Seep Well Field Area Bioremediation Treatability Study Results Report

Nevada Environmental Response Trust Site
Henderson, Nevada

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Acronyms/Abbreviations	Definition
AOI	area of interest
AWF	Athens Road Well Field
BCL	Basic Comparison Level
BEC	Basic Environmental Company, LLC
bgs	below ground surface
COD	chemical oxygen demand
COH	City of Henderson
DNA	deoxyribonucleic acid
DO	dissolved oxygen
DVSR	Data Validation Summary Report
EC	electrical conductivity
EVO	emulsified vegetable oil
FS	Feasibility Study
ft/day	feet per day
ft/ft	feet per foot
GES	Geotechnical and Environmental Services, Inc.
gpm	gallons per minute
GWETS	groundwater extraction and treatment system
IDW	investigation-derived waste
ISB	in-situ bioremediation
ITRC	Interstate Technology & Regulatory Council
lbs/ft^3	pounds per cubic foot
mg/kg	milligrams per kilogram
mL	milliliters
mm	millimeters
µg/L	micrograms per liter
mg/L	milligrams per liter
mV	millivolts
NAC	Nevada Administrative Code
NDEP	Nevada Division of Environmental Protection
NDWR	Nevada Division of Water Resources
NERT or Trust	Nevada Environmental Response Trust
NMR	nuclear magnetic resonance

Acronyms/Abbreviations	Definition
OU	Operable Unit
ORP	oxidation-reduction potential
PLFA	phospholipid fatty acids
PRG	Preliminary Remediation Goal
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RAOs	remedial action objectives
RNA	ribonucleic acid
rpm	revolutions per minute
Site	Nevada Environmental Response Trust site, Clark County, Nevada
SNWALVWPCT	Southern Nevada Water Authority, Las Vegas Wash Project Coordination Team
SRB	sulfate-reducing bacteria
SWF	Seep Well Field
TDEM	time domain electromagnetic
TDS	total dissolved solids
Tetra Tech	Tetra Tech, Inc.
TOC	total organic carbon
USEPA	United States Environmental Protection Agency
UIC	Underground Injection Control
UMCf	Upper Muddy Creek formation
UNLV	University of Nevada at Las Vegas
USFWS	United States Fish and Wildlife Services
VFAs	volatile fatty acids
Work Plan	*Seep Well Field Area Bioremediation Treatability Study Work Plan*
WRF	Water Reclamation Facility

CERTIFICATION

Seep Well Field Area Bioremediation Treatability Study Results Report
Nevada Environmental Response Trust Site
(Former Tronox LLC Site)
Henderson, Nevada

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

Office of the Nevada Environmental Response Trust

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

Not Individually, but Solely as President of the Trustee

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

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

Title: Solely as President and not individually

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Date: 8/13/19

CERTIFICATION

I hereby certify that I am responsible for the services described in this document and for the preparation of this document. The services described in this document have been prepared in a manner consistent with the current standards of the profession, and to the best of my knowledge, comply with all applicable federal, state, and local statutes, regulations, and ordinances. I hereby certify that all laboratory analytical data was generated by a laboratory certified by the NDEP for each constituent and media presented herein.

Description of Services Provided: Prepared Seep Well Field Area Bioremediation Treatability Study Results Report

August 13, 2019

Kyle Hansen, CEM
Field Operations Manager/Geologist
Tetra Tech, Inc.

Date

Nevada CEM Certificate Number: 2167
Nevada CEM Expiration Date: September 18, 2020

EXECUTIVE SUMMARY

This report summarizes the technical approach and findings for the Seep Well Field (SWF) Area Bioremediation Treatability Study conducted for the Nevada Environmental Response Trust (NERT or Trust) in Henderson, Nevada. This treatability study was implemented in accordance with the Nevada Division of Environmental Protection (NDEP)-approved *Final Seep Well Field Area Bioremediation Treatability Study Work Plan* (Work Plan) (Tetra Tech, 2016a).

This was the second treatability study conducted by the Trust to evaluate the effectiveness of using in-situ bioremediation (ISB) to reduce the flux of perchlorate mass in groundwater from the alluvium that is migrating towards the Las Vegas Wash and not currently being captured by the existing extraction well network known as the SWF. The first ISB treatability study, which was completed in 2016, evaluated ISB in a proof of concept approach that involved three injection wells and nine monitoring wells and was situated in a paleochannel within alluvial sediments. This study was designed to determine if the injection of carbon donor into the alluvial sediments would reduce perchlorate and chlorate concentrations in groundwater. This second treatability study incorporates lessons learned in the first study and expands the injection well network in an attempt to create a biologically active treatment zone to reduce perchlorate and chlorate concentrations in groundwater over a larger geographic area in a difference geologic setting.

Phase 1 Pre-Design Activities

In order to design the treatability study, several pre-design activities were performed to characterize the lithology, identify preferential flow pathways, assess localized vertical and horizontal distribution of perchlorate, and accurately identify groundwater flow directions and rates. The pre-design activities included geophysical surveys, soil boring and monitoring well installation, soil and groundwater sampling, aquifer testing (including slug tests, single-borehole dilution tests, and nuclear magnetic resonance [NMR] logging), and laboratory bench-scale studies. The main findings from the Phase 1 pre-design activities were as follows:

- The geology in the treatability study area consists of alluvium at ground surface, underlain by the Upper Muddy Creek formation (UMCf). The alluvium within the treatability study area is heterogeneous and consists of interbedded layers of sand, silt, and gravel. The depth to the alluvium/UMCf contact ranges from 33 – 54.5 feet below ground surface (bgs), with the depth averaging approximately 40 feet bgs. The UMCf is a visually distinct, very light greenish grey silty clay. A small paleochannel oriented approximately east-west is located within the treatability study area, as indicated by the deeper erosional contact between the alluvium and UMCf as well as a higher portion of gravel and cobbles in the alluvial sediments.
- Perchlorate was detected in soil samples collected from the vadose zone, upper alluvium, lower alluvium, and shallow UMCf at depths ranging from 1 – 69 feet bgs, with concentrations ranging from less than 0.010 milligrams per kilogram (mg/kg) to 12 mg/kg.
- Perchlorate was detected in groundwater samples collected from the alluvium at concentrations ranging from 170 micrograms per liter (μg/L) to 25,000 μg/L and in the UMCf at concentrations ranging from 7,800 μg/L to 8,300 μg/L. Other key parameters including chlorate, nitrate, and sulfate were detected in groundwater samples from the alluvium at concentrations as high as 67,000 μg/L, 18 milligrams per liter (mg/L), and 4,700 mg/L, respectively.
- Hydraulic conductivities measured in the alluvium ranged from 1.3 feet per day (ft/day) to 329.9 ft/day, with an average hydraulic conductivity of approximately 54 ft/day. NMR estimates of hydraulic conductivity generally agreed (within an order of magnitude) with estimates derived using slug testing.
- Alluvial groundwater flow rates within the paleochannel area were estimated to range from 12 to 119 ft/day, while groundwater flow rates in non-paleochannel areas ranged from 0.07 ft/day to 2 ft/day.
- Built upon the laboratory dataset acquired through the first of the Trust's ISB Treatability Studies, additional laboratory studies indicated that emulsified vegetable oil (EVO) was an effective electron

donor/carbon substrate that had the ability to enhance biodegradation of nitrate, chlorate, and perchlorate under the test conditions in both the alluvium and UMCf. Although not the focus of the field treatability study, laboratory tests were performed for the UMCf to collect data for future potential ISB studies that may target the UMCf.

- Batch microcosm results indicate that nitrate and chlorate were completely degraded to below laboratory detection limits within 10 days in the alluvium microcosms, while perchlorate was degraded to below laboratory detection limits within 20 days.
- Adsorption tests indicated that the UMCf adsorbs 1.9 times the amount of EVO compared to the alluvium soils.
- Results from the column studies indicated that the amount of oil sorption to the target geologic media is a function of not only the amount of oil that is added to the system but also the amount of water that is flushed through the column, and therefore, lower amounts of oil (with potential repeated injections) would be a preferred way to operate an ISB system in this geologic setting.

Phase 2 Treatability Study Implementation

The data collected during the Phase 1 pre-design were used to finalize the Phase 2 treatability study injection well design and injection protocol, which focused on the saturated alluvium at depths ranging from approximately 15 to 45 feet bgs. The final design consisted of two injection well transects installed approximately 400 feet upgradient of historic monitoring well PC-94, with the injection well transects spaced 100 feet apart. Each of the two injection well transect rows is approximately 750 feet in length and includes 10 injection well locations spaced approximately 75 feet apart, for a total of 20 injection well locations. At five of the twenty injection well locations, a paired injection well configuration was installed to test the potential benefits of this injection well configuration. This configuration consisted of two injection wells, each screened across separate treatment intervals and installed in separate boreholes. The depth of the injection well and length of the injection well screen were varied based on the field observed lithology for the alluvium and the depth to groundwater. In addition to the injection wells and monitoring wells previously installed as part of the Phase 1 pre-design effort, 15 additional monitoring wells were installed upgradient, in between, and downgradient of the injection well transects to further evaluate the effectiveness of ISB within the treatability study area.

Following completion of the injection and monitoring well installation and baseline groundwater monitoring to establish pre-injection conditions, injections of carbon substrate and amendments began in August 2017. Three injection events were performed during the treatability study in August/September 2017, January/February 2018, and June 2018. Carbon substrates and amendments injected over the three injection events included EOS® PRO, glycerin, phosphate solution, and sodium sulfite. Following injections of the carbon substrate solution, water was injected to optimize the distribution of the injectate solution. The water used during injections was groundwater extracted from upgradient monitoring wells.

Following each injection, groundwater samples were periodically collected from the effectiveness monitoring wells to evaluate the effectiveness of ISB on groundwater within the treatability study area. A total of 16 monitoring events (including baseline sampling) were performed during the treatability study. During each monitoring event, water levels were gauged, field parameters were collected, and groundwater samples were collected and analyzed for a variety of laboratory parameters. In addition, Bio-Trap® samplers were periodically deployed in select wells and analyzed to determine the type and health of the microbial populations. Three slug testing events were also conducted to estimate aquifer hydraulic conductivity in the treatability study area before and after injection of the substrate.

Treatability Study Findings and Conclusions

The main findings of the SWF Area Bioremediation Treatability Study are as follows:

- Nitrate, chlorate, and perchlorate degradation was initiated very rapidly following carbon substrate injections through the creation of a biologically active zone, which continued to sustain perchlorate degradation throughout the 14-month treatability study time frame. Denitrification (nitrate biodegradation) occurred very rapidly and preferentially compared to perchlorate and chlorate biodegradation in both the field and laboratory studies. Perchlorate and chlorate biodegradation generally followed denitrification and, once initiated, the two reductive processes were observed to occur concurrently at locations that recorded the best geochemical response to the carbon substrate injections. These results were similar to the first treatability study performed as a proof of concept study.

- The study demonstrated the ability of ISB using a slow-release carbon substrate to achieve the Preliminary Remedial Goal (PRG) for perchlorate in groundwater of 15 µg/L within the alluvium. Groundwater concentrations below the perchlorate PRG were attained and sustained at several groundwater monitoring well locations.
- Based on the results of the field treatability study, the maximum first-order perchlorate biodegradation rate constants in groundwater were determined to range from -0.09 day^{-1} to -0.25 day^{-1}. At these rates, perchlorate concentrations decreased very rapidly in groundwater as observed in the field treatability study immediately following the first injection event.
- This study indicated that the range of flow rates present in the SWF area (from 0.07 to 119 ft/day) and associated residence time due to these flow rates were not impediments to perchlorate biodegradation.
- Performing periodic injections into the injection wells over time was shown to gradually increase the overall biodegradation in groundwater over time. One reason for this improved degradation was the use of the EVO, which because of its chemical nature, tends to gradually coat the soil grains along the transect width over a larger area of the subsurface during subsequent injections, which creates a more uniform barrier over time. The average overall perchlorate biodegradation in groundwater for the monitoring wells located in between the injection well transects was shown to increase from 55 percent to 83 percent following the first and third injections, respectively. This key finding is important for evaluating the overall effectiveness and associated cost of a full-scale ISB remedy during the Feasibility Study (FS).
- The ability of the formation to accept substrate injections following three injection events indicates ISB is a feasible long-term option for groundwater in the alluvium within the NERT RI Study Area. Over the course of the three injection events, carbon substrate was injected in relatively the same time frames at flows greater than 5 gallons per minute (gpm) and pressures that were less than the maximum permissible. Injection pressures gradually increased from an approximate average of 5 pounds per square inch (psi) to 14 psi over the three injection events that were performed. Slightly higher injection pressures during subsequent injections is common and expected with ISB as a normal response to the engineered biomass growth on the subsurface media below. However, no injection well maintenance has been required to-date, indicating that the subsurface continues to be amenable to periodic injections of EVO.
- While achieving a specific reduction in plume mass was not an objective of this study, approximately 2,748 pounds of perchlorate were destroyed by ISB during the 14-month treatability study time frame. Following an initial large mass reduction after the first injection event, the sustained average perchlorate mass flux treated was approximately 3 pounds per day.

Path Forward

While the implementation of this treatability study achieved its objectives, *Treatability/Pilot Study Modification No.6 – Seep Well Field Area Bioremediation Treatability Study* (Tetra Tech, 2018) (Mod. 6) was submitted to and approved by NDEP to enable the Trust to continue substrate injections to develop a more thorough understanding of the key operation and maintenance components as they relate to long-term applications of ISB for use in the FS evaluations, given the biomass accumulations that were experienced by other parties in the area adjacent to the NERT RI Study Area under a different treatment approach. The objectives for continuation of the SWF Area Bioremediation Treatability Study include: (1) evaluation of injection frequencies and substrate quantities over time to provide optimal dosing that sustains the reducing conditions for ISB of perchlorate and chlorate in groundwater; and (2) development of a more in-depth understanding of the long-term operation and maintenance requirements of injection well networks associated with ISB systems (i.e., evaluation of maintenance measures to promote injection well longevity, if required).

As part of this continuation, injection events are anticipated to occur once every 5 to 6 months, but the exact timing and frequency will be determined based on effectiveness monitoring results. The first injection event under this modification (fourth injection event to date) was performed from January 23 – February 10, 2019. Additional injections will continue to be performed through remedial design (anticipated to be Q1 2023). Following injections, effectiveness monitoring will generally consist of groundwater sampling once every 6 weeks for a reduced set of analytes as described in Mod. 6. In addition, each injection well will be video logged before the fifth injection event to assess the condition of the well screens. Effectiveness monitoring will also continue for the duration of the treatability study through remedial design. Well maintenance activities will be performed, as required, on an as-needed basis. While efforts related to Mod. 6 are outside the scope of this report, quarterly progress updates will be submitted to NDEP throughout the implementation of Mod. 6, with a more detailed results report submitted on an annual basis at year-end.

1.0 INTRODUCTION

At the direction of the Nevada Environmental Response Trust (NERT or Trust), Tetra Tech, Inc. (Tetra Tech) has prepared this *Seep Well Field Area Bioremediation Treatability Study Results Report* for the NERT site (Site), located in Clark County, Nevada (Figure 1). This report is being submitted to the Nevada Division of Environmental Protection (NDEP) under the Interim Consent Agreement effective February 14, 2011. The report presents an evaluation of the results from the bench and field tests for in-situ bioremediation (ISB) of perchlorate in groundwater in the vicinity of monitoring well PC-94, east of the Seep Well Field (SWF), which is immediately upgradient of the Las Vegas Wash (Figure 1). The treatability study was implemented based on the NDEP-approved *Final Seep Well Field Area Bioremediation Treatability Study Work Plan* (Work Plan) (Tetra Tech, 2016a).

1.1 OBJECTIVES

The overall objective of this treatability study was to evaluate and demonstrate the effectiveness of using ISB to reduce the flux of perchlorate mass in groundwater that is migrating towards the Las Vegas Wash and not currently being captured by the existing extraction well network known as the SWF. This treatability study was the second ISB treatability study implemented by the Trust and built upon the results and lessons learned through implementation of the previous ISB treatability study that was performed downgradient of the Athens Road Well Field (AWF) near the City of Henderson (COH) Bird Viewing Ponds (as shown on Figure 1). This previous study was implemented as a proof of concept study and demonstrated that sustained in-situ perchlorate biodegradation is achievable via the addition of a slow-release carbon substrate, namely, emulsified vegetable oil (EVO) within an alluvial paleochannel that had an average groundwater flow velocity of 32 feet per day (ft/day). The SWF Area Bioremediation Treatability Study was implemented on a larger-scale and in a different geologic setting than the area where the previous treatability study has been performed, as this study is upgradient of a paleochannel and therefore, has a lower groundwater flow velocity within the injection zone itself.

Specific objectives of the SWF Area Bioremediation Treatability Study include the following:

- Evaluation of the feasibility and effectiveness of implementing ISB in the alluvium to reduce the groundwater perchlorate mass flux in the vicinity of monitoring well PC-94, located east of the SWF;
- Demonstrate the development and sustainment of a biologically active treatment zone by periodically injecting carbon donor in a different geologic environment than previously tested;
- Estimation of the zone of influence for substrate and biodegradation achievable during the treatability study;
- Perform bench-scale studies to affirm the biodegradability of perchlorate in soil and groundwater specific to this area, provide an estimate of the lag time and timeframe for perchlorate biodegradation, estimate the perchlorate degradation timeframe, examine the potential to utilize GWETS water for the carbon substrate distribution, and evaluate the adsorption potential of EVO for the treatability study area soil;
- Estimation or extrapolation of the longevity of the carbon substrate and frequency of carbon substrate replenishment required to reduce perchlorate contamination immediately downgradient of the treatability study injection transect;
- Examination of the approach and feasibility for full-scale transect treatment including required equipment, injection, and monitoring well layout; substrate addition and replenishment; and analytical sampling evaluation criteria.

1.2 REPORT ORGANIZATION

This report is organized as follows:

- **Introduction (Section 1.0):** Provides the primary objectives of this treatability study and organization of this report.
- **Technology Description (Section 2.0):** Provides an overview of perchlorate biodegradation and a summary of the previous ISB treatability study performed on the COH property, south east of the bird viewing ponds.
- **Phase 1 Pre-Design Field Activities (Section 3.0):** Provides a description and results summary of the field activities completed prior to implementing the treatability study in order to optimize and finalize the field test design.
- **Phase 1 Laboratory Bench-Scale Studies (Section 4.0):** Presents the objectives, procedures, and results of the laboratory bench-scale studies conducted at University of Nevada at Las Vegas (UNLV).
- **Phase 2 Field Treatability Study Activities (Section 5.0)**: Provides a summary of field treatability study activities including the injection and monitoring well installations, underground injection control (UIC) permitting, injection events, and effectiveness monitoring program.
- **Analysis of Results (Section 6.0):** Summarizes the geology and hydrogeology of the treatability study area and chemical, geochemical, and microbial results during the treatability study.
- **Summary of Key Findings (Section 7.0):** Presents the overall findings of the treatability study and provides cost considerations for future ISB implementation at the NERT site.
- **Path Forward (Section 8.0):** Presents path forward for the SWF Area Bioremediation Treatability Study.
- **References (Section 9.0):** Lists the documents referenced in this report.

2.0 TECHNOLOGY DESCRIPTION

The following subsections briefly describe the perchlorate biodegradation process, bioremediation as a treatment technology for perchlorate, and its application as related to the Site.

2.1 MICROBIOLOGY AND BIODEGRADATION OF PERCHLORATE

Perchlorate is the anionic component of ammonium perchlorate, a common solid rocket fuel booster ingredient. Perchlorate salts are very soluble in water, (approximately 200,000 milligrams per liter [mg/L] for ammonium perchlorate and approximately 2,100,000 mg/L for sodium perchlorate) and do not adsorb very strongly to most soils.

Perchlorate also tends to be biologically stable under aerobic conditions or when there is a limited source of organic carbon. However, in the presence of a suitable carbon substrate and after dissolved oxygen (DO) and nitrate have been depleted, perchlorate can act as a strong electron acceptor for anaerobic respiration. The first step in perchlorate biodegradation is carried out by the enzyme perchlorate reductase, wherein perchlorate is sequentially converted to chlorate and then to chlorite. A second enzyme, chlorite dismutase further reduces the chlorite to chloride and oxygen (ITRC, 2008). Although perchlorate biodegradation generally precedes chlorate biodegradation, the two processes can also occur simultaneously, particularly in the presence of organic carbon.

A variety of perchlorate-reducing bacteria have been isolated, some of which are strict anaerobes, while others are facultative microbes. Generally, perchlorate-reducing microorganisms are known to be quite ubiquitous in the subsurface and are also quite versatile. As a result, the key to successful groundwater treatment is understanding the chemical, geochemical, physical, geological, and hydrogeological conditions at a site, and then devising a prudent approach to engineer a successful remedial strategy. Physical, geological, and hydrogeological conditions are commonly quite established and fixed, and therefore a successful remedial strategy relies on the alteration and sustainment of the appropriate geochemical conditions for continual perchlorate biodegradation to occur. Favorable redox conditions that are appropriate for perchlorate biodegradation are less than 0 millivolts (mVs) and generally in the 0 to -100 mVs range. This range of redox is generally indicative of conditions wherein the aquifer is depleted of DO and nitrate itself gets consumed, leaving perchlorate the next preferred electron acceptor as the respiratory source for native microorganisms (ITRC, 2008).

2.2 BIOREMEDIATION OF PERCHLORATE

In aquifers that are aerobic or have a limited supply of natural organic carbon, the key to successfully attaining and sustaining the appropriate redox range is to add a carbon electron donor/substrate to the subsurface. Numerous carbon donors are available that can be injected into the groundwater via a variety of engineering configurations and the choice at a given site is based on several physical, chemical, geochemical, and economic factors. Bioremediation requires the engineered addition of a carbon substrate to the groundwater to optimize and sustain biodegradation of perchlorate in groundwater. All biodegradation occurs in situ and, as previously described, is generally carried out by native microorganisms which possess the enzymatic ability to completely reduce perchlorate to chloride and oxygen.

The addition of carbon substrate can be performed via a variety of engineering configurations such as vertical injection wells, direct push injection points, horizontal injection wells, continuous barriers, or in-situ bioreactors. The selection of the optimal configuration at a particular site depends on several factors including the nature and extent of the perchlorate plume and whether the treatment application is for source areas, large/long plumes, or plume containment.

Organic carbon substrates that have been typically used to treat perchlorate in groundwater can be broadly subdivided into three general groups that include: (i) water-soluble substrates such as glycerin or molasses; (ii) slow-release substrates such as EVO or Hydrogen Release Compound®; and (iii) solid substrates such as compost or wood chips. Combinations of these are also used in practice.

2.2.1 Previous ISB Treatability Study Summary

As indicated earlier in this section, a previous groundwater ISB treatability study was conducted from April 2015 to August 2016. The study was performed within the vicinity of the COH Water Treatment Facility, which is immediately upgradient of the Bird Viewing Preserve and mid-way between the AWF and SWF (location presented on Figure 1). The results and findings of this previous treatability study are presented in the *Groundwater Bioremediation Treatability Study Results Report* (Tetra Tech, 2016b). A summary of the layout, implementation, and major results and findings of this study was provided in the Work Plan. This study was performed on a small scale (just three injection wells) and for a short-term period (6 months of active treatment) as a proof of concept study with a screening level objective of demonstrating that ISB could be a viable technology at the NERT site. Overall, groundwater chemical, biochemical, and microbial data collected during the previous study indicated that the chosen slow-release carbon substrate, EVO, has the ability to create, sustain, and carry out biodegradation of perchlorate in groundwater under very high groundwater flow velocity conditions (average of 32 ft/day) in a paleochannel setting.

Key findings and lessons learned of the previous treatability study, including the continued use of EVO as the carbon substrate of choice in more permeable formations, injection well spacings, frequency of the injection events, injection protocol, and results of the bench-scale studies, were incorporated where appropriate in the SWF Area Bioremediation Treatability Study. However, because the previous proof of concept treatability study was performed in a different geologic environment and different spatial size and timeframe, the SWF Area Bioremediation Treatability Study has further refined objectives and is different from the previous treatability study as outlined below:

- As described in Section 6.1, the geology and hydrogeology of this area are different from the previous treatability study. Although treatment is still in the alluvium, the SWF Area Bioremediation Treatability Study area is indiscriminately heterogeneous. Although there is a paleochannel in the area, it is downgradient of the injection well transects; thereby injections performed in the SWF Area Bioremediation Treatability Study are not directly into a high flowing paleochannel environment, which was the case for the previous proof of concept study.
- The previous proof of concept treatability study only consisted of three injection wells, whereas the SWF Area Bioremediation Treatability Study has been designed as an engineered transect of injection wells in order to evaluate the creation and sustainment of a biologically active treatment zone. The objective of the larger treatment zone will provide data on any variable perchlorate degradation response and hydraulic conductivity changes that may be observed when ISB is implemented at this larger scale.
- The SWF Area Bioremediation Treatability Study was performed for a longer period of time and involved more injection events with varying quantities of carbon substrate in order to evaluate how ISB performs over time, including the degradation that could be sustained, variations in degradation patterns across the longer injection transect, and information on the operations, maintenance, and optimization of injection systems and injection wells.

3.0 PHASE 1 PRE-DESIGN FIELD ACTIVITIES

Prior to start-up of the SWF treatability study, several Phase 1 pre-design field activities were performed, with results used to finalize design details for treatability study implementation. Specifically, the objectives of the pre-design activities were to accomplish the following:

- Characterize the lithology in sufficient detail to refine the conceptual injection well spacing;
- Identify preferential flow pathways in order to better target injections;
- Assess localized vertical and horizontal distribution of perchlorate to appropriately target the treatability study;
- Accurately identify groundwater flow directions and rates to design the injection wells and perform injections to best address perchlorate migration through the treatability study area.

Phase 1 pre-design field activities were performed from January to March 2017 to gather the appropriate data to meet these objectives. The pre-design activities that were conducted included a biological survey, geophysical surveys, soil boring and monitoring well installation, soil and groundwater sampling, and aquifer testing (including slug tests, single-borehole dilution tests, and nuclear magnetic resonance [NMR] logging).. A summary of these activities, their purpose, and respective results are presented in this section. All field work described was conducted in general accordance with the existing *Field Sampling Plan, Revision 1* (ENVIRON, 2014) and the Work Plan. Although the target of this treatability study is perchlorate-contaminated groundwater that is present in the alluvium, limited data was also collected in the UMCf during field activities to evaluate soil and groundwater conditions in the upper portion of the UMCf to better understand the geology and perchlorate distribution in soil and groundwater within treatability study area.

3.1 ACCESS AGREEMENT

Due to the off-site location of the pre-design field activities and treatability study, the Trust negotiated an access agreement for all treatability study field activities from Basic Environmental Company, LLC (BEC). This access agreement was executed in November 2016 and will expire in May 2020, although it is anticipated the agreement will be amended to facilitate efforts related to Mod. 6. This agreement allows for completion of both Phase 1 pre-design and Phase 2 treatability study activities, which includes the pre-design activities described within this section and the treatability study activities described in Section 5.0.

3.2 BIOLOGICAL SURVEY

Although there is no designated critical habitat for threatened or endangered species within 0.5 mile of the project site (United States Fish and Wildlife Services [USFWS], 2016), threatened and endangered species have occasionally been documented along the Las Vegas Wash, which is approximately 1,400 feet north of the treatability study area. Although these species include the Yuma clapper rail (*Rallus longirostris yumanensis*), southwest willow flycatcher (*Empidonax traillii extimus*), yellow-billed cuckoo (*Coccyzus americanus*) (last recorded in 1998) (Southern Nevada Water Authority, Las Vegas Wash Project Coordination Team [SNWALVWPCT], 2008), no impacts to avian species from the treatability study activities were expected given that the riparian habitat lies outside of the treatability study footprint. Therefore, additional protection measures were not required.

In addition to the avian species, the desert tortoise (*Gopherus agassizii*) has been historically and occasionally observed in the vicinity of the Las Vegas Wash. As a result, prior to field activities, a biological habitat survey for the desert tortoise was conducted on December 12, 2016. During this survey, a trained biologist qualified to conduct desert tortoise monitoring walked the site and documented that no desert tortoise individuals, evidence of their presence, or other wildlife/wildlife burrows were observed within the treatability study area. The desert tortoise site clearance memorandum is provided in Appendix A.

3.3 GEOPHYSICAL DATA COLLECTION

Geophysical surveys were performed as a cost-effective way to improve identification and definition of potential preferential flow pathways and paleochannel morphology, as well as to characterize the alluvium/Upper Muddy Creek formation (UMCf) contact. These data were then used to determine the optimum placement for the pre-design soil borings and monitoring wells needed to characterize the treatability study area both lithologically and hydrogeologically.

Geophysical surveys were performed by Terra Physics with Tetra Tech oversight from January 3 – 11, 2017. Originally, time domain electromagnetic (TDEM) surveys were planned; however, Terra Physics recommended use of electrical resistivity to obtain higher resolution data in the shallow subsurface. Electrical resistivity surveys were performed along six geophysical survey lines within the treatability study area, as illustrated in Figure 2. Results indicated that there was a potential paleochannel crossing the study area, and therefore monitoring wells were placed to intercept that channel. However, the depth to UMCf contact in the electrical resistivity surveys tended to be deeper than the actual UMCf contact observed in boreholes (Section 3.4) indicating that electrical resistivity surveys may be more useful in identifying general paleochannel locations than in estimating the physical depth of the UMCf contact. Terra Physics's geophysical survey report is presented in Appendix B.

3.4 SOIL BORING AND MONITORING WELL INSTALLATION

Soil borings and monitoring wells were installed within the treatability study area to provide information on the lithology, hydrogeology, and contaminant distribution within the treatability study area. This section presents details of the installation activities and a summary of the soil and depth-discrete groundwater results. Local geology and accompanying cross sections are provided in Section 6.1, which collectively presents lithological data collected during both the Phase 1 pre-design and Phase 2 treatability study implementation phases.

3.4.1 Installation Activities

Field work associated with the installation of Phase 1 pre-design soil borings and monitoring wells was conducted from February 20 through March 17, 2017. Locations of pre-design soil borings/monitoring wells are presented in Figure 2.

3.4.1.1 Pre-Drilling Activities

Tetra Tech, on behalf of NERT, prepared and submitted all required applications and obtained required permits prior to the installation of soil borings and monitoring wells. A Monitor Well Drilling Waiver (Nevada Administrative Code [NAC] 534.441) and a Notice of Intent to Drill Card (NAC 534.320) were submitted to the Nevada Division of Water Resources (NDWR). The Monitoring Well Drilling Waiver also included a completed, signed, and notarized Affidavit of Intent to Plug a Monitoring Well as a required attachment.

Prior to drilling activities, Tetra Tech contacted USA North Utility Locating Services, reviewed available utility maps, and retained the services of a geophysical locator to check for underground utility lines. Each drilling location was cleared to a depth of 5 feet below ground surface (bgs) by hand augering.

3.4.1.2 Soil Boring Installation

Soil borings were installed at 20 locations, of which 10 were converted to monitoring wells (Section 3.4.1.3), within the planned treatability study footprint to provide area-specific lithological information and contaminant concentration data to incorporate into the development of the final treatability study design. Drilling and well installation activities were conducted by Cascade Drilling, LP using rotosonic drilling methods. At 15 of the 20 locations, soil borings were advanced through the saturated alluvium terminating at the contact with the UMCf, generally around 40 feet bgs. At the remaining five locations, soil borings were advanced through the saturated alluvium and approximately 15 feet into the UMCf to evaluate the local lithology. The continuous soil cores were logged from ground surface to total depth using the Unified Soil Classification System. Photographs of soil cores were also collected during drilling activities. Copies of the soil boring logs and core photographs are provided in Appendix C.

During soil boring installation, soil samples were collected for a variety of chemical, geotechnical, and microbial parameters to provide data to design the bench-scale and field-scale studies. As part of the soil sampling protocol, a total of 55 soil samples was collected from the vadose zone, saturated alluvium, and UMCf to evaluate perchlorate concentrations at depth. Soil samples for laboratory analysis were collected in laboratory-supplied containers, labeled, placed in plastic bags, and stored in a cooler on ice for transport under chain-of-custody documentation to the appropriate laboratory, either TestAmerica Laboratories, Inc. or Microbial Insights Inc. All soil samples were analyzed for perchlorate. Ten soil samples were also analyzed for additional parameters (soil pH, total organic carbon [TOC], total dissolved solids [TDS], total Kjeldahl nitrogen, phospholipid fatty acids [PLFA] and/or the perchlorate reductase gene) to provide additional characterization of the subsurface. Results from the chemical and microbial soil analyses conducted as part of the pre-design field activities are presented in Appendix D, Tables D.1 and D.2, respectively.

In addition to soil samples for analysis of chemical and microbial parameters, the Work Plan also specified that undisturbed soil samples would be collected upon reaching groundwater using a Shelby tube, or similar collection device. Although the work plan originally specified a Shelby tube sample from each borehole, a total of eight Shelby tube samples were collected at eight of the twenty soil boring locations, which was deemed representative of the various lithological units present within the area and sufficient to design the treatability study. This reduction during pre-design also allowed for the collection of additional undisturbed soil samples during the Phase 2 installation of the injection wells (discussed in Section 5.2). Six of the Shelby tube samples contained alluvium soil (two from 20-22.5 feet bgs and four from 30-32.5 feet bgs) and two Shelby tube samples contained UMCf soil from 47-49.5 feet bgs and 56-58.5 feet bgs. Shelby tubes were transferred to UNLV for analysis of physical parameters including moisture content, porosity, soil density, and soil grain size to be used by UNLV for planning/set-up of the laboratory bench-scale studies. Results are discussed as part of the bench-scale results in Section 4.2.

Depth-discrete groundwater samples were also collected from select boreholes within the alluvium, just above the top of the UMCf, and/or within the UMCf in accordance with the Work Plan to vertically profile the perchlorate extent. Depth-discrete groundwater samples were collected during advancement of the soil borings using a sealed push-ahead groundwater sampling tool. The tool was threaded to the base of the sonic drill rod and driven ahead of the casing into undisturbed soil at the target depth. The push-ahead tool was then partially unthreaded to expose slots allowing formation water to enter the previously sealed tool. The groundwater samples were then collected from the push-ahead tool using a disposable bailer. Depth-discrete groundwater samples were collected at 10 of the 20 boring locations from the upper alluvium (13 – 26 feet bgs), lower alluvium (32 – 41 feet bgs), and/or UMCf (46 – 50 feet bgs). All discrete groundwater samples were analyzed for perchlorate; a subset of samples was also analyzed for nitrate and TDS. Results from the discrete groundwater sample analyses conducted as part of the pre-design field activities are presented in Table D.3 in Appendix D.

Finally, saturated soil from the alluvium and UMCf was collected and transferred to UNLV to be used in the laboratory bench-scale studies described in Section 4.0. Soil was collected from both the alluvium and UMCf from soil borings SWFTS-BH04, SWFTS-BH08, and SWFTS-BH10.

3.4.1.3 Monitoring Well Installation

A total of 16 permanent monitoring wells were installed at 10 of the 20 soil boring locations to evaluate the horizontal and vertical extent of perchlorate concentrations and any hydraulic gradient changes with depth to optimize the treatability design. Paired monitoring wells were installed at six of the 10 boring locations in borings approximately 8 feet apart from one another to evaluate hydrogeologic and geochemical variation with depth within the study area. Specifically, at four of the 10 soil boring locations, paired monitoring wells were installed with one monitoring well screened in the upper alluvium and one monitoring well screened in the lower alluvium. At two of the 10 locations, well pairs were installed comprising of one monitoring well screened in the alluvium and one monitoring well screened in the UMCf. Due to the proximity of the paired wells, only the deep monitoring well within the well pair was lithologically logged. At the remaining four soil boring locations, single monitoring wells were installed and screened in the alluvium.

In general, monitoring wells were constructed using 2-inch diameter Schedule 40 polyvinyl chloride (PVC) casing and screened with 2-inch diameter, 0.020-inch slotted PVC well screen. Four monitoring wells (SWFTS-MW07A, SWFTS-MW08A, SWFTS-MW09A, and SWFTS-MW10A) were constructed with 4-inch diameter Schedule 40 PVC casing and were screened with 4-inch diameter, 0.020-inch slotted PVC well screen, which was required for single-borehole dilution testing (Section 3.6.2). All wells were completed with flush-mounted, traffic-rated well boxes, at an elevation of approximately 0.5-inches above grade. Following well construction, but no sooner than 48 hours after well construction was completed, the newly installed monitoring wells were developed using a surge block and bailer to swab and surge the filter pack and remove sediment from the wells. This process was followed by pumping with a submersible pump to purge the well of fine-grained sediment. Well development was considered complete when three to ten casing volumes of water had been removed from the well and index parameters (consisting of pH, specific conductivity, turbidity and temperature) were stable (within 10 percent) over three consecutive measurements.

3.4.1.4 Management of Investigation-Derived Waste

Investigation-derived waste (IDW) generated during the soil and monitoring well installation was managed in accordance with applicable state, federal, and local regulations and as described in *Field Sampling Plan, Revision 1* (ENVIRON, 2014). During the Phase 1 pre-design investigation of the treatability study area, IDW included soil cuttings, personal protective equipment, field consumables (such as plastic sheeting on which to place soil cores for logging), equipment decontamination water, and groundwater generated during depth-discrete groundwater sampling and well development.

Investigation-derived soil waste was containerized onsite in plastic lined, 10 cubic-yard roll-off bins. The roll-offs were labeled to indicate contents, source, and date when accumulation began. Soil cuttings contained in each of the roll-off bins were sampled for profiling purposes, with one composite soil sample collected from each bin. The samples were analyzed for the following: volatile organic compounds by United States Environmental Protection Agency (USEPA) Method 8260B; Resource Conservation and Recovery Act 8 Metals by USEPA Method 6020; flashpoint ignitability by USEPA Method SW846 7.1.2; pH by USEPA Method 9045C; perchlorate by USEPA Method 314.0; and toxicity characteristic leaching procedure – Metals by USEPA Method 1311 extraction/USEPA Method 6020. Results indicated that the soil cuttings were non-hazardous waste. All IDW was disposed of at Apex Landfill, Las Vegas, Nevada.

Wastewater generated during purging or decontamination activities was temporarily stored in 55-gallon drums and/or 500-gallon totes and transferred into the GW-11 Pond for onsite treatment in the groundwater extraction and treatment system.

3.4.2 Results

This section presents analytical results for soil and discrete-depth groundwater samples collected during Phase 1 pre-design soil boring and monitoring well installation. Discussion of geology within the treatability study area is provided in detail in Section 6.1. However, general lithology observed during pre-design drilling activities consisted of alluvium, comprised dominantly of silty sand and gravelly sand with minor lenses of sandy silt and clay, and UMCf, typically consisting of light greenish grey clay, was encountered below the alluvium at depths ranging from approximately 34.5 – 48 feet bgs.

3.4.2.1 Soil Analytical Results

As described in Section 3.4.1.2, soil samples were collected from the vadose zone, saturated alluvium, and UMCf. Soil analytical results are presented in Appendix D, Tables D.1 and D.2. Perchlorate results ranged from less than the sample detection limit of 0.010 milligrams per kilogram (mg/kg) to 12 mg/kg. Perchlorate was detected in soil samples collected from the vadose zone, upper alluvium, lower alluvium, and shallow UMCf at depths ranging from 1 – 69 feet bgs. The soil results are generally comparable to the baseline groundwater analytical data, which indicate higher concentrations in the areas of the paleochannel (discussed in Section 6.1). Perchlorate concentrations in the deepest soil samples collected from 60 to 69 feet bgs ranged from less than a sample detection limit of 0.012 mg/kg to 0.016 J mg/kg. The highest perchlorate concentrations were detected in soil samples collected from the unsaturated alluvium and UMCf. The perchlorate in the vadose zone was likely deposited by higher groundwater levels that were likely present when the infiltration ponds and ditches were still in use in Operable Unit (OU) 2, while the perchlorate in the UMCf likely reflects contaminants that migrated into the UMCf prior to installation of the SWF and have not yet migrated out. Concentrations of perchlorate detected above its leaching Basic Comparison Level (BCL) of 0.0185 mg/kg were detected in soil at depths up to 58 feet below grade within the UMCf. A detailed description of the horizontal and vertical extent of perchlorate, along with additional analysis on the upward migration of perchlorate, will be provided in the forthcoming Remedial Investigation (RI) Report for OU 3.

Ten soil samples were also analyzed for the additional constituents of TOC, TDS (on water extracted from the soil), PLFA, and perchlorate reductase gene to provide further characterization of the subsurface. TOC concentrations for soil samples collected from the alluvium ranged from 140 to 16,000 mg/kg. Soil samples collected from the UMCf had significantly higher TOC results, ranging from 36,000 to 120,000 mg/kg. TOC is likely high because of ancient deposits of plant material that is still undergoing decay. It is very unlikely that this plant material is providing an available and usable source of organic carbon for microorganisms based on the continuing aerobic groundwater condition. Plant material is often hard to degrade as it contains long chain organics such a lignin. TDS analyses performed on the water extracts indicate TDS concentrations ranged from 1,600 to 3,200 mg/L. Three soil samples, one each from the upper alluvium, lower alluvium, and UMCf, were also analyzed for soil pH, which ranged from 7.4 to 8.3 SU.

Three soil samples were sent to Microbial Insights for analysis of PLFA and the perchlorate reductase gene. Alluvium soil samples were collected from SWFTS-MW08C at 28 feet bgs and SWFTS-MW09B at 19 feet bgs. One UMCf soil sample was collected from SWFTS-MW08C at 51 feet bgs. Soil microbial results are presented in Appendix D, Table D.2. The total biomass was 1.8×10^5 cells/g in all three samples, a result which indicates a healthy microbial population. Perchlorate reductase numbers were greater than 10^4 cells/g in all three soil samples, which indicate that sufficient microbial populations with the ability to biodegrade perchlorate and other inorganic electron acceptors such as chlorate and nitrate are attached to the soil in the subsurface. The PLFA analysis on community structure in the soil indicates that a majority (approximately 59 percent) of the bacteria belongs to the Nsats structural group, a finding that indicates the native bacteria in soil may not be naturally diversified prior to the addition of a carbon substrate. The remaining portion of the microbial community structure was made up of approximately 16 percent Proteobacteria, 15 percent Firmicutes, 7 percent Sulfate Reducing Bacteria (SRB)/Actinomycetes, and 3 percent Eukaryotes in all samples. The presence of even low percentages of Proteobacteria in the soil indicates that the microbial population has the potential to eventually adapt and biodegrade perchlorate and other inorganic electron acceptors such as chlorate and nitrate. The physiological status ratio of a microbial community is typically expressed in terms of whether it has slowed growth and decreased permeability. The slowed growth ratio was relatively high, with ratios greater than 3 in all samples. Ratios at these levels indicate that the current natural subsurface conditions are likely to be lacking in an available carbon substrate; however, the ratio for decreased permeability was 0 for all soil samples despite the high values of slowed growth ratio, which strongly suggests that subsurface conditions are very unlikely to be toxic to microorganisms.

3.4.2.2 Discrete-Groundwater Analytical Results

As described in Section 3.4.1.2, depth-discrete groundwater samples were collected from 10 of the 20 boring locations from the upper alluvium, lower alluvium, and/or UMCf. These samples were analyzed for perchlorate, and select samples were also analyzed for nitrate and TDS. Perchlorate concentrations ranged from 860 to 24,000 micrograms per liter (μg/L) in the alluvium and from 10,000 to 11,000 μg/L in the UMCf. In general, groundwater samples collected from the upper and lower alluvium within the same boring had similar concentrations of perchlorate. This lack of variation of perchlorate concentration with depth in the saturated alluvium is consistent with the soil results discussed in Section 3.4.2.1 and indicates perchlorate concentrations in the alluvium are more spatially dependent than depth dependent. Four discrete-depth groundwater samples (two each from the upper and lower alluvium) were also analyzed for nitrate and TDS. Like perchlorate concentrations, TDS concentrations in groundwater, which ranged from 5,000 to 6,000 mg/L, did not vary significantly with depth in the saturated alluvium. Nitrate concentrations (ranging from 12 to 14 mg/L) indicated that there is sufficient nitrogen to serve as a macronutrient for native microorganisms during bioremediation. Depth-discrete groundwater results are presented in Appendix D, Table D.3.

3.5 GROUNDWATER SAMPLING

Following completion of well development activities, a comprehensive groundwater sampling event was performed the week of March 27, 2017 on all monitoring wells installed within the treatability study area as part of the pre-design activities. This event included collection of water levels and groundwater samples from the 16 newly installed wells and four existing monitoring wells (PC-58 [which is southwest of the study area], PC-91, PC-92, and PC-94). For purposes of finalizing design of Phase 2 of the treatability study, groundwater samples were analyzed for a variety of field and laboratory parameters, including perchlorate, chlorate, nitrate, TOC, TDS, sulfate, dissolved metals, and/or chloride. Groundwater samples were also collected from monitoring wells PC-94, which is screened in the alluvium, and SWFTS-MW08C, which is screened in the UMCf, and transported to UNLV for use in the bench-scale studies described in Section 4.0.

Depth to water measurements are provided in Appendix E, Table E.1. A summary of the pre-design groundwater concentration ranges of perchlorate and chlorate, as well as other noteworthy parameters with respect to the bioremediation process, is presented in ***Table 1***. Complete analytical results are provided in Appendix D, Table D.4. Groundwater sampling field low-flow purge logs are provided in Appendix E.

Table 1 Concentration Ranges in Groundwater During Pre-Design Groundwater Sampling

Analyte	Concentrations in the Alluvium (7.8 – 52.6 feet bgs)	Concentrations in the UMCf (43.5 – 69.5 feet bgs)
Perchlorate (µg/L)	170 – 25,000	7,800 – 8,300
Chlorate (µg/L)	< 10 – 67,000	39,000 – 55,000
Nitrate (mg/L)	< 0.11 – 18	7.6 – 13
Sulfate (mg/L)	570 – 4,700	2,400 – 2,800
TDS (mg/L)	2,600 – 5,300	6,500 – 6,700

Notes:
μg/L – micrograms per liter
mg/L – milligrams per liter
UMCf – Upper Muddy Creek formation
ft bgs – feet below ground surface
TDS – total dissolved solids

Perchlorate was detected in groundwater collected from all monitoring wells within the treatability study area. The highest perchlorate concentration of 25,000 μg/L was detected in groundwater from monitoring well SWFTS-MW02, which is located in the western portion of the study area, as shown in Figure 2. Paired monitoring wells screened in the upper and lower alluvium (namely, SWFTS-MW05A/B, SWFTS-MW07A/B, and SWFTS-MW09A/B) had similar perchlorate concentrations in groundwater in both upper and lower intervals. Perchlorate concentrations in groundwater samples from monitoring wells SWFTS-MW08C and SWFTS-MW10C, which are screened in the UMCf, ranged from 7,800 to 8,300 μg/L and are approximately 60 percent of the perchlorate concentrations measured in the groundwater samples collected from the monitoring wells in the overlying alluvium (SWFTS-MW08A and SWFTS-MW10A). Although this treatability study focuses on treatment of the alluvium, these elevated perchlorate concentrations in groundwater in the UMCf, combined with an upward gradient between the UMCf and alluvium, indicate that upflux/diffusion of contaminants from the UMCf during the treatability study could occur. Evaluation of upflux/diffusion of contaminants from the UMCf will be reported in the forthcoming RI Reports for OU-1/OU-2 and OU-3. Chlorate concentrations in groundwater are slightly higher than perchlorate concentrations; however, a similar pattern is observed with respect to vertical and horizonal distribution.

Nitrate, which is the most likely competing electron acceptor and carbon substrate consumer during perchlorate bioremediation, was detected at concentrations up to 18 mg/L in groundwater samples collected from monitoring wells screened in the alluvium. Sulfate and TDS were detected at concentrations up to 4,700 and 5,300 mg/L, respectively, in groundwater samples collected from the alluvium. These concentration levels of sulfate and TDS are in line with previous results obtained from the COH treatability study and, therefore, are not expected to be problematic for microbial degradation of perchlorate.

3.6 AQUIFER TESTING

The objective of the aquifer testing was to obtain information regarding aquifer hydraulic conductivity, groundwater flow velocity, and total and mobile porosity in the area where the treatability study was planned. These data were then used to assist in the design of the bench-scale laboratory column tests and field treatability study. Initial aquifer testing activities, including borehole dilution, slug testing, and NMR logging, were performed in April and May 2017 as part of the pre-design field activities. This section summarizes aquifer testing activities and associated results. The supporting summary memos, including AQTESOLV (HydroSOLVE, 2007) interpretation plots, borehole dilution test plots, and NMR logging profiles, are provided in Appendices F, G, and H, respectively.

3.6.1 Slug Testing

Slug tests were performed in all 16 newly installed wells in April 2017 to estimate location-specific aquifer hydraulic conductivity in the screened interval of the wells within the treatability study area. Prior to conducting each slug test, the water level in the well was measured with an electronic water level probe to determine the static groundwater level. An electronic pressure transducer/data logger was suspended in the well and water levels were monitored manually until static conditions were reestablished. A falling-head test was then conducted by smoothly lowering a length of weighted and sealed PVC pipe (slug) into the well, securing it in place above the transducer, and recording the rate of water level decline. Once static conditions were reestablished, a rising-head test was conducted by removing the slug and allowing the water level to again recover to static conditions while recording the rate of recovery. Barometric pressure changes during testing were monitored and recorded using a pressure transducer placed above the water table. Where feasible, multiple slug tests were performed in each well.

At the end of testing in each well, the pressure transducer was removed from the well and the water level displacement data were downloaded to a laptop computer and corrected for barometric pressure effects, if necessary. The corrected data were interpreted using AQTESOLV for Windows (Duffield, 2014). Where possible, both the falling-head and rising-head data were analyzed to cross-check the interpretation results.

Appendix F presents an overview of the results from the slug testing conducted as part of the pre-design. Hydraulic conductivities measured in the alluvium ranged from 1.3 ft/day in monitoring well SWFTS-MW08A to 329.9 ft/day in monitoring well SWFTS-MW09B, with an average hydraulic conductivity of approximately 54 ft/day. The large variation in hydraulic conductivity was due to the highly variable screened lithology, which ranged from silty sand to gravel. The estimated hydraulic conductivities are generally consistent with the logged lithology of the screened interval of the wells. In cases where the screened interval includes both coarse and finer-grained zones, the coarser zones would be expected to be the primary flow zones and therefore to dominate the hydraulic conductivity estimates. The average hydraulic conductivity for the two monitoring wells screened in the UMCf (SWFTS-MW08C and SWFTS-MW10C) was 2.4 ft/day, which is significantly higher than would be expected based on the logged lithology of sandy silt and clay. However, slug test results reported for the UMCf within other study areas have indicated that hydraulic conductivity values for the uppermost part of the UMCf consistently range from 1 to 10 ft/day, so the results for SWFTS-MW08C and SWFTS-MW10C are reasonable for the formation. The supporting summary memo, including AQTESOLV (HydroSOLVE, 2007) interpretation plots, is provided in Appendix F.

3.6.2 Single-Borehole Dilution Testing

Single-borehole dilution tests consisted of mixing a tracer compound into the groundwater in a well, and then observing the decline in tracer concentration in the well as a function of time using downhole instruments (Pitrak et al., 2007). Borehole dilution testing was performed in four new 4-inch monitoring wells, namely SWFTS-MW07A, SWFTS-MW08A, SWFTS-MW09A, and SWFTS-MW10A on April 12-13, 2017, to evaluate volumetric flow within the treatability study area using distilled water as a tracer. The results indicate that the groundwater flow velocities within the lower conductivity sediments observed at monitoring wells SWFTS-MW07A and SWFTS-MW08A are approximately 0.07 and 2 ft/day, respectively. These monitoring wells are located immediately upgradient of the injection well transects (further discussed in Section 5.2). Within the paleochannel area that is located downgradient of the injection well transects (further described in Section 6.1), the groundwater flow velocity was estimated to be 12 and 119 ft/day in monitoring wells SWFTS-MW09A and SWFTS-MW10A, respectively. For comparison purposes, the approximate groundwater flow rate observed within the paleochannel at the previous treatability study was approximately 32 ft/day. A detailed discussion of the borehole dilution test data and results as well as plots of single-borehole dilution testing data are provided in Appendix G.

3.6.3 Nuclear Magnetic Resonance Logging

In May 2017, NMR logging was performed on the 16 newly installed monitoring wells. This technology can be used in open or PVC-cased wells to provide high-resolution downhole estimates of hydraulic conductivity, total water content, total and mobile porosity, 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 is depended on the diameter of the well, because larger diameter wells require a tool that has a larger radius of investigation. All tools provided a measurement approximately every 1.5 to 2 feet of depth. The high-resolution estimates of hydraulic conductivity were compared to the lithologic logs and aquifer testing results for each well to assess the possibility of preferential flow.

Results from NMR logging are presented in Appendix H. NMR estimates of hydraulic conductivity generally agreed with estimates derived using slug testing within an order of magnitude. The slug test response tends to be governed by the highest hydraulic conductivity interval. Not only did the NMR data show that the highest hydraulic conductivities measured at each location generally corresponded best to the slug test result, but the NMR data also showed the depth at which that highest hydraulic conductivity zone occurred at each location. Therefore, the

NMR data was effective in identifying potential preferential flow pathways. Variation in NMR data between sandy, gravelly, silty, and clayey material often corresponded closely to logged lithologic changes.

The NMR profiles clearly indicate the transition from alluvium to UMCf. The water content increased sharply at the UMCf contact to approximately 50 percent, reflecting the increased proportion of clay in the UMCf relative to the alluvium. Average mobile porosities (similar to effective porosity) measured in the alluvium and the UMCf were 0.1 and 0.04, respectively. Although, the UMCf was not the target of this treatability study, the range of hydraulic conductivity in the UMCf was from approximately 0.1 to 3 ft/day.

4.0 PHASE 1 LABORATORY BENCH-SCALE STUDIES

Prior to implementation of the field treatability study, Tetra Tech contracted with UNLV's Environmental Engineering and Water Quality Laboratory to conduct laboratory batch microcosm tests and oil adsorption tests using both batch and column methods. The primary goals of the microcosm and adsorption tests were to evaluate ISB of perchlorate and its competitors, chlorate and nitrate, and to evaluate the adsorption of EVO in soil from the treatability study area. Although the SWF Area Bioremediation Treatability Study focuses on the alluvium, pre-design activities included some investigation into the UMCf within the treatability study area, which had perchlorate concentrations in groundwater of up to 9,300 μg/L. As a result, the laboratory studies included tests not only for the alluvium but also the UMCf in the event that remediation of the UMCf within this study area or potentially other similar study areas was deemed warranted at a later date. This addition resulted in minimal setup requirements and did not incur additional labor or equipment due to simultaneous studies being performed for the alluvium.

This section summarizes the objectives, pre-testing evaluation of soil and groundwater, and the general setup/procedures, brief findings, conclusions, and recommendations drawn from the microcosm and column studies. Appendix I provides the final UNLV report, which presents the complete details of the experimental approach, presentation of the data, and analysis of results.

4.1 BENCH-SCALE OBJECTIVES

The specific objectives of the bench-scale studies were as follows:

(i) Collection and Evaluation of Soil and Groundwater – Evaluate the soil from the treatability study area, including grain size, soil density, porosity, and moisture content, to understand the soil physical characteristics and perform mineralogical analyses to evaluate the compositional make-up of the soil in advance of the bench-scale and field treatability study.

(ii) Batch Microcosm Testing – Perform batch microcosm study to confirm the application of EVO to the soil and groundwater from the SWF area and provide an estimate of the acclimation, lag time, and perchlorate biodegradation time frame, including evaluation of groundwater from the field test location and effluent water from the onsite groundwater extraction and treatment system (GWETS) to evaluate the possibility of using effluent as an alternative to fresh water as a water source during injections, for this study, or elsewhere, where ISB could be performed. Hydrant water, which was proposed in the original work plan, was not evaluated because it was previously used successfully at the previous COH treatability study.

(iii) Batch and Column Adsorption Studies – Evaluate the rates of adsorption of EVO for the treatability study area soil and determine the rates of adsorption of the EVO to the various independent soil fractions and fines.

4.2 COLLECTION AND EVALUATION OF SOIL AND GROUNDWATER

Soil from the saturated alluvium and UMCf used in the laboratory bench-scale studies was obtained from soil cores during Phase 1 pre-design (soil boring and monitoring well installation as described in Section 3.4). Soil from the saturated alluvium and UMCf was collected from three soil borings (SWFTS-BH04, SWFTS-BH08 and SWFTS-BH10) from 9 – 38.5 feet bgs and 37 – 52 feet bgs, respectively. Approximately 3 gallons of soil cuttings were collected at each soil boring location. To generate composite soil representative of the alluvium and the UMCf in the treatability study area, equal volumes of soil cuttings from each of the three locations from the respective lithologic zones were blended in sterilized plastic pans using sterile hand shovels. About 2 kilograms of each blended sample were stored in air-tight bins for batch microcosm and batch adsorption tests. The remaining blended soils were sun-dried at UNLV for use in column testing of oil adsorption.

Eight undisturbed soil samples were collected from the alluvium at SWFTS-BH02, SWFTS-BH03, SWFTS-BH08, SWFTS-BH09, SWFTS-MW07B, SWFTS-MW09B and from the UMCf at SWFTS-MW08C and SWFTS-MW10C. The core samples were used to determine the particle size distribution, physical properties of the soil, and mineralogical composition of the soil. Groundwater for the bench-scale studies was collected from the alluvium at monitoring well PC-94 and from the UMCf at monitoring well SWFTS-MW08C in sterile 5-gallon bottles. In addition, effluent water from the existing GWETS at the NERT site was collected to evaluate the possibility of using the effluent as an alternative to fresh water as a water source during injections.

Complete analytical results from UNLV soil and groundwater characterization efforts are presented in Appendix I. A summary of the geotechnical and mineralogical analysis is provided herein.

4.2.1 Geotechnical Analysis

A combination of soil cuttings and undisturbed soil samples was used to characterize the soil properties in the treatability study area. Data obtained from this analysis were used for the design and set-up of the laboratory column adsorption tests. A combination of dry and wet sieving and hydrometer measurements was used to develop grain size distribution data for the alluvium and UMCf soil. In general, the soil from the alluvium has similar proportion of granular and coarser material, sand, and fine-grained silt and clay at all three locations. The UMCf soil is predominantly composed of fine-grained silt and clay, except for UMCf soil at SWFTS-BH08 where the UMCf contains approximately 40 percent sand by weight.

The alluvium has more than 60 percent sand-size or coarser grains and is expected to have a higher hydraulic conductivity, allowing more groundwater transport than the UMCf. The UMCf does not contain granules and coarser material but does contain approximately 15 to 40 percent sand. The high percentage of fine-grained silt and clay materials may hinder groundwater transport. Given that there are more adsorption sites in fine-grained soil that those in the coarse-grained soil, the EVO adsorption was expected to be greater in the UMCf than the alluvium for field applications.

Total porosity, wet bulk density, and moisture content of the soils were also determined in the laboratory to better understand the soil type/properties. In general, the total porosity of alluvium soil samples ranged from 31 to 48 percent and the moisture content ranged from 12 to 32 percent. The wet bulk density ranged from 119 to 139 pounds per cubic foot (lbs/ft^3). The soil sample collected from the UMCf at SWFTS-MW10C measured 52 percent total porosity with 38 percent moisture content. However, the soil sample collected from the UMCf at SWFTS-MW08C had a total porosity of 77 percent and moisture content of 82 percent, which is likely an inaccurate result due to drilling disturbance of the soil sample. The likelihood of drilling disturbance is further supported by the wet bulk density results, which indicate that the wet bulk density for soil from SWFTS-MW8C (71 lbs/ft^3) was half of the wet bulk densities at SWFTS-MW10C (116 lbs/ft^3).

4.2.2 Mineralogical Analysis

Mineralogical analysis using x-ray diffraction was performed on both the wet-blended alluvium soils as well as the UMCf soils from the borehole drill cuttings (SWFTS-BH04, SWFTS-BH08, and SWFTS-BH10). Results indicated that the dominant mineral in the alluvium is quartz (24.5 percent), which is almost four times higher than the quartz content in the UMCf (5.8 percent). The second key mineral in the alluvium is andesine (22.5 percent) which was not detected in the UMCf soils. UMCf soil is primarily composed of dolomite (63.3 percent), and montmorillonite clay (18.9 percent). By contrast, the alluvium soil contains only 4 and 7 percent of similar minerals, respectively. The mineral properties of these two soils reflect the soil types that are present in these two zones, with the alluvium being mostly sand with gravels while the UMCf is silty with some clay. The presence of montmorillonite clay at nearly 20 percent in UMCf soil is consistent with the comparatively lower bulk density. Detailed results of the laboratory testing and results are provided in Appendix I.

4.3 BATCH MICROCOSM STUDY

The batch microcosm studies described herein were performed to evaluate and affirm perchlorate and chlorate biodegradation characteristics and, using the chosen carbon substrate EVO obtained from EOS® Remediation, to evaluate the acclimation time and determine the approximate timeframe for biodegradation of perchlorate, chlorate, and nitrate.

4.3.1 Microcosm Setup and Effectiveness Monitoring

Two phases of batch microcosms were set up to evaluate biodegradation of perchlorate, chlorate and nitrate in groundwater and soil supplemented with EVO. The first phase comprised eight microcosms (with replicates for periodic sampling) and included testing of soils from the alluvium as well as the UMCf with groundwater from the treatability study area and GWETS effluent water. Batch microcosm tests were also conducted to evaluate the use of GWETS effluent water in the carbon substrate solution mixture and/or as chase water during injections. For the first phase of preliminary batch microcosms, soils from the alluvium and UMCf were each separately mixed with groundwater from the treatability study area and GWETS effluent water. Based on the results of these preliminary batch microcosms (discussed in Section 4.3.2), a second phase of six batch microcosms tests (with replicates for periodic sampling) was performed with soil and groundwater from the alluvium only to refine the amount of EVO required for biodegradation of the contaminants in the laboratory and to evaluate the impact of GWETS effluent water on biodegradation.

All microcosm tests were performed using 125 milliliter (mL) autoclave-sterilized borosilicate glass bottles. Each bottle was filled with 30 grams of soil and filled with groundwater or GWETS effluent water and EVO. The bottles were crimped closed using butyl rubber caps and aluminum rings to ensure anaerobic/anoxic conditions. The bottles were continuously mixed in a rotary shaker at 30 revolutions per minute (rpm) at room temperature. All tests were performed in duplicate. At predetermined time intervals (generally once every two days), the contents of one bottle and its duplicate were analyzed for perchlorate, chlorate, and nitrate to evaluate degradation over time in each microcosm environment. The analyses were performed on centrifuged or filtered samples as needed.

4.3.2 Results

The key results and findings from the first phase of batch microcosm testing, which included testing of soils from the alluvium and UMCf with groundwater from the treatability study area and GWETS effluent water, are as follows:

- Batch microcosm testing indicated that EVO was an effective electron donor/carbon substrate that had the ability to enhance biodegradation of nitrate, chlorate, and perchlorate under the test conditions in both the alluvium and UMCf microcosms using either groundwater or GWETS effluent water. The perchlorate removal was generally higher in the microcosms which used groundwater as opposed to those using GWETS water, primarily because of the higher starting concentrations in the groundwater microcosms (perchlorate is not present in the GWETS water and therefore, the microcosms get diluted at the beginning and have lower starting concentrations). However, the objective of evaluating the use of GWETS water to examine that it did not unduly inhibit perchlorate biodegradation was achieved, and therefore, this water source remains an option for future field bioremediation efforts.
- Because of the high nitrate concentrations in groundwater unique to this treatability study area (ranging from 8.3 to 15 mg/L), it was not deemed necessary to add an external source of nitrogen as a macronutrient.
- Results indicate that greater than 96 percent of the nitrate was degraded within 4 days, and all nitrate was below laboratory detection limits within 10 days in both the alluvium and UMCf. Chlorate was also completely degraded within the same time period.
- Perchlorate was degraded to below laboratory detection limits within 20 days in all alluvium microcosms and 10 days in the UMCf microcosms. The higher contaminant levels in the alluvium microcosms could

have resulted in the extended perchlorate degradation time. The rate of perchlorate degradation was also higher in the UMCf (greater than 0.0051 mg per hour as opposed to 0.0046 mg per hour in the alluvium microcosms), likely due to the greater presence of fines in the UMCf, which provides more attachment sites for microorganisms. However, on the field-scale of remediation time, this difference in degradation time frame is unlikely to be problematic because of the longer timeframes for which remediation is performed.

- The TDS concentrations of up to 7,000 mg/L from the treatability study area (although not as high as other areas of the Site, which have observed concentrations as high as 50,000 mg/L) did not prevent biodegradation of perchlorate, chlorate, or nitrate.

The key results of the second phase of batch microcosms, which were performed only on the soil and groundwater from the alluvium since that is the focus of the field treatability study and not the UMCf, are as follows:

- Nitrate was completely degraded within 6 days, even at the lowest dose tested.
- Perchlorate biodegradation began within approximately 10 days and was below laboratory detection limits by Day 20. There was no apparent difference in perchlorate removal rates for all the stoichiometric ratios used in the laboratory. Once acclimation occurred, there was very little difference between the hourly degradation rate of perchlorate, which on Day 20 was 0.0034 and 0.0035 mg per hour for the microcosms that were dosed at five and ten times the stoichiometric requirement, respectively. Therefore, in actual field situations, where timeframes are much longer for treatment, a dosage of five times the stoichiometric requirement appears to be adequate to completely degrade perchlorate based on the batch microcosm test results.
- The soluble chemical oxygen demand (COD) results indicated that more than 91 percent of the oil was adsorbed to soil within 2 days. By the end of the 20-day study period, only 60 to 70 percent of the initial oil remained adsorbed to the soil. As the oil in the liquid phase was exhausted, more oil desorbed from the soil into solution. This phenomenon is likely to occur in the field as well where a significant fraction of the added EVO will be adsorbed to the soil and provide a long-term source of organic carbon for perchlorate biodegradation. Oil dynamics were further evaluated in the soil adsorption studies.

4.4 OIL ADSORPTION AND DESORPTION STUDIES

In addition to batch microcosm studies, oil adsorption and desorption studies were also performed by UNLV, with the complete UNLV bench-scale summary report provided in Appendix I. Oil adsorption in soil from the alluvium and UMCf were studied by two methods: batch adsorption testing and soil column desorption tests. The oil adsorption rate provides information that can be used for field EVO dosing and assisting in the determination of the potential need and timeframe for rejuvenation of EVO. Due to the difference in particle size and mineralogical composition of soil within the alluvium and UMCf, adsorption and desorption tests were conducted on each soil type.

For batch adsorption tests, blended wet soil was used. Soil used in batch and column adsorption tests was blended, sun-dried, and sieved to less than 4 millimeters (mm) for alluvium soil and less than 2 mm for UMCf soil to be representative of the majority of the soil grain size within each zone. Sieving is important to remove random large grain size particles that are not representative of the majority of the actual soil in order to get unbiased results and is a standard procedure for sorption tests) The groundwater used for both batch and column tests was collected from monitoring wells PC-94 and SWFTS-MW08C for alluvium and UMCf tests, respectively.

4.4.1 Batch Adsorption Testing

4.4.1.1 Procedures

Batch adsorption testing was conducted with soil collected from the alluvium and UMCf with varying amounts of soil (specifically, 5, 10, 20, 25, and 30 grams of wet soil) and 100 milliliters (mL) of diluted oil (6 grams of oil per 100 mL of groundwater) in duplicate. After 24 hours of mixing on a rotary shaker, the bottles were centrifuged for 30 minutes at 3,000 rpm, the supernatant was discarded, and walls of the bottle were rinsed with nanopure water (highly purified water that has ions removed and little, if any, bacteria present that could result in microbial degradation and thus skew the results). The bottles were centrifuged again to discard any excess rinsate, with the process repeated twice. The settled soil was transferred to pre-weighed aluminum dishes, dried in an oven at 103±5°C for 24 hours, and weighed and ignited in a furnace at 550°C for 1 hour to obtain the volatile solids content. The aluminum dishes were weighed again after they were cooled. The amount of oil adsorbed was computed as the difference in weight of soil before and after ignition. The data were plotted and checked to obtain the best fit model.

4.4.1.2 Results

The main findings of the batch adsorption tests are as follows:

- The oil adsorption in soil from the alluvium was proportional to the amount of soil added to the batches. The percentage of oil adsorbed to the soil ranged from 22 to 64 percent. A similar linear relationship was observed for oil adsorption in the UMCf soil. The percentage of oil adsorbed to UMCf soil ranged from 14 and 89 percent. Therefore, the maximum adsorption was higher in the UMCf soil compared to the alluvium, which was expected because of the lithological and geochemical properties of these soils.
- The best fit adsorption isotherm model was the Langmuir model for both alluvium and UMCf soil. The specific absorption coefficient for alluvium soil was determined to be 0.124 grams of oil per gram (g/g) of dry soil and 0.104 g/g wet soil, and for the UMCf was determined to be 0.239 g/g dry soil and 0.184 g/g wet soil. These are on the higher side compared to typical literature values (EOS Design Protocol) likely due to the high calcium content of these soils.

4.4.2 Column Adsorption and Desorption Test

4.4.2.1 Procedures

The column adsorption and desorption test was conducted with oil at three saturation levels of 13 percent (low), 45 percent (medium), and 95 percent (high) using the specific oil adsorption coefficient obtained from the batch test. For each oil saturation level test, two 1-inch diameter columns that were 25 inches in length were set-up for each zone (alluvium and UMCf). Two columns were packed with alluvial soil and the other two columns were packed with UMCf soil. Prior to oil injections, the columns were saturated with groundwater from the respective lithological unit (i.e., alluvium groundwater used for alluvium soil columns and UMCf groundwater used for UMCf soil columns) for 3 days to simulate the saturated condition of the aquifer. The columns were compressed with carbon dioxide gas to remove any air pockets trapped in the soil prior to saturation with groundwater. After the 3-day saturation period, the various volumes of diluted oil were injected into the columns followed by the injection of flush water. The operation of the columns was stopped once a steady COD concentration was observed in the effluent. Following completion of the tests, the columns were cut into four 4-inch sections using a hacksaw. The hacksaw blade was cleaned after cutting each section to avoid cross-contamination. The soil sections were oven-dried, crushed, and baked at 550°C to analyze volatile solids representative of the amount of EVO adsorbed to the soil.

4.4.3 Results

The main findings of the column adsorption and desorption tests are as follows:

- The alluvium columns generated 5 milligrams (mg) COD, 20 mg COD, and 80 mg COD per pore volume in the low, medium, and high oil saturation trials, respectively, through desorption of the EVO. The UMCf columns generated 10 mg COD, 16 mg COD, and 40 mg COD per pore volume in the low, medium, and high oil saturation trials, respectively, through desorption of the oil. These results reflect the lithological differences between these two soil types.
- In the low and medium saturation level trials, the upper 4-inches adsorbed the majority of the oil for both the alluvium and UMCf columns. For the high saturation levels, however, the top four inches adsorbed the majority of the oil for the alluvium, whereas, for the UMCf column, the oil was distributed evenly throughout the column. This may have been due to the short circuiting of oil within the length of the UMCf column and also a reflection of the pressure that was applied for the UMCf testing (up to 15 pounds per square inch [psi]), which could have resulted in uneven movement of oil through the column. This phenomenon of short circuiting could also occur in the field, though the scale of the field study, field injection protocol, and three-dimensional nature of field applications may result in more even distribution over time if ISB is performed in the UMCf. These results indicate that in the field, when ISB is performed in the UMCf, the amount of oil that is injected should be on the lower side based on the two-dimensional studies performed in the laboratory.
- The oil adsorption in the top 4-inches of the alluvium column in the low, medium and high saturation levels were 0.026 g/g dry soil, 0.140 g/g dry soil and 0.141 g/g dry soil, respectively. The minimal variation in oil adsorption between the medium and high saturated levels indicated that beyond a certain dosage, oil will not adsorb to the soil as strongly, but instead gets desorbed and washed away or transported downgradient. A similar phenomenon was observed in the soil column testing that was performed for the City of Henderson Study (Tetra Tech, 2016b).
- The oil adsorption in the top 4-inches of the UMCf soil column in the low, medium and high saturation levels were 0.030 g/g dry soil, 0.435 g/g dry soil, and 0.260 g/g dry soil, respectively, which was higher than that in the alluvium. It appeared that there was likely more even distribution in the UMCf column with the higher dosages, once again because of the application of pressure and resulting short circuiting.

4.5 BENCH-SCALE SUMMARY

In summary, the laboratory studies performed in connection with the SWF area bioremediation treatability study by UNLV have indicated that the soil and groundwater in the alluvium and UMCf are very amenable to perchlorate (as well as chlorate and nitrate) biodegradation using EVO as the carbon substrate. The laboratory studies indicated that the microbial acclimation time and degradation time in the field may be very rapid based on the quick acclimation and degradation times (within 20 days) observed in the microcosms. The TDS levels in groundwater did not prevent rapid perchlorate biodegradation from occurring, a phenomenon which is also expected to occur in field conditions. The usage of GWETS water as a source of distribution water for the carbon substrate is a potential source when groundwater is unavailable in adequate quantities or when the source of the GWETS water is easily accessible and near a potential future field ISB treatment location. However, for this study local groundwater was selected for chase water since this water source did not result in the dilution of the initial perchlorate concentrations during injection. Finally, the sorption tests indicate that a fraction of the added EVO (irrespective of the dosage) was transported out of the column and generally does not attach to the soil. Therefore, caution needs to be exercised in making a decision on initial field EVO dosages and an approach that involves periodic lower dosages may be a prudent field approach. These conclusions and deductions including the rapid acclimation and degradation time for perchlorate and the value of periodic lower dosages of EVO injections will be incorporated into the design of future field treatability and pilot studies.

5.0 PHASE 2 FIELD TREATABILITY STUDY ACTIVITIES[1]

This section describes the Phase 2 field treatability study design activities, which includes details on the final injection and monitoring well layout and associated installation activities, a summary of the injection activities performed during the study, and an overview of the effectiveness monitoring program that was implemented to determine remedial effectiveness.

5.1 TREATABILITY STUDY LOCATION

The treatability study was performed approximately 500 feet east of the SWF extraction well network as shown in Figure 3. As explained in the Work Plan, this area was selected due to the presence of a different geologic setting than previously tested and elevated perchlorate concentrations in groundwater samples collected from monitoring well PC-94. Additionally, the perchlorate mass flux in groundwater in this vicinity is not being captured by the existing SWF network, which made it an ideal location for the treatability study.

5.2 INJECTION AND MONITORING WELL INSTALLATION

This section provides a summary of the injection and monitoring well installation that was completed as part of treatability study implementation. Both injection and surrounding monitoring wells were installed at locations to maximize treatability study effectiveness and properly evaluate ISB performance. Although the Work Plan presented a conceptual injection and monitoring well layout, the final quantity and location of the injection wells were finalized after completion of the pre-design field activities; they are described in the *SWF Bioremediation Treatability Study – Notification of Field Implementation Modification* (Tetra Tech, 2017). The final treatability study layout is presented in Figure 3, which also illustrates the groundwater potentiometric contours from the baseline groundwater sampling event in July 2017 (further discussed in Section 6.1.2). Field activities associated with injection and monitoring well installation were performed in May through June 2017. Well construction details are provided in Appendix C, along with the well construction and boring logs. The same pre-drilling activities described in Section 3.4.1.1 were followed prior to installation of the treatability study injection and monitoring wells. Prior to drilling monitoring wells in the vicinity of the GWETS pipeline, the location was cleared of utilities to a depth of 10 feet bgs by utilizing an air knife.

5.2.1 Injection Well Layout

Data collected during the Phase 1 pre-design activities indicated that there is considerable heterogeneity in the lithology over relatively short distances within the treatability study area. The soil type, thickness of the gravel intervals, and paleochannels vary in all three dimensions in the saturated subsurface. Because these factors suggest a high likelihood of variable flow pathways, the transport of organic carbon during injections was expected to be non-uniform. To counter the impacts of heterogeneity and non-uniform flow, two separate transects of injection wells were installed, with injection wells staggered within each of the transects to provide overlap of the injection wells' lateral influence. The two staggered injection well transects also allowed for a set of monitoring wells to be installed in between the two transects directly in the line of apparent groundwater flow, as well as offset from the direction of groundwater flow direction, to evaluate potential lateral influence of carbon substrate in this heterogeneous subsurface. Based on the potentiometric contouring that was performed using the pre-design data, the injection well transect orientation was slightly shifted compared to the conceptual layout

[1] It should be noted that treatability and pilot studies proposed after 2016 have included a work plan addendum that summarizes the Phase 1 activities and presents the final Phase 2 design.

provided in the NDEP-approved Work Plan. This reorientation of the injection well layout was summarized in the *SWF Bioremediation Treatability Study – Notification of Field Implementation Modification* (Tetra Tech, 2017).

The injection well transects were installed approximately 400 feet upgradient of historic monitoring well PC-94, with the injection well transects spaced 100 feet apart (Figure 3). Each of the two injection well transect rows is approximately 750 feet in length and includes 10 injection well locations spaced approximately 75 feet apart, for a total of 20 injection well locations. Because of the staggered transect configuration, an injection well spacing within each transect of 75 feet results in an effective injection well spacing that is approximately 37.5 feet. This injection well spacing was determined based on the hydrogeological characteristics, higher permeability in the alluvium, and observations from the previous treatability study performed on COH property, which employed a single line of three injection wells spaced approximately 60 feet apart. Observations from the previous COH treatability study indicated that in the presence of paleochannels or subsurface geologic materials possessing high permeability, injection well spacings of 60 feet could result in majorly advective flow of the carbon substrate in some areas. High groundwater flow rates (resulting in predominantly advective transport) due to the presence of a nearby paleochannel could result in limited dispersion and lateral movement of the carbon substrate perpendicular to the groundwater flow at this injection well spacing. Therefore, in order to maximize the lateral coverage and influence of the injected carbon substrate and provide a lateral overlap, an effective spacing of 37.5 feet was selected in this lithological setting where the permeability and groundwater flow rate is still relatively high, but is approximately half of the values observed in the previous COH treatability study. At five of the twenty injection well locations, a paired injection well configuration was installed that consisted of two injection wells, each screened across separate treatment intervals and installed in separate boreholes. This configuration was included in the injection well design at select locations to evaluate the advantages and disadvantages of using paired injection wells to maximize carbon distribution in more heterogeneous locations within the alluvium (i.e., differing lithology within a single boring that indicated a likely higher hydraulic conductivity zone in one portion of the saturated thickness which could take the majority of the injectate).

Soil borings for injection wells were advanced using hollow-stem auger drilling methods. Soil samples were collected from six injection well locations using California samplers. Samples were sent to Geotechnical & Environmental Services, Inc. (GES) for physical parameter analysis, including porosity, soil density, soil pH, and grain size distribution. Results generally correlated with the results from UNLV, which are summarized in Section 4.2. The geotechnical data is presented in Appendix D, Table D.5 and the GES data report is provided in Appendix J.

Injection wells were constructed with 2-inch diameter Schedule 40 PVC casing and screened with 2-inch diameter 0.020-inch slotted PVC. A review of the pre-design data indicated that the saturated alluvial thickness generally ranged from 20- to 30-foot thick (based on evaluation of depth to water measurements and depth of the alluvium/UMCf contact). Because the alluvium was the targeted media for the treatability study, this information provided initial guidance for the anticipated depth of the injection wells and lengths of the injection well screens. However, the final depth of the injection well and length of injection well screen varied at each location and were determined in the field based on the lithology and depth to groundwater observed during the drilling of each injection well. Specifically, the targeted screened interval at each location was designed to be a minimum of one foot below the water table and have a screen length ranging from 5 to 25 feet in length. The goal was to target the saturated thickness in the alluvium without crossing over the alluvium/UMCf contact (i.e., no injection wells screened in the UMCf). Shorter injection well screens were used in the paired injection well configurations (ranging from 5 to 10 feet in length) while longer screens were used in the single injection well locations (ranging from 15 to 25 feet in length). Injection wells were completed with flush-mounted, tamper-resistant (locked), traffic-rated well boxes, at an elevation approximately 0.5 inches above grade. Well development activities were completed following well construction as described in Section 3.4.1.3. Boring logs and well construction diagrams for all injection wells are provided in Appendix C.

5.2.2 Monitoring Well Layout

A monitoring well network, consisting of both upgradient and downgradient monitoring wells, was required to evaluate and determine the effectiveness of ISB within the treatability study area. The conceptual monitoring well network provided in the Work Plan was slightly adjusted based on the refined injection well transect layout, site features (such as the newly constructed Weir Water Treatment Plant), and incorporation of the pre-design monitoring wells, with the final layout summarized in the NDEP-approved *SWF Bioremediation Treatability Study – Notification of Field Implementation Modification* (Tetra Tech, 2017). In addition to the monitoring wells installed as part of the pre-design activities (described in Section 3.4.1.3), a total of 15 additional monitoring wells were installed upgradient, in between, and downgradient of the injection well transects at distances ranging from approximately 25 to 600 feet downgradient of the injection well transects (Figure 3).

Upgradient monitoring wells were installed to determine the perchlorate concentrations in groundwater that are migrating into the injection well transects and in groundwater to be extracted and used during injection operations. Two additional upgradient monitoring wells were added in the eastern portion of the study area to be used for extraction and were located in areas that had the potential for higher hydraulic conductivity zones based on evaluation of the pre-design data (i.e., higher hydraulic conductivity would likely result in improved groundwater extraction rates).

Monitoring wells in between and downgradient of the injection well transects were installed at varying distances to determine treatment effectiveness. The locations of monitoring wells were selected based on the results of the groundwater hydrogeological assessment (both potentiometric contouring and aquifer testing) and site-specific characteristics at designated locations in between and downgradient of the injection well transects. Specifically, monitoring wells were installed either directly inline or off-set of the expected groundwater flow pattern from the injection wells (determined through preliminary evaluations of the potentiometric contours developed using pre-design data). The monitoring well distances from the injection well transects varied from as close as 25 feet to as far as 600 feet, which were selected based on potential groundwater flow rates estimated from pre-design data, to evaluate the magnitude of contaminant biodegradation and associated response time following injections.

Monitoring wells were installed using a hollow-stem auger drill rig and constructed with 2-inch diameter Schedule 40 PVC casing and screened with 2-inch diameter 0.020-inch slotted PVC. The depth of the monitoring well and length of the well screen was determined in the field based on lithology and depth to groundwater, with the goal of generally screening the monitoring well from depth of water to the top of the UMCf. In general, monitoring wells were completed similar to injection wells with flush-mounted traffic-rated well boxes. Due to construction activities occurring at the Site during monitoring well installation, monitoring well SWFTS-MW23 was completed above-ground surrounded by bollards. Well development activities were completed following well construction as described in Section 3.4.1.3. Boring logs and well construction diagrams for all monitoring wells are provided in Appendix C.

5.3 CARBON SUBSTRATE INJECTIONS

Following completion of injection and monitoring well installation (Section 5.2) and baseline groundwater monitoring (described Section 5.4), injections of carbon substrate and amendments began in August 2017. Prior to the initiation of the treatability study, a Class V UIC General Permit for Long-Term Remediation was secured, which allows for the injection of fluids in the saturated subsurface. The general permit falls under NAC 445A.891. The permit was issued on May 30, 2017 and does not expire until the permit is cancelled. The following sections provide a summary of the three injection events. Injection summary tables for each injected event are provided in Appendix K.

5.3.1 Determination of Injectate Requirements

The injectate solution for each of the injection events included carbon substrate (EOS® PRO), glycerin, phosphate, sodium sulfite, and water. The primary components of the injectate solution are the carbon substrate and water, which is used for both dilution and subsurface distribution of the carbon substrate in order to create a biologically active zone.

The quantities of carbon substrate required during the first injection event were based primarily on:

- Results and findings of the pre-design activities described in Sections 3.0 and 4.0 (including both field and laboratory bench-scale studies);
- Chemistry and geochemistry of the groundwater collected during the baseline groundwater sampling event that occurred in July 2017 immediately prior to the injections (described in Section 6.2);
- Stoichiometric requirements for the carbon substrate based on the mass of perchlorate and other electron acceptors that would migrate through the treatability study area;
- Results and findings from the previous treatability study and literature case studies;
- Suitable factor of safety to account for heterogeneity and uncertainties in the subsurface; and
- Consultations with the EOS® PRO Remediation vendor.

The final carbon substrate quantities were based on the above information and a series of calculations to arrive at the dosing for the first injection event. Specifically, the following calculations were performed:

1) **Calculation of the Targeted Treated Soil Mass.** Based on the coverage of the injection wells resulting from the selected injection well spacing, number of injection wells, and targeted saturated thickness, the targeted treated soil mass was calculated as follows:

$$M_s = \left(\pi \cdot \frac{D^2}{4}\right) \cdot N_i \cdot T \cdot \rho_s$$

where

$M_s = mass\ of\ soil\ (pounds)$
$D = diameter\ (well\ spacing)$
$N_i = number\ of\ injection\ wells$
$T = treatment\ thickness$
$\rho_s = density\ of\ wet\ soil$

2) **Estimation of the substrate requirement.** This is the final step in which the substrate requirement is estimated using the result from the calculations presented in Step 5, the oil retention ratio, and the density of the substrate. The following equation was used to estimate the substrate requirement:

$$V_{sub} = (M_s \cdot R_o) \div \rho_{sub}$$

where

$V_{sub} = substrate\ volume\ (gallons)$
$M_s = mass\ of\ soil\ (pounds)$
$\rho_{sub} = density\ of\ substrate$
$R_o = oil\ retention\ ratio$

The oil retention ratio (R_o) is a site- and study-specific value that is approximated using site-specific data, bench-scale adsorption studies, lessons learned from previous NERT studies, literature values, prior practitioner experience, and vendor consultation. The oil retention ratio for this study was selected as 0.0026 pounds of oil per pound of soil targeted.

To calculate the total water required to dilute the carbon substrate and achieve adequate subsurface distribution, the following calculation was performed for each injection well to arrive at the final injection volume:

$$Vi = \left(\pi \cdot \frac{D^2}{4}\right) \cdot T \cdot \rho_w \cdot n_e$$

where

$Vi = injection\ volume\ (gallons\ of\ water)$

$D = distance\ (feet)$

$T = treatment\ thickness\ (feet)$

$\rho_w = density\ of\ water\ (gallons\ per\ cubic\ foot)$

$n_e = effective\ porosity$

As previously stated, remaining amendments included glycerin, phosphate, and sodium sulfite. Glycerin was added at a rate of approximately 2.5 percent (w/w) of the amount of EVO that was added during each event. Over the years, the quantity of this soluble substrate in the patented EVO product has been decreased because most sites have much slower groundwater flow velocities. At this site, the groundwater flow velocities are relatively high and therefore considerable quantities of oxygenated water flow past the injection well transect on a daily basis. In addition, the groundwater also contains high concentrations of nitrate (as high as 18 mg/L). Therefore, in order to provide adequate amounts of a readily available carbon substrate and decrease the microbial lag time at the inception of the study, adding small quantities of glycerin is desirable, as per Tetra Tech's experience and in consultation with the specialized vendor and EVO protocol authors.

The patented EVO product also contains only minor and nominal quantities of phosphorus. Because this key nutrient could be limiting in the aquifer and gets easily bound (organically and inorganically), particularly due to the presence of high concentrations of calcium, it is helpful to add small doses of phosphorus to the groundwater in order to prevent this nutrient from limiting microbial growth. Again, this addition was performed based on Tetra Tech's experience under similar aquifer and lithological conditions and consultation with the EVO vendor and EVO protocol authors. Phosphorus liquid as Aquapure® 3601 from Brenntag was added at the rate of approximately 1 percent (w/w) to the EVO during injections.

Finally, sodium sulfite was added to the injectate as an oxygen scavenger to chemically remove dissolved oxygen that is in the groundwater, which was used as a source of mixing and distribution water for the carbon substrate and added nutrients. The objective of adding sodium sulfite is to prevent any aerobic growth in both the aboveground substrate mixing tanks as well as to the attached solids and maximize the opportunity for anaerobic microorganisms that have the ability to biodegrade perchlorate to develop right from the inception. Sodium sulfite is a chemical that rapidly and almost instantaneously reacts upon contact with oxygen in water, and therefore, is the ideal and practical mechanism to hasten anaerobic conditions. Fundamental chemical stochiometric equations relating sodium sulfite to oxygen along with a factor of safety were used to estimate the quantity of sodium sulfite that was added to the water.

5.3.2 Summary of Injection Events

Three injection events were performed during the treatability study in August/September 2017, January/February 2018, and June 2018. This section summarizes the field activities, injectate quantities, and injection volumes for each of the three injection events.

5.3.2.1 Injection Event 1

The first injection event was performed from August 21, 2017 through September 11, 2017 by Cascade Technical Services under Tetra Tech oversight and direction. Cascade Technical Services performed the injections using a custom-built injection platform that was equipped with variable high-speed multi-stage centrifugal pumps, in-line mixers, injection/extraction hosing, meters, valves, and fittings.

A total of 20,001 gallons of EOS® PRO, 4,046 pounds of glycerin, 145 gallons of phosphate solution, and 303 pounds of sodium sulfite were injected during the first event (determined using the process described in Section 5.3.1). Glycerin was added to the injectate solution to serve as an immediate source of carbon to drive the groundwater anaerobic rapidly and reduce acclimation time at the start of the study. Because EOS® PRO is already formulated with minor quantities of macronutrients, namely phosphorus, only a nominal quantity of additional phosphate was added to the injectate solution. Finally, sodium sulfite was added to the injectate solution as an oxygen scavenger to remove dissolved oxygen in both the injectate and distribution water chemically and prevent aerobic microbial growth in the formation to the extent possible.

Prior to injecting, the carbon substrate solution was diluted at a ratio of 1:4 parts of EOS® PRO:water, which resulted in a total of approximately 77,960 gallons of dilution water being added to the injectate solution. Although the Work Plan stated that the likely water source would be a nearby COH hydrant, the NDEP-approved *SWF Bioremediation Treatability Study – Notification of Field Implementation Modification* (Tetra Tech, 2017) described the most appropriate water source would be groundwater from within the treatability study area extracted from upgradient monitoring wells. Although both site groundwater and GWETS effluent were an effective water source used in the bench-scale studies, site groundwater was selected for enhanced mixing of the carbon substrate within the injection well transects by using native water, minimal dilution effects since clean water was not being used, and overall water conservation. As a result, submersible pumps were placed in six monitoring wells located upgradient of the injection well transects (SWFTS-MW07A, SWFTS-MW08A, SWFTS-MW11, SWFTS-MW12, SWFTS-MW13, and SWFTS-MW17). Groundwater from these monitoring wells was extracted and transferred to the two 21,000-gallon frac tanks for use during injection operations.

Once the injectate solution was diluted with the extracted groundwater, the solution was injected into the injection wells via an injection manifold system that connected to nine injection wells at a single time. Upon completion of substrate injections, a total of 323,325 gallons of water were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transects and in the vicinity of the injection area. This quantity of water is equivalent to approximately one pore volume of groundwater and was estimated based on the designed spacing of the injection wells, average depth of the water horizon, and porosity in the alluvium in the vicinity in the treatability study area. As with the dilution water, all distribution water used during injections was obtained by extracting groundwater from upgradient monitoring wells. As summarized in the tables in Appendix K, the quantities of the injectate solution and distribution water varied between injection wells based on the screen lengths and thickness of the targeted formation at each injection location.

During injections, both flow rate and pressure were measured at each injection well. Injection rates averaged approximately 7 gallons per minute (gpm) while sustained pressures generally averaged 5 psi. Following completion of the injections, all equipment was dismantled and removed from the site. Due to the frac tanks containing extracted groundwater during injections, the tanks were cleaned prior to their removal from the site.

5.3.2.2 Injection Event 2

The second injection event was performed from January 22, 2018 through February 10, 2018, which was approximately 5 months after the first injection event. The timing of the second injection event was based on the effectiveness monitoring results following the first injection event, which are discussed in detail in Section 6.2. Under Tetra Tech's oversight and direction, Cascade Technical Services performed the injections using the same injection process described in Section 5.3.2.1.

Prior to the second injection event, groundwater samples were collected from injection wells and analyzed for TOC to determine the approximate residual carbon in the vicinity of the injection wells following the first injection. Using this data coupled with UNLV bench-scale studies performed in connection with the previously completed COH treatability study (Tetra Tech, 2016b), the carbon dosage for the second injection event was reduced to approximately 40 percent of the dosage that was injected during the first event. This reduction in substrate would allow for the evaluation of injecting lower quantities of carbon substrate and amendments to ascertain the thresholds and approximate longevity and influence of EOS® PRO, which is an objective of this study. Additionally, because groundwater samples were collected from injection wells and analyzed for TOC, this reduction of injectate quantities would enable evaluation of using TOC concentration data from injection wells as an indicator parameter to make decisions on timing and quantities of carbon substrate injections. Because some of the carbon from the injections adsorbs to the soil grains, the same dosage is not always required in subsequent injection events.

During the second injection event, a total of 7,703 gallons of EOS® PRO, 53 pounds of sodium sulfite, and 30,813 gallons of injectate dilution water were injected into the selected injection wells within the treatability study area. Neither glycerin nor the phosphate solution was injected during the second event because the groundwater remained anaerobic from the first injection event and the microbial community was also acclimated and robust; therefore, these additives were not deemed necessary. Upon completion of substrate injections, a total of 270,833 gallons of water was injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transects and in the vicinity of the injection area. In total, this injection event consisted of approximately 27% less injectate and water than the first injection event.

As summarized in the tables in Appendix K, the quantities of injectate and distribution water varied between injection wells based on TOC concentrations observed in these wells as well as screen lengths and the thickness of the targeted formation at each injection location. Of the 25 injection wells, only 16 received additional carbon substrate during the second injection event. These 16 injection wells also received a total quantity of injection water (injectate and follow up distribution water) equivalent to one pore volume. Based on the high TOC concentrations observed during sampling, the remaining nine of the 25 injection wells did not receive carbon substrate injections. Of these nine injection wells, six received 75 percent of the estimated single pore volume distribution water in order to attempt to flush the high levels of carbon substrate that remained within the vicinity of the injection well based on the high TOC concentrations observed in these wells prior to injections. The remaining three injection wells did not receive any water in order to evaluate if differences in injection flows and volumes would be noticed in follow-up injections when these wells were not flushed with any fluids in the second injection event.

Measurements of flow rate and pressure during the second injection event indicate that the average injection rate was approximately 6 gpm while sustained pressures generally averaged 10.3 psi. The average sustained pressure increased in comparison to the pressures observed during the first injection event, but the values were still substantially lower than the 35 psi UIC permit limit. A similar observation was made during the previously concluded COH study; the sustained pressure is likely due to the heightened level of desired microbial activity and EVO breakdown in the vicinity of the injection wells. Following completion of the injections, the frac tanks were cleaned and all equipment was dismantled and removed from the site.

5.3.2.3 Injection Event 3

The third injection event was performed from June 11, 2018 through June 30, 2018, which was approximately 5 months after the second injection event. The timing of the third injection event was based on the effectiveness monitoring results following the second injection event; those results are discussed in detail in Section 6.2. Under Tetra Tech's oversight and direction, Cascade Technical Services performed the injections using the same injection process described in Section 5.3.2.1.

During the third injection event, a total of 16,701 gallons of EOS® PRO, 4,045 pounds of glycerin, 149 gallons of phosphate solution, 310 pounds of sodium sulfite, and 66,800 gallons of injectate dilution water were injected into the selected injection wells within the treatability study area. The quantity of EOS® PRO was approximately 85 percent of that used in the first injection event, but double that used for the second injection event. The objective of this variation was to increase the timeframe for injection frequencies while simultaneously evaluating how decreased amounts (85 percent quantity reduction compared to the first injection event) would impact treatment effectiveness and carbon substrate longevity. Upon completion of substrate injections, a total of 336,237 gallons of water were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transects and in the vicinity of the injection area. As summarized in the tables in Appendix K, the quantities of EVO varied between injection wells based on the screen lengths and the thickness of the targeted formation at each injection location.

Measurements of flow rate and injection pressure at each well during the third injection event indicate that the average injection rate was approximately 5 gpm while sustained injection pressures generally averaged 14.2 psi. The average sustained injection pressure increased by approximately 4 psi compared to the average sustained injection pressures observed during injection event 2, but the values were still substantially lower than the 35 psi UIC permit limit and are generally expected during ISB operations. Following completion of the injections, the frac tanks were cleaned and all equipment was dismantled and removed from the site.

5.4 EFFECTIVENESS MONITORING PROGRAM

An effectiveness monitoring program was implemented to monitor both groundwater contaminant and geochemical changes following the injection events to evaluate and determine ISB effectiveness. As part of the effectiveness monitoring program, groundwater samples were periodically collected from both existing and newly installed injection and/or monitoring wells within the treatability study area. Groundwater sampling activities were conducted in accordance with the *Field Sampling Plan, Revision 1* (ENVIRON, 2014). Prior to groundwater sample collection, groundwater levels were gauged in all wells to be used in potentiometric contouring. Groundwater samples were collected using low-flow purging and sampling techniques. The pump discharge water was passed through a flow-through cell field water analyzer for continuous monitoring of field parameters (DO, specific conductivity, oxidation-reduction potential [ORP], pH, temperature, and turbidity), which were recorded on field sampling forms. The wells were sampled when purging was complete, which was based on when the field parameter readings and water levels stabilized. Field low-flow purge logs for all groundwater sampling events are provided in Appendix E.

A comprehensive groundwater sampling event was completed prior to carbon substrate injections to establish baseline conditions. The baseline sampling event included all newly installed injection and monitoring wells, as well as six existing monitoring wells (COH-2B1 [also sometimes referred by others as COH-2B], PC-58, PC-91, PC-92, PC-94, and PC-97). During the effectiveness monitoring events following injections, groundwater samples were periodically collected from monitoring wells installed as part of the treatability study (SWFTS-MW01 through SWFTS-MW25) and seven existing monitoring wells (COH-2B1, PC-58, PC-88, PC-91, PC-92, PC-94, and PC-97) located upgradient, in between, and downgradient of the injection well transect. As explained in Section 5.3.2, injection wells were also sampled prior to the second injection event to evaluate concentrations within the injection wells. Finally, the four monthly monitoring events following the third injection event (namely, July, August, September, and October 2018) also included groundwater sampling at seven monitoring wells that were installed east of Pabco Road as part of the May/June 2018 Phase 1 pre-design activities for the Las Vegas Wash Bioremediation Pilot Study (LVWPS-MW101A, LVWPS-MW104, LVWPS-MW107A, LVWPS-MW108A, LVWPS-MW109, LVWPS-MW111A, and LVWPS-MW112A). These monitoring wells were added to the program to evaluate if concentration reductions were observed slightly farther downgradient of the injection wells. Figure 4 presents a map of the monitoring wells that were periodically sampled as part of the effectiveness monitoring program.

After the first injection event, groundwater samples were collected on a weekly basis for the first month, biweekly basis for the second month, and then generally on a monthly basis throughout the remaining treatability study time frame (except for a biweekly event added immediately following the third injection event). Groundwater samples were analyzed for field, laboratory, and/or microbial parameters presented in ***Table 2***, which lists the various groundwater sampling parameters, laboratory methods, and purpose as related to the treatability study evaluation. Results from the effectiveness monitoring program are discussed in Section 6.2, with comprehensive data tables presented in Appendix D.

Table 2 Effectiveness Monitoring Parameters

Parameter	Analytical Method	Purpose
Field Parameters		
EC	Field Meter	Assess geochemical conditions
pH	Field Meter	
DO	Field Meter	
ORP	Field Meter	
Temperature	Field Meter	
Turbidity	Field Meter	
Ferrous Iron	HACH Field Kit	Assess effect of reducing conditions on iron
Sulfide	HACH Method 8131	Examine secondary geochemical impacts
Laboratory Parameters		
Perchlorate	EPA 314.0	Assess treatment effectiveness
TOC	SW9060/SM5310B	Assess carbon substrate distribution in the aquifer
TDS	SM2540C	Assess any impact of salts on delayed or slower perchlorate biodegradation in the flow through mode
Alkalinity	SM2320B	Assess geochemical conditions
Hexavalent Chromium	SW7199	Assess secondary impacts of treatment
Nitrate	EPA 300.0	Assess nitrate as the most likely competing electron acceptor and carbon substrate consumer
Sulfate	EPA 300.0	Assess sulfate as an electron acceptor and potential carbon substrate consumer
Total Nitrogen	EPA 351.2 and EPA 300.0	Examine the need for macronutrients
Total Phosphorus	E365.3	Examine the need for macronutrients
Manganese	SW6010B	Assess potential for biologically-driven dissolution of manganese
Methane	RSK175	Examine secondary geochemical impacts
Dissolved Metals(1)	SW6010B/6020	Assess secondary impacts of treatment and potential metals mobilization
VFAs	VFA-IC	Assess surrogate carbon substrate
Chlorate	E300.1	Assess treatment effectiveness and examination as intermediate by-product of perchlorate biodegradation
Chloride	E300.0	Potentially estimate conservative end-product of biodegradation
PLFA	Microbial Insights Method	Examine microbial response to carbon substrate addition

Parameter	Analytical Method	Purpose
Perchlorate Reductase Gene	Microbial Insights Method	Examine microbial response to carbon substrate addition

Acronyms and Abbreviations:
BL: Baseline
EC: Electrical conductivity
DO: Dissolved Oxygen
ORP: Oxidation-reduction potential
PLFA: Phospholipid Fatty Acids
TOC: Total organic carbon
TDS: Total dissolved solids
VFAs: Volatile Fatty Acids

(1) Metals include arsenic, chromium, iron, and manganese.

During the effectiveness monitoring period, and as detailed in the approved Work Plan, the monitoring program was periodically reevaluated and adjusted based on the results of the previous sampling events. As part of this evaluation, the following changes/additions to the effectiveness monitoring program were incorporated:

- Chloride and TDS were eliminated from the effectiveness monitoring program following the second injection event based on the consistent chloride and TDS concentrations observed during the first six effectiveness monitoring sampling events.
- Dissolved metals were analyzed in groundwater from all monitoring wells one month following the first injection event and select months before or after the second and third injection events. Six downgradient monitoring wells (namely, PC-94, SWFTS-MW03, SWFTS-MW10A, SWFTS-MW14, SWFTS-MW16, and SWFTS-MW25) were strategically selected to be sampled on a monthly basis for the duration of the study. These wells were selected to provide data for key locations within the study area, including monitoring wells in between the injection well transects, downgradient of the injection well transects within the main study area, and boundary wells located approximately 600 feet downgradient of the injection well transects to provide a representative dataset in key monitoring wells within the study area. Similarly, analysis of alkalinity, total nitrogen, phosphorus, methane and volatile fatty acids (VFAs) was also limited to select downgradient monitoring wells.
- Prior to the second injection event, perchlorate, TOC, and/or nitrate were analyzed in groundwater from injection wells to evaluate chemical conditions and potential residual carbon within the injection wells so that data could be used to assess carbon dosing during the second injection event.

5.4.1 Data Validation

A Data Validation Summary Report (DVSR) was prepared for the laboratory analytical data collected during the implementation of the SWF Area Bioremediation Treatability Study. The DVSR was prepared to assess the validity and usability of laboratory analytical data from well installation activities and groundwater monitoring associated with the ISB of perchlorate in groundwater. To aid in assessing data quality, Tetra Tech collected additional quality assurance and quality control (QA/QC) samples, which included equipment blanks, field blanks, field duplicates, and matrix spike/matrix spike duplicates. The QA/QC samples provided information on the effects of sampling procedures and assessed sampling contamination, laboratory performance, and matrix effects.

The DVSR is provided as Appendix L to this results report. The laboratory analytical data were verified and validated in accordance with procedures described in the *Quality Assurance Project Plan, Revision 2* (Ramboll Environ, 2017), "Data Validation Guidance" (NDEP, 2018), the NDEP December 2018 email (Dong, 2018) concerning multiple results, and the references contained therein. Aqueous samples were validated to Stage 2A. For soil samples, 90 percent of the data were validated to Stage 2B and 10 percent to Stage 4. The review process used professional judgment and guidance from the National Functional Guidelines to determine the final qualifiers, which were added to the database and presented in the DVSR tables.

6.0 ANALYSIS OF RESULTS

This section provides an analysis of the results from the Phase 2 treatability study activities, including a discussion of the treatability study area geology and hydrogeology, effectiveness monitoring results, and hydrogeological evaluation in response to the ISB injections.

6.1 TREATABILITY STUDY AREA GEOLOGY AND HYDROGEOLOGY

Data compiled during both Phase 1 pre-design and Phase 2 treatability study installation activities (described in Sections 3.4 and 5.2, respectively) were used to generate a summary of the geology and hydrogeology of the treatability study area. Geologic cross sections of the treatability study area are presented in Figures 5a, 5b, and 5c.

6.1.1 Geology

The geology in the treatability study area consists of alluvium at ground surface, underlain by the UMCf. Analysis of the lithologic logs from boreholes and wells installed in the treatability study area indicates that generally the uppermost 40 feet consist of Quaternary alluvium. The alluvium within the treatability study area is heterogeneous and consists of interbedded layers of sand, silt, and gravel. In general, the alluvium in the south and southwestern portion of the study area is finer with more silty fine sand and sandy clay layers, particularly in the upper alluvium, near SWFTS-BH01, SWFTS-MW07A/B, and SWFTS-IW01A/B. The UMCf is encountered immediately below the alluvium. Within the treatability study area, the UMCf is a visually distinct, very light greenish grey silty clay. The depth to the alluvium/UMCf contact ranges from 33 – 54.5 feet bgs (averaging approximately 40 feet bgs).

A small paleochannel oriented approximately east-west is located within the treatability study area, as indicated by the deeper erosional contact between the alluvium and UMCf as well as a higher portion of gravel and cobbles in the alluvial sediments. Contours of the UMCf surface and approximate centerline of the paleochannel are provided on Figure 6, with a cross section of the paleochannel shown on Figure 5c. This paleochannel is likely a smaller, sub-parallel channel related to the larger paleochannel associated with the Las Vegas Wash itself. Analysis of the NMR data from the treatability study indicates that the centerline of the paleochannel migrated towards the south over time, resulting in deposition of a wedge of coarser-grained sediment located south of the centerline of the original paleochannel.

6.1.2 Hydrogeology

The baseline July 2017 groundwater level gauging event indicated that the depth to groundwater in monitoring wells within the treatability study area ranges from approximately 6.5 to 27.5 feet bgs, and saturated thickness ranges from about 20 to 30 feet. Figure 7 presents the groundwater potentiometric surface in July 2017 for the treatability study area for all wells screened within the alluvium. Subsequent synoptic groundwater level gauging events performed during the effectiveness monitoring period indicated groundwater flow direction remained consistent over time with the baseline July 2017 conditions. Depth to water measurements collected during baseline and all effectiveness monitoring events are provided in Table E.1, in Appendix E.

In the treatability study area, the hydrogeology is governed by the local geology. The groundwater in the lower conductivity sediments to the south and southwest of the treatability study area flows toward the northwest and ultimately discharges into the small east-west paleochannel. Once groundwater enters the paleochannel, it tends to flow within the higher conductivity sediments towards the east and eventually turns northward toward the Las Vegas Wash in the vicinity of Pabco Road, as illustrated on Figure 7. Horizontal gradients are approximately 0.015 feet per foot (ft/ft) into the paleochannel and 0.0066 ft/ft within the paleochannel. There is a vertical upward gradient of 0.07 ft/ft from the UMCf into the alluvium based on monitoring well pairs SWFTS-MW08A/C and SWFTS-MW10A/C. The upward vertical gradient can result in the discharge of perchlorate-impacted groundwater from the UMCf into the alluvium. Discharge rates from the UMCf into the alluvium would be expected to be small in comparison to the horizontal groundwater flux within the alluvium but could be more noticeable in localized areas where more permeable portions of the UMCf are in contact with the alluvium. However, identifying and evaluating potential discharge locations was outside the scope of this study.

The flow rate in the lower hydraulic conductivity sediments outside of the paleochannel is approximately 0.07 to 2 ft/day, based on single-borehole dilution tests in wells SWFTS-MW07A and SWFTS-MW08A. Within the paleochannel, groundwater flow velocity is estimated to be 12 to 119 ft/day, indicated by single-borehole dilution test results from wells SWFTS-MW09A and SWFTS-MW10A. These groundwater flow velocity ranges are comparable to ones calculated using slug test hydraulic conductivity and effective porosity from NMR data, which range from 0.3 to 2 ft/day outside of the paleochannel and 0.4 to 31 ft/day within the paleochannel.

6.2 EFFECTIVENESS MONITORING RESULTS

A explained in Section 5.4, groundwater samples were periodically collected and analyzed for a variety of constituents during the treatability study to evaluate the aquifer's response to ISB injections and the effectiveness of ISB in remediating perchlorate and chlorate contamination in groundwater. This section provides an overview of the groundwater sampling results, including a discussion of the primary contaminants, additional chemical and geochemical parameters, and relationships among each of these parameters. Because perchlorate is the primary chemical of concern at the site and remediation of perchlorate is the main focus of this treatability study, Section 6.2.1 presents a detailed discussion of the perchlorate degradation response, estimate of perchlorate distribution, perchlorate biodegradation rates, and estimate of perchlorate mass destroyed during the treatability study. Other significant constituents, including chlorate, nitrate, and TOC, are also discussed in detail in Sections 6.2.2 through 6.2.4. Data for perchlorate, chlorate, nitrate, and TOC (as well as secondary parameters of dissolved arsenic, phosphorus, DO, and ORP) are depicted graphically in individual well trend profiles provided in Appendix M. Additional parameters (such as DO, ORP, sulfate and sulfide, metals, and others) have also been evaluated and are discussed in Sections 6.2.5 and 6.2.6. Data for all parameters can be found in the comprehensive data tables provided in Appendix D, Tables D.4 and D.6. Field logs from all groundwater sampling events are provided in Appendix E and the DVSR is provided in Appendix L.

6.2.1 Perchlorate

As explained in Section 2.1, perchlorate contamination in groundwater can biodegrade in the presence of a carbon substrate once DO, nitrate, and generally chlorate have been depleted. To evaluate the effectiveness of ISB, perchlorate concentrations in groundwater were evaluated throughout the study to monitor concentration changes when comparing baseline (pre-injection) sampling events to those sampling events performed post-injection. Two groundwater sampling events were performed in March and July 2017 to establish baseline pre-injection conditions. Following injections, groundwater sampling events were performed on either a weekly, biweekly, or monthly basis. An evaluation of the perchlorate degradation response, perchlorate distribution throughout the study area, degradation rates, and estimates of perchlorate mass removal is presented in the subsequent sections.

6.2.1.1 Perchlorate Degradation Response

This section provides a summary of the baseline conditions and subsequent perchlorate degradation response that was observed following each of the injection events that were detailed earlier in this report. ***Table 3*** summarizes the average perchlorate concentration reduction in groundwater observed in monitoring wells located in between and downgradient of the injection well transects throughout the study duration.

Table 3 Perchlorate Concentration Reductions During Treatability Study

Sampling Event	Event Description	Monitoring Well Location			
		Between Injection Well Transects		Downgradient of Injection Well Transects	
		No. of Wells = 4		No. of Wells = 16	
		Average	Maximum	Average	Maximum
Injection Event 1	Week 0	-	-	-	-
After Injection Event 1	Week 1	-54%	-100%	-60%	-100%
	Week 2	-53%	-100%	-67%	-100%
	Week 3	-55%	-100%	-67%	-100%
	Week 4	-47%	-100%	-72%	-100%
	Week 6	-55%	-100%	-64%	-100%
	Week 9	-66%	-100%	-67%	-100%
	Week 13	-56%	-94%	-58%	-99%
Injection Event 2	Weeks 19 - 21	-	-	-	-
After Injection Event 2	Week 23	-62%	-93%	-58%	-94%
	Week 28	-43%	-82%	-52%	-85%
	Week 33	-65%	-82%	-47%	-67%
Injection Event 3	Weeks 39 - 41	-	-	-	-
After Injection Event 3	Week 43	-74%	-100%	-66%	-97%
	Week 45	-87%	-100%	-71%	-97%
	Week 48	-83%	-100%	-69%	-94%
	Week 52	-85%	-100%	-68%	-88%
	Week 56	-87%	-100%	-66%	-82%

6.2.1.1.1 Baseline Groundwater Results

Perchlorate concentrations in groundwater measured during the two baseline sampling events ranged from 170 to 25,000 µg/L. The highest detection of 25,000 µg/L was measured in a groundwater sample collected from SWFTS-MW02, which is located in between the two injection well transects in the western portion of the treatability study area. In general, the highest perchlorate groundwater concentrations are observed near the approximate centerline of the paleochannel shown on Figures 6 and 7, suggesting that the higher conductivity sediments channel much of the perchlorate flux through the treatability study area. Groundwater samples collected from upgradient monitoring wells had perchlorate detections as high as 14,000 µg/L (SWFTS-MW07A). SWFTS-MW25, which is approximately 600 feet hydraulically downgradient of the second injection transect, had a baseline groundwater concentration of 17,000 µg/L.

6.2.1.1.2 Perchlorate Degradation Response Following Injection Event 1

The first carbon substrate injection event was performed in August/September 2017. Following completion of the first injection event, groundwater sampling was performed on a weekly, biweekly, and then monthly basis for a period of approximately 3 months (presented as Weeks 1, 2, 3, 4, 6, 9, and 13 in Table 3 above).

Perchlorate concentrations in groundwater exhibited rapid decreases following the first carbon injection event. Groundwater samples collected from all 20 monitoring wells located in between or downgradient of the injection well transects exhibited concentration reductions of perchlorate. Of these 20 monitoring wells, groundwater samples from 11 monitoring wells reflected perchlorate concentrations decreases of more than 80 percent when compared to baseline concentrations.

Of the four monitoring wells located in between the injection well transects, perchlorate concentrations in groundwater samples collected from two of the monitoring wells (SWFTS-MW14 and SWFTS-MW16) recorded substantial decreases within the first 2 months of sampling, with both monitoring wells yielding groundwater samples exhibiting perchlorate concentrations less than the federal PRG for perchlorate of 15 μg/L (Figures 8a, M.24, and M.26 [Appendix M]; Table D.4 [Appendix D]). Groundwater samples collected from the remaining two monitoring wells located in between the injection well transects (SWFTS-MW02 and SWFTS-MW15) indicated a more gradual response following the first injection event likely due to the high heterogeneity in the alluvial aquifer within this area or potential localized discharge from the UMCf. Specifically, perchlorate concentrations in groundwater collected from SWFTS-MW02 and SWFTS-MW15 reduced from 25,000 µg/L to 17,000 µg/L and from 15,000 µg/L to 9,900 µg/L, respectively, within the first 2 months following the first injection event (Figures 8a, M.8, and M.25; Table D.4).

Groundwater samples collected from monitoring wells located downgradient of the injection well transects also exhibited rapid decreases in perchlorate concentrations, with the average concentration reduction ranging from 58 to 72 percent following the first injection event (Table 3). Of the 16 monitoring wells located downgradient of the second injection well transect, groundwater samples from nine monitoring wells exhibited perchlorate concentration reductions greater than 80 percent when compared to their respective baseline concentrations. Perchlorate concentrations in groundwater samples collected from four downgradient monitoring wells (SWFTS-MW03, SWFTS-MW05B, SWFTS-MW09A, and SWFTS-MW10A) were reduced to less than the federal PRG for perchlorate of 15 μg/L in several groundwater sampling events conducted within the first 2 months following the first injection event (Figures 8a, M.9, M.12, M.18, and M.20; Table D.4). Groundwater samples collected from PC-94, which is a key historic monitoring well located approximately 400 feet downgradient of the second injection well transect, exhibited a perchlorate concentration decrease of 96 percent, from 14,000 µg/L during baseline to 540 µg/L within the first 6 weeks of post-injection groundwater sampling (Figures 8a and M.5; Table D.4). Another noteworthy observation was the perchlorate concentration reduction from 17,000 µg/L to 280 µg/L that was observed during the first week of sampling in the groundwater sample collected from monitoring well SWFTS-MW25, which is located approximately 600 feet downgradient of the second injection well transect (Figures 8a and M.35; Table D.4). The significant perchlorate concentration decrease observed in groundwater located this far downgradient of the injection well transect is likely attributable to fast groundwater flow along the small paleochannel, thereby transmitting the carbon substrate rapidly downgradient to the vicinity of monitoring well SWFTS-MW25.

Similar to monitoring wells SWFTS-MW02 and SWFTS-MW15 (located between the injection well transects), perchlorate biodegradation in groundwater was slower to respond in some areas located downgradient of the injection well transects. Specifically, groundwater samples collected from downgradient monitoring wells SWFTS-MW05A, SWFTS-MW18, and SWFTS-MW20 (with the exception of the Week 9 sampling event) generally did not reflect concentration decreases greater than 40 percent in the first 3 months (Figures 8a, M.11, M.28, and M.30; Table D.4). The reasons for the more gradual response to some monitoring wells between and downgradient of the injection well transects following the first injection event are likely the following: preferential flow pathways for carbon substrate migration; presence of paleochannels; and large lithological heterogeneity that was apparent during well drilling activities (as shown in the geologic cross sections depicted in Figures 5a, b, and c). In addition, perchlorate from the AMPAC plume is migrating in the vicinity of the Las Vegas Wash towards Pabco Road weir downgradient of the treatability study area and may be impacting groundwater quality at the most distant downgradient monitoring wells. A comparison of the boring logs from SWFTS-MW05A and SWFTS-MW05B indicates considerably more gravel present in SWFTS-MW05B, which could have resulted in more carbon substrate transport occurring predominantly in the lower alluvium compared to the upper alluvium. As a result, this larger quantity of gravel is likely the primary reason for the observed difference in perchlorate biodegradation response between these two monitoring wells. Secondly, filling of the soil pores and coating of the soil grains with EVO is sometimes a gradual process that occurs over time when heterogeneous lithology and longer injection well transects are involved. As a result, multiple injections could be required to establish a more complete biologically active treatment zone.

During the Week 13 sampling event (approximately 3 months following the first injection event), perchlorate concentrations in groundwater samples collected from several downgradient monitoring wells began to show a rebound in perchlorate concentrations of greater than 25 percent from their lowest concentrations attained following the first injection event (Figure 8b and Table D.4). This rebound signaled the need for the second injection event (described in Section 5.3.2).

6.2.1.1.3 Perchlorate Degradation Response Following Injection Event 2

The second carbon substrate injection event was performed in January/February 2018. As previously explained in Section 5.3.2, the carbon substrate injection quantities were reduced to approximately 40 percent of the dosage that was injected during the first event to evaluate injecting lower quantities of carbon substrate to ascertain the thresholds and approximate longevity and influence of EOS® PRO, which is an objective of this study. Following completion of the second injection event, groundwater sampling was performed on a monthly basis for a period of 3 months, noted as Weeks 23, 28, and 33 in Table 3.

Groundwater perchlorate concentrations generally remained at the same reduced levels observed towards the end of the monitoring period following the first injection event. Of the four monitoring wells located in between the injection well transects, perchlorate concentrations in groundwater samples collected from monitoring well SWFTS-MW02, which did not show much of a response following the first injection event, reduced from 19,000 µg/L to 4,400 µg/L following the second injection event (Figures 8b and M.8; Table D.4). However, groundwater perchlorate concentrations increased at monitoring wells SWFTS-MW14 and SWFTS-MW16, which previously had groundwater concentrations less than the federal PRG of 15 µg/L (Figures 8b, M.24, and M.26; Table D.4). As observed in Table 3, the average perchlorate concentration reduction was at or near the highest averages observed following the first injection event for monitoring wells in between the injection well transects; however, this reduction was primarily due to the substantial decrease at monitoring well SWFTS-MW02 as other monitoring wells, namely SWFTS-MW14 and SWFTS-MW16, began to rebound. The likely primary reason for these concentration rebounds was the reduced carbon substrate quantities that were injected during the second injection event, as detailed in Section 5.3.2.

The majority of monitoring wells located downgradient of the injection well transect continued to show a response to ISB injections. As shown in Table 3, the average perchlorate concentration reduction for monitoring wells located downgradient of the injection well transects was less than the reductions observed following the first injection event. One exception to this includes the groundwater concentration reductions observed in downgradient monitoring well SWFTS-MW20, which had a slow response following the first injection event. Groundwater concentrations in SWFTS-MW20 reduced from a high of 20,000 µg/L during baseline to a low of 6,600 µg/L following the second injection event (Figures 8b and M.30; Table D.4).

Perchlorate groundwater concentrations remained generally reduced at levels approximately 50 percent below their respective baseline concentrations following the second injection event even with the reduction in carbon substrate. Based on the responses observed following the second injection event, a third injection event was planned that would increase the dosage from the quantities used in the second injection event to enhance treatment effectiveness and carbon substrate longevity.

6.2.1.1.4 Perchlorate Degradation Response Following Injection Event 3

Following the slight concentration rebound observed in April 2018 (Week 33 as illustrated in Figure 8B), a third injection event was performed in June 2018 consisting of approximately 85 percent of the dosage of the first injection event but an increase of 45 percent of the dosage compared to the second injection event (as described in Section 5.3.3). Following the third injection event, five groundwater sampling events (noted as Weeks 43, 45, 48, 52, and 56 in Table 3) were performed, with two initially performed at 2-week intervals in July 2018, followed by monthly sampling through October 2018.

Overall, the perchlorate degradation response following the third injection event was much more pronounced in comparison to the response observed following the second injection event. As shown in Table 3, the average perchlorate concentration reductions observed in monitoring wells located in between the injection well transects were the highest averages to-date. Groundwater samples collected from the four monitoring wells located in between the injection well transects performed the best, which is demonstrated by the attainment of up to 87 percent average reduction in perchlorate concentrations following the third injection event. Groundwater samples from two of these four monitoring wells (SWFTS-MW14 and SWFTS-MW16) had perchlorate concentrations less than the federal PRG for perchlorate of 15 μg/L in multiple groundwater samples collected during this timeframe, which was the same response observed following the first injection event (Figures 8c, M.24, and M.26; Table D.4). Additionally, groundwater samples from monitoring wells SWFTS-MW02 and SWFTS-MW15 had the best response to-date. Perchlorate concentrations in groundwater samples collected from SWFTS-MW02 continued to show a general decreasing trend and achieved a new concentration low of 1,300 μg/L, which is approximately 95 percent less than baseline concentrations. Groundwater samples collected from monitoring well SWFTS-MW15 also indicated a general decreasing trend and a new low perchlorate concentration of 6,400 μg/L (approximate 57 percent decrease when compared to baseline). This trend is likely due to injected EVO gradually diffusing laterally and vertically across the injection well transects resulting in increased microbial activity (as discussed in Section 6.2.7) over the course of three injection events, resulting in a more complete coating of EVO on the soil grains and thereby creating a more complete biologically active zone for biodegradation of perchlorate-contaminated groundwater flowing past the injection well transects.

Perchlorate concentrations in groundwater samples collected from downgradient monitoring wells also exhibited significant reductions, with average concentration reductions similar to those observed following the first injection event. Groundwater from several monitoring wells attained their lowest concentrations to-date, namely, PC-91, SWFTS-MW05A, SWFTS-MW20, and SWFTS-MW24 (Figures 8c, M.3, M.11, M.30, and M.34; Table D.4). Several other monitoring wells, such as PC-94, SWFTS-MW03, SWFTS-MW05B, SWFTS-MW09A, SWFTS-MW10A, SWFTS-MW21, and SWFTS-MW25 also had perchlorate concentrations in groundwater that exhibited at least an 80 percent or greater decrease when compared to baseline concentrations following the third injection event (Figures 8c, M.5, M.9, M.12, M.18, M.20, M.31, and M.35; Table D.4). One anomaly is the groundwater perchlorate concentrations at monitoring well SWFTS-MW09B, which exhibited decreases of approximately 50%; however, this was not as significant as the response following the first injection event (Figure M.19). As shown in Table 3, the greatest average concentration decrease that was attained after the third injection event was 71 percent.

As discussed in Section 5.4, the four monthly monitoring events following the third injection event (July, August, September, and October 2018) also included groundwater sampling at seven monitoring wells that were installed east of Pabco Road as part of the May/June 2018 Phase 1 pre-design activities for the Las Vegas Wash Bioremediation Pilot Study (publication forthcoming). These monitoring wells were added to the program to evaluate if concentration reductions were observed slightly farther downgradient of the injection wells. Perchlorate concentrations slightly decreased in groundwater samples collected from three monitoring wells (LVWPS-MW108A, LVWPS-MW109, and LVWPS-MW111A) during these sampling events, which may be attributable to the injections performed for the SWF Area Bioremediation Treatability Study. However, additional data would need to be collected to determine if the downgradient influence from injections extends this far.

During the 4 months following the third injection event, it should be noted that average perchlorate concentrations in groundwater samples collected from upgradient monitoring wells also decreased by an average of 27 percent. This reduction is likely due to the upgradient activities associated with the COH Water Reclamation Facility (WRF). Specifically, the COH WRF periodically discharges perchlorate-free water to the ground surface known as Pond 13, which is approximately 2,600 feet upgradient of the SWF treatability study area. The timing of the perchlorate concentration decreases observed in upgradient wells coincides with the timeframe that would be expected for the water discharged to reach the SWF treatability study area. As a result, the timings would suggest that the decrease in perchlorate concentrations observed in upgradient wells following the third injection event may be from the migration of this water to the study area and could possibly account for some of the concentration decreases observed during this time period. However, the magnitude of the perchlorate concentration decreases observed in groundwater samples collected from upgradient monitoring wells is substantially lower than the magnitude of decreases observed in groundwater samples collected from monitoring wells located between and farther downgradient of the injection well transects, indicating that there was substantial direct destruction/degradation of perchlorate in groundwater as a result of the third injection event.

6.2.1.2 Estimate of Perchlorate Distribution

Figures 8a through 8c present perchlorate plume isoconcentration contour interpretations during the treatability study. Specifically, the baseline event is intended to represent pre-injection perchlorate concentrations in groundwater within the vicinity of the treatability study, followed by depictions of subsequent sampling events post-injection. These comparisons show significant reduction in perchlorate concentrations during the treatability study. As illustrated in the isoconcentration maps on Figures 8a through 8c (white contour interval), a biologically active treatment zone was created following each injection event. As described in Section 6.2.1.1, the response following the third injection event resulted in the greatest perchlorate concentration reduction and the creation of a more complete biologically active zone within the injection well transects for biodegradation of perchlorate-contaminated groundwater. As a result of this more complete treatment zone, the perchlorate plume downgradient of the injection well transects also continued to reduce in size and concentration when compared to the images following the first and second injection events. Nevertheless, this treatability study demonstrated that a biologically active treatment zone can be created and maintained through the injection of carbon donor (in this case EOS Pro®). Perchlorate in groundwater within this treatment zone was reduced to concentrations below 15 μg/L as illustrated by the white contour interval in Figures 8a through 8c. As upgradient groundwater flowed through the treatment zone, perchlorate was significantly reduced in concentration. In addition, perchlorate concentrations in groundwater downgradient of the treatment zone also reduced in concentration from baseline conditions. Given the presence of the AMPAC plume migrating in the northern portions of the treatability study area, the downgradient extent of perchlorate concentrations below 15 μg/L is somewhat limited. Some areas within the treatment zone had slightly less reduction in perchlorate concentrations, which may be due to the heterogeneous nature of the subsurface and localized presence of low permeability within that particular portion of the injection well transect. If implemented full-scale, additional injection wells would be installed within these low permeability zones to achieve a more uniform biologically active treatment zone.

In addition to the two-dimensional visualizations provided in Figures 8a – 8c, three-dimensional visualizations are also presented in Figures 8d and 8e. Specifically, Figure 8d provides three-dimensional visualization of perchlorate distribution during baseline and select monitoring events following each injection event. Figure 8e presents the perchlorate differential from the October 2018 and baseline sampling events (i.e., perchlorate treated during the treatability study).

6.2.1.3 Perchlorate Biodegradation Rates

Perchlorate biodegradation typically follows a first-order degradation pattern in accordance with the following equation:

$$C_t = C_0 e^{-kt}$$

where

C_t = concentration at time t
C_0 = initial concentration
k = rate constant of decline 1/days
t = time

As a result, concentration data were plotted to approximate first-order perchlorate biodegradation rate constants that were attainable during the study. As expected, the various monitoring wells responded to perchlorate biodegradation with different lag times and had different degradation paths. The two monitoring wells that exhibited the most significant and consistent perchlorate concentration reductions in groundwater samples were SWFTS-MW14 and SWFTS-MW16. As a result, data from these two monitoring wells were employed for computations to determine the maximum biodegradation rate observed during the treatability study. Furthermore, the biodegradation rates for these two monitoring wells were estimated after the lag time, using the steepest trajectory of the curve to obtain a typical first-order degradation plot. Based on these assumptions, the perchlorate first-order biodegradation rate constants that are attainable and sustainable (when carbon substrate is present) under optimal conditions ranges from -0.09 day^{-1} to -0.25 day^{-1}. As seen from the Appendix M figures, these rates are great enough to result in the rapid decrease in perchlorate concentrations observed in groundwater within a very short time period.

6.2.1.4 Estimation of Perchlorate Mass Removal

The objective of the mass removal estimation was to assess the effectiveness of ISB as a field technology to destroy perchlorate mass in the saturated subsurface. For purposes of this treatability study and mass removal estimation process, a number of assumptions were made as follows:

- Groundwater sampling data from the March and July 2017 sampling events were assumed to represent baseline conditions.
- Saturated thickness was assumed to be constant throughout this study.
- The area of interest (AOI) was defined to include only the areas investigated during this study. In other words, the AOI was located approximately between the 1541.5- and 1535-foot contours on Figure 7.

This section presents the methodology and analyses for the estimation of perchlorate mass that was biodegraded during the approximate 14-month treatability study period.

6.2.1.4.1 Data Sources

Data that were used for mass estimation were obtained from water level measurements and perchlorate concentrations in groundwater samples collected in or near the treatability study area. Some data were collected specifically for this treatability study, while other data were obtained from the NERT database maintained by Ramboll Environ and were collected from monitoring wells near the treatability study area. In addition, Ramboll Environ provided ArcGIS shapefiles and raw data representing groundwater elevations, perchlorate concentrations, and UMCf geologic surface elevations.

6.2.1.4.2 Procedures

As part of the mass removal calculations, a number of grid surfaces were first generated. These surfaces represented Qal/UMCf contact, groundwater elevation, saturated thickness, hydraulic conductivity, and perchlorate concentrations during each groundwater monitoring event following a carbon substrate injection.

- UMCf geologic surface. UMCf elevations from the new wells installed in the treatability study area were obtained from the borehole logs. UMCf elevations for existing wells were obtained from shapefiles provided by Ramboll Environ, and UMCf contours provided by Ramboll Environ were used to generate control points outside the AOI. A 20-foot grid spacing was used in contouring.
- Groundwater elevation surface. Groundwater elevation data from July 2017 were obtained from the treatability study area and nearby wells. A few locations outside of the treatability study area did not have July 2017 data available but were needed as control points; in these cases, the closest water level measurement to July 2017 was used. The groundwater elevation data were contoured using the same grid specifications as used for the UMCf contours.
- Saturated thickness. The saturated thickness in July 2017 was calculated from the UMCf and groundwater elevation surfaces.
- Hydraulic conductivity. The hydraulic conductivity estimates from slug tests performed on treatability study area alluvial wells were contoured to generate a continuous surface.
- Perchlorate concentration surfaces. Perchlorate concentrations were obtained from the March and July 2017 sampling events from both the study area and nearby wells, and the most recent perchlorate concentration contours outside of the treatability study area (Plate 6, Ramboll Environ, 2016) were digitized to provide control points. The perchlorate concentration data and control points were contoured together using the same 20-foot grid spacing. This process ensured that both the measured concentration data and the best-estimate most recent contours are represented in the resulting perchlorate distribution. The same control points were used for all other contoured perchlorate data sets. Data sets collected after injection to monitor the perchlorate concentration changes were thus combined with control points outside the AOI to eliminate edge effects within the AOI.

The next step was to estimate the amount of mass entering and leaving the AOI during each sampling event. To do this, the saturated thickness, perchlorate concentration, and hydraulic conductivity surfaces were used to develop saturated thickness, perchlorate concentration, and hydraulic conductivity estimates in cross sections through the upgradient and downgradient ends of the AOI. Next, Darcy's Law was used to calculate the volume of water entering and leaving the study area during each sampling event.

The flow area was calculated from the saturated thickness and the distance between the extracted points for each cross section. The volume of water passing through the cross section was calculated from the estimated hydraulic conductivity at each extracted point, the gradient (from the July 2017 potentiometric surface), and the effective porosity (estimated from area-specific NMR data). The volume of water passing through the cross section multiplied by the extracted perchlorate concentrations along the cross section results in the mass of perchlorate passing through that cross section each sampling event. However, due to spatial constraints in the data, the upgradient cross section actually passes through the injection transects, so only the baseline mass entering could be estimated from the cross section. Therefore, a multiplier was developed to adjust incoming mass by the overall change in concentration in each sampling event observed at the Seep Well Field area, which is located just upgradient of the treatability study area.

The third step was to estimate the amount of mass present in the AOI during each measurement event. The saturated thickness and concentration grids were used to estimate mathematically the mass of perchlorate present in the AOI. The average porosity of 25 percent obtained from NMR logging for the alluvial well screens within the treatability study area was used to estimate the mass present in pore spaces. Next, the net mass change in perchlorate mass between each measurement event was estimated using the mass that entered the study area during the elapsed time in between events, minus the mass that left the study area during the elapsed time, plus the change in mass present in the study area. If the calculated net mass change between measurement events was negative (i.e., the perchlorate increased in the area), then zero mass treatment was assumed for that time period. Finally, a time-weighted average was used to estimate the overall mass removal rate.

6.2.1.4.3 Results

Figure 9 presents a summary of the cumulative perchlorate mass destroyed during the treatability study. During the August 2017 through October 2018 timeframe, an estimate total of 2,748 pounds of perchlorate was destroyed from the groundwater in the vicinity of the treatability study area. The most substantial increase in mass removed occurred immediately following the first injection event, which destroyed an initial 1,811 pounds of perchlorate. Following the initial reduction, the average perchlorate mass destroyed was approximately 3 pounds per day during the treatability study.

6.2.2 Chlorate

Chlorate has been reported groundwater within the treatability study area at concentrations that are often higher than those of perchlorate. Chlorate is also amenable to anaerobic biodegradation, similar to perchlorate. Generally, perchlorate biodegradation precedes chlorate biodegradation, although the two processes can also occur simultaneously, particularly in the presence of organic carbon. Chlorate concentrations are summarized in Appendix D, Table D.4 and graphically depicted in Appendix M. Figures 10a through 10c present chlorate plume interpretations, which show significant reductions in chlorate concentrations similar to the perchlorate reductions observed in Figures 8a through 8c.

Chlorate concentrations in groundwater were measured during baseline ranging from less than 10 μg/L to 67,000 μg/L. The highest baseline chlorate concentration was measured in a groundwater sample collected from downgradient well SWFTS-MW05A and represents a concentration that is more than two times greater than the highest perchlorate concentration detected during baseline sampling.

In general, chlorate concentration trends followed a similar reducing pattern as the perchlorate concentration trends throughout the treatability study timeframe. The four monitoring wells located in between the two injection wells transects (namely, SWFTS-MW02, SWFTSMW14, SWFTS-MW15, and SWFTS-MW16) followed a similar response to the perchlorate decreases discussed in Section 6.2.1.1. As with perchlorate, groundwater chlorate sampling in monitoring wells SWFTS-MW14 and SWFTS-MW16 recorded concentrations below sample detection limits in multiple sampling events during the treatability study. The response of groundwater at monitoring well SWFTS-MW02, which was gradual following the first event and improved following the second injection event, exhibited a substantial decrease of approximately 99 percent following the third injection event. SWFTS-MW15, which was the slowest to respond of the four monitoring wells located in between the injection well transects, only recorded notable decreases following the third injection event, similar to the pattern observed for perchlorate decrease.

Chlorate concentrations rapidly decreased in groundwater samples collected from several downgradient monitoring wells immediately following the first injection event, with groundwater concentrations below sample detection limits at monitoring wells SWFTS-MW03, SWFTS-MW05B, SWFTS-MW09A, SWFTS-MW10A, and SWFTS-MW25. In addition to these monitoring wells, groundwater in PC-91 and SWFTS-MW01 exhibited chlorate concentration decreases to below sample detection limits following the third injection event. Other notable decreases include a greater than 95 percent reduction in groundwater chlorate concentrations at monitoring wells PC-94, SWFTS-MW09B, SWFTS-MW21, and SWFTS-MW24 during various post-injection effectiveness monitoring events.

Among the wells which did not respond as favorably, chlorate concentrations in groundwater samples collected from SWFTS-MW09B followed a similar trajectory as the perchlorate concentration decreases, with a rapid initial decrease (greater than 99 percent) during the first few weeks of sampling, followed by fluctuations throughout the study, and ultimately recording an approximate 50 percent during the final sampling event. Chlorate concentrations in groundwater from monitoring well SWFTS-MW05A also followed a similar pattern as perchlorate concentrations trends (and likely for the same reasons), but decreased by 50 percent following the third injection event, similar to the perchlorate response.

The biologically active treatment zone created through the injection of carbon donor also successfully degraded chlorate in groundwater. As shown in Figures 10 a through 10c, chlorate concentrations were reduced to levels below the groundwater BCL of 1,000 μg/L within this treatment zone footprint as well as throughout much of the downgradient portion of the study area. As upgradient groundwater flowed through the treatment zone, chlorate was also significantly reduced in concentration (below laboratory detection limits in some cases). Similar to what was described in Section 6.2.1.2, the treatment zone had a small gap that is the result of non-uniform distribution of carbon donor throughout the subsurface.

6.2.3 Nitrate

As discussed earlier in this report, nitrate concentrations were evaluated throughout the study since it is the most likely competing electron acceptor as well as a consumer of organic carbon substrate as described in Section 2.1. Both perchlorate and chlorate biodegradation generally commences when nitrate biodegradation (denitrification) is substantially complete, it could also occur concurrently along with nitrate biodegradation. In the presence of a continuing carbon source, and once DO and nitrate have been reduced, perchlorate acts as an electron acceptor for anaerobic respiration. Nitrate concentrations during the treatability study are summarized in Appendix D, Table D.4 and graphically depicted in Appendix M. Figures 11a through 11c present nitrate plume interpretations, which show significant reductions in nitrate concentrations during the treatability study.

Groundwater nitrate concentrations ranged from 0.84 to 18 mg/L during baseline sampling. The highest nitrate concentration of 18 mg/L was observed in a groundwater sample collected from monitoring well SWFTS-MW05A, which was also the same groundwater sample that had the highest chlorate concentration detected during the baseline sampling event.

As with perchlorate and chlorate concentrations trends, the four monitoring wells located in between the two injection wells transects (namely, SWFTS-MW02, SWFTSMW14, SWFTS-MW15, and SWFTS-MW16) followed a similar response to the ISB injections. Groundwater nitrate concentrations in monitoring wells SWFTS-MW14 and SWFTS-MW16 were less than sample detection limits during several rounds of groundwater sampling following injections. The response at groundwater monitoring well SWFTS-MW02, which was gradual following the first injection event and improved following the second injection event, showed a significant decrease in groundwater nitrate concentrations following the second injection event from 4.7 mg/L during the Week 23 event to 0.8 mg/L during the Week 28 event. This decrease is significant because this time period also corresponds to the largest groundwater perchlorate and chlorate concentration decreases observed in this monitoring well. The fourth monitoring well in between the injection well transects, SWFTS-MW15, was the slowest to respond, very similar to the perchlorate and chlorate response, and groundwater samples only recorded a decrease of 20 percent compared to baseline concentrations. This nitrate concentration decrease of 20 percent was much less than the 57 percent decrease observed in groundwater perchlorate concentrations and also less than the 35 percent decrease observed in groundwater chlorate concentrations during the same time period. Therefore, even though theoretically denitrification precedes perchlorate and chlorate biodegradation, in practice, these three could all biodegrade in tandem.

Nitrate concentrations in groundwater samples collected from 16 monitoring wells located downgradient of the injection well transects reduced by an average of 50 percent when compared to their baseline concentrations, with 12 of the 16 downgradient monitoring wells having groundwater concentrations less than 1 mg/L in several sampling events throughout the treatability study. Similar to perchlorate and chlorate, rapid decreases were observed in monitoring wells PC-94, SWFTS-MW01, SWFTS-MW03, SWFTS-MW05B, SWFTS-MW09A/B, SWFTS-MW10A, and SWFTS-MW25. These rapid decreases in nitrate groundwater concentrations were expected since nitrate is generally the preferred electron acceptor in the bioremediation process compared to perchlorate and chlorate. As presented in Figures 11a through 11c, nitrate concentrations were significantly reduced not only within the biologically active treatment zone but also in much of the downgradient portion of the study area.

6.2.4 Total Organic Carbon

As explained in Section 2.1, perchlorate can act as an electron acceptor for anaerobic respiration in the presence of a continuing carbon source and after DO and nitrate have been depleted. TOC can sometimes be a useful surrogate parameter to track the carbon substrate injectate in the groundwater and an indicator to determine the appropriate timing for reinjection activities. As a result, TOC was analyzed throughout the treatability study to monitor changes in concentrations after injections compared to baseline pre-injection concentrations. TOC concentrations during the treatability study are summarized in Appendix D, Table D.4 and graphically depicted in Appendix M.

The initial baseline groundwater sampling events performed in March and July 2017 indicated that TOC concentrations were less than 4.0 mg/L throughout the treatability study area. During the treatability study timeframe, TOC concentrations in groundwater samples collected from upgradient monitoring wells remained less than 5.7 mg/L.

During the first weekly groundwater sampling event following the first injection event, TOC concentrations significantly increased in groundwater samples collected from monitoring wells SWFTS-MW14 and SWFTS-MW16 located between the injection well transects with concentrations of 100 and 120 mg/L, respectively. Downgradient monitoring wells such as PC-94, SWFTS-MW01, SWFTS-MW05B, SWFTS-MW09A/B, SWFTS-MW10A, SWFTS-MW21, and SWFTS-MW25 also recorded noteworthy increases in groundwater TOC concentrations in comparison to baseline following the first injection event. These increases in TOC concentrations generally coincided with rapid decreases in perchlorate and chlorate concentrations, indicating the biochemical and microbial connection between these two indicator parameters soon after the first injection event. Furthermore, increases in TOC concentrations were more predominant in groundwater from monitoring wells screened in more permeable sediments near the paleochannel, including SWFTS-MW01, SWFTS-MW09A/B, SWFTS-MW10A, SWFTS-MW14, and SWFTS-MW25. Downgradient monitoring wells in the southeast portion of the study area screened in sediments farther from the paleochannel centerline, including SWFTS-MW05B and SWFTS-MW21, showed more gradual increases in TOC concentration in the 4 weeks following the first injection event.

Approximately 2 months following the first injection event, TOC concentrations returned to near-baseline conditions at all downgradient monitoring wells, with the exception of SWFTS-MW16 (located in between the injection well transects) where TOC concentrations in groundwater remained elevated at 110 mg/L. Three months after the first injection event, TOC concentrations in groundwater at SWFTS-MW16 decreased to 5.9 mg/L and all other downgradient monitoring wells had TOC concentrations in groundwater that measured less than 3.2 mg/L. This decrease in TOC concentration 3 months after the first injection event was associated with an observable rebound in perchlorate concentration, although perchlorate concentrations still remained much below baseline concentrations. The timing of the second injection event was determined based on these factors, as discussed in Sections 5.3.2 and 6.2.1.1.3.

TOC concentrations were also measured in groundwater from injection wells prior to the second injection event and were used in determining the quantity of EVO to be added to the various injection wells. TOC concentrations in groundwater varied considerably among the injection wells, with groundwater TOC concentrations less than 500 mg/L at wells SWFTS-IW01B, SWFTS-IW03, SWFTS-IW09, and SWFTS-IW10 and greater than 5,000 mg/L at wells SWFTS-IW07, SWFTS-IW08, SWFTS-IW17, and SWFTS-IW20. TOC concentrations in groundwater at the remaining injection wells ranged between 500 mg/L and 5,000 mg/L.

Following the second injection event, notable increases in groundwater TOC concentrations were observed at two monitoring wells located between the injection well transects, with concentrations of 670 mg/L and 7.7 mg/L in groundwater samples collected from SWFTS-MW14 and SWFTS-MW16, respectively. As previously explained, the modified injection regime during the second injection event included lower quantities of EVO injected into only select injection wells. Despite the minimal increase in TOC concentrations following the second injection event, groundwater samples from downgradient monitoring wells continued to show reduced perchlorate concentrations compared to their baseline concentrations. The lower perchlorate concentrations are likely due to migration of groundwater that was remediated within the biologically active treatment zone

As explained in Section 5.3.3, the third injection event included an increase in injectate solution quantities compared to those injected during the second injection event, with injection quantities equivalent to approximately 85 percent of the first injection event quantities. The third injection event resulted in substantial decreases in perchlorate, chlorate, and nitrate groundwater concentrations despite the fact that there was little increase in TOC in monitoring wells, with the exception of groundwater TOC concentrations of 180 mg/L at SWFTS-MW14 and 7.9 mg/L at SWFTS-MW16. This result is likely due to injected EVO gradually diffusing laterally and vertically across the injection well transects over the course of three injection events, resulting in a more complete coating of EVO on the soil grains, and thereby creating a more complete reducing zone for biodegradation of the perchlorate-contaminated groundwater flowing past the injection well transects.

In conclusion, although TOC is sometimes a useful indicator to determine the arrival of carbon substrate from injections, it is not always possible to use it as a quantitative indicator parameter for rejuvenation of EVO or to assist in the determination of the quantities of EVO that need to be periodically injected. In particular, for ISB systems that involve transects or barriers via injection wells, TOC measurements at the actual points of injection may not be particularly helpful as they could include biomass and organic particulates which tend to linger around the well screen and around the immediate formation itself, but may not accurately reflect biochemical conditions outside that immediate vicinity.

6.2.5 Collective Results for Primary Parameters

As described in sections 6.2.1 through 6.2.4, the results of the primary parameters of perchlorate, chlorate, nitrate, and TOC demonstrate that a biologically active treatment zone was created and maintained through the injection of carbon donor (in this case EOS Pro®). Perchlorate in groundwater within this treatment zone was reduced to concentrations below 15 μg/L and groundwater samples collected from farther downgradient monitoring wells also had significant concentration reductions of perchlorate. Similar results were observed for chlorate, with groundwater samples from several monitoring wells having chlorate concentrations below the sample detection limit. Nitrate, which is the most likely competing electron acceptor as well as a consumer of organic carbon substrate, also exhibited rapid and sustained reductions in concentrations when compared to baseline. Finally, TOC concentrations increased in groundwater samples from the monitoring wells located between the injection well transects and periodically in select downgradient monitoring wells. However, it is not always possible to use it as a quantitative indicator parameter for rejuvenation of EVO or to assist in the determination of the quantities of EVO that need to be periodically injected.

6.2.6 Additional Chemical and Geochemical Evaluation

This section provides a summary of the additional data collected during the treatability study. This includes DO, ORP, sulfate, and sulfide, and their influence on perchlorate biodegradation at the Site. A discussion of metals, including arsenic, iron, and manganese, has also been included due to the potential for metals mobilization during implementation of ISB systems. Finally, a short summary of the additional parameters, such as pH, alkalinity, TDS, VFAs, etc., is also presented to discuss their significance. Results for all parameters discussed herein are presented in the comprehensive data tables provided in Appendix D, Table D.4.

6.2.6.1 Dissolved Oxygen

DO measurements are often a useful parameter to ascertain geochemical conditions in the groundwater and to confirm that anaerobic conditions have been achieved and sustained during the creation of a biologically reductive groundwater environment, which is essential for perchlorate biodegradation. As a result, DO measurements were collected using field equipment as part of low-flow groundwater sampling during all effectiveness monitoring events.

Baseline readings prior to injections indicated a generally aerobic aquifer with DO readings up to 7.81 mg/L and averaging 1.93 mg/L. In general, DO concentrations in groundwater at upgradient monitoring wells in the eastern portion of the study area (SWFTS-MW12, SWFTS-MW13, and SWFTS-MW17) averaged 4.3 mg/L throughout the study. DO measurements of groundwater at upgradient monitoring wells in the western portion of the study area (PC-88, SWFTS-MW07A/B, SWFTS-MW08A, and SWFTS-MW11) averaged 1.5 mg/L throughout the study.

Following the first injection event, groundwater DO concentrations decreased in groundwater at several of the monitoring wells that exhibited significant reductions in perchlorate, chlorate, and/or nitrate concentrations, which indicated reducing conditions were established quickly following injections. DO concentrations in groundwater samples from several downgradient monitoring wells, such as SWFTS-MW20 and SWFTS-MW21, reduced from greater than 6 mg/L to less than 0.5 mg/L, a change indicative of strongly reducing conditions. Other notable DO concentration decreases to less than 0.5 mg/L were also observed in groundwater at monitoring wells SWFTS-MW01, SWFTS-MW03, SWFTS-MW10A, SWFTS-MW14, SWFTS-MW18, SWFTS-MW22, SWFTS-MW24, and SWFTS-MW25 following the first injection event. Finally, as described in Section 5.4, select injection wells were also sampled approximately 2 months following the first injection event. Field readings for DO ranged from 0.09 to 0.36 mg/L for all five injection wells tested (SWFTS-IW01A/B, SWFTS-IW06A/B, and SWFTS-IW17). These results further confirmed the strongly reducing conditions observed in monitoring wells and indicate that the biologically reduced zone was sustained 2 months following the first injection event.

Prior to the second injection event, DO concentrations in groundwater averaged 2.72 mg/L between the injection transects, indicating aerobic conditions similar to those observed at upgradient monitoring wells. Following the second injection event, field readings for DO indicated sustained aerobic conditions in groundwater at 3 of the 4 monitoring wells located between the injection well transects. The exception was SWFTS-MW16, where groundwater DO concentrations ranged from 0.15 to 0.49 mg/L in the 3 months following the second injection event. Groundwater DO concentrations in downgradient monitoring wells, such as SWFTS-MW05A, SWFTS-MW09A, SWFTS-MW09B, SWFTS-MW10A, and PC-94 fluctuated during this period. There also did not appear to be a correlation between DO and perchlorate concentrations at these well locations. It should also be noted that perchlorate concentrations in groundwater samples collected from these wells remained at the relatively same reduced concentration as they were prior to the second injection. The primary reason for this decreased performance following the second injection event is likely the reduced carbon substrate quantities that were injected during the second injection event, as detailed in Section 5.3.2.

Following the third injection event, reducing conditions were once again observed as evidenced by the low DO readings in groundwater at 3 of the 4 monitoring wells located between the injection well transects, which also coincided with sustained decreases in perchlorate concentrations during this period. However, there were fluctuations in DO concentrations during this period with readings in groundwater in monitoring wells SWFTS-MW02 and SWFTS-MW16 greater than 3.0 mg/L during one of the four sampling events, while perchlorate concentrations continued to remain very low at these locations during this same event. There was a similar lack of correlation between DO and perchlorate concentrations at several of the downgradient wells including SWFTS-MW05A, SWFTS-MW05B, SWFTS-MW10A during the four sampling events following the third injection event.

In summary, DO is a useful indicator during the early stages of ISB when carbon substrate is first injected into the groundwater. As the reductive transect continues to develop and the EVO begins to coat the soil grains along the injection well transects, there is lesser organic carbon that gets transported to downgradient locations. Even though overall perchlorate concentration decreases may be sustained or reduce further, such decreases may not be reflected in the DO concentrations of the groundwater at downgradient locations, because some of the perchlorate decrease may be due to upgradient decreases as groundwater flows through the vicinity of the biologically active treatment zone.

6.2.6.2 Oxidation-Reduction Potential

ORP readings sometimes provide a valuable tool to identify the redox conditions in groundwater and ascertain reducing conditions. At some sites, ORP readings correlate well with DO values and, therefore, provide a means to verify the extent of reduction. However, in aquifers with several electron acceptors and redox pairs, such as iron pairs, nitrogen pairs, perchlorate/chlorate/chloride and sulfur pairs, redox measurements may not always be accurate and inferences from these data should be made cautiously.

During the baseline sampling events in March and July 2017, ORP measurements collected from groundwater in all injection and monitoring wells averaged 100 mV, which is consistent with the aerobic conditions indicated by the DO concentrations within the treatability study area prior to injections. One week after the first injection event, field ORP readings indicated groundwater at upgradient monitoring wells continued to show positive ORP; however, 19 of the 20 monitoring wells located in between and downgradient of the injection well transects observed significant groundwater ORP reductions. Groundwater from twelve monitoring wells indicated strongly negative ORP readings of less than -150 mVs in several sampling events following the first injection event, indicating that the carbon substrate injections quickly established reducing conditions. This information is consistent with other groundwater concentration trends observed after the first injection event, including the rapid decreases in perchlorate, chlorate, and nitrate concentrations and increase in TOC concentrations. In contrast, ORP readings in groundwater at SWFTS-MW02 and SWFTS-MW15, which are located between the injection well transects, showed a more gradual trend towards reducing conditions. This gradual trend is consistent with more gradual reductions in perchlorate concentration at these locations, as discussed in Section 6.2.1.1. Strongly negative field readings for groundwater ORP ranging from -205.4 to -330.0 mV were measured at all five injection wells tested 2 months following the first injection event, which indicated the sustainment of reducing conditions within the injection well transects.

Following the second and third injection events, groundwater at downgradient monitoring wells had fluctuating ORP concentrations during the study, but, in general, ORP decreases (including negative readings) were observed that sometimes coincided with higher TOC concentrations and lower concentrations of perchlorate, chlorate, and nitrate. Monitoring well SWFTS-MW14 had groundwater ORP readings of less than -300 mV in all sampling events following the third injection event, which correlates to perchlorate concentrations in groundwater at this monitoring well consistently being below the federal PRG of 15 μg/L. Monitoring well SWFTS-MW15, which was described previously as slower to respond to injections, recorded its lowest groundwater ORP reading of -230 mV during the October 2018 sampling event. This strongly anaerobic ORP reading corresponded with the lowest groundwater perchlorate concentration observed at this well during the treatability study time frame.

Overall, ORP readings, similar to DO concentrations, provide a general indication of the rapid onset of reducing conditions in groundwater following carbon substrate injections, with monitoring wells that showed the most significant and consistent perchlorate biodegradation also appearing to be consistently reducing throughout the treatability study, as inferred from ORP readings.

6.2.6.3 Sulfate and Sulfide

Sulfate and sulfide are important secondary parameters to monitor during ISB applications to evaluate sulfate as an electron acceptor and potential carbon substrate consumer. Generally, sulfate reduction occurs only under very reducing conditions and after nitrate, chlorate, and perchlorate biodegradation has occurred. Sulfate biodegradation is not desirable for various reasons, primarily that it results in: (i) unnecessary consumption of carbon substrate; (ii) overproduction of sulfate-reducing microorganisms that could overtake perchlorate-reducing microorganisms; (iii) the formation of hydrogen sulfide; and (iv) loss of hydraulic permeability.

Baseline sulfate concentrations in groundwater averaged 2,000 mg/L, with groundwater sulfate concentrations at upgradient monitoring wells ranging from 900 to 2,900 mg/L throughout the treatability study. In general, groundwater at downgradient monitoring wells exhibited relatively stable sulfate concentrations during the treatability study. However, groundwater at some monitoring wells between and immediately downgradient of the injection well transects, including SWFTS-MW10A, SWFTS-MW14, and SWFTS-MW16, showed significant decreases in sulfate. Groundwater sulfate concentrations between the injection well transects at monitoring wells SWFTS-MW14 and SWFTS-MW16 observed reductions of 95 percent and 77 percent, respectively, when comparing baseline concentrations to the lowest concentrations observed during all sampling events. However, groundwater at both SWFTS-MW14 and SWFTS-MW16 showed increasing sulfate concentrations following the third injection event. Similarly, sulfate concentrations in groundwater at SWFTS-MW10A declined following the first injection event, but subsequently recovered to stable, near-baseline conditions following subsequent injection events. These results suggesting the local sulfate reduction observed is not a persistent problem, even with periodic injections of EVO. This finding and deduction is significant in that there appears to be sporadic sulfate reduction that is not predominating in groundwater and is not necessarily a continual process.

Groundwater sampling results for sulfide indicated limited sulfide production as a result of ISB processes. Relatively low, transient detections of sulfide occurred at 11 monitoring wells during the study. The highest detection of sulfide within the treatability study area was observed in groundwater at SWFTS-MW16, where measured sulfide concentrations reached 2 mg/L. However, sulfide was not detected during the final groundwater sampling event in October 2018, which is consistent with the return to baseline sulfate conditions at SWFTS-MW16 following the third injection event.

In conclusion, the limited sulfate reduction and sulfide production observed in this treatability study are consistent with the results of the previous ISB study performed at the City of Henderson facility (Tetra Tech, 2016b) and suggest the potential negative impacts of sulfate biodegradation in this high sulfate environment may be minimized and/or controlled during implementation of perchlorate bioremediation. The employment of the slow-release carbon substrate, EVO, is likely to be one reason for the limited sulfate reduction, because EVO comprises long-chain fatty acids that adsorb to the soil grains and gradually hydrolyze to provide the form of organic carbon (such as triglycerides) that is actually used by microorganisms in their growth and respiration process. This gradual hydrolytic process does not produce strongly reducing conditions and therefore, limits sulfate degradation. Secondly, the groundwater flow rates in this setting are relatively high, a physical phenomenon that may not provide sufficient residence time for sulfate biodegradation to prosper.

6.2.6.4 Metals

Under anaerobic conditions, metals such as arsenic, iron and manganese can be reduced, mobilized and precipitated out into the aquifer, which is a phenomenon that can sometimes increase metals concentrations and/or decrease hydraulic permeability in the aquifer. Accordingly, dissolved metals were analyzed during baseline and periodically during the treatability study to monitor metals mobilization. This section presents an evaluation of arsenic, iron, and manganese groundwater concentrations during the treatability study.

6.2.6.4.1 Arsenic

Arsenic is sometimes released from minerals in the saturated subsurface when reducing conditions are created following the injection of a carbon substrate. Arsenic concentrations often increase as soon as reducing conditions are attained or immediately after injections are performed because this element could have a higher solubility in anaerobic groundwater. Generally, under prolonged reducing conditions, particularly in the presence of sulfate and even minimal sulfide production, arsenic tends to return to a non-soluble state. Therefore, it is important to study the potential release of arsenic and its concentration trends over time.

Baseline dissolved arsenic concentrations ranged from 24 µg/L to 110 µg/L. Dissolved arsenic concentrations in groundwater at upgradient monitoring wells were as high as 130 µg/L during the treatability study. Following injections, arsenic concentrations in groundwater generally remained in line with baseline concentrations with the exception of groundwater concentrations at monitoring well SWFTS-MW14, which showed transient increases to above baseline/upgradient levels of 160 µg/L and 180 µg/L during the Week 4 and Week 23 sampling events. However, arsenic concentrations in groundwater at SWFTS-MW14 reduced shortly thereafter and declined to 13 µg/L by the final sampling event. Under reducing conditions, which prevailed consistently at SWFTS-MW14, the arsenic increase was followed by a rapid decline likely because the geochemical conditions created can also promote the production of sulfide from sulfate (even in very small quantities), which likely resulted in the precipitation of arsenic as arsenic sulfide in the subsurface. This process was observed in groundwater at several monitoring wells near the injection well transects with persistent reducing conditions, such as SWFTS-MW10A and SWFTS-MW16 where dissolved arsenic concentrations reduced by up to 84 percent and 90 percent, respectively, when compared to baseline concentrations. Therefore, arsenic release and mobilization are unlikely to be a secondary issue during the implementation of ISB using EVO as the carbon substrate.

6.2.6.4.2 Iron

Dissolved iron concentrations in groundwater were periodically evaluated during the treatability study due to the potential for iron to undergo reduction and mobilization under anaerobic conditions and precipitate out in the subsurface, potentially decreasing the hydraulic permeability in the aquifer. Baseline concentrations of dissolved iron were generally less than 1.5 mg/L, but groundwater at one monitoring well (SWFTS-MW22) measured 15 mg/L of dissolved iron during the July 2017 baseline sampling event. Groundwater samples were collected from all monitoring wells one month following the first injection event to evaluate metals mobilization. Groundwater concentrations for dissolved iron continued to measure less than 1.5 mg/L in groundwater at all monitoring wells with the exception SWFTS-MW16, where dissolved iron concentrations in groundwater increased slightly from 1.5 to 2.3 mg/L.

During the remaining time period of the treatability study, localized increases in dissolved iron concentrations, when compared to baseline concentrations, were observed in groundwater at several downgradient monitoring wells, namely PC-94, SWFTS-MW05B, SWFTS-MW14, SWFTS-MW16, and SWFTS-MW25. However, the maximum concentration of dissolved iron measured in groundwater at any downgradient monitoring well was only 4.5 mg/L and, in most cases, local increases in dissolved iron concentrations quickly declined to baseline concentrations. The lack of iron mobilization is further supported by field measurements of ferrous iron, which indicated only relatively low, transient detections of up to 2.5 mg/L of ferrous iron in groundwater.

6.2.6.4.3 Manganese

Like iron, manganese can also undergo reduction and mobilization under anaerobic conditions and precipitate out in the subsurface, potentially decreasing the hydraulic permeability in the aquifer. Baseline manganese concentrations in groundwater measured up to 2.3 and 1.7 mg/L for total and dissolved manganese, respectively. Following injections, manganese concentrations in groundwater immediately downgradient of the injection wells were elevated when compared to baseline because of the reducing conditions created by carbon injections. One month after the first injection event, elevated total and dissolved manganese concentrations were observed in groundwater at downgradient monitoring wells at concentrations of up to 11 mg/L (SWFTS-MW05B). Therefore, reducing conditions appeared to initially solubilize resident manganese at some areas within the treatability study area. However, groundwater samples from many of these locations with elevated manganese concentrations showed decreases in concentrations during subsequent sampling events, sometimes even returning to baseline conditions. The maximum groundwater manganese concentrations observed at monitoring well SWFTS-MW05B reduced during the last groundwater sampling event to 2.4 mg/L. Over time, manganese concentrations are expected to continue this downward trend. Furthermore, results from groundwater in the majority of the farther downgradient monitoring wells (with the exception of SWFTS-MW25 in which groundwater manganese concentrations increased from 1.2 mg/L during baseline to a maximum of 7.2 mg/L but have since decreased to 3.5 mg/L) did not show significant manganese concentration increases. Finally, manganese concentrations in groundwater samples collected from SWFTS-MW14 exhibited similar trends as arsenic (described in Section 6.2.4.1). Groundwater samples collected from SWFTS-MW14 initially indicated a slight increase in manganese concentrations, followed by several consistent decreases resulting in the final sampling event during the reporting period indicating concentrations had returned to below baseline concentrations. This indicates that manganese solubilization is contained within the treatability study area and does not appear to be mobilizing downgradient.

6.2.6.5 Other Parameters

A suite of several other parameters were periodically analyzed during the treatability study. A summary of these parameters and their significance is presented below. Results of each parameter are presented in the comprehensive data tables provided in Appendix D, Table D.4.

- Groundwater pH is an environmental factor that can affect microbial activity, with most species of microorganisms generally preferring a pH between 5.5 and 8.5 standard units. Biological reduction due to carbon substrate injection often leads to acid production, which results in the lowering of pH and causes potential stress on native microorganisms. During baseline sampling, groundwater pH ranged from 6.21 to 7.77 standard units. In general, groundwater pH remained within the ideal range. Occasionally groundwater pH measured was higher than 8 standard units during the study. However, these higher measurements were generally consistent with upgradient groundwater pH measurements. The presence of natural gypsum (calcium sulfate) in the aquifer and the formation of calcium carbonate as a by-product of the carbon dioxide produced by microbial respiration likely serves as a pH buffer. The buffering capacity of the aquifer minimizes pH changes during biological activity, thereby making this groundwater a favorable candidate for ISB and long-term carbon substrate injections.
- Alkalinity increases can indicate an increased level of microbial activity and can serve as an indirect indicator of groundwater that is undergoing biodegradation. Increases in alkalinity concentrations generally occur due to microbial respiration and production of carbon dioxide, which in solution could combine with native calcium to form calcium carbonate. Baseline alkalinity values in groundwater range from 110 to 240 mg/L. During the treatability study, groundwater from monitoring wells located between and immediately downgradient of the injection well transects showed considerable increases in alkalinity concentrations of up to 1,300 mg/L. These increases in groundwater alkalinity, compared to background concentrations, indicate that groundwater is undergoing biodegradation. The most persistently high alkalinity concentrations were observed at monitoring wells SWFTS-MW14 and SWFTS-MW16, which are located in between the injection well transects. As previously discussed in Section 6.2.1.1, both of these monitoring wells also observed groundwater perchlorate concentration decreases to below the federal PRG of 15 μg/L.
- TDS concentration in groundwater was analyzed to assess any impact of salts on delayed or slower perchlorate biodegradation. TDS concentrations ranged from 1,900 to 6,600 mg/L throughout the study. Although these are relatively high concentrations, the field treatability study (similar to the bench-scale treatability study) indicated that TDS concentrations at these levels did not hinder microbial activity and perchlorate biodegradation.
- Methanogenic conditions (signified by biological methane production) require highly reducing conditions that are generally not mandated for perchlorate biodegradation. However, methane was periodically evaluated during the treatability study as an additional indicator of the level of reducing conditions that were established following carbon substrate injections. During the treatability study, methane concentrations were detected above baseline concentrations at several locations, with maximum observed increases from less than 0.00025 mg/L to a high of 12 mg/L in groundwater at two monitoring wells located between the injection well transects following carbon substrate injections. Significant increases in methane concentrations compared to baseline concentrations were not observed in other downgradient monitoring wells. Given that the ORP levels were generally greater than - 200 mVs and sulfate reduction was minimal, it is unlikely that methanogenic conditions were created over most of the saturated subsurface during the study. Because of the limited production of methane and geochemical characterization of the reducing conditions, it is likely that the reducing conditions created were not

sufficient for significant methanogenesis to occur resulting in the generation of methane. Finally, any methane that is produced at the depth at which groundwater is being addressed is very likely to be rapidly oxidized to harmless carbon dioxide in the gravelly and sandy alluvium.

- During the treatability study, total nitrogen concentrations in groundwater generally decreased when compared to baseline concentrations at downgradient monitoring wells following carbon substrate injections. Baseline and upgradient total nitrogen concentrations ranged from 0.51 to 17 mg/L. During the study, total nitrogen concentrations in groundwater at downgradient monitoring wells ranged from less than 0.11 mg/L to 12 mg/L. The decrease in total nitrogen is likely the result of denitrification that was actively occurring in the groundwater as described in Section 6.2.3.
- Both dissolved and total phosphorus in groundwater were monitored during the treatability study because a phosphate solution was added to the injectate mixture to serve as a macronutrient for reduced acclimation time for the onset of perchlorate biodegradation. Results indicated that the addition of the phosphate solution resulted in localized increases in total phosphorus concentrations when compared to baseline concentrations. However, total phosphorus concentrations never exceeded the maximum concentration observed during baseline of 3.3 mg/L. This indicates that the augmented phosphorus was likely used as a nutrient, adsorbed to the soil, or combined with cations such as calcium, rather than increasing its concentration in groundwater.
- Hexavalent chromium is not present in groundwater at significant concentrations at the treatability study location. However, the starting low concentrations of 0.45 to 34 µg/L decreased even further in groundwater due the creation of reducing conditions and the resulting conversion to trivalent chromium, leading to its precipitation. One month following the first injection event, hexavalent chromium was not detected above the sample detection limit of 0.25 µg/L at several downgradient wells, despite continued upgradient concentrations of up to 33 µg/L.
- Selenium concentrations exhibited increases during the treatability study at concentrations of up to 510 µg/L in groundwater samples collected from SWFTS-MW14. However, concentrations were reducing towards the end of the reporting period at a concentration of 200 µg/L. Selenium is likely to behave the same as arsenic and manganese, where transient increases in concentrations may occur but will likely to return to baseline or below baseline concentrations within a relatively short time period.
- Volatile fatty acids (VFAs) were periodically analyzed at select downgradient wells to get an assessment of surrogate carbon substrate. These acids are produced continually during hydrolysis of the long-chain fatty acids of EVO and are more readily available substrates for hydrogen production and perchlorate biodegradation. Acetic acid, formic acid, lactic acid, and propionic acid were all detected post-injections during the treatability study; however, groundwater concentrations were generally low. However, acetic acid and propionic acid were detected at elevated concentrations as high as 1,400 mg/L and 100 J+ mg/L, respectively, in groundwater samples collected from monitoring well SWFTS-MW14, which as previously described exhibited substantial reductions in perchlorate and chlorate concentrations in groundwater.

6.2.7 Microbial Evaluation

Sampling was included in the effectiveness monitoring program to examine the microbial response to carbon substrate additions. As part of this microbial evaluation, samples were periodically collected from representative wells and analyzed for a variety of microbial parameters. This section presents a summary of this evaluation. Complete analytical results for the microbial analyses performed during the treatability study can be found in Appendix D, Table D.6. Microbial laboratory data reports are provided in Appendix N.

6.2.7.1 Bio-Trap® Sampling

Bio-Trap® samplers are patented devices available through a specialized microbial firm, Microbial Insights in Knoxville, Tennessee. Structurally, they are cylindrical containers with a diameter small enough to be deployed into a conventional monitoring well for a stipulated period of time (generally 30 to 60 days). The samplers contain a unique sampling matrix called Bio-Sep® beads, which are 2-4 mm in diameter and are an engineered composite of Nomex® and powdered activated carbon. When a Bio-Trap® sampler is deployed in a monitoring well, the Bio-Sep® beads absorb contaminants and nutrients present in the aquifer essentially becoming an in-situ microcosm with a very large surface area (~600 square meters per gram), which is readily colonized by subsurface microorganisms. Once the Bio-Trap® samplers are recovered from a monitoring well (30-60 days after deployment), deoxyribonucleic acid (DNA), ribonucleic acid (RNA), or PLFA can be extracted from the beads for CENSUS® or PLFA assays to evaluate the microbial community. In many ways, Bio-Trap® samplers provide an integrated vision of the microbial community rather than a onetime "snapshot" sampling event. Microorganisms colonize the beads and, therefore, the microbial communities are more likely to represent the active members of the subsurface microbial community.

Bio-Trap® samplers were deployed in a variety of injection and monitoring wells during the following events: July 2017 (baseline), October 2017 (2 months after the first carbon substrate injection event), and September/October 2018 (2 months following the third injection event). The Bio-Traps® were in-place for approximately 30 days and then were retrieved and shipped to Microbial Insights for analyses of PLFA and the perchlorate reductase enzyme.

6.2.7.2 Analysis of Microbial Results

Results of the microbial sampling indicated that the total viable biomass was present at a very healthy range of 10^4 to 10^5 cells/bead in both the injection and monitoring wells prior to the first injection event. During the Bio-Trap® sampling event following the first injection event, the data generally indicated a slight increase in biomass numbers. The highest biomass concentration was detected during the October 2018 sampling event (approximately 4 months following the third injection event) in groundwater from monitoring well SWFTS-MW14 at a concentration of 1.34 x 10^6 cells per bead. Generally, biomass concentrations above 10^5 cells per bead indicate that there a sufficient microbial population in the subsurface.

Although the perchlorate reductase enzyme was detected at concentrations generally less than 250 cells per bead prior to injections, the November 2017 sampling event (approximately 2 months after the first injection event) indicated a concentration in groundwater at SWFTS-MW16 of 1,330 cells per bead. The injection wells themselves did not show the presence of the perchlorate reductase enzyme in groundwater because perchlorate in the immediate vicinity of the injection well is likely to degrade very rapidly. Under these conditions, likely due to perchlorate being virtually absent in the vicinity of the injection wells itself due to the plentiful availability of organic carbon and rapid degradation slightly upgradient of the well itself due to radial distribution of the injection substrate, perchlorate reducing microorganisms as identified by the perchlorate reductase gene are generally present at numbers below Microbial Insight's method detection level. The perchlorate reductase enzyme was also absent in groundwater from downgradient monitoring well SWFTS-MW20, which is likely due to a very gradual decrease in perchlorate concentrations that was observed in this vicinity, as discussed in Section 6.2.1. Secondly, groundwater concentrations in this area, far downgradient from the injection wells themselves, are often reflective of cleaner groundwater, rather than active downgradient perchlorate degradation.

PLFA analysis on community structure indicated that, in general, more than half of the bacterial population belonged to the Proteobacteria structural group based on results from before and after injections in both injection and monitoring wells. Proportions of Proteobacteria are of interest because the Proteobacteria are one of the largest groups of bacteria and represent a wide variety of anaerobic and aerobic microorganisms. Proteobacteria are generally capable of adapting quickly to changes in the environment, such as the addition of a carbon substrate, and grow opportunistically when food is available. Their presence in large proportions is a strong sign of a microbial community that generally adapts very well to the environment and should possess the ability to biodegrade perchlorate in groundwater, which is evident based on the perchlorate concentration reductions observed during the treatability study.

Increases in the percentage of Firmicutes were also observed in groundwater from most of the wells, with increases by an order of magnitude before and after the first injection event. The increased presence of firmicutes generally indicates the growth of bacteria that can ferment the injected EVO and its daughter products to hydrogen for utilization by the microbes belonging to the Proteobacteria group for the reduction of perchlorate. The highest proportions (20 percent of the total bacterial community) of Firmicutes were observed in groundwater from the three injection wells that were sampled and analyzed three months following the third injection event, which indicates continued and sustained fermentation of EVO to hydrogen for perchlorate biodegradation. The lower percentages of SRB/Actinomycetes and Anaerobic Metal Reducers indicate that groundwater redox conditions were not overly reducing and were unlikely to encourage rampant sulfate biodegradation. General (Nsats) were generally around 30 percent or less, indicating that a diverse microbial community exists in groundwater. For the wells in which analyses was performed before and after the first injection event, Bio-traps® from two of the four locations (one injection well and one monitoring well) showed slight reductions, while Bio-traps® from the other two wells (also one injection well and one monitoring well) showed slight increases. However, these changes (decreases and increases) were not significant and were still below 30 percent in all wells, both before and after injections.

Finally, results for the slowed growth ratios decreased in several of the injection and monitoring wells, indicating that native microorganisms were responding positively to the addition of carbon substrate. In particular, for wells which were equipped with Bio-Traps® both before and after the first injection event, three of the four locations indicated groundwater decreases in slowed growth ratios and were all below 1.0. The slowed growth ratio for the Bio-Trap® collected from one of the monitoring wells located in between the two injection well transects decreased by almost 100 percent. The slowed growth ratio observed in Bio-Traps® from the three injection wells that were sampled and analyzed three months following the third injection event were all below 0.5 as a result of the presence of organic carbon that was injected in this vicinity. The Bio-Traps® from the two monitoring wells which continued to have relatively higher slowed growth ratios in groundwater were SWFTS-MW15 and PC-94. As outlined in Section 6.2, groundwater samples from monitoring well SWFTS-MW15 (one of the four monitoring wells located in between the two injection well transects) indicated a slow response to carbon substrate injections. Additionally, groundwater in the vicinity of monitoring well PC-94, which is much farther downgradient of the injection well transects, was unlikely to come in direct contact with organic carbon from injections (even though groundwater showed significant reduction in perchlorate concentrations likely from the migration of remediated groundwater flowing from the biologically active treatment zone). However, Bio-Traps® from both of these monitoring wells did show very low decreased permeability ratios in groundwater indicating that there was no apparent toxicity to microorganisms.

6.3 HYDROGEOLOGICAL EVALUATION

As part of the hydrogeological evaluation, both long-term water level monitoring and periodic aquifer slug testing was performed in select wells during the treatability study. This section summarizes the results from these activities. The comprehensive results from the slug testing and long-term water level monitoring are provided in Appendices F and O, respectively.

6.3.1 Slug Tests

The objective of the slug testing was to estimate aquifer hydraulic conductivity in the study area before and after injection of the substrate. Because the injection of substrate has the potential to decrease hydraulic conductivity, particularly in the vicinity of injection wells, hydraulic conductivity estimates in the same wells before and after injection were compared.

The first round of slug testing was performed in April 13 – 18, 2017, in wells SWFTS-MW01 through SWFTS-MW10A/C and on July 18 – 25, 2017, in the remaining monitoring wells SWFTS-MW11 through SWFTS-MW25 as well as all injection wells. During the post-injection rounds of slug testing, only select monitoring and injection wells were tested. Post-injection slug tests were conducted during the treatability study on the following dates:

- December 18 – 22, 2017
- January 15 – 17, 2018
- May 7 – 11, 2018

The tests consisted of monitoring water level displacements caused by the insertion or removal of a solid slug from a well. Water level displacement was measured using a pressure transducer; the data were then downloaded from the transducer and analyzed using commercially-available AQTESOLV software (HydroSOLVE, 2007). The baseline estimated hydraulic conductivities were generally consistent with the logged lithology of the screened interval of the wells.

Both injection and monitoring wells were retested after multiple rounds of injection had occurred. The monitoring wells subjected to re-testing were chosen to be between the injection well lines, immediately downgradient of the second injection well line, and farther (more than 200 feet) downgradient of the injection well lines. The following wells were retested:

- Injection wells: SWFTS-IW01A, SWFTS-IW05, SWFTS-IW06A, SWFTS-IW08, SWFTS-IW09, SWFTS-IW11, SWFTS-IW13A, SWFTS-IW13B, SWFTS-IW15, SWFTS-IW17, SWFTS-IW19, SWFTS-IW18, and SWFTS-IW20
- Between the injection wells: SWFTS-MW14 and SWFTS-MW16
- Immediately downgradient: SWFTS-MW-05B, SWFTS-MW10A, SWFTS-MW21
- Farther downgradient: SWFTS-MW03, SWFTS-MW09A, SWFTS-MW09B, SWFTS-MW25

The intent of testing the monitoring wells was to determine whether decreases in hydraulic conductivity persisted outside the immediate vicinity of the injection wells, and if so, how far the changes extended. Of the monitoring wells retested after multiple rounds of injections had occurred, only the two wells located between the injection well lines experienced decreases in hydraulic conductivity. Those two wells experienced essentially no change in December 2017 but a noticeable change (75 – 85 percent decrease) by May 2018. Due to uncertainties inherent to slug testing techniques, this decrease could still conceivably fall within the range of error of the test. The downgradient monitoring wells experienced slight increases and decreases between individual tests; these changes were within the range of expected differences between tests.

In contrast to the monitoring wells, the injection wells experienced sharp and universal decreases in hydraulic conductivity. These decreases were generally two to three orders of magnitude. However, after these apparent decreases in hydraulic conductivity, the subsurface was still able to accept three injection events during the study time frame. Evaluation of water collected from the injection wells indicated that the apparent decrease in hydraulic conductivity values at injection wells was likely due to biomass and/or EVO breakdown products present, likely on the injection well screens, rather than to an actual decrease in hydraulic conductivity of the formation. There were potential decreases in hydraulic conductivity noted in the monitoring wells between the injection transects, so some potential decrease in formation hydraulic conductivity would be expected near the injection wells.

A decrease in permeability with ISB is generally attributed to causes that include the presence of biomass, EVO breakdown products, and inorganic calcium compounds. Biomass could play a role in reducing permeability, although over time the biomass should self-respire endogenously and be less of a problematic factor. Because of the high groundwater flow velocities in the area, the predominantly gravelly and sandy nature of the formation, and the fact that the subsurface was able to accept injection water over three injection events, the phenomenon of reduced permeability is not likely to have an impact on the ability to continue injections of EVO into the groundwater for perchlorate biodegradation. However, if required, relatively simple and periodic well redevelopment steps can be undertaken as needed during remedial implementation and operation to address a decrease in injection well permeability, which will be evaluated as part of the study continuation further described in Section 8.0.

6.3.2 Long-Term Water Level Monitoring

Transducers were installed in 10 monitoring wells within the treatability study area to monitor water levels during the treatability study. In addition to the transducers, one barometric transducer was also installed within the study area. All instruments were installed prior to the first injection event in August 2017 so that hydraulic responses to the injections could be measured. Analysis of the transducer data showed that the maximum measured water level increase in response to injections was approximately one-foot, and as expected, the maximum responses were observed in the instrumented monitoring wells located between and immediately downgradient of the two injection well transects. Pressure responses decreased with distance away from the injection well lines such that the maximum water level increase observed about 200 ft downgradient was approximately 1 inch. Other than the response to injections, the primary influences on groundwater levels during the course of monitoring appeared to be regionally higher water levels in the winter to early spring and small increases in response to a few precipitation events.

Transducers were also installed in two wells (MW-K5 and PC-98R) in the vicinity of Pond 13 located near the COH WRF. One barometric transducer was installed in this location, as well. During the course of monitoring, sharp water level increases of 6-14 feet indicated that sizeable releases of treated effluent to COH Pond 13 occurred during October and November 2017 and in February 2018. These releases are part of the COH normal operations and are beyond the control of the Trust. However, monitoring of such releases is important because the treated effluent significantly dilutes perchlorate concentrations that reach the Seep Well Field and treatability study area via the paleochannel and via adjacent groundwater outside the paleochannel (as described in Section 6.2.1.1.4).

6.4 EFFECTIVENESS MONITORING SUMMARY

In summary, the effectiveness monitoring program evaluated numerous parameters to collect data to thoroughly evaluate the effectiveness of ISB during the treatability study. This program included not only primary contaminants of perchlorate and chlorate but also, as discussed herein, several other parameters to assess the overall aquifer response to the carbon substrate injections. In general, this monitoring program was similar to the monitoring program that was implemented during the first treatability study. However, during the effectiveness monitoring period for the SWF Area Bioremediation Treatability Study, and as detailed in the approved Work Plan, the monitoring program was periodically reevaluated and adjusted based on the results of the previous sampling events. These adjustments, which are summarized in Section 5.4, included a reduction in the frequency of dissolved metals, total nitrogen, phosphorus, methane, and VFAs and elimination of chloride and TDS following the second injection event. Although many of the upcoming treatability and pilot studies will include the same and/or additional effectiveness monitoring parameters to allow flexibility during sampling events, the monitoring programs will continue to be reevaluated during the studies to determine the optimal parameters to meet the study objectives.

7.0 SUMMARY OF KEY FINDINGS

This section presents the overall findings of the treatability study and provides cost considerations for future implementation of this technology at the NERT site.

7.1 TREATABILITY STUDY SUMMARY

Expanding on the results presented in Section 6.0, this section presents a summary of the overall treatability study results and draws conclusions in regard to the success of the SWF Area Bioremediation Treatability Study in treating perchlorate-contaminated groundwater. As described in Section 1.1, the objectives of the treatability study were as follows:

- Evaluation of the feasibility and effectiveness of implementing ISB in the alluvium to reduce the groundwater perchlorate mass flux in the vicinity of monitoring well PC-94, located east of the SWF;
- Demonstrate the development and sustainment of a biologically active treatment zone by periodically injecting carbon donor in a different geologic environment than previously tested;
- Estimation of the zone of influence for substrate and biodegradation achievable during the treatability study;
- Perform bench-scale studies to affirm the biodegradability of perchlorate in soil and groundwater specific to this area, provide an estimate of the lag time and timeframe for perchlorate biodegradation, estimate the perchlorate degradation timeframe, examine the potential to utilize GWETS water for the carbon substrate distribution, and evaluate the adsorption potential of EVO for the treatability study area soil;
- Estimation or extrapolation of the longevity of the carbon substrate and frequency of carbon substrate replenishment required to reduce perchlorate contamination immediately downgradient of the treatability study injection transect;
- Examination of the approach and feasibility for full-scale transect treatment including required equipment, injection, and monitoring well layout; substrate addition and replenishment; and analytical sampling evaluation criteria.

Performance criteria tables were generated to determine the success of this treatability study. These tables include a summary of the performance criteria, metrics, confirmation methods, and study demonstration and are presented in Appendix P.

Overall, groundwater in this area is amenable to biodegradation of perchlorate, chlorate, and nitrate. As demonstrated in this study, the periodic injections of EVO and amendments provided a sustained reducing environment in the subsurface and created a biologically active treatment zone, which is necessary for effective and continual perchlorate and chlorate biodegradation in the groundwater. The results, findings, and lessons learned from the SWF Area Bioremediation Treatability Study have been used to inform the Galleria Drive Bioremediation Treatability Study and the Las Vegas Wash Bioremediation Pilot Study (work plan addendum under Trust review as of the date of this report). They are also currently being used to optimize the continuing field effort at this location consistent with Mod. 6 (further discussed in Section 8.0) and inform the Unit 4 Source Area In-Situ Bioremediation Treatability Study.

The main findings and conclusions below draw upon the various tasks performed as part of the SWF Area Bioremediation Treatability Study.

- Nitrate, chlorate, and perchlorate degradation was initiated very rapidly following carbon substrate injections through the creation of a biologically active zone, which continued to sustain perchlorate degradation throughout the 14-month treatability study time frame. Denitrification (nitrate biodegradation) occurred very rapidly and preferentially compared to perchlorate and chlorate biodegradation in both the field and laboratory studies. Perchlorate and chlorate biodegradation generally followed denitrification and, once initiated, the two reductive processes were observed to occur concurrently at locations that recorded the best geochemical response to the carbon substrate injections.

- The study demonstrated the ability of ISB using a slow-release carbon substrate to achieve the groundwater perchlorate PRG of 15 µg/L in groundwater within the alluvium. Groundwater concentrations below the perchlorate PRG were attained and sustained at several groundwater monitoring well locations.
- Based on the results of the field treatability study, the maximum first-order perchlorate biodegradation rate constants in groundwater were determined to range from -0.09 day^{-1} to -0.25 day^{-1}. At these rates, perchlorate concentrations decreased very rapidly in groundwater as observed in the field treatability study immediately following the first injection event.
- This study indicated that the range of flow rates present in the SWF area (from 0.07 to 119 ft/day) and associated residence time due to these flow rates were not impediments to perchlorate biodegradation.
- The microbial activity in groundwater within the treatability study area was not hindered by the elevated TDS concentrations (up to 6,600 mg/L) as evidenced by the rapid onset of reducing conditions and perchlorate biodegradation following injections. Therefore, TDS concentrations at these levels do not appear to impact the development of a microbial consortium with the ability to biodegrade perchlorate, nor do they appear to have an impact on a lag time for biodegradation.
- Based on the studies performed for the SWF Area Bioremediation Treatability Study and previous *Groundwater Bioremediation Treatability Study* (Tetra Tech, 2016b), performing periodic injections into the injection wells over time was shown to gradually increase the overall biodegradation in groundwater following subsequent events. One reason for this improved degradation observation was the use of the EVO, which because of its chemical nature, tends to gradually coat the soil grains along the transect width, thereby attaching to more and more of the subsurface and creating a more uniform barrier over time. The average perchlorate biodegradation in groundwater for the monitoring wells located in between the injection well transects was shown to increase from 55 percent to 83 percent following the first and third injections, respectively.
- The treatability study indicated that approximately 2,748 pounds of perchlorate were destroyed during the 14-month treatability study time frame. Following the initial large mass reduction after the first injection event, the sustained average perchlorate mass flux treated was approximately 3 lbs/day.
- Perchlorate and other electron acceptors, such as chlorate and nitrate, can be feasibly remediated utilizing relatively long injection well transects comprised of vertical injection wells. Although the approach of two staggered injection well transects was shown to be effective at remediating perchlorate-contaminated groundwater during this treatability study, it may not be a significant advantage compared to a single injection well transect with closer injection well spacings. This is due to the indiscriminate heterogeneity with considerable variations in lithology both laterally and vertically over very short distances (i.e., the alluvium consists of interbedded layers of sand, silt, and gravel with large variations in permeability between these layers that may be isolated or connected).
- An evaluation of injection rates, injection pressures, and effectiveness monitoring results from downgradient monitoring wells indicate that paired injection wells do not appear to have significant advantages over single injection wells with longer screen lengths. An evaluation of the ratio of injection pressure to injection rate reveals that, in general, slightly higher ratios were observed at injection wells in the paired configuration than in the single injection well configuration. The higher ratios observed at the paired injection wells indicate higher injection pressures were required to achieve similar flow rates as the single injection wells. In addition, groundwater samples collected from monitoring well SWFTS-MW02, which is located downgradient of injection well pair SWFTS-IW01A/B, showed strong reducing conditions and substantial perchlorate concentration decreases but was somewhat slower to respond than many of the other effectiveness monitoring wells. Injection well locations SWFTS-IW01 and SWFTS-IW02 were selected to be paired due to the upper portion of the saturated alluvium consisting primarily of silty fine-

grained sand with layers of silt and clay, while the lower portion of the saturated alluvium consisted of coarser, well graded sand with gravel. Therefore, even with paired injection wells installed to enhance subsurface distribution, monitoring well SWFTS-MW02 was slower to respond, even though it eventually performed much better following multiple injection events. Similar results were observed with paired injection well SWFTS-IW06A/B and downgradient monitoring well SWFTS-MW15 as well as paired injection well SWFTS-IW13A/B and downgradient monitoring well SWFTS-MW20. It is likely that the slower responses of perchlorate reduction in groundwater at these locations are likely due to the heterogeneity of the subsurface. However, the paired injection well configuration, which was installed with the intent of improving injections in these areas, did not provide any distinct advantage over the single injection well configuration. Therefore, based on the data collected to-date, it appears that a paired injection well configuration in this geologic setting likely does not provide any additional benefits over single injection well construction. Paired injection wells could still be considered in areas with large saturated thicknesses (greater than 30 feet) or where there are distinct separate lithological layers or zones across large targeted treatment intervals. In particular, paired injection wells should be considered when there is a clear hydrogeologic separation of uniform lower permeability zones from high permeability zones throughout a subsurface vertical zone. At the SWF study area, there is considerable heterogeneity within very short distances (a few feet) both laterally and vertically, which does not provide a distinct advantage for paired injection wells because conditions can change very rapidly within a few feet downgradient or cross-gradient from an injection well pair.

- TOC concentrations measured in both injection and monitoring wells were not found to be a key indicator parameter to signify the dosage or timing for subsequent carbon substrate injections.
- DO concentrations and ORP readings provide a good early indication of the rapid onset of reducing conditions in groundwater when treatment first begins. In general, monitoring wells that showed the most significant and consistent perchlorate biodegradation also appeared to be consistently reducing, as inferred from DO and ORP readings.
- Limited sulfate reduction was observed in groundwater during the treatability study. The employment of the slow release carbon substrate, EVO, is likely the main reason for limited sulfate reduction, because EVO comprises long-chain fatty acids that very gradually hydrolyze and limit the amount of usable carbon for native microorganisms to use for biological deoxygenation, denitrification, and perchlorate/chlorate biodegradation. Secondly, the groundwater flow rates in this setting are relatively high and may not provide sufficient residence time for sulfate biodegradation to occur. Limited sulfide production was also observed, indicating that microbial-based sulfate reduction was largely contained.
- Secondary groundwater geochemical impacts including arsenic, iron, manganese, methane, and phosphorus were either limited or transient and did not appear to create a significant downgradient footprint of concern in groundwater.
- The ability of the formation to accept substrate injections following three injection events indicates ISB is a feasible long-term option for groundwater in the alluvium at this site. Over the course of the three injection events, carbon substrate was injected in relatively the same time frames at flows greater than 5 gpm and pressures that were less than the maximum permissible. Injection pressures gradually increased from an approximate average of 5 psi to 14 psi over the three injection events that were performed. Slightly higher injection pressures during subsequent injections is common and expected with ISB as a normal response to the engineered biomass growth on the subsurface media. However, no injection well maintenance has been required to-date, indicating that the subsurface continues to be amenable to periodic injections of EVO. As noted in the Section 8.0, future operations are planned to further evaluate changes in injection pressures and ascertain the optimal measures for long-term maintenance during ISB operations.

Based on the data collected and summarized in this report, the original objectives of the treatability study have been met. As previously explained, performance criteria tables presented in Appendix P identify the performance criteria established for this project and reports how well the treatability study performed against each of these criteria. As described in Section 8.0, additional objectives will be evaluated as part of the continuation of the treatability study.

7.2 PRELIMINARY COST-BENEFIT ANALYSIS

The SWF Area Bioremediation Treatability Study provides valuable information for developing preliminary cost considerations for potential full-scale implementation of ISB in the NERT RI Study Area. As requested by NDEP, these preliminary indications are presented in the following subsections, but are subject to revision based on additional observations during the continuation of the SWF Area Bioremediation Treatability Study and future treatability and pilot studies performed. During the Feasibility Study (FS), NERT will evaluate the applicability of a variety of remedial technologies in order to achieve the remedial action objectives (RAOs) established for the NERT RI Study Area.

7.2.1 Treatability Study Cost Summary

Table 4 provides a high-level cost summary for implementing this treatability study, which was completed within the approved budget. Costs for treatability studies can vary tremendously and are directly related to the type of study, requirement for pre-investigative and laboratory testing, extent of effectiveness monitoring and data collection, and the duration of the study. Data obtained and costs incurred during the treatability study will be used to inform the development of alternative costs in the FS; however, due to the nature of treatability studies, treatability study costs are inherently higher than likely larger scale operations, and cannot be easily extrapolated to represent actual larger-scale system design, installation, and operational costs. For example, treatment footprints, geologic setting, durations, and associated operational costs will vary significantly depending on the specific risk-based remedial action goals established during the FS and other alternative implementation and operational variables that have not yet been defined. Treatability studies also inherently higher in labor costs due to more detailed data evaluation and understanding of the results/science of the study; therefore, labor distribution for full-scale implementation and long-term operation and maintenance would vary significantly. Finally, it should be noted that a combination of different remedial technologies may be implemented together in full-scale treatment to achieve the RAOs, which would have a direct impact on full-scale effectiveness and costs.

Table 4 SWF Area Bioremediation Treatability Study Cost Summary

Task	Cost		
	Labor	ODCs	Subcontractors
Project Planning, Coordination, and Work Plan Preparation	$110,000	$0	$0
Pre-Design Field Activities	$380,000	$30,000	$190,000
Laboratory Bench-Scale Studies	$10,000	$0	$115,000
Design and Permitting	$40,000	$0	$0
Installation of Injection and Monitoring Wells; Baseline Characterization	$120,000	$60,000	$180,000
Carbon Substrate Injections (3 events)	$320,000	$570,000	$410,000
Effectiveness Monitoring (15 sampling events; 2 slug testing events)	$875,000	$115,000	$150,000

Task	Cost		
	Labor	ODCs	Subcontractors
Data Analysis and Reporting	$300,000	$0	$0
Subtotal	**$2,155,000**	**$775,000**	**$1,045,000**
Total			**$3,975,000**

Notes:
ODCs = Other direct costs such as materials, equipment, and travel.

7.2.2 Preliminary Cost Considerations for In-Situ Bioremediation

Detailed costs will vary significantly depending on the RAOs for portion of the NERT RI Study Area being addressed and other variables of the final remedy that have not yet been defined. These include, but are not limited to, the following:

- Extent of areas selected for ISB treatment;
- Depths and lithology targeted in each area selected for ISB treatment;
- Presence of buildings or other surface structures in the selected areas which make the installation of and access to injection wells more difficult; RAOs selected (i.e., source reduction or downgradient barrier treatment to achieve a specified cleanup goal such as the federal PRG of 15 μg/L);
- Potential combination of ISB with other technologies;
- Supply and demand to various technology components, such as EVO; and
- Potential cost efficiencies/discounts gained through Trust negotiations with consultants and/or vendors.

It is not traditionally the objective of a treatability study to estimate the cost of a remedial technology in a full-scale design. This is particularly applicable to NERT because the Remedial Investigation is not complete, and the FS is in the early stages of development (projected to be completed in mid-year 2021 for OU-1/2 and late 2021 for OU-3). During the FS, NERT will evaluate the applicability of a variety of remedial technologies in order to achieve the RAOs established for the NERT RI Study Area.

With respect to application of ISB, there are several important considerations with regards to the implementation and costs. The most important considerations relate to the final RAOs and the implementation configuration, areal extent and depths. For example, a single injection well transect might have an indefinite period of operation, because its duration would be controlled by the rate at which groundwater contaminants would migrate through the ISB treatment zone. On the other hand, if injection well transects were installed at varying distances, such as every 100 feet across the plume, the duration of operation might be reduced. Additionally, the lithology and targeted saturated thickness will also greatly influence the costs. For example, different lithologies will require different injection well spacings to ensure adequate carbon substrate distribution and a larger saturated thickness would likely require nested injection wells and greater quantities of carbon substrate. Other important cost considerations include the frequency of the injection events and long-term operation and maintenance of the injection well system (i.e., periodic injection well maintenance).

Although the execution of Mod. 6 will further evaluate the long-term operation and maintenance components of ISB to provide a greater level of costing accuracy in the FS (i.e., frequency of injection events and injection well maintenance; further discussed in Section 8.0), a preliminary evaluation of remedial costs and cost considerations for full-scale implementation of ISB is provided below.

Using data collected from the SWF Area Bioremediation Treatability Study, it is estimated that capital costs to install an ISB injection system could range from approximately $800,000 to $1,300,000 per 1,000 linear feet of injection well transect and approximately $700,000 to $1,000,000 for annual operating costs but could largely vary for a great number of reasons. Costs included herein are based on current rates for subcontractors and other direct costs (ODCs) (such as drillers, EVO, etc.) as of the date of this report. This conceptual-level cost estimate range is based on the following assumptions and basis of estimate:

- Capital costs include the installation of the injection and monitoring well network, baseline groundwater sampling, and completion of the first injection event to create the biologically active zone.
    - The injection well transect would be approximately 1,000 linear feet and approximately 40 feet deep, treating a saturated thickness of approximately 20 feet of alluvium with similar geology to that which is present within the SWF treatability study area. Based on this environmental setting, every 1,000 linear feet of transect would include 28 injection wells installed to a depth of approximately 45 feet bgs, located within a single injection well transect, with injection wells spaced approximately 35 feet apart. As explained above, ISB costs will vary greatly depending on lithology type (i.e., alluvium and/or UMCf) and targeted saturated thickness.
    - This scenario corresponds to treatment in transect formations in non-source areas, where perchlorate concentrations are generally less than 50,000 μg/L. The area of application would need to be further evaluated as part of the FS after review of the Remedial Investigation results. Other scenarios, such as source area application, may result in different approaches, including application of a grid-based injection well location design, injection of different amendments/quantities, and/or different injection approaches (such as targeted and short-term recirculation for better substrate distribution in key areas). To this extent, the actual cost of source area treatment may be more when compared to low concentration groundwater in the downgradient portions of the site; however, the cost of ISB per pound of contaminant treated may be less in higher concentration source areas.
    - The cost for the first injection event includes 24,000 gallons of EVO, which is a similar application rate to that which was implemented for the SWF Area Bioremediation Treatability Study. As previously explained, different levels of perchlorate contamination and/or lithology will greatly impact the quantities of carbon substrate and amendments required during injections.
    - It is assumed that no surface obstructions and/or utilities will have to be removed to access treatment areas.
- Annual operating costs include periodic injection events and quarterly groundwater monitoring.
    - The annual injection frequency is estimated to be once every six months as results to-date have determined that the injection frequency slowly reduces over time. This observation will be confirmed through continuation of the SWF Area Bioremediation Treatability Study (further discussed in Section 8.0). However, it should be noted that the injection frequency will vary depending on location based on groundwater flow rates in the vicinity of treatment. For example, paleochannel areas, which typically have faster groundwater flow rates, may require a more frequent addition of carbon substrate to maintain the reducing conditions required for perchlorate biodegradation.
    - The cost for each periodic injection event includes 24,000 gallons of EVO, which is a similar application rate to what was implemented for the SWF Area Bioremediation Treatability Study. As previously indicated, different levels of perchlorate contamination and/or lithology will greatly impact the quantities of carbon substrate and amendments required during injections. Additionally, costs may fluctuate over each injection event based on the effectiveness monitoring results observed and//or final frequency of injection events.

- No costs have been included for procurement and transportation of potable water for chase water as groundwater would be extracted and used as the water source during injection events.
- Annual monitoring costs include quarterly groundwater sampling of 10 monitoring wells for perchlorate, chlorate, nitrate, TOC, and sulfate. Additional monitoring may be required based on regulatory requirements.
- Periodic injection well maintenance will likely be required to extend the life of the injection wells, which will be further evaluated as described in Section 8.0. Costs have not been included for these potential well maintenance and/or replacements.

8.0 PATH FORWARD

As described in the NDEP-approved *Treatability/Pilot Study Modification No.6 – Seep Well Field Area Bioremediation Treatability Study* (Tetra Tech, 2018) (Mod. 6), continued substrate injections will be performed to develop a more thorough understanding of the key operation and maintenance components as they relate to long-term applications of ISB for use in the implementability evaluations in the FS. As summarized in Mod. 6, the objectives for continuation of the SWF Area Bioremediation Treatability Study are to evaluate the following:

- ***Injection Frequencies and Substrate Quantities*** – Injection protocol requirements are an important design consideration for the creation and maintenance of adequate anaerobic conditions for sustained perchlorate bioremediation. Generally, injection frequency and carbon substrate requirements for ISB systems can vary over the operational timeframe, particularly with passive systems that involve the periodic injection of slow-release carbon substrates, such as EVO, which tend to adsorb and persist in the saturated subsurface over time. Therefore, the injection frequency and required carbon substrate quantities are critical long-term operation and maintenance components that determine both remedy effectiveness and associated cost to maintain the remedial system. As part of this treatability study continuation, the injection frequencies and associated quantities of carbon substrate, nutrients, and distribution water will be evaluated over time to provide optimal dosing that sustains the reducing conditions for ISB of perchlorate and chlorate in groundwater.
- ***Injection Well Network Operation and Maintenance*** **–** Because injection wells are subject to periodic injection of EVO, nutrients, and distribution water, it is important for sustaining perchlorate biodegradation that the injection wells maintain the long-term ability to accept the carbon substrate. As injections occur, injection well screens and surrounding filter packs could accumulate biomass, inorganic precipitates, and EVO breakdown compounds. This phenomenon can result in changes to the injectability (i.e., increases in injection pressures required for subsurface distribution) and may require maintenance measures to promote injection well longevity and ensure successful long-term operation of ISB. Although no injection well maintenance has been required to-date, it is still important to develop a more in-depth understanding of the long-term operation and maintenance requirements of injection well networks associated with ISB systems at the NERT site. This beneficial information can be obtained by performing a variety of well maintenance techniques on injection wells within the SWF treatability study area and then monitoring the resulting effects on improved injectability.

In addition to the objectives outlined in Mod 6 and summarized above, it is also recommended that additional evaluation of residual EVO be performed. As previously explained in this report, periodic injections of EVO and distribution water into injection wells are expected to result in a more complete coating of the soil grains, as evidenced by the groundwater data and deductions following the third injection event. In particular, the coating of the oil to the soil grains is likely to have gradually occurred in the immediate vicinity of the injection well transects, between the injection wells. In order to evaluate and better understand this phenomenon of EVO movement and influence in the aquifer, it is recommended that in addition to traditional groundwater sampling and analyses, soil borings be drilled and samples analyzed for parameters such as TOC, VFAs, and microbial assays in order to evaluate movement and influence of the injected EVO surrounding the injection well network, including upgradient locations for appropriate background comparisons. A new treatability study modification will be prepared detailing the proposed additional sampling activities and submitted under separate cover.

As part of this continuation, injection events are anticipated to occur once every 5 to 6 months, but the exact timing and frequency will be determined based on effectiveness monitoring results. The first injection event under this modification (fourth injection event to date) was performed from January 23 – February 10, 2019. Additional injections will continue through remedial design (anticipated to be Q1 2023). Following injections, effectiveness monitoring will generally consist of groundwater sampling once every 6 weeks for a reduced set of analytes as described in Mod. 6. Effectiveness monitoring will also continue for the duration of the treatability study through remedial design. Well maintenance activities will be performed, as required, on an as-needed basis. However, downhole video logging will be completed on any wells where slug testing indicated a reduction in hydraulic conductivity during the treatability study in order to assess the current condition of the well screen and to assess the potential fouling of the well screens. This activity will be completed before the fifth injection event is implemented and will be outlined in the forthcoming treatability study modification.

Quarterly progress updates will be submitted to NDEP throughout the duration of Mod. 6 activities. More detailed annual results reports will be submitted to provide the following:

- Summary of field activities;
- Analytical results summary of groundwater samples collected during the reporting year;
- Evaluation of the continued effectiveness of ISB;
- Assessment of the on-going injection protocol; and
- Evaluation of the injection well maintenance activities, their effectiveness, and recommendations for periodic maintenance (if required/performed within the reporting year) for long-term remedial ISB operations.

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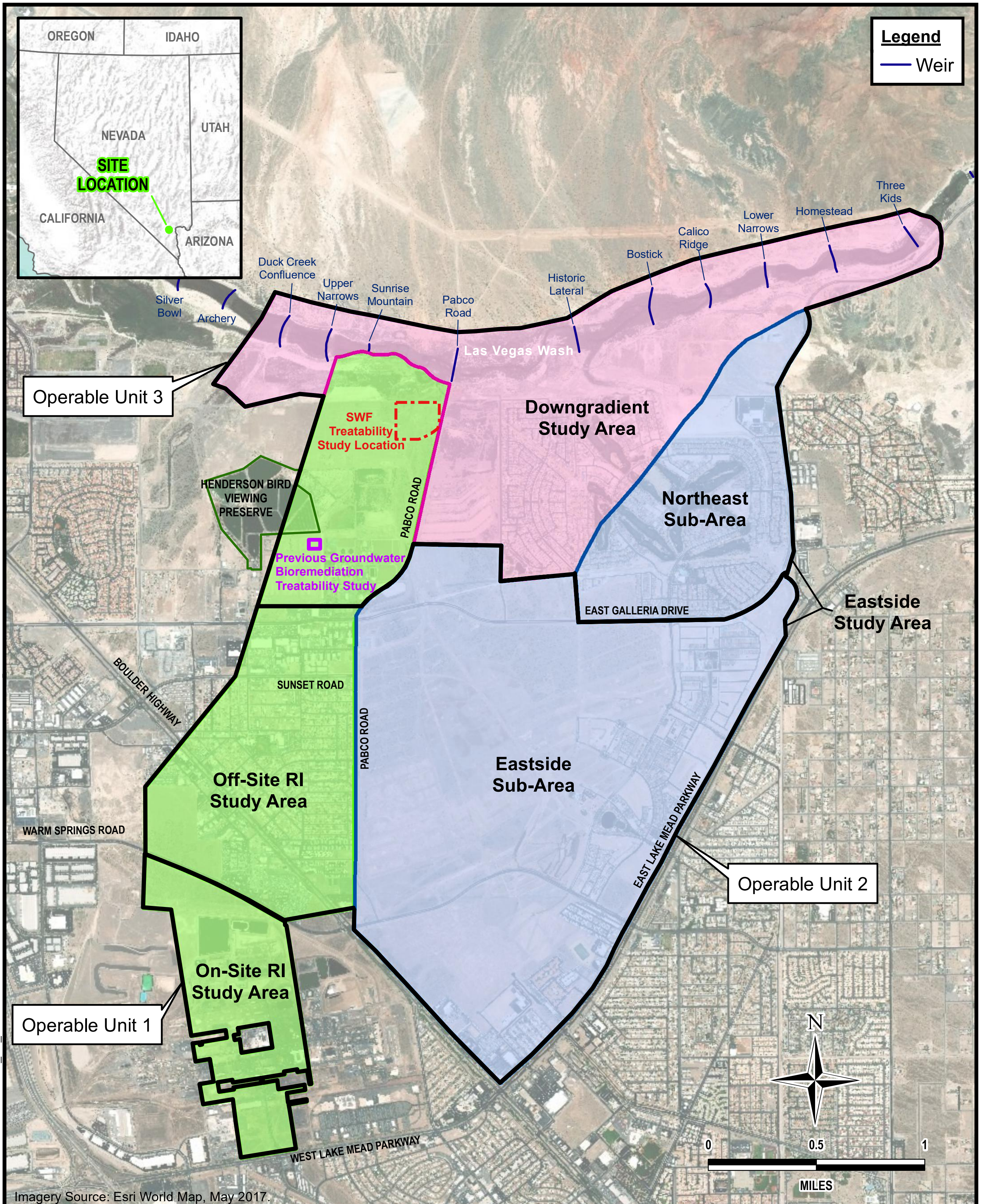
Figures



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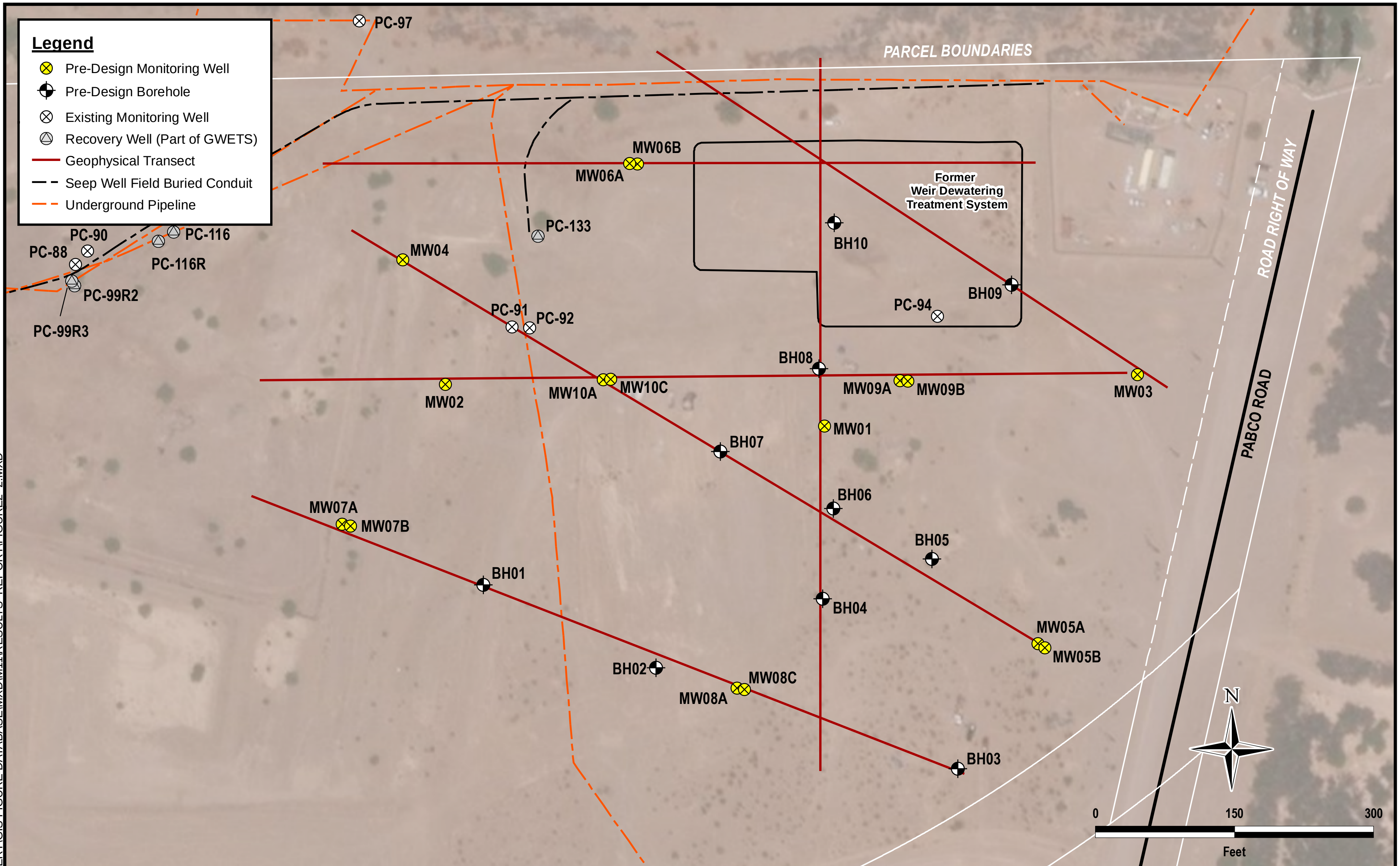
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

TREATABILITY STUDY LOCATION

PROJECT NO.:	117-7502018
DATE:	MAY 03, 2019
DESIGNED BY:	SRA

Figure No.
1



Notes:
1. The prefix 'SWFTS-' not shown for boreholes and wells labeled BH or MW. (MW03 = SWFTS-MW03).
2. Field test area located within parcel 161-31-101-002.
3. Imagery Source: Esri World Map, May 2017.

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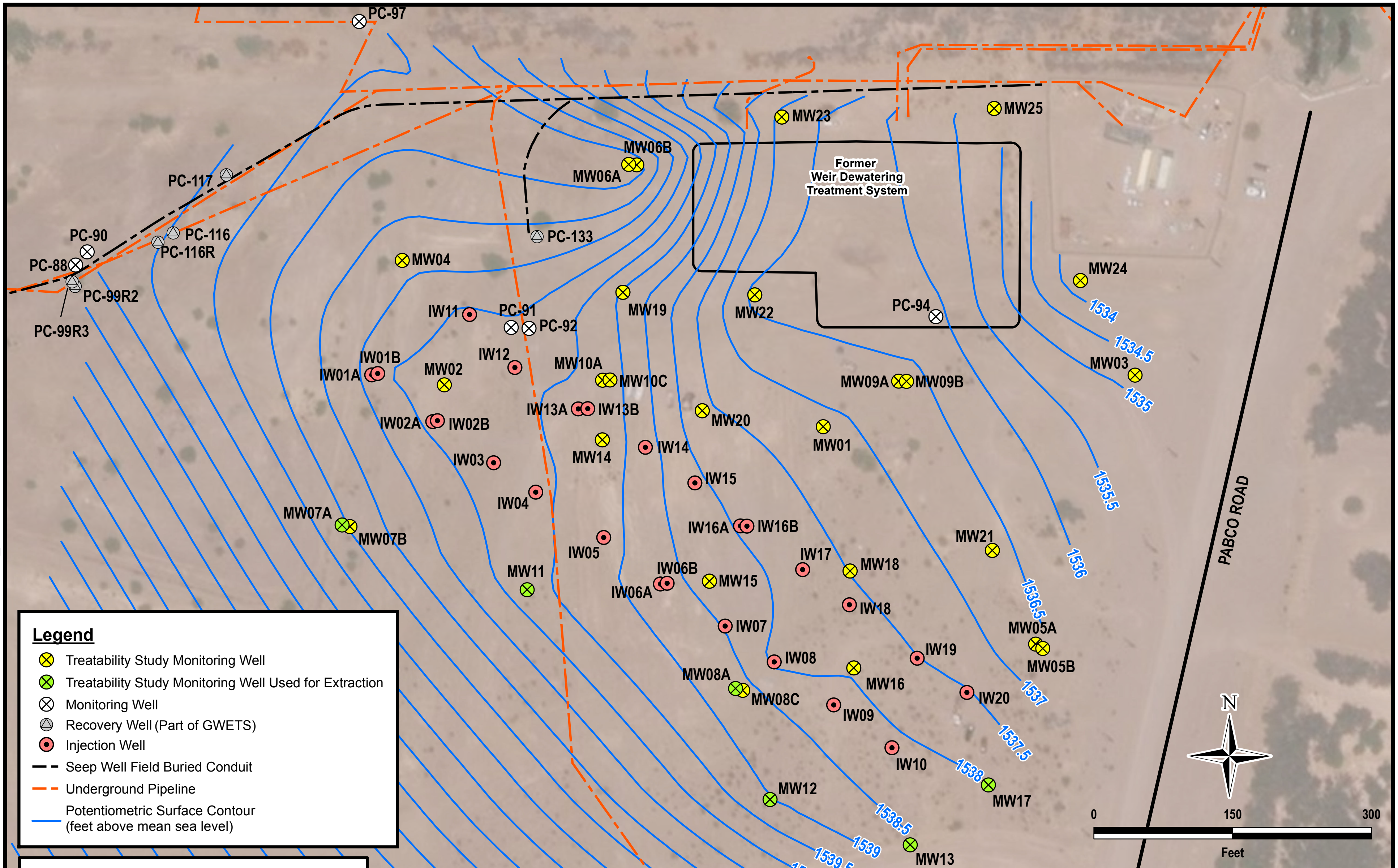
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

PRE-DESIGN FIELD ACTIVITIES

PROJECT NO.:	117-7502018
DATE:	APRIL 23, 2019
DESIGNED BY:	SRA

Figure No.
2



Notes:
1. Field Test Area located within Parcel 161-31-101-002.
2. The prefix 'SWTFS-' not shown for wells labeled as MW or IW. (MW03 = SWTFS-MW03)
3. Groundwater potentiometric contours presented are based on water levels collected during the baseline groundwater sampling event in July 2017.
4. Imagery Source: Esri World Map, May 2017.

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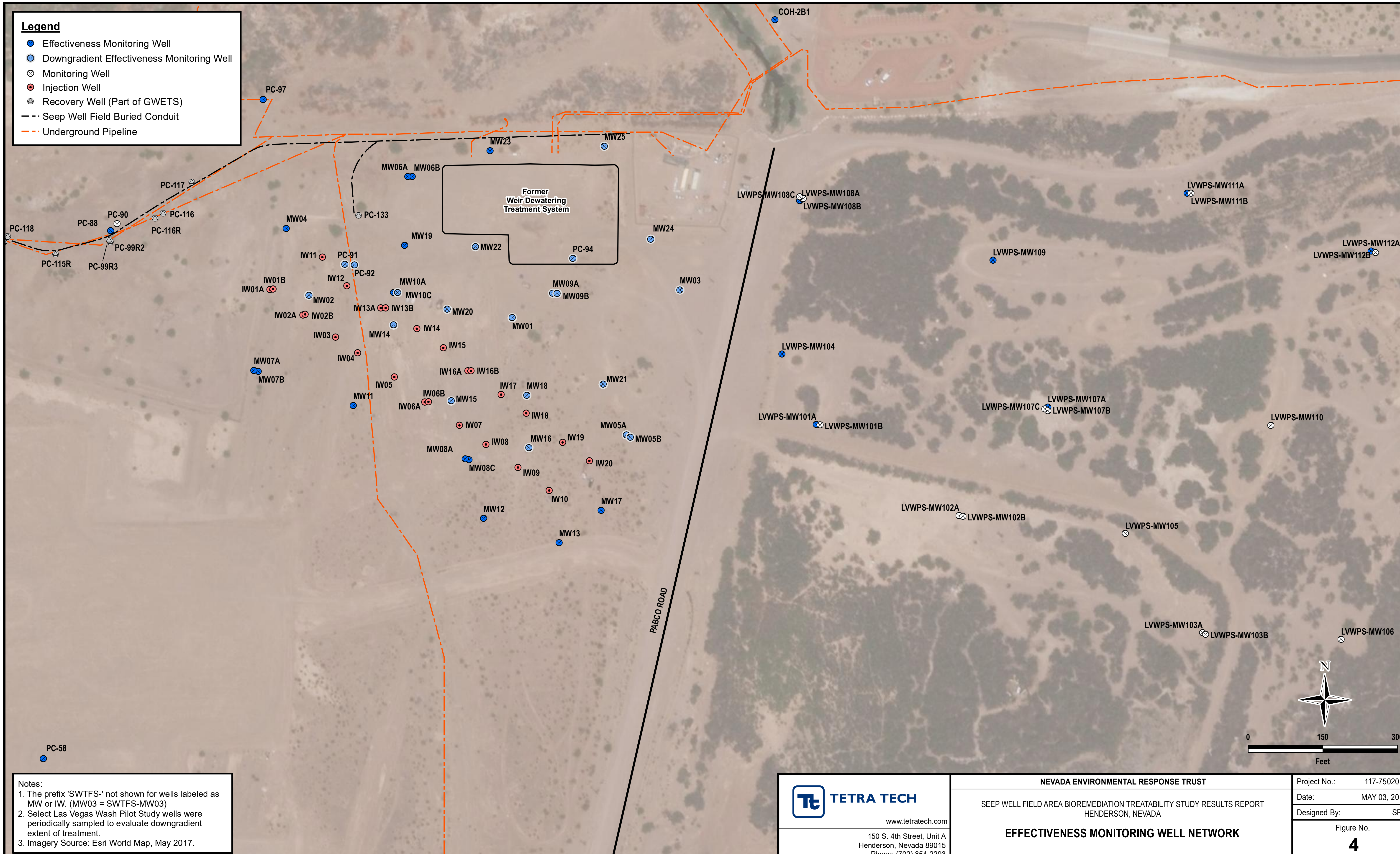
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

TREATABILITY STUDY LAYOUT

Project No.:	117-7502018
Date:	MAY 03, 2019
Designed By:	SRA
Figure No.	3

\\TTS100FS1\PROJECTS\NERT\GIS FIGURE DATABASE\MXD\M11\RESUTS_REPORT\FIGURE3.MXD



Notes:
1. The prefix 'SWTFS-' not shown for wells labeled as MW or IW. (MW03 = SWTFS-MW03)
2. Select Las Vegas Wash Pilot Study wells were periodically sampled to evaluate downgradient extent of treatment.
3. Imagery Source: Esri World Map, May 2017.

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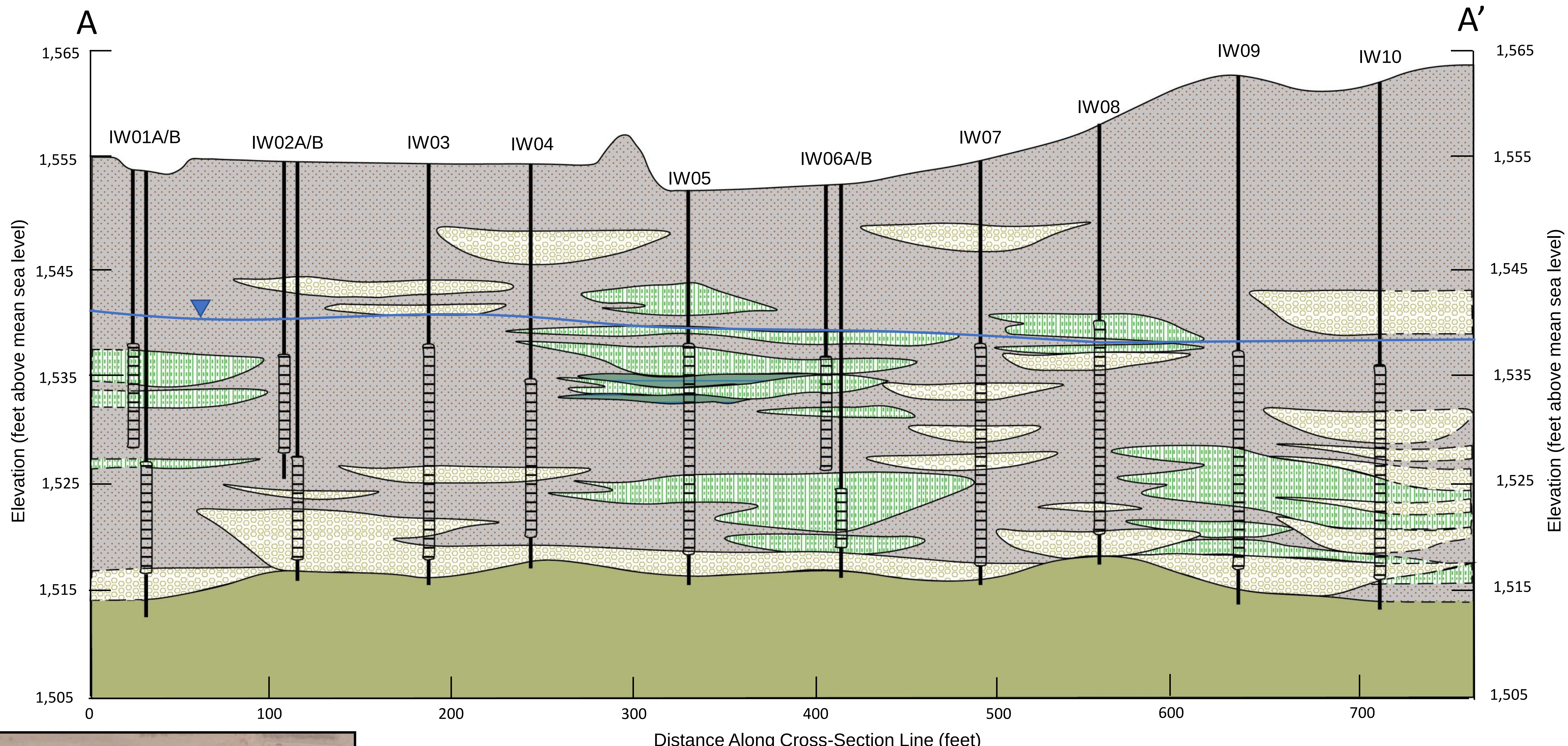
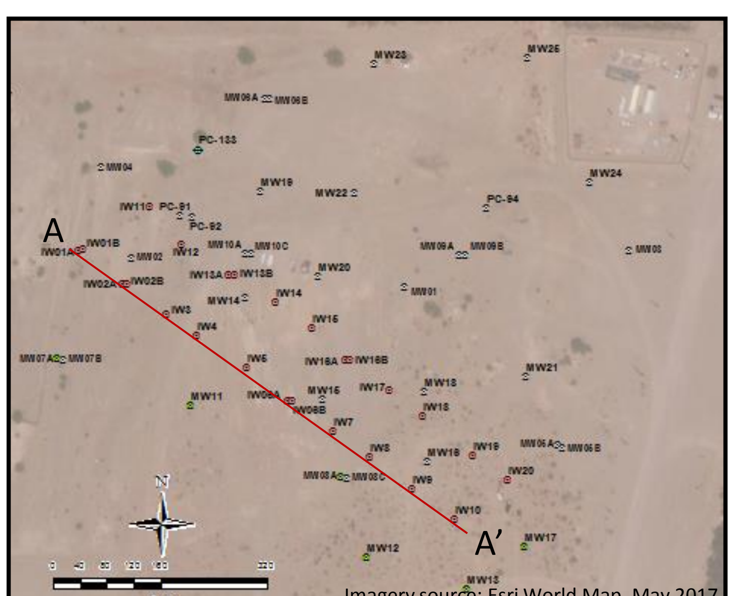
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

EFFECTIVENESS MONITORING WELL NETWORK

Project No.:	117-7502018
Date:	MAY 03, 2019
Designed By:	SRA
Figure No.	4





Alluvium – Sand

Alluvium – Gravel and Sand with Gravel Channel Fill (>30% Gravel)

Alluvium – Sandy Silt and Silty Sand (>30% Silt)

Alluvium– Sandy Clay (>30% Clay)

Upper Muddy Creek Formation – Silt and Clay

Water Table

Well Casing

Well Screen

Total Boring Depth

Notes:

1. Water level measurements were collected on January 22, 2018.
2. Well names contain the prefix “SWFTS” (e.g. SWFTS-IW01).

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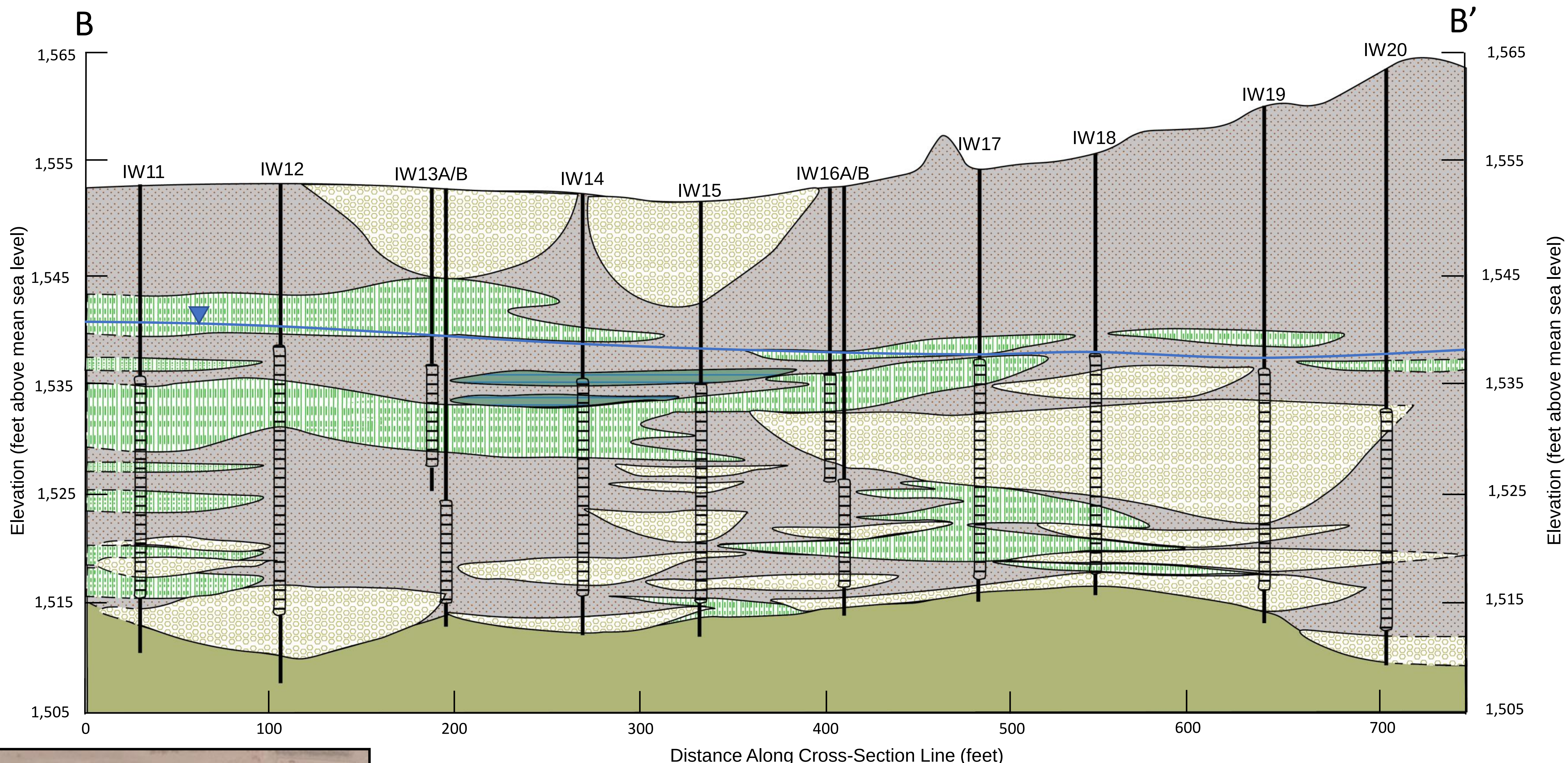
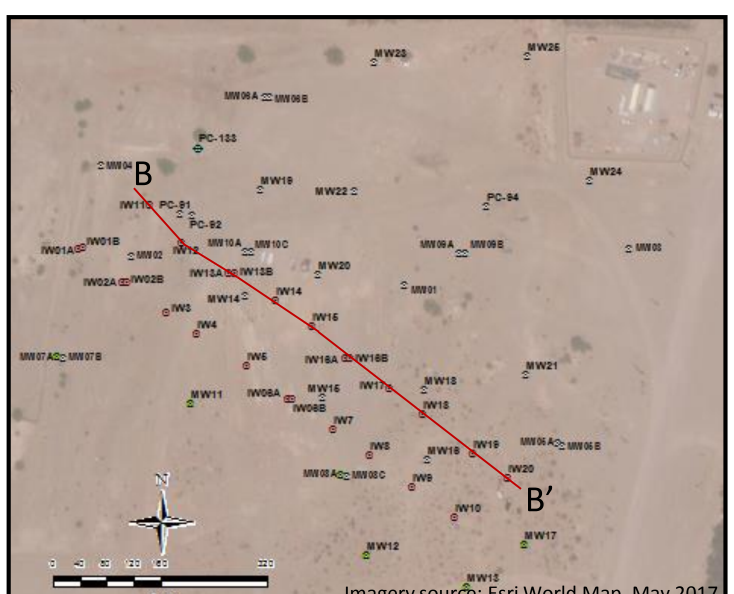
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

GEOLOGIC CROSS-SECTION A-A’

Project No.:	117-7502018
Date:	APRIL 24, 2019
Designed By:	MRB
Figure No.	5a





Alluvium – Sand

Alluvium – Gravel and Sand with Gravel Channel Fill (>30% Gravel)

Alluvium – Sandy Silt and Silty Sand (>30% Silt)

Alluvium– Sandy Clay (>30% Clay)

Upper Muddy Creek Formation – Silt and Clay

Water Table

Well Casing

Well Screen

Total Boring Depth

Notes:
1. Water level measurements were collected on January 22, 2018.
2. Well names contain the prefix “SWFTS” (e.g. SWFTS-IW01).

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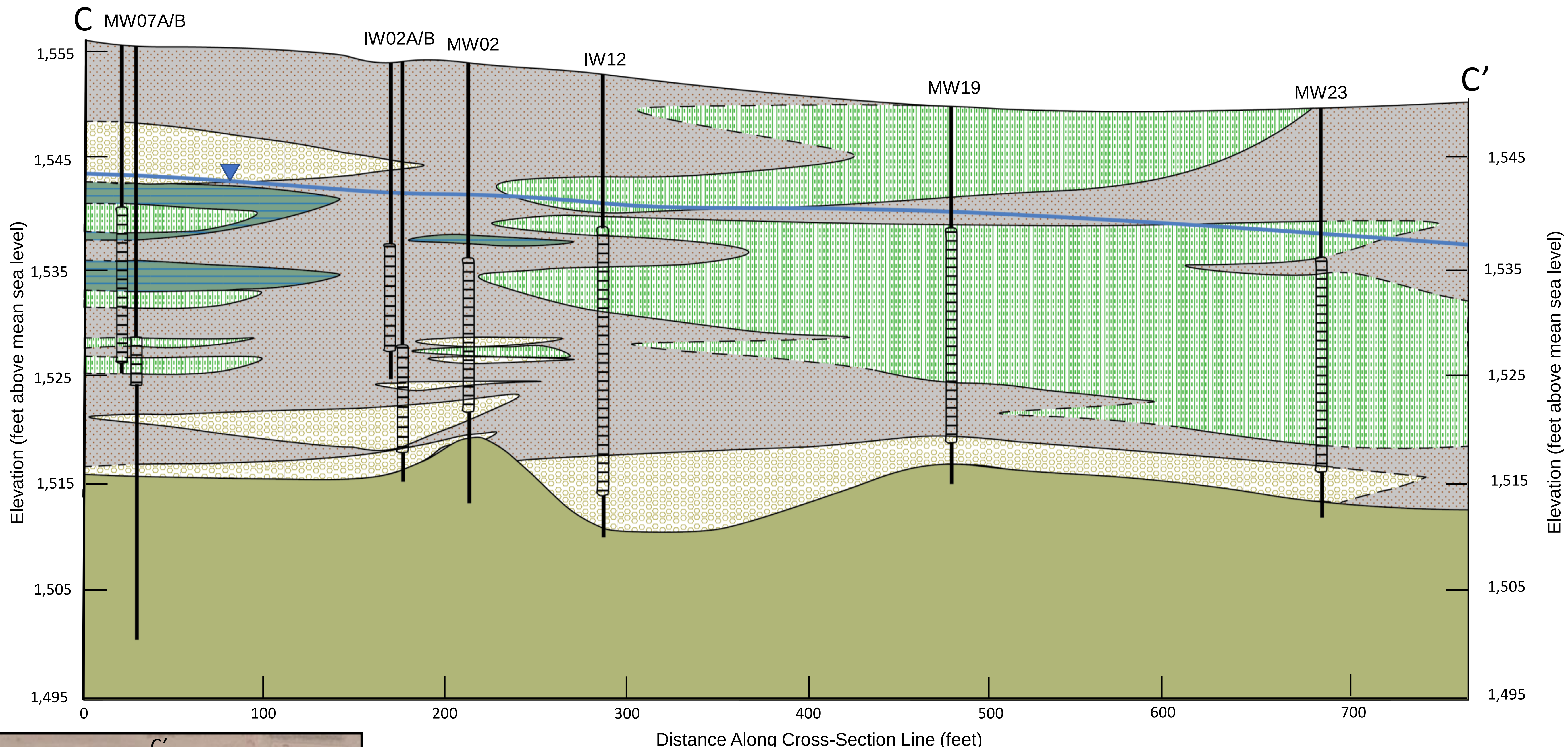
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

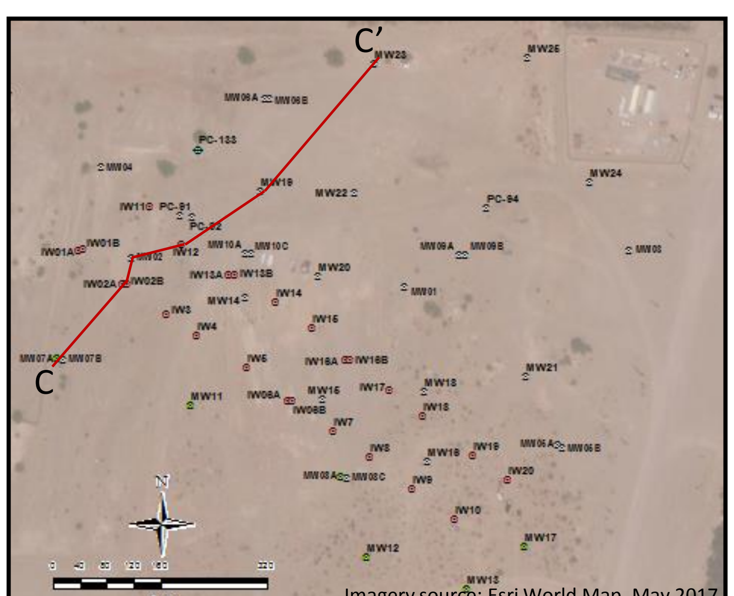
SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

GEOLOGIC CROSS-SECTION B-B’

Project No.:	117-7502018
Date:	APRIL 24, 2019
Designed By:	MRB
Figure No.	**5b**

\\tts134fs1\GEOLVOL1\PROJECTS\NERT\M17\Cross Sections\M17_Geo_Sections_AA_v3.pptx





- Alluvium – Sand
- Alluvium – Gravel and Sand with Gravel Channel Fill (>30% Gravel)
- Alluvium – Sandy Silt and Silty Sand (>30% Silt)
- Alluvium– Sandy Clay (>30% Clay)
- Upper Muddy Creek Formation – Silt and Clay
- Water Table
- Well Casing
- Well Screen
- Total Boring Depth

Notes:
1. Water level measurements were collected on January 22, 2018.
2. Well names contain the prefix “SWFTS” (e.g. SWFTS-IW01).

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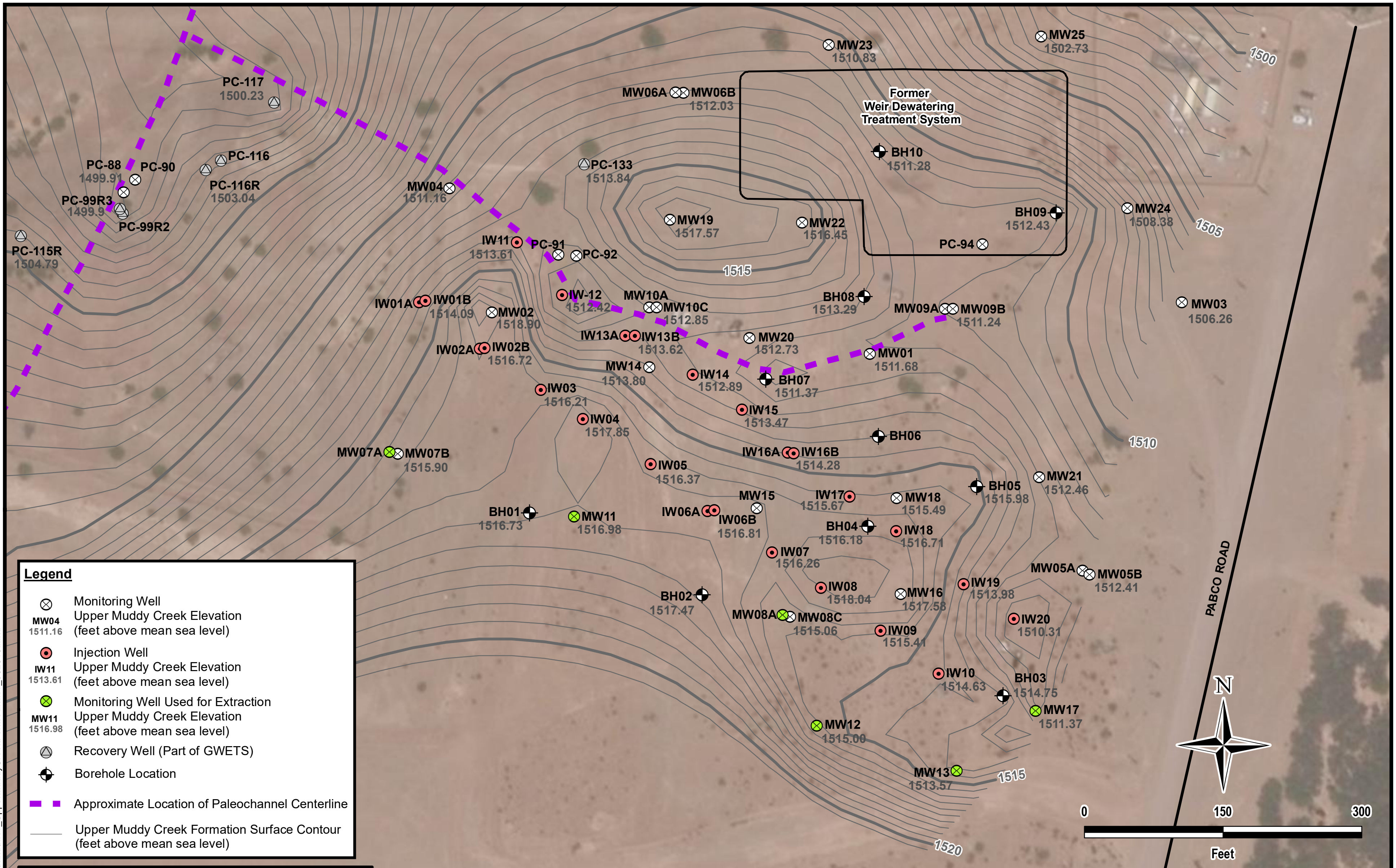
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

GEOLOGIC CROSS-SECTION C-C’

Project No.:	117-7502018
Date:	APRIL 24, 2019
Designed By:	MRB
Figure No.	5c

\\tts134fs1\GEOLVOL1\PROJECTS\NERT\M17\Cross Sections\M17_Geo_Sections_AA_v3.pptx



Notes:
1. The prefix 'SWTFS-' not shown for wells or borings labeled BH, MW or IW. (MW03 = SWTFS-MW03).
2. Upper Muddy Creek formation (UMCf) elevation shown for boreholes and wells installed as part of the treatability study. Borehole SWFTS-BH06 was terminated prior to encountering the UMCf.
3. Imagery Source: Esri World Map, May 2017.

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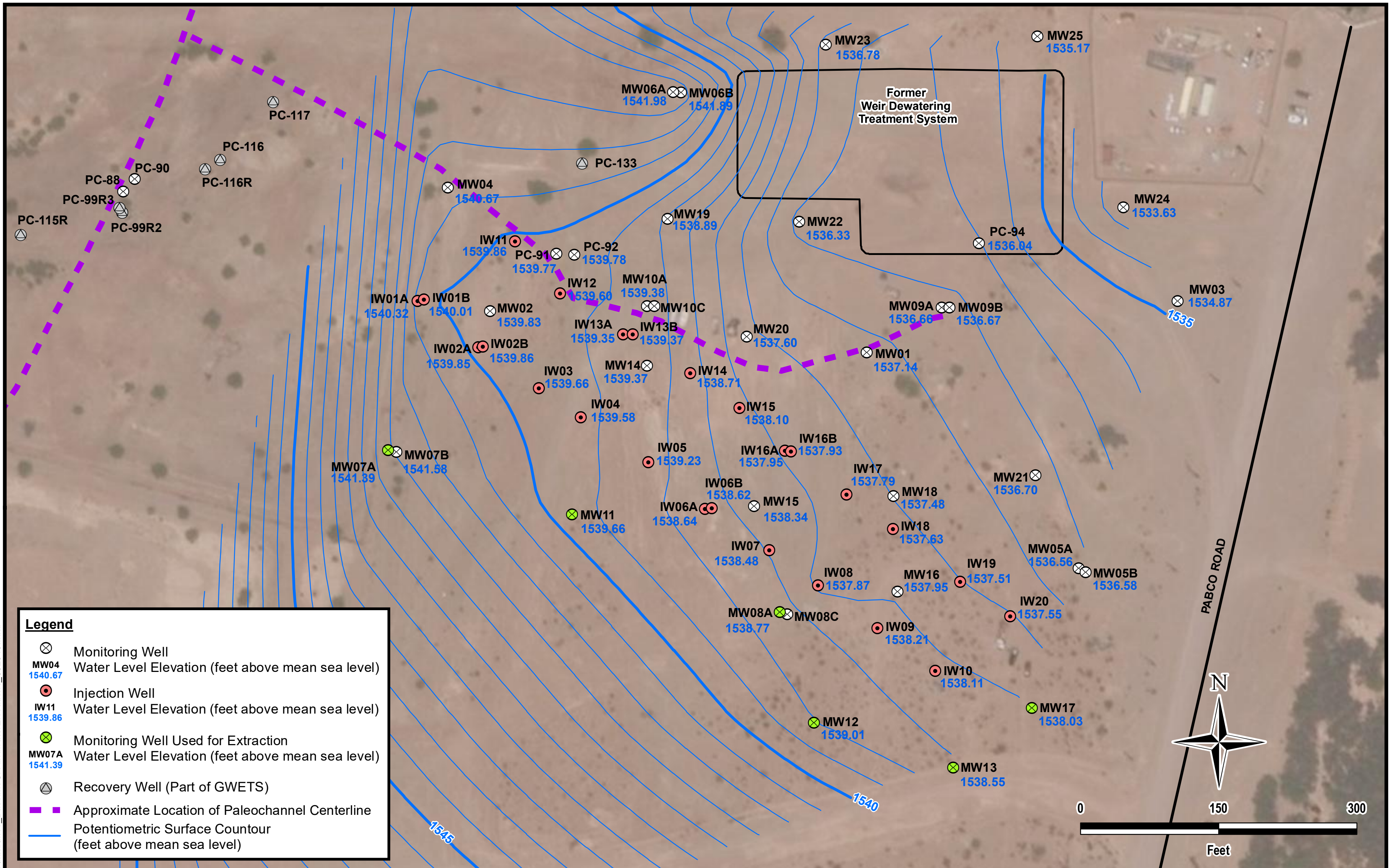
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

UPPER MUDDY CREEK FORMATION SURFACE

Project No.:	117-7502019
Date:	MAY 03, 2019
Designed By:	ES
Figure No.	6

\\tts134fs1\SUP-GIS\arcprj2\NERT\mxd\M11_UpperMuddyCreekFormSurface_032519.mxd



\\tts134fs1\SUP-GIS\arcprj2\NERT\mxd\M11_BaselineGroundwaterElevations_032519.mxd

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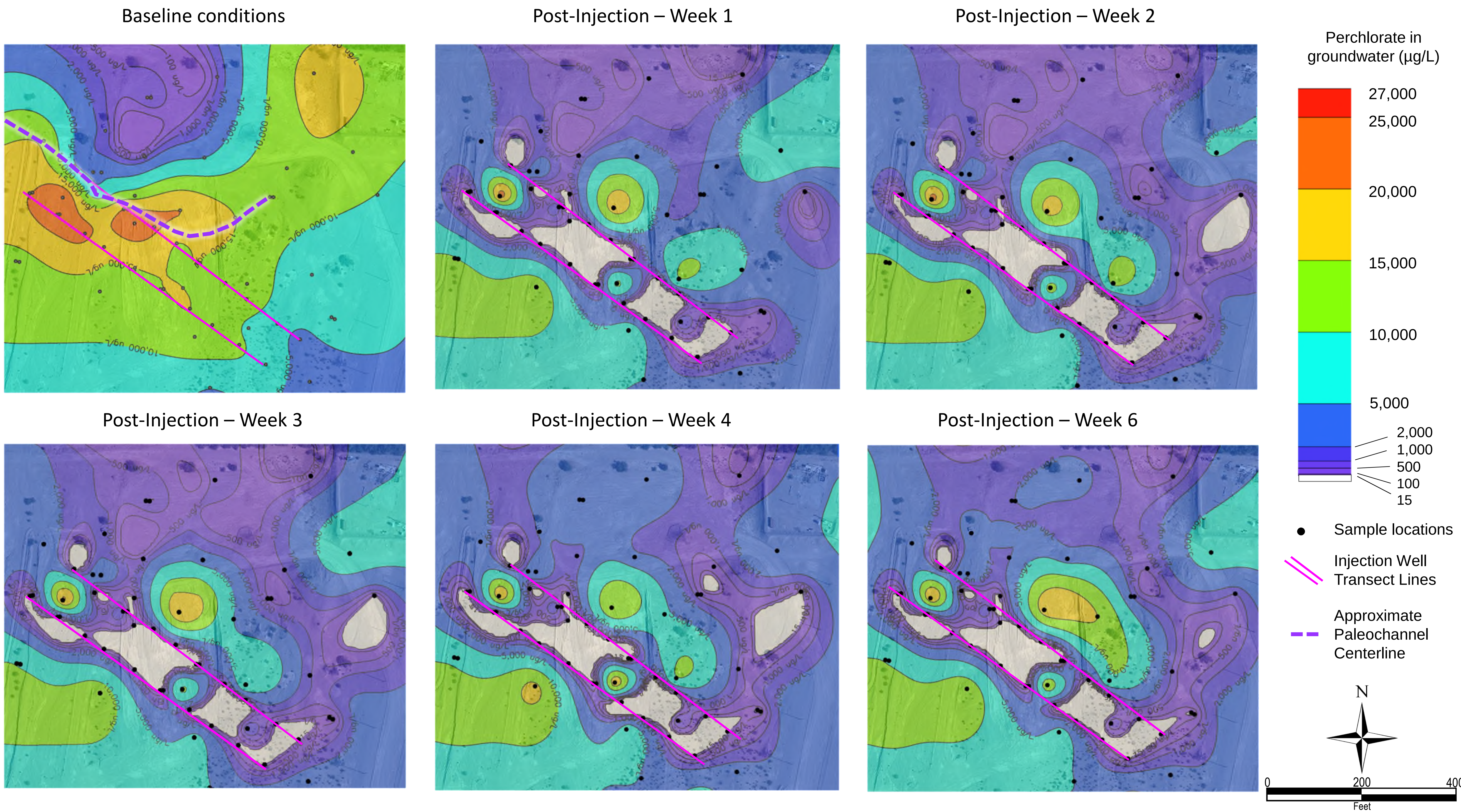
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

GROUNDWATER POTENTIOMETRIC SURFACE

Project No.:	117-7502019
Date:	MAY 03, 2019
Designed By:	ES
Figure No.	7



Notes:

1. Each image represents a horizontal slice through the interpolated perchlorate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first injection event in September 2017.

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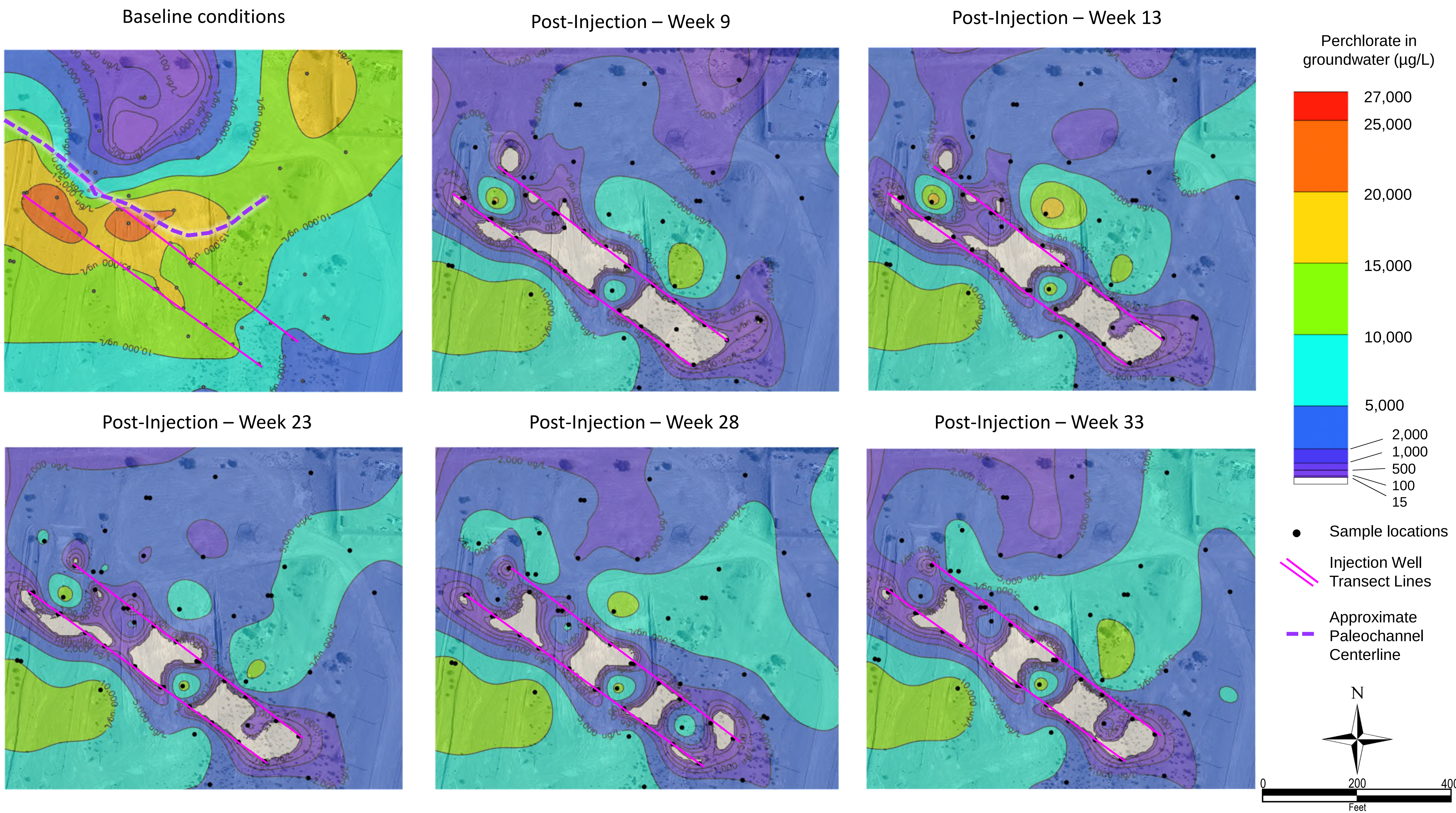
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER DURING THE TREATABILITY STUDY (WEEKS 1 TO 6)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	CKG
Figure No.	8a

\\tts134fs1\GEOSUPVOL1\PROJECTS\DATA\NERT\M11\EVS\ Report Figure 8a-c. Perchlorate_GW_Baseline_EM1-7_v3_combined



\\tts134fs1\GEOSUP\VOL1\PROJECTS\DATA\NERT\M11\EVS\ Report Figure 8a-c: Perchlorate_GW_Baseline_EM1-7_v3_combined

Notes:

1. Each image represents a horizontal slice through the interpolated perchlorate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first and second injection events.

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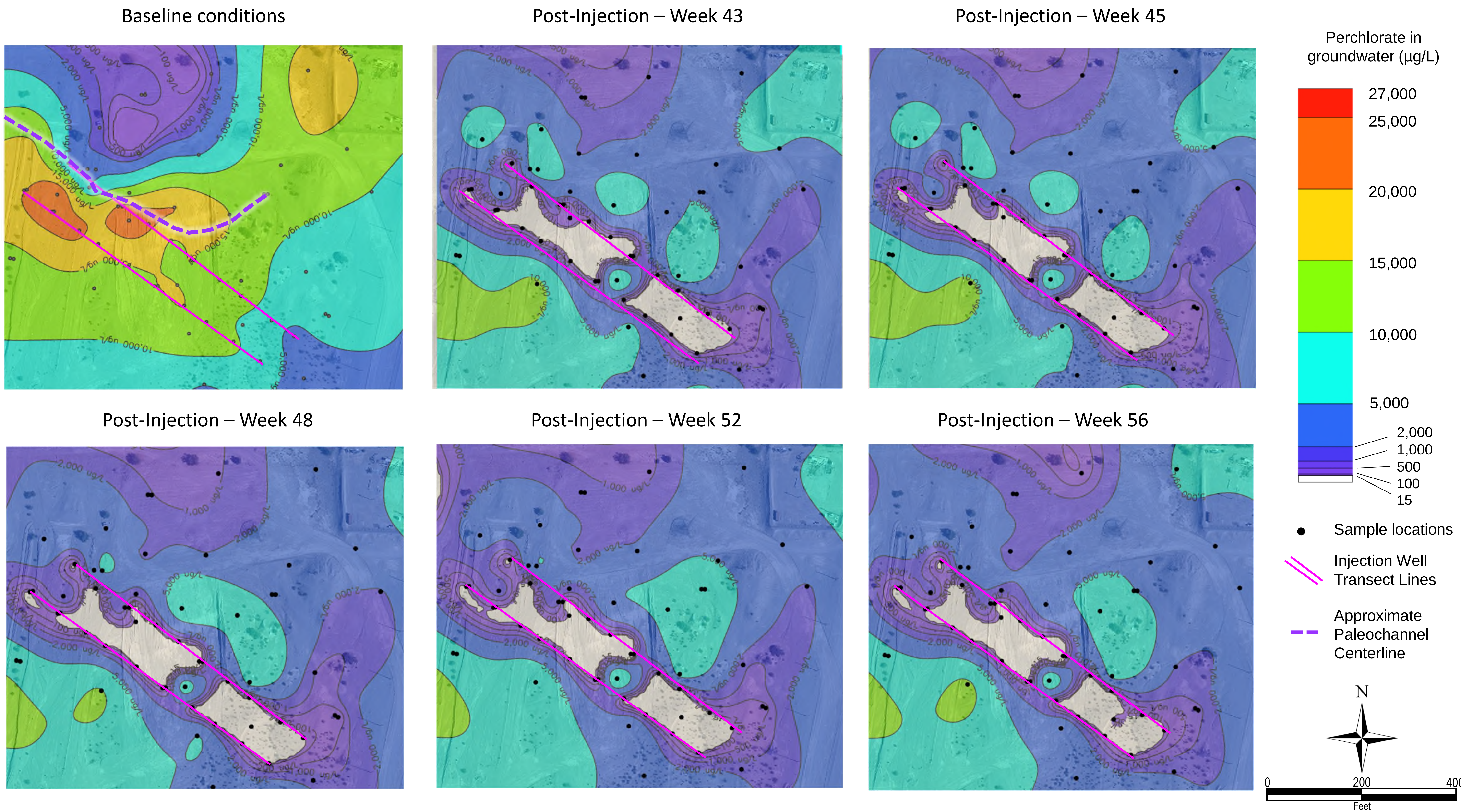
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER DURING THE TREATABILITY STUDY (WEEKS 9 TO 33)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	CKG
Figure No.	**8b**



\\tts134fs1\GEOSUPVOL1\PROJECTS\DATA\NERT\M11\EVS\ Report Figure 8a-c. Perchlorate_GW_Baseline_EM1-7_v3_combined

Notes:

1. Each image represents a horizontal slice through the interpolated perchlorate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the third injection event.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

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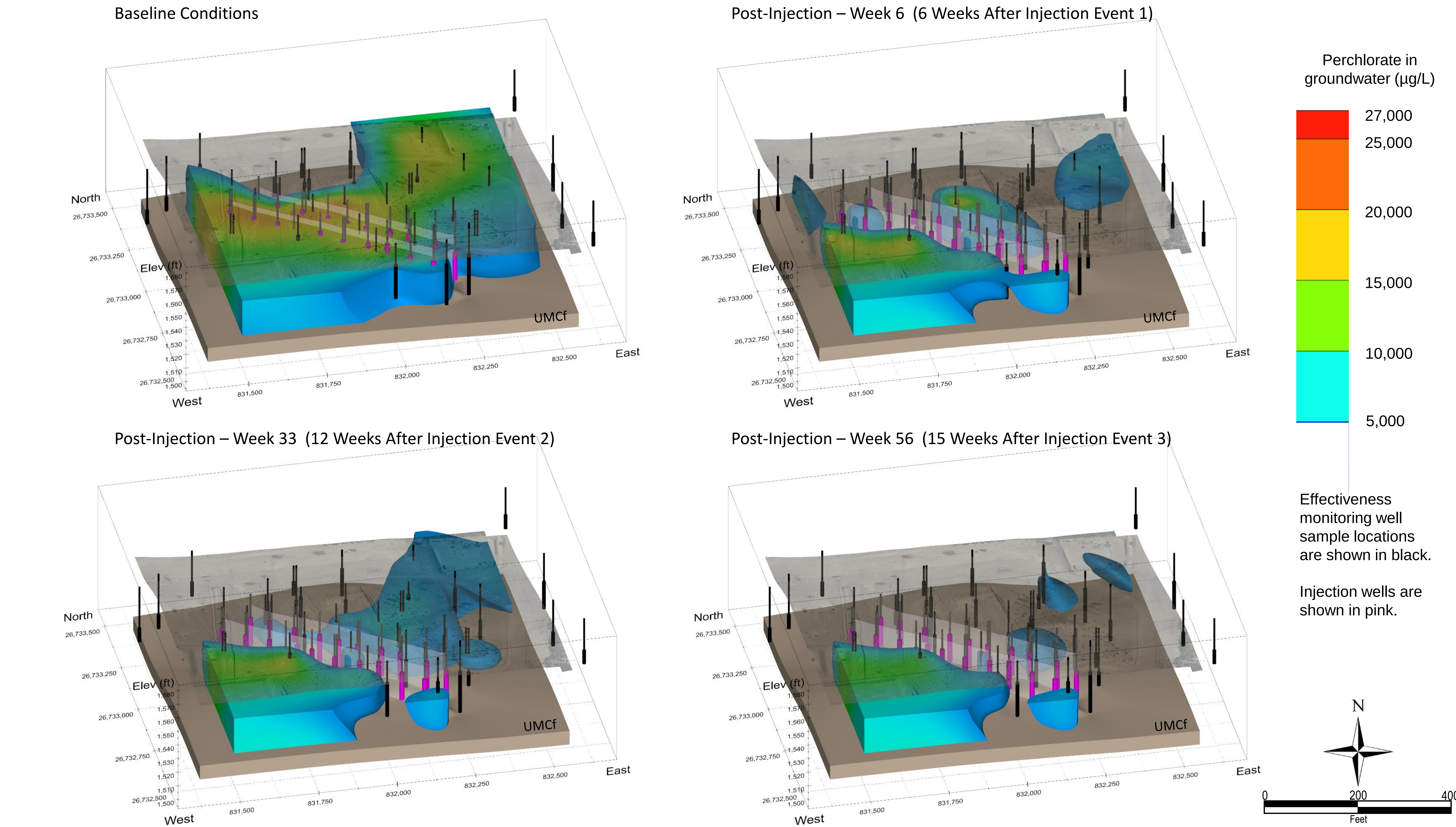
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER DURING THE TREATABILITY STUDY (WEEKS 43 TO 56)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	CKG
Figure No.	**8c**



Elev (ft) – Elevation in feet above mean sea level   µg/L – micrograms per liter   UMCf – Upper Muddy Creek formation

Notes:

1. Each image represents the interpolated perchlorate concentration plume in the alluvium where concentrations exceed 5,000 µg/L.
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions. Weeks 6, 33, and 56 represent concentrations following each of the three injection events.
3. Injection events occurred in August/September 2017, January/February 2018, and June 2018.

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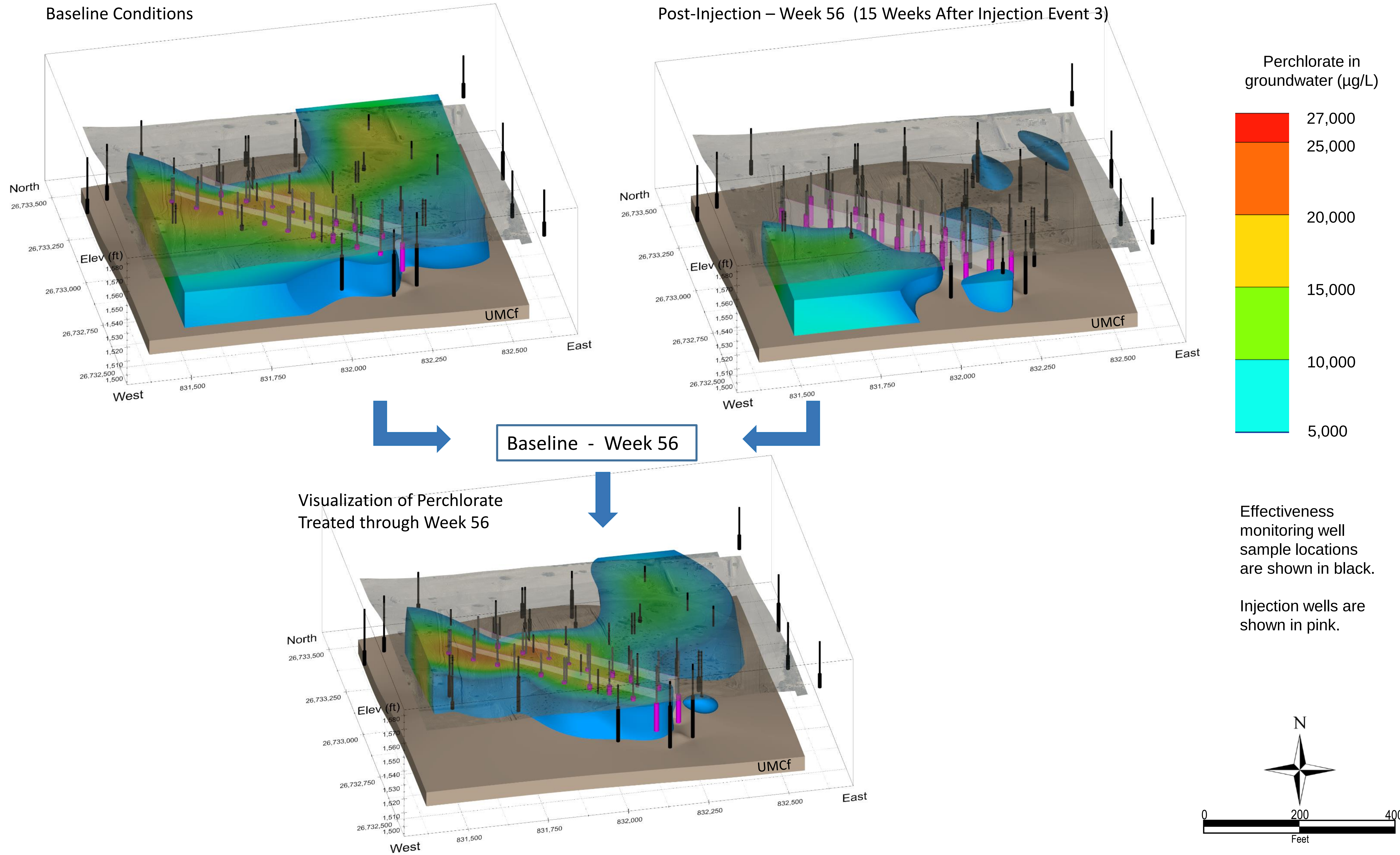
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

3D VISUALIZATION OF PERCHLORATE DISTRIBUTION IN GROUNDWATER DURING THE TREATABILITY STUDY

Project No.:	117-7502018
Date:	AUGUST 9, 2019
Designed By:	CKG
Figure No.	**8d**



Elev (ft) – Elevation in feet above mean sea level µg/L – micrograms per liter UMCf – Upper Muddy Creek formation

Notes:

1. Each image represents the interpolated perchlorate concentration plume in the alluvium where concentrations exceed 5,000 µg/L.
2. Week 56 differential perchlorate represents the difference between the baseline conditions and the week 56 conditions to create a visualization of perchlorate treated through week 56.
3. Injection events occurred in August/September 2017, January/February 2018, and June 2018.

\\tts134fs1\GEOSUPVOL1\PROJECTS\DATA\NERT\M11\EVS\ Report Figure 8e-f Perchlorate 3D Plume Weeks 0-6-33-56 combined_v2.pptx

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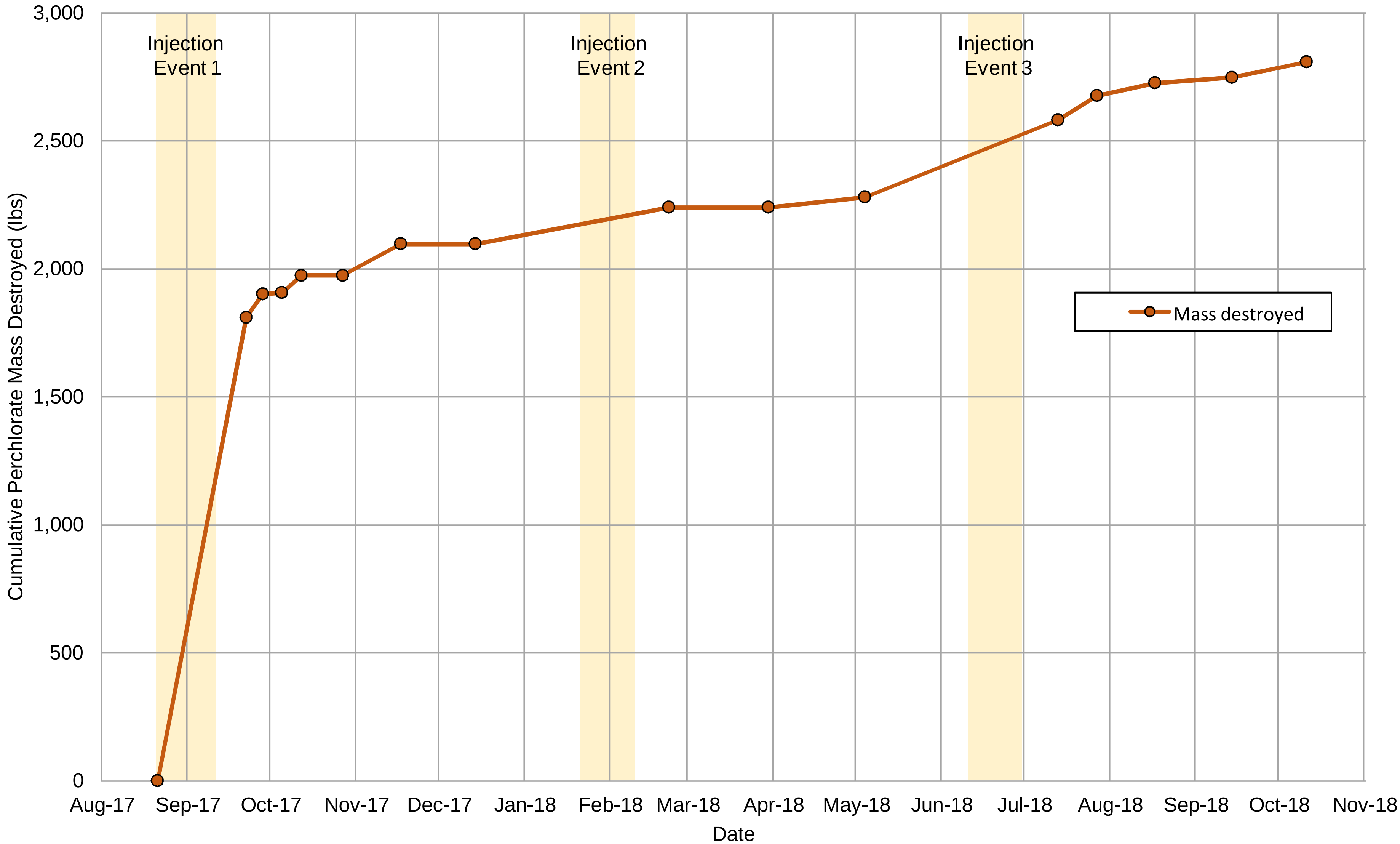
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

3D VISUALIZATION OF PERCHLORATE CONCENTRATION DIFFERENTIAL IN GROUNDWATER TREATABILITY STUDY WEEK 56

Project No.:	117-7502018
Date:	AUGUST 9, 2019
Designed By:	CKG
Figure No.	8e



\\tts134fs1\GEOSUPV\OL1\PROJECTS\NERT\M11\reporting\Mass Removal\Mass Removal.pptx

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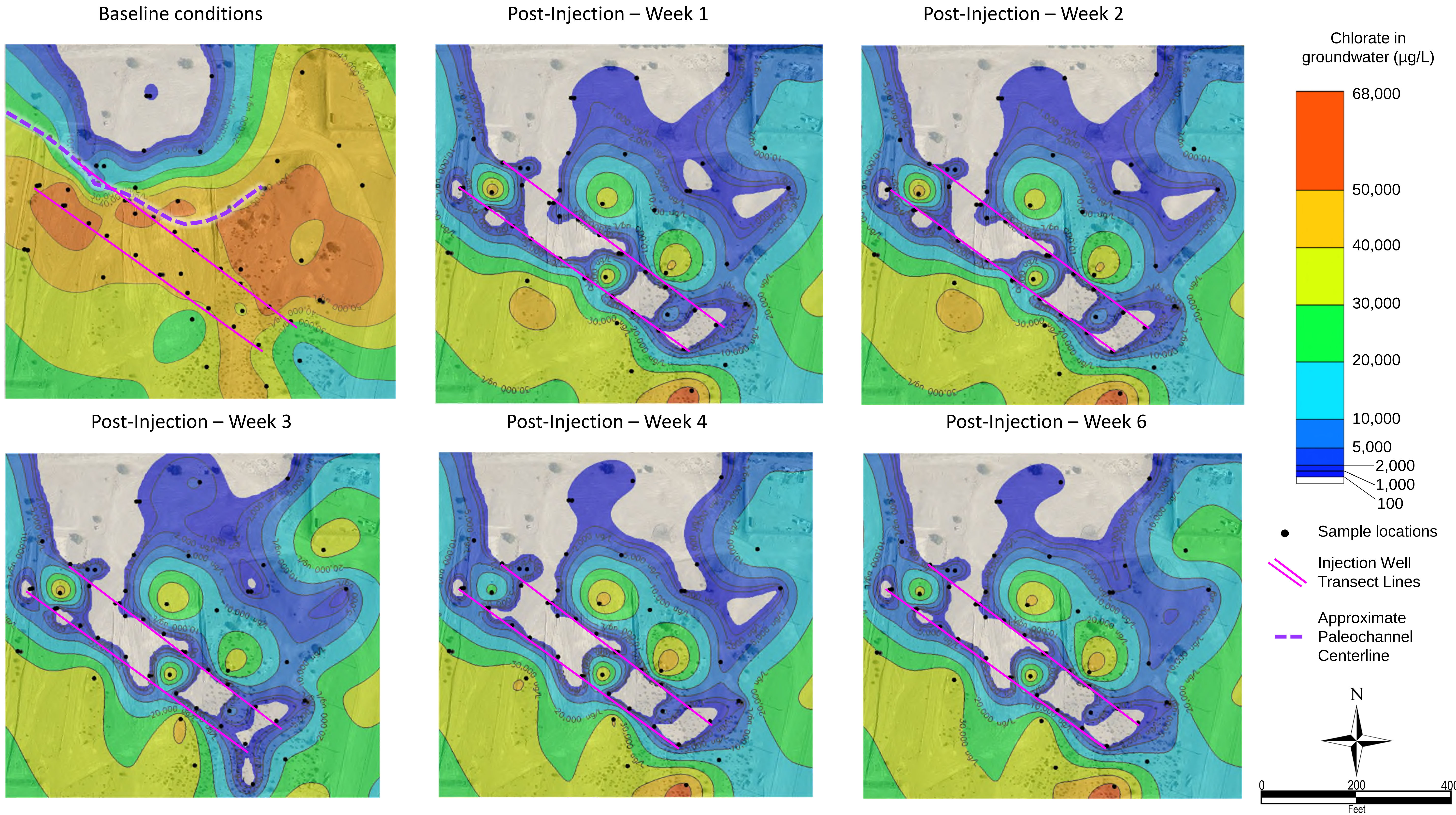
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

CUMULATIVE PERCHLORATE MASS DESTROYED

Project No.:	117-7502018
Date:	APRIL 24, 2019
Designed By:	ACC
Figure No.	9



Notes:
1. Each image represents a horizontal slice through the interpolated chlorate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first injection event in September 2017.

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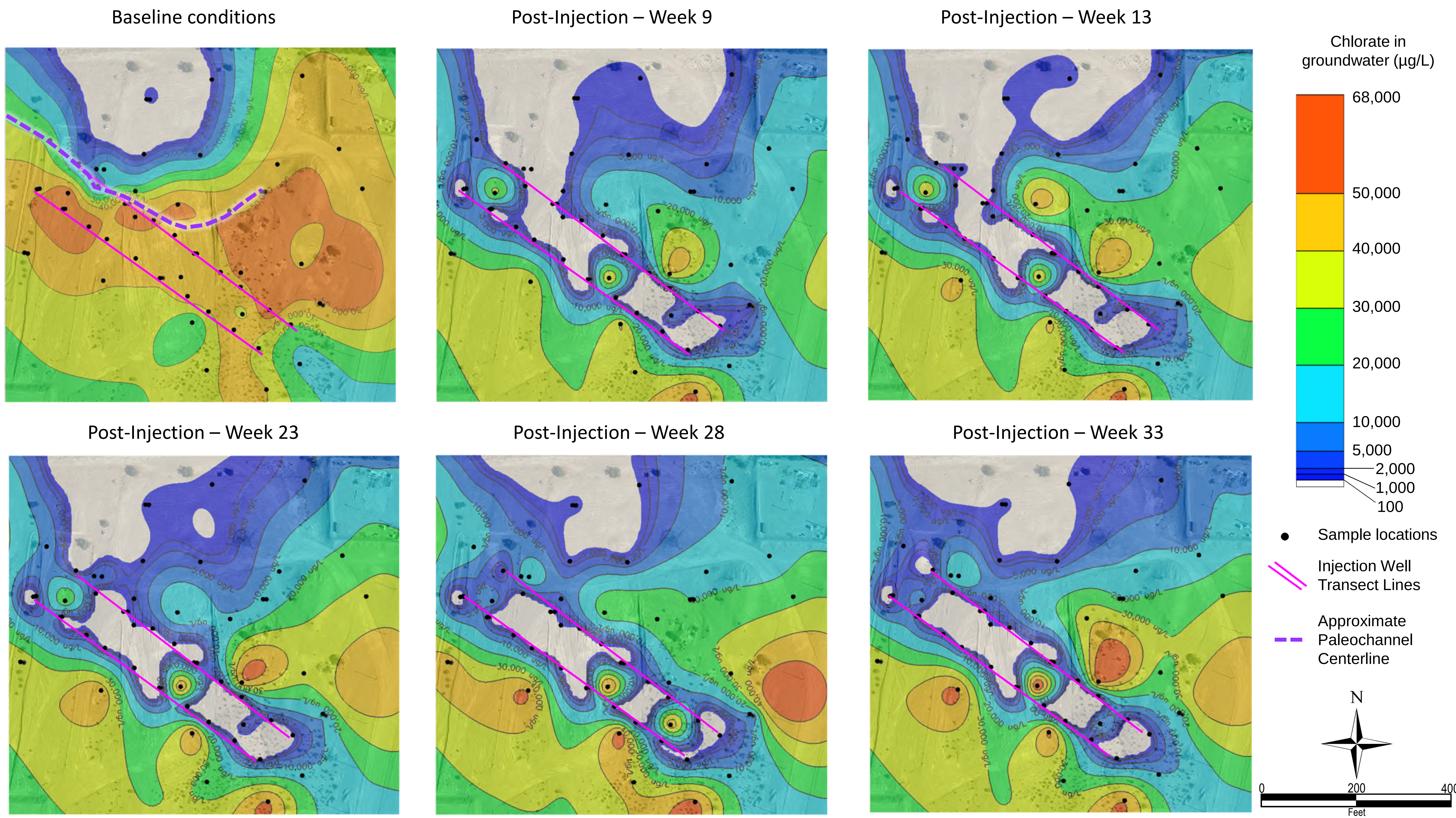
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

CHLORATE DISTRIBUTION IN GROUNDWATER DURING TREATABILITY STUDY (WEEKS 1 TO 6)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	BCS
Figure No.	**10a**

T:\NERT\M11\ppt_Figs\april2019\Report Figure 10a-c. chlorate_GW_Baseline_EM1-15_combined_v2



Notes:

1. Each image represents a horizontal slice through the interpolated chlorate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first injection event in September 2017.

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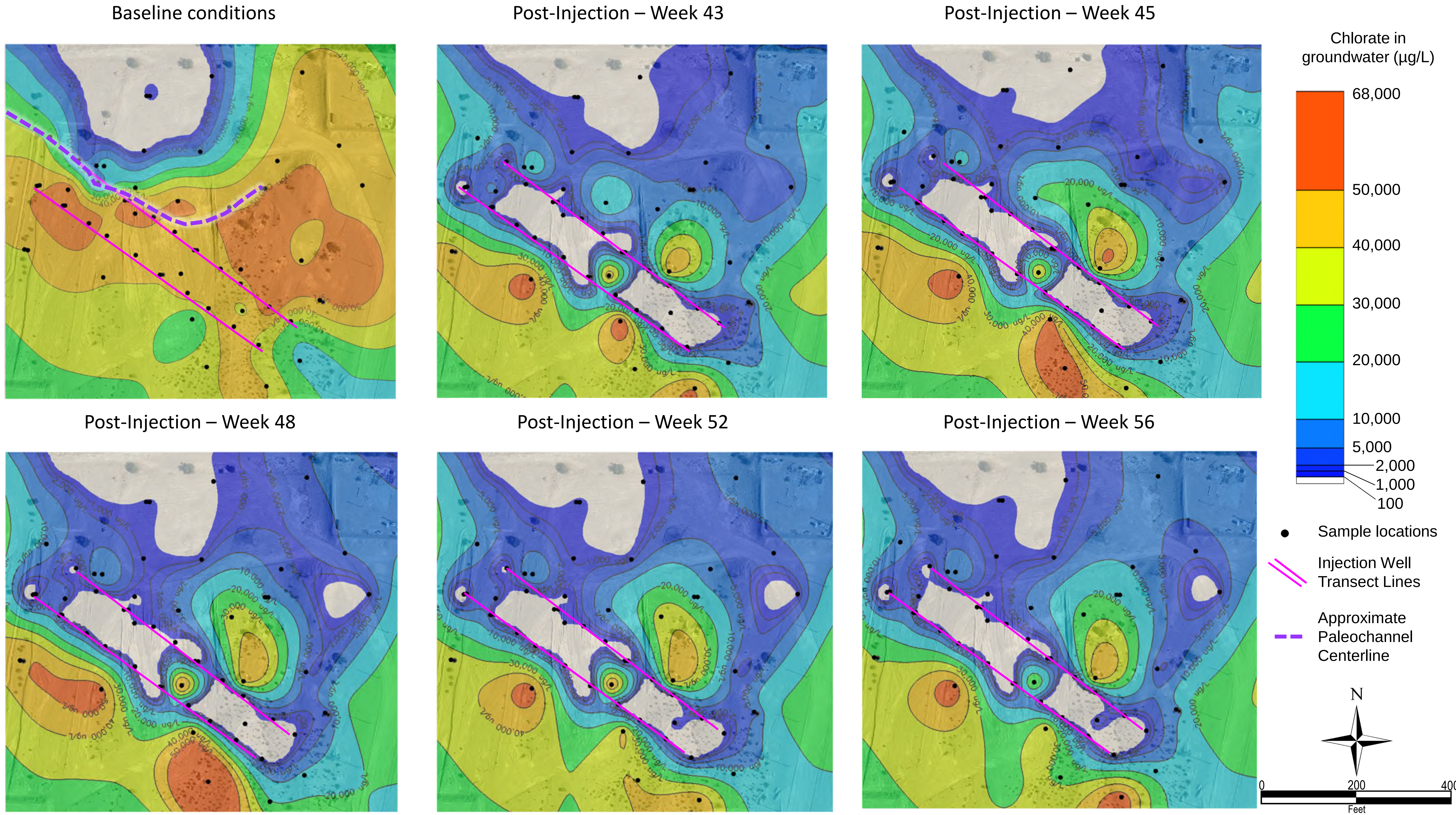
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

CHLORATE DISTRIBUTION IN GROUNDWATER DURING TREATABILITY STUDY (WEEKS 9 TO 33)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	BCS
Figure No.	**10b**

T:\NERT\M11\ppt_Figs\april2019\Report Figure 10a-c. chlorate_GW_Baseline_EM1-15_combined_v2



Notes:
1. Each image represents a horizontal slice through the interpolated chlorate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first injection event in September 2017.

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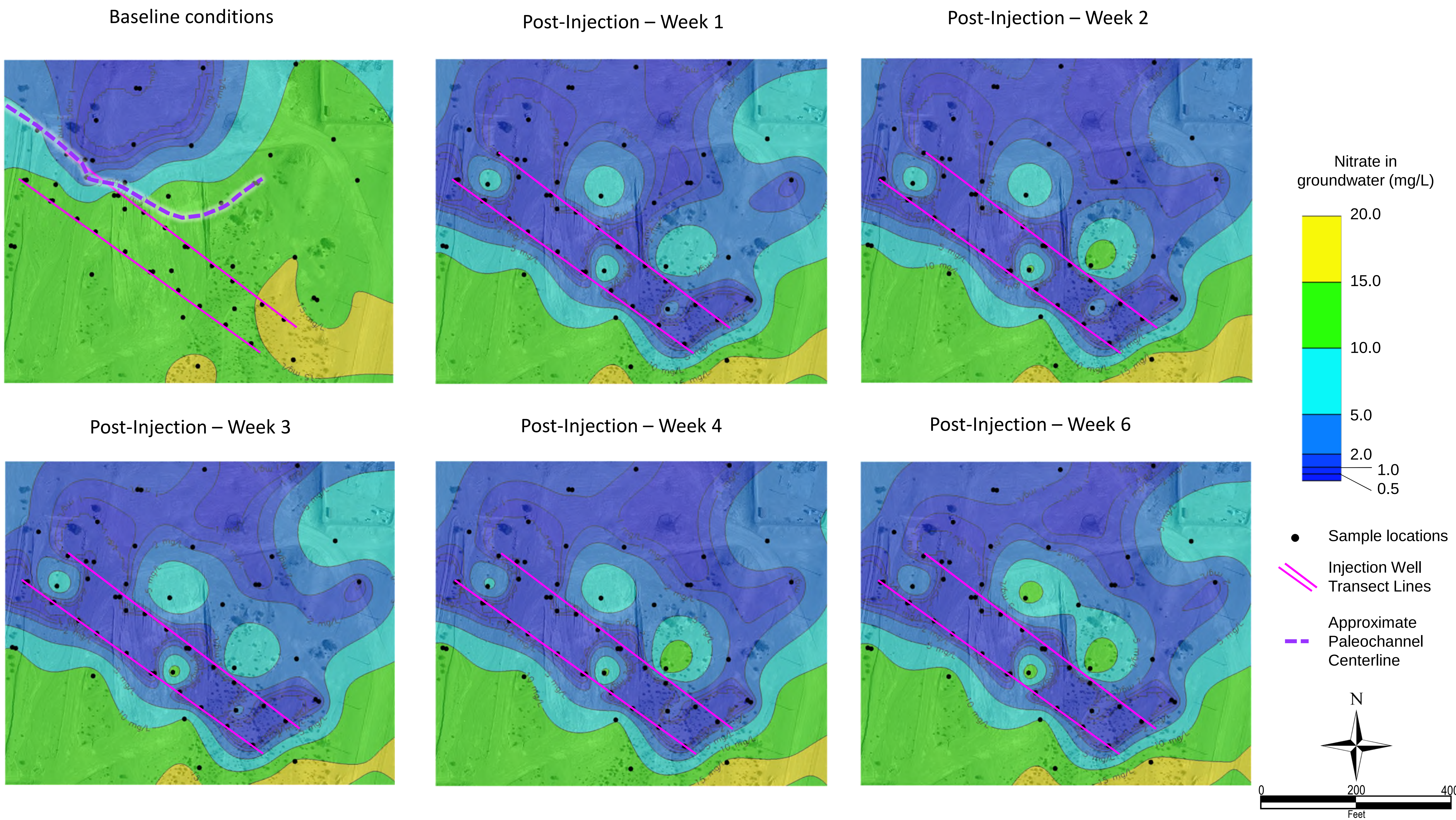
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

CHLORATE DISTRIBUTION IN GROUNDWATER DURING TREATABILITY STUDY (WEEKS 43 TO 56)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	BCS
Figure No.	**10c**

T:\NERT\M11\ppt_Figs\april2019\Report Figure 10a-c. chlorate_GW_Baseline_EM1-15_combined_v2



Notes:

1. Each image represents a horizontal slice through the interpolated nitrate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first injection event in September 2017.

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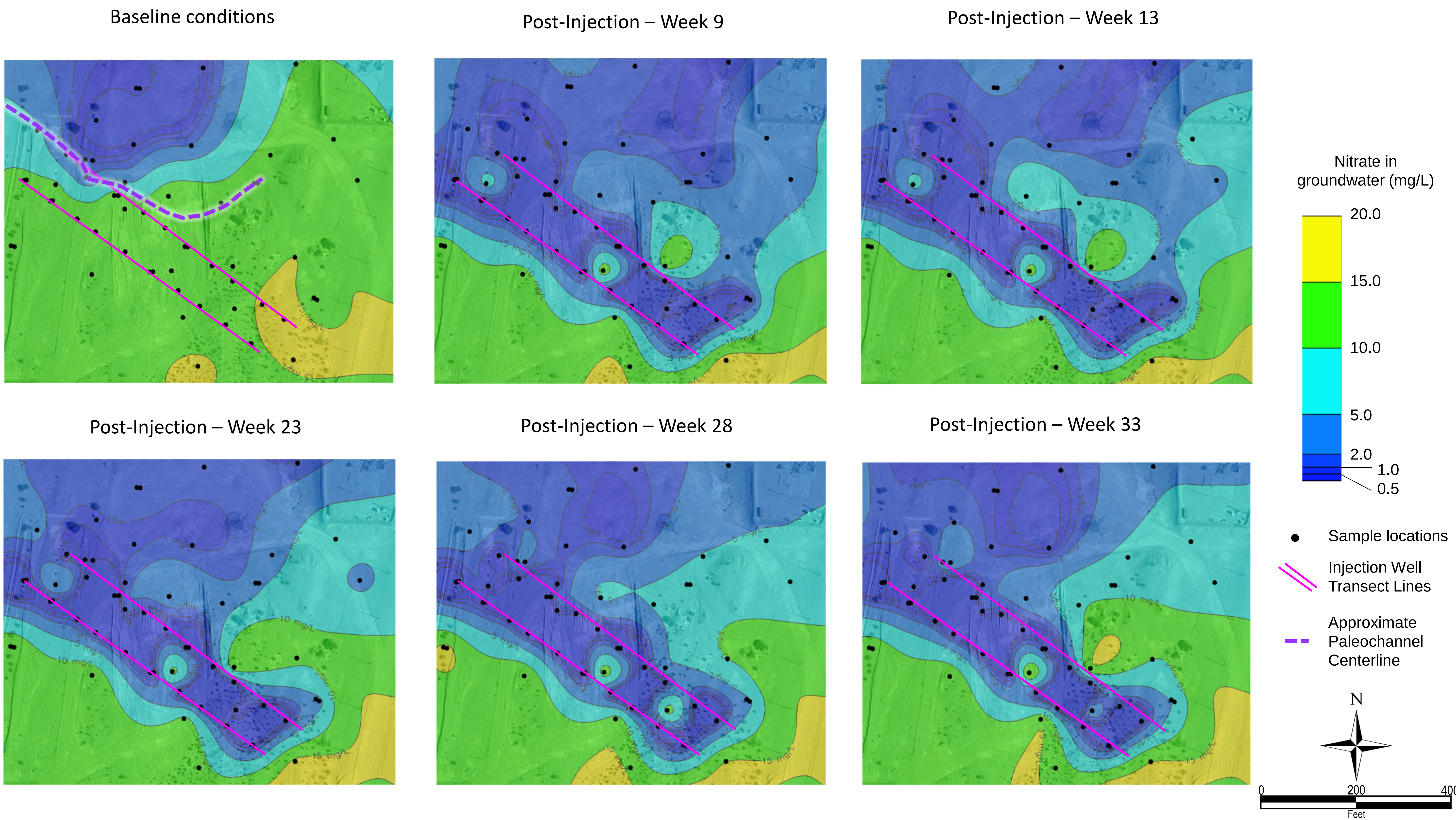
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY RESULTS REPORT
HENDERSON, NEVADA

NITRATE DISTRIBUTION IN GROUNDWATER DURING TREATABILITY STUDY (WEEKS 1 TO 6)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	BCS
Figure No.	11a

T:\NERT\M11\ppt_Figs\april2019\Report Figure 11a-c. Nitrate_GW_Baseline_EM1-15_combined_v4.ppt



Notes:

1. Each image represents a horizontal slice through the interpolated nitrate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first injection event in September 2017.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE
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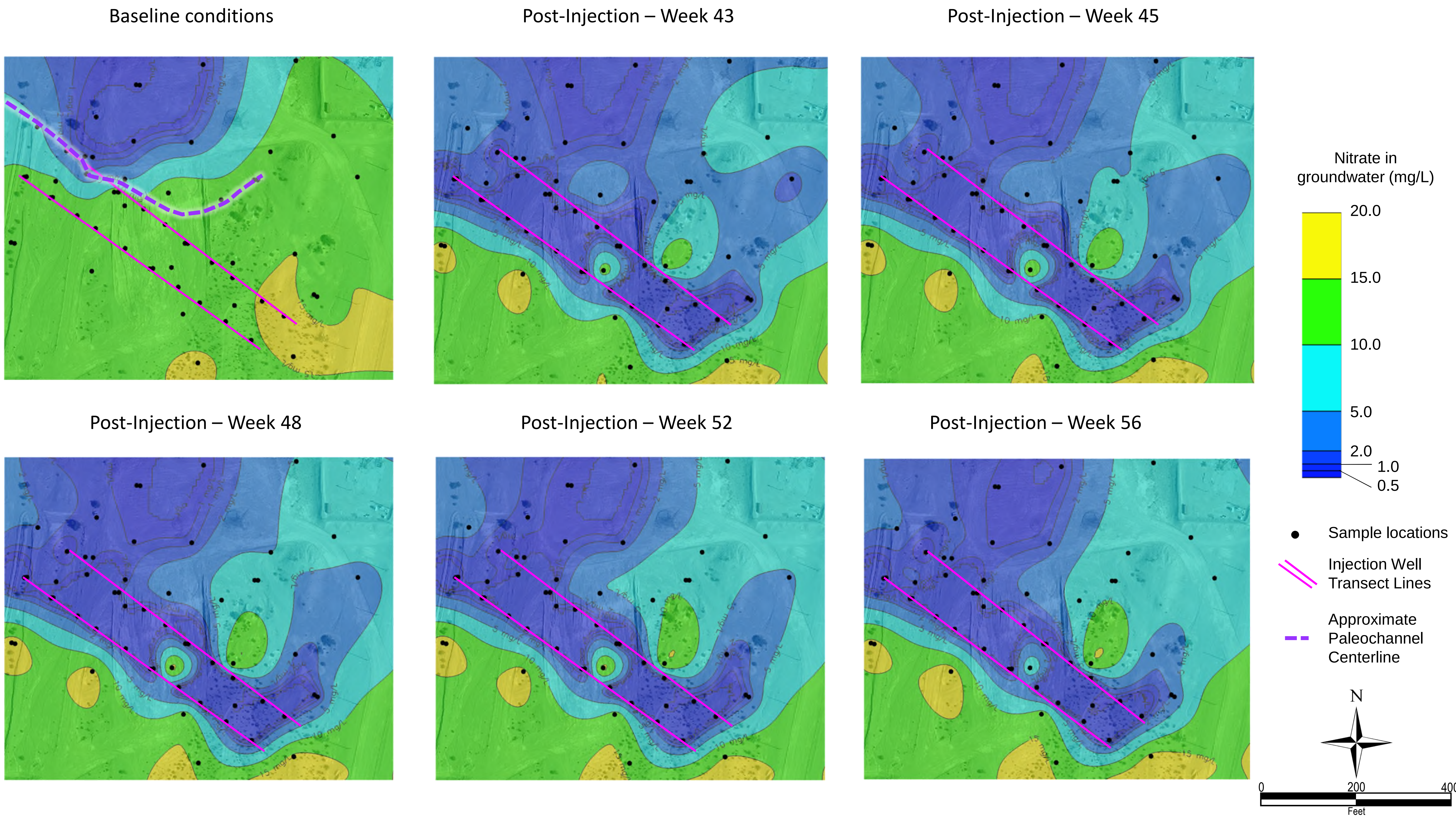
HENDERSON, NEVADA

NITRATE DISTRIBUTION IN GROUNDWATER DURING TREATABILITY STUDY (WEEKS 9 TO 33)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	BCS
Figure No.	11b

T:\NERT\M11\ppt_Figs\april2019\Report Figure 11a-c, Nitrate_GW_Baseline_EM1-15_combined_v4.ppt



Notes:
1. Each image represents a horizontal slice through the interpolated nitrate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, and June 2018. Images presented in this figure represent groundwater sampling events that have occurred following the first injection event in September 2017.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE
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NITRATE DISTRIBUTION IN GROUNDWATER DURING TREATABILITY STUDY (WEEKS 43 TO 56)

Project No.:	117-7502018
Date:	May 6, 2019
Designed By:	BCS
Figure No.	**11c**

T:\NERT\M11\ppt_Figs\april2019\Report Figure 11a-c. Nitrate_GW_Baseline_EM1-15_combined_v4.ppt