009, BRC also drilled soil borings in preparation for well installations. While the total depth sampled for each soil boring varied depending on the anticipated depth of the planned well, the maximum vertical extent of perchlorate contamination along Galleria Road is relatively consistent at approximately 80 feet bgs.

2.6.3 Groundwater Geochemistry

The field parameters, general chemistry, and metals analyses data from the ten monitoring wells along Galleria Road are shown in Table A-1. These data were collected by BRC and TIMET in 2014 and 2015, as well as AECOM on behalf of NERT in 2016. With the exception of MCF-05, which is screened in the Deep WBZ and has a much higher total dissolved solids content due to the presence of chloride salts, the geochemistry of the groundwater along Galleria Road is relatively consistent, with concentrations of individual constituents trending with the total dissolved solids content. Additional analytical data from other wells in the vicinity of the mid-plume boundary are summarized in Table A-2.

2.6.4 Data Gaps

In order to fully characterize the proposed field test area, additional geochemical data are necessary to address identified data gaps. Relevant data in the vicinity of the proposed field test area collected as part of the upcoming Phase 3 RI will be incorporated into future evaluations as it becomes available. However, additional geochemical data have also been identified as necessary to understand the full geochemical system in the area, including:

1. Characterization of the hydrogeology in greater detail and identification of preferential flow pathways.
2. Local assessment of vertical and horizontal distribution of perchlorate, chlorate, and other analytes (e.g. nitrate, hexavalent chromium) that could interfere with ZVI as a treatment to target remediation accordingly.
3. Local characterization of the baseline geochemical and biological conditions, including adsorbed metal content and total/dissolved organic carbon content.

3. TECHNOLOGY DESCRIPTION

This section provides a description of the technology for using ZVI for enhanced perchlorate biodegradation including the underlying scientific principles.

3.1 Properties of Perchlorate

Ammonium perchlorate was a historically manufactured in large quantities at the NERT site. Ammonium perchlorate is a salt that is highly soluble and dissociates completely to ammonium and perchlorate ions upon dissolving in water. The resulting perchlorate ions adsorb poorly to mineral surfaces, and therefore, perchlorate is not appreciably retarded during groundwater transport.

Despite being a strong oxidant perchlorate is very stable. Common reducing agents do not reduce perchlorate. Its low reactivity is a matter of kinetics rather than thermodynamic stability—in fact, reduction to chloride and chlorate are very favorable processes from a thermodynamic standpoint (Urbansky 2000). Perchlorate's properties make perchlorate difficult to remove physically and destroy chemically once released to groundwater. However, enzymes produced by bacteria can overcome the kinetic barrier to perchlorate reduction making in-situ bioremediation of perchlorate an effective remedial alternative, as described in the following sections.

3.2 Microbiology and Biodegradation of Perchlorate

Perchlorate-reducing bacteria are able to reduce perchlorate in the environment to chloride. In the presence of an electron donor and after dissolved oxygen (DO) and nitrate have been depleted, perchlorate can act as an electron acceptor for anaerobic respiration. By transferring electrons from the electron donor, perchlorate-reducing bacteria can reduce perchlorate sequentially to chlorate, chlorite, and finally to chloride (Coates and Achenbach 2004; Yu and Amrhein 2006). The first step in perchlorate biodegradation is carried out by the perchlorate reductase gene, wherein perchlorate is sequentially converted to chlorate and then to chlorite. A second gene, chlorite dismutase, further reduces the chlorite to chloride (ITRC 2008).

While perchlorate-reducing bacteria are generally understood to be ubiquitous in natural environments, they have been found to be more abundant at perchlorate-contaminated sites than at pristine sites (Logan 2001, Wu et al. 2001). These bacteria, though united by their ability to use perchlorate as a terminal electron acceptor, are diverse. Many perchlorate-reducing bacteria have the ability to reduce chemicals other than perchlorate, including oxygen, nitrate, and chlorate (Logan 2001). Both heterotrophic (use organic carbon for cell growth) and autotrophic (use inorganic carbon for cell growth) perchlorate-reducing bacteria have been identified, and as a group these bacteria have a variety of electron donor preferences including hydrogen, simple organic acids and alcohols, reduced humic substances, ferrous iron, and hydrogen sulfide (Logan 1998, Bruce et al. 1999, Miller and Logan 2000, Chaudhuri et al. 2002).

3.3 Previous and On-going Bioremediation at the NERT Site

Bioremediation of perchlorate within the NERT RI Study Area has been demonstrated previously, although not yet within the Eastside Study Area. Because the fundamental processes are so similar—stimulating in-situ biological reduction of perchlorate through the application of electron donor—these previous experiences provide useful information for the development of this treatability study and the companion study being developed by Tetra Tech.

A groundwater bioremediation treatability study was performed by Tetra Tech on behalf of the Trust between April 2015 and September 2016 within the vicinity of the City of Henderson (COH) Water Treatment Facility, which is immediately upgradient of the COH Bird Viewing Preserve and mid-way between the NERT AWF and Seep Well Field (SWF). As presented in the Groundwater Bioremediation Treatability Study Results Report (Tetra Tech 2016b), groundwater in the study 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 emulsified vegetable oil (EVO) product provided a reducing environment conducive to biodegrading perchlorate in the subsurface within the targeted area downgradient of the injection (Tetra Tech 2016b).

A second treatability study is currently being performed by Tetra Tech in the vicinity of the SWF extraction system in accordance with the NDEP-approved Seep Well Field Area Bioremediation Treatability Study Work Plan (Tetra Tech 2016a) (SWF Area Treatability Study). The overall objective of the SWF Area Treatability Study is to demonstrate the effectiveness of using bioremediation to reduce the flux of perchlorate mass that is migrating to the Las Vegas Wash and is not currently being captured by the existing SWF extraction well network.

3.4 ZVI as an Electron Donor

While organic carbon electron donors can enhance bacterial perchlorate reduction, they also can result in growth of other, non-target heterotrophic bacteria competing for electron donors. In contrast, dissolved hydrogen specifically enhances the activity of autotrophic perchlorate-reducing bacteria that can use hydrogen as an electron donor and inorganic carbon, like carbon dioxide (typically present and measured as alkalinity in groundwater), as a carbon source. Utilizing hydrogen as an electron donor has potential advantages; however, hydrogen-induced perchlorate reduction has not yet been attempted, and thus not yet demonstrated, at the NERT site.

ZVI can be used to promote reducing conditions and generate dissolved hydrogen to support anaerobic biodegradation. The process begins with the corrosion of iron in water to generate hydrogen. The corrosion of ZVI is shown in the following reaction:

$$Fe^0 + 2H_2O \rightarrow Fe^{2+} + 2OH^- + H_{2(g)}$$

The resulting reaction provides dissolved hydrogen to the aqueous system and increases the pH locally. The dissolved hydrogen can be used as an electron donor to support biological reduction processes including the reduction of perchlorate. Overall, the reduction of perchlorate coupled to hydrogen oxidation is shown in the following reaction (Urbansky 2000; Shrout et al. 2005):

$$ClO_4{}^- + 4Fe^0 + 8H^+ \rightarrow Cl^- + 4Fe^{2+} + 4H_2O$$

The use of ZVI as an electron donor to stimulate perchlorate reduction by autotrophic bacteria has been demonstrated in numerous laboratory studies including batch experiments by Yu et al. (2006), batch and column experiments by Son et al. (2006), column experiments by Yu et al. (2007), and column experiments by Huang and Sorial (2007). An attempted field-scale implementation by Deshusses and Matsumoto (2010) demonstrated some initial perchlorate reduction, but ultimately resulted in diminished perchlorate reduction capability. Over time the initially porous ZVI bed developed into cemented monoliths of iron and corrosion products, leading to preferential flow pathways and poor contact between water and the reactive media. Such a condition have been previously documented and earlier installations of ZVI systems identified approaches that can limit the negative impact of the secondary mineralization that occurs during the iron corrosion/carbonate reactions (e.g., Warner, et al, 1998). Deshusses and Matsumoto (2010) attributed the results to native water chemistry and experimental design decisions including the use of fine-particle ZVI and overdosing the system with sodium bicarbonate causing the corrosion and blockage. This study demonstrates the need for bench-scale testing using groundwater and soils from the field to identify site-specific geochemical reactions that may impact a field study.

Ramboll Environ is currently working on a project in northern California where, following installation of the system in 2006 (Dowman et al. 2006), sustained perchlorate removal has been observed for 10 years in an unpublished field demonstration-scale study using ZVI as the sole electron donor within an in-situ groundwater treatment system. Perchlorate concentrations upgradient of the ZVI range from 10-20 milligrams per liter (mg/l) while downgradient concentrations have been consistently below detection limits. Autotrophic perchlorate reducing bacteria, capable of using carbon dioxide as a carbon source for growth, are the most plausible explanation for this sustained performance without the addition of organic substrates or other amendments. In contrast with the Deshusses and Matsumoto (2010) study, no loss of permeability or diminished perchlorate reduction capability have been observed.

3.5 Groundwater Remediation Using ZVI

ZVI is a commercially and readily available material (primarily in granular form) and has been used for more than 25 years as an in-situ treatment material for remediating groundwater contaminated with a variety of industrial chemicals. ZVI has been used successfully for full-scale in-situ treatment of organic compounds such as chlorinated solvents, as well as for a range of inorganics such as arsenic, nickel, mercury, silver, cadmium, nitrate, sulfate, and radionuclides in a variety of geochemical environments.

A differentiating characteristic of ZVI groundwater remediation systems is their longevity. Full-scale ZVI systems installed as permeable reactive barriers have been demonstrated to remain effective 20 years after their installation (ITRC 2011; Warner 2011). The natural corrosion process of ZVI produces redox conditions that are favorable to reductive treatment mechanisms; however, this also results in conditions that are likely to promote precipitation of groundwater minerals. This phenomenon has long been seen as a potential problem with ZVI systems, but precipitation effects can result from the use of other in-situ groundwater treatment amendments as well. Permeability loss in any in-situ treatment approach can be addressed during the design phase. Bench-scale tests and field tests are critical to informing the design. Alternative construction and implementation methods, as well as alternative reactive media compositions and/or configurations can be employed to account for potential permeability loss. For example, design enhancements, including gradational emplacement methods (higher permeability zones at the upgradient face) or sacrificial pre-treatment reactive zones (e.g., pea gravel ZVI/organic carbon systems) may improve effectiveness and longevity of a system under certain conditions.

Numerous laboratory and modeling studies have explored the potential consequences of mineralization processes for ZVI longevity (e.g., Yabusaki et al. 2001; Kohn et al. 2005; Johnson et al. 2008; Wilkin and Puls 2003; Sass et al. 2002; Phillips et al. 2010). However, as noted by the ITRC (2011), ZVI systems rarely fail due to loss of permeability or reactivity. In a detailed evaluation of long-term ZVI system performance, nearly all in-situ systems that used ZVI to treat contaminants at field concentrations met their design goals; moreover, the major factor in the few that failed was design flaws (such as improper hydraulic characterization of a site), rather than depletion of media reactivity or media plugging (Henderson and Demond 2007).

3.6 Application of ZVI for NERT Groundwater Remediation

Groundwater at the mid-plume boundary in the Eastside Sub-Area is expected to contain significant concentrations of other constituents besides perchlorate that will be reduced by ZVI. These include chlorate, hexavalent chromium, nitrate, and sulfate. Previous biodegradation testing performed by the University of Nevada Las Vegas (UNLV) on behalf of the Trust has demonstrated that the degradation sequence for common chemicals in the NERT groundwater plume is 1) hexavalent chromium, 2) nitrate, 3) chlorate, 4) perchlorate, 5) sulfate (Batista 2017). Competition of these electron acceptors with perchlorate decreases degradation of perchlorate and thereby will reduce the ZVI reduction capacity (Liu, Ptacek, and Blowes 2014).

Chlorate will be reduced biologically via the perchlorate reduction pathway described in Section 3.2. Hexavalent chromium can be reduced abiotically by ZVI precipitating as trivalent chromium in the form of hydroxide mineral phases, thereby reducing ZVI reduction capacity and potentially contributing to ZVI passivation (Blowes et al. 1999). Although sulfate reduction is thermodynamically less favorable than nitrate and perchlorate reduction, studies show that sulfate reduction might undergo reduction in parallel with nitrate and perchlorate reduction (Mayer, Blowes, and Frind 2001). At the NERT site, previous studies at UNLV have demonstrated that around 5-15% sulfate reduction may occur; however it can be minimized by controlling electron donor feed and maintaining reduction potentials above -200 millivolt (mV) (Batista 2017).

Several researchers have evaluated biological reduction of nitrate using hydrogen gas (Grommen et al, 2006 and Rezania et al., 2007). Very few studies have addressed nitrate reduction using ZVI as a source of hydrogen (Shin et al. 2008, Oh et al., 2016). Most studies on ZVI reduction of iron are for abiotic reduction (Yang et al, 2005, Westerhoff, 2003, Lefevre et al, 2016). In general, nitrate reduction is slightly more favorable then perchlorate reduction (Nerenberg 2002) and the relevant reactions are as follows:

$$5H_2 + 2H^+ + 2NO_3^- \rightarrow N_2 + 6H_2O$$

$$Fe^0 + 2H_2O \rightarrow Fe^{2+} + 2OH^- + H_{2(g)}$$

Nitrate, along with the other constituents discussed in this section, will therefore require consideration so as to limit their potential negative impact to the ZVI treatment process. The performance of ZVI in the presence of these constituents, at concentrations representative of the mid-plume boundary, will be a focus of this treatability study as discussed in subsequent sections of this Work Plan.

4. PRE-DESIGN FIELD INVESTIGATION

The following sections outline the pre-design investigation, the purpose of which is to collect samples and generate data necessary for implementation of bench-scale and field testing. Tetra Tech is planning a similar pre-design investigation as part of their companion treatability study. To the extent feasible, Ramboll Environ and Tetra Tech will coordinate to gain efficiencies during the implementation of these activities. The pre-design field investigation activities include:

- Gaining the proper clearances to access the property and perform the investigation;
- Clearing the drilling locations for subsurface and overhead utilities;
- Performing a geophysical survey to guide the installation of soil borings and wells;
- Installing soil borings and monitoring wells to characterize the field test area and collect soil and groundwater to be used in the bench-scale testing (discussed in Section 5);
- Performing hydraulic testing to characterize hydrogeology in the field test area; and
- Managing investigation-derived wastes.

All field work described herein will be conducted in general accordance with the existing Field Sampling Plan, Revision 1 (ENVIRON, 2014b), the Site Management Plan (Ramboll Environ 2017c), and the Quality Assurance Project Plan (QAPP), Revision 2 (Ramboll Environ 2017b). Ramboll Environ, on behalf of NERT, will prepare and submit required applications and obtain required permits prior to field activities. Once approval is granted, an underground utility survey will be performed before drilling commences. All wells will be drilled in accordance with the Nevada Division of Water Resources (NDWR) requirements, following submittal of a Notice of Intent to Drill.

4.1 Objectives

The objectives of the pre-design activities include:

- Identify preferential flow pathways in order to properly locate and orient the field test and the performance monitoring well network;
- Characterize the hydrogeology in sufficient detail to refine the conceptual field test design;
- Assess localized vertical and horizontal distribution of perchlorate, chlorate, and other contaminants to target remediation accordingly;
- Characterize the baseline geochemical and biological conditions in the field test area; and
- Collect representative soil and groundwater from the field test area for use in bench-scale testing (see Section 5).

4.2 Access Agreement

Because the field test area is not located on property owned by the Trust, access and user agreements for all pre-design field investigation activities will need to be negotiated with the property owner, Basic Environmental Company, LLC (BEC). Access requirements are further discussed in Section 7.1.

4.3 Utility Clearance

Ramboll Environ 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 advancing the borings. Boring locations may be adjusted in the field based on the findings of the geophysical locator and utility locator service to avoid existing utilities, structures, or other site features. Prior to drilling, each location will also be cleared to a depth of 5 feet bgs either by hand augering or air knife operations.

4.4 Geophysical Survey

Surface geophysical surveys will be performed to chart the depth to the UMCf in an effort to identify potential paleochannels for the purposes of adjusting placement of soil borings and monitoring wells as well as the dimensions and orientation of the field test. One of the lessons learned during previous treatability studies (Tetra Tech 2016a) was that improved definition of preferential flow pathways and paleochannel morphology was needed prior to implementation of the field tests.

Time domain electromagnetic (TDEM) soundings have been successfully used to identify the top of the UMCf in prior treatability studies (Tetra Tech 2016b), and will be utilized to characterize the top of the UMCf and identify potential preferential flow pathways associated with paleochannels in the vicinity of the proposed field test area. The TDEM method has been used to successfully identify paleochannels in the UMCf in the Eastside Sub-Area (GEOVision 2003) including portions of the paleochannel that is mapped within the proposed field test area. However, the transect lines from the 2003 geophysical survey were located too far south to be of direct use for the purposes of this study.

Three transect lines are proposed in the vicinity of the field test area, as presented in Figure 5. The results of the geophysical surveys will be used to select appropriate locations for boreholes and monitoring wells to further characterize the subsurface conditions within the field test area. Soil borings will be advanced for additional characterization of the field test area and to confirm the geophysical survey interpretations (see Section 4.5.1).

4.5 Installation of Soil Borings and Monitoring Wells

Informed by the results of the surface geophysical surveys described in Section 4.4, soil borings and monitoring wells will be installed throughout the field test area to characterize local subsurface conditions and provide critical data for the design and alignment of the field test.

4.5.1 Soil Borings

Soil borings will be advanced to obtain area-specific lithological information, physical parameters, and chemical concentrations. Additionally, during boring installation, soil will be collected, preserved, and transported to the laboratory for use in the bench-scale tests (described in Section 5).

As described in Section 2.5.4, the water table generally occurs within the UMCf near the northern and eastern portions of the Eastside Sub-Area, where the alluvium has become dewatered. A review of available information indicates that the water table is in the uppermost portion of the UMCf in the vicinity of the field test area. Therefore, soil and groundwater sampling and analysis efforts will focus on the UMCf. If saturated alluvium is encountered within the field test area, then both pre-design investigation, bench-scale testing, and field testing will also include the alluvium as an additional focus of investigation and remediation.

Four soil borings will be advanced to perform detailed characterization of the unsaturated alluvium, saturated alluvium (where present), and the UMCf. These four soil borings will be advanced through the alluvium-UMCf contact (which is anticipated to be encountered at a depth of approximately 40 feet bgs) to a terminal depth of 120 feet bgs. The approximate locations of proposed soil borings are shown on Figure 5. Within each soil boring, shallow soil samples will be collected every 10 feet, but deeper soil samples will be collected at 1-foot intervals beginning 3 feet above the alluvium-UMCf contact to 20 feet below the contact. From 20 feet below the alluvium-UMCf contact to the terminal depth of 120 feet bgs, samples will again be collected on approximately 10-foot intervals.

An additional five soil borings will be advanced for additional characterization of the field test area and to confirm the geophysical survey interpretations, as shown on Figure 5. These soil borings will be advanced to a depth of 20 feet below the alluvium-UMCf contact (estimated terminal depth of 60 feet bgs). Soil samples will be collected every 10 feet unless field conditions indicate additional samples are warranted. Boring numbers and locations will be finalized after the geophysical surveys and subsurface clearing activities have been completed.

Soil samples will be analyzed for the parameters listed in Table 1. Soil retrieved using continuous core sampling equipment will be logged. For the four deep borings and other borings to be converted into monitoring wells (see Section 4.5.2), representative and relatively undisturbed samples will be selected for physical testing, which will include dry bulk density, specific gravity, grain density, total porosity, effective porosity, hydraulic conductivity, USCS soil classification, and grain size distribution.

Ramboll Environ will retain a licensed drilling contractor to advance the soil borings using rotosonic drilling methods to allow for the collection of continuous soil cores for lithologic logging and sampling. Before the drill rig mobilizes to each selected soil boring location, down-hole drilling equipment will be cleaned with a high-pressure, high-temperature water spray to avoid potential cross-contamination. As discussed above, soil borings will be advanced through the alluvium and penetrate into the top of the UMCf to evaluate soil conditions within the alluvium and interface of the alluvium and UMCf. A select number of soil borings will also be advanced further into the UMCf to evaluate soil conditions and perchlorate concentrations within the UMCf. The continuous soil cores will be logged by the on-site geologist from ground surface to total depth using the Unified Soil Classification System.

The drilling contractor will decontaminate soil collection 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.

Table 1. Proposed Soil Sampling Parameters

Parameter	Analytical Method	Purpose
Laboratory Parameters		
Perchlorate	E314.0	Estimate mass of perchlorate in saturated soil
TOC	SM5310B	Estimate available natural organic carbon
Soil pH	SW846 9045C	Assess geochemical conditions
Soluble Cations and Anions[1,2]	See Notes 1 and 2	Assess salt loading
TDS[2]	SM2540C	Assess salt loading
Dissolved Metals[3]	SW 846 6010/6020	Assess potential secondary impacts of treatment
Hexavalent Chromium	SW 846 7199	Assess potential secondary impacts of treatment such as mobilization potential of chromium into the groundwater under reducing conditions
Total Kjeldahl Nitrogen	Modified EPA Method 351.2	Evaluate potential nutrient availability in soil
Total Phosphorus	EPA 6010B	Evaluate potential nutrient availability in soil
PLFA	Microbial Insights Method[4]	Examine native/natural microbial characteristics
Perchlorate Reductase Gene	Quantitative Polymerase Chain Reaction (qPCR)	Examine native/natural microbial perchlorate degradation characteristics
Physical Soil Properties	Various	Assess physical properties of soils including dry bulk density, specific gravity, grain density, total porosity, effective porosity, hydraulic conductivity, USCS soil classification, and grain size distribution.

Acronyms and Abbreviations:

PLFA: Phospholipid Fatty Acids

TDS: Total dissolved solids

TOC: Total organic carbon

Notes:

1. Cations include sodium, potassium, calcium, and magnesium (Method SW6010). Anions include chloride, sulfate, nitrate (Method E300.0), carbonate, and bicarbonate (Method SM2320B).
2. Analysis to be performed on water extract prepared per method SW9056.
3. Metals include arsenic, chromium, iron, and manganese.
4. White 1995.

4.5.2 Monitoring Wells

Monitoring wells will be installed to evaluate the baseline groundwater conditions in the field test area and to monitor key parameters and how they respond during implementation of the field test. At a minimum, four wells will be installed, co-located with the four deep soil borings described in Section 4.5.1 and shown on Figure 5. If saturated alluvium is encountered, additional wells will be installed as paired wells with separate screened intervals in both the alluvium and UMCf. Additional borings described in Section 4.5.1 may also be converted to permanent monitoring wells. Decisions regarding which and how many borings to convert to monitoring wells and where paired wells will be installed will be based on geophysical survey data collected as described in Section 4.4 as well as review of the soil cores and lithology encountered during the soil boring installation. Additional monitoring wells will also be installed as part of the final design of the field test as discussed in Section 6.

Most of these wells will be constructed using 2-inch schedule 40 polyvinyl chloride (PVC) casing and screened with 2-inch diameter 0.020-inch slotted PVC well screen. The four wells co-located with the deep soil borings described in Section 4.5.1 will be installed with 4-inch diameter schedule 40 PVC casing and screened with 4-inch diameter slotted PVC well screen. These wells will be used for borehole dilution testing. The total depth and length of the well screens will be determined in the field based on the lithology and depth to groundwater. A washed #3/16 sand filter pack will be installed in the annular space around the well screens and extend up to two feet above the top of the screen intervals. The screen slot size and filter pack may be adjusted based on the lithology depth and results of depth-discrete sampling. The remainder of the annular space will be backfilled with two feet of hydrated bentonite, followed by neat cement grout. Wells will be completed with flush-mounted, tamper-resistant (locked), traffic-rated well boxes, at an elevation approximately one-half inch above grade.

Following the completion of well construction, but no sooner than 24 hours after well construction is complete, newly installed wells will be developed. 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 to purge the well of fine-grained sediment. Well development will be considered complete when three to ten 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 units and other parameters within 10 percent) over three consecutive measurements. All parameter readings will be recorded on well development logs.

Following well development, groundwater will be sampled and analyzed for a variety of field and laboratory parameters, described in more detail in Section 5, to establish baseline conditions.

Following installation of all groundwater monitoring wells, 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 North American Vertical Datum 88 with accuracies of 0.1 foot and 0.01 foot, respectively.

4.6 Hydraulic Testing

Hydraulic testing will consist of single borehole dilution tests, slug tests, and nuclear magnetic resonance (NMR) logging. Each of these methods have been used extensively during previous investigations conducted on behalf of the Trust.

4.6.1 Single-borehole Dilution Test

A single-borehole dilution test will be performed in each of the four newly installed 4-inch monitoring wells to evaluate volumetric flow in the UMCf and/or alluvium within the field test area. Results of the single-borehole dilution tests will be used to determine appropriate flow rates to be used in the field test design.

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 (e.g., Pitrak et al., 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.

Tracers used in single-borehole dilution tests are typically chloride or bromide salts, or fluorescent dyes. During the prior bioremediation treatability studies' preliminary testing activities, distilled water was successfully used as the tracer in five monitoring wells. Recent water quality results indicate that groundwater near the proposed treatability study location has a specific conductance generally ranging from 8,000 to 38,000 microsiemens per centimeter (AECOM 2017). The fairly high specific conductance would support the potential use of distilled water as a tracer. Water samples collected after well installation will therefore be analyzed for major cations and anions to confirm the suitability of distilled water as a tracer prior to use. If the specific conductance is low enough that distilled water would not serve as an appropriate tracer, other appropriate tracers will be evaluated.

4.6.2 Slug Tests

Slug tests will be performed in all newly installed wells to estimate location-specific aquifer hydraulic conductivity within the field test. The slug tests will be performed in accordance with American Society for Testing and Materials (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 or 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. For wells where the water table exists within the well screen, the falling head test will not be used (Butler 1998). Falling head and rising head tests should be repeated when possible. 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.

4.6.3 Nuclear Magnetic Resonance Logging

NMR logging will be performed on the newly installed wells. This technology can be used in open or PVC-cased 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 will provide a measurement approximately every 1.5 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 the possibility of vertical preferential flow.

4.7 Management of Investigation-Derived Wastes

Investigation-derived waste generated during the soil and groundwater investigation 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 2014b).

The investigation-derived waste that will be generated during the environmental investigation includes soil cuttings, personal protective equipment, equipment decontamination water, and groundwater generated during depth-discrete groundwater sampling and well development. Investigation-derived soil waste will be accumulated 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 quantity of material, one sample may be sufficient for characterization, or several samples may be composited in the field. Generally, a minimum of one sample will be collected for each 10 cubic yards of solid waste or each roll-off bin. Waste sample analysis will be determined by the receiving waste facility's analysis requirements. Waste water generated during purging or decontamination activities will be temporarily stored in 55-gallon drums and analyzed to determine the appropriate method of disposal. Previous treatability studies have generated waste water suitable for transfer into the GW-11 Pond. Drums, bins, and tanks will be labeled with "pending analysis" labels, the date accumulation began, contents source, and contact information, and stored in a designated area. Management of IDW will be performed in accordance with the requirements of the access agreement and the Trust's IDW Management Plan.

5. BENCH-SCALE TESTING

The following sections describe the proposed laboratory bench-scale testing program, which will provide information necessary to design and implement the field test program outlined in Section 6. The bench-scale testing program may be refined following the pre-design field investigation described in Section 4 of this work plan.

A phased approach is proposed for the bench-scale testing program such that knowledge gained in preceding tests may be used to inform subsequent tests; however, where appropriate to do so, tests will be performed in parallel to minimize the duration of the program. The bench-scale testing program consists of the following steps:

1. **Baseline characterization testing** of soil and groundwater collected from the field test area will be performed to assess concentrations of key chemical parameters important for subsequent batch microcosm and column testing.
2. **Batch microcosm testing** will be performed using soil and groundwater from the alluvium and UMCf collected during pre-design activities to demonstrate applicability of perchlorate biodegradation by ZVI under site conditions; assess acclimation times and biodegradation rates; and test effects of varying ZVI dose, nitrate, and other variables important for designing column and field tests.
3. **Flow-through column testing** will be performed using conditions established during batch microcosm testing to assess performance under dynamic flow conditions (simulating different residence times) and evaluate potential for clogging due to precipitation or biofouling in order to determine design parameters for the field test. The column testing design will also consider the results of hydraulic testing conducted during the pre-design field investigation.
4. **Geochemical and reactive transport modeling** will be performed to evaluate the performance and longevity of ZVI under site-specific conditions and to assist in design, performance evaluation, and system operation and monitoring.

The batch and column tests will be conducted at UNLV under the direction of Jacimaria R. Batista, Ph.D., PE using soil and groundwater collected during the pre-design field investigation. Dr. Batista has performed previous bench-scale treatability studies on behalf the Trust. Ramboll Environ will perform the data evaluation and geochemical and reactive transport modeling as described in Section 5.5.

5.1 Objectives

The bench-scale testing is an initial step in assessing the applicability of ZVI to promote biological reduction of perchlorate, chlorate, and other co-contaminants under site conditions. Information obtained from the bench-scale testing will be applied to the design and implementation of the field test (described conceptually in Section 6). While each test described herein will have its own specific objective(s), the primary objectives of the bench-scale testing include the following:

- Evaluate and determine the ZVI amount that promotes effective biodegradation of perchlorate and co-contaminants.
- Estimate the degradation rates of perchlorate and chlorate under approximate site geochemical conditions.

- Assess the effects of nitrate on perchlorate and chlorate degradation rates.
- Determine whether other amendments are required to limit potential negative impacts of nitrate and other competing constituents or otherwise enhance the performance of ZVI.
- Estimate potential impacts of secondary mineral precipitation and biofouling on longevity and performance under approximate site conditions.
- Improve and refine the field test and estimate the performance and longevity during and beyond the treatability study time frame by using reactive transport modeling.

5.2 Baseline Characterization Testing

Baseline characterization testing will be performed using methods and procedures followed during previous treatability studies performed on behalf of the Trust as described in this section. Soil and groundwater will be collected during the pre-design investigation from the UMCf (and alluvium, if saturated) for use in the bench-scale tests. Soil samples will be collected using sterilized containers and hand shovels. To obtain approximately homogeneous soil samples representative of the formation sediments, approximately equal volumes of borehole cuttings from each drilling horizon (i.e., every five feet) will be mixed together in sterilized plastic pans using sterile hand shovels. Groundwater samples will be collected from monitoring wells installed during the pre-design field investigation in accordance with the Field Sampling and Analysis Plan (ENVIRON, 2014b). Samples will be transported to UNLV on ice and stored in a refrigerator at 4 degrees Celsius.

Prior to analysis, the soil samples will undergo extraction with deionized (DI) water. Extraction entails adding sequential amounts of DI water to the samples and extracting the water using a centrifuge. Experience with soil from the NERT site has shown that rinsing a 30 gram (g) soil sample with 20 milliliters (mL) of DI water, followed by centrifugation to extract the water, repeated three times, is sufficient to remove the bulk of the contaminants. This procedure will be tested with samples collected during the pre-design field investigation and adjusted as needed. The extracted water from the soil and the groundwater samples will be analyzed for the parameters listed in Table 2.

Table 2. Analytical Methods to Analyze Groundwater and Soil Extracts

Parameter	Method Number	Equipment
COD	8000	Spectrophotometer (Hach DR 5000)
Nitrate	10020	Test ‘N Tube™ Vials
Ammonia	10205	Spectrophotometer (DR 5000)
Perchlorate and chlorate[1]	314.0	Ion Chromatograph (Dionex ICS-2000)
Phosphate	8048	Spectrophotometer (DR 5000)
Sulfate	8051	Spectrophotometer (DR 5000)
Total Iron	8008	Spectrophotometer (DR 5000)

Parameter	Method Number	Equipment
Hexavalent Chromium	8023	DR-900 Hach Colorimeter
Total Nitrogen	10071	Spectrophotometer (DR 5000)
TDS	160.1	Conductivity meter
pH	8156	pH Electrode
Total chromium	SM 3000	Thermo iCAP 6300 ICP-OES
Chloride	8225	Burette Titration

5.3 Batch Microcosm Testing

Batch microcosm testing can be used to test a number of variables in a relatively short period of time. Numerous small bottles are filled with site-specific soil and groundwater and spiked with the treatments intended to be tested. They are sealed and agitated as necessary to establish a well-mixed, but closed, micro-environment. At designated times the prepared bottles (the “microcosms”) are sacrificially sampled, i.e., all of the bottle contents are consumed during analysis; thus, numerous microcosm bottles compose a single test.

Following baseline characterization of the groundwater and soil samples (described in Section 5.2, batch microcosm tests will be conducted in two phases (plus a third contingency phase if deemed necessary), as summarized in Table 3.

Table 3. Summary of Batch Microcosm Tests

Phase	Description	Objectives
1	Sacrificial batch microcosms using site soil and groundwater varying ZVI dosage at high and low perchlorate concentrations. Addition of organic carbon (emulsified oil, acetate, and/or molasses) will be investigated in a subset of the batch microcosms.	Evaluate and demonstrate applicability of perchlorate biodegradation by ZVI under site conditions. Estimate perchlorate degradation performance for various dosages of ZVI. Evaluate ZVI corrosion rate and hydrogen generation with geochemical conditions representative of the study area. Determine the impacts of organic carbon amendment, mixed with ZVI, on reducing acclimation times and enhancing biodegradation. Evaluate secondary mineral precipitation and biomass formation.
2	Sacrificial batch microcosms using site soil and groundwater varying nitrate concentration at high and low perchlorate concentrations. Dosage of ZVI used will be determined in Phase 1. Addition of organic carbon will be investigated in a subset of the batch	Evaluate the impacts of varying nitrate concentration on ZVI performance. Verify the Phase 1 batch microcosm objectives in the presence of nitrate.

Phase	Description	Objectives
	microcosms using maximum anticipated nitrate concentration.	
3	Contingency Phase. If results from Phase 1 and/or Phase 2 are inconclusive, sacrificial batch microcosms using site soil and groundwater, evaluating other potential controlling factors will be initiated.	Investigate other potential controlling factors such as chlorate, chromium, sulfate, and calcium. Other factors may be investigated based on findings from the pre-design field investigation and Phase 1 and 2 batch microcosm tests.

5.3.1 Methods and Materials

Batch microcosm tests will be performed as sacrificial microcosms using blended soil and groundwater collected from the proposed field test area amended with ZVI and ancillary amendments (as specified). Once baseline concentrations of perchlorate, nitrate, chromium, and chlorate are determined in the groundwater and aquifer solids, an approximate amount of required ZVI will be calculated from stoichiometric biodegradation reactions. Dissolved oxygen concentrations also will be measured and included in the calculation of electron donor demand. Once the stoichiometric amount is calculated, then ZVI amounts varying between 10-100 times the stoichiometric amount will be tested in preliminary batch tests to select appropriate ZVI amounts for subsequent testing. Baseline concentrations of dissolved nitrogen and phosphorous will be measured to evaluate potential macronutrient demand. If macronutrients are determined to be necessary, a mixture of diammonium phosphate and or urea will be used as a nutrient source in the laboratory microcosms testing. In the nutrient requirement calculations, a typical bacterial cell composition of $C_5H_7O_2N$ will be assumed.

Each batch microcosm test will include approximately 30 g of wet soil. The soil will be transferred into autoclaved 125 ml borosilicate bottles. Depending on the moisture of the saturated zone soil samples, the volume of added groundwater will be adjusted to provide a consistent liquid:solid ratio. Approximately 100 mL of groundwater will be added to each bottle followed by addition of the calculated amount of oil or soluble substrate (if specified). The bottles will be flushed with nitrogen or helium gas for 15 minutes to remove oxygen. Finally, ZVI will be added and bottles will be closed with a butyl rubber cap and crimped sealed with an aluminum ring. Bottles will be wrapped in aluminum foil and placed in a rotary shaker to mix at 23℃ ± 2℃. At established time intervals, the bottles will be taken out of the shaker and sacrificially sampled. The contents of the bottles will be extracted using a combination of centrifugation and filtration. The bottle contents will be transferred to a refrigerated centrifuge and extracted for analysis. The extracted water will be analyzed or preserved for future analysis. Part of the extracted water and soil from the first and last sacrificial microcosm bottles will also be examined for total bacterial counts and speciation of perchlorate, nitrate, and sulfate reducing bacteria.

5.3.2 Phase 1 Batch Microcosm Tests

The phase 1 batch microcosms will examine the applicability of perchlorate reduction by various amounts of ZVI based on site-specific concentrations of perchlorate, chlorate, and co-contaminants. Various treatment mixtures (specified percentages) will be examined by changing ZVI:perchlorate stoichiometric ratios. If initial tests indicate that an amendment is required to reduce negative impacts of nitrate or other constituents, the amendment mixtures also will be evaluated. Phase 1 of the batch tests will determine the first estimate of ZVI treatment composition and operational perchlorate concentration range. The necessity of organic carbon for establishing bacterial cell growth will also be evaluated. The information obtained from phase 1 microcosms will be used to design and conduct phase 2 microcosms. Phase 1 testing is anticipated to take 6-8 weeks.

5.3.3 Phase 2 Batch Microcosm Tests

The phase 2 batch microcosms will evaluate the impact of nitrate on ZVI performance with and without an organic carbon source for support of cell growth. Specifically, phase 2 microcosms will be conducted to evaluate the impacts of high concentrations of nitrate on the biodegradation kinetics and to determine the extent in which nitrate will constrain the perchlorate/chlorate degradation process.

Because nitrate is an important competitor/inhibitor as described in Section 3.6, it is important to estimate the effects of nitrate concentration (measured as perchlorate:nitrate ratio) on ZVI performance. Phase 2 microcosms will assess ZVI dosage while varying concentrations of perchlorate and nitrate within representative field concentration ranges. The higher and lower perchlorate:nitrate ratios will be established based on a statistical analysis of field data. The effect of adding an organic carbon source in the presence of nitrate will also be assessed.

Phase 2 results will be used to further refine the first estimation of ZVI treatment composition obtained from phase 1. The testing process in both phases are an iterative process and will be reviewed and adjusted at each step based on the outcomes of previous steps. Phase 2 testing is anticipated to take 4-6 weeks. Some of the tests in phases 1 and 2 can be conducted concurrently.

5.3.4 Phase 3 Batch Microcosm Tests

The phase 3 batch microcosms are a contingency phase. If phase 1 and 2 batch tests fail to define effective and consistent conditions for perchlorate biodegradation, phase 3 batch tests will be conducted to determine and investigate the effect of other factors (e.g., hexavalent chromium, chlorate, sulfate, calcium) on ZVI performance. The ZVI treatment composition obtained from phase 1 and 2 batch tests will be used to conduct phase 3 batch tests.

As discussed in Section 3.6, previous biodegradation testing performed by UNLV on behalf of the Trust has demonstrated that the degradation sequence for common chemicals in groundwater at the NERT site is 1) hexavalent chromium, 2) nitrate, 3) chlorate, 4) perchlorate, 5) sulfate (Batista 2017). Competition of these electron acceptors with perchlorate decreases degradation of perchlorate and thereby reduces the ZVI reduction capacity (Liu, Ptacek, and Blowes 2014). Also, studies show that presence of calcium may promote perchlorate reduction by ZVI, presumably by buffering pH at the biologically favorable range. To evaluate these other potentially controlling factors, the phase 3 batch microcosms will vary the concentration of some or all of these factors at pre-determined ZVI treatment composition. The results of the pre-design field investigation will also be reviewed to determine if there may be any other constituents that could impact ZVI performance that may need to be evaluated as part of the phase 3 batch tests.

The ZVI treatment composition estimated in phases 1 and 2 will be updated and revised as necessary based on phase 3 results. Phase 3 of microcosms are anticipated to run for 4-6 weeks.

5.3.5 Batch Microcosm Test Sampling Plan

Table 5 outlines the proposed plan for sampling and analysis of the microcosm batch tests. Specific sampling procedures and analytical methods will be developed in collaboration with UNLV. Sampling frequencies may be adjusted depending on observed degradation rates.

Table 4. Proposed Sampling Plan for Batch Microcosm Testing

Parameter	Purpose	Frequency
Water quality	Assess general water quality/geochemistry (Specifically measure DO, ORP, pH, electrical conductance, turbidity, temperature)	Baseline plus every two days
Perchlorate, Chlorate, Nitrate, Chromium	Assess treatment effectiveness	Baseline plus every two days
Total Organic Carbon	Assess carbon in the aquifer	Baseline plus every two days
Dissolved hydrogen	Electron donor assessment	Baseline plus every two days
Total Dissolved Solids	Assess any impact of salts	Baseline, middle, and end of tests
Nitrate, Sulfate	Assessment of competing electron acceptors	Baseline plus every two days
Total N and P	Examine the need for micronutrients	Baseline plus every two days
Alkalinity, Fe^{2+}, Methane, Sulfide	Examine secondary geochemical impacts	Baseline, middle, and end of tests
Dissolved Metals (partial)	Assess secondary impacts of treatment (includes As, Mn, and CrVI)	Baseline, middle, and end of tests
Dissolved Metals (full)	Examine geochemical conditions in detail for modeling (Requires full list of major dissolved metals: Ag, As, B, Ba, Be, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Mo, Mg, Mn, Na, Ni, Pb, Sb, Se, Tl, Zn), and U)	Source water and selected microcosms (to be determined)
Chloride	Potential estimation of conservative end-product of biodegradation	Baseline plus every two days
Microbial Testing	Examine microbial community responses to amendments (target reductase and chlorite dismutase plus community profile, PLFA)	Baseline and end of tests; additional as necessary

Notes:

1. Analytical methods will be identified in collaboration with UNLV. Frequency may be adjusted.
2. Quality Assurance/Quality Control (QA/QC) plan will be developed in collaboration with UNLV. It is anticipated that duplicates will be run on 5% of the solution samples for certain analyses critical to effectiveness monitoring, e.g., perchlorate and chlorate. Typical QA/QC runs will consist of blanks, daily calibration check samples, and runs of standard reference materials, when available.

5.4 Column Testing

Following the completion of the batch microcosm tests, flow-through column testing will be conducted. The column testing will be used to assess the effectiveness of a flow-through ZVI system simulating field conditions, providing additional information useful in the design of a remedial approach. Specifically, the column testing will be used to refine design parameters and investigate the following:

- Assess the necessary residence time for ZVI in contact with contaminated groundwater in order to achieve necessary performance.
- Evaluate the hydraulic behavior of ZVI treatment matrix and potential permeability decreases (clogging) due to secondary mineral precipitation and biofouling.
- Estimate perchlorate degradation rate under simulated field conditions and assess the breakdown products to rule out incomplete contaminant degradation in a flow through system.
- Assess the potential for metals mobilization.
- Compare the flow-through system performance with the data and observations from the batch microcosm tests, and provide information to project likely performance of the field test implementation and potential full-scale design.
- Evaluate the need for possible sequential treatment and/or potential needs for pre- or post-treatment provisions (e.g., to remove nitrate in-situ prior to a perchlorate treatment zone) to meet performance goals.
- If necessary, evaluate organic carbon types and dosage to provide carbon for bacterial cell growth.

The column tests will provide a greater degree of understanding of the potential issues (e.g., clogging caused by secondary mineral precipitation and/or biofouling) that could arise during the field test and full-scale implementation. Moreover, potential engineering solutions will be simulated in the column tests. This section describes the currently anticipated simulation conditions, which might be adjusted based on the results of the batch microcosm tests and the pre-design field investigation. Table 5 below summarizes the proposed column testing program.

Table 5. Summary of Column Tests

Column	Description	Objectives
1	Flow-through column test of ZVI using site soil and groundwater varying flow rates to simulate alluvial flow conditions.	Determine ZVI performance for average and short residence time conditions. (The specific residence times will be established following the pre-design field investigation.)
2	Flow-through column test of ZVI using site soil and groundwater varying flow rates to simulate UMCf flow conditions.	Determine ZVI performance for long residence time condition. (The specific residence time will be established following the pre-design field investigation.)
3	Flow-through column test of ZVI using site soil and groundwater simulating the injection of organic carbon to enhance performance by providing carbon for bacterial cell growth.	Determine organic carbon source type and required stoichiometric amount.
4	Flow-through column test of ZVI using site soil and groundwater simulating a hybrid system employing solid organic carbon to enhance performance by providing carbon for bacterial cell growth.	Determine organic carbon source type and required stoichiometric amount.

5.4.1 Methods and Materials

A set of four columns are anticipated to be used to evaluate biological reduction of perchlorate under site-specific conditions. The columns will be built of transparent PVC to allow visual observations to be made. The dimensions of the columns will be determined in collaboration with UNLV following the pre-design field investigation. Specific details of the experimental design and column build-out will also be done in collaboration with UNLV and will be re-evaluated and adjusted based on the results obtained from the batch microcosm tests. In general, the columns will be packed with the following types of solids:

- Coarse silica sand (-8 to +50) (e.g. Monterey Sands);
- Coarse granular ZVI (-8 to +50);
- Soil collected from a representative saturated zone in the UMCf (and alluvium, if saturated); and
- Other materials as necessary (e.g., organic carbon to stimulate cell growth).

Packed columns will be fed from the bottom with groundwater from the field test area to ensure full saturation of the pore volume. The applied pressure will be adjusted based on the solid material composition of the packed columns. Porosity and hydraulic conductivity of the columns will be measured before and after the tests. To estimate hydraulic conductivity, falling head permeameter tests will be conducted. Groundwater collected during the pre-design field investigation will be stored at the laboratory in sufficient quantities at 4˚C until time of use.

5.4.2 Column Test Operating Conditions

The results of the pre-design field investigation and batch test results will be used together to establish the column test operating conditions (e.g., flow rates). Based on existing data, the columns will be operated at a constant temperature so that groundwater and the test columns will be maintained at temperatures similar to those present at the field test area (~25˚C).

Column tests are anticipated to run for 12-16 weeks. One or more may be selected to run for a longer duration depending on the initial test run. The columns will be checked each week day to ensure proper flow and general operation.

5.4.3 Column Study Sampling Procedures

Table 7 outlines a proposed sampling plan for the column tests. Specific sampling procedures and analytical methods will be developed in collaboration with UNLV. Effluent flowrate will be measured daily. Sampling frequencies may be adjusted based on initial results. Perchlorate and chlorate will only be analyzed when nitrate concentrations are less than 1 mg/L, but earlier effluent samples (i.e., collected before nitrate concentrations are less than 1 mg/L) will be preserved for perchlorate analyses at a later date, if needed. Column effluent monitoring may be adjusted based on the results of baseline characterization (described in Section 5.2).

Table 6. Proposed Sampling Plan for Column Testing

Parameter	Purpose	Frequency
Water quality	Assess general water quality/geochemistry (Specifically measure DO, ORP, pH, electrical conductance, turbidity, temperature)	Source water baseline Influent: daily Effluent: daily
Perchlorate, Chlorate	Assess treatment effectiveness	Source water baseline Influent: 2x per week Effluent: 2x per week
TOC / COD	Assess carbon in the aquifer	Source water baseline Influent: 2x per week Effluent: 2x per week
Dissolved hydrogen	Electron donor assessment	Source water baseline Influent: 2x per week Effluent: 2x per week
Total Dissolved Solids	Assess any impact of salts	Source water baseline Influent: every 2 weeks Effluent: every 2 weeks
Nitrate, Sulfate	Assessment of competing electron acceptors	Source water baseline Influent: 2x per week Effluent: 2x per week
Total N and P	Examine the need for micronutrients	Source water baseline Influent: 2x per week Effluent: 2x per week
Alkalinity, Fe^{2+}, Methane, Sulfide	Examine secondary geochemical impacts	Source water baseline Influent: 2x per week Effluent: 2x per week

Parameter	Purpose	Frequency
Dissolved Metals (partial)	Assess secondary impacts of treatment (includes As, Mn, and CrVI)	Source water baseline Influent: 2x per week Effluent: 2x per week
Dissolved Metals (full)	Examine geochemical conditions in detail for modeling (Requires full list of major dissolved metals: Ag, As, B, Ba, Be, Ca, Cd, Cr, Co, Cu, Fe, Hg, K, Mo, Mg, Mn, Na, Ni, Pb, Sb, Se, Tl, Zn), and U)	Source water baseline Influent: every 4 weeks Effluent: every 4 weeks
Chloride	Potential estimation of conservative end-product of biodegradation	Source water baseline Influent: 2x per week Effluent: 2x per week
Microbial Testing	Examine microbial community responses to amendments (target reductase and chlorite dismutase plus community profile, PLFA)	Source water baseline Influent: every 4 weeks Effluent: every 4 weeks
Porosity of packed column	To assess clogging/biofouling	Before and after column tests
Hydraulic conductivity of packed column	To assess clogging/biofouling (falling head permeameter test)	Before and after column tests

Notes:

1. Analytical methods will be identified in collaboration with UNLV.
2. Quality Assurance/Quality Control (QA/QC) plan will be developed in collaboration with UNLV. It is anticipated that duplicates will be run on 5% of the solution samples for certain analyses critical to effectiveness monitoring, e.g., perchlorate and chlorate. Typical QA/QC runs will consist of blanks, daily calibration check samples, and runs of standard reference materials, when available.

5.5 Geochemical and Reactive Transport Modeling

The biogeochemical processes associated with perchlorate reduction by ZVI are coupled with flow and transport. Assessing performance of a ZVI groundwater treatment system requires integrating these complex, often kinetically-limited, biogeochemical processes within a heterogeneous flow field. Geochemical and reactive transport modeling provides insight into these processes allowing improved assessment of the performance of ZVI systems.

Comprehensive, process-based reactive transport modeling is a versatile tool for evaluating and improving conceptual models of in-situ groundwater treatment systems (K. Ulrich Mayer, Blowes, and Frind 2001; Williams et al. 2007). By simultaneously accounting for the physical transport processes and a suite of biogeochemical reactions, both kinetic and equilibrium controlled, while maintaining stoichiometric and system mass balance, a level of evaluation of complex systems can be achieved that would not otherwise be possible (Steefel et al. 2015). Reactive transport models are commonly used for the quantitative investigation of flow, transport and reaction processes in porous media. These models are used to evaluate experiments, design remedial systems, and assist with the interpretation of field data (Boudreau, Meysman, and Middelburg 2004;

Kang, Lichtner, and Zhang 2006; MacQuarrie and Mayer 2005; Steefel et al. 2003; Wang and Van Cappellen 1996).

5.5.1 Approach

The MIN3P code (K.U. Mayer et. al 2002, 2014), as discussed below, is anticipated to be used to evaluate the performance and longevity of a ZVI system to treat perchlorate/chlorate under site-specific conditions. One- and two-dimensional models will be used with batch and column testing data to establish a geochemical conceptual model of the system. This geochemical conceptual model will assist in design improvement, performance evaluation, and system longevity by providing information about kinetic reaction pathways, geochemical and biological inhibition factors, by-products and end-products evaluation in the reactive zone and downgradient, ZVI passivation by secondary mineral precipitations and biofilm growth (biofouling) and their effect on clogging and permeability reduction in long term. These objectives will be achieved in a stepwise manner by gradually increasing the bio-physio-chemical complexity of the conceptual model. The following approach is proposed:

- Develop an initial geochemical model based on bench-scale testing and prepare an equilibrium model suitable for the field test area geochemistry and at a reducing/high pH environment;
- Develop a geochemical model based on bench-scale testing ;
- Construct one/two-dimensional reactive transport models to investigate the effect of nitrate reduction and clogging on perchlorate/chlorate reduction, longevity and effectiveness of field test based on bench-scale testing;
- The models will be used for series of sensitivity and scenario analysis to evaluate and quantify the system behavior with respect to most likely as well as extreme bio-geochemical and hydrogeological conditions;
- The models will be used to evaluate the performance of the field test.

The MIN3P code was developed as a multicomponent reactive transport model for variably-saturated porous media in one, two or three spatial dimensions and three phases (solid-liquid-gas). The model can also be used as a batch model for equilibrium speciation problems, kinetic batch problems or for the generation of pC-pH-diagrams. MIN3P has been used by research groups, federal agencies and consulting companies to simulate performance of permeable reactive barriers for different applications as well as contaminants like chromium, TCE, PCE, inorganic compounds, acid mine drainages, generation and attenuation of acid rock drainage in mine waste (K.U. Mayer, Frind, and Blowes 2002), source zone natural attenuation of hydrocarbon spills in variably saturated media, land application of food processing waste water, and biogeochemical cycling of silicon in forest soils (Steefel et al. 2015).

MIN3P is characterized by a high degree of flexibility with respect to the definition of the geochemical reaction network to facilitate the application of the model to a wide range of hydrogeological and geochemical problems. Chemical processes included are homogeneous reactions in the aqueous phase, such as complexation and oxidation-reduction reactions, as well as heterogeneous reactions, such as ion exchange, surface complexation, mineral dissolution-precipitation and gas exchange reactions. Reactions within the aqueous phase and dissolution-precipitation reactions can be considered as equilibrium or kinetically-controlled processes. Microbially-mediated reactions can be described using a multiplicative Monod approach (K.U. Mayer et al. 2014).

5.5.2 Data Requirements

The data being collected during the pre-design field investigation and bench-scale testing are sufficient for the reactive transport model development. Additional sequential extraction testing to estimate sorption capacity of the solid phase would be required if surface complexation is to be modeled. Surface complexation does not play a role in perchlorate/chlorate remediation; however, it does play a role in chromium treatment or possible arsenic release from the native aquifer materials. If bench-scale testing suggests that these processes may be important, additional data collection may be considered. Mineralogical testing (e.g. presence of carbonates that may interact with a high pH environment) also can provide supplementary information in cases where unanticipated results are encountered during bench-scale testing.

6. FIELD TEST CONCEPTUAL DESIGN

The following sections outline the conceptual design of the field test that will follow the bench-scale testing. The field program described herein is conceptual and will be further developed following the evaluation of both the bench-scale testing and the pre-design field investigation work described in this work plan. Prior to implementing the field test, a Work Plan Addendum presenting the final field test design (including any modifications to the proposed conceptual design) will be submitted to NDEP, as discussed in Section 9. The conceptual design includes:

- Conceptual approach;
- Overview of the field test design objectives;
- Description of the field test location;
- Conceptual layout and overview of the field test design components;
- Preliminary design considerations;
- Description of performance monitoring, including both groundwater quality monitoring and hydraulic monitoring; and
- Performance evaluation methods.

The performance monitoring program may be modified or refined based on the results of the pre-design field investigation and the bench-scale testing. All field work will be conducted in accordance with the requirements of the Field Sampling Plan, Revision 1 (ENVIRON, 2014b), the Site Management Plan (Ramboll Environ 2017c), and the Quality Assurance Project Plan (QAPP), Revision 2 (Ramboll Environ 2017b).

6.1 Conceptual Approach

The goal of the design will be to construct a field test comprised of ZVI (and other amendments if deemed necessary from bench-scale testing) that is to be operated as a passive flow-through system. Therefore, the system is intended to be designed to assure that the targeted portion of groundwater flow is intercepted by the treatment zone and that substantial flow beneath, around, or above the reactive zone does not occur, or at least does not occur beyond specified design tolerances. The system must also be designed such that the dimensions of the reactive zone are adequate to achieve the contact time between reactants and reactive media required to achieve a specified level of performance. Designing such a system requires understanding the site-specific hydrogeology and geochemistry, nature and extent of contamination, chemical properties, and specific performance characteristics the reactive media. Therefore, the pre-design field investigation (described in Section 4) and bench-scale testing (described in section 5) are integral steps in the field test design.

6.2 Objectives

The ZVI field test will be used to evaluate both design criteria and performance objectives for a potential full-scale application of the ZVI technology to mitigate migration of contaminants downgradient of the mid-plume containment boundary. The bench-scale testing will be used to develop design compositions for the ZVI treatment matrix that will be emplaced under field conditions. The field testing will evaluate configurations and/or compositions in the field, along with implementation/construction methods. The specific objectives of the conceptual field testing program are anticipated to include, but may not be limited to:

- Evaluate the feasibility and effectiveness of a ZVI treatment system installed within the UMCf (and alluvium, if saturated) to reduce perchlorate mass flux that is migrating through the Eastside Sub-Area at the mid-plume containment boundary.
- Evaluating system alignments and construction methods for constructability under field conditions.
- Evaluating geochemical and biochemical conditions to assess treatment effectiveness, geochemical/biochemical changes to the aqueous system including potential precipitation/mobilization of metals, and to assess the conditions that will affect longevity of the treatment.
- Evaluate what effects ZVI mass and configuration of the reactive zone have on dissolved hydrogen concentration and downgradient extent of influence.
- Evaluating hydraulic conditions for potential groundwater mounding and ability to maintain appropriate residence time (as established during bench-scale testing).
- Evaluating the appropriateness of selected monitoring parameters, as well as determining an appropriate monitoring interval for assessing system performance.
- Provide critical information applicable to the remedial alternatives evaluation in the forthcoming FS.

The field test is not necessarily intended to achieve final water quality objectives as may be defined in the final remedy, but rather to test the treatment method under field conditions and provide key design and performance criteria. Performance objectives therefore are to be defined based on the technical design requirements, and not solely on water quality criteria consistent with potential clean up goals for target constituents.

6.3 Field Test Location

The currently identified location for the field test will consist of an area approximately 2,400 feet wide (east to west) and 850-1250 feet long (north to south) located immediately south of Galleria Road along the approximate mid-plume containment boundary (Figures 3, 4, 5, and 6). This area was selected based on available access to the location, presence of concentrations of perchlorate in groundwater representative of the subject area for which a potential full-scale remedy would be considered; potential for having localized areas of saturated alluvium; ability to use heavy construction equipment; and would be close enough to, but would not interfere with, the parallel bioremediation treatability test being performed by Tetra Tech on behalf of NERT.

6.4 Conceptual Layout

The conceptual layout consists of separating the area into four sub-areas each approximately 600 feet wide (east to west) in which the different test conditions would be evaluated. The 600 feet width is established to provide sufficient distance so that the individual field tests will not hydraulically or geochemically influence neighboring tests. Within each sub-area, a field test gallery will be constructed consisting of a reactive treatment zone and an upgradient and a downgradient monitoring well network. The intent of these galleries is to test system alignments and construction/installation methods. The conceptual layout is shown in Figure 6. The ZVI test composition, including amount of ZVI to be installed, potential need for organic carbon to support bacterial cell growth, and/or the addition of other ancillary amendments will be selected based on the bench-scale testing results, as discussed in Section 6.5. The current conceptual design for each test gallery consists of the following components:

- Gallery 1 – an approximately 50-100 foot wide reactive zone oriented perpendicular to groundwater flow, using a trench or large diameter boring installation approach and intended to test application of ZVI in an area where the predominant mass flux is within the UMCf.
- Gallery 2 – an approximately 50-100 foot wide reactive zone oriented perpendicular to groundwater flow, using a trench or large diameter boring installation approach and intended to test application of ZVI in an area where a paleochannel may represent a preferential flow path. If saturated alluvium is not encountered in Gallery 2, this gallery may be used to test a reactive zone to treat vertical mass flux (see below).
- Gallery 3 – an approximately 50-100 foot wide reactive zone oriented perpendicular to groundwater flow, using a directional jet injection installation approach and intended to test application of ZVI in an area with no channelized flow focused primarily on the UMCf.
- Gallery 4 – reserved for a potential additional test gallery to be determined following bench-scale testing and the pre-design field investigation. For example, this gallery could be used to test a reactive zone designed to treat vertical mass flux (see discussion below) or could be used to test a nitrate pre-treatment zone if bench-scale testing results warrant further evaluation of such an option.
- Monitoring wells installed within each gallery (wells located upgradient, downgradient, and within each reactive zone) for monitoring treatment performance in each gallery.
- Monitoring wells installed outside the lateral extent of the galleries to assess water quality and hydraulic conditions outside of the galleries for control and to evaluate external conditions that may influence the test.

If saturated alluvium is encountered in any of the galleries, a well cluster will be installed to monitor groundwater elevations within both the alluvium and underlying UMCf to assess the vertical gradient and relative contaminant concentrations. If vertical mass flux is determined to be significant, then the gallery may be designed with a reactive zone oriented perpendicular to vertical flow, i.e., installed as a lens within the UMCf in close proximity to the alluvium-UMCf contact. A reactive zone in this orientation may be accomplished through directional jet injection techniques to fracture the formation radially from vertical wells. Gallery 2 may be used to test this approach in the event that saturated alluvium is not encountered. Appendix B contains information on the directional jet injection techniques that would be considered in this scenario.

In galleries 1 and 2, the decision as to the use of trench construction methods or large diameter borings will depend on the residence time and how much ZVI is necessary to achieve target conditions and what the subsurface conditions are like in the field test area. Higher groundwater velocities and higher perchlorate/chlorate/nitrate concentrations will require larger reactive zones. Large reactive zones with high ZVI content can be installed using trenches, but have depth and constructability limitations. Large diameter borings are more flexible, but they are not an efficient means to install large volumes of reactive media.

In gallery 3, directional jet injection as a method of ZVI emplacement would be evaluated to assess constructability and performance of such a system. The injection design would consist of a line of injection wells and directional jet injection from one well to the next to create a linear reactive zone. This method may be a successful means of efficiently installing ZVI deeper into the UMCf. Appendix B contains information on directional jet injection techniques.

The galleries will be oriented parallel to the predominant groundwater flow direction in the area. An exception to this configuration may be considered if groundwater velocities are found to be very high within a paleochannel. In this case, a reactive zone installed within and oriented in the same direction as the channel may be necessary to achieve the proper residence time. The dimensions of the reactive zone and the spacing of monitoring wells will depend on the results of the pre-design investigation and bench-scale testing. In Figure 6 the reactive zone is shown as a nominal 100 feet in width.

6.5 Preliminary Design Specifications

As noted previously, the location, dimensions, layout, content, and emplacement methods of this conceptual field test will require refinement following pre-design investigation and bench-scale testing of the approach. Following completion of the pre-design field investigation and bench-scale testing described in Sections 4 and 5, respectively, a Work Plan Addendum will be prepared presenting the final field test design. However, based on Ramboll Environ's previous experience with the technology, certain preliminary design specifications and options are discussed in this section.

For galleries 1 and 2, the trench method of installation would involve slurry wall construction techniques similar to how the barrier wall was constructed downgradient of the Interceptor Well Field (IWF) at the NERT site. The large diameter borings would use rotosonic drilling techniques to advance 8-inch diameter borings in an array to create a reactive zone. In both installation methods, careful backfilling of the ZVI mixture is important to avoid bridging and to maintain consistent ZVI content throughout the full vertical profile. Generally, if large diameter borings are used, higher percentages of ZVI are emplaced when compared to trenched systems. Ramboll Environ has used both installation approaches to emplace ZVI and stimulate biological reduction processes at other sites.

The ZVI test composition for trenched systems will likely be composed of a low percentage (likely between 10 and 50% by weight) of granular ZVI within the size fraction of -8 to +50 mixed with silica sand of a similar size composition. The ZVI mixture for large diameter borings will likely have higher percentages of ZVI. The ZVI emplaced via directional injections will likely not include silica sand, but may require a carrier liquid (typically potable water). If bench-scale testing results indicate that organic carbon or other ancillary amendments are necessary these would be introduced either upgradient or downgradient of the ZVI reactive zone to avoid potential clogging issues. These ancillary amendments are typically introduced via injection well.

This conceptual design may be modified based on the results of the bench-scale testing and pre-design field investigation. Alternative construction and implementation methods, as well as alternative reactive media compositions and/or configurations may be considered. For example, design enhancements, including gradational emplacement methods (higher permeability zones at the upgradient face) or sacrificial pre-treatment reactive zones (e.g., pea gravel ZVI/organic carbon systems) may improve effectiveness and longevity of a system under certain conditions. Hydraulically-induced flow, achieved via groundwater extraction, may also be necessary to achieve flow through the test galleries. This is sometimes necessary for small-scale test systems. Groundwater extraction would only be used to achieve flow for testing purposes; it is not anticipated that groundwater extraction would be part of a full-scale design.

6.6 Performance Monitoring Plan

The performance monitoring approach will be developed following the completion of bench-scale testing and as part of the design of the field test. The conceptual approach is to assess the two primary components of the treatment system – the treatment process and the hydraulic performance – by constructing and using a monitoring well network.

6.6.1 Performance Monitoring Wells

A monitoring well network, consisting of both upgradient and downgradient monitoring wells will be designed and installed to evaluate field test effectiveness. Upgradient monitoring wells will be used to determine the perchlorate concentrations in groundwater that are migrating into the test galleries. Downgradient monitoring wells will be installed at strategic locations downgradient of the reactive zone to monitor for treatment effectiveness. In addition to the wells discussed in Section 4.5.2, up to 16 additional monitoring wells may be installed at varying distances upgradient and downgradient of the test galleries. The exact number and location of performance monitoring wells may be modified based on the results of the slug tests and the single borehole tests, estimations of groundwater velocity, and other subsurface conditions in the area.

Monitoring wells will be constructed of 2-inch schedule 40 PVC casing and screened with 2-inch diameter 0.020-inch slotted PVC well screen and #3/16 filter pack. The slot size and filter pack may be adjusted based on the results of the soil physical parameter analyses. The depth of each well and length of well screen will be determined in the field based on lithology and depth to groundwater. Dual-nested or paired monitoring wells may be used to separate screened intervals, if conditions warrant. Wells will be completed with flush-mounted, tamper-resistant (locked), traffic-rated well boxes, at an elevation approximately one-half inch above grade. Following the completion of well construction, but no sooner than 24 hours after well construction is complete, the newly installed wells will be developed.

6.6.2 Groundwater Sampling Procedures

Groundwater sampling activities will follow the guidance of the Field Sampling and Analysis Plan (ENVIRON, 2014b). Prior to groundwater sample collection, groundwater levels will be gauged in all wells to be used in potentiometric contouring. Groundwater samples will be collected using low-flow purging and sampling techniques. During low-flow purging of the wells, purge rates are not to exceed 500 mL/min in order 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, dissolved oxygen, and oxidation reduction potential). Field parameters will be monitored and recorded on field sampling forms during purging.

6.6.3 Performance Monitoring

To establish baseline conditions, groundwater samples will be collected from all monitoring wells in the field test area as well as the following wells just outside the field test area (subject to availability/accessibility): DBMW-1, DBMW-3, AA-20, BEC-9, MCF-05, ES-10, and ES-11. After construction of the galleries has been completed, groundwater samples will be periodically collected from both upgradient and downgradient monitoring wells. A variety of field, laboratory, and microbial parameters that may be evaluated during the field test are listed in Table 7, which presents the parameters, associated methods, purpose, and potential sampling frequency.

Effectiveness monitoring wells will include newly installed monitoring wells, as well as existing monitoring wells, in the vicinity including wells installed in the vicinity of the field test area as part of the Phase 3 RI. Additionally, some or all of the monitoring wells installed during the pre-design field investigation may be sampled during the field test to assist in evaluating performance. The actual frequency of sampling, selected wells, and specific parameters to be sampled during each individual event will be determined during the test and based on the results from prior events. In addition, slug tests may be repeated periodically during the field test to examine any changes in hydraulic conductivity as a result of geochemical processes. Specialized microbial analyses, namely, PLFA analyses and the presence of the perchlorate reductase gene will be determined via the employment of Bio-Traps® in select wells during the study.

Table 7. Proposed Sampling Plan for Field Test Performance Monitoring

Parameter	Purpose	Frequency
Water quality	Assess general water quality/geochemistry (Specifically measure DO, ORP, pH, electrical conductance, turbidity, temperature)	Baseline plus weekly for first month; monthly after first month
Perchlorate, Chlorate	Assess treatment effectiveness	Baseline plus weekly for first month; monthly after first month
Total Organic Carbon	Assess carbon in the aquifer	Baseline plus monthly
Dissolved hydrogen	Electron donor assessment	Baseline plus monthly (to start at least one month after installation)
Total Dissolved Solids	Assess any impact of salts	Baseline, middle, and end of tests
Nitrate, Sulfate, Hexavalent Chromium	Assessment of competing electron acceptors	Baseline plus weekly to monthly after first month
Alkalinity	Assessment of available inorganic carbon	Baseline plus weekly for first month; monthly after first month
Full cation/anion list including ferrous and ferric iron	Assessment of general hydrogeochemistry for assessing longevity and mineralization and mass balance on chloride	Baseline plus monthly to quarterly after first quarter

Parameter	Purpose	Frequency
Microbial Testing	Examine microbial community responses to amendments (target reductase and chlorite dismutase plus community profile, PLFA)	Baseline and end of tests; additional as necessary

6.6.4 Hydraulic Monitoring

Hydraulic monitoring will be performed to assess the following key conditions:

- Hydraulic gradient within and adjacent to each test gallery;
- Prevalence of hydraulic mounding upgradient or within each test gallery;
- Prevalence of non-uniform flow (as determined by an analysis of continuity of hydraulic gradient combined with analysis of geochemical results in each test gallery); and
- Potential loss of permeability (as evaluated through the use of single well hydraulic tests, e.g., slug tests).

Water levels will be monitored at least weekly in all system wells for the first month, then monthly thereafter. The exception is that within 24 hours of a precipitation event of greater than 0.25 inches in a 6 hour time frame, water levels will be measured. Pressure transducers will be deployed in at least one upgradient well, one well within each test gallery, and at least one downgradient well in each test gallery to best characterize real-time hydraulic conditions. The mapping of hydrogen distribution will be evaluated to assess range of influence of the treatment (as a reflection of hydraulic conditions) from each gallery. Single well hydraulic tests will be performed on a subset of wells before and after the field test and as necessary during the test to assess the potential loss of permeability in the downgradient formation and/or within the reactive zones.

6.6.5 Hydraulic Modeling and Mass Flux Evaluation

In conjunction with groundwater monitoring, a groundwater model will be developed to assist with evaluating the effectiveness of the treatability study. The model, along with field data, will be used to estimate both the groundwater flux and chemical constituent flux through the treatment zones. The groundwater model results will be used, along with field data, to estimate the amount of perchlorate mass destroyed and amount of perchlorate mass that remains in the subsurface after the treatability study is completed. Specifically, the groundwater model for this Work Plan will be based on the Phase 6 groundwater flow and transport model (Phase 6 Model), which is scheduled to be completed by March 2018. The Phase 6 model will be modified to focus on the treatability study area by using grid refinement and site-specific material properties measured by field techniques and laboratory analyses, such as geophysics, NMR, slug tests, and physical properties. Once constructed, the modified groundwater model will be calibrated to the groundwater response to field tests conducted during this study. Then, this model will be used to calculate groundwater flux through treatment galleries to estimate perchlorate mass destroyed during the field test.

7. ACCESS AND PERMITTING REQUIREMENTS

Both an access agreement and multiple permits will be required prior to performing pre-design and field test implementation associated with this treatability study. This section presents a summary of the access and permit requirements that will likely be required for the implementation of the activities described in this Work Plan.

7.1 Access Negotiations

Due to the off-site location of the treatability study, the Trust will acquire land use authorization for all field activities. As described in Section 4.2, the proposed area for the pre-design and treatability study is located on land owned by BEC. As a result, Ramboll Environ, on behalf of NERT, will prepare and submit all required applications for access to this parcel in coordination with the Trust's attorneys. It should be noted that the treatability study location may be adjusted based on conditions prescribed by BEC.

7.2 Permitting

There will be a series of permits required for the various activities that are being proposed as part of the treatability study. In addition to the permits described herein, a review of other potential permitting requirements was conducted. Based on project design, several regulatory requirements likely will not apply. A review of installation activities associated with the pre-design and treatability study phases indicates that the soil disturbance will be less than 0.25 acres; therefore, a dust control permit will not be required. Authorization under the construction stormwater general permit administered by NDEP is not anticipated because cumulative disturbances are not anticipated to exceed one acre. Lastly, there will be no wastewater discharges from well operation.

7.2.1 Well Installation Permitting

Both pre-design and field treatability study activities will require a Nevada Administrative Code (NAC) 534.441 Monitor Well Drilling Waiver and a NAC 534.320 Notice of Intent Card prior to installation of monitoring wells associated with the pre-design phase and injection and monitoring wells as part of the field treatability study. The Monitoring Well Drilling Waiver also requires a completed, signed, and notarized Affidavit of Intent to Abandon a Well as an attachment. As required, all injection 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. To the extent that any injection and monitoring wells associated with this treatability study are to be abandoned, they would be done so 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.

7.2.2 NDEP – Underground Injection Control Program

The treatability study will require an underground injection control (UIC) permit for the injection of ZVI and potential ancillary amendments into the saturated subsurface. Specifically, an application for a Class V General Permit for Long-Term Remediation UIC permit, pursuant to NAC 445A, will be required. The permit application requires completion of UIC Form U200 – Permit Application and UIC Form U210 – Notice of Intent.

7.2.3 Water Appropriations Permit

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) may be required if extraction of groundwater is needed to achieve flow through any of the test galleries. While the test galleries will be designed to operate passively it is possible that extraction-induced flow may be necessary, which sometimes occurs in small-scale test systems. If necessary, the extraction would most likely be done on the downgradient side of a test gallery to create a stronger hydraulic gradient inducing flow through the test gallery. Typically, the extraction rates necessary are relatively low.

8. DATA MANAGEMENT, VERIFICATION, AND VALIDATION

8.1 Data Management

All data collected during the pre-design field investigation and throughout operation of the treatability study will be managed in the NERT project database. These data include but are not limited to analytical data, groundwater elevation data, field-measured sampling parameter data, and sample location information. Data management responsibilities include the following tasks: 1) downloading and tracking data as it is generated to assess completeness; 2) coordinating with laboratory and field personnel on data generation and management issues including missing and incorrectly reported data; 3) inputting data into the database and maintaining it in an organized, transparent, and readily accessible manner and in accordance with NDEP requirements; and 4) performing Quality Assurance/Quality Control checks on the database. Ramboll Environ will facilitate sharing of data with Tetra Tech and coordination of any subsequent subtasks related to the two companion treatability studies.

8.2 Data Verification and Certification

Data verification evaluates whether a data set is complete, correct, and consistent with expectations or program requirements. Data verification will be conducted as soon as possible following receipt of the data from the analytical laboratory or from field personnel. Specific data verification responsibilities and requirements for various data types are described in the QAPP, Revision 2 (Ramboll Environ 2017b).

Collected data will be certified in accordance with NDEP requirements. A certification page signed by a Certified Environmental Manager (CEM) will accompany all data submittals that are to be reported to NDEP.

8.3 Data Validation

Data validation evaluates the analytical quality of a data set and occurs after data verification. Ramboll Environ will coordinate efforts for data validation, which will be performed by an independent contractor consistent with the most current versions of USEPA's National Functional Guidelines (USEPA 2017 and 2016) and NDEP's validation guidance. A summary of validation guidelines and additional data validation procedures specific to the RI/FS are described in the QAPP, Revision 2 (Ramboll Environ 2017b).

Consistent with recent NDEP guidelines, analytical data will be validated to Stage 2A, given the intended use of data is to support technology selection in the forthcoming FS. Per the January 11, 2017 email from Weiquan Dong, P.E., PhD, on behalf of NDEP-BISC , analytical data for NERT treatability studies only require validation to Stage 2A (NDEP 2017).

8.4 Quality Assurance/Quality Control (QA/QC)

The overall goal of QA/QC procedures is to assure that comparable and representative data are produced during the implementation of the treatability study and that data quality is consistently assessed and documented with respect to its precision, accuracy, sensitivity, and completeness. Ramboll Environ will enforce implementation of QA/QC procedures as they relate to collection and completeness of data from field and laboratory operations. QA/QC procedures and specifications applicable to sampling and analysis conducted as part of the RI/FS are described in the QAPP.

9. REPORTING

Monthly status updates will be provided to the Trust and NDEP summarizing the progress and results of the pre-design field activities, bench-scale testing, and field test implementation.

Following completion of the pre-design field investigation and bench-scale testing described in Sections 4 and 5, respectively, a Work Plan Addendum will be prepared and submitted to NDEP presenting the final field test design. This addendum will include:

- Summary of pre-design field activities, including results of geophysical analyses, soil borings and well installations, and hydraulic testing;
- Analytical results summary of soil and groundwater samples collected during the pre-design field activities;
- Summary of bench-scale testing activities, including preliminary results of batch microcosm testing, column testing, and geochemical and reactive transport modeling;
- Final field test design, including proposed ZVI layout within each test gallery, ZVI test composition, use of other amendments, and finalized performance monitoring plan.

Following completion of the field test, a final report summarizing treatability study activities (including final results of the pre-design field investigation, bench-scale testing, and field testing) and results of the performance evaluation will be prepared and submitted to NDEP.

10. SCHEDULE

A general schedule for the primary deliverables and activities associated with implementing the pre-design and treatability study activities is presented in Table 8. This schedule is contingent upon Trust, NDEP, and US EPA approval of this Work Plan, Trust budgetary approval and notice to proceed, completion of access agreements, and obtaining all necessary permits. Ramboll Environ will coordinate with Tetra Tech to gain efficiencies where appropriate, such as collection of background and pre-design data, well installations, and report preparation.

Table 8. Preliminary Project Schedule

Task / Milestone	Estimated Start Date	Estimated Completion Date
Pre-Design Field Activities	January 2018	June 2018
Laboratory Bench-Scale Tests	February 2018	June 2018
Treatability Study Implementation and Monitoring	July 2018	June 2019
Reporting	July 2019	September 2019

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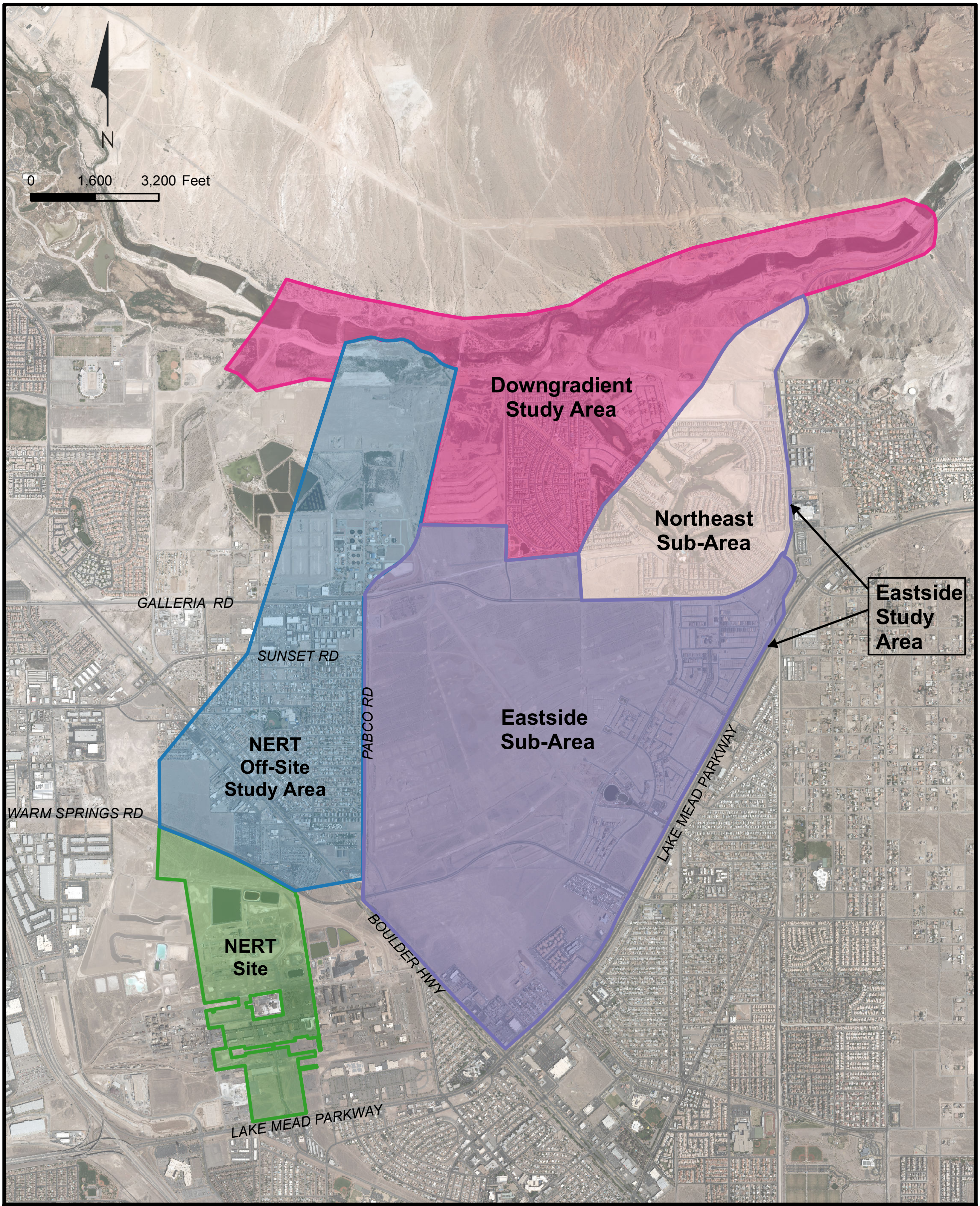
FIGURES



RAMBOLL ENVIRON

Remedial Investigation Study Area Overview
Galleria Road ZVI-Enhanced Bioremediation
Treatability Study Work Plan
Nevada Environmental Response Trust Site; Henderson, Nevada

Figure
1

Drafter: KL | Date: 9/29/2017 | Contract Number: 21-41400C | Approved: | Revised:

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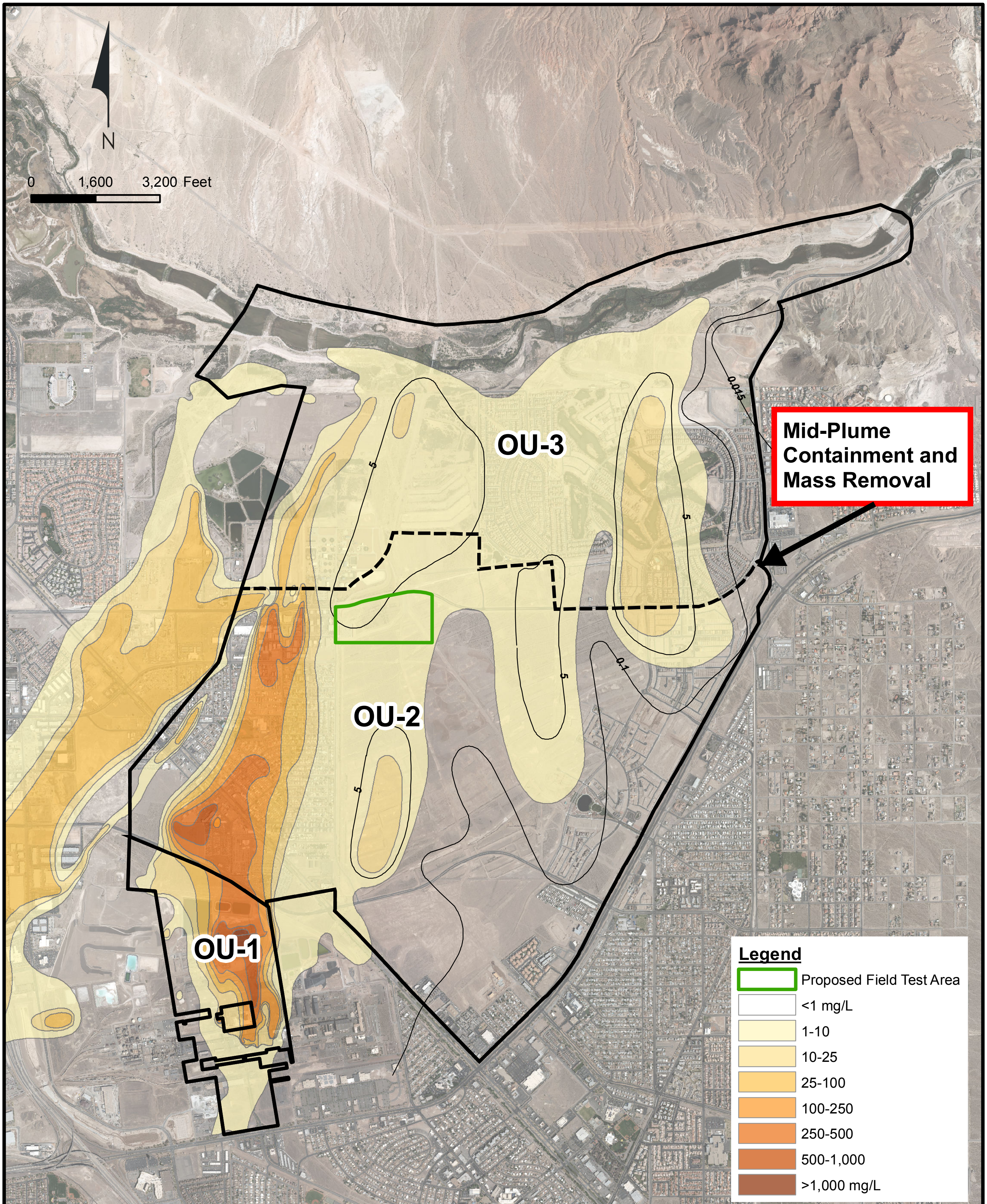

RAMBOLL ENVIRON

Operable Unit Boundaries

Galleria Road ZVI-Enhanced Bioremediation
Treatability Study Work Plan
Nevada Environmental Response Trust Site; Henderson, Nevada

Figure
2

Drafter: KL	Date: 9/28/2017	Contract Number: 21-41400C	Approved:	Revised:

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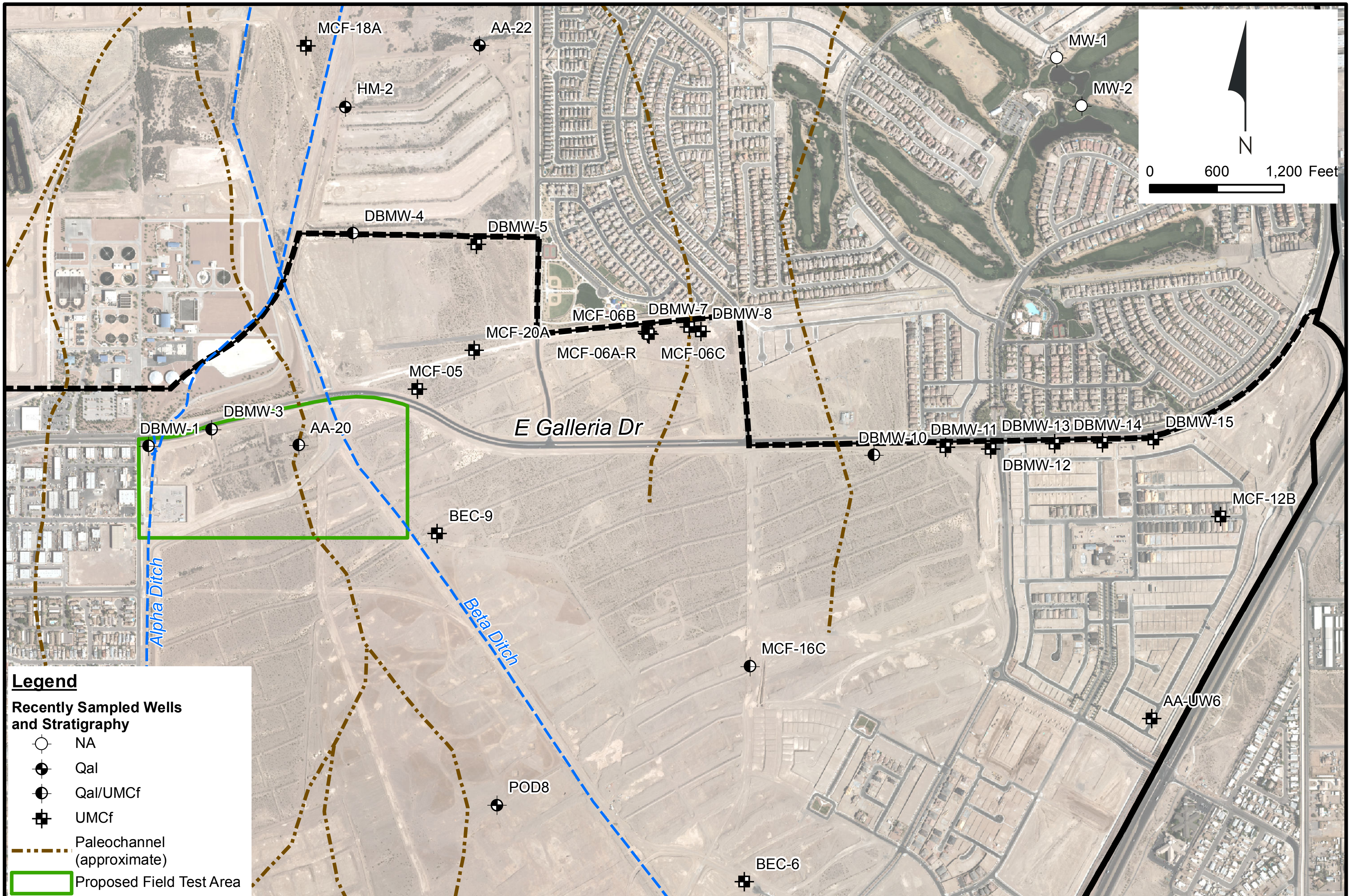

RAMBOLL ENVIRON

Mid-Plume Boundary - Recently Sampled Wells

Galleria Road ZVI-Enhanced Bioremediation Treatability Study Work Plan

Nevada Environmental Response Trust Site; Henderson, Nevada

Figure **3**

Drafter: KL Date: 9/28/2017 Contract Number: 21-41400C Approved: Revised:

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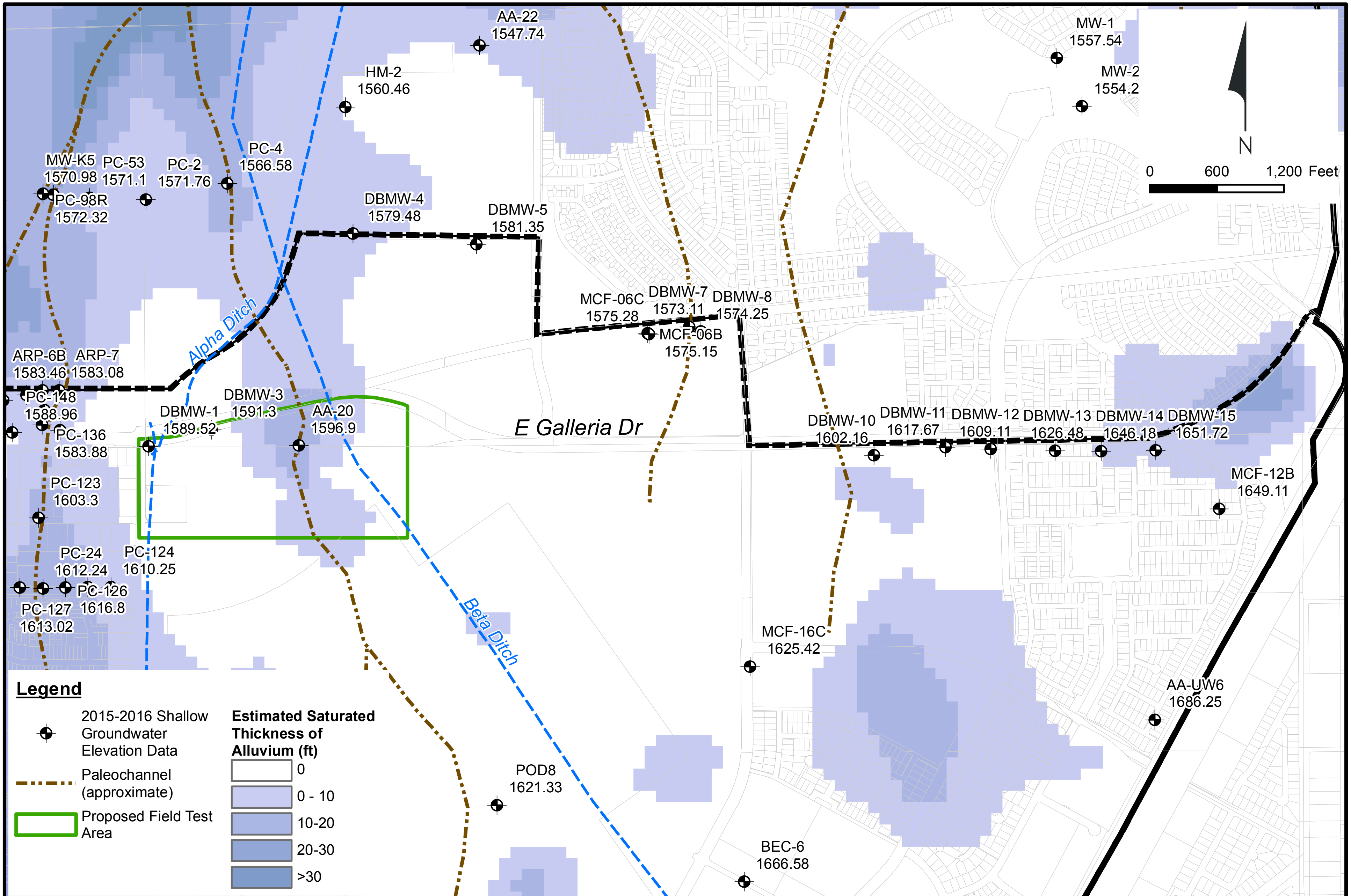

RAMBOLL ENVIRON

Mid-Plume Boundary - Estimated Saturated Alluvium

Galleria Road ZVI-Enhanced Bioremediation Treatability Study Work Plan

Nevada Environmental Response Trust Site; Henderson, Nevada

Figure **4**

Drafter: KL Date: 9/28/2017 Contract Number: 21-41400C Approved: Revised:

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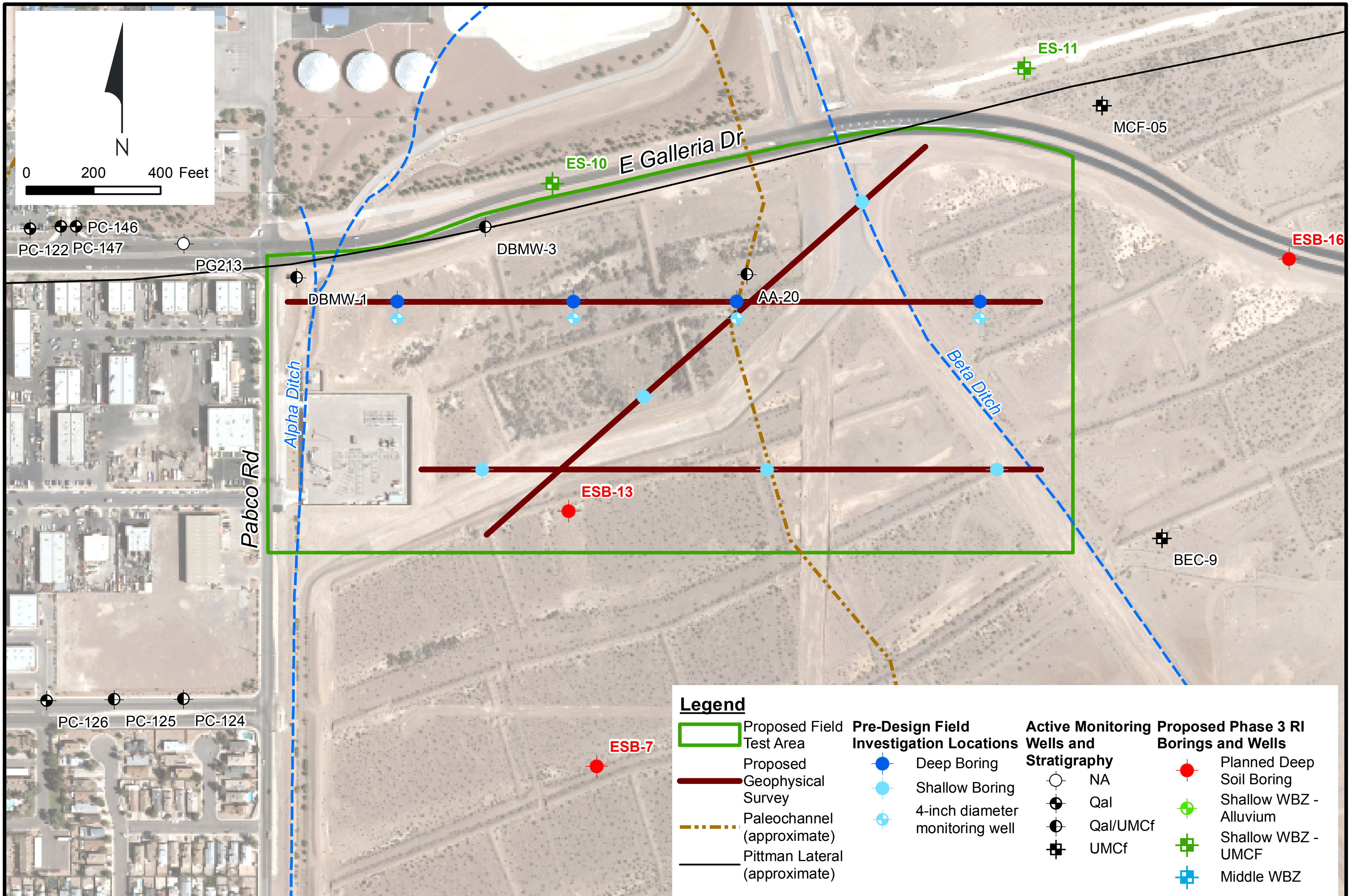

RAMBOLL ENVIRON

Proposed Field Test Area - Pre-Design Field Investigation

Galleria Road ZVI-Enhanced Bioremediation Treatability Study Work Plan

Nevada Environmental Response Trust Site; Henderson, Nevada

Figure **5**

Drafter: KL | Date: 9/28/2017 | Contract Number: 21-41400C | Approved: | Revised:

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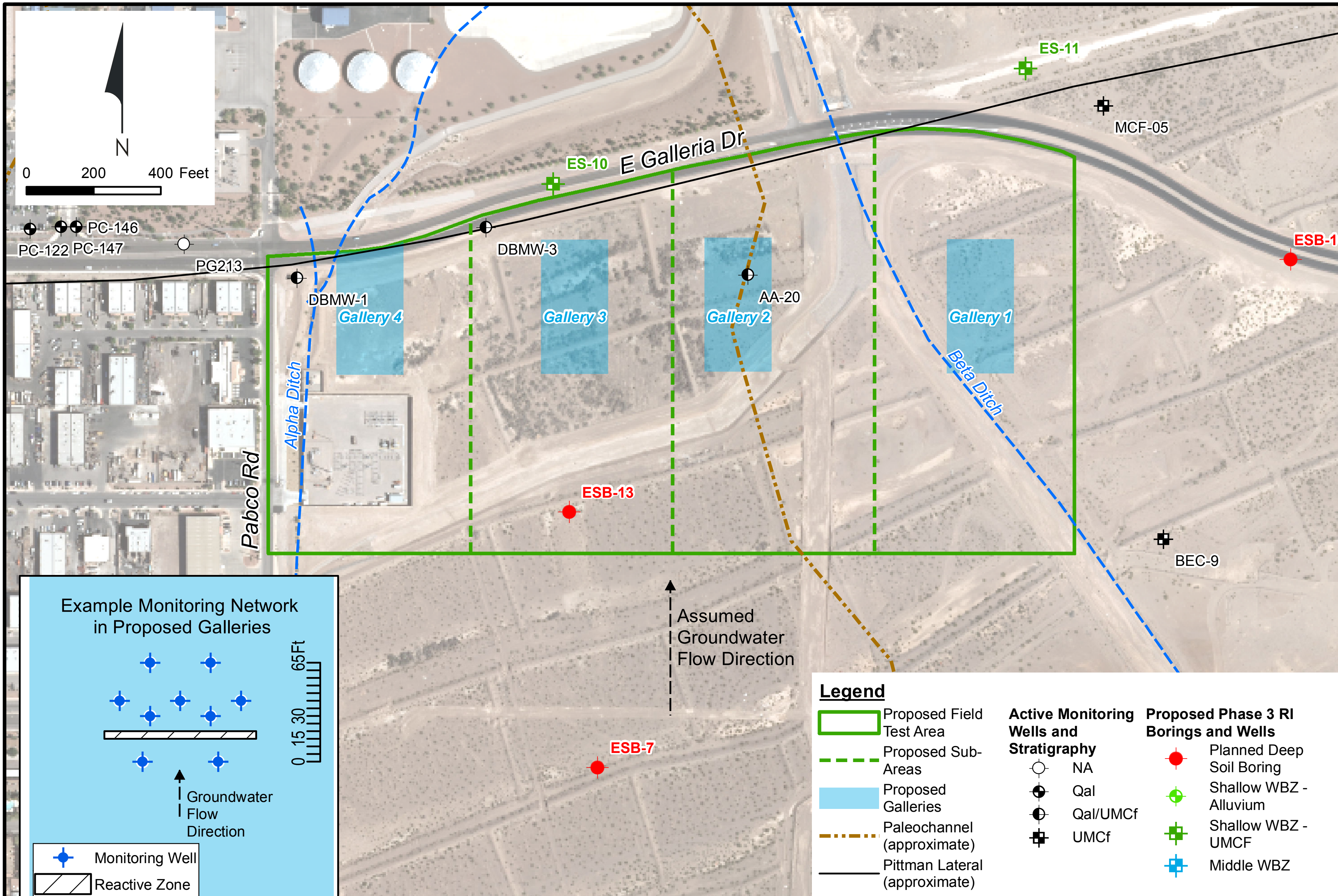

RAMBOLL ENVIRON

Proposed Field Test Area - Conceptual Design
Galleria Road ZVI-Enhanced Bioremediation Treatability Study Work Plan
Nevada Environmental Response Trust Site; Henderson, Nevada

Figure
6

Drafter: KL Date: 9/28/2017 Contract Number: 21-41400C Approved: Revised:

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APPENDIX A
EXISTING DATA AT THE MID-PLUME BOUNDARY

TABLE A1: DATA SUMMARY ALONG GALLERIA ROAD, 2014-2016

Nevada Environmental Response Trust Site

Henderson, Nevada

Chemical Group	Chemical	Unit	DBMW-1	DBMW-3	AA-20	MCF-05	DBMW-10	DBMW-11	DBMW-12	DBMW-13	DBMW-14	DBMW-15
Physical	Depth to Groundwater	ft bgs	34 - 35	26 - 32	29	42	59	42 - 47	52 - 57	43 - 49	32 - 40	32 - 39
	Depth to UMCf	ft bgs	40	31	27	25	60	30	30	30	36	36
	Screen Interval	ft bgs	19 - 49	19 - 39	10 - 30	220 - 230	55 - 75	45 - 75	45 - 75	45 - 75	35 - 65	40 - 65
Field	Conductivity	µS/cm	--	8900 - 13000	7100 - 9300	--	3500 - 3600	8500 - 15000	8200 - 9500	9600 - 12000	6500 - 9900	5900 - 12000
	Dissolved Oxygen	mg/L	4.7 - 6.5	4.5	6.3	1.9	--	--	--	--	--	--
	Field Conductivity	µS/cm	7900	--	7300	74000	--	--	--	--	--	--
	Field pH	SU	7.1	--	7.2	9.3	--	--	--	--	--	--
	Iron, Ferrous	mg/L	0	0	0	--	--	--	--	--	--	--
	Oxidation Reduction Potential	mV	12 - 49	69	42 - 63	120	--	--	--	--	--	--
	Temperature	deg c	20 - 26	22	23 - 25	24	--	--	--	--	--	--
	Turbidity	NTU	0.56 - 1.0	1.0	0.18 - 52	420	--	--	--	--	--	--
	pH	SU	7.4	5.3 - 7.7	5.9 - 7.4	--	5.2 - 5.5	5.3 - 7.0	5.2 - 6.4	5.5 - 5.8	4.8 - 5.9	6.4 - 7.2
General Chemistry	Alkalinity	mg/L	--	64	78 - 82	--	68 - 96	68	74 - 170	130 - 6000	50 - 95	130
	Alkalinity, Bicarbonate [As CaCO3]	mg/L	--	64	78 - 82	--	68 - 96	68	74 - 170	130 - 6000	50 - 95	130
	Alkalinity, Carbonate [As CaCO3]	mg/L	--	0.54	0.54	--	0.54	0.54	0.54	0.54 - 14	0.54	0.54
	Anion Cation Balance Difference	percent	--	-8.8 - 0.15	-0.37 - 2.3	--	-5.9 - 0.78	-3.3 - -1.1	-6.6 - -0.38	-9.9 - 6.9	-16 - -3.8	-11 - 50
	Bromide	mg/L	5.0	0.36 - 2.4	0.41 - 2.5	13 - 25	0.63 - 0.64	0.13 - 0.15	0.49 - 2.0	1.9 - 6.0	0.48 - 0.84	0.24 - 0.97
	Bromine	mg/L	--	0.72 - 4.8	0.82 - 2.8	--	1.3	0.050 - 0.30	0.98 - 4.0	3.8 - 12	0.050 - 1.7	0.48 - 1.9
	Chlorate	mg/L	22	47 - 49	28 - 30	0.50 - 2.0	0.34 - 0.50	28 - 31	13 - 25	17 - 24	0.10 - 13	1.4 - 5.9
	Chloride	mg/L	1100	1800	970 - 1000	19000 - 27000	320 - 330	2000	1100 - 1900	2000 - 2100	600 - 800	550
	Chlorine	mg/L	--	3600	1900	--	640 - 660	3400 - 4000	2200 - 3800	4000 - 4400	1200 - 2200	340 - 1100
	Dissolved Solids (total)	mg/L	5900 - 6000	8300 - 8600	5200 - 6100	76000 - 120000	2100 - 2200	9900	6400 - 9800	7300 - 8500	5600 - 7100	7700
	Fluoride	mg/L	--	0.18	0.35 - 0.40	--	0.43 - 0.65	0.17	0.11 - 0.22	0.073 - 0.10	0.20 - 0.34	0.59
	Hydroxide alkalinity	mg/L	--	0.54	0.54	--	0.54	0.54	0.54	0.54 - 14	0.54	0.54
	Nitrate	mg/L	--	15	7.7 - 8.9	--	12	21	15 - 24	26 - 27	11 - 15	11
	Nitrite	mg/L	--	1.5	0.15 - 1.5	--	0.60	0.60 - 1.5	1.5	1.5	0.15 - 0.60	0.60 - 1.5
	Orthophosphate	mg/L	--	0.39	0.39 - 0.46	--	0.078	0.16 - 0.39	0.16 - 0.39	0.39 - 0.88	0.078 - 0.20	0.16 - 0.39
	Perchlorate	mg/L	7.6 - 9.0	8.3 - 9.8	3.8 - 34	0.095 - 0.63	0.34 - 0.36	13 - 15	--	12 - 20	5.4 - 13	3.4 - 4.7
	Sulfate	mg/L	--	3900	2700 - 2800	--	980 - 1000	4300	3000 - 4400	2300 - 2400	3000 - 4500	4900
Metals	Aluminum	mg/L	0.22 - 0.45	0.17 - 1.7	0.065 - 0.45	--	1.0 - 1.2	0.17 - 0.55	0.31 - 17	21 - 40	7.3 - 13	5.0 - 26
	Antimony	µg/L	37 - 75	8.4 - 75	8.4 - 75	--	8.4	8.4	8.4	8.4	8.4	8.4
	Arsenic	mg/L	0.099 - 0.13	0.10 - 0.14	0.10 - 0.14	--	0.059 - 0.064	0.0059 - 0.054	0.042 - 0.075	0.056 - 0.081	0.10 - 0.16	0.13 - 0.26
	Barium	µg/L	21 - 42	14 - 42	13 - 42	--	19 - 32	26 - 27	15 - 170	240 - 410	94 - 170	71 - 340
	Beryllium	µg/L	2.8 - 5.7	1.8 - 5.7	1.8 - 5.7	--	1.8	1.8	1.8	1.8 - 1.9	1.8	1.8
	Boron	mg/L	2.9 - 3.3	4.0 - 4.7	2.6 - 2.9	--	1.0 - 1.1	1.9 - 3.6	2.0 - 3.8	3.8	3.9 - 4.3	3.8 - 5.5
	Cadmium	µg/L	3.4 - 6.7	0.50 - 6.7	0.50 - 6.7	--	0.50	0.50	0.50 - 0.61	0.50 - 0.66	0.50	0.50
	Calcium	mg/L	610 - 710	560 - 640	610 - 680	--	220 - 230	590	590 - 670	830	440 - 590	490

TABLE A1: DATA SUMMARY ALONG GALLERIA ROAD, 2014-2016

Nevada Environmental Response Trust Site

Henderson, Nevada

Chemical Group	Chemical	Unit	DBMW-1	DBMW-3	AA-20	MCF-05	DBMW-10	DBMW-11	DBMW-12	DBMW-13	DBMW-14	DBMW-15
Metals	Chromium (total)	µg/L	55 - 110	92 - 110	34 - 90	25 - 110	13 - 14	58 - 72	61 - 65	54 - 72	34 - 56	19 - 47
	Chromium VI	µg/L	60 - 70	69 - 70	30 - 41	1.0 - 2.0	12	54 - 61	39 - 59	23 - 24	21 - 51	12 - 20
	Cobalt	µg/L	27 - 54	1.1 - 54	1.1 - 54	--	1.1	1.1	1.1 - 5.7	7.5 - 13	2.5 - 4.5	1.4 - 8.4
	Copper	µg/L	21 - 42	3.4 - 42	3.7 - 42	--	2.3 - 3.4	2.3 - 4.5	3.4 - 18	36 - 40	8.5 - 15	6.3 - 38
	Hardness (total)	mg/L	--	3400 - 3500	2600 - 2700	--	900 - 950	3200 - 4700	3100 - 4900	3100 - 3800	2000 - 2600	2300 - 2800
	Iron	mg/L	0.13 - 0.26	0.25 - 2.0	0.11 - 0.26	--	0.16 - 1.4	0.28 - 0.54	0.29 - 16	18 - 32	6.2 - 11	4.2 - 25
	Lead	µg/L	11 - 32	1.4 - 40	0.98 - 28	--	0.87 - 1.3	0.87 - 1.6	0.87 - 9.7	14 - 21	5.0 - 8.1	3.0 - 14
	Lithium	mg/L	0.44 - 0.51	0.52 - 0.69	0.33 - 0.44	--	0.16	0.59 - 1.4	0.67 - 1.3	0.58 - 0.72	0.39 - 0.42	0.33 - 0.49
	Magnesium	mg/L	260 - 300	400 - 450	220 - 260	--	84 - 90	780	410 - 790	430	210 - 230	260
	Manganese	µg/L	10 - 20	4.4 - 37	4.4 - 20	--	5.1 - 35	7.2 - 11	7.1 - 430	530 - 890	130 - 230	82 - 480
	Mercury	µg/L	0.027 - 0.13	0.027	0.027 - 0.15	--	--	--	--	--	--	--
	Molybdenum	mg/L	0.75 - 0.87	1.8 - 2.8	0.63 - 0.78	--	0.023 - 0.026	0.064 - 0.12	0.062 - 0.14	0.11 - 0.14	0.077 - 0.15	0.14 - 0.19
	Nickel	µg/L	26 - 51	3.4 - 51	3.5 - 51	--	2.1 - 4.0	2.1 - 5.8	4.0 - 18	28 - 36	6.2 - 12	4.9 - 27
	Phosphorus (total)	mg/L	0.14 - 0.28	0.28	0.14 - 0.28	--	--	--	--	--	--	--
	Potassium	mg/L	47 - 65	100 - 160	33 - 41	--	46 - 50	590	190 - 410	160	100 - 120	120
	Selenium	mg/L	0.13	0.12 - 0.23	0.068 - 0.13	--	0.0080	0.016 - 0.025	0.0080 - 0.029	0.058 - 0.069	0.020 - 0.024	0.018 - 0.025
	Silicon	mg/L	34 - 39	29 - 36	33 - 39	--	--	--	--	--	--	--
	Silver	µg/L	9.9 - 20	4.1 - 20	4.1 - 20	--	4.1	4.1	4.1	4.1	4.1	4.1
	Sodium	mg/L	610 - 800	1100 - 1600	730 - 920	--	220 - 240	850	410 - 820	950	630 - 910	1100
	Strontium	mg/L	15 - 19	11 - 15	10 - 12	--	5.4 - 5.6	11 - 14	11 - 12	14 - 17	9.9 - 14	12 - 13
	Sulfur	mg/L	870 - 1000	1200 - 1300	890 - 960	--	--	--	--	--	--	--
	Thallium	µg/L	5.5 - 11	2.8 - 5.5	2.8 - 11	--	2.8	2.8	2.8	2.8	2.8	2.8
	Tin	µg/L	50 - 100	5.4 - 100	5.4 - 100	--	5.4	5.4	5.4	5.4	5.4	5.4
	Titanium	mg/L	0.013 - 0.025	0.025 - 0.055	0.013 - 0.025	--	0.025 - 0.035	0.019 - 0.025	0.025 - 0.51	0.65 - 0.66	0.25 - 0.35	0.21 - 1.0
	Tungsten	µg/L	--	10	10	--	10	10	10	10	10	10
	Uranium (total)	µg/L	8.0 - 11	7.9 - 10	16 - 22	--	7.0 - 7.1	11 - 25	32 - 41	17 - 27	5.2 - 15	11 - 23
	Vanadium	µg/L	44 - 88	53 - 88	42 - 88	--	31 - 32	12 - 13	15 - 48	45 - 76	29 - 50	36 - 81
	Zinc	µg/L	83 - 170	41 - 170	41 - 170	--	41 - 47	41 - 47	47 - 130	63 - 140	41 - 47	47 - 88
	Zirconium	µg/L	5.0 - 26	26	5.0 - 26	--	--	--	--	--	--	--

TABLE A2: ADDITIONAL DATA SUMMARY, 2014-2016

Nevada Environmental Response Trust Site

Henderson, Nevada

Chemical Group	Chemical	Unit	MCF-18A	HM-2	DBMW-4	BEC-9	MCF-20A	DBMW-5	AA-22	POD8	MCF-06A-R	MCF-06B
Physical	Depth to Groundwater	ft bgs	20	23 - 26	24	--	70	25	32	70 - 71	--	55
	Depth to UMCf	ft bgs	21	N/A	25	37	17	12	31	74	43	43
	Screen Interval	ft bgs	360 - 400	N/A	10 - 30	44 - 59	340 - 380	15 - 35	11 - 31	43 - 73	350 - 370	67 - 82
Field	Conductivity	µS/cm	--	--	7100 - 7700	6400 - 7200	--	6900 - 7600	--	5600 - 6300	--	35000 - 47000
	Dissolved Oxygen	mg/L	0.56	0.83	4.5	--	0.63	5.2	5.1	2.0	1.2	1.9
	Field Conductivity	µS/cm	240000	7100	7400	--	160000	7000	7100	--	160000	38000
	Field pH	SU	7.0	7.6 - 7.9	7.3	--	6.9	7.3	7.3	--	8.6	8.2
	Iron, Ferrous	mg/L	--	--	--	--	--	--	--	0	--	--
	Oxidation Reduction Potential	mV	170	150	150	--	14	170	43	48	-21	230
	Temperature	deg c	26	17	25	--	25	24	23	22	22	23
	Turbidity	NTU	61	22	0.37	--	26	31	180	3.4	2.9	0.41
	pH	SU	--	--	4.8 - 7.4	5.7 - 7.4	--	6.1 - 7.4	--	6.3 - 7.3	--	6.8 - 8.2
General Chemistry	Alkalinity	mg/L	--	--	84 - 92	120 - 130	--	82	--	170 - 180	--	66
	Alkalinity, Bicarbonate [As CaCO3]	mg/L	--	--	84 - 92	120 - 130	--	82	--	170 - 180	--	66
	Alkalinity, Carbonate [As CaCO3]	mg/L	--	--	0.54	0.54	--	0.54	--	0.54	--	0.54
	Anion Cation Balance Difference	percent	--	--	-3.8 - -3.5	-21 - 3.0	--	-8.1 - -2.8	--	-6.3 - 4.9	--	-11 - 2.6
	Bromide	mg/L	25 - 94	2.5	0.32 - 5.0	0.32 - 1.4	25	0.32 - 2.9	2.5	0.73 - 1.3	120	0.25 - 13
	Bromine	mg/L	--	--	0.64 - 3.0	0.64 - 2.8	--	0.64 - 3.2	--	1.5 - 2.6	--	0.050
	Chlorate	mg/L	1.0 - 2.0	33 - 36	73 - 77	2.6 - 3.7	0.50 - 2.0	95 - 97	100	1.1 - 1.4	1.7	1.3 - 2.8
	Chloride	mg/L	100000	910 - 1000	1100 - 1300	970 - 1000	49000 - 50000	1200 - 1300	1300	530	56000	7000 - 7200
	Chlorine	mg/L	--	--	2200 - 2600	1900 - 2000	--	2600 - 2800	--	1100	--	14000 - 16000
	Dissolved Solids (total)	mg/L	170000 - 190000	4700 - 5900	5200 - 5900	4600 - 5200	150000 - 160000	5400 - 5500	3600	4600 - 4800	180000	39000 - 46000
	Fluoride	mg/L	--	--	0.23 - 0.40	0.30 - 0.45	--	0.19	--	0.65 - 0.71	--	0.10
	Hydroxide alkalinity	mg/L	--	--	0.54	0.54	--	0.54	--	0.54	--	0.54
	Nitrate	mg/L	--	17 - 18	17 - 22	35	--	21	--	18 - 20	--	1.8
	Nitrite	mg/L	--	0.70	1.5	1.5	--	1.5	--	0.15 - 1.5	--	3.0 - 30
	Orthophosphate	mg/L	--	--	0.39 - 0.75	0.39 - 1.0	--	0.39	--	0.39 - 0.53	--	0.78 - 5.2
	Perchlorate	mg/L	0.095	3.4 - 6.1	5.6 - 50	--	0.095	2.2 - 6.9	7.1	0.30 - 0.48	0.095	2.7 - 32
	Sulfate	mg/L	--	2400	2400 - 2800	2200 - 2300	--	2500	--	2300	--	19000
Metals	Aluminum	mg/L	--	0.050	0.51 - 1.1	0.31 - 0.38	--	0.33 - 0.37	--	0.22 - 1.1	--	0.087 - 0.65
	Antimony	µg/L	--	0.50	8.4	8.4	--	1.7 - 8.4	--	8.4 - 75	--	8.4 - 84
	Arsenic	mg/L	--	0.098	0.13	0.11 - 0.13	--	0.12 - 0.15	--	0.070 - 0.10	--	0.0059 - 0.059
	Barium	µg/L	--	9.4	27 - 37	18 - 20	--	12 - 13	--	18 - 42	--	30 - 33
	Beryllium	µg/L	--	--	1.8	1.8	--	0.35 - 1.8	--	1.8 - 8.0	--	1.8 - 18
	Boron	mg/L	--	--	2.6 - 2.8	1.1 - 1.9	--	2.0 - 2.5	--	2.4 - 3.1	--	4.1 - 6.8
	Cadmium	µg/L	--	2.0	0.50	0.50	--	0.10 - 0.50	--	0.50 - 8.0	--	0.50 - 5.0
	Calcium	mg/L	--	670	620 - 670	510 - 710	--	730	--	390 - 500	--	540

TABLE A2: ADDITIONAL DATA SUMMARY, 2014-2016

Nevada Environmental Response Trust Site

Henderson, Nevada

Chemical Group	Chemical	Unit	MCF-18A	HM-2	DBMW-4	BEC-9	MCF-20A	DBMW-5	AA-22	POD8	MCF-06A-R	MCF-06B
Metals	Chromium (total)	µg/L	20 - 100	38 - 52	87 - 120	26 - 31	2.5 - 5.0	90 - 140	80	14 - 67	5.0	5.0 - 50
	Chromium VI	µg/L	1.0	42 - 46	89 - 100	19 - 20	1.0	110 - 140	99	10 - 20	1.0	1.0 - 23
	Cobalt	µg/L	--	2.5	1.2 - 1.4	1.1	--	0.60 - 1.1	--	1.1 - 54	--	1.1 - 11
	Copper	µg/L	--	5.0	3.4 - 4.2	2.3 - 3.4	--	2.3 - 3.4	--	2.3 - 44	--	4.5 - 170
	Hardness (total)	mg/L	--	--	2500 - 2700	1900 - 2800	--	2800	--	1700 - 2100	--	13000 - 18000
	Iron	mg/L	--	0.014	0.51 - 1.1	0.32 - 0.37	--	0.44 - 0.46	--	0.13 - 0.31	--	0.16 - 1.5
	Lead	µg/L	--	2.5	2.0 - 6.1	0.87 - 1.4	--	0.85 - 0.87	--	0.87 - 40	--	3.9 - 8.7
	Lithium	mg/L	--	--	0.33 - 0.35	0.25 - 0.39	--	0.36 - 0.38	--	0.30 - 0.40	--	4.6 - 6.5
	Magnesium	mg/L	--	250	230 - 250	150 - 250	--	240	--	190 - 250	--	3800
	Manganese	µg/L	--	10	26 - 42	8.7 - 14	--	5.8 - 8.4	--	7.6 - 26	--	12 - 21
	Mercury	µg/L	--	0.10	--	--	--	--	--	0.027 - 0.14	--	--
	Molybdenum	mg/L	--	--	0.11 - 0.12	0.073 - 0.076	--	0.042 - 0.066	--	0.044 - 0.050	--	2.0 - 2.8
	Nickel	µg/L	--	5.9	4.0 - 5.3	6.0 - 6.9	--	2.7 - 3.2	--	3.5 - 51	--	4.0 - 710
	Phosphorus (total)	mg/L	--	--	--	--	--	--	--	0.14 - 0.28	--	--
	Potassium	mg/L	--	170	75 - 85	42 - 66	--	61	--	26 - 36	--	3900
	Selenium	mg/L	--	--	0.0080 - 0.034	0.0080 - 0.039	--	0.013 - 0.034	--	0.021 - 0.046	--	0.080 - 0.11
	Silicon	mg/L	--	--	--	--	--	--	--	42 - 45	--	--
	Silver	µg/L	--	--	4.1	4.1	--	0.82 - 4.1	--	4.1 - 20	--	4.1 - 41
	Sodium	mg/L	--	590	620 - 730	290 - 510	--	600	--	540 - 730	--	4400
	Strontium	mg/L	--	--	11 - 13	8.4 - 14	--	13 - 14	--	4.4 - 12	--	7.4 - 10
	Sulfur	mg/L	--	--	--	--	--	--	--	810 - 850	--	--
	Thallium	µg/L	--	--	2.8	2.8	--	0.64 - 2.8	--	2.8 - 11	--	6.3 - 28
	Tin	µg/L	--	--	5.4	5.4	--	1.1 - 5.4	--	5.4 - 100	--	5.4 - 54
	Titanium	mg/L	--	--	0.025 - 0.066	0.015 - 0.025	--	0.032	--	0.013 - 0.026	--	0.013 - 0.025
	Tungsten	µg/L	--	--	10	10	--	2.0 - 10	--	10	--	10 - 100
	Uranium (total)	µg/L	--	--	27 - 28	56 - 62	--	21 - 32	--	38 - 50	--	1.3 - 12
	Vanadium	µg/L	--	33	61 - 64	33 - 37	--	17 - 22	--	25 - 88	--	12 - 120
	Zinc	µg/L	--	10	41 - 47	41 - 47	--	9.3 - 41	--	41 - 170	--	47 - 410
	Zirconium	µg/L	--	--	--	--	--	--	--	5.0 - 26	--	--

TABLE A2: ADDITIONAL DATA SUMMARY, 2014-2016

Nevada Environmental Response Trust Site

Henderson, Nevada

Chemical Group	Chemical	Unit	MCF-06C	DBMW-7	DBMW-8	BEC-6	MCF-16C	MW-1	MW-2	AA-UW6	MCF-12B
Physical	Depth to Groundwater	ft bgs	55	56	55 - 56	59	64 - 65	6.3	26	51 - 56	62 - 64
	Depth to UMCf	ft bgs	43	41	41	55	70	N/A	N/A	33	52
	Screen Interval	ft bgs	44 - 59	50 - 70	48 - 68	65 - 80	53 - 73	N/A	N/A	37 - 57	64 - 84
Field	Conductivity	µS/cm	9200 - 12000	--	8100 - 11000	5400	7100 - 12000	--	--	4300 - 5600	4100 - 5400
	Dissolved Oxygen	mg/L	4.8	6.1	6.2	--	--	3.3	3.3	--	--
	Field Conductivity	µS/cm	9300	8200	8600	--	--	8200	7100	--	--
	Field pH	SU	7.1	7.3	7.2	--	--	7.6	7.6	--	--
	Iron, Ferrous	mg/L	--	--	--	--	--	--	--	--	--
	Oxidation Reduction Potential	mV	37	190	47	--	--	200	180	--	--
	Temperature	deg c	24	25	27	--	--	18	18	--	--
	Turbidity	NTU	50	0.11	1.4	--	--	160	1.7	--	--
	pH	SU	5.6 - 7.2	--	5.8 - 7.4	7.6	5.6 - 7.7	--	--	5.2 - 6.1	5.5 - 7.6
General Chemistry	Alkalinity	mg/L	90 - 98	--	60	63	76 - 82	--	--	120 - 160	50 - 58
	Alkalinity, Bicarbonate [As CaCO3]	mg/L	90 - 98	--	60	63	76 - 82	--	--	120 - 160	50 - 58
	Alkalinity, Carbonate [As CaCO3]	mg/L	0.54	--	0.54	0.54	0.54	--	--	0.54	0.54
	Anion Cation Balance Difference	percent	-18 - 3.4	--	-20 - 5.1	-1.2	-21 - -1.4	--	--	-2.0 - 6.6	-6.4 - 4.4
	Bromide	mg/L	0.13 - 5.0	5.0	0.13 - 5.0	0.23	0.35 - 1.3	2.5	2.5	0.44 - 1.0	0.44 - 0.65
	Bromine	mg/L	0.050 - 0.32	--	0.050	0.46	0.70 - 2.6	--	--	0.88 - 2.0	0.88 - 1.3
	Chlorate	mg/L	6.5 - 9.9	7.6 - 8.0	6.1 - 10	0.10	13 - 17	16	11	0.10	3.3 - 5.3
	Chloride	mg/L	1700 - 2000	1400 - 1500	1400 - 1600	290	960 - 1000	1100	870	220 - 260	370 - 410
	Chlorine	mg/L	3400 - 4000	--	3200 - 3800	580	1900 - 2000	--	--	440 - 560	740 - 820
	Dissolved Solids (total)	mg/L	7000 - 7400	6300	5800 - 6300	4600	4700 - 12000	6300	5600	4000 - 4200	3300 - 3800
	Fluoride	mg/L	0.20 - 0.31	--	0.17	0.19	0.37 - 0.60	--	--	0.28 - 0.37	0.29 - 0.50
	Hydroxide alkalinity	mg/L	0.54	--	0.54	0.54	0.54	--	--	0.54	0.54
	Nitrate	mg/L	49	--	46	0.043	16 - 23	--	--	8.6 - 12	5.8 - 7.4
	Nitrite	mg/L	1.5	--	1.5	0.060	0.15 - 1.5	--	--	0.060 - 0.60	0.60
	Orthophosphate	mg/L	0.39	--	0.39	0.44	0.80 - 0.92	--	--	0.11 - 0.35	0.16 - 0.43
	Perchlorate	mg/L	5.6	4.4 - 4.6	7.0	0.0018	8.4 - 9.4	8.8	7.4	0.045 - 0.054	4.2 - 5.1
	Sulfate	mg/L	2700 - 3000	--	2100	2800	2200 - 7000	--	--	2200 - 2500	1700 - 2100
Metals	Aluminum	mg/L	2.3 - 4.2	--	0.16 - 0.67	0.087	0.065 - 0.087	--	--	0.71 - 9.7	0.087 - 0.12
	Antimony	µg/L	8.4	--	8.4	8.4	8.4	--	--	8.4	8.4
	Arsenic	mg/L	0.039 - 0.055	--	0.038 - 0.042	0.068	0.017 - 0.034	--	--	0.072 - 0.12	0.036 - 0.076
	Barium	µg/L	60 - 100	--	8.8 - 14	25	16 - 17	--	--	15 - 200	11 - 30
	Beryllium	µg/L	1.8	--	1.8	1.8	1.8	--	--	1.8	1.8
	Boron	mg/L	1.7 - 2.3	--	1.1 - 1.7	2.8	0.96 - 6.4	--	--	1.9 - 2.8	1.8 - 1.9
	Cadmium	µg/L	0.50	--	0.50	0.50	0.50	--	--	0.50	0.50
	Calcium	mg/L	610 - 720	--	820	520	480 - 490	--	--	490 - 500	390 - 420

TABLE A2: ADDITIONAL DATA SUMMARY, 2014-2016

Nevada Environmental Response Trust Site

Henderson, Nevada

Chemical Group	Chemical	Unit	MCF-06C	DBMW-7	DBMW-8	BEC-6	MCF-16C	MW-1	MW-2	AA-UW6	MCF-12B
Metals	Chromium (total)	µg/L	64 - 78	63 - 66	63 - 72	5.0	99 - 120	41	22	8.5 - 19	16 - 22
	Chromium VI	µg/L	72 - 140	79 - 81	70 - 81	0.015	80 - 120	49	24	3.3 - 3.9	14 - 22
	Cobalt	µg/L	1.2 - 1.7	--	1.1	1.1	1.1	--	--	1.1 - 2.9	1.1
	Copper	µg/L	2.9 - 3.4	--	2.3 - 3.4	3.4	2.3 - 3.4	--	--	2.6 - 9.7	2.3 - 3.4
	Hardness (total)	mg/L	2800 - 3500	--	2500 - 3300	2000	1800 - 5700	--	--	2000 - 2600	1600
	Iron	mg/L	2.5 - 3.9	--	0.23 - 0.69	0.44	0.10 - 0.16	--	--	1.0 - 8.8	0.11 - 0.16
	Lead	µg/L	2.3 - 3.5	--	0.87 - 0.92	1.9	0.87 - 2.2	--	--	1.3 - 6.8	0.87
	Lithium	mg/L	0.46 - 0.61	--	0.27 - 0.35	0.92	0.30 - 1.8	--	--	0.29 - 0.33	0.22 - 0.23
	Magnesium	mg/L	310 - 410	--	320	150	150 - 1200	--	--	190 - 200	150 - 160
	Manganese	µg/L	85 - 120	--	4.4 - 11	120	4.4 - 10	--	--	58 - 230	7.5 - 12
	Mercury	µg/L	--	--	--	--	--	--	--	--	--
	Molybdenum	mg/L	0.23 - 0.30	--	0.074 - 0.087	0.23	0.22 - 0.32	--	--	0.061 - 0.095	0.031 - 0.064
	Nickel	µg/L	7.0 - 8.9	--	2.6 - 4.0	4.0	2.0 - 4.0	--	--	2.0 - 9.1	2.0 - 4.0
	Phosphorus (total)	mg/L	--	--	--	--	--	--	--	--	--
	Potassium	mg/L	210 - 290	--	80	140	38 - 700	--	--	69 - 85	72 - 84
	Selenium	mg/L	0.0080 - 0.048	--	0.0080 - 0.014	0.0080	0.037 - 0.051	--	--	0.012	0.017 - 0.022
	Silicon	mg/L	--	--	--	--	--	--	--	--	--
	Silver	µg/L	4.1	--	4.1	4.1	4.1	--	--	4.1	4.1
	Sodium	mg/L	590 - 790	--	670	530	300 - 630	--	--	360 - 400	340 - 350
	Strontium	mg/L	11 - 14	--	11 - 15	10	7.9 - 8.0	--	--	9.8 - 10	8.5
	Sulfur	mg/L	--	--	--	--	--	--	--	--	--
	Thallium	µg/L	2.8	--	2.8	2.8	2.8	--	--	2.8	2.8
	Tin	µg/L	5.4	--	5.4	5.4	5.4	--	--	5.4	5.4 - 10
	Titanium	mg/L	0.098 - 0.12	--	0.026 - 0.028	0.025	0.013 - 0.025	--	--	0.023 - 0.26	0.025
	Tungsten	µg/L	10	--	10	10	10	--	--	10	10
	Uranium (total)	µg/L	19 - 32	--	16 - 22	1.2	9.9 - 16	--	--	5.0 - 11	5.6 - 5.7
	Vanadium	µg/L	17 - 19	--	12	12	12 - 42	--	--	19 - 37	12 - 17
	Zinc	µg/L	41 - 47	--	41 - 47	47	41 - 47	--	--	41 - 47	41 - 47
	Zirconium	µg/L	--	--	--	--	--	--	--	--	--

APPENDIX B
DIRECTIONAL JET INJECTION TECHNIQUES

Creating Permeable Reactive Zones With Jet Fracturing

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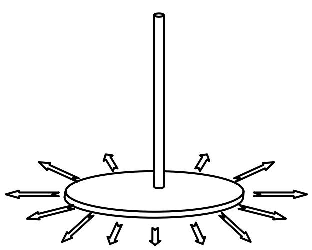
A traditional permeable reactive barrier (PRB) comprises a subsurface body of active material that is constructed to intercept groundwater flow and to destroy dissolved contaminants during transit through it. One common embodiment involves filling a trench with granular reagent such as iron. While perfectly satisfactory for shallow applications in open spaces, trenching requires broad surface access and requires removal of overburden soil and rock that may not be contaminated. Also trenches cannot be advanced efficiently beyond limiting depth.

Alternatively, hydraulic fracturing can be used to construct two dimensional structures that, when properly oriented, intercept in situ flux like a PRB. Fractures can be created at any depth of interest within environmental restoration, and a small set of wells can be utilized to create the fractures that compose the intercepting, reactive zones. The key challenges to this application of hydraulic fracturing are establishing the orientation of the fracture and assuring a continuous, holiday-free sheet-like structure.

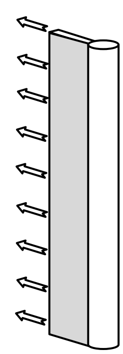
Creation of Hydraulic Fractures

Hydraulic fractures are created when fluid pressure generates stress that overcomes the mechanical strength of the surrounding earth media – either soil or bedrock. The orientation of a nucleated fracture depends upon how pressure is applied. For instance, a horizontal fracture can be created by pressurizing a horizontal disk-shaped cavity that intersects a short segment of a wellbore, as suggested by the sketch at the left. FRx routinely uses this approach to create discrete, sand-filled fractures to enhance delivery of treatment materials into low permeability media. However, a horizontal feature does not serve to directly intercept lateral flux in a very permeable system.



Model of the creation of a horizontal, symmetrical fracture to serve as a fluid distributor for delivery of substrate solution into low permeability media.

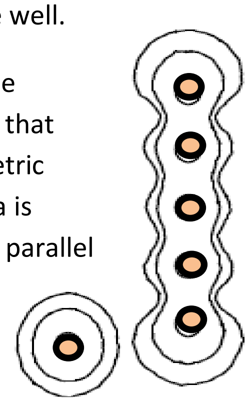
A vertical fracture will nucleate if a long, vertical slot is created along the wall of a borehole and pressurized. By controlling the direction of the slot, the azimuth of the fracture can be established, as suggested by the sketch to the right, and oriented to intercept groundwater flow. However, maintaining a stable, open boring to conduct treatment material into the resulting fracture can prove difficult. Furthermore, in tall targets, a single vertical kerf does not offer much control over the vertical distribution, and a particular range of the target may receive a disproportionate share of treatment material.



A vertically oriented fracture can propagate from a vertical kerf along a well.

Note that both these methods seek to exploit a small, two dimensional shape to effect a larger two dimensional shape (the PRB) of the same orientation - the symmetric horizontal fracture follows from the horizontal disk while the vertical fracture follows from the vertical kerf. There is, however, another way to create the appropriate in situ stress field for a desired fracture. Rather than apply pressure through a single, discrete geometric shape, we can rely upon the summation of stresses around a multitude of single, essentially line-like, features that we create from the well.

In particular, the appropriate state of stress for nucleating a vertical fracture can be developed by the summation of a series of parallel, pressurized horizontal tunnels that emanate from the borehole. The stress around a single horizontal tunnel is symmetric around the axis of the tunnel, and the mechanical failure of the surrounding media is along an arbitrary plane that includes the axis of the tunnel. In contrast, when five parallel tunnels are pressurized, stress accumulates between the tunnels and effectively defines a plane, which will serve as the root of the fracture. The adjacent sketch conveys these principles.

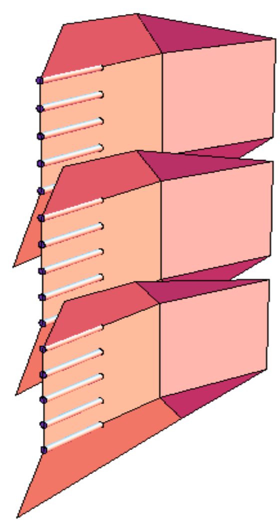


Contours of stress induced by pressurizing a single cylinder (left) and five parallel cylinders (right.)

The task of creating the horizontal tunnels can be accomplished easily with a high pressure water jet. The kinetic energy of a 10,000 psi water jet rapidly erodes a tunnel as deep as several feet even in heavy, dense soils such as clays and silts. Such pressure also can cut through PVC and grout in about 15 seconds, which allows the jet to be deployed at discrete points within a PVC casing. Use of casing maintains the stability of the borehole.

Since the jets create discreet holes in the PVC casing, subsets of holes can be addressed individually – an array of pressurization tunnels does not need to be created simultaneously from the top to the bottom of the target interval. A small collection of jets can be isolated by a pair of packers, and discrete vertical fractures nucleated along segments of the boring. This gives better control over the placement of treatment materials. For instance, treatment materials can be omitted from impermeable units that intersect the injection location while adequate fractures can be created in underlying as well as overlying targets.

Recognizing the natural heterogeneity and irregularity within soil units, we cannot expect all of the induced vertical fractures to align. Some will, while others will diverge or propagate in parallel but distinct planes. For example, the adjacent schematic suggests how the essentially vertical fractures created from three groups of five jetted tunnels might nest and overlap. In reality, fractures extend substantially farther than the extent of the nucleation tunnels. Fractures have three dimensional character, as suggested in the sketch. A significant portion of the fracture panels will remain within the plane of nucleation even though native in situ stress may prefer another azimuth. If the fractures do not intersect and accumulate, then the parallel sheets will offer a collective residence time to the intercepted groundwater flux.



An illustration of the concept of nearly coincident vertical fractures. Size of nucleation tunnels relative to fracture extent exaggerated to better illustrate the role of governing the orientation of the fractures.

Jet Fracturing Through Dedicated Wells

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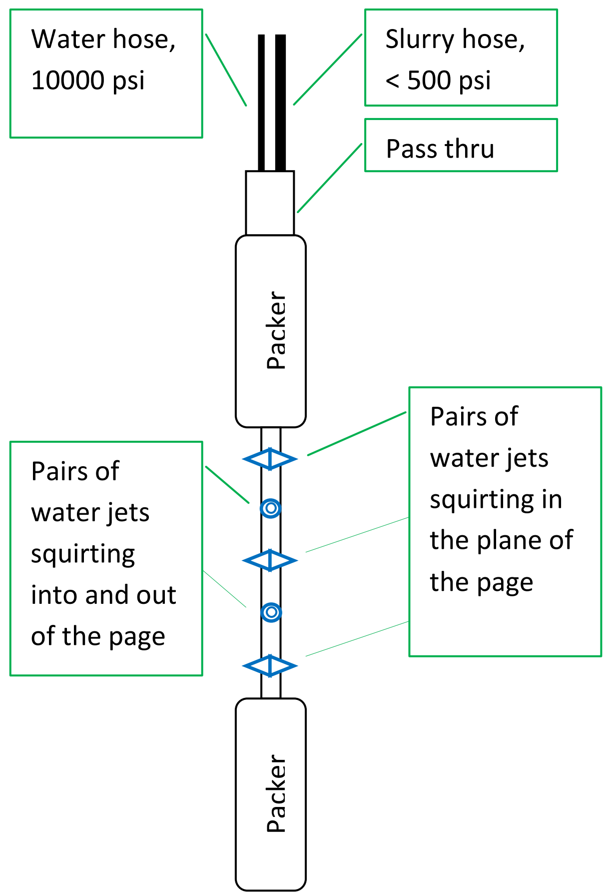
Jet-assisted fracturing utilizes the kinetic energy of high-pressure water jets to distribute injected slurry throughout the soil matrix. These effects occur in addition to forms that follow from hydraulic fracturing phenomena that may happen simultaneously. In addition, the energy of the jets assists in the penetration of dense or tough soils. The technology was developed and used successfully at a site in Bordentown, New Jersey. It has since been deployed at several other sites.

The Fracturing Lance



The jet fracturing lance consists of a pair of packers straddling a collection of waterblast nozzles that are pointed horizontally. The nozzles are arranged in pairs to counterbalance the recoil force of the individual nozzles. (Certainly other counterbalance configurations such as triplets and quads are possible conceptually, but may require nearly infeasible mechanical arrangements.) The lance used for the Bordentown project used five pairs of nozzles spaced a foot apart. Fewer or somewhat greater number of pairs are possible, and the spacing can be changed easily. Also, the Bordentown lance pointed the nozzles in two directions as shown (both parallel and perpendicular to the plane of the schematic.) Alternatively, the nozzles could be arranged in the same plane to effect a “wall” action, or a variety of azimuths could be elected.

Water is delivered to the lance via a standard waterblast hose. It enters the packer through a pass-thru that we have fabricated for that purpose. From the pass-thru to the bottom jet, the water is conducted thru a carefully selected network of high strength stainless steel tubing.

Treatment slurry is delivered to the lance through a conventional injection service hose. That hose also connects to the pass-thru block, which directs the slurry into the straddled interval.

Application

The jet fracturing process is performed in 4-inch PVC wells. The wells are constructed by a method that ensures a competent grout seal in the annulus between the casing and the borehole, thus guaranteeing that material injected at any particular elevation does not have a free pathway to overlying or underlying intervals. Mud rotary methods have proven to be successful, and other methods should be satisfactory.

The jet-assisted fracturing lance directs its 10,000-psi jets against the inside of the PVC casing. The jets have sufficient strength to penetrate the solid PVC casing and the surrounding grout. Turbulence outside of the casing and grout sheath mixes the simultaneously injected slurry with soil. Work done at the DOE Portsmouth facility with a similar lance showed that the disrupted zone extended as much as five feet from the parent well – a result consistent with well jetting work done at the US EPA Center Hill Laboratory in the early 1990's. In addition, the delivery of fluid (the sum of jetting water and slurry) induces stresses that result in nucleation of small hydraulic fractures that result in farther distribution of material. As a result, monitoring wells offset by as much as 25 feet may be impacted immediately during the injection process.

After delivering a designed volume of slurry to the interval, the packers and the lance can be moved upwards along the well to treat additional zones sequentially.

High Pressure Water Unit

This package typically is delivered on a utility trailer. Its major components include a diesel engine, a triplex pump, a fuel tank, and a water surge tank. These units weigh 8500 lb. Skid mount units are manufactured, but are less readily available. Water pressurized by this pump is conducted in hoses designed for waterblasting service. The operator of this unit stands on the ground, so the operating footprint is about 20 feet X 12 feet.

Treatment Material Pump

The pump used for this service should be compatible with the remediation materials as well as capable of accomplishing the desired rate and requisite pressure. Slurries of abrasive granular materials, such as iron, preclude the use of many fluid pumps but can be managed by piston pumps such as the one pictured here. Progressing cavity pumps also can delivery slurries. Liquid treatment materials can be pumped with more commonly available equipment.

Injection pressures typically do not exceed a few hundred psi, but each site will impose its particular requirements. The volumetric rate should exceed 25 gpm for adequate process performance as well as cost-effective deployment.

Jet Fracturing- Cased Hole Construction

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Well Construction

The jet fracturing process is performed in 4-inch PVC wells. The wells are constructed by a method that ensures a competent grout seal in the annulus between the casing and the borehole, thus guaranteeing that material injected at any particular elevation does not have a free pathway to overlying or underlying intervals.

Drilling Technology - Sonic, hollow stem auger, and mud rotary, have proven to be successful, and other methods should be satisfactory. Sonic may have a slight advantage. Air rotary may prove problematic.

Diameter – Two (2) inches of grout is required for this technique. Boreholes for 4-inch wells should be eight (8) inches in diameter.

Depth – Deepest target injection depth plus 7 feet.

Well Materials - The well material should be schedule 40, flush thread, 4-inch, PVC riser, with NO SCREEN SECTION. Centralizers should be used on the PVC riser every ten feet. The riser should be fitted with end caps or plugs at top and bottom.

Well Completion – The wells should be tremmie grouted, floated in, or installed by any method that ensures a continuous grout seal from bottom to top and around the PVC. Note: The grout is a standard mix of Portland cement and bentonite.

No screen, sand, or pure bentonite is to be used.

Surface Completion - The wells can be completed within flush mount man holes if subsequent future injection work is anticipated. Temporary wells can be completed without manhole with a 6-inch stick-up.