Las Vegas Wash Bioremediation Pilot Study Results Report

Nevada Environmental Response Trust Site

Henderson, Nevada

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LIST OF ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
ARARs	applicable or relevant and appropriate requirements
AWF	Athens Road Well Field
BOR	United States Bureau of Reclamation
COH	City of Henderson
COPCs	chemicals of potential concern
DO	dissolved oxygen
DVSR	Data Validation Summary Report
EVO	emulsified vegetable oil
EVS	Earth Volumetric Software
ft bgs	feet below ground surface
ft/day	feet per day
ft/ft	feet per foot
gpm	gallons per minute
IDW	investigation-derived waste
ISB	in-situ bioremediation
ITRC	Interstate Technology & Regulatory Council
lbs/day	pounds per day
LLAs	Licensed Location Authorizations
lbs /day	pounds per day
LVW or Wash	Las Vegas Wash
µg/L	micrograms per liter
mg/kg	milligram per kilogram
mg/L	milligrams per liter
mm/mm	millimeters per millimeter
mVs	millivolts
NDEP	Nevada Division of Environmental Protection
NERT or Trust	Nevada Environmental Response Trust
NDWR	Nevada Division of Water Resources
NMR	nuclear magnetic resonance
Nsats	normal saturated groups
ODCs	other direct costs
ORP	oxidation-reduction potential
OU-3	Operable Unit 3

Acronyms/Abbreviations	Definition
PLFA	phospholipid fatty acids
ppb	parts per billion
PRG	Preliminary Remedial Goal
psi	pounds per square inch
PVC	polyvinyl chloride
QA/QC	quality assurance/quality control
RAO	remedial action objective
RCRA	Resource Conservation and Recovery Act
RI/FS	Remedial Investigation and Feasibility Study
ROI	radius of influence
SWF	Seep Well Field
TDS	total dissolved solids
Tetra Tech	Tetra Tech, Inc.
TOC	total organic carbon
UIC	Underground Injection Control
UMCf	Upper Muddy Creek formation
UMCf-cg	UMCF-coarse grained facies
UNLV	University of Nevada at Las Vegas
USEPA	United States Environmental Protection Agency
VFAs	volatile fatty acids
Water Appropriation Permit	Permit to Appropriate the Public Waters of the State of Nevada for Environmental Purposes

CERTIFICATION

Las Vegas Wash Bioremediation Pilot 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, President, not individually, but solely in his representative capacity as President of the Nevada Environmental Response Trust Trustee

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

Title: Solely as President and not individually

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

Date: 6/26/25

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 Las Vegas Wash Bioremediation Pilot Study Results Report.

June 27, 2025

David S. Wilson, CEM
Principal Engineer
Tetra Tech, Inc.

Date

Nevada CEM Certificate Number: 2385
Nevada CEM Expiration Date: September 19, 2026

EXECUTIVE SUMMARY

This report summarizes the technical approach and findings for Phase 2 of the Las Vegas Wash Bioremediation Pilot Study (Pilot Study) conducted on behalf of the Nevada Environmental Response Trust (NERT or Trust) in Clark County, Nevada. This Pilot Study was implemented in accordance with the Nevada Division of Environmental Protection (NDEP)-approved *Las Vegas Wash Bioremediation Pilot Study Work Plan Addendum* (Tetra Tech, 2019a), which presented the results of the Phase 1 pre-design investigation and final Phase 2 Pilot Study design. The bifurcation of the Pilot Study into two distinct phases afforded the Trust the opportunity to evaluate newly available data collected during Phase 1 pre-design activities to determine the optimal objectives and implementation strategy for the Phase 2 design and implementation of the Pilot Study.

The overall objective of the Pilot Study was to demonstrate and evaluate effectiveness and implementability of in-situ bioremediation (ISB) to reduce perchlorate concentrations in a geologically complex area immediately upgradient of the Las Vegas Wash (Wash). Previous ISB treatability studies performed for NERT focused on implementation of ISB within the alluvium and more transmissive paleochannel deposits. This Pilot Study builds on those previous results by also evaluating implementation of ISB in the Upper Muddy Creek formation (UMCf), where the presence of high concentrations of perchlorate have been observed, some of which are likely contributing concentrations of perchlorate above applicable standards to the overlying alluvium and surface water due to contaminant upflux. Because full-scale remediation may be required in both alluvium and select areas within the UMCf, this Pilot Study was needed to examine ISB in varying lithologies, saturated thicknesses, and chemical/geochemical compositions of the groundwater that would likely be encountered during full-scale remediation.

Pilot Study Location Overview

The Pilot Study location was selected to evaluate remediation in a geologically complex area where perchlorate-contaminated groundwater is thought to be migrating into the Wash. The location of this Pilot Study has several unique site characteristics when compared to other treatability studies that made it ideal for testing. Key differentiators from other areas include:

- Location immediately upgradient from the Wash, where surface water sampling results indicate perchlorate-impacted groundwater may be discharging into the Wash along its southern bank downgradient of the Pilot Study area;
- Three distinct, but reasonably well-connected lithological units to be tested including:
    - Alluvium – highly heterogenous ranging from silty sand to sandy gravel with minor lenses of sandy silt and clay due to the presence of paleochannels;
    - Upper Muddy Creek formation (UMCf) – underlies the alluvium and consists of silt to silty fine sand and is locally faulted; and
    - Coarse-grained facies of the UMCf (UMCf-cg) – present in the eastern portion of the Pilot Study area where the UMCf coarsens and is interbedded with a wedge of alluvial fan material above the fault zone adjacent to the bedrock outcrop.
- Large, saturated thicknesses in all three lithological units;
- Wide range of groundwater flow rates ranging from 2 feet per day (ft/day) to 250 ft/day in the alluvium and 0.3 ft/day to 1.2 ft/day in the UMCf/UMCf-cg based on data collected during Phase 1 of the Pilot Study;
- Large, deep paleochannel upgradient of the ancestral fluvial deposits associated with the historic Wash that has flow rates that are likely representative of other paleochannels that could be targeted for remediation by a final remedy;
- Presence of a fault zone, which can influence distribution of injectate; and
- Different chemical and geochemical composition from other studies that are evaluating the UMCf (i.e., Unit 4 Source Area ISB Treatability Study).

Phase 2 Pilot Study Implementation

The final Pilot Study design presented in the Work Plan Addendum included the implementation of ISB via injections of a carbon substrate solution into three separate, small injection well transects (referred to herein as Zones 1, 2, and 3) and an approach for data collection from each zone. The remediation zones and their targeted lithologies were as follows: Zone 1 – UMCf Only, Zone 2 – Combination of Alluvium and UMCf, and Zone 3 – UMCf-cg Only. The following were installed as part of Phase 2 implementation:

- A total of 64 injection wells were installed at 37 injection well locations distributed throughout the three Pilot Study zones. Due to the large, saturated thickness of the alluvium and unconsolidated UMCf/UMCf-cg within the targeted remediation zones, injection wells were installed in single or nested well configuration depending on the targeted treatment interval along the injection well transect. 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 UMCf/UMCf-cg combined with the depth to groundwater.
- In addition to the monitoring wells installed as part of the Phase 1 pre-design effort, new monitoring wells were installed to enhance the existing monitoring well network for data collection during the Pilot Study. A total of 103 monitoring wells were installed at 43 locations that were either upgradient, cross-gradient, or downgradient of the injection well transects within the three remediation zones. This included installation of 11 initial pilot borings in Zones 1 and 3 to determine optimal placement of injection well transect.
- Five extraction wells were installed within the Pilot Study area to be used as the water source during injection activities.
- As part of the tracer dye study, a total of 18 dose-response monitoring wells were installed within each of the three zones to collect data to assess the radius of influence (ROI) of the injection wells, estimate effective porosity of the formation near each injection well transect, evaluate travel times of the injectate/dye, and determine whether water from the UMCf discharges into the alluvium and vice versa (i.e., the evaluation of the upflux component).

Phase 2 Injections

The first injection event, which was performed in all three zones of the Pilot Study, was performed in December 2020. The injectate solution consisted of carbon substrates (emulsified vegetable oil, specifically EOS® PRO, and glycerin), tracer dye (rhodamine WT for the alluvium or fluorescein for the UMCf/UMCf-cg), amendments (phosphate and sodium sulfite), and extracted groundwater from the extraction wells. Following injection of the carbon substrate solution, additional extracted groundwater was injected to optimize the distribution of the injectate solution. Two additional injection events were performed in April 2021 and October 2021 for the Zone 2 – Alluvium Only, while only one additional injection event was performed in October 2021 for the UMCf/UMCf-cg in Zones 1, 2, and 3. More frequent injections were required for the Zone 2 alluvium due to the presence of the large paleochannel and elevated groundwater flow rates present in the alluvium compared to the UMCf and UMCf-cg. The injectate solution was slightly altered from the first injection event by reducing the EOS® PRO quantity to 85 percent of the initial first injection event quantity and eliminating phosphate (analytical results indicated the presence of sufficient phosphorus in the subsurface) and tracer dye.

Phase 2 Effectiveness Monitoring Program

To evaluate ISB effectiveness, an effectiveness monitoring program was implemented to monitor both groundwater contaminant and geochemical changes before and after ISB injections. A total of 20 monitoring events (including baseline sampling) were performed during the Pilot Study. The comprehensive baseline sampling event included all newly installed injection, extraction, dose-response, and monitoring wells, as well as all 64 Phase 1 pre-design monitoring wells (LVWPS-MW201A/B through LVWPS-MW226A/B). Effectiveness monitoring events following injections generally occurred monthly, although the frequency varied slightly by remediation zone based on the targeted lithology. The monitoring well network associated with each of the three remediation zones included a total of 108 monitoring wells, which consists of 11 pre-design monitoring wells installed as part of Phase 1 and 97 newly installed monitoring wells. An additional 16 monitoring wells were also sampled less frequently during the Pilot Study timeframe to: 1) evaluate potential remedial impacts in areas located farther downgradient of the Zone 2 study area due to the paleochannel influence; and 2) determine contaminant concentrations in monitoring wells used for extraction operations during injections. 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. Lastly, as part of the on-going monthly surface water sampling, surface water samples were collected from three transect locations within the Wash that are located downgradient of the Pilot Study area between Historical Lateral and Homestead Weirs.

For the tracer dye study, baseline samples were collected from the 122 monitoring wells and 18 dose-response monitoring wells located within each of the three remediation zones and analyzed for tracer dye. Groundwater samples were collected from dose-response monitoring wells and analyzed for dye using a fluorometer during the injection process, with periodic groundwater samples collected for lab analysis for confirmation of field fluorometer readings. At the conclusion of the first injection event, samples were also collected from 100 monitoring wells located throughout the Pilot Study area. In addition, groundwater and surface water samples collected during the first six months of effectiveness monitoring events following the first injection event were analyzed for tracer dye.

Baseline aquifer testing performed prior to injection activities included single borehole dilution testing, NMR logging, and slug testing. Single borehole dilution tests were performed in select monitoring wells to evaluate and characterize groundwater flow rates in the three remediation zones. NMR logging was performed to delineate any localized preferential flow pathways within Zones 1 and 3 Pilot Study areas. Baseline slug testing was performed in 105 newly installed wells prior to injection activities to estimate baseline hydraulic conductivity, and 3 post-injection slug testing events were performed on 26 monitoring wells to evaluate potential changes to hydraulic conductivity resulting from carbon substrate injections. In addition, a network of 15 transducers were maintained in Pilot Study monitoring wells to provide data for long-term water level monitoring.

Pilot Study Findings and Conclusions

The main findings of the Pilot Study are as follows:

- Overall, groundwater within the Pilot Study area was amenable to biodegradation of perchlorate, chlorate, and nitrate. Periodic injection of emulsified vegetable oil (EOS® PRO) created biologically active zones in all three lithologic units (alluvium, UMCf, and UMCf-cg) necessary for the biodegradation of perchlorate and chlorate.
- The Pilot Study demonstrated the ability of ISB using a slow-release carbon substrate (EOS® PRO) to achieve the groundwater perchlorate Preliminary Remedial Goal (PRG) of 15 micrograms per liter (µg/L) in groundwater samples collected from several monitoring wells screened within the alluvium, UMCf, and UMCf-cg.
- Denitrification occurred rapidly and preferentially compared to perchlorate and chlorate biodegradation. Perchlorate and chlorate biodegradation generally followed denitrification and once initiated, the two reductive processes occurred concurrently at locations that recorded the best geochemical response to the carbon substrate injections.
- Although significant reductions in perchlorate and chlorate concentrations were observed in both the shallow and deep alluvium, slightly better results were observed in the intervals with lower groundwater velocities that allowed for more residence time to complete perchlorate biodegradation.
- In select treatment intervals with higher groundwater flow rates, although reducing conditions were established, there were several instances where perchlorate reductions were notably less and did not achieve concentrations less than the PRG of 15 µg/L. As a result of the heterogeneity of the subsurface and variability in groundwater flow rates, if ISB is selected as a component of the NERT final remedy, the injection well design may include multiple injection well transects and/or varying injection frequencies depending on the groundwater flow rate of the targeted formation to achieve a more uniform biologically

active treatment zone that could enhance and maximize perchlorate biodegradation to increase residence times.

- Performing periodic injections into the injection wells was shown to gradually increase the overall biodegradation in groundwater over time. One reason for this improved degradation was the use of emulsified vegetable oil (EOS® PRO), which because of its chemical nature, tends to gradually coat the soil grains along the injection well transect width over a larger area of the subsurface during subsequent injections, creating a more uniform biologically active zone over time. 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 alluvium, UMCf and UMCf-cg to accept substrate injections following three injection events indicates ISB is a feasible long-term option for groundwater remediation within the NERT Remedial Investigation Study Area. Over the course of the Pilot Study, injection pressures only slightly increased compared to the injection pressures encountered in the first injection event (i.e., 2 pounds per square inch [psi] to 13 psi in the alluvium). Additionally, no injection well maintenance was required during the 18-month Pilot Study, indicating that the subsurface continues to be amenable to periodic injections of emulsified vegetable oil (EOS® PRO).
- Dual treatment in both the alluvium and UMCf resulted in more mass being treated over time and/or improved use of carbon substrate in both alluvium and UMCf in lithologic situations similar to Zone 2 where the UMCf and overlying alluvium are connected.
- The ISB injections into Zone 3 UMCf-cg were more effective (i.e., greater subsurface distribution of injectate) than the ISB injections into Zone 1 UMCf due to the difference in the lithology within each zone. Although ISB was effective in the Zone 1 UMCf where injectate was distributed, hydrogeologic controls on groundwater flow resulted in more pronounced preferential flow pathways through the faulted UMCf and into the overlying alluvium downgradient of the injection well transect. In addition, slug tests indicated that the UMCf-cg had a higher hydraulic conductivity than the UMCf, which resulted in improved lateral distribution of the injectate in Zone 3 UMCf-cg compared to Zone 1 UMCf.
- 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 in the alluvium, UMCf, and/or UMCf-cg.
- Approximately 1,810 pounds of perchlorate were destroyed during the 18-month Pilot Study time frame. The results indicated that more mass was destroyed in the UMCf-cg within the Zone 3 study area compared to the UMCf in Zones 1 and 2 combined.
- Installation of nested wells as opposed to single clustered injection wells resulted in significant cost savings of approximately 30 percent per injection well for the dual nested configuration and 40 percent per injection well for the triple nested configuration. Results indicate that both dual- and triple-nested well configurations can effectively distribute the injectate in both horizontal and vertical directions. Nested injection wells may also provide an additional benefit of allowing application of carbon substrate at different frequencies and doses for various depth intervals at the same location, depending on depth-specific variables, such as contaminant concentrations, effective porosity, and groundwater flow velocity.

Findings of the tracer dye study are as follows:

- The tracer dye and total organic carbon concentrations in groundwater collected from the cross-gradient monitoring wells in Zone 2 indicated that the injectate was distributed both horizontally and vertically in the subsurface and confirmed a targeted ROI of 17.5 feet for the alluvium and 12.5 feet for the UMCf
- In the alluvium, the effective porosity was in the range originally anticipated based on aquifer data collected during the design phase (approximately 6 percent). In the UMCf and UMCf-cg, the effective porosity ranged from approximately 1 to 3 percent, which is less than the original conservative estimate used for distribution water calculations during the design phase. These lower effective porosity results

indicated that less distribution water was required and therefore, a field modification was made to decrease the follow-up distribution water volumes.

- In the Zone 2 alluvium, the shortest travel time to the Wash (located approximately 850 feet downgradient) was 15 days, which equates to an average of 57 feet per day (ft/day). However, the Zone 2 alluvium groundwater velocities calculated using tracer dye peaks rather than the leading edge indicated groundwater velocities ranging from 1 ft/day to 13 ft/day.
- Travel times within Zone 1 and Zone 2 UMCf indicate a groundwater flow velocity of approximately 0.3 ft/day. Zone 3 UMCf-cg groundwater velocities calculated from tracer peaks were faster than those estimated for the UMCf, with groundwater velocities ranging from less than 0.2 ft/day to 2 ft/day.
- Detections of the UMCf-injected fluorescein in samples collected from downgradient alluvial monitoring wells located within Zones 1, 2, and 3 confirmed that groundwater from the UMCf/UMCf-cg discharges into the alluvium (upflux). Furthermore, small detections of rhodamine, which was only injected into the alluvium, were present in groundwater samples collected from the underlying UMCf in Zone 2, suggesting that some degree of downflux is also occurring.

Path Forward

The Pilot Study results have generated a substantial data set and provided valuable information with respect to the effectiveness and implementability of an ISB remedy that will be used in the forthcoming FS to evaluate the technology, its application within the NERT Remedial Investigation Study Area, and associated costs.

1.0 INTRODUCTION

On behalf of the Nevada Environmental Response Trust (NERT or Trust), Tetra Tech, Inc. (Tetra Tech) has prepared this *Las Vegas Wash Bioremediation Pilot Study Results Report* (referred to as Results Report) for Operable Unit (OU) 3 of the NERT Remedial Investigation (RI) Study Area, 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 Las Vegas Wash Bioremediation Pilot Study (referred to as the Pilot Study) was conceptualized in 2017 with an overall project objective to demonstrate and evaluate the effectiveness and implementability of in-situ bioremediation (ISB) to reduce perchlorate concentrations in a geologically complex area immediately upgradient from the Las Vegas Wash (referred to as the Wash). The Pilot Study was separated into two distinct phases (Phases 1 and 2), which afforded the Trust the opportunity to evaluate newly available data to determine the optimal strategy for design and implementation of the final pilot study. As part of this Pilot Study, several documents (two Work Plans and one Treatability/Pilot Study Modification) were submitted and approved by NDEP. A summary of these documents and their significance to the Pilot Study are presented below:

- *Las Vegas Wash Bioremediation Pilot Study Work Plan* (Tetra Tech, 2017) (referred to as Work Plan) – The original Work Plan, which was submitted on September 22, 2017, presented a conceptual design for implementation of the ISB Pilot Study and provided details on the Phase 1 pre-design activities to be conducted prior to finalizing Phase 2 Pilot Study design. The Phase 1 pre-design activities of the Work Plan were conceived and implemented to supplement information about the lithology, hydrogeology, and contaminant distribution of two potential Pilot Study areas selected for pre-design investigation located immediately upgradient of the Wash near the Pabco Road and Calico Ridge Weirs. The Work Plan was approved by NDEP on October 16, 2017.
- *Treatability/Pilot Study Modification No. 2 – Las Vegas Wash Bioremediation Pilot Study* (Tetra Tech, 2018) (referred to as Modification No. 2) – Following NDEP approval of the Work Plan, Phase 1 of the Pilot Study, which included both pre-design field activities and laboratory bench-scale studies, was implemented from March 2018 to July 2018. Based on the results of the initial Phase 1 pre-design activities, additional pre-design work was recommended in Modification No. 2 to properly define the extent of contamination and develop a more thorough understanding of the complex geology in the Pilot Study area. Modification No. 2 was submitted on August 17, 2018 and subsequently approved by NDEP on August 23, 2018.
- *Las Vegas Wash Bioremediation Pilot Study Work Plan Addendum* (Tetra Tech, 2019a; referred to as the Work Plan Addendum) – Following NDEP approval of Modification No. 2, the additional Phase 1 pre-design field work was performed from August 2018 to January 2019. The combined Phase 1 pre-design activities produced valuable information that significantly expanded the understanding of the lithology, hydrogeology, and contaminant distribution in the Pilot Study area and informed the conceptual site model near the Wash, which will benefit the Trust's overall Remedial Investigation/Feasibility Study (RI/FS) implementation strategy. The results of the Phase 1 pre-design field and laboratory activities, combined with additional experience gained through the ongoing implementation of other NERT treatability studies, were used to refine the final Pilot Study objectives and design. The Phase 1 results and refined Phase 2 Pilot Study objectives and design were presented in the Work Plan Addendum, which was submitted to NDEP on November 11, 2019. The Work Plan Addendum was approved by NDEP on December 11, 2019.

Phase 2 of the Pilot Study, which included installing injection and monitoring wells, performing ISB injections, and implementing an effectiveness monitoring program, began in December 2019 and was completed in December 2022. All Phase 2 work was implemented in accordance with the NDEP-approved Work Plan Addendum, with minor field adjustments as noted herein. This Results Report presents a summary of the Phase 2 Pilot Study activities and an evaluation of the Phase 2 results. It is anticipated that this Results Report will be utilized during the preparation of the OU-3 FS.

1.1 OBJECTIVES

The activities described in this Results Report are being conducted to support remedy selection as part of the RI/FS process. Currently, the RI is being conducted in three operable units (OU): OU-1 (former manufacturing operations); OU-2 (offsite area immediately north of OU-1 and generally south of Galleria Drive); and OU-3 (offsite area generally north of Galleria Drive and extending northward to the Wash). These investigation sub-areas are now collectively referred to as the NERT RI Study Area (**Figure 1**). The Pilot Study area is located within OU-3 as shown in **Figure 1**.

The remedial action objective (RAO) established for OU-3, located north of Galleria Drive, and extending to the Wash, is to mitigate the discharge of chemicals of potential concern (COPCs) in groundwater to the Wash (Ramboll Environ, 2024). Based on recent data collected during the on-going surface water sampling program, an estimated 24.6 pounds per day (lbs/day) of perchlorate mass flux to the Wash was measured between the Pabco Road and Rainbow Gardens weirs (Ramboll, 2022). As a result, additional technical evaluation of location-specific remedial options was deemed necessary to support remedy selection in areas adjacent to the Wash.

As established in the Work Plan and Work Plan Addendum, the overall objective of the Pilot Study is to demonstrate and evaluate the effectiveness and implementability of ISB in a geologically complex area where perchlorate-contaminated groundwater is migrating into the Wash as evidenced from previous investigations in the NDEP Downgradient Study Area (AECOM, 2018). This Pilot Study builds on the results from the previous ISB treatability study performed downgradient of the Athens Road Well Field (AWF) near the City of Henderson (COH) Bird Viewing Ponds (Tetra Tech, 2016) and the Seep Well Field (SWF) Area Bioremediation Treatability Study (Tetra Tech, 2019b). An overview of the ISB treatability and pilot studies performed as part of NERT's overall RI/FS implementation strategy are provided in Section 2.2.1.

Although the previous COH and SWF area bioremediation treatability studies focused only on the alluvium and more transmissive paleochannel deposits, this Pilot Study also evaluated implementation of ISB in the UMCf, in which ISB field testing for remediation of perchlorate had not been evaluated previously. It is important to evaluate the effectiveness and implementability of ISB in the UMCf due to the presence of high concentrations of perchlorate that have been observed in the UMCf, some of which are likely contributing concentrations of perchlorate above applicable standards to the overlying alluvium and surface water due to contaminant upflux. Therefore, this Pilot Study was needed to examine ISB in varying lithologies, saturated thicknesses, and chemical/geochemical compositions of the groundwater that would likely be encountered if utilized as part of full-scale remediation.

Upon completion of the various OU-3 area treatability and pilot studies and OU-3 RI and risk assessments, it will be the objective of the OU-3 FS to produce an array of potential remedies for OU-3 by incorporating all available study data, nature and extent of COPCs (as identified in the forthcoming OU-3 RI Report) and potential risks to human health and the environment (as identified in the various forthcoming risk assessments relevant to OU-3) . This Pilot Study is intended to provide key information needed for the FS to evaluate design, optimization/scale-up, and cost of an ISB approach and its effectiveness to achieve the RAO of mitigating the perchlorate mass flux to the Wash if ISB is selected as part of the final remedy.

1.2 REPORT ORGANIZATION

This report is organized as follows:

- **Introduction (Section 1.0):** Provides the primary objectives of this Pilot Study and organization of this report.
- **Technology Description (Section 2.0):** Provides an overview of perchlorate biodegradation, a summary of previous and on-going ISB treatability and pilot studies performed to date, and a summary of lessons learned from previous studies that were taken into consideration in the design and execution of this Pilot Study.
- **Pilot Study Location Overview (Section 3.0):** Provides a description of the Pilot Study location, geology, hydrogeology, and nature and extent of contamination.
- **Phase 2 Pilot Study Approach (Section 4.0):** Presents a high-level overview of the Pilot Study design, including introduction of three separate Pilot Study zones.
- **Phase 2 Pilot Study Implementation (Section 5.0):** Summarizes Phase 2 field Pilot Study activities including access and permitting, completion of the Phase 1 bench-scale study, site preparation, injection and monitoring well installations, injection events, aquifer testing. and effectiveness monitoring.
- **Zone 1 Summary and Evaluation of Results (Section 6.0):** Presents the Zone 1 objectives, geology and hydrogeology and discusses the chemical, geochemical, and microbial results during the Pilot Study.
- **Zone 2 Summary and Evaluation of Results (Section 7.0):** Presents the Zone 2 objectives, geology and hydrogeology and discusses the chemical, geochemical, and microbial results during the Pilot Study.
- **Zone 3 Summary and Evaluation of Results (Section 8.0):** Presents the Zone 3 objectives, geology and hydrogeology and discusses the chemical, geochemical, and microbial results during the Pilot Study.
- **Long-Term Water Level Monitoring of the Pilot Study Area (Section 9.0):** Presents the results from the long-term water level monitoring program implemented for the larger Pilot Study area.
- **Surface Water Monitoring (Section 10.0):** Presents the results from the monthly surface water samples collected from the Wash in areas downgradient of the Pilot Study footprint.
- **Summary of Key Findings (Section 11.0):** Presents the overall findings from the Pilot Study and provides cost considerations for future ISB implementation within the NERT RI Study Area.
- **References (Section 12.0):** Lists the documents referenced in this report.

2.0 TECHNOLOGY DESCRIPTION

The following subsections briefly describe the perchlorate biodegradation process, ISB as a treatment technology for perchlorate, and its application as related to the NERT RI Study Area.

2.1 MICROBIOLOGY AND BIODEGRADATION OF PERCHLORATE

Perchlorate is the anionic component of ammonium perchlorate. 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 function as an 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 (Interstate Technology & Regulatory Council [ITRC], 2008). Although chlorate biodegradation generally precedes perchlorate 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 ubiquitous and versatile in the subsurface. As a result, successful groundwater treatment requires understanding the chemical, geochemical, physical, geological, and hydrogeological conditions at a site, and then engineering 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. 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 conditions are indicative of conditions wherein the aquifer is depleted of DO and nitrate is generally 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 naturally 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 that 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. 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: 1) water-soluble substrates such as glycerin or molasses; 2) slow-release substrates such as emulsified vegetable oil (EVO) or Hydrogen Release Compound®; and 3) solid substrates such as compost or wood chips. Combinations of these substrates are also used in practice.

2.2.1 Previous Bioremediation Applications

To date, five ISB studies have either been completed or are on-going throughout the NERT RI Study Area. These studies range from small, short duration proof of concept studies to larger-scale pilot studies. ***Table 1*** presents a high-level overview of each of the ISB studies and their key differentiators.

Table 1 In-Situ Bioremediation Treatability and Pilot Study Overview

Study Features	Groundwater ISB TS	SWF Area ISB TS	Galleria Drive ISB TS[1]	Las Vegas Wash ISB Pilot Study			Unit 4 Source Area ISB TS[2]
Status	Completed	Completed (Final reporting in progress)	Phase 1 complete; Phase 2 not implemented	Completed			Phase 1 complete; Phase 2 on-going
Differentiators	Proof of Concept	Different geology; lower flow rate	UMCf; unique geochemistry	First Pilot Study, geologically complex area, three lithological units to be treated			High concentration source area
Targeted Treatment Lithology	Alluvium	Alluvium	UMCf	Alluvium	UMCf	UMCf-cg	UMCf
Targeted Treatment Interval (ft bgs)	20 to 35	15 to 45	65 to 85	25 to 95	80 to 175	60 to 180	83 to 118
General Lithology	Sandy silt with gravel (paleochannel)	Sand, gravel, silt lenses	Silt/clay layers; gypsum throughout	Sand, gravel, some silt lenses (paleochannel)	Silt to silty fine sand; little to no gypsum	Coarse-grain, silty sand with up to 10% gravel	Mostly clay, some silt
Groundwater Flow Velocity (ft/day)	32	10	3	2 to 30	0.01 to 0.6	0.01 to 1.2	0.5 to 1
Primary Reagent Injected	Emulsified Vegetable Oil	Emulsified Vegetable Oil	Emulsified Vegetable Oil	Emulsified Vegetable Oil			Molasses
Injection Strategy	Periodic; Injection Wells	Periodic; Injection Well Transects	Not Applicable[1]	Periodic; Nested Injection Well Transect	Periodic; Single/Nested Injection Well Transect	Periodic; Single/Nested Injection Well Transect	Daily Pulse; Injection/ Extraction via Wells Installed in Grid Pattern
Maximum Groundwater Concentrations							
Perchlorate (µg/L)	34,000	25,000	14,000	8,600	16,000	13,000	5,300,000
Chlorate (µg/L)	130,000	67,000	19,000	24,000	22,000	18,000	33,000,000
Nitrate (mg/L)	17	18	38	23	17	17	87
Sulfate (mg/L)	2,200	4,700	19,000	2,400	3,100	2,700	1,400
TDS (mg/L)	7,600	6,700	43,000	5,900	8,500	6,200	58,000

Notes:
TS – Treatability Study
ft bgs – feet below ground surface
ft/day – feet per day
µg/L – micrograms per liter
mg/L – milligrams per liter
TDS – total dissolved solids
UMCf – Upper Muddy Creek formation
UMCf-cg – UMCf-coarse-grain facies
(1) The Galleria Drive Bioremediation Treatability Study was not implemented due to the sale of the land parcel originally proposed for the treatability study. Alternative locations for implementing the study were evaluated, but site conditions that were deemed unfavorable for the

implementation of the study. The Trust has elected to terminate the study as it felt a sufficient data set will be available for the FS (Tetra Tech, 2020).

(2) The Unit 4 Source Area ISB Treatability Study is located within OU-1 and is a treatability study focusing on ISB of a high concentration source area.

As presented in ***Table 1***, each study has a unique set of characteristics, with variations in targeted lithology, targeted treatment interval (i.e., variation from relatively small to large saturated thicknesses), groundwater flow velocities, groundwater concentrations (perchlorate concentrations ranging from 8,600 to 5,300,000 micrograms per liter [μg/L]), and geochemical characteristics (such as high sulfate and total dissolved solids [TDS] concentrations). Because of these variations in treatability and Pilot Study conditions, important data related to effectiveness, implementability, and cost of an ISB remedy in a variety of lithological settings is necessary and will be available for evaluation in the forthcoming OU-3 FS.

Key findings and lessons learned to date from previous and on-going ISB treatability and pilot studies indicate that ISB could be a viable technology within the NERT RI Study Area. Overall, groundwater chemical, geochemical, and microbial data collected so far indicate that slow-release carbon substrate (e.g., EVO) has successfully demonstrated the ability to create, sustain, and facilitate biodegradation of perchlorate in groundwater under a range of groundwater flow velocity conditions (average of 10 to 32 ft/day) in a small portion of a fast-flowing alluvial paleochannel as well as in general alluvial material consisting of sand, gravel, and silt lenses. Key findings from previous studies that were incorporated into the design and execution of this Pilot Study are summarized below.

- Nitrate, chlorate, and perchlorate degradation has been initiated rapidly following carbon substrate injections through the creation of a biologically active zone, which has continued to sustain perchlorate biodegradation for an extended period of time. Denitrification (nitrate biodegradation) occurred 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.
- ISB through the injections of EVO, which has been the carbon substrate selected for laboratory and field testing in most treatability studies to date, has proven to be effective in creating and sustaining reducing conditions in groundwater and can achieve groundwater perchlorate concentration reductions to below the Preliminary Remedial Goal (PRG) of 15 µg/L in groundwater within the alluvium. Groundwater concentrations below the perchlorate PRG have been attained and sustained in samples collected from several groundwater monitoring well locations during previous studies.
- Relatively high groundwater flow rates (e.g., 32 ft/day) and short residence times have generally not been an impediment to ISB of perchlorate.
- Periodic injections into the injection wells over time has been 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 injection well transect, thereby attaching to increasingly more of the subsurface and creating a more uniform barrier over time.
- Based on the data collected to-date, it appears that a paired injection well configuration (two injection wells installed in a cluster formation but screened across different treatment intervals) does not provide any additional benefits over single injection well construction. Paired injection wells could still be considered in areas with large, saturated thicknesses (i.e., greater than 30 feet) or where there are distinct separate lithological layers or zones across large, targeted treatment intervals. Paired injection wells could also be considered when there is a clear hydrogeologic separation of uniform lower permeability zones from high permeability zones throughout a subsurface vertical zone.
- The ability of the alluvium to accept substrate injections over numerous subsequent injection events indicates ISB is a feasible long-term option for alluvial groundwater within the NERT RI Study Area.

Results from the SWF Area Bioremediation Treatability Study indicate that common injection well maintenance techniques can be successfully employed if injection pressures increase and/or injection rates decrease over time after numerous injection events (Tetra Tech, 2022).

- High TDS concentrations (greater than 5,000 mg/L) in previous study areas did not have an impact on the development of a microbial consortium with the ability to biodegrade perchlorate, nor did it appear to have an impact on acclimation time for perchlorate biodegradation.
- Limited sulfate reduction was observed in groundwater during treatability studies performed in the alluvium. 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 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 the alluvial setting are often relatively high and may not provide sufficient residence time for sulfate biodegradation to occur. Limited sulfide production has also been observed, indicating that microbial-based sulfate reduction has been 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.

3.0 PILOT STUDY LOCATION OVERVIEW

The Pilot Study area is located upgradient from the Wash on Clark County and City of Henderson-owned property (**Figure 2**). This area was selected for the Pilot Study to evaluate remediation in a geologically complex area where perchlorate-contaminated groundwater is thought to be migrating into the Wash. The location of this Pilot Study has several unique site characteristics when compared to other treatability studies that made it ideal for testing. Key differentiators from other areas include:

- Location immediately upgradient from the Wash
- Three lithological units to be tested – alluvium, UMCf, and coarse-grained UMCf (UMCf-cg)
- Large saturated thicknesses in all three lithological units
- Wide range of groundwater flow rates
- Large, deep paleochannel upgradient of the ancestral fluvial deposits associated with the historic Wash that has groundwater flow rates that are likely representative of other paloechannels that could be targeted for remediation by a final remedy
- Fault-zone channel
- Different chemical and geochemical composition from other studies that are evaluating the UMCf (i.e., Unit 4 Source Area ISB Treatability Study; see ***Table 1***)

This section provides descriptions of the geology, hydrogeology, and nature and extent of contamination within the Pilot Study area based on data collected during Phase 1 of the Pilot Study. Complete details on the previous Phase 1 results are presented in the Work Plan Addendum (Tetra Tech, 2019a) which was approved by NDEP on December 11, 2019. Additional details regarding hydrogeologic properties of the various units based on Phase 2 activities are further discussed in Sections 6, 7 and 8 of this Results Report.

3.1 GEOLOGY

A conceptual block diagram of the Pilot Study area is presented on **Figure 3**. Within the Pilot Study area, the ground surface slopes downward to the northeast toward the Wash. Bedrock outcrops in the eastern portion of the study area and influences both groundwater flow and local geology. The bedrock outcropping in the study area is mapped as Horse Springs formation, which locally consists of carbonate rocks interbedded with sandstone, siltstone, and shale (Plume, 1989; Bell and Smith, 1980). The lithology encountered during drilling suggests that the bedrock outcrop on the eastern side of the study area is part of a fault-bounded block and that unconsolidated valley-fill sediments of the alluvium and UMCf were deposited on the western, down-dropped portions of the fault zone.

Saturated alluvium, ranging from silty sand to sandy gravel with minor lenses of sandy silt and clay, is present throughout the study area, overlying the UMCf. The thickness of the alluvium is greatest near the Wash, where sand and gravel extend to approximately 120 feet bgs. Often, main basin drainages such as the Wash have existed for a long time and have underlying paleochannels near their current location. The existence of numerous paleochannels converging on the current Wash location implies that a significant paleochannel exists at or near the current Wash location. Based on the depths to the erosional contact between the alluvium and UMCf observed in the study area, the deep alluvium adjacent to the Wash likely reflects an ancestral fluvial deposits associated with the historic Las Vegas Wash (further described in the forthcoming Remedial Investigation Report for OU-3). During the drilling activities performed for the Pilot Study, a generally north-south oriented paleochannel was identified through the center of the Pilot Study that trends towards the Calico Ridge Weir, as shown on **Figure 3**.

The UMCf in the Pilot Study area is primarily composed of silt to silty fine sand. The deeper portions of the UMCf are semi-consolidated with abundant gypsum. Near the bedrock outcrop in the eastern portion of the Pilot Study area, the UMCf coarsens and is interbedded with a wedge of alluvial fan material, which likely represents coarse-grained facies of the UMCf (UMCf-cg). The UMCf-cg consists of silty sand with up to 10 percent angular to subangular gravel interbedded with finer grained UMCf . These gravels are commonly angular carbonate clasts, suggesting the sediments originated locally from the Horse Springs formation.

In the eastern portion of the study area, bedrock was encountered below the UMCf-cg. Bedrock encountered at depth was primarily sandstone and siltstone, which is consistent with mapped lithologies of the Horse Springs formation (Plume, 1989). The depth to bedrock, which ranges from approximately 100 feet bgs to 235 feet bgs, is likely fault controlled as shown on **Figure 3**. Faulting adjacent to the bedrock outcrop has resulted in deep, unconsolidated UMCf-cg up to 235 feet bgs on the western, down-dropped side of the fault zone.

3.2 HYDROGEOLOGY

Conceptually, the groundwater flow in the Pilot Study area is governed by two primary hydrogeologic influences: 1) the Wash and its underlying ancestral fluvial deposits; and 2) the fault zone and associated paleochannels. Because the materials filling the fault zone and paleochannels are generally more transmissive than the surrounding materials, groundwater flow appears to be converging toward the fault zone and paleochannels **(Figure 3)**. Hence, the unconsolidated UMCf is likely discharging into the ancestral fluvial deposits underlying the Wash and into the fault zone.

Groundwater was generally encountered at approximately 30 feet bgs in the alluvium throughout the Pilot Study area. Once saturation was encountered, all underlying materials were also saturated. Groundwater flow in the northern portion of the study area is towards the east-northeast, approximately paralleling the Wash. Groundwater flow in the center and southern portions of the Pilot Study area is primarily towards the north, paralleling the paleochannel and fault zone described in Section 3.1.

The magnitudes of the vertical gradients are generally small and vary from weakly upward to weakly downward. These relatively low gradients are reflective of reasonably good connections between the various lithological units. Connectivity between the alluvium and UMCf/UMCf-cg was a key design consideration for implementation of ISB in the Pilot Study area, where the alluvium and underlying UMCf/UMCf-cg are both contaminated and contaminant flux between lithologic units is likely.

Previous characterization efforts during Phase 1 indicated an average hydraulic conductivity of approximately 92 ft/day in the alluvium, with groundwater flow velocities ranging from about 2 to 250 ft/day. The highest groundwater flow velocities (91, 100, and 251 ft/day) were measured in shallow monitoring wells located immediately adjacent to the Wash within the ancestral fluvial deposits. The groundwater flow velocities within approximately 500 feet of the Wash in the Pilot Study area are significantly faster (approximately an order of magnitude greater) than observed in the tributary paleochannels in the vicinity of the SWF Area Bioremediation Treatability Study area and the In-Situ Bioremediation Treatability Study performed near the COH Bird Viewing Ponds (Tetra Tech, 2016). This discovery is important because the high groundwater flow velocities near the Wash will complicate implementation of potential future remedies. Therefore, placement of a remedial system near the Wash requires careful consideration and should account for these higher groundwater flow velocities. The areas away from the immediate vicinity of the Wash indicate that alluvial groundwater flow velocities range from about 2 to 30 ft/day, which is similar to the flow velocities encountered in the alluvium in the previous Groundwater ISB Treatability Study near the COH ponds (Tetra Tech, 2016) but higher than the SWF Area ISB Treatability Study (Tetra Tech, 2019b).

In the western portion of the Pilot Study area, the unconsolidated UMCf had an average hydraulic conductivity of approximately 1 ft/day. In the eastern portion of the Pilot Study area below the alluvium near the fault zone adjacent to the bedrock outcrop, the UMCf-cg had an average hydraulic conductivity of 6 ft/day. With respect to groundwater flow rates, the unconsolidated UMCf and UMCf-cg have significantly lower groundwater flow velocities than the alluvium, averaging 0.3 ft/day and ranging from 0.01 to 1.2 ft/day. A comparison of the unconsolidated UMCf and UMCf-cg groundwater flow velocity estimates shows that the average and range of velocities for each unit are nearly identical. The similar hydrogeologic properties of the two facies of the UMCf are not surprising as the UMCf-cg still contains a significant portion of fines and is commonly interbedded with fine grained UMCf.

Transducer data from monitoring wells collected since 2018 within the study area and near the Wash have indicated that water levels within many of the monitoring wells were visibly influenced by water level fluctuations in the Wash, which show daily groundwater elevation changes that correspond closely to the Wash surface water elevation changes. Three weirs (Bostick, Calico Ridge, and Lower Narrows) are located in portions of the Wash that are in the general vicinity of the study area. The weirs have significant effects on the nearby perchlorate concentrations in groundwater because the lower concentration surface water tends to enter the groundwater system just upgradient of the weirs and groundwater tends to seep back into the Wash downgradient of the weirs. The effects of the complex flow pattern and associated perchlorate concentration changes were incorporated into the planning and execution of an effectiveness monitoring program to determine remedial effectiveness.

3.3 NATURE AND EXTENT OF CONTAMINATION

Soil, groundwater, and surface water samples were collected during the Pilot Study to evaluate the vertical and horizontal distribution of COPCs. A detailed discussion of analytical results from the Phase 1 pre-design investigation is presented in the Work Plan Addendum, Section 3.2 and Appendix H (Tetra Tech, 2019a). The sections that follow present a summary of data from the Work Plan Addendum and provide an overview of the nature and extent of COPCs in the affected environmental media based on previous data collection in the study area.

3.3.1 Soil and Groundwater

In general, perchlorate and chlorate were detected in both soil and groundwater samples collected from the alluvium and unconsolidated UMCf/UMCf-cg. Perchlorate concentrations in soil samples ranged from less than 0.0011 to 17 milligram per kilogram (mg/kg), with detections primarily in the saturated alluvium and unconsolidated UMCf/UMCf-cg at depths up to 170 feet bgs. However, soil samples collected from 170-230 feet bgs within the fault zone adjacent to the bedrock outcrop had perchlorate detections ranging from 0.13 to 0.32 mg/kg. A summary of the groundwater concentration ranges of perchlorate and chlorate prior to study implementation, as well as other noteworthy parameters with respect to the bioremediation process, is presented in ***Table 2***.

Table 2 Concentration Ranges in Groundwater – Pilot Study Area

Analyte	Concentrations in the Alluvium (10 – 120 ft bgs)	Concentrations in the Unconsolidated UMCf/UMCf-cg (60 – 234 ft bgs)	Concentrations in the Semi-consolidated UMCf(1) (75 – 205 ft bgs)
Perchlorate (μg/L)	110 – 8,600	<0.50 – 16,000	<0.50 – 1,400
Chlorate (μg/L)	<10 – 24,000	<10 – 22,000	<20 – 3,500
Nitrate as N (mg/L)	2.6 – 23	<0.11 – 17	<0.28 – <5.5
Sulfate (mg/L)	640 – 2,400	1,400 – 3,100	2,000 – 14,000
TDS (mg/L)	1,900 – 5,900	3,200 – 8,500	4,200 – 36,000

Notes:
ft bgs – feet below ground surface
μg/L – micrograms per liter

mg/L – milligrams per liter
TDS – total dissolved solids
UMCf – Upper Muddy Creek formation
UMCf-cg – Upper Muddy Creek formation – coarse grained facies

1. Monitoring wells LVWPS-MW219B and LVWPS-MW219C, which are screened in alternating layers of unconsolidated UMCf, semi-consolidated UMCf, and reworked Horse Springs Formation, were grouped with semi-consolidated UMCf.

3.3.2 Surface Water

Pursuant to the *Groundwater and Surface Water Monitoring Program, Sampling and Analysis Plan, Revision 3* (Ramboll, 2022), surface water samples are currently being collected monthly to evaluate the mass flux of perchlorate migrating into the Wash. Surface water samples are analyzed for perchlorate, chlorate, and TDS. The results from these sampling events are presented as part of the Semi-Annual and Annual Performance Monitoring Reports and detailed evaluation of the surface water and mass loading to the Wash will be performed as part of the forthcoming OU-3 RI.

Based on the July – December 2022 sampling results presented on Figure 9, the latest 2022 Semi-Annual Performance Memorandum (Ramboll, 2024 and Attachment 1 to this Results Report), the calculated perchlorate mass entering the Wash downstream of Pabco Road was 50.3 lbs/day during the performance period. This value is the difference in estimated loading between Pabco Road and Rainbow Gardens (Ramboll, 2024). Pilot Study activities were performed in an upgradient location of where the largest increase in perchlorate mass flux into the Wash occurs, namely immediately downstream of Calico Ridge Weir, which has an estimated mass flux of 25.8 lbs/day.

In addition to the ongoing monthly surface water sampling program, additional surface water samples were collected as part of the Phase 1 pre-design activities in July 2018 between Historic Lateral and Homestead Weirs, with perchlorate concentrations ranging from 1.6 J to 72 μg/L. The highest perchlorate concentration of 72 μg/L was detected in surface water at a location downgradient of Lower Narrows Weir. Where surface water samples were collected in a transect configuration, perchlorate concentrations were often greater near the southern bank than near the northern bank of the Wash, which indicates perchlorate-impacted groundwater may be discharging into the Wash along its southern bank downgradient of the Pilot Study area.

In general, chlorate concentrations in surface water follow a similar pattern to perchlorate concentrations. Chlorate in surface water samples collected between the Historic Lateral and Homestead Weirs during the Phase 1 pre-design ranged from 79 to 370 μg/L. Like perchlorate, chlorate concentrations were commonly highest near the southern bank of the Wash downgradient of the Pilot Study area.

4.0 PHASE 2 PILOT STUDY APPROACH

This section summarizes the Phase 2 Pilot Study approach presented in the Work Plan Addendum. As explained in Section 1.1, the purpose of the Pilot Study is to collect data needed to evaluate the key FS criteria (effectiveness, implementability, and cost) and to gather additional data in this complex geologic setting to inform the evaluation of ISB as a potential component to the final remedy. The Pilot Study approach was developed to assess the complexities of the study area, including significant geological heterogeneity, large and deep paleochannels, fault-zone channels, large saturated thicknesses of alluvium, UMCf, and UMCf-cg, and perchlorate and chlorate at concentrations and depths greater than previously expected. Additionally, based on the data collected during the Phase 1 activities and other investigations (AECOM, 2018), groundwater within the Pilot Study area flows into the Wash and contributes to the perchlorate mass flux observed between the Historic Lateral and Rainbow Gardens Weir. The discovery of these complexities presented the opportunity to refine the general approach of the Pilot Study toward a more detailed set of objectives that are specific to effectiveness, implementability, and cost of ISB in different lithologies in an area upgradient of the Wash that will likely require remediation as part of the full-scale remedy implemented for OU-3.

The final Pilot Study design presented in the Work Plan Addendum included three separate, small injection transects (referred to herein as Zones 1, 2, and 3) and an approach for data collection from each zone. The remediation zones and their targeted lithologies are as follows: Zone 1 – UMCf Only, Zone 2 – Combination of Alluvium and UMCf, and Zone 3 – UMCf-cg Only (shown on **Figure 4**). Advantages to this zoned approach included the following:

- Smaller, isolated zones allowed for an evaluation of more detailed objectives, and therefore, maximized the usefulness of the data collected during this study with respect to effectiveness, implementability and costs as they relate to a particular lithological setting.
- The design of injection transects into separate zones allowed for isolation and evaluation of ISB in three different subsurface environments (deep alluvial paleochannel and large saturated thicknesses of both UMCf and UMCf-cg) to evaluate ISB performance independent of the interactions with other areas. For example, a single, large injection well transect would have made it more difficult to discern how ISB performed in any individual setting (i.e., alluvium, UMCf, or UMCf-cg) and therefore, would have limited the formation-specific data obtained during the Pilot Study to inform the potential full-scale design and associated cost components during evaluation of an ISB remedy in the FS.
- Evaluation of UMCf and UMCf-cg only in Zones 1 and 3 allowed for assessment of ISB effectiveness associated with contaminant upflux (i.e., does remediation of the UMCf/UMCf-cg in an area with a known upward gradient have any effect on concentrations in the overlying alluvium groundwater).
- Separate, smaller transects minimized the footprint and disturbed area associated with the Pilot Study.
- Hydraulic monitoring during injections and extraction of groundwater could be monitored in these distinct environments to collect data for updating the existing groundwater model for more accurate evaluation of possible extraction or injection-based components for the final remedy (i.e., pump and treat) during the FS.

The activities performed during Phase 2 to complete this approach presented in the Work Plan Addendum are described in Section 5; and the objectives, location and orientation of the injection well transect(s), number and spacing of injection wells, targeted injection intervals, injection protocols, and effectiveness monitoring results are presented for Zones 1, 2, and 3 in Sections 6, 7, and 8, respectively.

5.0 PHASE 2 PILOT STUDY IMPLEMENTATION

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

5.1 ACCESS AGREEMENTS AND PERMITTING

This section presents a summary of the access agreements and multiple permits that were obtained prior to implementation of the Pilot Study.

5.1.1 Access Agreements

The Trust obtained access agreements for all field Pilot Study activities (including site preparation activities, installation of wells, injections, and effectiveness monitoring) from the applicable agencies and property owners, which included COH, Clark County, and the United States Bureau of Reclamation (BOR) as follows:

- The initial COH agreement to install and sample wells was approved on March 6, 2018 and remains active through December 31, 2024. Licensed Location Authorizations (LLAs) under this agreement were obtained on July 22, 2020 for all Phase 2 monitoring wells installed on COH property (LLAs PWPM2020005811, PWPM2020005812, PWPM2020005813, PWPM2020005814, and PWPM2020005815). The Trust obtained an additional access agreement from COH for use of the COH landfill as a staging area on October 14, 2020. NERT submitted a request to Terminate the Right of Entry and the COH accepted the Notice of Termination on October 18, 2022.
- The Clark County agreement, which included road improvements, installation of extraction, injection, and monitoring wells, injections, and effectiveness monitoring, was approved on May 15, 2018 and remains active through September 1, 2023.
- The BOR agreement, which was approved for installation and use of monitoring wells on October 11, 2018, was authorized under the March 2018 *Finding of No Significant Impact LC-17-19 for Final Environmental Assessment, Right of Use – Downgradient Study Area Activities* (BOR, 2018). Although the time duration is not specifically stated in the March 2018 document, the agreement says it will be in place for the duration of the investigations of the OU-3 Study Area.

5.1.2 Permitting

The following permits were required prior to implementation of the Pilot Study.

- Dust Control Permit – Per the Clark County Department of Air Quality, a dust control permit was required because the soil disturbance during the Pilot Study installation activities was greater than 0.25 acres. The Dust Control Permit was issued on March 17, 2020. Following completion of drilling activities, the dust control permit was terminated on June 16, 2020.
- Well Permits – Pilot Study activities required submittal of a NAC 534.441 Monitoring Well Drilling Waiver and a NAC 534.320 Notice of Intent Card prior to installation of extraction, injection, and monitoring wells. The Monitoring Well Drilling Waiver also included as an attachment a completed, signed, and notarized Affidavit of Intent to Abandon a Monitoring Well. A total of nine waivers were submitted and approved for Phase 2 Pilot Study activities in 2020. As required, all extraction, injection, and monitoring wells were drilled by a licensed well driller pursuant to Nevada Revised Statutes 534.160 and were constructed pursuant to NAC Chapter 534 – Underground Water and Wells.

- Underground Injection Control (UIC) Permit – A UIC Permit Modification to the existing permit GU07RL-51057 was required for authorization of the injection of carbon substrate, amendments, dye, and water into the saturated subsurface. The UIC Permit Modification was issued on October 16, 2020 and will remain active until a notice of termination is submitted following abandonment of all injection wells active under GU07RL-51057. The UIC permit requires semi-annual injection reports, which have been submitted since authorization of the permit, to provide a summary of injection activities during each reporting period.
- Water Appropriation Permit – Pursuant to Nevada Revised Statutes 533.335 and 533.437, an application for a Permit to Appropriate the Public Waters of the State of Nevada for Environmental Purposes (Water Appropriation Permit) was submitted to support the extraction of groundwater from nearby monitoring wells used as distribution water during injection operations. The Water Appropriation Permit was issued on September 28, 2020. The Water Appropriation Permit requires annual extraction reports, which have been submitted since authorization of the permit, to be provide data on the total water extracted during the calendar year.

5.2 COMPLETION OF PHASE 1 BENCH-SCALE STUDIES

As part of Phase 1 pre-design activities, bench-scale laboratory studies were performed by the University of Nevada at Las Vegas (UNLV) using site-specific soil and groundwater from the Pilot Study area. The bench-scale laboratory studies included:

- Batch sorption and column sorption/desorption tests – The sorption tests were performed for both the alluvium and UMCf to understand the interactions of site-specific soil with the EVO, including substrate movement and how it desorbs over time, to support biodegradation.
- Column Diffusion Studies – These studies were designed to simulate the upward migration of perchlorate from the UMCf into the alluvium and help understand the hydraulic, physical, and chemical relationship between these two lithological zones.

Although the bench-scale studies began during the Phase 1 pre-design time period, the studies were not completed at the time of the preparation and submittal of the Work Plan Addendum. As a result, the results are summarized herein, with the final UNLV bench-scale report that provides complete details of the experimental approach, presentation of the data, and analysis of results provided in Appendix A.

5.2.1 Batch Sorption and Column Sorption/Desorption

Bench-scale laboratory studies have been performed as part of previous and on-going treatability studies and have provided significant data on the biodegradation potential of perchlorate and other electron acceptors, as well as information on the potential longevity of the carbon substrate. As explained in Sections 2.7 and 3.3 of the Work Plan Addendum (Tetra Tech, 2019a), although batch microcosm testing was not performed for soil and groundwater from the Pilot Study areas, microcosm testing has been performed on similar alluvium and UMCf soil and groundwater as part of the SWF Area Bioremediation Treatability Study (Tetra Tech, 2019b). Results from these batch microcosm studies have shown that most of the nitrate in groundwater is degraded completely within four days when using EVO as the carbon substrate. Batch microcosms also indicated that perchlorate degraded completely within 10 days for trials in the UMCf using EVO and within 20 days in the alluvium with the same carbon substrate.

EVO batch sorption/desorption tests on soil and groundwater from the UMCf were performed to understand the interactions of site-specific soil with EVO and compare these results to previous ranges determined as part of bench-scale testing for the SWF Area Bioremediation Treatability Study. As part of this testing, different quantities of wet soil from the upper UMCf (58-65 feet bgs) were placed in centrifuge tubes with known quantities of EVO. Standard adsorption test procedures of centrifuging, supernatant extraction, and soil incineration were used to determine the adsorption capacity of soil. Results indicated that the oil adsorption in wet soil ranged from 0.015 to 0.093 grams of oil/gram of soil for the alluvium and 0.054 to 0.1 grams of oil/gram of soil for the UMCf, which is approximately 2 to 2.5 times less than the adsorption results for the UMCf determined during the bench-scale study associated with the on-going SWF Area Bioremediation Treatability Study. This indicated that the quantities of EVO required for the Pilot Study were likely to be lower in comparison to the quantities required for the SWF Area Bioremediation Treatability Study.

As part of the sorption/desorption column testing, four columns were prepared, with two columns packed with soil from the alluvium and two columns packed with soil from the UMCf. These column tests were run at low, medium, and high soil sorption capacity determined from the batch sorption tests. The tests were also operated using the approximate field groundwater flow rates that were determined in the field, which was done so by applying pressure to simulate field conditions. Results indicated for the low, medium, and high sorption capacities are summarized below.

- Low Sorption Capacity Experiment – Results indicated that the amount of oil (measured as chemical oxygen demand) that was released from the effluent was twice as much in the UMCf columns compared to the alluvium columns. This was due in part to the capacities being higher in the UMCf compared to the alluvium.
- Medium Sorption Capacity Experiment – A similar observation was determined for the medium sorption capacity experiment when comparing the elution between the UMCf and the alluvium. However, the amounts that were eluted between the low sorption experiments and the high sorption experiments were similar. This indicated that doubling of the initial EVO dosage in either the UMCf or the alluvium is unlikely to increase the elution in the field, which further indicated that both of these media retain more of the injectate and have greater longevity at higher dosages. It was also noted that the oil retention in the soil columns was independent of distance within the column indicating that field injection of EVO will likely result in fairly uniform distribution downgradient of the injection point, which augurs well for in situ bioremediation success. In general, independent of soil types (alluvium or UMCf), more than 95% of the oil was retained in the soil over the 82 days of the experiment’s operation. This result indicates that field longevity would be expected to be prolonged, which is also a positive indication of ISB success. However, it may be noted that hydraulic flow is multi-directional in the field and subject to lithological variability over much larger distances, which would likely mean that field longevity could be less than that observed in a more controlled and smaller laboratory setting.
- High Sorption Capacity Experiment – Results indicated that a majority of the injectate was either retained by the soil or could have floated at the top of the soil column. In particular, this observation was noted for the UMCf column for which the dosage was higher compared to the alluvium. Irrespective of the alluvium or UMCf, the results indicated that the saturation capacities determined by the batch sorption tests should be compared to sorption capacities from previous studies, literature studies, and EVO protocols in order not to needlessly overdose the groundwater. This finding is also important due to observations of clogging and difficulty of maintaining flows in the laboratory column studies (both alluvium and UMCf) and the need to resort to pressurized injections to maintain, restore, and simulate estimated field flow velocities.

5.2.2 Column Diffusion Study

Column diffusion studies were also performed to simulate the upward migration of perchlorate from the UMCf into the alluvium and help establish the hydraulic, physical, and chemical relationship between these two lithological zones. Overall, the results indicated that diffusion of the major targeted ions, namely, nitrate, chlorate, and perchlorate, occurred irrespective of the pressure gradients that were applied for the tests. The diffusion patterns based on initial concentrations, effluent concentrations, and attainment of concentrations less than detection limits in the effluent were different for nitrate compared to those observed for chlorate and perchlorate. This result was likely due to the different ionic properties of these three anions. The study also noted that the attainment of concentrations below sample detection limits in the effluent for both perchlorate and chlorate after a certain period of operation were also likely because a certain portion of the ions remain in the soil that is subject to flushing due to the attainment of chemical equilibrium. Lastly, the results indicated that the diffusion of ions in the UMCf soils occurred even at pressure gradients as low as 0.1 millimeter per millimeter (mm/mm). However, for the more clayey soils, much higher-pressure gradients (as high as 2.97 mm/mm) were required for flows to occur and diffusion of ions to be observed.

The overlying conclusion from these column diffusion studies demonstrates and would suggest that if the UMCf is not remediated, diffusion of ions is likely to occur over time into the alluvium. It is understood the pressure gradients would vary within the Pilot Study area, and therefore, the resident gradient at a particular vicinity would govern or control the amount of ionic diffusion that would occur. The column diffusion tests also indicate that diffusion of ions at a particular location would also depend on the type of ion, its concentration in the UMCf, and the clay content and other lithological properties. It is entirely possible that some vicinities within the UMCf could have limited but prolonged diffusion, whereas other locations may be undergoing substantially more diffusion in a shorter time period.

5.3 INITIAL SITE PREPARATION

Existing access roads within the general Pilot Study area were unimproved dirt roads that, in select locations, were too soft and/or rutted to allow vehicles to safely access the work areas. In order to implement the work, gravel was placed in select locations to slightly raise the road elevation, improve the driving surface, and/or reduce the potential for erosion and release of fugitive dust during drilling, injection, and/or monitoring activities. Additionally, a staging area was established for temporary storage of materials and equipment during drilling and injection activities, to park or turn-around vehicles, and to perform other work activities. This staging area was located within proximity to the general Pilot Study area within the fenced COH landfill.

5.4 PILOT STUDY WELL NETWORK

This section provides a summary of the well installation activities that were completed as part of Phase 2 Pilot Study implementation. In accordance with the approved Work Plan Addendum, extraction, injection, and monitoring wells were installed at strategic locations to maximize Pilot Study effectiveness and evaluate ISB performance (Tetra Tech, 2019a). The final Pilot Study well network is presented on **Figure 5**, which also illustrates the groundwater potentiometric contours from the baseline groundwater sampling event in October 2020. Well construction details are provided in Appendix B, along with the well construction and soil boring logs.

Field activities associated with injection and monitoring well installation were performed in two mobilizations from February through June 2020 on Clark County property and September through October 2020 on COH property. Prior to drilling activities, Tetra Tech contacted USA North Utility Locating Services to identify potential subsurface utilities in the remote Pilot Study area, where there is a low potential for buried utilities. In addition, hand augering was performed to a depth of 5 feet bgs for each location prior to drilling to check for utilities prior to using mechanical equipment.

5.4.1 Injection Well Installation

Based on the design presented for each zone in Section 5.0 of the Work Plan Addendum, a total of 64 injection wells were installed at 37 injection well locations distributed throughout the three Pilot Study zones. Due to the large, saturated thickness of the alluvium and unconsolidated UMCf/UMCf-cg within the targeted remediation zones, injection wells were installed in either a single or nested well configuration depending on the targeted injection interval along the injection well transect. The injection well depths and targeted screened interval vary depending on zone and location within the zone, and were based on the depth to water, depth of the alluvium/UMCf/UMCf-cg contact, and subsequent contact of the semi-consolidated UMCf or bedrock observed during well installation. Depending on the thickness of the targeted treatment interval, the nested injection well configurations either consisted of two or three separately screened injection wells installed within the same borehole to optimize carbon substrate distribution. Where injection wells were installed in both the alluvium and the UMCf in Zone 2, separate boreholes were used for the nested injection wells installed in the alluvium, and single injection wells installed in the unconsolidated UMCf, due to the different injection well spacings and to maintain better control of the carbon substrate injections. Details of the final injection well layouts for each remediation zone are provided in Sections 6.2, 7.2, and 8.2, for Zones 1 through 3, respectively.

Injection wells were installed using rotosonic drilling methods. All injection wells were constructed with 2-inch diameter, Schedule 40 or 80 polyvinyl chloride (PVC) depending on the planned well depth; generally, Schedule 40 PVC was used for wells screened shallower than approximately 150 feet bgs, while Schedule 80 PVC was used for deeper injection wells. Injection well screen size and sand pack at each injection well location was determined based on the lithology observed during drilling. Generally, injection wells screened in the alluvium were installed with 0.020-inch slotted screen and #3 silica sand, while injection wells screened in the UMCf/UMCf-cg were installed with 0.010-inch slotted screen and #2/16 silica sand. The sand filter pack was installed in the annular space around the well screen and extended 2 feet above the top of the screened interval. The remainder of the annular space was backfilled with a minimum 2 feet of hydrated bentonite, followed by neat cement grout to ground surface. To ensure adequate space for the sand pack and bentonite seal, a minimum 2-inch annulus was provided for each injection well.

Because of the large, saturated thickness that was targeted for bioremediation (up to 175 feet depending on targeted lithology and location within the injection well transect), a pragmatic approach for determining injection well screen lengths was adopted for purposes of Pilot Study implementation. Specifically, depending on the injection well location, associated lithology, and preferential flow zones within each remediation zone, each injection well was constructed with varying injection well screen lengths of up to a maximum of 35 feet. Exact screen intervals were determined based on the lithology observed during drilling. A minimum 5-foot spacing with a bentonite seal was placed in between screened intervals to minimize communication between injection intervals. The majority of injection wells were completed with flush-mounted, traffic-rated well boxes, at an elevation of approximately 0.5-inch above grade. Injection wells within the Zone 3 area included a combination of both flush-mounted and above-ground completions. For injection wells installed immediately downgradient of the COH landfill stormwater drainage, aboveground well completions were used to reduce the potential for surface water runoff to inadvertently enter the well. Following injection well construction, but no sooner than 48 hours after construction was completed, each of the newly installed injection wells was developed. Following installation, all injection wells were surveyed by a Nevada-licensed land surveyor.

5.4.2 Monitoring Well Installation

To provide a sufficiently effective monitoring well network for each of the three remediation zones, the final Pilot Study design included both newly proposed and existing monitoring wells installed as part of Phase 1 pre-design activities and other site investigations. New monitoring wells were installed at a total of 43 locations at varying distances upgradient, cross-gradient, and downgradient of the injection well transects within the three remediation zones and included an initial 11 monitoring wells (referred to herein as pilot borings) in Zones 1 and 3 to determine optimal placement of the injection well transects (further discussed in Section 6.2 and 8.2, respectively). The new monitoring locations each consisted of either a single monitoring well or a cluster of monitoring wells to evaluate remediation within the various targeted injection intervals within the alluvium and/or unconsolidated UMCf/UMCf-cg. At two locations within each remediation zone, a cluster of three dose-response monitoring wells were installed immediately downgradient of the injection well transects to support the tracer dye study (summarized in Appendix C). Dose-response monitoring wells were screened across the same depth intervals as the nearby injection wells. In Zone 1 and Zone 3, the third dose-response monitoring well at each location was screened in the alluvium immediately above the alluvium-UMCf contact to evaluate if injectate was entering the alluvium in the immediate vicinity of the injection well transects. Details of the final effectiveness monitoring well layout for each remediation zone are provided in Sections 6.2, 7.2, and 8.2 for Zones 1 through 3, respectively.

Monitoring wells were constructed of 2-inch Schedule 40 or 80 PVC casing and screened with 2-inch diameter, slotted PVC well screen at varying intervals within the alluvium and unconsolidated UMCf/UMCf-cg. Monitoring wells were installed by the same methods and procedures as the injection wells discussed in Section 5.4.2. Final depths and screened intervals for the paired/clustered monitoring wells were selected based on lithology encountered during installation of the initial boring at each location. Monitoring wells were completed with flush-mounted, traffic-rated well boxes at an elevation approximately 0.5 inch above grade. One monitoring well within the Zone 3 study area was completed above-ground due to its location immediately downgradient of the COH landfill stormwater drainage. Following monitoring well construction, but no sooner than 48 hours after construction was complete, each of the newly installed monitoring wells was developed. Following installation, all monitoring wells were surveyed by a Nevada-licensed land surveyor.

5.4.3 Extraction Well Installation

The Pilot Study design incorporated the use of groundwater from extraction wells installed within the Pilot Study area as the water source during injection activities, based on the considerations presented in Section 5.4.2 of the Work Plan Addendum and past experience at the SWF Area Bioremediation Treatability Study. Five extraction wells were installed based on initial hydraulic testing (borehole dilution and slug tests) and the estimated water needs for the Pilot Study injection activities. Extraction wells were constructed of 6-inch Schedule 80 PVC casing and screened with 6-inch diameter, wire-wrapped stainless steel well screen. In general, extraction well screens were installed immediately above the UMCf contact to maximize the alluvial water column above the extraction well screen. Extraction wells were installed in cross-gradient locations outside of the remediation zones to minimize potential hydraulic influence of extraction activities on concurrent injections within the remediation zones, as shown on **Figure 5**. Additionally, monitoring well LVWPS-MW206B, which is a 4-inch monitoring well installed as part of Phase 1 pre-design activities, was also used as an extraction well due to its ideal location between remediation zones, and given slug testing and nuclear magnetic resonance (NMR) results indicated a hydraulic conductivity of up to 191 ft/day. As described in Section 5.1.2, a Water Appropriation Permit was obtained to authorize extraction of groundwater from LVWPS-MW206B and the five newly installed wells to be used as distribution water during injection operations.

5.4.4 Management of Investigation-Derived Waste

Investigation-derived waste (IDW) generated during well installation was managed in accordance with applicable state, federal, and local regulations and as described in the Field Sampling Plan, Revision 1 (ENVIRON, 2014). During Phase 2 implementation of the Pilot Study, 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 well development.

Investigation-derived soil waste was containerized onsite in plastic lined, 20 cubic-yard roll-off bins. The roll-off bins were labeled to indicate contents, source, and date when accumulation began. Soil cuttings contained in the roll-off bins were sampled for profiling purposes, with one composite soil sample collected from one roll-off bin. The samples were analyzed for the following parameters: volatile organic compounds by United States Environmental Protection Agency (USEPA) Method 8260B; Resource Conservation and Recovery Act (RCRA) 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 on-site treatment in the groundwater extraction and treatment system.

5.5 INJECTIONS

Following completion of injection and monitoring well installations (Section 5.4) and baseline groundwater monitoring (described in Section 5.7), the first injection event, which included carbon substrate, amendments, tracer dye, and water, occurred in December 2020. Two additional injection events, which included carbon substrate, select amendments, and water, were performed during the Pilot Study in April 2021 and October 2021. The following sections provide an operational summary of activities related to the three injection events, while zone-specific details (such as injection quantities and rates) for Zones 1, 2, and 3 are provided in Sections 6, 7, and 8, respectively. A detailed summary of the dye tracer injections performed as part of the first injection event and results is provided in Appendix C. Injection summary tables for each injection event are provided in Appendix D.

5.5.1 Injection Event 1

Mobilization and set-up activities associated with the first injection event began on November 30, 2020. Injections into injection wells at all three remediation zones (Zones 1, 2, and 3) were performed from December 7, 2020 to December 22, 2020. The injections were performed in general accordance with the Field Guidance Document for Injections (provided as Appendix K in the Work Plan Addendum) by Cascade Technical Services under Tetra Tech oversight and direction. Cascade Technical Services supplied a custom-built injection/extraction system that was equipped with variable high-speed multi-stage centrifugal pumps, injection/extraction hosing, mixing tanks, meters, valves, and fittings.

Prior to injection activities, submersible pumps were installed at each of the six extraction wells (LVWPS-EW01 through LVWPS-EW05 and LVWPS-MW206B). Extracted groundwater was pumped from the extraction well field to the tanks used for batch mixing of the carbon substrate solution via PVC pipe or hose. Prior to the injections, step-rate water injection tests were performed using extracted groundwater prior to the injection into each remediation zone to determine injection rates so that the injection design could be modified based on the performance of each injection well. During the step-rate tests, the extracted groundwater was pressure-injected into the injection wells through a manifold with hoses equipped with quick disconnect fittings. Pressure gauges and a flow totalizer were used to monitor the pressure and flow rates during injection at each injection well. The injection pressures and flow rates per injection well were maximized to the extent possible based on injection operation capabilities and the ability of the formation to accept the injectate under pressures within the limits of the UIC Permit.

Following the determination of achievable injection rates and pressures, the carbon substrate injection solution was prepared in batch mixing tanks using extracted groundwater for dilution of the carbon substrate. The injectate solution included carbon substrate, namely EOS® PRO, additional amendments (glycerin, phosphate solution, and sodium sulfite), and tracer dye (either Rhodamine WT or fluorescein depending on the targeted zone). 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. In addition, tracer dye was injected into each remediation zone during the first injection event. Fluorescein was introduced into the UMCf during the first injection event in each of the three zones, while a different dye, Rhodamine WT, was introduced into the alluvium during the first injection event.

A summary of the key factors considered when determining injectate quantities, the calculation process that was used for preliminary estimates, and the results of those estimations were summarized in Appendix I of the Work Plan Addendum. The quantities of carbon substrate and amendments required for each remediation zone during the first injection event were based primarily on:

- Final construction details of the injection wells and associated lithological and soil characteristics of the alluvium and unconsolidated UMCf/UMCf-cg that were observed during well installation;
- Chemistry and geochemistry of the groundwater collected during the baseline groundwater sampling event that occurred immediately prior to injections from the newly installed Pilot Study injection and monitoring wells;
- Stoichiometric requirements for the carbon substrate based on the mass of perchlorate and other electron acceptors that will migrate through the Pilot Study area;
- Results and findings of the previous University of Nevada at Las Vegas (UNLV) laboratory studies, field treatability studies, and literature case studies.

Based on the key information described above, the final quantities of carbon substrate, amendments (glycerin, phosphate solution, and sodium sulfite), and tracer dye were added to the batch mixing tanks. Prior to injecting, the carbon substrate solution was diluted with extracted groundwater at a ratio of 1:4 parts of EOS® PRO: extracted groundwater. The injectate solution was then thoroughly mixed, with samples collected and tested for specific gravity to ensure the injectate solution was adequately mixed prior to injection into the subsurface. Samples were also collected and analyzed with field fluorometers to measure the final tracer dye concentration prior to injections. Once sampling confirmed the injectate solution was adequately mixed, the injection process began by performing pressurized injections of the injectate solution into the injection wells via an injection manifold system that was connected to up to 18 injection wells at a single time, with the number of injection wells connected varying by zone. Injection quantities into each injection well varied based on injection well spacing, injection well screened intervals, and lithology. Specific quantities injected into each of the three remediation zones are provided in Appendix D and discussed in Sections 6.3, 7.3, and 8.3 for Zones 1, 2, and 3, respectively. During active injections, both flow rate and pressure were measured at each injection well and recorded in electronic field data collection forms. Injection rates and sustained pressures varied based on injection well screen length, targeted formation, and local lithologic heterogeneity.

During active injections, groundwater from the nearby downgradient dose-response monitoring wells was monitored for the presence of dye by visual observation and field fluorometers to determine when breakthrough of the dye occurred and log the concentrations of dye at specific cumulative injection volumes. Samples of the injectate solution and groundwater from the dose-response monitoring wells were also collected for laboratory analysis on a daily basis during active injections to confirm the field-measured dye concentrations. The real-time data collected from the dose-response monitoring wells during the active injections were then used to calculate the effective porosity for the alluvium, UMCf, and UMCf-cg within each of the remediation zones. Calculations of effective porosity based on dose-response monitoring assumed that when the concentration of the injected tracer peaks in the samples collected from the dose-response monitoring wells, the injectate has evenly filled the cylinder of soil between the injection well and that dose-response monitoring well. Therefore, the effective porosity of the target formation can then be calculated using the volume of injectate as a fraction of the volume of that cylinder. It should be noted that the actual tracer distribution will be increasingly nonuniform with increasing heterogeneity of the subsurface. Therefore, and as specified in the Work Plan Addendum, multiple dose response wells were installed and tested within each of the target remedial zones to provide a more robust study of effective porosity and illustrate variability in estimated effective porosity introduced by subsurface heterogeneity. Following breakthrough of dye in the dose-response monitoring wells, field personnel also visually monitored other nearby (non-dose-response) monitoring wells for tracer dye to better assess the radius of influence (ROI) of the injection wells. Lastly, charcoal samplers were installed prior to the injections in nearby monitoring wells (upgradient, downgradient, and cross-gradient monitoring wells in the immediate vicinity of the injection well transects within each remediation zone) and retrieved (along with a grab groundwater sample) following completion of the first injection event.

Upon completion of carbon substrate injections, distribution water was injected into each injection well to optimize the distribution of carbon substrate both within the injection well transects and in the vicinity of the injection areas. The quantity of distribution water was designed to be equivalent to approximately one pore volume of groundwater and was estimated based on the designed spacing of the injection wells, saturated thickness of the treatment interval, and estimated porosity of the formation. Prior to injection of distribution water, the new real-time data collected from the dose-response monitoring wells during the active carbon substrate injections were used to refine the effective porosity and recalculate the distribution water quantities using these new values of effective porosity.

This recalculation process resulted in no changes in distribution water quantities for the Zone 2 alluvium. However, the field-determined effective porosity was less than originally estimated for the Zones 1, 2, and 3 UMCf/UMCf-cg. As a result, the Zones 1, 2, and 3 UMCf and UMCf-cg distribution water volumes were proportionately reduced using the new porosity estimates. A more detailed discussion of these results is provided for Zones 1, 2, and 3 in Sections 6.3, 7.3, and 8.3, respectively.

As with the dilution water, all distribution water used during injections was obtained by extracting groundwater from the extraction wells (LVWPS-EW01 through LVWPS-EW05 and LVWPS-MW206B). Although the lower than anticipated porosity estimates resulted in lower distribution water volumes, at a minimum, each of the injection wells were flushed with at least six borehole volumes (calculated based on the borehole diameter, screened interval, and filter pack porosity).

Following completion of the injections, all equipment was dismantled and removed from the Pilot Study area with demobilization of the majority of injection equipment by December 23, 2020. Due to the frac tanks containing extracted groundwater during injections, the tanks were cleaned prior to their removal from the Pilot Study area. Frac tanks, residual materials, and equipment were demobilized in late December 2020 through early January 2021.

5.5.2 Injection Event 2

The second injection event was performed from April 12 to April 21, 2021, approximately 4 months after the first injection event using the same injection process described in Section 5.5.1. The second injection event included injections into only the Zone 2 alluvium, which required a slightly increased injection frequency compared to the UMCf injections, due to the presence of the large paleochannel and elevated groundwater flow rates in the alluvium within Zone 2.

As with the first injection event, extracted groundwater used for dilution and distribution water during injections was obtained from six extraction wells (LVWPS-EW01 through LVWPS-EW05 and LVWPS-MW206B). The injectate solution for the second injection event included carbon substrate, namely EOS® PRO, select amendments (glycerin and sodium sulfite), and extracted groundwater used as dilution water (using the same ratio of 1:4 parts of EOS® PRO: extracted groundwater). The carbon dosage for the second injection event was reduced to approximately 85 percent of the dosage that was injected during the first injection event. This reduction in substrate allowed 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. Because some of the carbon from the injections remains adsorbed to the soil grains and does not get utilized, the same dosage is not always required in subsequent injection events. Previous treatability studies have also indicated sustained perchlorate concentration reductions using a reduced quantity in subsequent injection events. Phosphate solution was also not injected during the second event because the Phase 1 soil sampling and analyses from the Pilot Study area indicated the presence of bound phosphorus in the subsurface. Therefore, while it was deemed necessary to initially add dissolved phosphorus in the first injection event for this micronutrient to not be limiting during the rapid microbial growth expected with EVO addition, it was not required for subsequent injections. Lastly, tracer dye was not included in the injectate solution.

Upon completion of carbon substrate injections, distribution water was again injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. As with the dilution water, all distribution water used during injections was obtained by extracting groundwater from the extraction wells. The volume of distribution water was increased proportional to the decrease in carbon substrate solution to maintain the same total injection volume, despite the reduced carbon dosage.

5.5.3 Injection Event 3

Mobilization and set-up activities associated with the third injection event began on October 4, 2021. Injections into injection wells in all three remediation zones (Zones 1, 2, and 3) were performed from October 7 to October 24, 2021, approximately 6 months after the second injected performed in Zone 2 alluvium and 10 months after the first injection event performed in the UMCf/UMCf-cg within Zones 1, 2, and 3. The third injection event was performed using the same injection process described in Section 5.5.1.

Extracted groundwater used for dilution and distribution water during injections was once again obtained from six extraction wells (LVWPS-EW01 through LVWPS-EW05 and LVWPS-MW206B). The injectate solution for the third injection event included carbon substrate, namely EOS® PRO, select amendments (glycerin and sodium sulfite), and extracted groundwater used as dilution water (using the same ratio of 1:4 parts of EOS® PRO: extracted groundwater). Similar to the second injection event, the injectate solution during the third injection event again included a carbon dosage of approximately 85 percent of the dosage that was injected during the first event and phosphate was not included in the mixture for the same reasons described in Section 5.5.2. Similar to the second injection event, no tracer dye or phosphorus was included in the third injection event.

Upon completion of substrate injections, distribution water was injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. In general, the volume of distribution water was increased proportional to the decrease in carbon substrate solution to maintain the same total injection volume, despite the reduced carbon dosage. All distribution water used during injections was obtained by extracting groundwater from the extraction wells (LVWPS-EW01 through LVWPS-EW05 and LVWPS-MW206B. Although the lower than anticipated porosity estimates resulted in lower distribution water volumes, at a minimum, each of the injection wells was flushed with at least six borehole volumes (using the borehole diameter, screened interval, and filter pack porosity).

5.6 AQUIFER TESTING

Several aquifer tests were performed during the Pilot Study, including NMR logging, slug tests, borehole dilution tests, and implementation of a tracer study. Specifically, NMR logging was performed within each of the 11 pilot boring monitoring wells in March 2020 to further delineate any localized preferential flow pathways within the Zone 1 and Zone 3 Pilot Study areas prior to injection well installation. Slug tests were performed on all newly installed monitoring wells to determine pre-injection hydraulic conditions. Borehole dilution tests were performed in newly installed monitoring wells at 30 new locations, with the focus being on characterizing the groundwater flow rates in areas downgradient of the injection wells. Lastly, a tracer dye was included in the injections as discussed in Section 5.5.1 to provide additional data to aid in the evaluation of study objectives including the ROI of the injection wells, travel times of the injectate/dye, upflux from the UMCf to the overlying alluvium, and the effective porosity of the formation near each injection well transect.

Following carbon substrate injections, which included the injection of a tracer dye, samples were collected throughout the Pilot Study area and analyzed for the presence and concentration of dye. Periodic slug tests were also periodically performed during the Pilot Study to examine subsurface conductivity changes following carbon substrate injections. In addition to slug testing, transducers were installed in select upgradient, cross-gradient, and downgradient monitoring wells within each of the three remediation zones and in monitoring wells near the extraction wells. Data was downloaded from the transducers on a quarterly basis to evaluate hydraulic response during injection and extraction operations, determine vertical and horizontal gradients in the alluvium and UMCf, and assess localized groundwater/surface water interactions over time within the Pilot Study area.

This section summarizes the general procedures of the aquifer testing activities. The results of the aquifer testing for the Zone 1, Zone 2, and Zone 3 study areas are presented in Sections 6.6, 7.6, and 8.6. The supporting summary technical memorandums for the NMR logging, borehole dilution testing, slug testing (including AQTESOLV [HydroSOLVE, 2007] plots), transducer data collection, and dye tracer study are presented in Appendices E, F, G, H, and C, respectively.

5.6.1 Nuclear Magnetic Resonance Logging

NMR logging was performed within each of the 11 pilot boring monitoring wells in March 2020 to further delineate any localized preferential flow pathways within the Zone 1 and Zone 3 Pilot Study areas. This technology can be used in open borings or PVC-cased wells to provide high-resolution downhole estimates of hydraulic conductivity, total water content, total water-filled porosity, mobile porosity (approximately equivalent to effective 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 depended on the diameter of the well, because larger diameter wells require a larger 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 monitoring well to assess the possibility of preferential flow. NMR logging results for Zones 1 and 3 are presented in Appendix E and discussed in Sections 6.6.1 and 8.6.1.

5.6.2 Single-Borehole Dilution Testing

Single-borehole dilution tests were performed in select monitoring wells to evaluate volumetric flow in the alluvium, UMCf, and UMCf-cg within the remediation zones, with focus on characterizing the groundwater flow rates in areas downgradient of the injection wells. These tests consisted of mixing a tracer compound into the groundwater in a monitoring well and observing the decline in tracer concentration in the monitoring well as a function of time using downhole instruments (Pitrak et al. 2007). The decline in tracer concentration in the well was due to dilution by volumetric groundwater flow, with results used to estimate groundwater velocity in the immediate vicinity of the monitoring well.

Tracers used in single-borehole dilution tests are typically chloride or bromide salts, or fluorescent dyes. Due to the tracer injection component of the Pilot Study discussed in Section 5.6.5, fluorescent dye tracers were not used. The high specific conductance of groundwater in the Pilot Study area supported the use of distilled water or stabilized Lake Mead water (SLMW) as a tracer. Distilled and SLMW water have successfully been used as the tracer during pre-design testing activities. As a result, single-borehole dilution tests using SLMW as the tracer were performed in 30 newly installed monitoring wells in October and November 2020. The supporting summary technical memorandum is provided in Appendix F. Borehole dilution test results for each of the remediation zones are discussed in Sections 6.6.2, 7.6.1, and 8.6.2.

5.6.3 Slug Tests

Slug tests were performed in 105 newly installed wells including 11 pilot boring monitoring wells, 89 monitoring wells, and 5 extraction wells to estimate location-specific aquifer hydraulic conductivity in the screened interval of wells within the Pilot Study area. Pilot boring monitoring wells were tested in February and March 2020, with the remainder of the baseline slug tests conducted over two events in June/July 2020 and October/November 2020. In addition, three post-injection slug testing events were performed on 26 monitoring wells in June/July 2021, January 2022, and June/July 2022 to evaluate potential changes to hydraulic conductivity resulting from carbon substrate injections.

The slug tests were performed in general accordance with ASTM International Standard D 4044-96 (ASTM International, 2008). Prior to conducting each slug test, the water level in the monitoring well was measured manually with an electronic water level probe to determine the static groundwater level. An electronic pressure transducer/data logger was suspended in the monitoring well and water levels were monitored manually until static conditions were reestablished. A falling-head test was then conducted by displacement of groundwater by the insertion of either a solid or pneumatic slug 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.

At the end of each test, the pressure transducer was removed from the monitoring 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. The supporting summary technical memorandum (including AQTESOLV [HydroSOLVE, 2007] plots is provided in Appendix G, Slug testing results for each of the remediation zones are discussed in Sections 6.6.3, 7.6.2, and 8.6.3

5.6.4 Transducer Installation and Data Collection

As part of Phase 1 pre-design activities, transducers were installed in 15 monitoring wells within four monitoring well cluster locations, which included LVWPS-MW201A/B, LVWPS-MW206A/B/C/D/E, LVWPS-MW210A/B/C/D/E, and LVWPS-MW222A/B/C. These same 15 monitoring wells remained instrumented during Phase 2 activities. Multiple wells in a cluster were instrumented to provide data for characterization of vertical gradients. One barometric transducer was also deployed in the Pilot Study area to facilitate the compensation of water level monitoring data for changes in barometric pressure. Data were recorded on 15-minute intervals and downloaded every 3 to 6 months during the Pilot Study until they were removed in June 2022. Results of the transducer data collection and evaluation are presented in Appendix H and Section 9.2.

5.6.5 Tracer Injection

As part of the injection design, tracer dyes were injected and periodically monitored to provide additional data to aid in the evaluation of study objectives. Specific objectives of the tracer study were as follows:

- Assess ROI of the injection wells;
- Estimate effective porosity of the formation near each injection well transect;
- Evaluate travel times of the injectate/dye; and
- Determine whether water from the UMCf discharges into the alluvium and vice versa (i.e., the evaluation of the upflux component).

Prior to injection activities, baseline groundwater and surface water samples were submitted to Ozark Underground Laboratory (OUL) to establish background concentrations of tracer dye in the Pilot Study area to ensure that no tracer dye was already present in the system from tests performed elsewhere, industrial processes, or any other sources. Samples of EVO were also submitted to OUL to confirm that tracer dye could be accurately measured (i.e., the presence of EVO does not inhibit or interfere with the tracer dye analysis) in Pilot Study samples that contained EVO. Results of this laboratory testing confirmed that fluorescein and rhodamine concentrations could be accurately measured in samples that contained EVO.

To collect data to evaluate the objectives described above, two separate fluorescent dye tracers were used during the Pilot Study. Fluorescein was introduced into the UMCf during the first injection event in each of the three zones, while Rhodamine WT introduced into the alluvium during the first alluvium injection event into Zone 2. Fluorescein and Rhodamine WT were selected so that commercially available field probes (previously purchased as part of the Downgradient RI) could be used to perform field assessment of tracer dye concentrations during injection. Rhodamine WT was introduced into Zone 2 alluvium at a target concentration of 800 parts per billion (ppb), and fluorescein dye was introduced into the UMCf/UMCf-cg in Zone 1, Zone 2, and Zone 3 at a target concentration of 400 ppb. The concentration of dye was selected in part based on the detection limits of the field probes. In addition, the concentration of injected dye was such that it was visible during injections and near the injections but would dilute to non-visible levels prior to reaching the Wash. Dye was included as part of the injectate during the first injection event in each zone, which was performed between December 7 and December 22, 2020.

As described in Section 5.4.2, two dose-response monitoring well clusters, each consisting of three monitoring wells, were installed approximately 7 feet from the injection well transects within each of the three zones to determine the effective porosity of the targeted formation. During the injection process, groundwater from dose-response monitoring wells was monitored using visual observation and fluorometers to log the concentrations of dye at specific cumulative injection volumes and to determine when breakthrough occurred at each dose-response monitoring well. Groundwater samples were also collected from the dose-response monitoring wells for laboratory analysis on a daily basis during active dye injections to confirm the field-measured dye concentrations. Lastly, samples of the injectate solution were periodically collected and analyzed for dye to confirm the targeted injection dye concentrations.

Field personnel also visually monitored nearby cross-gradient and downgradient monitoring wells during injection activities for tracer dye to better assess the ROI of the injection wells. Whenever visual breakthrough of dye occurred at nearby monitoring wells during injection activities, periodic field measurements of dye concentration were also performed at those monitoring locations. Additionally, charcoal samplers were installed prior to the injections in a total of 100 nearby monitoring wells located upgradient, downgradient, and cross-gradient of the injection well transect within each remediation zone. The benefit of charcoal samplers was that the charcoal would continue to collect dye within the monitoring well over a period of time by concentrating the dye within the sample, which improved the chances of detecting low concentrations of dye. Following completion of the injection event, the charcoal samplers were retrieved from the monitoring wells and submitted to OUL for dye analysis. Upon retrieval of the charcoal sampler, a groundwater sample was also collected from each monitoring location. Analysis of the charcoal samplers, which were present in monitoring wells throughout injection activities, allowed for a qualitative evaluation of tracer dye presence, even at relatively low concentrations, in groundwater at monitoring wells located where groundwater velocities were sufficiently high that dye may appear prior to completion of injection activities. However, charcoal samplers were intended to provide qualitative data only (i.e., presence/absence of tracer dye). Following a positive detection of tracer dye on a charcoal sampler, the concurrently collected groundwater sample was analyzed to determine tracer dye concentration. This two-step analysis process allowed for presence/absence analysis of charcoal samplers at all locations but also permitted quantitative analysis of groundwater samples when the dye was found to be present.

Charcoal samplers, groundwater samples, and surface water samples were also periodically collected during the Pilot Study during the first six months following the first injection event (further discussed in Section 5.7). Groundwater samples were analyzed for the dye to collect data to evaluate the remaining primary objective of assessing potential upflux. A summary of the dye tracer study and analytical results are provided in Appendix C and discussed in Sections 6.6.4, 7.6.3, and 8.6.4 for Zones 1, 2, and 3, respectively.

5.7 EFFECTIVENESS MONITORING PROGRAM

This section describes the monitoring program that was implemented during the Pilot Study, which consisted of periodic groundwater monitoring, surface water sampling, and aquifer testing. The data collected was used to assess the effectiveness of ISB in reducing contaminant concentrations, determine the frequency and timing of subsequent injection events, and monitor for changes in the hydrogeologic environment during the study.

5.7.1 Groundwater Monitoring

To evaluate ISB effectiveness, an effectiveness monitoring program was implemented to monitor both groundwater contaminant and geochemical changes following injection events. As part of this program, groundwater samples were periodically collected from both existing and newly installed monitoring wells within the Pilot 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 effluent 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 I.

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, extraction, dose-response, and monitoring wells, as well as all 64 Phase 1 pre-design monitoring wells (LVWPS-MW201A/B through LVWPS-MW226A/B). During the effectiveness monitoring events following injections, groundwater samples were periodically collected from monitoring wells within each remediation zone located upgradient and downgradient of each of the injection well transects. The monitoring well network associated with each of the three remediation zones included a total of 108 monitoring wells, which consists of 11 pre-design monitoring wells installed as part of Phase 1 and 97 newly installed monitoring wells. An additional 16 monitoring wells (11 pre-design monitoring wells installed as part of Phase 1 and 5 newly installed extraction wells) were also sampled less frequently during the Pilot Study timeframe to: 1) evaluate potential remedial impacts in areas located farther downgradient of the Zone 2 study area due to the paleochannel influence; and 2) determine contaminant concentrations in monitoring wells used for extraction operations during injections. Because injections did not target semi-consolidated material, monitoring wells within the Pilot Study area screened within semi-consolidated material were not included in the effectiveness monitoring program. Details of the Zones 1, 2, and 3 effectiveness monitoring well networks are provided in Sections 6.2.2, 7.2.2, and 8.2.2, respectively. **Figures 6 through 8** present maps of the monitoring wells that were periodically sampled.

The frequency of the groundwater monitoring events varied depending on remediation zone. In general, groundwater monitoring occurred monthly with the following exceptions:

- Biweekly groundwater sampling was performed during the first 2 months following the first injection event into the alluvium within the Zone 2 study area to capture initial reductions that were likely to be observed sooner than in other areas due to higher groundwater flow rates in the alluvium.
- Due to the slower groundwater flow rates, the frequency of UMCf groundwater sampling was reduced to bimonthly approximately 4 months following each of the two UMCf/UMCf-cg injection events.
- No groundwater monitoring event occurred during October 2021 due to active injection activities associated with the third injection event taking place that same month.
- Sampling of the additional 16 monitoring wells (11 Phase 1 pre-design monitoring wells and 5 extraction wells) and a comprehensive synoptic gauging event were performed on a quarterly basis.

During the Pilot Study, groundwater samples were periodically collected and analyzed for a variety of field, laboratory, and microbial parameters listed in

Table 3, which presents the analyses, associated methods, and purpose.

Table 3 Groundwater Effectiveness Monitoring Protocol

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	E314.0	Assess remediation effectiveness
Chlorate	E300.1B	Assess remediation effectiveness
TOC	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
Nitrate	E300.0	Assessment of nitrate as the most likely competing electron acceptor and carbon substrate consumer
Sulfate	E300.0	Assessment of sulfate as an electron acceptor and potential carbon substrate consumer
Total Nitrogen	E351.2/E300.0	Examine the need for micronutrients
Total Phosphorus	E365.3	Examine the need for micronutrients
Methane	RSK175	Examine secondary geochemical impacts
Dissolved Metals(1)	SW6010B/6020	Assess secondary impacts of remediation
Hexavalent Chromium	E218.6 and SW7199	Examine impact of reductive biological treatment on hexavalent chromium in groundwater
VFAs	VFA-IC	Surrogate carbon substrate assessment
Tracer Dye	Fluorescence	Assess hydraulic properties
PLFA	Microbial Insights PLFA	Examine microbial response to carbon substrate addition
Perchlorate Reductase Enzyme	Microbial Insights Census-DNA	Examine microbial response to carbon substrate addition

Notes:
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, calcium, chromium, iron, and manganese.

As part of the baseline groundwater sampling event, groundwater samples collected from all injection and monitoring wells were analyzed for perchlorate, chlorate, and nitrate. Groundwater samples collected from all monitoring wells within each remediation zone were also analyzed for sulfate and total organic carbon (TOC). Additionally, groundwater samples were collected from 27 monitoring wells (three locations within each of the three remediation zones, with each location consisting of three monitoring wells at varying depths) and analyzed for the larger suite of field and laboratory analytes listed in

Table 3 to further establish the baseline geochemical environment of the subsurface. Bio-Traps® were deployed in clustered monitoring wells at one upgradient and one downgradient location within each remediation zone (total of six locations) during the baseline sampling event and remained in the monitoring wells for approximately 30 days. The purpose of the Bio-traps® was to evaluate the microbial response to the carbon substrate addition. Once retrieved, the Bio-traps® were sent to Microbial Insights for analysis of phospholipid fatty acids (PLFA) and the presence and quantification of the perchlorate reductase enzyme.

For the tracer study, baseline samples were collected from the 122 monitoring wells and 18 dose-response monitoring wells located within each of the three remediation zones and analyzed for tracer dye to ensure that no tracer dye was already present in the system from tests performed elsewhere, industrial processes, or any other source. Groundwater samples were collected from dose-response monitoring wells and analyzed for dye using a fluorometer during the injection process, with periodic groundwater samples collected for lab analysis for confirmation of field fluorometer readings. At the conclusion of the first injection event, samples were also collected from 100 monitoring wells located throughout the Pilot Study area, which included dose-response monitoring wells, monitoring wells located either immediately upgradient or within 50 feet downgradient or cross-gradient of the injection well transects, and all monitoring wells screened within the alluvium that are part of the Zone 2 remediation area.

During post-injection monitoring events, groundwater samples were collected from the effectiveness monitoring wells and analyzed for perchlorate, chlorate, nitrate, sulfate, and TOC. These monitoring wells (plus the 11 pre-design monitoring wells in areas located farther downgradient of the Zone 2 study area due to the paleochannel influence) were also analyzed for tracer dye (including all dyes selected for injections) during biweekly and monthly sampling events for the first 6 months following the first injection event. Additionally, groundwater samples collected from up to 27 monitoring wells (three locations within each of three remediation zones, each location consisting of three monitoring wells at varying depths) were also analyzed for the parameters listed in

Table 3. During the September 2021 and March 2022 effectiveness monitoring events following injections, Bio-traps® were again deployed in clustered monitoring wells in the same six locations to evaluate PLFA and the presence of the perchlorate reductase enzyme. Results from the effectiveness monitoring program for Zones 1, 2, and 3 are discussed in Sections 6.7, 7.7, and 8.7, respectively. Comprehensive data tables are presented in Appendix J.

5.7.1.1 Data Validation

A Data Validation Summary Report (DVSR) was prepared for the laboratory analytical data collected during the implementation of the Pilot 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 K 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, 2017), *Quality Assurance Project Plan, Revision 3* (Ramboll, 2018), *Quality Assurance Project Plan, Revision 5* (Ramboll, 2020), *Quality Assurance Project Plan, Revision 6* (Ramboll, 2021), *NDEP Data Verification and Validation Requirements* (NDEP, 2018), and the references contained therein. Aqueous samples were validated to Stage 2A. Approximately 90 percent of soils data were validated to Stage 2B and 10 percent to Stage 4. The review process used professional judgment and guidance from the USEPA National Functional Guidelines to determine the final qualifiers, which were added to the database and presented in the DVSR tables.

5.7.2 Surface Water Monitoring

As explained in Section 3.3.2, surface water samples are currently collected on a monthly basis to evaluate the mass flux of perchlorate migrating into the Wash. Surface water samples are analyzed for perchlorate, chlorate, and TDS. As part of the on-going monthly surface water sampling, surface water samples are collected from three transect locations within the Wash that are located downgradient of the Pilot Study area between Historical Lateral and Homestead Weirs, namely LVW5.3, LVW4.75, and LVW4.2. In addition to these three transect locations (LVW5.3, LVW4.75, and LVW4.2), surface water samples were also collected for dye analysis from three additional locations along the southern bank of the Wash (i.e., LVWPS4.4, LVWPS4.8, and LVWPS4.9; shown on **Figure 9**). An attempt was made to collect a sample from the LVW 5.1 area, but samples were not able to be collected due to access issues associated with the dense vegetation in this area.

For monthly surface water sampling events that occurred during the Pilot Study timeframe, surface water samples from these six locations were also analyzed for TOC. Baseline and monthly surface water samples collected during the first six months following the first injection event were also analyzed for tracer dye. During transect sampling, samples for dye analysis were collected from a location near the southern bank of the Wash, rather than from the transect locations. All seven sampled locations were field located using GPS. Surface water samples were collected using similar techniques to those used during collection of monthly surface water samples. Samples for dye analysis were collected by attaching the charcoal sampler to a weight and placing it in the water near the bank of the Wash, with collection of the sample approximately one week later. Multiple samplers were emplaced to ensure that one could be retrieved later for analysis. Field parameters (temperature, pH, turbidity, EC, DO, and ORP) were also monitored and recorded on field sampling forms prior to sample collection. All samples were validated as described in Section 5.7.1.1.

6.0 ZONE 1 SUMMARY AND EVALUATION OF RESULTS

As introduced earlier, the Pilot Study area consisted of three zones, each with different conditions and objectives. The focus of the Zone 1 study area was to evaluate bioremediation in the UMCf at a location within the Pilot Study footprint that contained the highest detections of perchlorate in groundwater during Phase 1 pre-design activities. Specifically, perchlorate was detected at 16,000 µg/L and 9,200 µg/L in the Phase 1 groundwater samples collected from monitoring wells LVWPS-MW204B and LVWPS-MW217B, respectively, which are both screened within the unconsolidated UMCf from approximately 100 to 120 feet bgs (**Figures 4 through 6**). Bioremediation activities in Zone 1 focused on perchlorate present within the unconsolidated UMCf only for three primary reasons: 1) Concentrations of perchlorate decrease dramatically with depth as the UMCf transitions from unconsolidated to semi-consolidated; 2) Step-rate injection testing performed as part of the Galleria Drive Bioremediation Treatability Study (Tetra Tech, 2019c) indicated that ISB would be difficult to implement in the semi-consolidated UMCf due to the extremely low injection rates achieved in this formation; and 3) Groundwater flow velocities in the overlying alluvium near the Wash are extremely high, much higher than alluvium elsewhere in the NERT RI Study Area, which would likely result in insufficient residence time if ISB were attempted in the alluvium in Zone 1. Based on these findings and conclusions, implementation of ISB in Zone 1 focused only on the unconsolidated portion of the UMCf.

This section summarizes the Zone 1 objectives, study design, injection activities, geology, hydrogeology, and effectiveness monitoring results.

6.1 OBJECTIVES

Evaluation of ISB within Zone 1 that focused on the UMCf allowed for assessment of the following specific objectives as previously outlined in the Work Plan Addendum (Tetra Tech, 2019a).

- Determine if ISB can effectively create a biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater within the UMCf and compare the effectiveness with respect to variations in lithology between the UMCf within Zone 1 and UMCf-cg within Zone 3 (discussed in Section 8.0).
- Evaluate ISB implementation and operational components within the UMCf, including injection protocols, achievable injection rates, subsurface distribution of injectate, injection well spacing, and construction methods.
- Determine whether remediation in the UMCf in an area with elevated perchlorate and chlorate concentrations in groundwater and a known upward gradient has meaningful effect on contaminant concentrations in the overlying alluvium groundwater, and if so, whether the effect differs depending on the UMCf lithology (comparison of results from Zones 1 and 3). These data can be used to evaluate the potential effectiveness of remediation of small areas of elevated concentrations in the UMCf with respect to achieving long-term remedial goals for OU-3.
- Determine the approximate length of time that ISB could be expected to affect concentrations in the UMCf, and the resulting injection frequency required to maintain these concentration reductions.
- Evaluate if dual-nested injection wells are effective in delivering substrate to large, saturated thicknesses of the UMCf because nested injection wells can be a cost-effective option as opposed to multiple separate injection wells.

6.2 PILOT STUDY LAYOUT AND WELL DESIGN

Both injection and monitoring wells were installed in the Zone 1 study area as described in Section 5.4. The layout of the injection well transect and monitoring well network was designed to collect data for evaluation of the Zone 1 objectives. **Figure 6** presents the layout of the Zone 1 injection well transect and monitoring well network. Well construction details and soil boring logs for all injection and monitoring wells are provided in Appendix B.

6.2.1 Injection Wells

As presented in the Work Plan Addendum, the injection well transect within the Zone 1 study area was designed to be approximately 200-foot long, consisting of nested injection wells at eight locations spaced approximately 25 feet apart and screened within the UMCf, and oriented perpendicular to groundwater flow. Full design details related to general location and injection well spacing are summarized in the Work Plan Addendum (Tetra Tech, 2019a).

An initial pilot boring installation phase was performed to determine optimal placement of the 200-foot-long injection well transect due to the high level of site heterogeneity. Five pilot borings (LVWPS-U1-MW01B through LVWPS-U1-MW05B) were installed in an approximate 300-foot staggered row situated perpendicular to groundwater flow and generally in line with existing monitoring well cluster LVWPS-MW204. Each pilot boring was drilled to a depth up to 165 feet bgs, terminated at the top of the semi-consolidated UMCf, and subsequently converted to a 4-inch diameter, Schedule 80 PVC monitoring well and screened with 4-inch diameter slotted PVC well screen in the deepest portion of the unconsolidated UMCf. Following well construction and development, groundwater samples were collected and analyzed for perchlorate and chlorate to determine contaminant distribution along the pilot boring transect. Additionally, slug testing and NMR logging were performed to further delineate localized preferential flow pathways. These results were used to select the location of the 200-foot-long injection well transect, which ultimately was situated in an area with the highest groundwater perchlorate and chlorate concentrations in the UMCf as well as the most heterogeneous portion of the investigated pilot boring area. The monitoring wells installed as part of the pilot boring phase ultimately became part of the effectiveness monitoring program for the Pilot Study.

Following completion of the pilot boring installation and testing, eight Zone 1 injection wells were installed in a dual-nested well configuration (two separately screened injection wells installed within the same borehole). The injection well depths within each nested pair averaged 117 feet bgs for the shallow UMCf (designated as “A” wells) and 150 feet bgs for the deep UMCf (designated as “B” wells). Injection well screened intervals were selected to target the impacted portion of the unconsolidated UMCf, which varied in thickness from 55 to 70 feet. Injection well construction details, including total depths and screened intervals, are provided in Appendix B, Table B.1.

6.2.2 Effectiveness Monitoring Wells

Eleven monitoring well clusters throughout the Zone 1 study area at varying distances upgradient and downgradient from the injection well transect were included in the effectiveness monitoring program to provide an effective monitoring well network to meet the detailed study objectives and determine remediation effectiveness following ISB injections. The effectiveness monitoring well layout consisted of monitoring wells located at two upgradient and nine downgradient locations within the Zone 1 study area. Monitoring well cluster LVWPS-MW217, which was installed as part of Phase 1 pre-design activities, was also incorporated into the effectiveness monitoring program and is included in the nine downgradient monitoring locations. The names of Zone 1 monitoring wells screened in the alluvium included a prefix of “LVWPS-A1”, while Zone 1 monitoring wells screened in the UMCf included a prefix of “LVWPS-U1”. Due to the large saturated thickness of the UMCf in Zone 1, the monitoring well names also included a suffix of either an “A” or “B”, which indicated wells screened in the shallow or deep unconsolidated UMCf, respectively. Additional details regarding the monitoring well layout are noted as follows:

- Two monitoring well clusters were installed 60 feet upgradient from the injection well transect to determine the contaminant concentrations in groundwater migrating through the injection well transect and refine the mass flux entering the Zone 1 study area. The northernmost cluster included two monitoring wells screened at different intervals within the unconsolidated UMCf, while the southernmost cluster only included one monitoring well screened within the unconsolidated UMCf due to the limited thickness of unconsolidated UMCf in this area. Each upgradient monitoring well cluster also included one monitoring well screened in the alluvium.

Nine downgradient monitoring well clusters were included in the effectiveness monitoring program to monitor ISB effectiveness and estimate the zone of influence of the carbon substrate following injections in the Zone 1 study area. These nine monitoring well clusters were located at varying distances between approximately 25 and 150 feet downgradient of the injection well transect and positioned throughout the study area both directly in line and off-set from the individual injection wells to evaluate remediation with respect to the heterogeneity and preferential flow paths. The nine monitoring well clusters included a total of 22 monitoring wells, which consisted of the installation of 14 new monitoring wells and incorporation of the five pilot boring wells and one existing monitoring well cluster of three monitoring wells (LVWPS-MW217A/B/C). Due to the large, saturated thickness of the targeted unconsolidated UMCf within the Zone 1 study area, each monitoring location included two monitoring wells screened in different intervals within the unconsolidated UMCf. In addition, five of the nine monitoring locations included one monitoring well screened within the alluvium to monitor for potential reductions in the alluvium as a result of injections into the underlying UMCf.

In addition to the 11 effectiveness monitoring well clusters listed above, two clusters of dose-response monitoring wells, with each cluster consisting of three monitoring wells, were installed immediately downgradient of the injection well transect (less than 5 feet away) to support the tracer dye study presented in Section 5.4.3 of the Work Plan Addendum (Tetra Tech, 2019c). Two of the three dose-response monitoring wells at each well cluster were screened in the UMCf across the same depth intervals as the nearby injection wells. The third dose-response monitoring well at each location was screened in the alluvium immediately above the alluvium-UMCf contact to evaluate if injectate was entering the alluvium in the immediate vicinity of the injection well transect.

6.3 ZONE 1 INJECTIONS

As presented in Section 5.5, two carbon substrate injection events were performed as part of Zone 1 Pilot Study activities. The following sections provide details of the two injection events conducted at Zone 1 injection wells screened in the unconsolidated UMCf. Injection summary tables including injection volumes, flow rates, and pressures for each injection well are provided in Appendix D. As described in Section 5.7.1, the five extraction wells installed in the alluvium outside of the remediation zones (**Figure 5**) during Phase 2 were sampled during the baseline sampling event in September/October 2020 prior to the first injection event and on a quarterly basis thereafter to determine contaminant concentrations in monitoring wells used for extraction operations during injections. Data for all parameters for groundwater samples collected from extraction wells are presented in the comprehensive data tables provided in Appendix J, Table J.1. Field logs from all groundwater sampling events are provided in Appendix I and the DVSR is provided in Appendix K.

6.3.1 Modified Injection Approach

During well development activities following installation of the Zone 1 injection well transect, it was discovered that one of the dual-nested UMCf injection wells (LVWPS-U1-IW06A/B) within the Zone 1 injection well transect had a blockage in the shallow well (noted as the “A” well) when the pumps/bailers could not be lowered deeper than approximately 28 feet bgs (a depth above the water table). After further evaluation, it was determined that this blockage was a bulge in the PVC casing that likely formed from the heat generated by the grout curing during the installation process, causing the PVC well casing to deform. Although not common, under certain circumstances, it is possible for PVC to warp from the heat generated during the grout curing process. Following discovery, the bulge was shaved down, which allowed a pump/bailer to pass through the injection well for development. The PVC shavings were then bailed from the well.

Although the bulge in the injection well casing was modified to allow equipment to pass through this location, there was a concern that the resulting well casing at this depth may not have been able to endure pressurized injections. As a result, a modified injection approach was employed at LVWPS-U1-IW06A, which involved installation of packers during injections to ensure injections are completed below the impacted section of the well casing. This process was relatively simple and is commonly used in injection practices to isolate or target specific depth intervals for injections. Prior to injections into LVWPS-U1-IW06A, the packers were connected to the PVC riser pipe, lowered inside the injection well to a depth immediately below the impacted section of the well casing, and inflated with air via tubing extending from the packers to the surface. The packers were inflated to a pressure of 1.2 times the maximum planned injection pressure. Once the packers were inflated, the injections proceeded as usual. The packer pressure was monitored to maintain the targeted injection pressure during injections.

6.3.2 Injection Details

The first injection event in Zone 1 was performed from December 13 to December 14, 2020. Prior to initiating carbon substrate injections, a brief step-rate injection test using extracted groundwater only was performed to determine if an initial targeted injection rate of 5 gallons per minute (gpm) per injection well was feasible. The step-rate injection test indicated that an injection rate of 5 gpm was possible at relatively low sustained pressures (up to a maximum of 26.5 psi).

During the first injection event, approximately 27,600 gallons of carbon substrate solution were injected into the Zone 1 injection wells. The solution consisted of approximately 5,505 gallons of EOS® PRO, 44 gallons of glycerin, 35 gallons of phosphate solution,70 pounds of sodium sulfite, and 22,045 gallons of injectate dilution water (extracted groundwater from nearby extraction wells). In addition, fluorescein dye was added to the carbon substrate solution to achieve a target concentration of 400 ppb. As summarized in the tables in Appendix D, the quantities of EOS® PRO varied between injection wells based on the screen lengths and thickness of the targeted formation at each injection location. Upon completion of carbon substrate injections, approximately 6,437 gallons of water were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to refine the effective porosity values and recalculate the corresponding distribution water quantities for the program. These results indicated that the field-determined effective porosity was less than originally estimated during the design for the Zone 1 UMCf, with a revised calculated effective porosity of 2.0 percent and 1.2 percent for the shallow and deep UMCf, respectively. As a result, the Zone 1 UMCf distribution water volumes were proportionately reduced using the new porosity estimates. During injections, both flow rate and pressure were measured at each injection well. Injection rates averaged approximately 5 gpm while sustained pressures generally averaged 11 psi.

The second injection event in Zone 1 was performed from October 19 to October 21, 2021, approximately 10 months after the first injection event. The timing of the second injection event was based on the beginning of perchlorate, chlorate, and nitrate concentration rebounds in conjunction with a decrease in TOC concentrations to near baseline conditions in samples collected from key monitoring wells (further discussed in Section 6.7). Due to the extensive mounding observed during the first injection event and in an effort to improve subsurface distribution, a slightly altered injection scheme was utilized during the second injection event. Rather than inject into all 16 injection wells at once, every other injection well pair was active at a given time. The goal of this scheme was to improve subsurface distribution by reducing competing pressures from neighboring injection wells. During the second injection event, approximately 20,800 gallons of carbon substrate solution comprising 4,152 gallons of EOS® PRO, 35 gallons of glycerin, 17 pounds of sodium sulfite, and 17,008 gallons of injectate dilution water (extracted groundwater from nearby extraction wells) were injected into Zone 1 injection wells. The quantity of EOS® PRO was approximately 85 percent of that used in the first injection event. The objective of reducing the EOS® PRO 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 carbon substrate injections, a total of 10,229 gallons of water were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. This higher volume of distribution water during the second injection event (compared to the first event) was selected to maintain an overall injection volume of approximately one pore volume at each injection well, despite the lower target carbon substrate solution volume (85 percent of the first injection event). Results from groundwater samples collected from extraction wells prior to the second injection event indicated a slightly elevated average perchlorate concentration of 4,540 μg/L compared to the average perchlorate concentration of 2,900 μg/L measured prior to the first injection event. Therefore, the concentration of perchlorate in the injectate solution and follow-up distribution water during the second injection event may have been higher than the previous injection event. Lastly, injection rates averaged approximately 4 gpm while sustained pressures generally averaged 7 psi during the second injection event, which indicated no apparent decreases in injection well performance between the first and second injection events.

6.3.3 Hydraulic Response

A significant hydraulic response was observed during Zone 1 injections. The injections into Zone 1 injection wells were under pressure, which resulted in a significant rise in hydraulic head in surrounding monitoring wells and rise of the dye-tagged water to ground surface elevations at some monitoring well locations. Approximately 90 minutes after the injection started, the hydraulic head at the deep dose-response monitoring wells (LVWPS-U1-DR01B and LVWPS-U1-DR02B) had risen from approximately 30 feet bgs to ground surface elevation. Within 3 hours of active injections, the same rise in head to ground surface was observed at the shallow dose-response monitoring well LVWPS-DR01A and downgradient monitoring well LVWPS-U1-MW08B, which is located approximately 25 feet downgradient of the injection well transect. Although the potentiometric surface of the UMCf was raised approximately 30 feet to ground elevation, no measurable rise in groundwater elevation was detected at dose-response monitoring wells screened in the alluvium. In addition, no fluorescein tracer dye was observed in the alluvial dose-response monitoring wells located approximately 7 feet downgradient of the injection well transects. The significant rise in hydraulic head observed at dose-response and downgradient monitoring wells screened in the UMCf indicates a low effective porosity, which was confirmed through dye sampling in the dose-response monitoring wells and subsequent recalculation of effective porosity as described in Section 5.5.1.

Carbon substrate solution was also observed during active injections at all four dose-response monitoring wells screened in the UMCf (LVWPS-U1-DR01A, LVWPS-U1-DR01B, LVWPS-U1-DR02A, and LVWPS-U1-DR02B), in two monitoring wells located approximately 25 feet downgradient of the injection well transect (LVWPS-U1-MW08A and LVWPS-U10MW08B), and in two monitoring wells located approximately 60 feet upgradient from the injection well transect (LVWPS-U1-MW06B and LVWPS-U1-MW07). This upgradient response was expected based on the revised calculated low effective porosities, which causes injectate solution to move farther from the injection points (both upgradient and downgradient) during injections, particularly when injecting under pressure.

6.4 ZONE 1 GEOLOGY

Data from the soil boring and monitoring well installation activities were compiled to provide a description of the geology for the Zone 1 study area. A geological cross-section of Zone 1 is presented on **Figure 10a**. Saturated alluvium, ranging from silty sand to sandy gravel with minor lenses of sandy silt, is present throughout the Pilot Study area, overlying the UMCf. The thickness of the alluvium is greatest near the Wash, where sand and gravel extend up to 120 feet bgs. Zone 1 is located approximately 350 feet south of the Wash. Often, main basin drainages, such as the Wash, have existed for a long time and have underlying ancestral fluvial deposits near their current location. As shown on **Figure 10a**, the alluvium within Zone1 is heterogeneous with a high proportion of relatively coarse sediments in the deeper alluvium immediately above the contact with the UMCf. These coarse channel fill deposits are likely associated with the ancestral fluvial deposits underlying the Wash.

The UMCf in Zone 1 is encountered at approximately 85 to 90 feet bgs and is primarily composed of silt to silty fine sand. In general, the shallow portions of the unconsolidated UMCf in Zone 1 from 90 to 120 feet bgs are finer than the deeper portions of the unconsolidated UMCf from 120 to 150 feet bgs. These shallow and deep portions of saturated unconsolidated UMCf generally correlate to the screened intervals of the Zone 1 injection and monitoring wells, which are noted with the suffixes A and B, respectively. In addition, the deep unconsolidated UMCf in Zone 1 contains distinctive layers of white to light grey poorly graded, fine-grained sand. Although these thin sand layers do not appear to be laterally continuous, they are likely more transmissive than the surrounding UMCf, and therefore may influence the preferential flow pathways within Zone 1 UMCf and the ROI of the deep Zone 1 injection wells.

The deepest portions of the UMCf in Zone 1 are semi-consolidated with abundant gypsum below approximately 150 to 160 feet bgs. Approximately 60 feet upgradient from the injection well transect at LVWPS-U1-MW07, the semi-consolidated UMCf is significantly shallower at 115 feet bgs. In addition, the distinctive light grey sand lenses were encountered between 104 and 106 feet bgs, which is approximately 40 feet shallower than observed at the injection well transect. These observations together suggest the presence of faulting in the vicinity of Zone 1. Although the primary fault system is proximal to the bedrock outcrop in the eastern portion of the Pilot Study area, additional subsidiary faults are likely present subparallel to the primary fault system throughout the Pilot Study area, creating secondary porosity within the UMCf. Fault-associated secondary porosity likely results in preferential flow pathways within the UMCf and may create pathways for discharge from the UMCf into the overlying alluvium.

6.5 ZONE 1 HYDROGEOLOGY

As discussed in Section 3.2, groundwater flow in the Pilot Study area is governed by two primary hydrogeologic influences: 1) the Wash and its underlying ancestral fluvial deposits, and 2) the fault zone and its associated paleochannel. The Zone 1 area is located immediately adjacent to the Wash in the northwestern portion of the Pilot Study area, where groundwater is towards the east/northeast, approximately paralleling the Wash (**Figure 5**). Phase 1 pre-design borehole dilution testing indicated the highest groundwater flow velocities of up to 250 ft/day were in shallow monitoring wells closest to the Wash. Furthermore, monitoring well LVWPS-MW217A, which is in the northern portion of the Zone 1 study area, had such a high groundwater flow velocity that the tracer water was removed as fast as it could be emplaced during pre-design borehole dilution testing. Therefore, no estimates of groundwater flow velocity could be made. These elevated groundwater flow velocities are due to the proximity to the Wash and its underlying ancestral fluvial deposits. Due in part to these high groundwater velocities, the Pilot Study design did not include any injections into Zone 1 alluvium, but rather focused on implementation of ISB in the UMCf. However, fractures, faults, and erosional channels in the UMCf form cross-connecting pathways from the UMCf to the alluvium. Therefore, although ISB injections were performed only into the UMCf in Zone 1, treated groundwater from the UMCf was expected to follow preferential flow pathways and discharge into the alluvium.

Figure 6 includes a groundwater potentiometric surface of the unconsolidated UMCf in Zone 1 during baseline sampling in October 2022. As with the alluvium, the groundwater flow within the UMCf roughly parallels the Wash, with a calculated average east-northeastward hydraulic gradient of 0.006 feet per foot (ft/ft). Groundwater levels were gauged on a quarterly basis during the Pilot Study, and these subsequent synoptic groundwater level gauging events performed during the effectiveness monitoring period indicated groundwater flow direction remained consistent over time with the baseline October 2020 conditions. Depth to water measurements are provided in Appendix I, Table I.1. The magnitude of the vertical gradients between the alluvium and the UMCf and between the shallow and deep UMCf is generally small, ranging from about 0.021 ft/ft upward to 0.001 ft/ft downward. These relatively low gradients are reflective of reasonably good connections between the various lithological units. In general, the magnitude of the upward vertical gradients increases with proximity to the Wash.

6.6 ZONE 1 HYDROGEOLOGICAL EVALUATION

As previously explained in Section 5.6, an aquifer testing program was implemented to obtain information regarding aquifer hydraulic conductivity, groundwater flow velocity, and total and mobile porosity in the Pilot Study area. Additionally, a fluorescein dye was injected during the first Zone 1 injection event and samples collected post-injection to periodically monitor for the presence of dye. This additional dye data aided in the evaluation of study objectives including determining the ROI of the injection wells, travel times of the injectate/dye, upflux from the UMCf to the overlying alluvium, and the effective porosity of the formation near the injection well transect. This section summarizes the results from the aquifer testing activities (i.e., NMR logging, borehole dilution testing, slug testing, and tracer dye study) performed in the Zone 1 study area during the Pilot Study. The supporting summary memos for the tracer study, NMR logging, borehole dilution testing, and slug testing, are presented in Appendices C, E, F, and G, respectively.

6.6.1 Nuclear Magnetic Resonance Logging Results

NMR logging, which was described in Section 5.6.1, was performed in each of the five pilot monitoring wells within Zone 1 to further delineate localized preferential flow pathways within the Pilot Study areas prior to selecting the final placement of the Zone 1 injection well transect. The high-resolution estimates of hydraulic conductivity were compared to the lithologic logs and aquifer testing results for each pilot boring to assess the possibility of preferential flow. Results from NMR logging are presented in Appendix E. 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. The average mobile porosity (similar to effective porosity) measured in the UMCf at Zone 1 pilot borings was 11 percent. NMR estimates of hydraulic conductivity generally agreed with estimates derived using slug testing within an order of magnitude, particularly at locations higher in the borehole. NMR results indicate that the drilling-related disturbance zone surrounding the borehole appears to have been the greatest in the deepest portion of each borehole based on the data indicating that the NMR tool did not consistently penetrate the formation past the disturbance zone around the borehole. This is observable in the logs as sporadic large increases in the hydraulic conductivity, particularly in the sand-packed interval where the disturbance zone was not grouted. These irregularities have been observed in previous applications of NMR logging at the Galleria Drive Bioremediation Treatability Study (Tetra Tech, 2019c) and did not affect the Pilot Study because aquifer properties were estimated using several aquifer testing methods, except that site-specific conditions might render one method less reliable.

6.6.2 Borehole Dilution Testing Results

Using the procedures presented in Section 5.6.2 and Appendix F, single-borehole dilution tests were performed at three monitoring well clusters screened in the UMCf (LVWPS-U1-MW01A/B, LVWPWS-U1-MW04A/B, and LVWPS-U1-MW05A/B) and in two monitoring wells screened in the alluvium (LVWPS-A1-MW04 and LVWPS-A1-MW05) to evaluate groundwater flow velocities in the Zone 1 study area. Groundwater flow rates at alluvial monitoring wells LVWPS-A1-MW04 and LVWPS-A1-MW05 measured 10 and 30 ft/day, respectively. Although these alluvial groundwater velocities are lower than results from the Phase 1 monitoring well LVWPS-MW217A, where the groundwater flow velocity was so high that the tracer water migrated (and disappeared) as fast as it could be emplaced, they are similar to other flow rates observed in the Pilot Study area. The groundwater flow rate in the shallow UMCf in the Zone 1 study area was determined to be approximately 0.2 ft/day, based on single-borehole dilution tests in wells LVWPS-U1-MW01A, LVWPWS-U1-MW04A, and LVWPS-U1-MW05A. The groundwater flow rate in the deep UMCf at these same monitoring well locations was more variable, ranging from 0.04 ft/day to 0.3 ft/day. These results are generally consistent with Phase 1 borehole dilution testing results. The groundwater flow velocity ranges calculated from Phase 2 borehole dilution testing are comparable to those calculated using the baseline slug test hydraulic conductivity and effective porosity from the tracer study, which average 0.3 ft/day and 0.6 ft/day in the shallow and deep UMCf, respectively. A complete summary of the borehole dilution testing and results is provided in Appendix F.

6.6.3 Slug Tests

Using the procedures described in Section 5.6.3 and Appendix G, slug tests were performed in several phases during Phase 2 implementation to estimate location-specific aquifer hydraulic conductivity within the Zone 1 study area. Appendix G presents results from the slug testing events conducted as part of Phase 2 of the Pilot Study.

The first slug testing event was performed from February 29 to March 1, 2020 to test all newly installed pilot boring monitoring wells prior to final selection of the Zone 1 injection well transect location, as discussed in Section 6.2.1. Hydraulic conductivities measured in the deep UMCf ranged from 0.5 ft/day in monitoring well LVWPS-U1-MW05B to 3 ft/day in monitoring well LVWPS-U1-MW02B, with an average hydraulic conductivity of approximately 1.3 ft/day. The final location of the Zone 1 injection well transect, which was situated to be upgradient from LVWPS-U1-MW02B and LVWPS-U1-MW04B, where the highest hydraulic conductivities were observed, was in part selected based on these pilot boring slug testing results.

After installation of the Zone 1 effectiveness monitoring well network, slug testing was performed at all newly installed monitoring wells from June 18 to June 19, 2020. This baseline slug testing event indicated that the estimated hydraulic conductivities of the shallow and deep UMCf in Zone 1 were similar, with average hydraulic conductivities of 1.2 ft/day and 1.1 ft/day, respectively. The highest hydraulic conductivities within the Zone 1 study area of approximately 2 ft/day were observed at monitoring wells LVWPS-U1-MW05A, LVWPS-U1-MW08A, LVWPS-U1-MW08B, and LVWPS-U1-MW09A.

Following carbon substrate injections, slug tests were performed periodically throughout the Pilot Study to examine subsurface conductivity changes following carbon substrate injections. Three post-injection slug testing events were performed on five Zone 1 monitoring wells in June/July 2021, January 2022, and June/July 2022. The mean hydraulic conductivities observed during post-injection testing were within the same order of magnitude as the baseline for all five monitoring wells evaluated post-injection. However, monitoring wells LVWPS-U1-MW07 and LVWPS-U1-MW08A, which are located within approximately 50 feet of the injection well transect in Zone 1, both indicated average post-injection hydraulic conductivities approximately 2.4 times lower than baseline conditions. Although post-injection hydraulic conductivity values indicated decreases at select locations, the injection rates during the second injection event in Zone 1 did not show comparable decreases. Both monitoring wells where testing indicated a decreasing trend in hydraulic conductivity over time were located within the ROI of the carbon substrate injections, with groundwater sampling results indicating an increase in TOC concentrations following injections confirming the arrival of carbon substrate solution. All other monitoring wells downgradient of the injection well transects experienced no significant change in hydraulic conductivity.

6.6.4 Dye Results

As presented in Section 5.6.5, the Pilot Study design included injection of fluorescein dye during the first Zone 1 injection event and periodic monitoring to provide data to evaluate tracer study objectives including the ROI of injection wells, travel times of the injectate/dye, upflux from the UMCf to the overlying alluvium, and the effective porosity of the formation near each injection well transect. The tracer dye monitoring program included qualitative (i.e., presence/absence) analysis of charcoal samplers that were installed in monitoring wells during injection activities and between effectiveness monitoring events, as well as quantitative analysis of tracer dye concentration in groundwater samples. If tracer dye was detected in the charcoal sampler, indicating the arrival of tracer dye at the monitoring location, the groundwater sample collected from that same monitoring well location was then analyzed to determine the dye concentration in the groundwater. This two-step analysis process allowed for presence/absence dye analysis at all monitoring locations and also permitted quantitative analysis where the dye was found to be present. A complete discussion of the dye study, including dye analytical results, is provided in Appendix C.

During injection activities, the fluorescein-tagged carbon substrate solution appeared in samples collected from monitoring wells LVWPS-U1-MW06B and LWVPS-U1-MW07, which are located approximately 60 feet upgradient from the injection well transect. Fluorescein-tagged carbon substrate solution was also observed during active injections in samples collected from all four dose-response monitoring wells screened in the UMCf (LVWPS-U1-DR01A, LVWPS-U1-DR01B, LVWPS-U1-DR02A, and LVWPS-U1-DR02B) and two monitoring wells screened in the UMCf that were located approximately 25 feet downgradient of the injection well transect (LVWPS-U1-MW08A and LVWPS-U1-MW08B). As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to estimate the effective porosity of the UMCf in Zone 1. These results indicated that the field-determined effective porosity was less than originally estimated during the design of injection quantities for the Zone 1 UMCf, with a revised calculated effective porosity for the shallow and deep UMCf of 2 percent and 1 percent, respectively. These low effective porosities calculated for the UMCf in part explain the migration of the injectate solution farther than expected from the injection points (both upgradient and downgradient) during injections. In addition, the injectate solution likely followed preferential flow pathways (i.e., sand lenses or fracture networks associated with faulting) in the UMCf to appear farther downgradient than expected. Once the injection activities ceased, the migration of fluorescein downgradient under the natural gradient of the formation was quite slow in the UMCf based on flow rates of 0.04 ft/day to 0.3 ft/day estimated from borehole dilution testing. Dye was not detected in samples collected from monitoring wells screened in the UMCf farther than approximately 32.5 feet downgradient, where it was detected at low concentrations in groundwater samples collected from monitoring well LVWPS-U1-MW02B approximately 3 months after the first injection event.

Farther downgradient of the Zone 1 injection well transect, fluorescein dye rapidly migrated into the alluvium along preferential flow pathways likely including faults, fractures, and/or incised paleochannels in the UMCf. Fluorescein was detected in charcoal samplers collected approximately 1 month after dye injection from three downgradient monitoring wells screened in the alluvium, namely, LVWPS-A1-MW09, LVWPS-A1-MW10, and LVWPS-MW217A, which were located 100 to 150 feet downgradient of the injection well transect. Once the dye entered the alluvium, the dye rapidly traveled more than 1,300 feet within the first month, as indicated by detection of fluorescein in samples collected from LVWPS-MW210B (location shown on **Figure 5**), which was the farthest downgradient monitoring well within the Pilot Study area. This rapid rate of travel in the alluvium was expected given that the Phase 1 borehole dilution test results indicated alluvial groundwater flow velocities of greater than 90 ft/day in areas adjacent to the Wash. In addition, low detections of fluorescein above background concentrations were observed in the surface water samples collected in the Wash itself, indicating that the Zone 1 UMCf ultimately discharges to the ancestral fluvial deposits underlying the Wash and then to the Wash itself within the Pilot Study area (further discussed in Section 9.3).

6.7 EFFECTIVENESS MONITORING RESULTS

As explained in Section 5.7, groundwater samples were collected on a monthly and bimonthly basis and analyzed for a variety of constituents to evaluate the aquifer’s response related to ISB injections into the unconsolidated UMCf in the Zone 1 study area. 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 these parameters. Because perchlorate is the primary chemical constituents associated with this Pilot Study, Section 6.7.1 presents a detailed discussion of the perchlorate degradation response, an estimate of perchlorate distribution, and an estimate of perchlorate mass destroyed during the Pilot Study. Other significant constituents, including chlorate, nitrate, and TOC, are discussed in Sections 6.7.2 through 6.7.4, with a collective summary of these primary parameters results presented in Section 6.7.5. Additional parameters, including DO, ORP, pH, sulfate, sulfide, metals, and methane, have also been evaluated and are discussed in Section 6.7.6, while an evaluation of the groundwater microbial analytical results is provided in Section 6.7.7.Data for all parameters are presented in the comprehensive data tables provided in Appendix J, Tables J.1 throughJ.3, while calculated percent change in perchlorate concentrations compared to baseline concentrations for Zone 1 monitoring wells are provided in Appendix J, Table J.4. Data for perchlorate, chlorate, nitrate, TOC, arsenic, phosphorus, DO, and ORP are depicted graphically in individual well trend profiles provided in Appendix L, Figures L.1 through L.27. Field logs from all groundwater sampling events are provided in Appendix I and the DVSR is provided in Appendix K.

6.7.1 Perchlorate

As explained in Section 2.1, perchlorate in groundwater can biodegrade in the presence of a carbon substrate once DO, nitrate, and generally chlorate have been depleted. Perchlorate concentrations in groundwater were evaluated throughout the study to monitor concentration changes when comparing the baseline (pre-injection) sampling event to those sampling events performed following each of the two injection events into the unconsolidated UMCf within the Zone 1 study area. This monitoring program included monitoring wells located at significant distances downgradient of the injection well transect (distances ranging from 25 to 150 feet from the injection well transect), where concentration reductions may be minimal due to the limited study duration and short injection well transect length that likely results in migration of groundwater into the study area that did not pass directly through the biologically active zone. As such, this limits the extent of farther downgradient treatment that can be observed as part of this small-scale Pilot Study. Evaluations of the perchlorate degradation response, perchlorate distribution throughout the Zone 1 study area, and estimates of perchlorate mass removal are presented in the subsequent sections. Perchlorate concentration data collected from the Zone 1 study area are summarized in Appendix J, Tables J.1 and J.4 and graphically depicted in Appendix L, Figures L.1 through L.27. **Figures 11a-c and 12a-c** present perchlorate plume interpretations for the shallow and deep UMCf, respectively, during the Pilot Study for the Zone 1 study area, which are discussed in Section 6.7.1.2.

6.7.1.1 Perchlorate Degradation Response

This section provides a summary of the baseline conditions and subsequent perchlorate degradation response that was observed following each of the two injection events summarized in Section 6.3. Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages. ***Table 4*** summarizes the average and maximum perchlorate concentration changes in groundwater observed as percentage change when compared to the baseline concentrations in both shallow and deep UMCf monitoring wells located upgradient and downgradient of the injection well transect throughout the study duration. Analytical data used in the calculations for concentration changes during the Pilot Study are presented in Appendix J, Table J.1. A detailed summary of percentage change in perchlorate concentrations compared to baseline concentrations for all Zone 1 monitoring wells is provided in Appendix J, Table J.4.

Table 4 Zone 1 Perchlorate Concentration Changes During Pilot Study

Event Description	Sampling Event	Monitoring Well Location					
		60 Feet Upgradient of Injection Well Transect		25 Feet Downgradient of Injection Well Transect		50 to 150 Feet Downgradient of Injection Well Transect	
		No. of Wells = 3		No. of Wells = 6		No. of Wells = 10	
		Average	Maximum	Average	Maximum	Average	Maximum
After Injection Event 1	Month 1	-57%	-99%	-43%	> -99%	21%	-41%
	Month 2	-38%	-91%	-23%	-99%	15%	-45%
	Month 3	-22%	-68%	-19%	-99%	19%	-34%
	Month 4	-17%	-39%	-22%	-93%	12%	-52%

Event Description	Sampling Event	Monitoring Well Location					
		60 Feet Upgradient of Injection Well Transect		25 Feet Downgradient of Injection Well Transect		50 to 150 Feet Downgradient of Injection Well Transect	
		No. of Wells = 3		No. of Wells = 6		No. of Wells = 10	
		Average	Maximum	Average	Maximum	Average	Maximum
	Month 6	-1%	-18%	-25%	-99%	13%	-50%
	Month 8	-11%	-32%	-21%	-97%	11%	-50%
After Injection Event 2	Month 11	-71%	-99%	-43%	-99%	-14%	-58%
	Month 12	-63%	-99%	-40%	-99%	-2%	-71%
	Month 13	-66%	-99%	-30%	-99%	10%	-52%
	Month 14	-63%	-99%	-28%	-99%	8%	-59%
	Month 16	-61%	-99%	-29%	-99%	-6%	-59%
	Month 18	-43%	-99%	-31%	-99%	15%	-59%

Notes:

1. Percentage change in perchlorate concentration is calculated relative to the pre-injection baseline groundwater sampling event in September/October 2020 (labeled as event BL04 in Appendix J, Table J.1). Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages.
2. The calculation for average concentration change accounts for both increases and decreases in concentrations compared to baseline.
3. The maximum change shown is the most significant reduction in concentration compared to baseline concentrations and is represented by the most negative percentage calculated.

6.7.1.1.1 Baseline Groundwater Results

Groundwater samples were collected from monitoring wells screened in the alluvium and both the shallow and deep UMCf in September/October 2020 as part of baseline sampling activities. Perchlorate concentrations in groundwater ranged from 1,900 µg/L to 4,400 µg/L in the alluvium, from 1,100 µg/L to 10,000 µg/L in the shallow UMCf, and from 1,700 µg/L to 7,100 µg/L in the deep UMCf. The highest detection of 10,000 µg/L was measured in a groundwater sample collected from LVWPS-U1-MW05A, which is located approximately 50 feet downgradient of the injection well transect in the southern portion of the Zone 1 area and screened in the shallow UMCf.

6.7.1.1.2 Perchlorate Degradation Response Following Injection Event 1

Following completion of the first injection event in December 2020, groundwater sampling was performed monthly for the first 4 months and then reduced to bimonthly sampling until the second injection event in October 2021. This pattern resulted in groundwater sampling events being conducted during Months 1, 2, 3, 4, 6, and 8 following the first injection event. Groundwater samples were collected from all monitoring wells screened in both the alluvium and shallow/deep UMCf (as described in Section 6.2.2) to monitor for potential contaminant concentration reductions resulting from ISB injections into the UMCf within the Zone 1 study area. Results following the first injection event are summarized below.

- Samples were collected from four upgradient or cross-gradient monitoring wells following the first injection event to evaluate concentrations outside of the targeted treatment area.

- Groundwater analytical data from samples collected from monitoring wells LVWPS-U1-MW03B and LVWPS-U1-MW06A, which are located approximately 60 feet cross-gradient and upgradient of the Zone 1 injection well transect, respectively, indicate that perchlorate concentrations in areas outside of the influence of Zone 1 ISB injections generally remained stable or showed slight increases above baseline concentrations following the first injection event. Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U1-MW03B ranged from 5,100 μg/L to 6,300 μg/L following the first injection event compared to a baseline concentration of 4,300 μg/L (Appendix L, Figure L.4). Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U1-MW06A ranged from 1,200 μg/L to 1,400 μg/L following the first injection event compared to a baseline concentration of 1,100 μg/L (Appendix L, Figure L.1).
- Perchlorate concentration reductions were reported in samples collected from the remaining two upgradient monitoring wells screened in the UMCf, namely LVWPS-U1-MW06B and LVWPS-U1-MW07 (Appendix L, Figures L.2 and L.3). Specifically, results from groundwater samples collected one month following the first injection event indicated that perchlorate concentrations reduced from 1,700 μg/L to 21 μg/L in the sample collected from LVWPS-U1-MW06B (99 percent reduction) and from 4,100 μg/L to 430 μg/L in the sample collected from LVWPS-U1-MW07 (90 percent reduction). Concentration reductions in areas located upgradient of the injection well transects are not surprising given the low effective porosities observed and calculated during injection activities discussed in Section 6.3. Low effective porosity causes injectate solution to move farther from the injection points (both upgradient and downgradient) during injections, particularly when injecting under pressure. This was evident following the first injection event given the increase in total organic carbon concentration in the groundwater samples collected from these monitoring wells. Following the Month 1 sampling event, perchlorate concentrations in groundwater samples collected from upgradient monitoring wells LVWPS-U1-MW06B and LVWPS-U1-MW07 began to increase, with concentrations ranging from 370 μg/L to 4,000 μg/L. By the Month 8 sampling event (last event prior to the second injection event), the perchlorate concentrations in groundwater samples collected from both monitoring wells returned to pre-injection conditions, which was expected because carbon substrate would not be expected to naturally migrate into upgradient areas.

- Three of the six monitoring wells screened in the shallow or deep UMCf and located approximately 25 feet downgradient of the injection well transect (LVWPS-U1-MW01B, LVWPS-U1-MW08A, and LVWPS-U1-MW08B) exhibited notable perchlorate concentration decreases compared to baseline concentrations following the first injection event (Appendix L, Figures L.6 through L.8).
  - Results from the groundwater sample collected from monitoring well LVWPS-U1-MW01B during Month 1 indicated a perchlorate concentration of 510 μg/L, which represented a 93 percent reduction in perchlorate concentration when compared to the baseline concentration of 7,100 μg/L. However, perchlorate concentrations substantially increased to greater than 8,000 μg/L in groundwater samples collected from LVWPS-U1-MW01B during Months 2 and 3, and then reduced slightly in groundwater samples collected in Months 4, 6, and 8 with concentrations ranging from 5,500 μg/L to 6,200 μg/L. This monitoring well was located in the northern portion of the Zone 1 study area and is likely influenced by groundwater migrating into the Zone 1 study area that does not pass through the injection well transect. Initially, the carbon substrate that is added can have a positive influence due to the distribution water transporting organic carbon for perchlorate biodegradation despite perchlorate-laden groundwater flow from the northern portions. However, the regular transport of untreated perchlorate-laden water that moves towards this monitoring well over time impacts concentrations because this location may not continue to receive carbon-rich water because it is not directly in the path of injections.

- During the first month following the first injection event, groundwater samples collected from monitoring wells LVWPS-U1-MW08A and LVWPS-U1-MW08B indicated perchlorate concentrations of less than 0.31 μg/L and 3.9 μg/L, respectively, which are below the PRG of 15 μg/L and represent a greater than 99 percent reduction when compared to baseline concentrations of 4,700 μg/L and 2,800 μg/L, respectively. Perchlorate concentrations in groundwater samples collected from LVWPS-U1-MW08A continued to indicate strong concentration reductions of greater than 93 percent through Month 8 (prior to the second injection event), with concentrations ranging from less than 0.31 μg/L to 310 μg/L. Although concentration reductions continued to be greater than 98 percent through Month 3 in groundwater samples collected from LVWPS-U1-MW08B, perchlorate concentrations began to slightly increase during the Month 4 sampling event (concentration of 700 μg/L) and continued this increasing trend through Month 8 to a concentration at 1,400 μg/L, which represents a 50 percent reduction compared to baseline. The increase is likely due to a gradual exhaustion of organic carbon from the first injection event and continuing influx of perchlorate-laden water from upgradient locations.

- Results from groundwater samples collected from the remaining three monitoring wells screened in the shallow or deep UMCf and located approximately 25 feet downgradient of the injection well transect (LVWPS-U1-MW01A, LVWPS-U1-MW02A, and LVWPS-U1-MW02B) indicated perchlorate concentration fluctuations and/or minimal concentration decreases following the first injection event, with concentrations ranging from 1,900 μg/L to 7,800 μg/L (Appendix L, Figures L.5, L.9, and L.10). The variability in the concentration reductions observed at well clusters located approximately 25 feet downgradient of the injection well transect illustrates the preferential flow pathways in Zone 1 based on the geologic heterogeneity of the UMCf discussed in Section 6.4. At the LVWPS-U1-MW01 cluster (located in the northern portion of the Zone 1 study area), groundwater samples collected from the deep UMCf (LVWPS-U1-MW01B) indicated perchlorate concentration reductions immediately after the first injection event, which is consistent with the lower effective porosity of the deep UMCf and larger ROI of the deep Zone 1 injection wells. The stronger response in the deep UMCf compared to the shallow UMCf could be related to the thin sand layers observed in the deep UMCf, which likely provided a preferential flow pathway in the deep UMCf during injections. The LVWPS-U1- MW02A/B well cluster is located somewhat father downgradient (approximately 32 feet), and no significant perchlorate response was observed in groundwater samples collected from either monitoring well at this location after the first injection event. This suggests that unlike at the LVWPS-U1-MW01A/B and LVWPS-U1-MW08A/B clusters, no significant preferential flow pathways existed in the immediate vicinity of the LVWPS-U1-MW02A/B well cluster (i.e., the thin sand layers in the deep UMCf were likely not laterally continuous near LVWPS-U1-MW02B, and the secondary porosity associated with faulting did not create a flow pathway between the injection well transect and LVWPS-U1-MW02B).
- Groundwater samples were collected from the four monitoring wells located approximately 50 feet downgradient of the injection well transect and screened in the shallow or deep UMCf (LVWPS-U1-MW04A, LVWPS-U1-MW04B, LVWPS-U1-MW05A, and LVWPS-U1-MW05B) (Appendix L, Figures L.11 through L.14). Although perchlorate concentration reductions did not occur in the groundwater samples collected from LVWPS-U1-MW05B, perchlorate concentrations in groundwater samples collected from LVWPS-U1-MW05A slightly reduced when compared to a baseline concentration of 10,000 μg/L, with reductions ranging from 5 percent to 17 percent following the first injection event (i.e., concentrations ranging from 8,300 μg/L to 9,500 μg/L). A combination of preferential flow pathways and extremely low groundwater flow rates at LVWPS-U1-MW04B (approximately 0.04 ft/day) likely prevented the arrival of injectate and/or treated groundwater arriving in the vicinity of the monitoring well cluster LVWPS-U1-MW04A/B during the first eight months of monitoring following the first injection event.
- Six monitoring wells screened in the shallow or deep UMCf and located approximately 100 to 150 feet downgradient of the injection well transect (LVWPS-U1-MW09A, LVWPS-U1-MW09B, LVWPS-MW217B, LVWPS-MW217C, LVWPS-U1-MW10A, and LVWPS-U1-MW10B) were also sampled following the first

injection event (Appendix L, Figures L 15 through L. 20). Of these, perchlorate concentration reductions were reported in groundwater samples collected from monitoring wells LVWPS-U1-MW09B and LVWPS-U1-MW10B. Perchlorate concentration reductions in groundwater samples collected from LVWPS-U1-MW09B ranged from 34 to 52 percent during the eight months following the first injection event, with concentrations ranging from 3,100 μg/L to 4,200 μg/L compared to a baseline concentration of 6,400 μg/L. The response in this deep UMCf monitoring well located approximately 100 feet downgradient just one month after the first injection event suggests monitoring well LVWPS-U1-MW09B is located along a preferential flow pathway associated with deep sand lenses and/or faulting within the deep UMCf. Perchlorate concentrations reduced from a baseline concentration of 4,600 μg/L to 2,900 μg/L in the groundwater sample collected from LVWPS-U1-MW10B two months following the first injection event (representing a 37 percent reduction in concentrations). However, geochemical data in groundwater collected from LVWPS-U1-MW10B suggest that these reductions could be attributed to natural fluctuations, which can be expected due to this monitoring well being located approximately 150 feet downgradient of the injection well transect. Following this initial decrease, perchlorate concentrations increased over the next six months, with a perchlorate concentration of 5,300 μg/L during the Month 8 sampling event. No concentration reductions were observed in groundwater samples collected from LVWPS-MW217B or LVWPS-MW-217C, a finding which is not unexpected given that this well cluster is located 100 feet downgradient along the extreme northern edge of the Zone 1 study area and is likely primarily influenced by groundwater migrating into the Zone 1 study area that does not pass through the biologically active zone in the vicinity of the injection well transect.

- Following the first injection event, perchlorate concentrations in groundwater in the overlying alluvium both upgradient and downgradient of the injection well transect fluctuated but remained similar to or slightly greater than baseline concentrations (Appendix L, Figures L.21 through L.27). One exception to this is the reduction in perchlorate concentrations in groundwater samples collected from one monitoring well screened in the alluvium (LVWPS-A1-MW10), with perchlorate concentrations reducing from 4,400 μg/L during baseline to 2,500 μg/L in August 2021 (approximately 43 percent reduction in 8 months following the first injection event) (Appendix L, Figure L.27). This is likely due to the upward migration of EVO and/or treated groundwater from the vicinity of LVWPS-U1-MW08A and LVWPS-U1-MW08B, which is located directly upgradient from LVWPS-A1-MW10. As previously explained in Section 6.6.4, these results are supported by the tracer dye data, which indicated upward migration of EVO and/or treated groundwater from the UMCf into the alluvium downgradient of monitoring well cluster LVWPS-U1-MW08A/B, as evidenced by the appearance of fluorescein dye in samples collected from alluvial monitoring wells LVWPS-MW217A, LVWPS-A1-MW09, and LVWPS-A1-MW10. As discussed in Section 6.4, secondary porosity in the UMCf associated with faults likely creates preferential flow pathways for upflux from the UMCf into the overlying alluvium. Significant reductions in perchlorate observed in the overlying alluvium during effectiveness monitoring events are likely to be short-lived because of the high groundwater velocities of greater than 250 ft/day in the Zone 1 alluvium due to the proximity to the Wash (presented in the Phase 1 results discussion in the Work Plan Addendum [Tetra Tech, 2019c]).

6.7.1.1.3 Perchlorate Degradation Response Following Injection Event 2

Following completion of the second injection event in October 2021, groundwater sampling was performed monthly for the first 4 months and then reduced to bimonthly sampling until completion of the Pilot Study's 18-month monitoring program. This resulted in groundwater sampling events being conducted during Months 11, 12, 13, 14, 16, and 18. Results following the second injection event are described below.

- Groundwater analytical data from samples collected from monitoring well LVWPS-U1-MW03B, which is located approximately 60 feet cross-gradient of the Zone 1 injection well transect suggests that groundwater concentration trends for perchlorate in the UMCf the vicinity of Zone 1, but outside of the influence of ISB injections, remained relatively stable following the second injection event. Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U1-MW03B ranged from 5,000 µg/L to 5,500 µg/L following the second injection event (Appendix L, Figure L.4).

- Perchlorate concentration reductions were observed in all three upgradient monitoring wells screened in the shallow or deep UMCf, namely LVWPS-U1-MW06A, LVWPS-U1-MW06B, and LVWPS-U1-MW07, during the first month following the second injection event (Appendix L, Figures L.1 through L.3). Although perchlorate concentrations in groundwater samples collected from LVWPS-U1-MW06A only reduced by 15 percent in the first month following the second injection event when compared to baseline, perchlorate concentrations reduced by greater than 98 percent in samples collected from LVWPS-U1-MW06B and LVWPS-U1-MW07 during the first 4 months after the second injection event (concentrations ranging from 2.2 µg/L to 48 µg/L). During the final two sampling events of the Pilot Study, perchlorate concentrations began to increase in samples collected from LVW-U1-MW06B (ranging from 280 µg/L to 720 µg/L), but reductions were sustained at greater than 99 percent in samples collected from LVWPS-U1-MW07. Results from groundwater samples collected from LVWPS-U1-MW07 were below the PRG of 15 µg/L during four of the six sampling events, with concentrations below the sample detection limit of 0.31 µg/L during the last two sampling events. As previously explained, this upgradient response was expected based on the low effective porosities observed and calculated during injection activities, which resulted in the injectate solution moving farther from the injection points (both upgradient and downgradient) during injections. Overall, the reductions were more pronounced following the second injection event, which correlated with larger and more sustained increases of total organic carbon in the vicinity of these monitoring wells.
- Five of the six monitoring wells screened in the shallow or deep UMCf and located approximately 25 feet downgradient of the injection well transect (LVWPS-U1-MW01A, LVWPS-U1-MW01B, LVWPS-U1-MW02B, LVWPS-U1-MW08A, and LVWPS-U1-MW08B) exhibited notable perchlorate concentration decreases compared to baseline concentrations following the second injection event (Appendix L, Figures L.5 through L.10).
    - The results from the groundwater samples collected from LVWPS-U1-MW01A and LVWPS-U1-MW01B indicated 33 percent and 28 percent reductions in perchlorate concentrations, respectively, during the first month following the second injection event. Specifically, perchlorate concentrations in groundwater samples collected from LVWPS-U1-MW01A decreased from a baseline concentration of 6,100 µg/L to 4,100 µg/L, while perchlorate concentrations in groundwater samples collected from LVWPS-U1-MW01B decreased from a baseline concentration of 7,100 µg/L to 5,100 µg/L. Although perchlorate concentrations in samples collected from LVWPS-U1-MW01A increased back to baseline concentrations for the remainder of the Pilot Study, perchlorate concentrations in samples collected from LVWPS-U1-MW01B reduced to a low of 2,400 µg/L (representing a 66 percent reduction in concentrations when compared to baseline) in the sampling event that occurred approximately two months following injections. Perchlorate concentrations in groundwater samples collected from this monitoring well for the remainder of the study ranged from 5,200 µg/L to 6,500 µg/L. As previously stated, this monitoring well cluster is located in the northern portion of the Zone 1 study area and is likely influenced by groundwater migrating into the Zone 1 study area that does not pass directly through the injection well transect, which reduces the long-term impact from the carbon substrate additions.
    - Although minimal reduction was observed following the first injection event, perchlorate concentrations in groundwater samples collected from LVWPS-U1-MW02B notably decreased during all six sampling events following the second injection event, with concentrations ranging from 1,100 µg/L to 1,800 µg/L (compared to a baseline concentration of 2,400 µg/L). The greatest perchlorate concentration reduction was observed approximately three months after the second injection event in January 2022, when perchlorate concentrations reduced to 1,100 µg/L, which

represented a 54 percent reduction when compared to baseline concentrations. The relatively slow initial groundwater response to ISB injections in the vicinity of LVWPS-U1-MW02B was likely due to the lack of preferential flow pathways between the injection well transect and this well location. Therefore, the response observed at LVWPS-U1-MW02B is likely more representative of natural groundwater flow through primary porosity as opposed to secondary porosity through preferential flow pathways.

    - Groundwater samples collected from monitoring wells LVWPS-U1-MW08A and LVWPS-U1-MW08B both indicated perchlorate concentration reductions of greater than 85 percent during all six sampling events following the second injection event. Specifically, perchlorate concentrations in samples collected from LVWPS-U1-MW08A indicated a greater than 99 percent concentration reduction when compared to baseline (4,700 μg/L) following the second injection event, with perchlorate concentrations ranging from less than 0.31 μg/L (during four of the six sampling events) to 4.7 μg/L. Perchlorate concentrations in groundwater samples collected from LVWPS-U1-MW08B reduced from a baseline concentration of 2,800 μg/L to concentrations ranging from 36 μg/L to 420 μg/L following the second injection event. Microbial analyses (discussed in Section 6.7.7) also indicated the presence of a favorable environment for perchlorate biodegradation, with microbial data indicating increased biomass, increased fermenters (firmicutes) for EVO degradation and carbon production, and low slowed growth ratios suggestive of the presence of adequate amounts of organic carbon for native microorganisms to thrive.

- Groundwater samples were collected at the four monitoring wells screened in the shallow or deep UMCf and located approximately 50 feet downgradient of the injection well transect (LVWPS-U1-MW04A, LVWPS-U1-MW04B, LVWPS-U1-MW05A, and LVWPS-U1-MW05B) (Appendix L, Figures L.11 through L.14). Samples collected from LVWPS-U1-MW05A and LVWPS-U1-MW05B indicated concentration reductions of 22 percent and 71 percent, respectively, during the first month following the second injection event. The perchlorate concentration reductions continued for the remainder of the Pilot Study in samples collected from LVWPS-U1-MW05A, with reductions ranging from 13 percent to 50 percent following the second injection event (concentrations ranging from 5,000 μg/L to 8,700 μg/L, compared to a baseline concentration of 10,000 μg/L). Perchlorate concentrations in samples collected from LVWPS-U1-MW05B fluctuated the remainder of the Pilot Study, with concentrations ranging from 1,500 μg/L to 12,000 μg/L. Perchlorate concentration reductions were not observed in samples collected from monitoring well cluster LVWPS-U1-MW04A/B following the second injection event. As previously stated, a combination of preferential flow pathways and extremely low groundwater flow rates at LVWPS-U1-MW4B (approximately 0.04 ft/day) likely prevented the arrival of injectate and/or treated groundwater arriving in the vicinity of the monitoring well cluster LVWPS-U1-MW04A/B.
- During the first month following the second injection event, perchlorate concentrations reduced in groundwater samples collected from five of the six monitoring wells screened in the shallow or deep UMCf and located approximately 100 to 150 feet downgradient of the injection well transect (namely, LVWPS-U1-MW09A, LVWPS-U1-MW09B, LVWPS-MW217B, LVWPS-MW217C, and LVWPS-U1-MW10B) (Appendix L, Figures L.15 through L.20). These results indicate a stronger response in these farther downgradient monitoring wells compared to concentration reductions following the first injection event. Of these, perchlorate concentration reductions were generally sustained throughout the remainder of the Pilot Study in groundwater samples collected from LVWPS-U1-MW09B, LVWPS-U1-MW10B, and LVWPS-MW217C, which are screened in the deep UMCf. Specifically, the following perchlorate concentration reductions were observed: 55 percent to 59 percent in groundwater samples collected from LVWPS-U1-MW09B (concentrations ranging from 2,600 μg/L to 3,100 μg/L compared to a baseline concentration of 6,400 μg/L); 7 percent to 28 percent in samples collected from LVWPS-U1-MW10B (concentrations ranging from 3,300 μg/L to 4,700 μg/L compared to a baseline concentration of 4,300 μg/L); and 3 percent to 34 percent in samples collected from LVWPS-MW217C (concentrations ranging from 4,100 μg/L to 6,000 μg/L compared to a baseline concentration of 6,200 μg/L). These more

significant reductions in the deep UMCf but not the shallow UMCf in groundwater samples collected from the farther downgradient monitoring wells are consistent with the observation that injectate and treated groundwater from the shallow UMCf could be upfluxing from the UMCf into the overlying alluvium at some locations prior to reaching the shallow UMCf at LVWPS-MW-217B, LVWPS-U1-MW09A, and LVWPS-U1-MW10A.

- Lastly, perchlorate concentrations in groundwater samples collected from upgradient monitoring wells screened in the overlying alluvium (LVWPS-A1-MW06 and LVWPS-A1-MW07) remained similar to or slightly higher than baseline concentrations following the second injection event (Appendix L, Figures L.21 and L.22). However, more widespread impacts to perchlorate concentrations in the alluvium downgradient of the injection well transect were observed following the second injection event. Specifically, perchlorate concentrations reduced in groundwater samples collected from all five downgradient monitoring wells screened in the alluvium between 50 and 150 feet during the first month following the second injection event (Appendix L, Figures L.23 through L.27). The most significant result was a perchlorate detection of 12 mg/L in the groundwater sample collected from LVWPS-A1-MW09, which is below the PRG of 15 mg/L and represents a concentration reduction of greater than 99 percent. As previously explained, these results are supported by the tracer dye data, which indicated upward migration of EVO and/or treated groundwater from the UMCf into the overlying alluvium downgradient of monitoring well cluster LVWPS-U1-MW08A/B. The first sampling event following the second injection event was conducted approximately 3 weeks following injections, which is one week sooner when compared to the first sampling event following the first injection event into Zone 1 UMCf. This earlier sampling may in part explain the more widespread degradation response in the alluvium captured in the data immediately following the second injection event because of the quicker sampling turnaround after injections, as high groundwater velocities in Zone 1 alluvium would quickly dilute a perchlorate degradation response signal in the alluvium associated with injection activities (as observed in the data with concentrations in the alluvium generally returning to baseline concentration levels three to four months following the second injection event).

6.7.1.2 Estimate of Perchlorate Distribution

Figures 11a-c and 12a-c present perchlorate plume isoconcentration contour interpretations during the Pilot Study for the shallow UMCf present from 90 to 120 feet bgs and for the deep UMCf present from 120 to 150 feet bgs within the Zone 1 study area, respectively. The baseline event in October 2020 is intended to represent pre-injection perchlorate concentrations in groundwater within the vicinity of the Zone 1 study area, followed by depictions of subsequent sampling events occurring post-injection. As illustrated in the isoconcentration maps on **Figures 11a-c and 12a-c**, a biologically active treatment zone was created following each injection event, with perchlorate concentrations in groundwater within both the shallow and deep UMCf reduced to below 15 μg/L at multiple locations. These comparisons show reductions in perchlorate concentrations in the immediate vicinity of the injection well transect with reductions extending approximately 60 feet upgradient and 50 feet downgradient in both the shallow and deep UMCf. As discussed in Sections 6.7.1.1.2 and 6.7.1.1.3, perchlorate concentration reductions greater than 90 percent compared to baseline concentrations were observed in upgradient monitoring wells screened in the UMCf. As shown on **Figure 11b**, perchlorate concentrations significantly decreased in samples collected from two upgradient monitoring wells, with results from samples collected from one monitoring well indicating concentrations below the PRG of 15 μg/L following the second injection event. This upgradient response was due to preferential flow pathways in the subsurface in combination with the low effective porosities observed and calculated during injection activities discussed in Section 6.3. The combination of preferential flow pathways and low effective porosity can cause injectate solution to move farther from the injection points (both upgradient and downgradient) during injections, particularly when injecting under pressure.

A review of pre-injection hydrogeological data indicates that influence from ISB could be expected to be observed approximately 22 feet to 165 feet downgradient under the natural gradient of the formation by the end of the 18-

month Pilot Study using the estimated groundwater flow velocities from borehole dilution testing for the UMCf of approximately 0.04 feet/day to 0.3 feet/day. These relatively low groundwater velocity estimates were supported by the dye results, as dye was not detected in samples collected from monitoring wells screened in the UMCf farther than approximately 32.5 feet downgradient during the six-month tracer dye study. Furthermore, farther downgradient of the Zone 1 injection well transect, fluorescein dye rapidly migrated into the alluvium along preferential flow pathways likely including faults, fractures, and/or incised paleochannels in the UMCf. As a result, the isoconcentration maps presented in **Figures 11a-c and 12a-c** are relatively consistent throughout the Pilot Study due to the low groundwater velocity combined with the upflux of groundwater from the UMCf into the alluvium.

As described in Section 6.7.1.1, the response following the second injection event resulted in the greatest perchlorate concentration reduction, with concentrations in the deep UMCf reducing at the farther downgradient locations (up to 150 feet downgradient of the injection well transect), a result which is likely due to the higher proportion of sand layers in the deep UMCf compared to the shallow UMCf. Some areas within the treatment zone had less reduction in perchlorate concentrations, which is likely due to the heterogeneous nature of the subsurface, localized preferential flow paths due to laterally discontinuous sand beds and secondary porosity generated by faulting, and groundwater that did not flow through the relatively short injection well transect migrating into farther downgradient portions of the Zone 1 study area. While acknowledging that the design of the Pilot Study was compact and specific to meet the study objectives, the design of a full-scale remedy would be significantly different, and if implemented full-scale, the injection well transect would likely extend across a much larger distance and potentially include multiple injection well transects to achieve a more uniform biologically active treatment zone.

6.7.1.3 Estimation of Perchlorate Mass Removal

The mass flux of perchlorate passing through each of the three zones was estimated by using available baseline data collected in September/October 2020 prior to injections and the commercially available Earth Volumetric Software (EVS) to create site-specific, three-dimensional distributions of hydraulic conductivity, perchlorate, and groundwater elevation. Calculations of mass flux were then performed by calculating the mass flux of water passing through a vertical plane and by multiplying that by the concentration of perchlorate in the water. The "kriging" geostatistical method was used for interpolation during this process. The calculation process was as follows:

1. A 3D block representing the hydraulic conductivity of the subsurface was generated by interpolation of the slug-test data collected during the Pilot Study (data provided in Appendix G).
2. A 3D block representing the hydraulic gradient was generated by interpolating the hydraulic head pressures measured in the groundwater wells in the area, then processing it using the gradient module in EVS.
3. A 3D block of the perchlorate concentrations was developed based on interpolation of the concentrations of perchlorate observed in groundwater samples collected from each of the monitoring wells during baseline (data provided in Appendix J, Table J.1).
4. The resulting values for each node in each block were then multiplied together to create a 3D block representing the product of hydraulic conductivity, hydraulic gradient, and perchlorate concentration at each node.
5. The resultant 3D block was then sliced using a cross-sectional plane that was approximately the same length as the injection well transect but placed at a location downgradient of the injection well transect. The height of the plane was the thickness of the target geologic unit. Figures showing the locations of each of the cross-sectional planes are provided in Appendix M.

6. The volumetrics module of EVS was then used to integrate the cross-sectional area associated with each of the nodes on the plane and the mass-flux product block to calculate the total mass flux at every node to get a single mass flux value for the cross-sectional plane. As part of this process, the volumetrics module accounted for the conversion from the perchlorate concentration units of micrograms per liter to pounds.

Using this mass flux calculation method and the site-specific data collected during the Pilot Study prior to and following injections, respective perchlorate mass flux estimates were developed for Zone 1, which were subsequently used to estimate the perchlorate mass removal achieved during the Pilot Study as described below.

To constrain the effects of treatment to the area around and downgradient from the injection wells, the measured effect of the treatment itself was processed using interpolation in 3D. To do this, the change in concentration relative to the initial baseline concentration was calculated for each monitoring well and each sampling event. The resulting “change matrix” was then used to generate a 3D block of the change in perchlorate concentration relative to the initial baseline concentration. EVS determines the distribution of mass using interpolation and extrapolation routines (i.e., kriging), which not only calculates concentrations between known data points but also outside of known data points. Because of this, the “change matrix” process was implemented to eliminate the effects on mass estimates related to interpolation and extrapolation artifacts associated with potential increases or decreases in concentration beyond the immediate study area. By limiting the model to concentration changes in groundwater at individual well locations, the “change matrix” calculation process provided control for areas outside of the immediate treatment area. This additional step prevented extrapolated concentration decreases beyond the immediate treatment area from appearing as successful treatment and artificially inflating the estimated mass removed. The resulting 3D block was then subtracted from the initial baseline 3D block of perchlorate concentration on a node-by-node basis to produce a representative distribution of perchlorate for each effectiveness monitoring event.

Following the calculation process described above, the 3D blocks for hydraulic conductivity and hydraulic gradient were combined with the 3D block of perchlorate concentration to calculate the mass flux through the Zone 1 study area for each sampling event. The difference in mass passing through the downgradient cross-sectional plane relative to baseline conditions thereby represents the reduction in mass associated with the injections. The resultant estimates for flux of perchlorate mass removed and perchlorate mass removed for each sampling event are provided in Appendix M, Table M.1. Using this calculation process, an estimated total of 74 pounds of perchlorate was destroyed from the groundwater in the Zone 1 study area during the Pilot Study. It is estimated that of the 74 pounds of perchlorate destroyed, approximately 49 pounds were destroyed in the overlying alluvium and 25 pounds in the UMCf. This is not unexpected due to the extremely high groundwater flow rates present in the overlying alluvium resulting in a substantial mass flux through the alluvium in the Zone 1 study area.

6.7.2 Chlorate

Chlorate is present in groundwater within the Zone 1 study area at concentrations that are often slightly higher than those of perchlorate. Chlorate is also amenable to anaerobic biodegradation, similar to perchlorate. Generally, chlorate biodegradation precedes perchlorate biodegradation, although the two processes can also occur simultaneously, particularly in the presence of organic carbon. Chlorate concentrations are summarized in Appendix J, Table J.1 and are graphically depicted in Appendix L, Figures L.1 through L.27.

Chlorate concentrations in groundwater were measured during baseline and ranged from 9,000 μg/L to 16,000 μg/L in the alluvium, from 3,300 μg/L to 16,000 μg/L in the shallow UMCf, and from 3,800 μg/L to 12,000 μg/L in the deep UMCf. The highest baseline chlorate concentrations were measured in groundwater samples collected from downgradient alluvial well LVWPS-A1-MW05 and downgradient shallow UMCf well LVWPS-U1-MW10A.

In general, chlorate concentration trends followed a similar reducing pattern as the perchlorate concentration trends throughout the Pilot Study timeframe (discussed in Section 6.7.1.1). Noteworthy chlorate results from the Pilot Study are summarized below.

- Chlorate concentration reductions were also observed in all three upgradient monitoring wells screened in the shallow or deep UMCf, namely LVWPS-U1-MW06A, LVWPS-U1-MW06B, and LVWPS-U1-MW07 during the majority of the sampling events performed over the 18-month Pilot Study (Appendix L, Figures L.1 through L.3). Chlorate concentrations reduced by greater than 98 percent when compared to baseline concentrations in samples collected from LVWPS-U1-MW06B and LVWPS-U1-MW07 in the first month following the first injection event. Specifically, chlorate decreased from a baseline concentration of 3,800 μg/L to 8.7 μg/L in groundwater samples collected from LVWPS-U1-MW06B, while chlorate reduced from a baseline concentration of 7,700 μg/L to 110 μg/L in groundwater samples collected from LVWPS-U1-MW07. Although concentrations rebounded some in the subsequent months following the first event, the reductions observed following the second injection event were more pronounced, with reductions of greater than 94 percent sustained through the remainder of the Pilot Study in samples collected from both LVWPS-U1-MW06B and LVWPS-U1-MW07. Despite perchlorate concentration reductions that were generally less than 15 percent in samples collected from LVWPS-U1-MW06A following the first injection event, chlorate concentrations consistently decreased following the second injection event, with a chlorate concentration of less than the sample detection limit of 24 μg/L (representing a reduction of greater than 99 percent) during the final groundwater sampling event. This correlates with the results of the microbial samples collected from this location, indicating that the microbial biomass population was the greatest following the second injection event, with the percentage of firmicutes (generally due to fermenters reacting to a greater amount of carbon production from EVO) also increasing substantially. Additionally, the ratio of slowed growth was at its lowest, indicating that carbon was available at this location for biodegradation following the second injection event. As previously explained, this upgradient response was expected based on the low effective porosities, which resulted in the injectate solution moving farther from the injection points (both upgradient and downgradient) during injections.
- Chlorate results in groundwater samples collected from the six monitoring wells screened in the shallow or deep UMCf and located approximately 25 feet downgradient of the injection wells (LVWPS-U1-MW01A, LVWPS-U1-MW01B, LVWPS-U1-MW02A, LVWPS-U1-MW02B, LVWPS-U1-MW08A, and LVWPS-U1-MW08B) indicated similar concentration reduction trends as perchlorate following both the first and second injection events (Appendix L, Figures L.5 through L.10). Specifically, results from the groundwater samples collected from LVWPS-U1-MW01A and LVWPS-U1-MW01B indicated a better, more sustained response following the second injection event, with chlorate concentration reductions of up to 44 percent and 68 percent, respectively. For example, after an initial decrease to 1,100 μg/L in the first month, results from groundwater samples collected from LVWPS-U1-MW01B indicated chlorate concentrations ranging from 6,600 μg/L to 13,000 μg/L following the first injection event compared to concentrations ranging from 3,800 μg/L to 8,500 μg/L following the second injection event. Results from the samples collected from LVWPS-U1-MW08A and LVWPS-U1-MW08B indicated chlorate concentration reductions greater than 99 percent in the majority of the sampling events throughout the Pilot Study, with concentrations below sample detection limits in the samples collected from LVWPS-U1-MW08A in 10 out of the 12 sampling events. Lastly, chlorate concentrations did not decrease in samples collected from LVWPS-U1-MW02A but did decrease in samples collected from LVWPS-U1-MW02B, with a 71 percent reduction in chlorate concentration during the final month of the Pilot Study (1,200 μg/L in June 2022 compared to baseline concentration of 4,100 μg/L).
- Groundwater results for chlorate in samples collected from the four monitoring wells screened in the shallow or deep UMCf and located approximately 50 feet downgradient of the injection well transect (LVWPS-U1-MW04A, LVWPS-U1-MW04B, LVWPS-U1-MW05A, and LVWPS-U1-MW05B) were similar to perchlorate, with minimal changes were observed in chlorate concentrations following the first injection event (Appendix L, Figures L.11 through L.14). However, chlorate concentration reductions improved within the three months following the second injection event in samples collected from LVWPS-U1-MW05A and LVWPS-U1-MW05B, with chlorate concentration reductions of up to 49 percent and 68 percent, respectively. One notable difference when compared to perchlorate concentration trends is the

reduction in chlorate concentrations in samples collected from LVWPS-U1-MW04B in the sampling events following the second injection event, which included reductions of up to 40 percent compared to baseline concentrations. Ultimately, chlorate concentrations generally returned to baseline levels by the conclusion of the Pilot Study.

- Of the six monitoring wells screened in the shallow or deep UMCf and located approximately 100 to 150 feet downgradient of the injection well transect (namely, LVWPS-U1-MW09A, LVWPS-U1-MW09B, LVWPS-MW217B, LVWPS-MW217C, LVWPS-U1-MW10A, and LVWPS-U1-MW10B), chlorate concentration reductions were the greatest in samples collected from LVWPS-U1-MW09B, with reductions of up to 70 percent when compared to baseline concentrations (Appendix L, Figures L.15 though L.20). Specifically, chlorate concentrations in the groundwater samples collected from LVWPS-U1-MW09B reduced from a baseline concentration of 11,000 μg/L to 5,900 μg/L during the Month 1 sampling event. This overall decreasing concentration trend continued, with the lowest chlorate concentration of 3,300 μg/L detected in groundwater collected during the final sampling event (70 percent reduction compared to baseline). Additionally, chlorate concentration reductions in samples collected from LVWPS-U1-MW09A, LVWPS-MW217B, LVWPS-MW217C, and LVWPS-U1-MW10A improved after the second injection event when compared to concentration reductions following the first injection event and were generally sustained throughout the remainder of the Pilot Study. Specifically, reductions ranged from 8 percent to 27 percent in samples collected from LVWPS-U1-MW09A, 14 to 35 percent in samples collected from LVWPS-MW217B, 10 to 26 percent in samples collected from LVWPS-MW217C, and 19 percent to 38 percent in samples collected from LVWPS-U1-MW10A (concentrations detailed in Appendix J, Table J.1).
- Lastly, chlorate concentrations reduced in groundwater samples collected from all five downgradient monitoring wells screened in the alluvium following the second injection event (Appendix L, Figures L.23 through L.27). The most significant result was the greater than 96 percent chlorate concentration reduction in all groundwater samples collected from LVWPS-A1-MW09 following the second injection event, with concentrations ranging from less than the sample detection limit of 24 μg/L to 580 μg/L (compared to a baseline concentration of 15,000 μg/L). As previously explained, these results are supported by the tracer dye data, which indicated upward migration of EVO and/or treated groundwater from the UMCf into the overlying alluvium downgradient of monitoring well cluster LVWPS-U1-MW08A/B.

6.7.3 Nitrate

Nitrate concentrations were evaluated during the Pilot Study because it is the most likely competing electron acceptor as well as a consumer of organic carbon substrate. Although both perchlorate and chlorate biodegradation generally commence when nitrate biodegradation (denitrification) is substantially complete, it could also occur concurrently with nitrate biodegradation. In the presence of a continuing carbon source, and generally once DO and nitrate have been reduced, perchlorate acts as an electron acceptor for anaerobic respiration. Nitrate concentrations during the Pilot Study are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.1 through L.27.

Groundwater nitrate concentrations generally ranged from 10 mg/L to 19 mg/L during baseline sampling, but with a few exceptions. Nitrate concentration reductions followed a similar reducing pattern as perchlorate and chlorate concentrations throughout the Pilot Study timeframe (discussed in Sections 6.7.1.1 and 6.7.2, respectively). Noteworthy nitrate results from the Pilot Study are summarized below.

- Nitrate concentrations were also reduced when compared to baseline in the majority of the samples collected from upgradient monitoring wells LVWPS-U1-MW06B and LVWPS-U1-MW07, which are screened in the UMCf (Appendix L, Figures L.2 and L.3). During baseline, nitrate was reported at 11 mg/L and 5.6 mg/L in samples collected from LVWPS-U1-MW06B and LVWPS-U1-MW07, respectively. Following injections, the nitrate concentration in samples collected from these wells averaged 2 mg/L, with 16 of the 24 samples collected indicating nitrate concentrations less than 1.0 mg/L. As previously explained, this upgradient response was expected based on the preferential flow pathways and low effective porosity of the subsurface, which resulted in the injectate solution moving farther from the injection points (both upgradient and downgradient) during injections.

- During the first month immediately following the first injection event, nitrate concentrations reduced in samples collected from LVWPS-U1-MW01B, LVWPS-U1-MW08A, and LVWPS-U1-MW08B, which are the same wells located approximately 25 feet downgradient of the injection well transect for which sample results indicated perchlorate and chlorate reductions (Appendix L, Figures L6 through L.8). Specifically, nitrate concentrations reduced from 13 mg/L and 10 mg/L to less than 0.14 mg/L in the samples collected from LVWPS-U1-MW08A and LVWPS-U1-MW08B, respectively. Nitrate concentrations also reduced from 13 mg/L to 1.5 mg/L in the samples collected from LVWPS-U1-MW01B.
- Nitrate results in groundwater samples collected from the six monitoring wells screened in the shallow or deep UMCf and located approximately 25 feet downgradient of the injection wells (LVWPS-U1-MW01A, LVWPS-U1-MW01B, LVWPS-U1-MW02A, LVWPS-U1-MW02B, LVWPS-U1-MW08A, and LVWPS-U1-MW08B) indicated similar concentration reduction trends as perchlorate following both the first and second injection events (Appendix L, Figures L.5 through L.10). Specifically, results from the groundwater samples collected from LVWPS-U1-MW01B indicated nitrate concentration reductions ranging from 8 to 88 percent, with the greatest concentration reductions being observed in the same months as the greatest perchlorate and chlorate concentration reductions (i.e., immediately following the first and second injection events, with a nitrate concentration as low as 1.5 mg/L compared to a baseline concentration of 13 mg/L). Results from the samples collected from LVWPS-U1-MW08A and LVWPS-U1-MW08B indicated nitrate concentration reductions greater than 95 percent in the majority of the sampling events, with nitrate concentrations consistently below detection limits in the samples collected from LVWPS-U1-MW08A. Lastly, nitrate concentrations did not decrease in samples collected from LVWPS-U1-MW02A but did decrease in samples collected from LVWPS-U1-MW02B, with a nitrate concentration reduction average of approximately 50 percent throughout the Pilot Study. Specifically, the baseline nitrate concentration in the sample collected from LVWPS-U1-MW02B was 11 mg/L, compared to a post-first injection event average concentration of 7.4 mg/L and a post-second injection event average concentration of 4.6 mg/L.
- In general, minimal nitrate concentration reductions were observed in the results from the samples collected from the four monitoring wells screened in the shallow or deep UMCf and located approximately 50 feet downgradient of the injection well transect (LVWPS-U1-MW04A, LVWPS-U1-MW04B, LVWPS-U1-MW05A, and LVWPS-U1-MW05B) (Appendix L, Figures L.11 through L.14). Two notable exceptions to this were the nitrate concentration reductions of 51 percent and 73 percent when compared to baseline in samples collected from LVWPS-U1-MW04A and LVWPS-U1-MW05B, respectively, following the second injection event. However, each of these reductions was observed during a single sampling event, and concentrations returned to baseline conditions in the remaining sampling events.
- Despite notable perchlorate and chlorate concentration reductions in the farther downgradient wells, minimal nitrate reduction was observed in the samples collected from the six monitoring wells screened in the shallow or deep UMCf and located approximately 100 to 150 feet downgradient of the injection well transect (namely, LVWPS-U1-MW09A, LVWPS-U1-MW09B, LVWPS-MW217B, LVWPS-MW217C, LVWPS-U1-MW10A, and LVWPS-U1-MW10B) (Appendix L, Figures L.15 through L.20). This phenomenon is sometimes due to the range of microorganisms that are native to the aquifer, wherein there could be a preference for perchlorate and chlorate respiration which provides more energy compared to nitrate, even though nitrate uptake generally precedes the degradation of these other electron acceptors.
- Lastly, nitrate concentrations in groundwater in the overlying alluvium both upgradient and downgradient of the injection well transect fluctuated but generally remaining similar to or slightly higher than baseline concentrations (Appendix L, Figures L.21 through L.27). One notable nitrate concentration change was

the reduction from 16 mg/L in baseline to 0.028 mg/L in the groundwater sample collected from alluvium well LVWPS-A1-MW09 immediately following the second injection event (Appendix L, Figure L.25). This is similar to the perchlorate and chlorate concentration reductions observed following the second injection event, which is likely due to the upward migration of EVO and/or treated groundwater from the UMCf into the overlying alluvium downgradient of monitoring well cluster LVWPS-U1-MW08A/B.

6.7.4 Total Organic Carbon

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 Pilot Study to monitor changes in concentrations after injections compared to baseline pre-injection concentrations. TOC concentrations during the Pilot Study are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.1 through L.27.

The initial baseline groundwater sampling event performed in October 2020 indicated that TOC concentrations were approximately 2 mg/L throughout the Zone 1 study area. Noteworthy TOC results from the Pilot Study are summarized below.

- TOC concentrations increased in samples collected from upgradient monitoring wells LVWPS-U1-MW06B and LVWPS-U1-MW07, which are screened in the UMCf, following each of the two injection events (Appendix L, Figures L.2 and L.3). TOC concentrations remained elevated throughout the majority of the sampling events in samples collected from LVWPS-U1-MW07, with TOC concentrations as high as 260 mg/L compared to a baseline concentration of 0.8 mg/L. TOC concentrations decreased over the remainder of the Pilot Study to concentrations of 1.8 mg/L and 11 mg/L in samples collected from LVWPS-U1-MW06B and LVWPS-U1-MW07. respectively. As previously explained, this upgradient response was expected based on the low effective porosities, which resulted in the injectate solution moving farther from the injection points (both upgradient and downgradient) during injections.
- During the first monthly groundwater sampling event following the first injection event, TOC concentrations significantly increased in groundwater samples collected from monitoring wells LVWPS-U1-MW08A and LVWPS-U1-MW08B (located approximately 25 feet downgradient of the injection well transect) with increases from an average baseline concentration of 1.5 mg/L to 300 mg/L and 230 mg/L, respectively (Appendix L, Figures L.7 and L.8). These increases further confirm the presence of low effective porosity and preferential flow pathways that exist in the subsurface from the injection well transect to the vicinity of monitoring wells LVWPS-U1-MW08A and LVWPS-U1-MW08B. These increases in TOC concentrations also generally coincided with rapid decreases in perchlorate, chlorate, and nitrate concentrations, indicating the biochemical and microbial connection between this indicator parameter and contaminant concentrations soon after the first injection event. TOC concentrations remained significantly greater than baseline concentrations for approximately 4 months following the first injection event. During the sampling event performed in Month 6 following the first injection event, TOC concentrations notably decreased to 8.5 mg/L and 10 mg/L in samples collected from LVWPS-U1-MW08A and LVWPS-U1-MW08B, respectively. The sampling event performed in Month 8, prior to the second injection event, indicated TOC concentrations were approximately 4 mg/L in samples collected from both monitoring wells, which was close to baseline concentrations and signaled the need for a second injection event. Although perchlorate concentrations remained significantly below baseline concentrations, this decrease in TOC concentration was associated with an observable increase in perchlorate concentrations.
- TOC concentration increases were also observed in the samples collected from upgradient monitoring wells LVWPS-U1-MW06B and LVWPS-U1-MW07, with increases from an average baseline concentration of 1.7 mg/L to concentrations of 12 mg/L and 210 mg/L, respectively, during the first month following the first injection event (Appendix L, Figures L.2 and L.3). As previously explained, this upgradient response

was expected based on the low effective porosities, which resulted in the injectate solution moving farther from the injection points (both upgradient and downgradient) during injections. As with the samples collected from the downgradient monitoring wells, TOC concentrations decreased over the 8 months between the two injection events to concentrations below 2 mg/L in samples collected from both monitoring wells prior to the second injection event. These decreases in TOC concentrations were associated with observable increases in perchlorate concentrations.

- The TOC data collected following the first injection event was used to determine the timing for the second injection event, as discussed in Section 6.3.2. Following the second injection event, notable increases in groundwater TOC concentrations were again observed in the samples collected from monitoring wells LVWPS-U1-MW08A and LVWPS-U1-MW08B (located approximately 25 feet downgradient of the injection well transect). The sample collected from LVWPS-U1-MW08A during the first month following the second injection event indicated a TOC concentration of 1,400 mg/L, which was the highest TOC concentration detected within the Zone 1 study area during the Pilot Study and significantly above the baseline concentration of 1.7 mg/L. Although TOC concentrations remained elevated when compared to baseline, TOC concentrations were significantly lower in samples collected from LVWPS-U1-MW08B (ranging from 3.6 mg/L to 24 mg/L compared to a baseline concentration of 1.3 mg/L), which is likely due to the presence of more transmissive sand layers within the deeper UMCf resulting in more migration of the emulsified vegetable oil. Even though transmissive sand layers often translate to an earlier arrival of higher concentrations of TOC, the higher flow rates also often result in a more rapid depletion of organic carbon as well. At the end of the 18-month Pilot Study, TOC concentrations in samples collected from LVWPS-U1-MW08A and LVWPS-U1-MW08B remained above baseline concentrations with final study concentrations of 38 mg/L and 20 mg/L, respectively. This data indicates that there was lingering availability of organic carbon at these locations. The ratios of slowed growth from microbial assays of the samples collected from these two locations were also low, indicating that there was sufficient carbon still available for microorganisms to flourish.
- A significant increase in TOC concentration was also observed immediately after the second injection event in the groundwater sample collected from LVWPS-A1-MW09, which is screened in the alluvium and located approximately 100 feet downgradient of the injection well transect (Appendix L, Figure L.25). Specifically, TOC concentrations increased from a baseline concentration of 1.6 mg/L to 87 mg/L after the second injection event. Perchlorate, chlorate, and nitrate reductions were also observed during the same sampling event in the samples collected from LVWPS-A1-MW09. The presence of elevated TOC concentrations in the alluvium at approximately 100 feet downgradient of the injection well transect indicates upward migration of EVO downgradient of the injection well transect. TOC concentrations did not increase in any other samples collected from the alluvium, including those samples collected from monitoring wells located closer to the injection well transect. This data suggests that the perchlorate degradation response and tracer dye observed in samples collected from the Zone 1 alluvial monitoring wells were likely predominantly from the upflux of treated groundwater from the UMCf into the overlying alluvium rather than migration of the injectate solution. Following the increase immediately after the second injection event, TOC concentrations quickly returned to levels similar to baseline concentrations, which is not unexpected due to the fast groundwater flow rates in the alluvium in this area.
- Groundwater samples collected from several remaining downgradient monitoring wells (namely, LVWPS-U1-MW01B, LVWPS-U1-MW02B, LVWPS-U1-MW05A, LVWPS-U1-MW09B, LVWPS-U1-MW10B) indicated perchlorate concentration reductions despite the minimal changes in TOC concentrations. The lower perchlorate concentrations are likely due to migration of groundwater that was remediated within the biologically active treatment zone near the injection well transect.

The TOC concentration data collected over the 18-month study provides valuable information to determine the longevity of the EVO and potential injection frequencies for a full-scale effort if a similar remedial technology was selected as a component of the NERT final remedy. The data also confirm the presence of low effective porosity and significant preferential flow paths within the Zone 1 shallow and deep UMCf, as well as upward migration into the overlying alluvium. Lastly, although notable TOC concentration increases were only present in samples collected from four monitoring wells, perchlorate concentrations decreased in samples collected from other downgradient monitoring wells that did not also show TOC concentration increases. This finding indicates the likely downgradient movement of treated groundwater migrating from the injection well transect, a phenomenon that is commonly observed in transect-based bioremediation.

6.7.5 Collective Results for Primary Parameters

As described in Sections 6.7.1 through 6.7.4, the results of the primary parameters of perchlorate, chlorate, nitrate, and TOC demonstrate that bioremediation of perchlorate occurred within both the shallow and deep UMCf in samples collected from monitoring wells located primarily along preferential flow paths within the Zone 1 study area and within the overlying alluvium due to upward migration in areas located downgradient of the injection well transect. Results show that in areas where groundwater samples indicated an increase in TOC concentrations, reductions were also observed in perchlorate, chlorate, and nitrate concentrations. In four of the five locations that saw notable increases in TOC concentrations (i.e., LVWPS-U1-MW07, LVWPS-U1-MW08A, LVWPS-U1-MW08B, and LVWPS-A1-MW09), perchlorate concentrations in groundwater were reduced to below the PRG of 15 μg/L. (Appendix L, Figures L.3, L.7, L.8, and L.25, respectively). Groundwater samples collected from other downgradient monitoring wells also had notable concentration reductions of perchlorate despite minimal changes in TOC concentrations.

6.7.6 Additional Chemical and Geochemical Evaluation

This section provides a summary of the additional data collected during the Pilot Study from the Zone 1 study area. This includes DO, ORP, sulfate, and sulfide, as well as the geochemical relevance of each parameter in relation to perchlorate biodegradation. During the Pilot Study, groundwater samples were also collected from three clustered well locations within Zone 1 (namely, LVWPS-A1-MW04, LVWPS-U1-MW04A/B, LVWPS-A1-MW06, LVWPS-U1-MW06A/B, LVWPS-A1-MW10, and LVWPS-U1-MW10A/B) and analyzed for an extended suite of parameters as described in Section 5.7. As a result, a discussion of metals, pH, alkalinity, TDS, methane, total nitrogen, phosphorus, hexavalent chromium, and volatile fatty acids (VFAs) is presented to discuss their significance on the Pilot Study findings. Results for all parameters discussed herein are presented in the comprehensive data tables provided in Appendix J, Tables J.1 and J.2. DO, ORP, and sulfate concentrations during the Pilot Study are graphically depicted in Appendix L, Figures L.1 through L.27.

6.7.6.1 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 averaging approximately 2.04 mg/L and ranging from 0.68 to 6.71 mg/L. Following the first injection event, DO concentrations decreased in groundwater samples collected from several of the monitoring wells within the Zone 1 study area, with an average DO concentration of 1.0 mg/L in the first sampling event after the first injection event. These reductions in DO concentrations indicate that reducing conditions were rapidly established following the first injection event. DO concentrations in groundwater samples from several monitoring wells, such as LVWPS-U1-MW04B, LVWPS-U1-MW06B, LVWPS-U1-MW08A, and LVWPS-U1-MW08B, reduced to less than 0.5 mg/L, a change indicative of strongly reducing conditions. Other notable DO concentration decreases to less than 1.0 mg/L were also observed in groundwater samples collected from monitoring wells LVWPS-U1-MW01B, LVWPS-U1-MW02A, LVWPS-U1-MW02B, LVWPS-U1-MW05B, LVWPS-U1-MW06A, LVWPS-U1-MW07, LVWPS-U1-MW09A, and LVWPS-U1-MW09B following the first injection event. Despite other parameter results indicating the need for the second injection event (i.e., perchlorate concentration increases and/or TOC concentration decreases), DO concentrations generally remained consistently decreased during all sampling events after the first injection event, with no notable return to aerobic conditions (i.e., DO concentrations prior to the second injection were less than 0.5 mg/L in samples from four monitoring wells and less than 1.0 mg/L in samples from nine monitoring wells). Therefore, results from Zone 1 indicate that DO may not be the prime indicator of the need for additional injection events, particularly due to the high percentage of fine-grained material, wherein some of the TOC may be adsorbed more strongly to the soil grains.

Following the second injection event, field readings for DO indicated an average DO concentration of 0.84 mg/L. DO concentrations reduced to less than 0.5 mg/L in groundwater samples from 12 of the 20 monitoring wells screened in the UMCf within the Zone 1 study area (namely, LVWPS-U1-MW01B, LVWPS-U1-MW02B, LVWPS-U1-MW03B, LVWPS-U1-MW04B, LVWPS-U1-MW05B, LVWPS-U1-MW06A, LVWPS-U1-MW06B, LVWPS-U1-MW07, LVWPS-U1-MW08A, LVWPS-U1-MW08B, LVWPS-U1-MW09B, and LVWPS-MW217C). Other notable DO concentration decreases to less than 1.0 mg/L were observed in groundwater samples collected from monitoring wells LVWPS-U1-MW02A and LVWPS-U1-MW09A following the second injection event. Strongly anaerobic conditions were also present in the groundwater samples periodically collected from four of the alluvial monitoring wells (LVWPS-A1-MW04, LVWPS-A1-MW09, LVWPS-A1-MW10, and LVWPS-MW217A).

In summary, DO can be a useful indicator during the initial stages of ISB when carbon substrate is first injected into the groundwater. As the reductive transect continues to develop and EVO begins to coat the soil grains along the injection well transect, less organic carbon is transported to downgradient locations. Even though overall perchlorate concentration decreases may be sustained or further reduced, 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 downgradient flow water that was treated in the upgradient biologically active treatment zone. Secondly, as stated above, in areas with a higher fines content, as in the UMCf, there is a tendency for the added organic carbon and its degradation products to adsorb more strongly and for a longer period of time. This results in the slow release or desorption of the organic carbon and its degradation products over time into the groundwater, which is sufficient to maintain the DO at anaerobic levels, but not sufficient for prolonged and sustained perchlorate, chlorate, and nitrate degradation.

6.7.6.2 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 the reducing conditions. 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 event in October 2020, ORP measurements collected from groundwater in the UMCf averaged 24 mV). However, results of samples collected from select monitoring wells during the baseline sampling indicated aerobic conditions based on DO concentrations, but anaerobic conditions based on ORP measurements (for example, a DO concentration of 3.1 mg/L and ORP measurement of -172.1 mV in the sample collected from LVWPS-U1-MW08B). Although not as pronounced as the change observed with DO concentrations following the first injection event, the average ORP measurement in the UMCf groundwater was -17 mV after the first injection event, indicating a shift towards anaerobic conditions. Strongly negative field readings for groundwater ORP of less than - 300 mV were measured in samples from all monitoring wells where an increase in TOC concentration was also observed (i.e., LVWPS-U1-MW07, LVWPS-U1-MW08A, and LVWPS-U1-MW08B), a trend which generally continued during the time period between the first and second injection event.

Although the sampling event immediately following the second injection event recorded the lowest DO concentrations as well as some of the lowest perchlorate concentrations, ORP measurements were higher than baseline, with an average ORP of 93 mV. As a result, the ORP measurements do not correlate with the data collected for several other parameters during this sampling event. As previously mentioned, redox measurements may not always be accurate in aquifers with several electron acceptors and redox pairs. The remaining sampling events following the second injection event indicated anaerobic conditions based on average ORP measurements ranging from -38 mV to -67 mV.

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 Pilot Study, as inferred from ORP readings. However, during some sampling events, redox measurements did not correlate well with the supporting data from other analytes.

6.7.6.3 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 strongly 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 averaged approximately 1,970 mg/L in the groundwater samples collected from the monitoring wells screened in the shallow and deep UMCf within the Zone 1 study area. In general, groundwater at downgradient monitoring wells exhibited relatively stable sulfate concentrations during the Pilot Study, with the overall average sulfate concentrations in each event ranging from 1,400 mg/L to 1,711 mg/L. However, groundwater samples collected from LVWPS-U1-MW08A showed significant decreases in sulfate after each injection event. Specifically, sulfate concentrations in samples collected from LVWPS-U1-MW08A decreased from a baseline concentration of 1,500 mg/L to 410 mg/L in the sample collected approximately 3 months after the first injection event. Although sulfate concentrations had increased to 1,000 mg/L in the Month 8 sampling event performed before the second injection event, sulfate concentrations again reduced following the second injection event, with sulfate concentrations less than 10 mg/L in the samples collected from LVWPS-U1-MW08A during the last four sampling events of the Pilot Study. Sulfate concentrations also reduced by up to 58 percent in the samples collected from LVWPS-U1-MW08B following the second injection event, with a low concentration of 590 mg/L compared to a baseline concentration of 1,400 mg/L. Lastly, sulfate concentrations reduced in the samples collected from upgradient monitoring well LVWPS-U1-MW07 screened in the UMCf, with the lowest sulfate concentration of 450 mg/L detected in the sample collected approximately 4 months following the second injection event.

Sulfide was monitored at one upgradient monitoring well cluster (LVWPS-A1-MW06, LVWPS-U1-MW06A and LVWPS-U1-MW06B) and two downgradient monitoring well clusters (LVWPS-A1-MW04, LVWPS-U1-MW04A, LVWPS-U1-MW04B, LVWPS-A1-MW10, LVWPS-U1-MW10A, and LVWPS-U1-MW10B). Sulfide was detected at low concentrations of up to 2 mg/L in samples collected from the upgradient deep UMCf monitoring well LVWPS-U1-MW06B following the second injection event. Sulfide was not detected in any samples collected from the downgradient monitoring wells in Zone 1 during the Pilot Study.

Although sulfate concentrations did significantly reduce in samples collected from monitoring wells with increased TOC concentrations, the overall sulfate results suggest that sulfate reduction is not persistent throughout the Zone 1 study area. The limited sulfate reduction observed in the Zone 1 study area is consistent with the results of previous ISB studies performed within the NERT RI Study Area and suggests the potential negative impacts of sulfate biodegradation in this high sulfate environment may be minimized and/or controlled during implementation of perchlorate bioremediation. Despite perchlorate concentration reductions and anaerobic conditions observed in samples collected from downgradient monitoring wells during the study, overall sulfate reduction was minimized likely due to the employment of the slow-release carbon substrate, EVO, 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.

6.7.6.4 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 permeability in the aquifer. To monitor for potential metals mobilization, dissolved metals were analyzed during baseline and periodically during the Pilot Study within the Zone 1 study area at one upgradient monitoring well cluster (LVWPS-A1-MW06, LVWPS-U1MW06A and LVWPS-U1-MW06B) and two downgradient monitoring well clusters (LVWPS-A1-MW04, LVWPS-U1-MW04A, LVWPS-U1-MW04B, LVWPS-A1-MW10, LVWPS-U1-MW10A, and LVWPS-U1-MW10B). This section presents an evaluation of arsenic, iron, and manganese groundwater concentrations during the Pilot Study.

6.7.6.4.1 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 37 µg/L to 74 µg/L. Following injections, arsenic concentrations in groundwater generally remained in line with baseline concentrations with the exception of groundwater concentrations at monitoring well LVWPS-U1-MW06B, which showed transient increases to above baseline concentrations of 270 µg/L and 97 µg/L during the November 2021 and December 2021 sampling events performed during the two months following the second injection event. However, arsenic concentrations in groundwater samples collected from LVWPS-U1-MW06B reduced shortly thereafter and declined to 28 µg/L by the final sampling event in June 2022. Under reducing conditions, which prevailed consistently at LVWPS-U1-MW06B, 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 small quantities), which likely resulted in the precipitation of arsenic as arsenic sulfide in the subsurface. Despite this brief upgradient increase, arsenic concentration increases were not observed in samples collected from farther downgradient monitoring wells. Therefore, arsenic release and mobilization are unlikely to be a secondary issue during the implementation of ISB using EVO as the carbon substrate.

6.7.6.4.2 Iron

Dissolved iron concentrations in groundwater were periodically evaluated during the Pilot Study due to the potential for iron to undergo reduction and mobilization under anaerobic conditions and precipitate out in the subsurface, potentially decreasing the permeability in the aquifer. Baseline concentrations of dissolved iron were less than 0.64 mg/L. During the study, groundwater concentrations for dissolved iron generally continued to measure less than 0.64 mg/L in groundwater at all monitoring wells except for three samples collected from LVWPS-U1-MW06B, where dissolved iron concentrations in groundwater increased slightly from 0.64 to as high as 1.4 mg/L. However, this relatively minor increase in concentration was short-lived, with concentrations returning to below 0.17 mg/L in all final sampling events performed from January to June 2022. The lack of iron mobilization is further supported by field measurements of ferrous iron, which was not detected during the Pilot Study at any of the monitoring wells for which this parameter was sampled and analyzed.

6.7.6.4.3 Manganese

Like iron, manganese can also undergo reduction and mobilization under anaerobic conditions and precipitate out in the subsurface, potentially decreasing the permeability in the aquifer. Baseline dissolved manganese concentrations in groundwater measured up to 0.076 mg/L. Following injections, manganese concentrations in groundwater samples collected from LVWPS-U1-MW06B increased to a concentration high of 0.49 mg/L, which is below the groundwater screening level for manganese of 0.801 mg/L. Results from groundwater samples collected from the downgradient monitoring wells did not show manganese concentration increases above baseline concentrations. This stability in manganese concentrations indicates that manganese solubilization is contained within the Zone 1 study area and does not appear to migrate downgradient.

6.7.6.5 Other Parameters

A suite of several other parameters was periodically analyzed during the Pilot Study. A summary of these parameters and their significance is presented below. Except for pH, which was sampled at all wells during all events, these other parameters were only analyzed in select wells (i.e., upgradient wells LVWPS-A1-MW06, LVWPS-U1-MW06A and LVWPS-U1-MW06B; and downgradient wells LVWPS-A1-MW04, LVWPS-U1-MW04A, LVWPS-U1-MW04B, LVWPS-A1-MW10, LVWPS-U1-MW10A, and LVWPS-U1-MW10B) in accordance with the Work Plan Addendum. Results for each parameter are presented in the comprehensive data tables provided in Appendix J, Tables J.1 and J.2.

- Groundwater pH is an environmental factor that can affect microbial activity, with most species of microorganisms generally preferring a neutral pH between 5.5 and 8.5 standard units. During baseline sampling, groundwater pH ranged from 7.08 to 7.38 standard units. In general, groundwater pH remained within the ideal range, with an overall average pH after injections of 7.06 standard units, with only three of the more than 200 samples collected having a pH outside the ideal range. 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. However, 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 serve as pH buffers. 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 within the Zone 1 study area ranged from 96 to 140 mg/L. During the Pilot Study, groundwater from monitoring well LVWPS-U1-MW06B showed considerable increases in alkalinity concentrations following the second injection of up to 470 mg/L in November 2021. These increases in groundwater alkalinity to more than twice the background concentrations indicated that groundwater is undergoing biodegradation. As previously discussed in Section 6.7.1.1, samples from this monitoring well also displayed significant groundwater perchlorate concentration decreases of greater than 99 percent when compared to baseline.
- TDS concentrations in groundwater were analyzed to assess the impact of salts on delayed or slower perchlorate biodegradation. TDS concentrations ranged from 2,100 to 4,700 mg/L throughout the study. Although these are relatively high concentrations, the Pilot Study (similar to the bench-scale study [Tetra Tech, 2019a]) 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 Pilot Study as an additional indicator of the level of reducing conditions that were established following carbon substrate injections. During the Pilot Study, methane concentrations were detected above baseline concentrations at several locations, with maximum observed increases from less than 0.00063 mg/L to a high of 29 and 18 mg/L in groundwater samples collected from LVWPS-U1-MW06A and LVWPS-U1-MW06B, respectively. Methane that is produced at the depth at which groundwater is being addressed is likely to be rapidly oxidized to harmless carbon dioxide in the UMCf and overlying gravelly and sandy alluvium. Significant increases in methane concentrations compared to baseline concentrations were not observed in other downgradient monitoring wells.
- Total nitrogen concentrations in groundwater generally decreased during the Pilot Study when compared to baseline concentrations in samples collected from LVWPS-U1-MW06B (baseline concentration of 13 mg/L, followed by post-injection concentrations ranging from 0.33 mg/L to 10 mg/L). The decrease in total nitrogen is likely the result of denitrification that was actively occurring in the groundwater as described in Section 6.7.3. Despite the reductions of total nitrogen, high nitrate concentrations in the Pilot Study area groundwater combined with the efforts of four bench-scale studies and three field treatability/pilot studies indicate that there is sufficient nitrogen present in the groundwater and therefore, should not be a limiting nutrient for bioremediation.
- Phosphorus in groundwater was monitored during the Pilot Study because a phosphate solution was added to the injectate mixture during the first injection event 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 transient localized increases in total phosphorus concentrations when compared to baseline concentrations, but concentrations quickly returned to at or below baseline concentration levels. 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 Pilot Study location, with baseline concentrations ranging from 1.61 μg/L to 63.1 μg/L. Periodic concentration decreases were observed in samples collected from all monitoring wells sampled, with concentrations in samples collected from LVWPS-U1-MW06B decreasing to below the sample detection limit of 0.150 μg/L.
- Volatile fatty acids 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, butyric acid, formic acid, and propionic acid were detected in isolated sampling events performed post-injections during the Pilot Study; however, groundwater concentrations were generally low. Acetic acid was detected as high as 320 mg/L in samples collected from LVWPS-U1-MW06B, while both acetic acid and propionic acid were detected at elevated concentrations as high as 130 mg/L and 120 mg/L, respectively, in groundwater samples collected from monitoring well LVWPS-U1-MW04B. Sampling events that indicated elevated concentrations of acetic and/or propionic acids correspond to sampling events with perchlorate concentration reductions.

6.7.7 Microbial Evaluation

Microbial sampling was included in the effectiveness monitoring program to examine the microbial response to carbon substrate injections. As part of this microbial evaluation, samples were collected from one upgradient well cluster (LVWPS-U1-MW06A and LVWPS-U1-MW06B) and one downgradient well cluster (LVWPS-U1-MW08A and LVWPS-U1-MW08B) within Zone 1 during the baseline sampling event and two additional post-injection sampling events (approximately 10 and 16 months following the first injection event). This section presents a summary of this microbial evaluation for Zone 1. Complete analytical results for the microbial analyses performed during the Pilot Study are found in Appendix J, Table J.3; microbial laboratory data reports are provided in Appendix N.

6.7.7.1 Bio-Trap® Sampling and Analysis

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 millimeter 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 large surface area (~600 square meters per gram), which is readily colonized by subsurface microorganisms. 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.

Once the Bio-Trap® samplers are recovered from a monitoring well (approximately 30 days after deployment), deoxyribonucleic acid (DNA), ribonucleic acid (RNA), or PLFA can be extracted from the beads for CENSUS® and/or PLFA assays to evaluate the microbial community. Additionally, the Bio-Trap® samplers can also be analyzed for specific enzymes related to a particular site contaminant, such as the perchlorate reductase enzyme for this Pilot Study. A brief description of the microbial analysis and its importance to perchlorate biodegradation is provided below.

- **PLFA Analysis** – PLFAs are a main component of the membrane (essentially the "skin") of microbes and provide a powerful tool for assessing microbial responses to changes in their environment. Analysis of the types and amount of PLFAs provides a broad-based understanding of the entire microbial community with information obtained in the key areas of viable biomass, community structure, and metabolic activity.
    - <u>Viable Biomass</u> – PLFA analysis is a reliable and accurate method for the determination of viable microbial biomass. Although phospholipids break down rapidly upon cell death, the biomass calculations based on PLFA content do not measure dead cells, but only the active and viable microbial population. Biomass levels are typically reported as cells per bead.
    - <u>Community Structure</u> – PLFAs can be separated into specific types and profiles that reflect the proportions of the categories of organisms present in a sample. Determining which bacterial groups are present and their relative distributions within the community can provide information on what metabolic processes are occurring at that location. Community structure is presented as a percentage (%) of the total amount of PLFAs and is translated to the related bacterial classification within the overall community structure. The main bacterial groups that are presented via PLFA analyses are:
        - Proteobacteria – One of the largest groups of bacteria that represents a wide variety of both aerobe and anaerobes. They grow opportunistically, quickly taking advantage of available food and adapt quickly to changes in the environment.
        - Firmicutes – Anaerobic fermenting bacteria that use carbon (such as EVO) to produce hydrogen that is then consumed by perchlorate reducing microorganisms.
        - Actinomycetes/sulfate reducers and anaerobic metal reducers – Group of bacteria that are used to gauge the presence and strength of the reducing conditions present in the aquifer.
        - Eukaryotes – Include fungi and protozoa and their abundance indicates that groundwater is relatively contaminant free as these organisms generally prefer smaller microorganisms.

        - Normal saturated groups (Nsats) – Generally present in all microorganisms and provides information on the diversity of the microbial community.
    - Physiological status – The membranes of microorganisms adapt to the changing conditions of its environment that are reflected in the PLFAs. Toxic compounds could disrupt the membrane and some bacteria respond by producing trans fatty acids instead of the usual cis fatty acids to strengthen the cell. The physiological status ratios are reported as Decreased Permeability (ratio of trans/cis) and Slowed Growth (ratio of cy/cis ratio), both of which are based on dividing the amount of the fatty acid induced by environmental conditions by the amount of its precursor. A marked increase in either of these ratios suggests a change in environment, which is less favorable to the gram negative proteobacteria population. The ratio for slowed growth is a relative measure that is suggestive of reduced available substrate (food). A larger ratio for decreased permeability suggests that the environment has become more toxic to the microbial populations, requiring energy expenditure to produce trans fatty acids in order to make the membrane more rigid.
- **Perchlorate reductase enzyme (*pcr*A) –** The perchlorate reductase (pcr) enzyme mediates the initial breakdown of perchlorate to chlorate and chlorite. It is coded for by the pcr enzyme that consists of subunits *pcr*A through D. *Pcr*A is the most valuable of these subunits that is identifiable by advanced molecular biological methods and is a good indicator of perchlorate biodegradation in groundwater.

6.7.7.2 Analysis of Microbial Results

Bio-Trap® samplers were deployed in one upgradient well cluster (LVWPS-U1-MW06A and LVWPS-U1-MW06B) and one downgradient well cluster (LVWPS-U1-MW08A and LVWPS-U1-MW08B) during the pre-injection baseline sampling event and two post-injection events (approximately 10 and 16 months following the first 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.

Results of the baseline microbial sampling indicated that a robust microbial population was present in the groundwater in the vicinity of Zone 1 prior to the injection events. Although the perchlorate reductase enzyme was present at a population of less than $2.5x10^2$ cells per bead, the overall biomass populations during baseline were greater than $2.42x10^5$ cells per bead in both the shallow and deep UMCf. PLFA analysis on community structure indicated that more than 70 percent of the bacterial population belonged to the proteobacteria group. Their presence in large proportions is a strong sign of a microbial community that generally adapts well to the environment and possesses the ability to biodegrade perchlorate in groundwater. The decreased permeability ratio in the samples collected from all four monitoring wells during baseline sampling ranged from 0 to 0.25, which indicates almost negligible signs of toxicity to the native microorganisms prior to injections. On the other hand, the ratios for slow growth ranged from 1.42 to 3.53, which indicates low availability of carbon as a food source for native microorganisms in the Zone 1 study area prior to injections.

Following injections, the perchlorate reductase enzyme remained the same as baseline (less than $2.5x10^2$ cells per bead) in the samples collected from both upgradient and downgradient wells during both post-injection sampling events. Although it did not appear that there was a change in the perchlorate-degrading capability of microorganisms in the aquifer, this is likely because the timing of the microbial sampling did not coincide with the proliferation of perchlorate biodegradation. Therefore, it did not appear that there was a change in the perchlorate-degrading capability of microorganisms in the aquifer.

Proteobacteria percentages also generally remained the same as baseline in the samples collected from the upgradient monitoring wells (LVWPS-U1-MW06A and LVWPS-U1-MW06B). However, proteobacteria percentages decreased by approximately 20 to 50 percent in the post-injection samples collected from the downgradient wells (LVWPS-U1-MW08A and LVWPS-U1-MW08B). The percentage of Nsats, which are generally present in all microorganisms, notably increased in samples collected from both upgradient and downgradient locations, with the most significant increase observed in the samples collected from downgradient monitoring well LVPWS-U1-MW08A (increase from 18.54 percent during baseline to 45.26 percent during the last sampling event). This indicates a redistribution of the microbial community from diverse to slightly less diverse. The increased percentages of firmicutes in the microbial community in the post-injection samples collected from both downgradient wells was also significant, with increases from approximately 3 percent in baseline to 16.26 and 10.92 percent in post-injection samples collected from LVWPS-U1-MW08A and LVWPS-U1-MW08B, respectively. 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.

Finally, the slowed growth ratios decreased substantially in groundwater from both upgradient and downgradient locations, which indicates the strong availability of carbon for microbial consumption and is also one reason for the rise in percentage of firmicutes. The ratios of decreased permeability slightly increased in the post-injection samples collected from downgradient monitoring wells but were still less than 1.0. Although an increase in the ratios of decreased permeability could sometimes signify a build-up of toxicity, the ratios were less than 1.0 and the bacterial community structure did not hamper the overall microbial degradation process during the study as evidenced by the perchlorate concentration reductions observed in the samples collected from these wells.

6.8 ZONE 1 SUMMARY

The results summarized herein for Zone 1 provided sufficient data to meet the objectives of the Pilot Study and will support evaluation of ISB as a potential component of the NERT final remedy in the forthcoming OU-3 FS. The fulfillment of the study objectives is summarized below and provided in tabular format in the performance criteria tables provided as Appendix O.

- Objective 1 – Determine if ISB can effectively create a biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater within the UMCf and compare the effectiveness with respect to variations in lithology between the UMCf within Zone 1 and UMCf-cg within Zone 3 (discussed in Section 8.0). Data collected indicate the following:
    - A biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater was created both upgradient and downgradient of the Zone 1 injection well transect. Groundwater perchlorate concentrations of less than 0.31 µg/L were achieved in samples collected from both the shallow and deep UMCf and DO concentrations throughout the Zone 1 study area indicated a substantial shift from aerobic conditions to anaerobic conditions post-injection (baseline average of 2.3 mg/L to less than 1 mg/L post-injection). Although a biologically active zone was created, the injectate travelled along preferential flow paths throughout the faulted-UMCf, which resulted in greater contaminant concentration reductions in some areas compared to others. The design of a full-scale ISB remedy would be significantly different than the compact Pilot Study design, and if selected as a component of the NERT final remedy, the injection well transect would likely extend across a much larger distance and potentially include multiple injection well transects to substantially improve distribution throughout the preferential flow paths that exist in the UMCf as opposed to just those that existed near the 200-foot injection well transect that was installed in the Zone 1 study area.
- Objective 2 – Evaluate ISB implementation and operational components within the UMCf, including injection protocols, achievable injection rates, subsurface distribution of injectate, injection well spacing, and construction methods. Data collected indicate the following:
    - Injections were performed in both the shallow and deep treatment interval within each nested injection well cluster at the same time, with the injection rates adjusted so that each injection well within a cluster would finish the injection process at generally the same time interval. The goal of performing injections in this manner was to achieve relatively even subsurface distribution within

the long-screened intervals of the nested injection well while also attempting to account for variability and non-uniform groundwater flow and lithology. As explained in Section 6.6.4, the injectate solution, tagged with fluorescein dye appeared in samples collected from all four dose-response monitoring wells screened in the shallow and deep UMCf. This indicates that the injections were successful in vertically distributing the injectate in both the shallow and deep UMCf using this injection method with the dual-nested injection wells and did not preferentially go into one interval over the other.

- The study generated a substantial dataset related to achievable injection rates and pressures, with average injection rates of 5 gpm and injection pressures of 10 psi. During the injections, the injectate was observed in upgradient and downgradient monitoring wells that were situated along direct preferential flow paths and less so in other areas. As a result, it is important to maintain relatively low injection rates and pressures to minimize distribution along those paths and instead to achieve more evenly distributed injectate around the injection well to create a more uniform biologically active zone.
- As described in Section 6.3.2, the dose-response monitoring related to the dye injections indicated a significantly lower mobile (effective) porosity compared to the values estimated using the data collected during pre-design activities. This lower effective porosity resulted in a reduction in distribution water requirements in the UMCf, which is an important data point for the forthcoming FS when evaluating the implementability and cost of an injection remedy into the UMCf.
- Lastly, an injection well spacing of 25 feet, resulting in an injection ROI of 12.5 feet, was determined to be reasonable based on the overall response to the injections into the UMCf within Zone 1. This finding adds to NERT's growing knowledgebase of ISB implementation experience and the operational data collected during this study provides important information for evaluation of a potential full-scale ISB remedy in the UMCf in the forthcoming FS and the scale-up requirements related to injection quantities, rates/pressures, and durations.

- Objective 3 – Determine whether remediation in the UMCf in an area with elevated perchlorate and chlorate concentrations in groundwater and a known upward gradient has an effect on contaminant concentrations in the overlying alluvium groundwater, and if so, whether the effect differs depending on UMCf lithology (comparison of results from Zones 1 and 3). Data collected indicate the following:
    - Fluorescein was detected in charcoal samplers collected approximately 1 month after dye injection from three downgradient monitoring wells screened in the alluvium, namely, LVWPS-A1-MW09, LVWPS-A1-MW10, and LVWPS-MW217A, which are located 100 to 150 feet downgradient of the injection well transect. TOC concentration increases were also observed in samples collected from downgradient alluvial monitoring well LVWPS-A1-MW09 during the first month following the second injection event. Additionally, groundwater perchlorate concentrations significantly reduced in downgradient alluvial monitoring wells located approximately 100 to 150 feet downgradient of the injection well transect following the second injection event. These results confirm the presence of an upward gradient and that injections into the UMCf can reduce concentrations in the overlying alluvium.
- Objective 4 – Determine the approximate length of time that ISB could be expected to affect concentrations in the UMCf, and the resulting injection frequency required to maintain these concentration reductions. Data indicate the following:
    - Treatment effectiveness is directly related to groundwater flow within the UMCf that is governed by a variety of unique location-specific hydrogeologic variables, with preferential flow occurring along secondary porosity generated by faulting, along bedding planes within the UMCf, and within laterally discontinuous beds of coarser sediments. In addition, the depth of the UMCf contact with the alluvium varies, especially where alluvial paleochannels are eroded into the surface of the

UMCf. In general, groundwater flow through primary porosity under natural gradients is slower in the UMCf than the UMCf-cg (as in Zone 3).

- The injectate solution was transported upgradient and downgradient along preferential flow paths to select wells (i.e., LVWPS-A1-MW09, LVWPS-U1-MW06B, LVWPS-U1-MW07, LVWPS-U1-MW08A, and LVWPS-U1-MW08B). Samples collected from monitoring well LVWPS-U1-MW08A indicated that perchlorate concentrations remained below the PRG of 15 μg/L for more than 6 months following the second injection event.
- Areas not along the preferential flow paths were much slower to respond, with decreases observed beginning around Month 8 and slowly decreasing more over time in samples collected from monitoring wells LVWPS-U1-MW02B and LVWPS-U1-MW05A, which are located 25 to 50 feet downgradient of the injection well transect. This was not unexpected given that the groundwater flow rate was around 0.2 ft/day in the shallow UMCf and ranged from 0.04 ft/day to 0.3 ft/day.

- Objective 5 – Evaluate if dual-nested injection wells are effective in delivering substrate to large, saturated thicknesses of the UMCf because nested injection wells can be a cost-effective option as opposed to multiple separate injection wells. Data collected indicated the following:
  - Installation of nested wells as opposed to single clustered injection wells resulted in a cost savings of approximately 30 percent per well cluster for dual nested configuration.
  - During active injections, the injectate solution was observed in both sets of shallow and deep dose-response monitoring wells located immediately downgradient of the injection wells. These results indicate that the injectate was distributed both horizontally and vertically in the subsurface, despite the large, saturated thickness of the UMCf.
  - Injectate solution directly migrated along preferential flow paths approximately 50 feet upgradient and 25 feet downgradient during the injections in both the shallow and deep zones of the unconsolidated UMCf. The injectate solution was observed in both the shallow and deep UMCf as evidenced by TOC concentration increases in samples collected from monitoring wells screened as shallow as 94 to 119 feet bgs and as deep as 125 to 150 feet bgs. This data point indicates that a dual-nested well configurations can effectively distribute the injectate in both horizontal and vertical directions.

7.0 ZONE 2 SUMMARY AND EVALUATION OF RESULTS

The focus of the Zone 2 study area was to evaluate the effectiveness and implementability of bioremediation within a main paleochannel that consists of a large, saturated thickness of alluvium overlying a smaller saturated thickness of UMCf. The groundwater flow rates within the main deep paleochannel in the Zone 2 study area are likely representative of groundwater flow rates within other paleochannels upgradient of the Wash. Additionally, the unconsolidated UMCf that underlies the alluvial paleochannel was included in the remedial approach implemented for the Zone 2 study area to evaluate the combination of remediation in both the alluvium and UMCf. This Zone 2 design contrasts with the Zone 1 and Zone 3 designs, which did not include injections into the alluvium but rather only targeted the unconsolidated UMCf or UMCf-cg, respectively.

This section summarizes the Zone 2 objectives, study design, injection activities, geology, hydrogeology, and effectiveness monitoring results.

7.1 OBJECTIVES

Evaluation of ISB within Zone 2 focused on both the alluvium and UMCf allowed for assessment of the following specific objectives as previously outline in the Work Plan Addendum.

- Determine if ISB can effectively create a biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater within a main, deep paleochannel located upgradient of the Wash, which will be important data to evaluate in the FS because targeting such paleochannels will most likely be a key component of the final remedy.
- Verify ISB effectiveness and injectate distribution in large, saturated thicknesses of alluvium, which are up to three times greater within the Zone 2 study area than has been evaluated in previous treatability studies.
- Determine if synergistic effects occur when both alluvium and UMCf are injected with carbon substrate; combined remediation of these two units has not previously been evaluated.
- Evaluate injectate distribution in a dual-nested injection well configuration within the alluvium (previously only tested in single/paired injection wells) because nested injection wells can be a cost-effective option for large, saturated thicknesses as opposed to multiple separate injection wells.
- Evaluate implementation of single injection wells in the UMCf, which is in contrast to the Zone 1 and Zone 3 implementation in the UMCf and UMCf-cg where both dual-nested and triple-nested injection wells were evaluated.
- Verify that ISB implementation and operational components within the alluvium are in line with previous studies or if variations are required based on the large, saturated alluvium targeted, with particular focus on carbon substrate distribution, evaluation of optimal chase water quantities, and injection frequencies required to maintain a biologically active zone for perchlorate and chlorate biodegradation.

7.2 PILOT STUDY LAYOUT AND WELL DESIGN

Both injection and monitoring wells were installed in the Zone 2 study area as described in Section 5.4. The layout of the injection well transect and monitoring well network was designed to collect data for evaluation of the Zone 2 objectives. **Figures 7a-c** present the layout of the Zone 2 injection well transect and monitoring well network. Well construction details and soil boring logs for all injection and monitoring wells are provided in Appendix B.

7.2.1 Injection Wells

As presented in the Work Plan Addendum, the injection well transect within the Zone 2 study area was designed to be approximately 300-foot long, which is slightly longer than 200-foot injection transect length installed within the Zone 1 and Zone 3 study areas. Because the paleochannel environment varies across the entire width of the channel (i.e., historical cut banks, meanders across the channel width through time, point bars, and high and low energy environments), it was important for the injection well transect to span across those different environments so that the variability associated with them could be evaluated during the study. Because the Zone 2 study area was evaluating ISB treatment in both the alluvium and UMCf, the injection well transect area consisted of nine dual-nested injection wells spaced approximately 35 feet apart in the alluvium and 12 single injection wells spaced approximately 25 feet apart in the UMCf. The injection well spacing in the alluvium was slightly larger than the spacing in the UMCf due to the varying geologic and hydraulic properties between the two lithological units. Full design details related to general location and injection well spacing are summarized in the Work Plan Addendum (Tetra Tech, 2019).

Due to the large, saturated thickness of the alluvium within the deep paleochannel, the nine alluvial injection wells were installed in a dual-nested well configuration with varying injection well depths and screened intervals based on the depth of water and subsequent depth of the alluvium/UMCf contact. The injection well depths within each nested pair averaged 61 feet bgs for the shallow alluvium (designated as "A" wells) and 91 feet bgs for the deep alluvium (designated as "B" wells). Injection well screened intervals were selected to target the impacted potion of the alluvium, which varied in thickness from 30 to 70 feet.

The 12 single injection wells screened in the UMCf were installed along the same 300-foot transect line, with an average UMCf injection well depth of 124 feet bgs. Injection well screened intervals were selected to target the impacted portion of the UMCf, which varied in thickness from 15 to 30 feet. Injection well construction details, including total depths and screened intervals, are provided in Table B.1.

7.2.2 Effectiveness Monitoring Wells

Sixty-six monitoring wells installed throughout the Zone 2 study area at varying distances upgradient and downgradient from the injection well transect were included in the effectiveness monitoring program to provide a effective monitoring well network to meet the detailed study objectives and determine remediation effectiveness following ISB injections into both the alluvium and UMCf. The effectiveness monitoring well layout consisted of 49 new monitoring wells installed in either a single or clustered configuration at three upgradient, two cross-gradient, and 20 downgradient locations within the Zone 2 study area. Additionally, 17 existing monitoring wells at 11 locations throughout the Zone 2 study area, which included wells installed as part of Phase 1 pre-design activities, were also incorporated into the effectiveness monitoring program. The names of Zone 2 monitoring wells screened in the alluvium included an "LVWPS-A2" prefix, while Zone 2 monitoring wells screened in the UMCf included an "LVWPS-U2" prefix. Due to the large saturated thickness of the alluvium in Zone 2, the monitoring well names also included a suffix of either an "A", "B", or "C", which indicated wells screened in the shallow, deep, or deepest alluvium, respectively. Additional details regarding the monitoring well layout are noted as follows:

- Three monitoring well clusters were installed approximately 60 feet upgradient from the injection well transect to determine the contaminant concentrations in groundwater migrating through the injection well transect and refine the mass flux entering the Zone 2 study area. Each upgradient monitoring well cluster included two monitoring wells screened in the alluvium and one monitoring well screened in the UMCf.
- Two monitoring well clusters (each with three monitoring wells similar to the upgradient wells; total of six monitoring wells) were installed cross-gradient of the injection well transect to provide information regarding lateral distribution of contaminants just outside the targeted area as well as information regarding the ROI of injection wells. The cross-gradient monitoring wells screened within the alluvium were installed approximately 17 feet from the injection well transect, while cross-gradient monitoring wells screened in the UMCf were installed approximately 12 feet from the injection well transect. These distances represented the approximate targeted ROI of the injection wells (i.e., half the distance between the injection wells).

- Downgradient monitoring wells screened in the alluvium were installed at nine locations at varying distances from the injection well transect (generally located 50, 100, 200, and 350 feet downgradient; total of 21 monitoring wells) while downgradient monitoring wells screened in the UMCf were installed at seven locations at varying distances from the injection well transect (generally located 25, 50, and 100 feet downgradient; total of seven monitoring wells). These downgradient monitoring wells were installed to monitor ISB effectiveness and help estimate the ROI of the carbon substrate following injections. This monitoring well layout was selected based on the rate and direction of the groundwater flow within the alluvium and UMCf within the Zone 2 study area so that the downgradient extent of remediation could potentially be quantified, and results could be observed within the 18-month Pilot Study duration. Due to the higher groundwater flow rates observed in the alluvium when compared to the groundwater flow rates observed in the UMCf, monitoring wells screened in the alluvium were spaced at farther distances downgradient of the injection well transect than the monitoring wells screened in the UMCf. As with the other study areas, the monitoring wells were not only spaced along the length of the study area but also spatially varied throughout the study area both directly in-line and off-set from the individual injection wells to evaluate remediation with respect to the heterogeneity and preferential flow paths that exist throughout the study area.
- Eleven existing monitoring well locations (totaling 17 monitoring wells), which were installed as part of Phase 1 pre-design activities, were also incorporated into the effectiveness monitoring program. Six of these 17 monitoring wells were selected to be sampled on a monthly basis throughout the Pilot Study: 1) monitoring well cluster LVWPS-MW208A/B (located approximately 200 feet downgradient of the injection well transect), 2) monitoring well cluster LVWPS-MW223A/B/C (located approximately 250 feet downgradient of the injection well transect) and 3) monitoring well LVWPS-MW221A (located approximately 300 feet cross-gradient of the injection well transect). The remaining 11 existing monitoring wells were incorporated into the monitoring program on a quarterly basis to monitor for potential remedial effects farther downgradient within the paleochannel and included the following: LVWPS-MW207, LVWPS-MW209/A, LVWPS-MW210A/B, LVWPS-MW211, LVWPS-MW212A/B, LVWPS-MW218A, LVWPS-MW220A, and LVWPS-MW224A These 11 existing monitoring wells were also sampled monthly for the first six months for the presence of dye only.
- In addition to the 66 effectiveness monitoring wells listed above, two clusters of dose-response monitoring wells, with each cluster consisting of three monitoring wells, were installed immediately downgradient of the injection well transect (less than 5 feet away) to support the tracer dye study presented in Section 5.4.3 of the Work Plan Addendum (Tetra Tech, 2019a). At each dose-response monitoring well cluster, the dose-response monitoring wells were screened across the same depth interval as the nearby injection wells, with two of the three dose-response monitoring wells screened in the alluvium and one of the dose-response monitoring wells screened in the UMCf.

7.3 ZONE 2 INJECTIONS

As presented in Section 5.5, three carbon substrate injection events were performed in the alluvium and two carbon substrate injection events were performed in the UMCf as part of Zone 2 Pilot Study activities. The following sections provide details of the injection events conducted at Zone 2 injection wells screened in the alluvium and unconsolidated UMCf. Injection summary tables including injection volumes, flow rates, and pressures for each injection well are provided in Appendix D. As described in Section 5.7.1, the five extraction wells installed in the alluvium outside of the remediation zones (**Figure 5**) during Phase 2 were sampled during the baseline sampling event in September/October 2020 prior to the first injection event and on a quarterly basis thereafter to determine contaminant concentrations in monitoring wells used for extraction operations during injections. Data for all parameters for groundwater samples collected from extraction wells are presented in the comprehensive data tables provided in Appendix J, Table J.1. Field logs from all groundwater sampling events are provided in Appendix I and the DVSR is provided in Appendix K.

7.3.1 Injection Details for Zone 2 Alluvium

The first injection event in Zone 2 alluvium was performed from December 7 to December 11, 2020. During the first injection event, approximately 67,800 gallons of carbon substrate solution were injected into Zone 2 injection wells screened in the alluvium. The solution consisted of approximately 13,468 gallons of EOS® PRO, 259 gallons of glycerin, 84 gallons of phosphate solution,182 pounds of sodium sulfite, and 53,874 gallons of injectate dilution water (extracted groundwater from nearby extraction wells). As summarized in the tables in Appendix D, the quantities of EOS® PRO varied between injection wells based on the screen lengths and thickness of the targeted formation at each injection location. Upon completion of carbon substrate injections, approximately 190,100 gallons of water were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. Rhodamine WT dye was added to the carbon substrate solution and the first two batches of follow up distribution water to achieve a target concentration of 800 ppb. Addition of tracer dye to the first 15% of the distribution water helped ensure the objectives of the tracer study were met, given the high overall designed volume of injectate in the alluvium. As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to refine the effective porosity values and recalculate the corresponding distribution water quantities for the program. These results indicated that the field-determined effective porosity was similar to the estimated porosity, with a calculated effective porosity of approximately 6 percent for the alluvium in Zone 2. During injections, both flow rate and pressure were measured at each injection well. Injection rates averaged approximately 13 gpm while sustained pressures averaged 2 psi. At nine of the eighteen alluvial injection wells, sustained pressures of 0 psi were measured throughout the event, even at injection rates of up to 23 gpm.

The second injection event in Zone 2 alluvium was performed from April 16 to April 20, 2021, approximately 4 months after the first injection event. The timing of the second injection event was based on the decreases in TOC concentrations observed at key monitoring wells (further discussed in Section 7.7.4.1). During the second injection event, approximately 57,800 gallons of carbon substrate solution comprising 11,565 gallons of EOS® PRO, 217 gallons of glycerin, 200 pounds of sodium sulfite, and 46,573 gallons of injectate dilution water (extracted groundwater from nearby extraction wells) were injected into Zone 2 alluvial injection wells. As previously explained in Section 5.5.2, the quantity of EOS® PRO was approximately 85 percent of that used in the first injection event and neither tracer dye nor phosphate solution was included in the second injection event. Upon completion of carbon substrate injections, a total of 200,865 gallons of distribution water (extracted groundwater from nearby extraction wells) were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. This higher volume of distribution water during the second injection event was selected to maintain an overall injection volume of approximately one pore volume at each injection well, despite the lower target carbon substrate solution volume (85 percent of the first injection event). During the second injection event, injection rates averaged approximately 13 gpm while sustained pressures averaged 7 psi, which indicated a slight increase injection pressure compared to the first injection event.

The third injection event in Zone 2 alluvium was performed from October 7 to October 11, 2021, approximately 6 months after the first injection event. The timing of the third injection event was based on the beginning of slight perchlorate, chlorate, and/or nitrate concentration increases in conjunction with a decrease in TOC concentrations in samples collected from key monitoring wells (further discussed in Section 7.7.4.1). During the third injection event, approximately 57,300 gallons of carbon substrate solution comprising 11,475 gallons of EOS® PRO, 219 gallons of glycerin, 200 pounds of sodium sulfite, and 45,546 gallons of injectate dilution water (extracted groundwater from nearby extraction wells) were injected into Zone 2 alluvial injection wells. As with the second injection event, the quantity of EOS® PRO was approximately 85 percent of that used in the first injection event and neither tracer dye nor a phosphate solution was included in the injectate solution. Upon completion of carbon substrate injections, a total of 199,700 gallons of distribution water (extracted groundwater from nearby extraction wells) were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. Results from groundwater samples collected from extraction wells prior to the third injection event indicated a slightly elevated average perchlorate concentration of 4,540 μg/L compared to the average perchlorate concentration of 2,900 μg/L measured prior to the first injection event. Therefore, the concentration of perchlorate in the injectate solution and follow-up distribution water during the third injection event may have been higher than the previous injection events.

During the third injection event, injection rates averaged approximately 11 gpm while sustained pressures averaged 13 psi, which indicated a slight increase injection pressure compared to the second injection event. This small increase in injection pressures is expected with periodic carbon substrate injections. As multiple injections are performed, injection well screens and surrounding filter packs can sometimes accumulate biomass, inorganic precipitates, and/or EVO breakdown compounds (such as oleate). This phenomenon can result in changes to the injectability (i.e., increases in injection pressures required for subsurface distribution) and may require injection well maintenance measures to promote injection well longevity and ensure successful long-term operation of ISB. This operational component of implementing ISB has been evaluated as part of the SWF Area Bioremediation Treatability Study (Tetra Tech, 2019b; Tetra Tech, 2022). Although a trend of slightly increasing injection pressures was observed during the second and third injection events, all injection wells continued to accept their designed volumes of injectate solution at reasonable injection rates and pressures during all injection events, and no injection well maintenance was required.

7.3.2 Injection Details for Zone 2 UMCf

The first injection event in Zone 2 UMCf was performed from December 20 to December 22, 2020. A brief step-rate injection test using extracted groundwater only was performed prior to initiating carbon substrate injections. The results demonstrated that injectability of the Zone 2 UMCf was variable with a feasible injection rate of up to 7 gpm at a pressure of 35 psi at LVWPS-U2-IW01, but an injection rate of only 2 gpm was achieved at that same pressure farther to the east at LVWPS-U2-IW04.

During the first injection event, approximately 17,250 gallons of carbon substrate solution were injected into the Zone 2 UMCf injection wells. The solution consisted of approximately 3,209 gallons of EOS® PRO, 21 gallons of glycerin, 22 gallons of phosphate solution, 18 pounds of sodium sulfite, and 14,054 gallons of injectate dilution water (extracted groundwater from nearby extraction wells). In addition, fluorescein dye was added to the carbon substrate solution to achieve a target concentration of 400 ppb. As summarized in the tables in Appendix D, the quantities of EOS® PRO varied between injection wells based on the screen lengths, thickness of the targeted formation at each injection location, and achievable injection rates/quantities per injection well. Upon completion of carbon substrate injections, approximately 800 gallons of distribution water (extracted groundwater from nearby extraction wells) were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to refine the effective porosity values and recalculate the corresponding distribution water quantities for the program. These results indicated that the field-determined effective porosity was less than originally estimated during the design for the Zone 2 UMCf, with a revised calculated effective porosity of approximately 1 percent. When the Zone 2 UMCf distribution water volumes were proportionally reduced using the new porosity estimate, the resultant volume of designed distribution water was quite low. As a result, a minimum of six borehole volumes of distribution water was injected into each injection well.

During injections, both flow rate and pressure were measured at each injection well. Injection rates averaged approximately 2 gpm while sustained pressures averaged 30 psi. Overall, injection wells screened in the Zone 2 UMCf indicated lower injection capacity compared to the injection wells in Zones 1 and 3 (discussed in Section 6.3.2 and Section 8.3.1, respectively). Sustained injection pressures observed were higher in the eastern portion of the transect, where the saturated thickness of unconsolidated UMCf is thinnest (**Figure 10b**). Three of the 12 injection wells screened in Zone 2 UMCf, namely, LVWPS-U2-IW06, LVWPS-U2-IW07, and LVWPS-IW10, did not accept the target injection volumes at the permissible maximum injection pressure of 45 psi due to the low effective porosity of the formation in the vicinity of these injection wells. LVWPS-U2-IW06 and LVWPS-U2-IW07 were located in an area of thin unconsolidated UMCf just above a bedrock high. As a result, the screened intervals were shorter and the observed geology in these intervals included a larger proportion of strongly cemented material, which was the likely reason for the decreased injection capacity due to the low effective porosity. The screened interval in monitoring well LVWPS-U2-IW10 was located in significantly finer-grained material (nearly 100% silt and clay) as compared to other injection wells in this transect and located in an area with only a thin zone of unconsolidated UMCf. Because the injection wells did not accept the targeted quantity of injectate solution due to the low effective porosity, the designed injectate volumes for injection wells LVWPS-U2-IW06, LVWPS-U2-IW07, and LVWPS-U2-IW10 were redistributed among the remaining nine injection wells based on the screen lengths and thickness of the targeted formation at each injection location.

The second injection event in Zone 2 UMCf was performed from October 11 to October 13, 2021, approximately 10 months after the first injection event. The timing of the second injection event was based on the beginning of perchlorate, chlorate, and nitrate concentration rebounds in conjunction with a decrease in TOC concentrations to near baseline conditions in samples collected from key monitoring wells (further discussed in Section 7.7). During the second injection event, approximately 13,900 gallons of carbon substrate solution comprising 2,789 gallons of EOS® PRO, 20 gallons of glycerin, 10 pounds of sodium sulfite, and 10,915 gallons of injectate dilution water (extracted groundwater from nearby extraction wells) were injected into Zone 2 UMCf injection wells. As previously explained in Section 5.5.2, the quantity of EOS® PRO was approximately 85 percent of that used in the first injection event and neither tracer dye nor phosphate solution was included in the second injection event. Upon completion of carbon substrate injections, a total of 744 gallons of distribution water (extracted groundwater from nearby extraction wells) were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. This volume of distribution water during the second injection event represents a six-borehole volume flush. Results from groundwater samples collected from extraction wells prior to the second injection event indicated a slightly elevated average perchlorate concentration of 4,540 μg/L compared to the average perchlorate concentration of 2,900 μg/L measured prior to the first injection event. Therefore, the concentration of perchlorate in the injectate solution and follow-up distribution water during the second injection event may have been higher than the previous injection event.

During the second injection event, injection rates averaged approximately 3 gpm while sustained pressures averaged 34 psi. Again, three of the 12 injection wells did not receive their targeted volume of carbon substrate solution during the second event. As with the first injection event, LVWPS-U2-IW06, LVWPS-U2-IW07, and LVWPS-IW10 could only achieve flow rates of up to 0.1 gpm at the maximum allowable pressure of 45 psi. The designed volumes for injection wells LVWPS-U2-IW06, LVWPS-U2-IW07, and LVWPS-U2-IW10 were redistributed among the remaining nine injection wells based on the screen lengths and thickness of the targeted formation at each injection location. No significant reduction in injection well performance was observed at the remaining 12 injection wells.

7.3.3 Hydraulic Response

The hydraulic response in the alluvium and UMCf was observed during the first Zone 2 injection event. The hydraulic head rose approximately 0.25 feet to 0.5 feet in the shallow and deep alluvium, respectively, at cross-gradient monitoring well clusters LVWPS-A2-MW04A/B and LVWPS-A2-MW05A/B, which are located approximately 17 feet from the injection well transect. As expected, the hydraulic response in the less permeable Zone 2 UMCf was much more dramatic. Four monitoring wells were monitored during the first injection event in the Zone 2 UMCf, including LVWPS-U2-MW04 and LVWPS-U2-MW05, which are screened in the UMCf approximately 12 feet cross-gradient of the injection well transect, and monitoring wells LVWPS-U2-MW06 and LVWPS-U2-MW18, which are located 25 feet downgradient of the injection well transect. The change in hydraulic head at these four monitoring wells was highly variable, ranging from about one foot to nearly 30 feet. The wide range in hydraulic response to injections in Zone 2 demonstrates the complex hydrogeologic controls (i.e., exposure of bedding planes due to a deep erosional paleochannel, secondary porosity associated with faulting, etc.) on groundwater flow in Zone 2 UMCf. The largest increase in hydraulic head of approximately 28 feet was observed at LVWPS-U2-MW06, where the hydraulic conductivity measured only 0.1 ft/day. Together, these results suggest this portion of the UMCf is less permeable than at LVWPS-U2-MW18 (the other monitoring well located 25 feet downgradient), which was located in the vicinity of the Zone 2 fault zone.

During active injections, the dose response and nearby monitoring wells were also monitored for the presence of injectate solution during the first injection event. Carbon substrate solution was observed in all four dose-response monitoring wells screened in the alluvium (LVWPS-A2-DR01A, LVWPS-A2-DR01B, LVWPS-A2-DR02A, and LVWPS-A2-DR02B) and the four monitoring wells located 17 feet cross-gradient of the injection well transect (LVWPS-A2-MW04A, LVWPS-A2-MW04B, LVWPS-A2-MW05A, LVWPS-A2-MW05B) during the first injection event into the Zone 2 alluvium. However, the carbon substrate was not observed farther downgradient in the alluvium during active injections.

During injections into the Zone 2 UMCf, carbon substrate solution was observed at both dose-response monitoring wells screened in the UMCf (LVWPS-U2-DR01 and LVWPS-U2-DR02) as well as the dose-response monitoring wells screened in the deep alluvium (LVWPS-A2-DR01B and LVPWS-A2-DR02B). The presence of carbon substrate solution in the deep alluvium dose-response monitoring wells was expected, due to the sequence of Zone 2 injections (i.e., alluvium first followed by UMCf). However, the presence of fluorescein dye within the carbon substrate solution indicates that injectate was flowing from the UMCf into the alluvium in close proximity of the injection well transect. This illustrates the cross-connecting flow between the UMCf and alluvium in Zone 2 due to faulting and the deep alluvial paleochannel within Zone 2, which is important to confirm the synergistic effects that can occur when both alluvium and UMCf are treated concurrently.

7.4 ZONE 2 GEOLOGY

Data from the soil boring and monitoring well installation activities were compiled to provide a description of the geology of the Zone 2 study area. A geologic cross-section of Zone 2 is presented in **Figure 10b**. Saturated alluvium, ranging from silty sand to sandy gravel with minor lenses of sandy silt, is present throughout the Pilot Study area, overlying the UMCf. Based on the depths to the erosional contact between the alluvium and UMCf observed in the study area, the deep alluvium adjacent to the Wash likely reflects the ancestral fluvial deposits. During the drilling performed during Phase 1 pre-design activities, a generally north-south oriented paleochannel was identified through the center of the Pilot Study that trends towards the Calico Ridge Weir. The location of the Zone 2 injection well transect was selected to target this paleochannel, as shown on **Figure 5**. During Phase 2 drilling, the approximate centerline of the paleochannel was discovered to be located approximately 100 feet west of the location estimated based on the data available during development of the Work Plan Addendum. Therefore, the Zone 2 injection well transect was shifted 100 feet to the west from the location presented in Work Plan Addendum to ensure the objectives of the Pilot Study were met.

As shown in **Figure 10b**, the alluvium within Zone 2 is highly heterogeneous. The uppermost unsaturated alluvium is comprised of a relatively high proportion of finer alluvial sediments (silty sand and sandy silt). From approximately 30 to 55 feet bgs, the uppermost saturated alluvium in Zone 2 is coarser, dominantly comprising gravel and sand with gravel channel fill. Below 55 feet bgs, the deeper saturated alluvium is the most heterogeneous, containing coarser channel fill flanked by lenses of finer silty sands and silts. The erosional contact between the alluvium and the UMCf ranges from approximately 70 feet bgs to 115 feet bgs within Zone 2. The alluvium is deepest in the vicinity of nested injection wells LVWPS-A2-IW04A/B and single injection well LVWPS-U2-IW01, where the UMCf is encountered 115 feet bgs and the saturated thickness of the alluvium reaches 83 feet. The approximate centerline of the deep paleochannel in Zone 2 corresponds to the surface expression of the fault through Zone 2, as the block of UMCf to the west of the fault zone was dropped down in response to extensional forces. This likely created a low-lying area above the fault zone, which was then filled with channel deposits. However, the paleochannel migrated generally eastward (with some back-and-forth) over time, so there are finer-grained lenses of fill overlie the basal (oldest) portion of paleochannel as the channel's cut bank and point bar changed location over time.

In general, the unconsolidated UMCf within Zone 2 contains a lower proportion of sand compared to the UMCf in Zone 1 and the UMCf-cg in Zone 3. In particular, the UMCf in the eastern portion of the Zone 2 injection well transect is relatively fine and stiff, with the material containing a higher percent clay, above the fault-bounded block of bedrock. In the western portion Zone 2, the deepest portions of the UMCf are semi-consolidated with abundant gypsum below approximately 135 feet bgs. The thickness of the unconsolidated UMCf in Zone 2 is highly variable, ranging from 30 feet at LVWPS-U2-IW07 to greater than 65 feet at LVWPS-U2-IW04, due to the combination of faults and the erosional contact with the overlying alluvium.

7.5 ZONE 2 HYDROGEOLOGY

The hydrogeology of Zone 2 is governed by two primary hydrogeologic influences: a deep paleochannel in the alluvium and the Zone 2 fault zone in the UMCf. Because the materials filling the fault zone and the paleochannels are generally more transmissive than the surrounding materials, groundwater flow appears to be converging toward the fault zone and paleochannels.

In the basal (oldest) portion of the Zone 2 alluvium, groundwater flow tends to follow that paleochannel northward. However, the Zone 2 paleochannel gradually migrated to a more northeasterly alignment over time, so the shallower (younger) alluvial flow directions tend to be toward the northeast, as shown in **Figures 7a and 7b**. The calculated average northeastward hydraulic gradient of the shallow and deep alluvium in Zone 2 measured 0.004 ft/ft and 0.005 ft/ft, respectively. The north-south oriented paleochannel bisected by the Zone 2 injection well transect ultimately joins with the ancestral fluvial deposits downgradient of the Zone 2 study area, were flow turns eastward paralleling the Wash. The ancestral fluvial deposits associated with the Wash dominates overall alluvial flow in the Pilot Study area due to the high groundwater flow velocity in and hydraulic conductivity of the sediments associated with the ancestral fluvial deposits l. The Zone 2 paleochannel discharges into the ancestral fluvial deposits as opposed to discharging directly into the Wash. As a result, the water originating in Zone 2 tends to flow downgradient parallel to the Wash. Although pre-design data suggested that groundwater was discharging to the Wash downgradient of the Calico Ridge Weir, dye data collected during Phase 2 suggests that the groundwater discharging at Calico Ridge Weir is sourced from much farther west, in the vicinity of Zone 1. Instead, Zone 2 groundwater likely flows much farther parallel to the Wash and therefore, would be expected to discharge somewhere northeast of the Pilot Study area. Surface water analytical results for the tracer study are discussed in more detail in Section 9.3.

The hydrogeology of the UMCf in Zone 2 is dominated by the fault zone and associated fracturing. Because the forces causing this fault were extensional in nature, the tendency is for the sediments around the fault to be more permeable and amenable to flow. In addition, fracture networks associated with fault can result in localized areas of high secondary porosity resulting in preferential flow pathways within the UMCf. In extensional fault systems, there tends to be enhanced flow along the lineament of the fault (though fault gouge may form a barrier to flow perpendicular to the fault). As shown on **Figure 7c**, groundwater in the UMCf is generally flows towards the northeast, similar to groundwater in the overlying alluvium. Near LVWPS-U2-IW05, the groundwater flow direction in Zone 2 UMCf is locally more northward following the Zone 2 fault because the fault forms a preferential flow pathway. The calculated average hydraulic gradient of the UMCf in Zone 2 measured 0.006 ft/ft.

The fault zone in the eastern portion of the injection well transect and the deep paleochannel eroded into the surface of the UMCf in the western portion of the injection well transect allow the potential for cross-connecting flow between the alluvium and the UMCf in Zone 2. Exposure of bedding planes through faulting means that groundwater flow in the UMCf following those bedding planes can easily discharge into the alluvium abutting them. The same phenomenon is caused when beds were partially eroded within the paleochannel during deposition of the alluvium. Finally, preferential flow along the extensional fault itself forms a connection to the overlying alluvium. Vertical gradients both within the alluvium and between the alluvium and the UMCf in this area ranged from 0.01 ft/ft upward to 0.03 ft/ft downward, depending on the exact lithology and structure in the area. As a result, some migration of water from the UMCf into the alluvium and from the alluvium into the UMCf in the Zone 2 study area is expected.

7.6 ZONE 2 HYDROGEOLOGICAL EVALUATION

As previously explained in Section 5.6, an aquifer testing program was implemented to obtain information regarding aquifer hydraulic conductivity, groundwater flow velocity, and total and mobile porosity in the Pilot Study area. Additionally, Rhodamine WT and fluorescein dyes were injected into the alluvium and UMCf, respectively, during the first Zone 2 injection event, with samples collected post-injection to periodically monitor for the presence of dye. This additional dye data aided in the evaluation of study objectives including ROI of the injection wells, travel times of the injectate/dye, interactions between the alluvium and UMCf, and the effective porosity of the formations near the injection well transect. This section summarizes the results from the aquifer testing activities (borehole dilution testing, slug testing, and tracer dye study) performed in the Zone 2 study area during the Pilot Study. The supporting summary memos for the tracer study, borehole dilution testing, and slug testing are presented in Appendices C, F, and G, respectively.

7.6.1 Borehole Dilution Testing Results

Using the procedures presented in Section 5.6.2 and Appendix F, single-borehole dilution tests were performed in 10 monitoring wells screened in the alluvium (LVWPS-A2-MW08A/B/C, LVWPS-A2-MW09A/B, LVWPS-A2-MW14A/B, and LVWPS-A2-MW17A/B/C) and four monitoring wells screened in the UMCf (LVWPS-U2-MW08, LVWPS-U2-MW09, LVWPS-U2-MW14, and LVWPS-U2-MW17) to evaluate groundwater flow velocities in the Zone 2 study area. Groundwater flow rates within the alluvium generally increased with depth. Estimated flow velocities for monitoring wells screened in the shallow alluvium averaged approximately 12 ft/day and ranged from 4 ft/day to 31 ft/day, whereas estimated flow velocities in the deep alluvium averaged 55 ft/day and ranged from 5 to 122 ft/day. Although flow velocities were slightly higher than anticipated in select alluvial monitoring wells, these results are generally consistent with Phase 1 borehole dilution testing results. The groundwater flow rate in the UMCf within the Zone 2 study area was determined to be average of 0.2 ft/day, based on single-borehole dilution tests in wells LVWPS-U2-MW08, LVWPS-U2-MW09, LVWPS-U2-MW14, and LVWPS-U2-MW17, and LVWPS-MW223C. These flow velocities are similar to those estimated for the UMCf in Zone 1. The groundwater flow velocity ranges calculated from Phase 2 borehole dilution testing are comparable to ones calculated using the baseline slug test results for hydraulic conductivity and effective porosity from the tracer study, which averaged approximately 10 ft/day in the alluvium and 0.5 ft/day in the UMCf. A summary of the borehole dilution tests and results is provided in Appendix F.

7.6.2 Slug Tests

Using the procedures described in Section 5.6.3 and Appendix G, slug tests were performed in several phases during Phase 2 implementation to estimate location-specific aquifer hydraulic conductivity within the Zone 2 study area. Appendix G presents results from the slug testing events conducted as part of Phase 2 of the Pilot Study.

After installation of the Zone 2 effectiveness monitoring well network, slug testing was performed at all newly installed monitoring wells during two mobilizations from June 19 to June 24, 2020 and October 30 to November 11, 2020. Baseline slug test results indicated that the estimated hydraulic conductivities of the shallow and deep alluvium in Zone 2 were a similar order of magnitude, with average hydraulic conductivities of 150 ft/day and 105 ft/day, respectively. The highest hydraulic conductivities estimated for the alluvium of 352 ft/day and 327 ft/day were measured at shallow monitoring wells LVWPS-A2-MW11A and LVWPS-A2-MW14A, respectively. Baseline slug test results of monitoring wells screened in the UMCf indicated an average estimated hydraulic conductivity of 0.3 ft/day, which was lower than both the UMCf in Zone 1 and the UMCf-cg in Zone 3 (discussed in Sections 6.6.3 and 8.6.3, respectively).

Following carbon substrate injections, slug tests were performed periodically throughout the Pilot Study to examine subsurface conductivity changes following carbon substrate injections. Three post-injection slug testing events were performed on nine monitoring wells screened in the alluvium and four monitoring wells screened in the UMCf in June/July 2021, January 2022, and June/July 2022. In general, the mean hydraulic conductivities observed during post-injection testing were within the same order of magnitude as the baseline for all 13 monitoring wells evaluated post-injection, which indicates there were no significant reductions in permeability associated with carbon substrate injections.

7.6.3 Dye Results

As presented in Section 5.6.5, the Pilot Study design included injection of Rhodamine WT dye into the alluvium and injection of fluorescein dye into the UMCf during the first Zone 2 injection event. Following injections, periodic monitoring was performed to provide data to evaluate tracer study objectives including the ROI of injection wells, travel times of the injectate/dye, upflux from the UMCf to the overlying alluvium, and the effective porosity of the formation near each injection well transect. The tracer dye monitoring program included qualitative (i.e., presence/absence) analysis of charcoal samplers that were installed in monitoring wells during injection activities and between effectiveness monitoring events, as well as quantitative analysis of tracer dye concentration in groundwater samples. If tracer dye was detected in the charcoal sampler, indicating the arrival of tracer dye at the monitoring location, the groundwater sample collected from that same monitoring well location was then analyzed to determine the dye concentration in the groundwater. This two-step analysis process allowed for presence/ absence dye analysis at all monitoring locations and also permitted quantitative analysis where the dye was found to be present. A complete discussion of the dye study, including dye analytical results, are provided in Appendix C.

7.6.3.1 Dye Results in Zone 2 Alluvium

During injection activities into the Zone 2 alluvium, the carbon substrate solution tagged with Rhodamine WT dye appeared in samples collected from all four dose-response monitoring wells screened in the alluvium (LVWPS-A2-DR01A, LVWPS-A2-DR01B, LVWPS-A2-DR02A, and LVWPS-A2-DR02B) and all four alluvial cross-gradient monitoring wells (LVWPS-A2-MW04A, LVWPS-A2-MW04B, LVWPS-A2-MW05A, and LVWPS-A2-MW05B). These results confirm the target alluvial ROI of 17.5 feet was achieved. As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to estimate the effective porosity of the alluvium in Zone 2. Results from this monitoring indicated that the Zone 2 alluvium generally had an effective porosity of approximately 6 percent, which was within the expected designed range.

As expected, the high groundwater flow velocity in the alluvium resulted in the presence of dye in samples collected from many of downgradient monitoring wells during active injections or within a few days after injections were completed. Approximately three to five days after injection activities were completed, rhodamine dye was detected in groundwater samples collected from all Zone 2 alluvial dose-response monitoring wells, one cross-gradient alluvial monitoring well cluster, and at least one alluvial monitoring well in each of the 50-foot downgradient monitoring well clusters (including wells LVWPS-A2-MW08B/C, LVWPS-A2-MW09A/B, and LVWPS-A2-MW14A/B). In addition, approximately two weeks after the Zone 2 alluvium injections were completed, rhodamine dye was also detected in samples collected from the majority of monitoring wells located immediately downgradient of the injection well transect to as far as 850 feet downgradient of the injection well transect (i.e., LVWPS-MW210A and LVWPS-MW210B). These results are likely reflective of rhodamine dye travelling along the fastest flow path associated with the deep paleochannel and suggest groundwater flow velocities of approximately 57 ft/day, which are consistent with the high groundwater flow velocities estimated for the deep alluvium from borehole dilution testing. Also as expected, the groundwater flow in the alluvium generally followed the Zone 2 paleochannel down to the ancestral fluvial deposits underlying the Wash. Rhodamine dye was not detected in the Wash itself downgradient of the Pilot Study area. The lack of rhodamine dye in surface water and the appearance of fluorescein dye in the Wash more than 1,500 feet downgradient of Zone 1 (discussed in Section 6.6.4) together indicate that groundwater can travel great distances and at high velocity within the ancestral fluvial deposits prior to discharging into the Wash. Therefore, discharge of rhodamine dye into the Wash may have been observable farther downstream of the Pilot Study area, although samples outside of the Pilot Study area were not analyzed for dye.

Another objective of the dye study was to evaluate the connectivity between the alluvium and UMCf within the Pilot Study area. As a result, samples collected from Zone 2 monitoring wells were analyzed for both rhodamine (injected into the alluvium) and fluorescein (injected into the UMCf). As explained in forthcoming Section 7.6.3.2, fluorescein appeared in both deep alluvial dose-response monitoring wells LVWPS-A2-DR01B and LVWPS-A2-DR02B during injections, which illustrates the connectivity of the alluvium and the UMCf due to faulting and the deep alluvial paleochannel within Zone 2. In addition, effectiveness monitoring results indicated fluorescein detections in groundwater samples collected from three monitoring wells screened in the deep alluvium including LVWPS-A2-MW04B, LVWPS-A2-MW08C, and LVWPS-A2-MW17C. The continued detection of fluorescein in samples collected from these downgradient monitoring locations up to six months after the first injection event suggests that there is likely a continued flux of groundwater from the UMCf to the alluvium at these locations, rather than a slug of fluorescein-tagged groundwater associated only with injection activities.

7.6.3.2 Dye Results in Zone 2 UMCf

During injection activities in Zone 2 UMCf, fluorescein-tagged carbon substrate solution was detected in samples collected from both dose-response monitoring wells screened in the UMCf (LVWPS-U2-DR01, LVWPS-U2-DR02) and one cross-gradient monitoring well located approximately 12 feet from the injection well transect (LVWPS-U2-MW05). Although fluorescein was not detected in groundwater collected from cross-gradient monitoring well LVWPS-U2-MW04 using the field fluorimeter during injection activities, fluorescein was detected in the charcoal sampler collected from LVWPS-U2-MW04 during the first effectiveness monitoring sampling event. Furthermore, an increase in TOC (a proxy for arrival of carbon substrate solution discussed in Section 7.7.4.2) was observed in groundwater collected from LVWPS-U2-MW04, which confirms the target ROI was achieved. In addition, during injection activities, fluorescein appeared in both deep alluvial dose-response monitoring wells LVWPS-A2-DR01B and LVWPS-A2-DR02B, which illustrates the connectivity of the alluvium and the UMCf due to faulting and the deep alluvial paleochannel within Zone 2. Once the fluorescein dye migrated into the alluvium along preferential flow pathways including faults, fractures, and/or the incised paleochannel in the UMCf, the dye rapidly flowed downgradient within the alluvium. Fluorescein was detected in samples collected approximately 1 month after dye injection from monitoring wells screened in the deep alluvium up to 100 feet cross-gradient and downgradient, namely, LVWPS-A2-MW04B, LVWPS-A2-MW08C, LVWPS-A2-MW13B, and LVWPS-A2-MW17C.

As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to estimate the effective porosity of the UMCf in Zone 2. These results indicated that the field-determined effective porosity was less than originally estimated during the design of injection quantities for the Zone 2 UMCf, with a revised calculated effective porosity of approximately 1 percent, which is similar to the UMCf/UMCf-cg in Zones 1 and 3 (discussed in Sections 6.6.4 and 8.6.4). The injection well performance of three injection wells in Zone 2 UMCf including LVWPS-U2-IW06, LVWPS-U2-IW07, and LVWPS-U2-IW10 (discussed in Section 7.3.2), suggests that in select portions on the injection well transect where the unconsolidated UMCf is thin, the effective porosity of the UMCf is likely even lower than 1 percent. These low effective porosities calculated for the UMCf in part explain the migration of the injectate solution farther from the injection points (both upgradient and downgradient) during injections. In addition, the injectate solution likely followed preferential flow pathways (i.e., bedding planes and fracture networks associated with faulting) in the UMCf to appear farther downgradient than expected. Once the injection activities ceased, the migration of fluorescein downgradient under the natural gradient of the formation was quite slow. Fluorescein was not detected at either of the monitoring wells screened 25 feet downgradient within the UMCf, namely, LVWPS-U2-MW06 and LVWPS-U2-MW18, during the six-month dye study, which suggest flow rates of less than 0.1 ft/day.

However, fluorescein dye was detected in the charcoal sampler collected from monitoring well LVWPS-U2-MW14, which is located 50 feet downgradient of the injection well transect, approximately ten days after Zone 2 UMCf injection activities. In addition, three months after the first injection event, fluorescein dye was detected at LVWPS-MW223C, which is located 200 feet downgradient of the injection well transect. The rapid travel time of fluorescein at monitoring locations 50 feet and 200 feet downgradient in the eastern portion of the study area is likely due to the higher groundwater velocities within secondary porosity associated with the fault zone. Additionally, these samples were also analyzed for rhodamine, which was not detected at any of these sample locations. The absence of rhodamine dye in samples collected from these monitoring locations supports this conclusion of more rapid flow through the UMCf, rather than due to cross-connections with the alluvium.

Lastly, both rhodamine and fluorescein were detected in samples collected during the first month following injections from monitoring wells LVWPS-U2-MW12 and LVWPS-U2-MW17, which were located approximately 100 feet downgradient of the injection well transect and screened in the UMCf. The arrival of fluorescein and rhodamine dyes together at these monitoring locations illustrates the varied vertical gradients ranging from 0.01 ft/ft upward to 0.03 ft/ft downward and the cross-connecting flow pathways between the alluvium and the UMCf within Zone 2.

7.7 EFFECTIVENESS MONITORING RESULTS

As explained in Section 5.7, groundwater samples were collected on a biweekly, monthly, and/or bimonthly basis (sampling frequency dependent on targeted lithology) and analyzed for a variety of constituents to evaluate the aquifer's response related to ISB injections into the alluvium and unconsolidated UMCf in the Zone 2 study area. This section provides an overview of the groundwater sampling results, including a discussion of the primary chemical constituents, additional chemical and geochemical parameters, and relationships among these parameters. Because perchlorate is the primary chemical of concern associated with this Pilot Study, Section 7.7.1 presents a detailed discussion of the perchlorate degradation response, an estimate of perchlorate distribution, and an estimate of perchlorate mass destroyed during the Pilot Study. Other significant constituents, including chlorate, nitrate, and TOC, are discussed in Sections 7.7.2 through 7.7.4, with a collective summary of these primary parameters results presented in Section 7.7.5. Additional parameters, including DO, ORP, pH, sulfate, sulfide, metals, and methane, have also been evaluated and are discussed in Section 7.7.6 while an evaluation of the groundwater microbial analytical results is provided in Section 7.7.7. Data for all parameters are presented in the comprehensive data tables provided in Appendix J, Tables J.1 through J.3, while calculated percent change in perchlorate concentrations compared to baseline concentrations for Zone 2 monitoring wells are provided in Appendix J, Tables J.5 and J.6. Data for perchlorate, chlorate, nitrate, TOC, arsenic, phosphorus, DO, and ORP are depicted graphically in individual well trend profiles provided in Appendix L, Figures L.28 through L.87. Field logs from all groundwater sampling events are provided in Appendix I and the DVSR is provided in Appendix K.

7.7.1 Perchlorate

Perchlorate concentrations in groundwater were evaluated throughout the study to monitor concentration changes when comparing the baseline (pre-injection) sampling event to those sampling events performed following each of the three injection events into the alluvium and two injection events into the unconsolidated UMCf within the Zone 2 study area. This monitoring program included monitoring wells located at significant distances downgradient of the injection well transect, where concentration reductions may be minimal due to the limited study duration and short injection well transect length that likely results in migration of groundwater into the study area that did not pass directly through the biologically active zone. As such, this limits the extent of farther downgradient treatment that can be observed as part of this small-scale Pilot Study. Evaluations of the perchlorate degradation response, perchlorate distribution throughout the Zone 2 study area, and estimates of perchlorate mass removal are presented in the subsequent sections. Perchlorate concentration data collected from the Zone 2 study area are summarized in Appendix J, Tables J.1, J.5, and J.6 and graphically depicted in Appendix L, Figures L.28 through

L.87. **Figures 13a-d, 14a-d, and 15a-c** present perchlorate plume interpretations during the Pilot Study for the shallow alluvium, deep alluvium, and UMCf, respectively, within the Zone 2 study area, which are discussed in Section 7.7.1.3.

7.7.1.1 Perchlorate Degradation Response in the Alluvium

This section provides a summary of the baseline conditions and subsequent perchlorate degradation response that was observed following each injection event into the alluvium summarized in Section 7.3. Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages. ***Table 5Table 4*** summarizes the average and maximum perchlorate concentration changes in groundwater observed as percentage change when compared to baseline concentrations in groundwater collected from shallow and deep alluvial monitoring wells located upgradient and downgradient of the injection well transect throughout the study duration. Analytical data used in the calculations for concentration changes during the Pilot Study are presented in Table J.1. A detailed summary of the percentage change in perchlorate concentrations compared to baseline concentrations for all Zone 2 monitoring wells screened in the alluvium is provided in Appendix J, Table J.5.

Table 5 Zone 2 Alluvium Perchlorate Concentration Changes During Pilot Study

Event Description	Sampling Event(1)	Monitoring Well Location							
		60 Feet Upgradient of Injection Well Transect		17 Feet Cross-gradient of Injection Well Transect		50 to 100 Feet Downgradient of Injection Well Transect		200 to 250 Feet Downgradient of Injection Well Transect	
		No. of Wells =7		No. of Wells = 4		No. of Wells = 14		No. of Wells = 4	
		Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
After Injection Event 1	Week 2	14%	-15%	-60%	-99%	-54%	-99%	-14%	-59%
	Month 1	-5%	-15%	-75%	-99%	-60%	-99%	90%	-97%
	Week 6	24%	-17%	-67%	-99%	-52%	-99%	-47%	-96%
	Month 2	-1%	-10%	-63%	-99%	-51%	-99%	-44%	-93%
	Month 3	4%	-13%	-61%	-99%	-51%	-99%	-47%	-88%
	Month 4	9%	-4%	-62%	-99%	-49%	-99%	-40%	-84%
After Injection Event 2	Month 5	5%	-10%	-74%	-99%	-77%	-99%	-59%	-85%
	Month 6	-1%	-13%	-70%	-99%	-66%	-99%	-49%	-87%
	Month 7	6%	-10%	-72%	-99%	-63%	-99%	-36%	-79%
	Month 8	3%	-11%	-76%	-99%	-55%	-99%	-19%	-84%
	Month 9	3%	-17%	-69%	-99%	-52%	-99%	-34%	-95%
After Injection Event 3	Month 11	19%	5%	-95%	-99%	-71%	-99%	-58%	-91%
	Month 12	9%	-17%	-88%	-99%	-51%	-99%	-37%	-96%
	Month 13	4%	-8%	-93%	-99%	-51%	-99%	-32%	-90%
	Month 14	0%	-13%	-80%	-99%	-47%	-99%	-34%	-87%
	Month 15	8%	-10%	-80%	-99%	-45%	-99%	-31%	-85%
	Month 16	4%	-16%	-80%	-99%	-45%	-99%	-32%	-94%
	Month 17	2%	-8%	-78%	-99%	-39%	-99%	-29%	-98%
	Month 18	8%	-4%	-73%	-99%	-39%	-99%	-27%	-99%

Notes:
1. Percentage change in perchlorate concentration is calculated relative to the pre-injection baseline groundwater sampling event in September/October 2020 (labeled as event BL04 in Appendix J, Table J.1). Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages.
2. The maximum change shown is the most significant reduction in concentration as represented by the most negative percentage calculated.
3. The calculation for average concentration change accounts for both increases and decreases in concentrations compared to baseline.
4. No groundwater sampling was performed in October 2021 (Month 10) due to injection activities associated with the third injection event.

7.7.1.1.1 Baseline Groundwater Results

Groundwater samples were collected from monitoring wells screened in the alluvium in September/October 2020 as part of baseline sampling activities. Perchlorate concentrations in groundwater ranged from 170 μg/L to 4,400 μg/L in the alluvium, with results generally consistent in both the shallow and deep alluvium. The highest detection in the alluvium of 4,400 μg/L was measured in a groundwater sample collected from LVWPS-A2-MW12A, which was located approximately 100 feet downgradient of the injection well transect in the middle of the Zone 2 study area and screened in the shallow alluvium from 35 to 45 feet bgs.

7.7.1.1.2 Perchlorate Degradation Response Following Injection Event 1

Following completion of the first injection event in December 2020, groundwater sampling was performed on a biweekly basis for the first two months, followed by monthly thereafter. This pattern resulted in six groundwater sampling events being conducted during Months 1 through 4. Groundwater samples were collected from all monitoring wells screened in the alluvium (as described in Section 7.2.2) to monitor for potential contaminant concentration reductions as a result of ISB injections into the alluvium within the Zone 2 study area. Results following the first injection event are summarized below.

- Perchlorate concentrations in samples collected from upgradient monitoring wells generally ranged from 1,100 μg/L to 4,200 μg/L (Appendix L, Figures L.28 through L.34). The highest upgradient perchlorate concentrations were generally observed in groundwater samples collected from monitoring wells LVWPS-A2-MW02A/B, which are centrally located upgradient of the injection well transect (**Figures 7a and 7b**). In general, upgradient concentrations remained consistent in samples collected from each monitoring well throughout the sampling events following the first injection event, indicating a relatively stable environment outside of the Zone 2 study area. Unlike in Zone 1, notable perchlorate concentration reductions were not observed in samples collected from the upgradient monitoring well clusters. Reductions in upgradient areas were not expected given the more transmissive nature of the alluvial sediments compared to the UMCf (i.e., injectate solution would not be expected to travel as far upgradient during injection activities).
- Perchlorate concentration reductions ranging from 18 percent to greater than 99 percent were observed following the first injection event in samples collected from the four cross-gradient monitoring wells located approximately 17 feet from either end of the injection well transect (LVWPS-A2-MW04A, LVWPS-A2-MW04B, LVWPS-A2-MW05A, and LVWPS-A2-MW05B) (Appendix L, Figures L.35 through L.38) . Perchlorate concentration reductions were the most prominent in the samples collected from the cross-gradient monitoring well cluster LVWPS-A2-MW05A/B, which was located to the east of the injection well transect, compared to the westernmost cross-gradient monitoring well cluster LVWPS-A2-MW04A/B. The better response to the injections along the eastern side compared to the western side of the injection well transect was expected based on the northeastern groundwater flow direction within the alluvium shown on **Figures 7a and 7b**. Details of the concentration trends of the cross-gradient monitoring well clusters are summarized below:
    - Perchlorate concentrations in the samples collected from the eastern deep alluvium monitoring well LVWPS-A2-MW05B reduced from a baseline concentration of 1,900 μg/L to below the PRG of 15 μg/L during all six sampling events following the first injection event. Perchlorate concentrations in the samples collected from the eastern shallow alluvium LVWPS-A2-MW05A reduced from a baseline concentration of 2,400 μg/L to as low as 310 μg/L, with concentration reductions averaging 63 percent following the first injection event. This data also correlates with the elevated TOC concentrations of up to 280 mg/L (compared to a pre-injection concentration of 0.7 mg/L) indicating the presence of the injectate solution in samples collected from these monitoring wells following the first injection event (discussed in Section 7.7.4.1).

- Perchlorate concentration reductions of up to 49 percent and 81 percent were observed following the first injection event in the samples collected from LVWPS-A2-MW04A and LVWPS-A2-MW04B, respectively. Specifically, perchlorate concentrations in groundwater samples collected from shallow alluvium monitoring well LVWPS-A2-MW04A reduced from a baseline concentration of 4,100 μg/L to concentrations ranging from 2,100 μg/L to 2,900 μg/L following the first injection event. Perchlorate concentrations in groundwater samples collected from deep alluvium monitoring well LVWPS-A2-MW04B were more pronounced following the first injection event, with concentrations reducing from a baseline concentration of 3,400 μg/L to concentrations ranging from 650 μg/L to 2,800 μg/L. Once again, this data correlates with elevated TOC concentrations up to 51 mg/L following the first injection event.

- Groundwater samples collected from monitoring wells located 50 feet downgradient of the injection well transect following the first injection event indicated the following notable perchlorate concentration reductions (Appendix L, Figures L.39 through L45).
  - Perchlorate concentration reductions ranging from 26 percent to greater than 99 percent when compared to baseline concentrations were observed in all samples collected from the LVWPS-A2-MW08A/B/C monitoring well cluster, which is located approximately 50 feet downgradient of the injection well transect and in the western portion of the Zone 2 study area in the vicinity of the large, deep paleochannel (Appendix L, Figures L.39 through L41). The average perchlorate concentration reduction in the samples collected from the shallow alluvium wells (LVWPS-A2-MW08A and LVWPS-A2-MW08B) following the first injection event was approximately 40 percent. Specifically, perchlorate concentrations in samples collected from monitoring well LVWPS-A2-MW08A reduced from a baseline concentration of 2,700 μg/L to concentrations ranging from 750 μg/L to 2,000 μg/L following the first injection event. Perchlorate concentrations in samples collected from monitoring well LVWPS-A2-MW08B reduced from a baseline concentration of 3,800 μg/L to concentrations ranging from 2,100 μg/L to 2,800 μg/L following the first injection event. Although reductions were observed in the shallow alluvium, it is likely that perchlorate-contaminated groundwater is migrating into the Zone 2 study area in the vicinity of monitoring well cluster LVWPS-A2-MW08A/B/C that does not pass through the biologically active zone near the injection well transect due to the northeastern groundwater flow direction in the western portion of the study area (**Figure 7a**). Results from the samples collected from deep alluvium monitoring well LVWPS-A2-MW08C indicated perchlorate concentration reductions of greater than 99 percent, with perchlorate concentrations reducing from a baseline concentration of 4,100 μg/L to concentrations ranging from less than 0.31 μg/L to 140 μg/L (including concentrations below the PRG of 15 μg/L during two sampling events). These strong reductions illustrate the more northerly groundwater flow direction and higher groundwater flow velocities observed in the deep, coarse-grained sediments of the Zone 2 paleochannel (greater than 30 ft/day) resulting in greater and more rapid transport of the injectate downgradient. Despite the high groundwater flow rates within the paleochannel, reductions of greater than 92 percent were sustained in all samples collected from LVWPS-A2-MW08C in all six events following the first injection event.
  - Results from the samples collected from monitoring well cluster LVWPS-A2-MW14A/B, which was located approximately 50 feet downgradient of the injection well transect and in the middle of the Zone 2 study area, indicated perchlorate concentration reductions ranging from 14 percent to greater than 99 percent when compared to baseline concentrations (Appendix L, Figures L.42 through L43). The largest perchlorate concentration reductions were observed in the samples collected from shallow alluvial monitoring well LVWPS-A2-MW14A, with reductions ranging from 92 percent to greater than 99 percent in the six events following the first injection event (concentrations ranging from 13 μg/L to 200 μg/L compared to a baseline concentration of 2,600 μg/L). Results from the microbial sampling performed at this location (discussed in Section 7.7.7)

indicate that native microorganisms responded favorably, with an increased presence of perchlorate reducing bacteria, increased overall biomass populations, and enhanced community structure. With respect to the deep alluvium at this location, perchlorate concentrations reduced in samples collected from deep alluvial monitoring well LVWPS-A2-MW14B, but reductions were considerably lower when compared to the shallow alluvium, with results ranging from 14 percent to 50 percent (concentrations ranging from 1,400 μg/L to 2,400 μg/L compared to a baseline concentration of 2,800 μg/L). The results of the samples collected from this well cluster correlate with the difference in groundwater flow rates between the shallow and deep alluvium. Specifically, borehole dilution testing indicated a groundwater flow rate of approximately 4 ft/day in shallow alluvial monitoring well LVWPS-A2-MW14A and approximately 88 ft/day in the deep alluvial monitoring well LVWPS-A2-MW14B. Based on these flow rates, it would be expected that the reductions would be greater and longer lasting in the shallow alluvium compared to the deep alluvium, which has an elevated groundwater flow rate that may not always allow sufficient residence time for complete degradation of perchlorate.

    - Following the first injection event, perchlorate concentration reductions ranging from 6 percent to 71 percent when compared to baseline concentrations occurred in samples collected from monitoring well cluster LVWPS-A2-MW09A/B, which was located approximately 50 feet downgradient of the injection well transect in the far eastern portion of the Zone 2 study area (Appendix L, Figures L.44 through L45). The largest perchlorate concentration reductions occurred in the samples collected from shallow alluvial monitoring well LVWPS-A2-MW09A, with reductions ranging from 12 percent to 71 percent following the first injection event (concentrations ranging from 1,000 μg/L to 3,000 μg/L compared to a baseline concentration of 3,400 μg/L). The lowest perchlorate concentration detected in samples collected from LVWPS-A2-MW09B was four months following the first injection event with a concentration of 720 μg/L compared to a baseline concentration of 1,600 μg/L. The far eastern location of the LVWPS-A2-MW09A/B monitoring well cluster likely results in groundwater migrating into the Zone 2 study area that does not pass through the biologically active zone in the vicinity of the injection well transect. Initially, the carbon substrate that is added can have a positive influence due to the distribution water transporting organic carbon for perchlorate biodegradation despite perchlorate-laden groundwater flow from the northern portions. However, the regular transport of untreated perchlorate-laden water that moves towards this monitoring well over time impacts concentrations because this location may not continue to receive carbon-rich water due to it not being directly in the path of injections. Similar to the results of the samples collected from the LVWPS-A2-MW14A/B monitoring well cluster, perchlorate concentration reductions in this area were greater in the shallow alluvium compared to the deep alluvium. Borehole dilution testing of this well cluster indicated groundwater flow velocities of 6 ft/day and 122 ft/day in monitoring wells LVWPS-A2-MW09A and LVWPS-A2-MW09B, respectively. The combination of the well location and high groundwater flow rate in monitoring well LVWPS-A2-MW09B is the likely reason for the low perchlorate concentration reduction in samples collected from this well, which averaged 18 percent following the first injection event.

- Groundwater samples were collected from the four monitoring well clusters located approximately 100 feet downgradient of the injection well transect (LVWPS-A2-MW11A/B/C, LVWPS-A2-MW12A/B, LVWPS-A2-MW13A/B, and LVWPS-A2-MW17A/B/C). Samples from several monitoring wells indicated significant perchlorate concentration reductions following the first injection event (Appendix L, Figures L. 46 through L.55).
    - Results from the samples collected from the monitoring well cluster LVWPS-A2-MW11A/B/C, which is located on the western edge of the Zone 2 study area, only indicated slight perchlorate concentration reductions ranging from 3 percent to 29 percent following the first injection event (Appendix L, Figures L.53 through L.55), with concentrations reducing from an average baseline

concentration of 3,167 μg/L to an average concentration of 2,872 μg/L following the first injection event. These reductions are minimal due to the location of this monitoring well cluster, which is west of the paleochannel and not downgradient of the injection well transect based on a review of groundwater flow directions presented in **Figures 7a and 7b**.

- Monitoring well cluster LVWPS-A2-MW17A/B/C is located directly along the approximate paleochannel centerline (**Figures 7a/7b**). Samples collected from both LVWPS-A2-MW17B and LVWPS-A2-MW17C indicated perchlorate concentration reductions of greater than 70 percent in multiple sampling events following the first injection event (Appendix L, Figures L.47 and L.48). Specifically, perchlorate concentrations in samples collected from monitoring well LVWPS-A2-MW17B ranged from 530 μg/L to 1,600 μg/L following the first injection event compared to a baseline concentration of 2,700 μg/L. Similar results were present in the samples collected from monitoring well LVWPS-A2-MW17C, with concentrations ranging from 570 μg/L to 1,300 μg/L compared to a baseline concentration of 2,200 μg/L. In contrast, perchlorate concentrations in groundwater samples collected from the shallowest alluvial monitoring well at this location, LVWPS-A2-MW17A, fluctuated but generally did not indicate reductions of greater than 24 percent following the first injection event (Appendix L, Figure L.46). The variability in the response between the shallow and deep alluvium at the LVWPS-A2-MW17A/B/C monitoring well cluster illustrates the difference in the groundwater flow direction between the shallow and deep alluvium due to the Zone 2 paleochannel and its impact on perchlorate biodegradation. As shown on **Figure 7a**, the groundwater flow direction in the shallow alluvium in the western portion on the Zone 2 study area is to the northeast, which results in LVWPS-A2-MW17A being located generally cross-gradient of the injection well transect. In contrast, monitoring wells screened in the deep alluvium at this location (LVWPS-A2-MW17B and LVWPS-A2-MW17C) are downgradient of the injection well transect as groundwater flow converges along the paleochannel resulting in a stronger northernly component to groundwater flow in the deep alluvium (**Figure 7b**).
- Perchlorate concentration reductions ranging from 70 percent to greater than 99 percent were observed in samples collected from monitoring well cluster LVWPS-A2-MW12A/B following the first injection event (Appendix L, Figures L.49 and L.50). This monitoring well cluster is located in the middle of the Zone 2 study area and directly downgradient of monitoring well cluster LVWPS-A2-MW14A/B, in which samples following the first injection event also indicated significant perchlorate concentration reductions. Perchlorate concentrations in samples collected from shallow alluvial monitoring well LVWPS-A2-MW12A significantly reduced from a baseline concentration of 4,400 μg/L to concentrations ranging from less than 0.31 μg/L to 32 μg/L following the first injection event. Additionally, perchlorate concentrations were detected below the PRG of 15 μg/L in five of the six sampling events. Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-A2-MW12B also significantly reduced from a baseline concentration of 4,000 μg/L to concentrations ranging from 12 μg/L to 1,200 μg/L.
- Monitoring well sampling results from the LVWPS-A2-MW13A/B monitoring well cluster, which is located along the eastern edge of the study area, indicated concentration increases in samples collected from shallow alluvial monitoring well LVWPS-A2-MW13A but concentration decreases of up to 98 percent in samples collected from deep alluvial monitoring well LVWPS-A2-MW13B following the first injection event (Appendix L, Figures L.51 and L.52). Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-A2-MW13B reduced from a baseline concentration of 2,200 μg/L to concentrations ranging from 38 μg/L to 610 μg/L following the first injection event. The stronger response in the deep alluvium at this location may in part be due to lower groundwater velocities in the shallow alluvium compared to the deep alluvium. Additionally, because this monitoring well was located on the eastern edge of the Zone 2 study area, LVWPS-A2-MW13A may be more influenced by groundwater migrating into the Zone 2

study area that does not pass through the biologically active zone in the vicinity of the injection well transect.

- Of the two monitoring well clusters located approximately 200 feet downgradient of the injection well transect (namely, LVWPS-MW208A/B and LVWPS-MW223A/B), results of samples collected from both deep alluvial monitoring wells LVWPS-MW208B and LVWPS-223B indicated perchlorate concentration reductions greater than 90 percent during multiple sampling events (Appendix L, Figures L.56 through L.59). Specifically, perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-MW208B significantly reduced from a baseline concentration of 2,100 μg/L to concentrations ranging from 63 μg/L to 870 μg/L. Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-MW223B also significantly reduced from a baseline concentration of 3,300 μg/L to concentrations ranging from 270 μg/L to 2,100 μg/L. Lastly, samples collected from shallow alluvial monitoring well LVWPS-MW223A indicated perchlorate concentration reductions of up to 78 percent following the first injection event with a concentration low of 730 μg/L compared to a baseline concentration of 3,300 μg/L. Perchlorate concentrations gradually increased after this sampling event and essentially returned to baseline conditions at four months following the first injection event. The response at monitoring well cluster LVWPS-MW223A/B was expected based on the groundwater flow directions in both the shallow and deep alluvium.
- Noteworthy sample results from remaining monitoring wells located greater than 200 feet in either the cross-gradient or downgradient direction are summarized below. Reductions observed in these areas are particularly important because these areas are significantly impacted by groundwater migrating into the Zone 2 study area that does not pass through the biologically active zone in the vicinity of the injection well transect. Therefore, reductions observed in samples collected from monitoring wells located this far away from the injection well transect is a valuable data point in the evaluation of the extent of impacts from the injections, which will be considered during evaluation of an ISB remedy during the forthcoming FS.
    - Samples collected from monitoring well clusters LVWPS-A2-MW15A/B and LVWPS-A2-MW16A/B, which are located west of the paleochannel and approximately 200 and 350 feet downgradient of the injection well transect, respectively, indicated perchlorate concentration reductions generally averaging greater than 10 percent, with individual reductions of up to 35 percent (Appendix L, Figures L.60 through L.63). The most notable reduction of 35 percent was observed in the Month 2 sample collected from shallow alluvial monitoring well LVWPS-A2-MW15A, with a concentration of 2,200 μg/L compared to a baseline concentration of 3,400 μg/L.
    - Approximately six weeks following the first injection event, perchlorate concentrations reduced to as low as 850 μg/L compared to a baseline concentration of 2,000 μg/L (reduction of 58 percent) in the samples collected from monitoring well LVWPS-MW211, which is located approximately 650 feet downgradient of the injection well transect (Appendix L, Figure L.68).
    - Perchlorate concentration reductions ranging from 27 percent to 43 percent were observed in samples collected from monitoring wells LVWPS-MW218A and LVWPS-MW221A, which are located approximately 625 feet downgradient and approximately 300 feet cross-gradient of the Zone 2 injection well transect, respectively (Appendix L, Figures L.64 and L.72). The most notable reduction of 43 percent was observed in the samples collected from shallow alluvial monitoring well LVWPS-MW-218A, which reduced from a baseline concentration of 5,100 μg/L to 2,900 μg/L following the first injection event. The results from the samples collected from LVWPS-MW218A could also be influenced by the reductions observed in the Zone 1 study area (i.e., concentration reductions observed in the alluvium from the injections performed in the UMCf within the Zone 1 study area; discussed in Section 6.7.1).

7.7.1.1.3 Perchlorate Degradation Response Following Injection Event 2

Following completion of the second injection event in April 2021 (approximately 4 months after the first injection event), groundwater sampling was performed on a monthly basis, resulting in a total of five groundwater sampling events being conducted during Months 5 through 9. Groundwater samples were collected from all monitoring wells screened in the alluvium (as described in Section 7.2.2) to monitor for potential contaminant concentration reductions as a result of ISB injections into the alluvium within the Zone 2 study area. Results following the second injection event are summarized below.

- Similar to the results following the first injection event, notable perchlorate concentration reductions were not observed in samples collected from the upgradient monitoring well clusters, with perchlorate concentrations ranging from 1,300 μg/L to 4,200 μg/L and remaining relatively consistent with results following the first injection event as well as baseline (Appendix L, Figures L.28 through L.34). Reductions in upgradient areas were not expected given the more transmissive nature of the alluvial sediments compared to the UMCf.
- Similar to the results after the first injection event, results of the samples collected from the four cross-gradient monitoring wells located approximately 17 feet from either end of the injection well transect (LVWPS-A2-MW04A, LVWPS-A2-MW04B, LVWPS-A2-MW05A, and LVWPS-A2-MW05B) indicated perchlorate concentration reductions ranging from 33 percent to greater than 99 percent (Appendix L, Figures L.35 through L.38). Perchlorate concentration reductions improved in the samples collected from deep alluvial monitoring well LVWPS-A2-MW04B, with reductions greater than 95 percent in all sampling events compared to an average reduction of 64 percent following the first injection event (i.e., average perchlorate concentration of 99 μg/L following the second injection event compared to an average concentration of 1,220 μg/L following the first injection event). This correlates with the arrival of the injectate solution as demonstrated by a substantial increase in TOC concentrations during the Month 5 sampling event, which had not been previously detected at these concentrations. Perchlorate concentrations in the samples collected from deep alluvial monitoring well LVWPS-A2-MW05B remained below the PRG of 15 μg/L during all five sampling events following the second injection event. Lastly, perchlorate results during Months 5 through 9 were similar to the results after the first injection event in the samples collected from the shallow alluvium wells LVWPS-A2-MW04A and LVWPS-A2-MW05A.
- Groundwater samples collected from monitoring wells located 50 feet downgradient of the injection well transect following the second injection event indicated the following notable perchlorate concentration reductions (Appendix L, Figures L.39 through L.45).
  - Perchlorate concentration reductions averaged 90 percent in samples collected from all three monitoring wells in the LVWPS-A2-MW08A/B/C monitoring well cluster (Appendix L, Figures L.39 through L.41). Although minimal concentration reductions were observed in the samples collected from LVWPS-A2-MW08A and LVWPS-A2-MW08B following the first injection event, perchlorate concentrations substantially reduced following the second injection event, with reductions of up to 99 percent in samples collected from both monitoring wells. Perchlorate concentrations reduced from a baseline concentration of 2,700 μg/L to concentrations ranging from 21 μg/L to 200 μg/L in the samples collected from LVWPS-A2-MW08A following the second injection event. Similar reductions were observed in the samples collected from LVWPS-A2-MW08B, which reduced from a baseline concentration of 3,800 μg/L to concentrations ranging from 25 μg/L to 490 μg/L following the second injection event. As previously explained in Section 7.7.1.1.2, the groundwater flow rates are lower in the shallow alluvial monitoring wells LVWPS-A2-MW08A and LVWPS-A2-MW08B compared to the deep alluvial monitoring well LVWPS-A2-MW08C. This is likely the reason for the rapid response in the deep alluvium during Months 1 through 4 following the first injection event and the strong but slower response in the shallow alluvium during Months 5 through 9 following the second injection event. Also previously noted, perchlorate-contaminated groundwater that does not pass through the biologically active zone is migrating into the Zone 2

study area in the vicinity of monitoring well cluster LVWPS-A2-MW08A/B/C due to the northeastern groundwater flow direction in the western portion of the study area (**Figure 7a**). As a result, reductions of greater than 90 percent in 11 of the 15 samples collected from this area following the second injection event indicate a positive response to the injections. If ISB is selected as a component of the NERT final remedy, the injection well transect would be extended across a much larger distance and/or oriented to address fluctuations in groundwater flow direction.

- Results from the samples collected from monitoring well cluster LVWPS-A2-MW14A/B continued to indicate similar trends following the second injection event (Appendix L, Figures L.42 and L.43). Consistent perchlorate concentration reductions of greater than 98 percent were observed in samples collected from monitoring well LVWPS-A2-MW14A, with concentrations ranging from 14 μg/L to 64 μg/L compared to a baseline concentration of 2,600 μg/L. Lower perchlorate concentration reductions ranging from 7 percent to 43 percent were observed in the samples collected from monitoring well LVWPS-A2-MW14B, with concentrations ranging from 1,600 μg/L to 2,600 μg/L compared to a baseline concentration of 2,800 μg/L. As previously explained, these results correlate with the difference in groundwater flow rates between the shallow and deep alluvium of approximately 4 ft/day and 88 ft/day, respectively, which likely does not result in sufficient residence time for complete degradation of perchlorate in the deep alluvium. Secondly, the injectate likely dissipates at this distance (50 feet) from the injection well transect over time in the faster flowing deep alluvium, resulting in reductions in available carbon for microorganisms to degrade perchlorate.
- Following the second injection event, perchlorate concentration reductions of up to 50 percent were observed in samples collected from monitoring well cluster LVWPS-A2-MW09A/B, which was similar to the response after the first injection event (Appendix L, Figures L.44 and L.45). The greatest perchlorate concentration reduction within this monitoring well cluster occurred in the samples collected from shallow alluvial monitoring well LVWPS-A2-MW09A, with concentrations ranging from 1,700 μg/L to 3,200 μg/L compared to a baseline concentration of 3,400 μg/L. As discussed in Section 7.7.1.1.2, this monitoring well cluster is on the eastern edge of the study area and therefore, is likely impacted by groundwater migrating into the Zone 2 study area that does not pass through the biologically active zone in the vicinity of the injection well transect. Because of this, the carbon substrate that is injected can initially have a positive influence; however, the regular transport of untreated perchlorate-laden water that moves towards this monitoring well over time impacts concentrations because this location may not continue to receive carbon-rich water because it is not directly in the path of injections.

- Groundwater sampling results during Months 5 through 9 in samples from the four monitoring well clusters located approximately 100 feet downgradient of the injection well transect (LVWPS-A2-MW11A/B/C, LVWPS-A2-MW12A/B, LVWPS-A2-MW13A/B, and LVWPS-A2-MW17A/B/C) generally indicated similar concentration trends as the results following the first injection event, but also included improved concentration reductions in samples from some locations. Noteworthy results from the samples collected from each of these monitoring well clusters following the second injection event are provided below.
  - Results from the samples collected from the monitoring well cluster LVWPS-A2-MW11A/B/C continued to indicate only minimal reductions (up to 13 percent), which is likely due to this monitoring well cluster being located west of the paleochannel and not downgradient of the injection well transect based on a review of groundwater flow directions presented in **Figures 7a and 7b** (Appendix L, Figures L.53 through L.55).
  - Perchlorate concentrations in monitoring well LVWPS-A2-MW17C, which is located in monitoring well cluster LVWPS-A2-MW17A/B/C situated directly along the approximate paleochannel

centerline (**Figures 7a/7b**), indicated a continued decreasing trend following the second injection event (Appendix L, Figure L.48). Specifically, perchlorate concentrations ranged from less than 0.31 μg/L to 440 μg/L, which represent reductions ranging from 80 percent to greater than 99 percent following the second injection event compared to a baseline concentration of 2,200 μg/L. Following the second injection event, perchlorate concentrations also reduced to less than 0.31 μg/L in the sample collected from LVWPS-A2-MW17C during the Month 7 sampling event. Although perchlorate concentrations were reduced when compared to baseline concentrations in samples collected from monitoring wells LVWPS-A2-MW17A and LVWPS-A2-MW17B, reductions were much lower, with reductions ranging from 8 percent to 56 percent when compared to baseline concentrations (Appendix L, Figures L.46 and L.47).

- Similar to the results following the first injection event, perchlorate concentration reductions ranging from 65 percent to greater than 99 percent were observed in samples collected from monitoring well cluster LVWPS-A2-MW12A/B during Months 5 through 9 (Appendix L, Figures L.49 and L.50). Once again, perchlorate concentrations in samples from shallow alluvial monitoring well LVWPS-A2-MW12A were less than the sample detection limit and below the PRG of 15 μg/L in all sampling events following the second injection event. Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-A2-MW12B also significantly reduced from a baseline concentration of 4,000 μg/L to concentrations ranging from 40 μg/L to 1,400 μg/L (reductions ranging from 65 percent to greater than 99 percent).
- Although perchlorate concentrations increased in samples collected from shallow alluvial monitoring well LVWPS-A2-MW13A following the first injection event, concentrations reduced by 94 percent after the second injection event with a Month 5 concentration of 69 μg/L compared to a baseline concentration of 1,200 μg/L (Appendix L, Figure L.51). Perchlorate concentrations continued to be reduced by 50 percent to 75 percent in the subsequent sampling events (Months 6, 7, and 8) but returned to baseline concentrations prior to the third injection event. Perchlorate concentrations were likely initially slow to reduce in samples from shallow alluvial monitoring well LVWPS-A2-MW13A due to slower groundwater flow rates in the shallow alluvium, which likely resulted in a delay in transport of injectate and/or treated groundwater. Additionally, because this monitoring well was located on the eastern edge of the Zone 2 study area, LVWPS-A2-MW13A may be more influenced by groundwater migrating into the Zone 2 study area that does not pass through the biologically active zone in the vicinity of the injection well transect, which is likely the reason for the return to baseline concentrations towards the end of the sampling period following the second injection event. Perchlorate concentration reductions continued to be significant in samples collected from the deep alluvial monitoring well LVWPS-A2-MW13B, with an average concentration reduction of 93 percent following the second injection event (Appendix L, Figure L.52). Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-A2-MW13B reduced from a baseline concentration of 2,200 μg/L to concentrations ranging from 65 μg/L to 270 μg/L following the second injection event.

- Of the two monitoring well clusters located approximately 200 feet downgradient of the injection well transect (namely, LVWPS-MW208A/B and LVWPS-MW223A/B), results from samples collected from both deep alluvial monitoring wells LVWPS-MW208B and LVWPS-223B continued to indicate significant perchlorate concentration reductions ranging from 57 percent to 95 percent (Appendix L, Figures L.56 through 59). Specifically, perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-MW208B reduced from a baseline concentration of 2,100 μg/L to concentrations ranging from 310 μg/L to 900 μg/L following the second injection event. Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-MW223B indicated improved reductions, with concentrations ranging from 180 μg/L to 690 μg/L compared to a baseline concentration of 3,300 μg/L and an average perchlorate concentration of 1,048 μg/L following the first injection event.

- Results of the samples collected from monitoring wells located at distances greater than 200 feet in either the cross-gradient or downgradient direction were similar following the second injection event compared to the results following the first injection event. Specifically, perchlorate concentration reductions continued to average approximately 12 percent in samples collected from monitoring well clusters LVWPS-A2-MW15A/B and LVWPS-A2-MW16A/B (Appendix L, Figures L.60 through L.63). Results also indicated consistent perchlorate concentration reductions ranging from 19 percent to 48 percent in samples collected from monitoring wells LVWPS-MW211, LVWPS-MW218A, and LVWPS-MW221A (Appendix L, Figures L.64, L.68, and L.72). The most notable reduction of 48 percent was observed in the Month 5 sample collected immediately following the second injection event from shallow alluvial monitoring well LVWPS-MW221A, with a concentration of 510 μg/L compared to a baseline concentration of 990 μg/L. Perchlorate concentrations in samples collected from LVWPS-MW218A also reduced by 47 percent during the Month 6 sampling event with a concentration of 2,700 μg/L compared to a baseline concentration of 5,100 μg/L. As noted previously, the results from the samples collected from LVWPS-MW218A could also be influenced by the reductions observed in the Zone 1 study area (i.e., concentration reductions observed in the alluvium from the injections performed in the UMCf within the Zone 1 study area; discussed in Section 6.7.1).

7.7.1.1.4 Perchlorate Degradation Response Following Injection Event 3

Following completion of the third injection event in October 2021 (approximately 5.5 months after the second injection event), groundwater sampling was performed on a monthly basis for the remainder of the Pilot Study, resulting in a total of eight groundwater sampling events being conducted during Months 11 through 18. Groundwater samples were collected from all monitoring wells screened in the alluvium (as described in Section 7.2.2) to monitor for potential contaminant concentration reductions as a result of ISB injections into the alluvium within the Zone 2 study area. Results following the third injection event are summarized below.

- Similar to the results following the first and second injection events, perchlorate concentrations did not reduce in samples collected from the upgradient monitoring well clusters following the third injection event. Reductions in upgradient areas were not unexpected given the more transmissive nature of the alluvial sediments compared to the UMCf. Perchlorate concentrations in samples collected from upgradient monitoring wells ranged from 1,200 μg/L to 3,900 μg/L following the third injection event, which are similar to concentrations observed following the first and second injection events (Appendix L, Figures L.28 through L.34).
- Results of the samples collected from the four cross-gradient monitoring wells located approximately 17 feet from either end of the injection well transect (LVWPS-A2-MW04A, LVWPS-A2-MW04B, LVWPS-A2-MW05A, and LVWPS-A2-MW05B) indicated the best perchlorate concentration reductions observed during implementation of the Pilot Study ranging from 82 percent to greater than 99 percent in the first sampling event following the third injection event (Month 11) (Appendix L, Figures L.35 through L.38). Perchlorate concentrations ranged from 750 μg/L to 2,500 μg/L compared to a baseline concentration of 4,100 μg/L in the samples collected from the western shallow alluvium well LVWPS-A2-MW04A, which is an improved average post-injection concentration reduction of 60 percent compared to overall average reductions of 36 percent and 43 percent following the first and second injection events, respectively. Samples collected from LVWPS-A2-MW04B also indicated improvement with perchlorate concentration reductions consistently greater than 97 percent when compared to baseline in the six months following the third injection event. These sampling events also included three detections of perchlorate concentrations ranging from 5.2 μg/L to 15 μg/L, which are less than or equal to the PRG of 15 μg/L (Months 11, 12, and 14). Perchlorate concentrations in samples collected from LVWPS-A2-MW04B remained significantly reduced throughout the eight months following the third injection event, with a final concentration of 1,100 μg/L compared to a baseline concentration of 3,400 μg/L (68 percent reduction). Results from the samples collected from LVWPS-A2-MW05A, which is the shallow alluvium well on the

eastern side of the injection well transect, also indicated significant improvement in concentration reductions with an average reduction of 80 percent following the third injection event (compared to average reductions of 59 percent and 48 percent following the first and second injection events, respectively). Sample results from LVWPS-A2-MW05A also included one detection of perchlorate at 9.1 μg/L, which is below the PRG of 15 μg/L. Perchlorate concentrations in samples collected from LVWPS-A2-MW05A remained significantly reduced throughout the eight months following the third injection event, with a final concentration of 620 μg/L compared to a baseline concentration of 2,400 μg/L (74 percent reduction). Lastly, perchlorate concentrations in the samples collected from deep alluvial monitoring well LVWPS-A2-MW05B remained below the PRG of 15 μg/L during all eight sampling events following the third injection event, with a final concentration less than the sample detection limit of 0.31 μg/L.

- Groundwater samples collected from monitoring wells located 50 feet downgradient of the injection well transect following the third injection event indicated the following notable perchlorate concentration reductions.
  - Perchlorate concentration reductions were greater than 91 percent in samples collected from all three monitoring wells in the LVWPS-A2-MW08A/B/C well cluster during the Month 11 sampling event (first sampling event following the third injection event) (Appendix L, Figures L.39 through L.41). During this Month 11 sampling event, perchlorate concentrations were less than 0.31 μg/L in samples collected from both LVWPS-A2-MW08B and LVWPS-A2-MW08C. Perchlorate concentrations remained below the PRG of 15 μg/L in samples collected from LVWPS-A2-MW08C in six of the eight sampling events following the third injection event, with a final concentration of 180 μg/L compared to a baseline concentration of 4,100 μg/L (96 percent reduction). Although perchlorate concentrations remained reduced by greater than 77 percent in the final samples collected from LVWPS-A2-MW08A and LVWPS-A2-MW08C, perchlorate concentrations in samples collected from LVWPS-A2-MW08B returning to baseline concentrations in the final sampling event. This correlates with the gradual reduction of TOC concentrations in samples collected towards the end of the study and is valuable data point in the evaluation of long-term injection frequency if ISB were selected as a component of the NERT final remedy.
  - Results from the samples collected from monitoring well cluster LVWPS-A2-MW14A/B continued to indicate similar trends following the third injection event (Appendix L, Figures L.42 and L.43). Consistent perchlorate concentration reductions of greater than 98 percent were observed in samples collected from monitoring well LVWPS-A2-MW14A, with four of the eight sampling events including perchlorate concentrations less than PRG of 15 μg/L and a final concentration of less than the sample detection limit of 0.31 μg/L. Lower perchlorate concentration reductions ranging from 4 percent to 36 percent were observed in the samples collected from monitoring well LVWPS-A2-MW14B, with concentrations ranging from 1,800 μg/L to 2,800 μg/L (same as the baseline concentration). As previously explained, these results correlate with the difference in groundwater flow rates between the shallow and deep alluvium of approximately 4 ft/day and 88 ft/day, respectively, which likely does not allow sufficient residence time for complete degradation of perchlorate in the deep alluvium.
  - Immediately following the third injection event, perchlorate concentration reductions were 65 percent (1,200 μg/L compared to a baseline concentration of 3,400 μg/L) and 43 percent (910 μg/L compared to a baseline concentration of 1,600 μg/L) in samples collected from monitoring wells LVWPS-A2-MW09A and LVWPS-A2-MW09B, respectively (Appendix L, Figures L.44 and L.45). Similar to the response after the second injection event, these initial reductions were not sustained over multiple sampling events, with final concentrations of 2,700 μg/L and 1,800 μg/L in samples collected from LVWPS-A2-MW09A and LVWPS-A2-MW09B, respectively. As previously explained in Sections 7.7.1.1.2 and 7.7.1.1.3, this monitoring well cluster is on the eastern edge

of the study area and therefore, is likely impacted by groundwater migrating into the Zone 2 study area that does not pass through the biologically active zone in the vicinity of the injection well transect.

- Groundwater sampling results during Months 11 through 18 in samples from the four monitoring well clusters located approximately 100 feet downgradient of the injection well transect (LVWPS-A2-MW11A/B/C, LVWPS-A2-MW12A/B, LVWPS-A2-MW13A/B, and LVWPS-A2-MW17A/B/C) generally indicated similar concentration trends as the results following the first and second injection events. Noteworthy results from the samples collected from each of these monitoring well clusters following the third injection event are provided below.
  - Results from the samples collected from the monitoring well cluster LVWPS-A2-MW11A/B/C continued to indicate minimal reductions (ranging from 0 percent to 35 percent) (Appendix L, Figures L.53 through L.55), which is likely due to this monitoring well cluster being located west of the paleochannel and not downgradient of the injection well transect based on a review of groundwater flow directions presented in **Figures 7a and 7b**. Perchlorate concentrations during the final Month 18 sampling event were similar to baseline concentrations in samples collected from all wells within the LVWPS-A2-MW11A/B/C cluster.
  - Perchlorate concentration reductions continued to be greater in samples collected from deep alluvial monitoring well LVWPS-A2-MW17C compared to shallow alluvium wells LVWPS-A2-MW17A and LVWPS-A2-MW17B (Appendix L, Figures L.46 through L.48). However, perchlorate concentration reductions were less pronounced in samples collected from deep alluvial monitoring well LVWPS-A2-MW17C following the third injection event compared to previous injection events. Specifically, perchlorate concentrations ranged from 640 μg/L to 1,300 μg/L, representing reductions of 41 percent to 71 percent following the third injection event compared to reductions ranging from 80 percent to greater than 99 percent following the second injection event. However, concentrations in samples collected from LVWPS-A2-MW17C began reducing in the final three months of the Pilot Study, with the lowest concentration of 640 μg/L detected in the final sample collected from this monitoring well. Although perchlorate concentrations were reduced when compared to baseline concentrations in samples collected from monitoring wells LVWPS-A2-MW17A and LVWPS-A2-MW17B, reductions were much lower, with reductions ranging from 8 percent to 44 percent and final concentrations eight months following the third injection event at levels similar to baseline concentrations.
  - Similar to the results following the first and second injection events, perchlorate concentration reductions ranging from 43 percent to greater than 99 percent were observed in samples collected from monitoring well cluster LVWPS-A2-MW12A/B during Months 11 through 18 (Appendix L, Figures L.49 and L.50). Once again, perchlorate concentrations in samples from monitoring well LVWPS-A2-MW12A reduced to below the PRG of 15 μg/L in all sampling events following the third injection event, including the final sampling event occurring approximately eight months following the third injection event. Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-A2-MW12B also significantly reduced from a baseline concentration of 4,000 μg/L to concentrations ranging from 720 μg/L to a final concentration of 2,300 μg/L.
  - Perchlorate concentration reductions continued to be observed in samples collected from both LVWPS-A2-MW13A and LVWPS-A2-MW13B (Appendix L, Figures L. 51 and L. 52). Although perchlorate concentrations were reduced by 48 percent in the Month 11 sampling event (first sampling event following the third injection event) in samples collected from shallow alluvial monitoring well LVWPS-A2-MW13A, perchlorate concentrations began to steadily increase for the remainder of the Pilot Study, with a concentration of 1,800 μg/L (slightly greater than baseline) during the final Month 18 sampling event. Perchlorate concentration reductions

continued to be significant in samples collected from the deep alluvial monitoring well LVWPS-A2-MW13B, with an average concentration reduction of 78 percent following the third injection event. Perchlorate concentrations in samples collected from deep alluvial monitoring well LVWPS-A2-MW13B reduced from a baseline concentration of 2,200 μg/L to concentrations ranging from 150 μg/L to a final concentration of 670 μg/L.

- Of the two monitoring well clusters located approximately 200 feet downgradient of the injection well transect (namely, LVWPS-MW208A/B and LVWPS-MW223A/B), results from samples collected from both deep alluvial monitoring wells LVWPS-MW208B and LVWPS-223B continued to indicate significant perchlorate concentration reductions ranging from 14 percent to greater than 99 percent (Appendix L, Figures L.56 through L.59). Perchlorate concentration reductions were the most prominent in samples collected from LVWPS-MW223B, in which the final perchlorate concentration was 44 μg/L (lowest to date) compared to a baseline concentration of 3,300 μg/L. Perchlorate concentration reductions ranged from 14 percent to 68 percent in samples collected from LVWPS-MW208B following the third injection event, which was less reduction than observed following previous injection events. Additionally, the lowest perchlorate concentration of 670 μg/L was detected immediately following the third injection event, with concentrations generally increasing for the remainder of the Pilot Study, with a final concentration of 1,800 μg/L. This result correlates to the lack of TOC concentration increases following the second and third injection events (previously slightly increased to 11 mg/L following the first injection event).
- Results of the samples collected from monitoring wells located at distances greater than 200 feet in either the cross-gradient or downgradient direction were similar following the third injection event compared to the results following the first and second injection events. Specifically, perchlorate concentration reductions averaged approximately 17 percent in samples collected from monitoring well clusters LVWPS-A2-MW15A/B and LVWPS-A2-MW16A/B (Appendix L, Figures L.60 through L.63). Results also indicated consistent perchlorate concentration reductions ranging from 20 percent to 61 percent in samples collected from monitoring wells LVWPS-MW211, LVWPS-MW218A, and LVWPS-MW221A (Appendix L, Figures L.64, L.68, and L.72). The most notable reduction of 61 percent was observed in the Month 11 sample collected from shallow alluvial monitoring well LVWPS-MW221A, with a concentration of 390 μg/L compared to a baseline concentration of 990 μg/L. Perchlorate concentrations in samples collected from LVWPS-MW218A also reduced by 47 percent during the Month 12 sampling event with a concentration of 2,700 μg/L compared to a baseline concentration of 5,100 μg/L. Final Pilot Study concentrations in samples collected from these wells indicated a continued reduction ranging from 20 to 41 percent compared to baseline concentrations.

7.7.1.2 Perchlorate Degradation Response in the UMCf

This section provides a summary of the baseline conditions and subsequent perchlorate degradation response that was observed following each injection event into the UMCf summarized in Section 7.3. Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages. ***Table 6Table 4*** summarizes the average perchlorate concentration reduction in groundwater observed in monitoring wells located upgradient and downgradient of the injection well transect throughout the study duration. Analytical data used in the calculations for concentration changes during the Pilot Study are presented in Table J.1. A detailed summary of percentage change in perchlorate concentrations compared to baseline concentrations for all Zone 2 monitoring wells screened in the UMCf is provided in Appendix J, Table J.6.

Table 6 Zone 2 UMCf Perchlorate Concentration Changes During Pilot Study

Sampling Event	Event Description	Monitoring Well Location							
		60 Feet Upgradient of Injection Well Transect		12 Feet Cross-gradient of Injection Well Transect		25 to 50 Feet Downgradient of Injection Well Transect		100 – 200 Feet Downgradient of Injection Well Transect	
		No. of Wells = 3		No. of Wells = 2		No. of Wells = 5		No. of Wells = 3	
		Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
After Injection Event 1	Month 1	-18%	-76%	-99%	-99%	-18%	-33%	-60%	-99%
	Month 2	-11%	-44%	-99%	-99%	-22%	-34%	-42%	-56%
	Month 3	-20%	-93%	-99%	-99%	-18%	-39%	-36%	-53%
	Month 4	0%	-31%	-99%	-99%	-29%	-83%	-33%	-51%
	Month 6	-4%	-56%	-99%	-99%	5%	-43%	-30%	-56%
	Month 8	15%	-25%	-99%	-99%	-6%	-48%	-19%	-37%
After Injection Event 2	Month 11	-55%	-100%	-99%	-99%	-54%	-99%	-51%	-75%
	Month 12	-28%	-100%	-99%	-99%	-43%	-99%	-24%	-56%
	Month 13	-61%	-100%	-99%	-99%	-43%	-99%	-37%	-63%
	Month 14	-34%	-100%	-98%	-99%	-36%	-89%	-46%	-74%
	Month 16	-33%	-100%	-99%	-99%	-40%	-95%	-42%	-67%
	Month 18	-30%	-99%	-99%	-99%	-39%	-99%	-37%	-72%

Notes:
1. Percentage change in perchlorate concentration is calculated relative to the pre-injection baseline groundwater sampling event in September/October 2020 (labeled as event BL04 in Appendix J, Table J.1). Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages.
2. The calculation for average concentration change accounts for both increases and decreases in concentrations compared to baseline.
3. The maximum change shown is the most significant reduction in concentration as represented by the most negative percentage calculated.

7.7.1.2.1 Baseline Groundwater Results

Groundwater samples were collected from Zone 2 monitoring wells screened in the UMCf in September/October 2020 as part of baseline sampling activities. Perchlorate concentrations in groundwater ranged from 160 μg/L to 12,000 μg/L in the UMCf. The highest detection in the UMCf of 12,000 μg/L was measured in a groundwater sample collected from LVWPS-U2-MW09, which was located approximately 50 feet downgradient of the injection well transect in the far eastern portion of the Zone 2 study area and screened in the UMCf from 85 to 105 feet bgs.

7.7.1.2.2 Perchlorate Degradation Response Following Injection Event 1

Following completion of the first injection event in December 2020, groundwater sampling was performed on a monthly basis for the first two months, followed by monthly thereafter. This pattern resulted in six groundwater sampling events being conducted during Months 1 through 8. Groundwater samples were collected from all monitoring wells screened in the UMCf (as described in Section 7.2.2) to monitor for potential contaminant concentration reductions as a result of ISB injections into the UMCf within the Zone 2 study area. Results following the first injection event are summarized below.

- Perchlorate concentration reductions of up to 93 percent were observed in samples collected from one of the three upgradient monitoring wells screened in the UMCf, namely, LVWPS-U2-MW01 (Appendix L, Figures L.75 through L.77). Specifically, perchlorate concentrations reduced from a baseline concentration of 360 μg/L to a Month 1 concentration of 85 μg/L and then a Month 3 concentration of 26 μg/L, before slowly increasing to a Month 8 concentration of 270 μg/L. Similar to the upgradient response observed in the Zone 1 study area (discussed in Section 6.7.1), this upgradient response was expected at some locations due to the low effective porosities observed and calculated during injection activities discussed in Section 7.3. Low effective porosity can cause the injectate solution to move farther from the injection points (both upgradient and downgradient) during injections, particularly when injecting under pressure. Perchlorate concentrations in the remaining two upgradient monitoring wells remained near or above baseline concentrations. Perchlorate concentrations in groundwater samples collected from LVWPS-U2-MW02 ranged from 5,600 μg/L to 8,300 μg/L following the first injection event, an increase compared to a baseline concentration of 5,200 μg/L, while perchlorate concentrations in groundwater samples collected from LVWPS-U2-MW03 ranged from 1,800 μg/L to 2,500 μg/L compared to a baseline concentration of 2,100 μg/L.
- Samples were collected from two cross-gradient monitoring wells located approximately 12 feet from either end of the injection well transect (LVWPS-U2-MW04 and LVWPS-U2-MW05). Perchlorate concentrations were reduced to below the PRG of 15 μg/L in all samples collected from both monitoring wells following the first injection event (Appendix L, Figures L.78 and L.79). Specifically, perchlorate concentrations reduced from baseline concentrations of 160 μg/L and 9,300 μg/L in samples collected from LVWPS-U2-MW04 and LVWPS-U2-MW05, respectively, to less than 0.31 μg/L in samples collected from both wells. This data also correlates with the elevated TOC concentrations of up to 1,100 mg/L (compared to a pre-injection concentration of 0.41 mg/L) indicating the presence of the injectate solution in samples collected from these monitoring wells following the first injection event (discussed in Section 7.7.4.2).
- Groundwater samples were collected from the two monitoring wells located approximately 25 feet downgradient of the injection well transect following the first injection event (LVWPS-U2-MW06 and LVWPS-U2-MW18) (Appendix L, Figures L.80 and L.81). Perchlorate concentrations in samples collected from monitoring well LVWPS-U2-MW18, which is located on the eastern side of the study area, ranged from 4,400 μg/L to 5,800 μg/L compared to a baseline concentration of 8,400 μg/L, representing reductions ranging from 29 percent to 48 percent. Perchlorate concentration reductions were not observed in samples collected from monitoring well LVWPS-U2-MW06, which was located on western

side of the study area and screened in the UMCf from approximately 122 feet bgs to 142 feet bgs in the portion of the UMCf that underlies the paleochannel centerline. The lack of response at monitoring well LVWPS-U2-MW06 following the first injection event is likely due to the lower permeability of the UMCf at this location. Baseline slug testing indicated that the hydraulic conductivity of the UMCf at monitoring wells LVWPS-U2-MW06 and LVWPS-U2-MW18 measured 0.1 ft/day and 1.9 ft/day, respectively.

- Perchlorate concentrations reduced by an average of 15 percent in samples collected from the three monitoring wells located approximately 50 feet downgradient of the injection well transect (namely, LVWPS-U2-MW08, LVWPS-U2-MW09, and LVWPS-U2-MW14) (Appendix L, Figures L.82 through L.84). Although relatively minor, it was not expected to see these reductions following the first injection event given the average groundwater flow rate was 0.15 ft/day in these monitoring wells, which equates to more than 300 days travel time from the injection well transect. Only minimal initial reductions were observed in the samples collected from LVWPS-U2-MW08, which was not unanticipated due to the location of this monitoring well and the northeastern groundwater flow direction within the western side of the study area that likely results in perchlorate-contaminated groundwater migrating into the Zone 2 study area that does not pass through the biologically active zone near the injection well transect (**Figure 7c**). Samples collected from monitoring well LVWPS-U2-MW09 indicated perchlorate concentration reductions ranging from 17 percent to up to 83 percent following the first injection event, with concentrations as low as 2,000 μg/L during the Month 4 sampling event compared to a baseline concentration of 12,000 μg/L. However, perchlorate concentrations increased to above baseline by Month 8. Similar to LVWPS-U2-MW08, this monitoring well was located along the edge of the study area, which likely results in perchlorate-contaminated groundwater migrating into the area that does not pass through the injection well transect.
- Groundwater samples were collected from two monitoring wells located approximately 100 feet downgradient of the injection well transect (LVWPS-U2-MW12 and LVWPS-U2-MW17) and one monitoring well located approximately 200 feet downgradient of the injection well transect (LVWPS-MW223C). Unexpectedly, perchlorate concentrations reduced in samples collected from all three monitoring wells, with reductions ranging from 9 percent to greater than 99 percent (Appendix L. Figures L.85 through L.87). The most prominent reduction was observed in the Month 1 sample collected from LVWPS-MW223C, which indicated a reduction from a baseline concentration of 5,700 μg/L to a Month 1 concentration of 46 μg/L. Although this level of reduction was not sustained, perchlorate concentration reductions continued in samples collected from this well, with an average reduction of 50 percent (concentrations ranging from 2,500 μg/L to 3,600 μg/L) in the subsequent sampling events. Lastly, a 60 percent reduction in perchlorate concentrations was also observed in the Month 1 sample collected from LVWPS-U2-MW17 (concentration of 1,800 μg/L compared to a baseline concentration of 4,500 μg/L). This result correlated with an initial increase in TOC concentration, indicating the presence of the injectate solution at this far downgradient location. However, concentrations slowly returned to baseline levels by the Month 8 sampling event.

7.7.1.2.3 Perchlorate Degradation Response Following Injection Event 2

Following completion of the second injection event in October 2021, groundwater sampling was performed on a monthly basis for the first two months, followed by monthly thereafter. This pattern resulted in six groundwater sampling events being conducted during Months 11 through 18. Groundwater samples were collected from all monitoring wells screened in the UMCf (as described in Section 7.2.2) to monitor for potential contaminant concentration reductions as a result of ISB injections into the UMCf within the Zone 2 study area. Results following the second injection event are summarized below.

- Following the second injection event, more extensive perchlorate concentration reductions were observed upgradient of the injection well transect compared to the first injection event (Appendix L, Figures L.75 through L.77). Perchlorate concentration reductions of greater than 99 percent were observed in samples collected from two of the three upgradient monitoring wells (LVWPS-U2-MW01 and LVWPS-U2-MW02).

Perchlorate concentrations were also detected at concentrations that were equal to or below the PRG of 15 μg/L in four of the six samples collected from LVWPS-U2-MW02, with a final concentration of 61 μg/L (compared to a baseline concentration of 5,200 μg/L). As previously described, this upgradient response was expected at some locations due to the low effective porosities observed during injection activities discussed in Section 7.3.2. Perchlorate concentrations in the samples collected from the remaining upgradient monitoring well LVWPS-U2-MW03 remained near or above baseline concentrations, ranging from 1,800 μg/L to 2,800 μg/L compared to the baseline concentration of 2,100 μg/L.

- Samples collected from the two cross-gradient monitoring wells located approximately 12 feet from either end of the injection well transect (LVWPS-U2-MW04 and LVWPS-US2-MW05) continued to indicate perchlorate concentrations below the PRG of 15 μg/L in all but one sample collected from both monitoring wells following the second injection event (Appendix L, Figures L.78 and L.79). This data also continued to correlate with the elevated TOC concentrations (discussed in Section 7.7.4.2) indicating the presence of the injectate solution in samples collected from these monitoring wells.
- Following the second injection event, perchlorate concentration reductions improved in the groundwater samples collected from the two monitoring wells located approximately 25 feet downgradient of the injection well transect (LVWPS-U2-MW06 and LVWPS-U2-MW18; Appendix L, Figures L.80 and L.81). Perchlorate concentration reductions ranged from 89 percent to greater than 99 percent in samples collected from monitoring well LVWPS-U2-MW18 when compared to baseline concentrations. The lowest perchlorate concentration of 21 μg/L was detected in the sample collected during the Month 13 sampling event, with the second lowest perchlorate concentration of 34 μg/L detected in the final Month 18 sampling event. These concentrations represent a greater than 99 percent concentration reduction when compared to the baseline concentration of 8,400 μg/L. As discussed in Section 7.7.7, microbial analyses at this location indicated the presence of the perchlorate reducing enzyme at 10^4 levels, which is indicative of a robust perchlorate reducing microbial population. Although minimal reductions were observed following the first injection event, perchlorate concentrations in samples collected from LVWPS-U2-MW06 reduced to 2,300 μg/L immediately following the second injection event, which represents a 44 percent reduction compared to the baseline concentration of 4,100 μg/L. As discussed in Section 7.7.7, microbial analyses at this location indicated a doubling of the percentage of fermenters in groundwater, which trigger the supply of carbon that is useable to native microorganism during perchlorate biodegradation. Additionally, microbial analyses indicated an order of magnitude increase in biomass populations to 10^5 levels, indicating the presence of a robust microbial population. Perchlorate concentrations in samples collected from this well generally increased in subsequent events, with a final concentration of 3,500 μg/L (slightly below baseline of 4,100 μg/L).
- The overall average perchlorate concentration reduction doubled following the second injection event in samples collected from the three monitoring wells located approximately 50 feet downgradient of the injection well transect (namely, LVWPS-U2-MW08, LVWPS-U2-MW09, and LVWPS-U2-MW14) (Appendix L, Figures L.82 through L.84). Perchlorate concentration reductions were the most pronounced in the samples collected from LVWPS-U2-MW14, which is located in the center of the study area. Perchlorate concentration reductions averaged approximately 71 percent following the second injection event compared to an average reduction of 15 percent following the first injection event. Perchlorate concentrations in samples collected from LVWPS-U2-MW14 reduced from a baseline concentration of 11,000 μg/L to a low concentration of 160 μg/L in the Month 11 sampling event (immediately following the second injection event). This improved response was expected during the later months of the Pilot Study in this farther downgradient location due to the low groundwater flow rate estimate at 0.19 ft/day in this monitoring well, which equates to an approximate travel time of approximately nine months following injections. Although perchlorate concentrations remained significantly reduced in samples collected from LVWPS-U2-MW14, perchlorate concentrations increased for the remainder of the Pilot Study, with a final concentration of 4,900 μg/L (representing 55 percent reduction). Perchlorate concentration reductions averaged 27 percent in samples collected from LVWPS-U2-MW09, with the lowest concentration of 8,000

μg/L detected in the final sample (reduction of 33 percent compared to a baseline concentration of 12,000 μg/L. Perchlorate concentrations were generally not observed in samples collected from LVWPS-U2-MW08. As previously explained, these wells were located in areas where perchlorate-contaminated groundwater likely migrates into the Zone 2 study area that does not pass through the biologically active zone near the injection well transect (**Figure 7c**).

- Groundwater samples collected from the two monitoring wells located approximately 100 feet downgradient of the injection well transect (LVWPS-U2-MW12 and LVWPS-U2-MW17) and the monitoring well located approximately 200 feet downgradient of the injection well transect (LVWPS-MW223C) continued to indicate the same level of perchlorate concentration reductions that were observed following the first injection event (i.e., 25 percent average reduction in samples collected from LVWPS-U2-MW12 and LVWPS-U2-MW17 and 68 percent average reduction in samples collected from LVWPS-U2-MW223C) (Appendix L, Figures L.85 through L.87). The most prominent reductions were observed in samples collected from LVWPS-MW223C, with concentrations ranging from 1,400 μg/L to 2,500 μg/L compared to a baseline concentration of 5,700 μg/L. These reduced concentrations were generally sustained in the final months of the Pilot Study, with a final concentration of 1,600 μg/L (representing a 72 percent reduction). Additionally, perchlorate concentrations reduced in samples collected from LVWPS-U2-MW12, with the lowest perchlorate concentration of 4,900 μg/L detected in the final Month 18 sampling event (representing a 44 percent reduction compared to a baseline concentration of 8,800 μg/L).

7.7.1.3 Estimate of Perchlorate Distribution

Figures 13a-d, 14a-d, and 15a-c present perchlorate plume isoconcentration contour interpretations during the Pilot Study for the shallow alluvium present from 35 to 60 feet bgs, deep alluvium present from 60 to 100 feet bgs, and the underlying UMCf present from 83 to 141.5 feet bgs within the Zone 2 study area, respectively. As previously explained, the baseline event in October 2020 is intended to represent pre-injection perchlorate concentrations in groundwater within the vicinity of the Zone 2 study area, followed by depictions of subsequent sampling events occurring post-injection. These figures illustrate the creation and sustainment of a biologically active treatment zone following each injection event, with perchlorate concentrations in groundwater within both the shallow and deep alluvium and the UMCf reduced to below 15 μg/L at multiple locations. As illustrated in the isoconcentration maps on **Figures 13a-d and 14a-d**, perchlorate concentrations below the PRG of 15 μg/L extend farther downgradient in the shallow alluvium compared to the deep alluvium. However, a more widespread overall reduction in perchlorate concentrations was observed in the deep alluvium compared to the shallow alluvium. These results are consistent with the hydrogeology of the alluvium discussed in Sections 7.5 and 7.6, which indicate that groundwater flow rates within the alluvium generally increase with depth. Estimated flow velocities for monitoring wells screened in the shallow alluvium averaged approximately 12 ft/day whereas estimated flow velocities in the deep alluvium averaged 55 ft/day. Based on these flow rates, it would be expected that the reductions would be greater and longer lasting in the shallow alluvium compared to the deep alluvium, which has an elevated groundwater flow rate that may not always allow for sufficient residence time for complete degradation of perchlorate.

Figures 15a-c, which present the perchlorate isoconcentration contours for the UMCf during the Pilot Study, show that the biologically active zone extended upgradient from the injection well transect, similar to the response in the Zone 1 UMCf. Extension of the biologically active zone upgradient in the UMCf but not the alluvium was expected due to the more transmissive nature of the alluvial sediments compared to the UMCf. In addition, significant perchlorate concentration reductions were observed in the UMCf but were not as widespread or as far downgradient as observed in the alluvium. The comparisons presented in **Figures 15a-c** show reductions in perchlorate concentrations in the immediate vicinity of the injection well transect with significant reductions extending approximately 25 feet downgradient following the first injection event and 100 feet downgradient following the second injection event. This improved response farther downgradient was expected during the later months of the Pilot Study due to the low groundwater flow rate estimate of 0.2 ft/day for the UMCf within the Zone 2 study area. Based on this groundwater flow rate, influence from ISB would be expected to be observed approximately 110 feet downgradient under the natural gradient of the formation by the end of the 18-month Pilot Study.

Perchlorate concentrations in the UMCf reduced significantly following the first injection event in samples collected from select monitoring wells located farther downgradient in the vicinity of the approximate paleochannel centerline (**Figure 15a**). As discussed in Section 7.7.1.2.2, these results correlated with an initial increase in TOC concentration, indicating the presence of the injectate solution. The deep paleochannel eroded into the surface of the UMCf in the western portion of the injection well transect allows the potential for cross-connecting flow between the alluvium and the UMCf in Zone 2. Exposure of bedding planes through erosion during deposition of the alluvium means that groundwater flow in the UMCf following those bedding planes can easily discharge into the alluvium abutting them. Furthermore, vertical gradients both within the alluvium and between the alluvium and the UMCf ranged from 0.01 ft/ft upward to 0.03 ft/ft downward, depending on the exact lithology and structure in the area. As a result, some migration of water from the UMCf into the alluvium and from the alluvium into the UMCf in the Zone 2 study area is expected.

As explained in Sections 7.7.1.1 and 7.7.1.2, some areas within the treatment zone had less reduction in perchlorate concentrations, which is likely due to the heterogeneous nature of the subsurface, localized preferential flow paths and groundwater that did not flow through the relatively short injection well transect migrating into farther downgradient portions of the Zone 2 study area. While acknowledging that the design of the Pilot Study was compact and specific to meet the study objectives, the design of a full-scale remedy would be significantly different, and if selected as a component of the NERT final remedy, the injection well transect would likely extend across a much larger distance and potentially include multiple injection well transects to achieve a more uniform biologically active treatment zone.

7.7.1.4 Estimation of Perchlorate Mass Removal

The mass flux of perchlorate passing through the Zone 2 study area was estimated for baseline and subsequent post-injection sampling events using the methods previously described in Section 6.7.1.3 to determine the reduction in perchlorate mass following injections. The resultant estimates for flux of perchlorate mass removed and perchlorate mass removed for each sampling event are provided in Appendix M, Table M.1. Using this calculation process, an estimated total of 1,650 pounds of perchlorate was destroyed from the groundwater in the Zone 2 study area during the Pilot Study. It is estimated that of the 1,650 pounds of perchlorate destroyed, 1,598 pounds of perchlorate were destroyed in the alluvium, with the remaining 52 pounds of perchlorate destroyed in the UMCf. For comparison, the mass destroyed within the Zone 2 study area was significantly more than the mass destroyed in the Zones 1 and 3 study areas. This result was due to the alluvium treatment in the Zone 2 study area, which was the targeted interval where the majority of the mass was destroyed due to the substantially higher flow rates resulting in more mass flux through the treatment zone. When comparing the mass destroyed within the Zone 2 UMCf to the mass destroyed in the UMCf and UMCf-cg in the Zones 1 and 3 study areas, the mass destroyed in the Zone 2 UMCf was more than the Zone 1 study area but less than the Zone 3 study area (i.e., 52 pounds in Zone 2 compared to 25 pounds in Zone 1 and 86 pounds in Zone 3).

7.7.2 Chlorate

Chlorate is present in groundwater within the Zone 2 study area at concentrations that are often slightly higher than those of perchlorate. As previously explained, chlorate is also amenable to anaerobic biodegradation, similar to perchlorate. Chlorate concentrations are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.28 through L.87. Chlorate results from the Pilot Study for the alluvium and UMCf are summarized in Sections 7.7.2.1 and 7.7.2.2, respectively.

7.7.2.1 Chlorate in the Alluvium

Chlorate concentrations in groundwater were measured during baseline and ranged from 200 µg/L to 14,000 µg/L in the alluvium, with results generally consistent in both the shallow and deep alluvium. The highest baseline chlorate concentrations were measured in groundwater samples collected from shallow alluvial monitoring well LVWPS-MW207 and deep alluvial monitoring well LVWPS-MW218A, both of which are located more than 400 feet downgradient of the Zone 2 injection well transect. Of the monitoring wells located within 250 feet of the injection well transect, chlorate concentrations were the highest in the sample collected from deep alluvial monitoring well LVWPS-A2-MW11C, with a chlorate detection of 11,000 µg/L. In general, chlorate concentration trends followed a similar or better reducing pattern as the perchlorate concentration trends throughout the Pilot Study timeframe (discussed in Section 7.7.1.1). Noteworthy chlorate results from the Pilot Study are summarized below.

- Samples collected from all four cross-gradient monitoring wells exhibited substantial chlorate concentration decreases during the Pilot Study (Appendix L, Figures L.35 through L.38). Similar to the perchlorate concentration reductions, results were initially the best in samples collected from the LVWPS-A2-MW05A/B monitoring well cluster located on the eastern side of the injection well transect. However, over time, chlorate concentrations reductions improved in the samples collected from the LVWPS-A2-MW04A/B monitoring well cluster. The average chlorate concentration reduction in samples collected from all four monitoring wells following the first injection event was approximately 59 percent, with chlorate concentrations below the sample detection limit in all samples collected from LVWPS-A2-MW05B compared to a baseline concentration of 2,300 µg/L. Reductions improved following the second injection event, with an overall average reduction of 73 percent, which included concentrations below detection limits in multiple samples collected from LVWPS-A2-MW04B and LVWPS-A2-MW05B. Immediately following the third injection event (Month 11 sampling event), samples from the four cross-gradient monitoring wells indicated chlorate concentrations ranging from 91 percent to greater than 99 percent. This reducing trend continued through the end of the Pilot Study, with an overall average chlorate concentration reduction of 93 percent following the third injection event. Chlorate concentrations were detected below sample detection limits in 21 samples collected from the cross-gradient monitoring wells during the Pilot Study. The final Month 18 sampling event indicated concentrations less than sample detection limits in samples collected from LVWPS-A2-MW05A and LVWPS-A2-MW05B (compared to baseline concentrations of 3,900 µg/L and 2,300 µg/L, respectively). Chlorate concentrations in the samples collected from the LVWPS-A2-MW04A/B cluster also remained significantly reduced with concentrations of 1,100 µg/L and 57 µg/L during the final Month 18 sampling event compared to baseline concentration of 5,300 µg/L and 7,300 µg/L, respectively.
- Samples collected from all seven monitoring wells located approximately 50 feet downgradient of the injection well transect (LVWPS-A2-MW08A, LVWPS-A2-MW08B, LVWPS-A2-MW08C, LVWPS-A2-MW09A, LVWPS-A2-MW09B, LVWPS-A2-MW14A, and LVWPS-A2-MW14B) exhibited a reduction in chlorate concentrations during the Pilot Study (Appendix L, Figures L.38 through L.45). Chlorate concentration reductions initially ranged from 5 to greater than 99 percent during the Month 1 sampling event following the first injection event. By the end of the Pilot Study, chlorate concentrations had reduced to below sample detection limits in samples collected from all monitoring wells at some point during the study, with the majority of these greater than 99 percent reductions occurring following the third injection event. Of the 56 samples collected following the third injection event from these seven monitoring wells, results from 38 of the samples indicated chlorate concentrations below 50 µg/L (compared to an average baseline concentration of 4,814 µg/L). There are a few notable differences when comparing chlorate concentration trends to perchlorate concentration trends. Although perchlorate concentrations in samples collected from monitoring well cluster LVWPS-A2-MW09A/B were generally low (average of 20 percent reduction during the Pilot Study), chlorate concentrations reductions improved throughout the study, with the last six sampling events indicating chlorate concentration reductions greater than 98 percent and

majority of the samples at concentrations below sample detection limits (compared to baseline concentrations of 5,500 μg/L and 2,100 μg/L for LVWPS-A2-MW09A and LVWPS-A2-MW09B, respectively). Similar trends were also observed in samples collected from LVWPS-A2-MW08A, with concentrations reducing from a baseline concentration of 2,100 μg/L to less than the sample detection limit in the final six sampling events. These differences may be attributed to the elevated groundwater flow rates and position of these wells along the far eastern and western portions of the study area, which may not allow sufficient residence time for complete degradation of perchlorate but does allow for complete chlorate degradation. As previously explained, chlorate biodegradation typically precedes perchlorate biodegradation.

- Chlorate concentration reductions of greater than 99 percent were consistently achieved in samples collected from seven of the ten monitoring wells located approximately 100 feet downgradient from the injection well transect (i.e., monitoring well clusters LVWPS-A2-MW12A/B, LVWPS-A2-MW13A/B, and LVWPS-A2-MW17A/B/C) (Appendix L, Figures L.46 through L.52). The majority of these samples indicated chlorate concentrations below sample detection limits following the third injection event compared to baseline concentrations ranging from 2,100 μg/L to 5,700 μg/L. Chlorate concentration reductions were minimal in samples collected from monitoring well cluster LVWPS-A2-MW11A/B/C, also located approximately 100 feet from the injection well transect, which is similar to perchlorate. This was likely due to the location of this monitoring well cluster being west of the paleochannel and not downgradient of the injection well transect based on a review of groundwater flow directions presented in **Figures 7a and 7b** (Appendix L, Figures L.53 through L.55).
- Of the two monitoring well clusters located approximately 200 feet downgradient of the injection well transect, results of samples collected from LVWPS-MW223A, LVWPS-MW223B, and LVWPS-MW208A indicated chlorate concentration reductions greater than 99 percent (compared to an average baseline concentration of 4,967 μg/L) during multiple sampling events, including in all samples collected during the last seven months of the Pilot Study (Appendix L, Figures L.56 through L.59).
- Noteworthy sample results from remaining monitoring wells located greater than 200 feet in either the cross-gradient or downgradient direction are summarized below.
    - Similar to perchlorate, samples collected from monitoring well clusters LVWPS-A2-MW15A/B and LVWPS-A2-MW16A/B, which are located west of the paleochannel and approximately 200 and 350 feet downgradient of the injection well transect, respectively, indicated chlorate concentration reductions generally averaging 10 percent, with individual reductions of up to 50 percent (Appendix L, Figures L.60 through L.63).
    - Chlorate concentrations reduced from a baseline concentration of 3,200 μg/L to less than sample detection limits during the last six months of the Pilot Study in the samples collected from monitoring well LVWPS-MW211, which is located approximately 650 feet downgradient of the injection well transect (Appendix L. Figure L.68).
    - Reductions ranging from 22 percent to greater than 99 percent were observed in samples collected from monitoring well LVWPS-MW209A, which is located approximately 625 feet downgradient of the injection well transect along the approximate location of the paleochannel centerline (Appendix L, Figure L.71). Perchlorate concentrations in samples collected from monitoring well LVWPS-MW209A were less than 150 μg/L in the final two sampling events (compared to a baseline concentration of 6,800 μg/L).
- Lastly, chlorate concentration reductions of up to 71 percent and 99 percent were observed in samples collected from upgradient monitoring wells LVWPS-A2-MW01A and LVWPS-A2-MW01B, respectively, following the third injection event (Appendix L, Figures L.29 and L.30). Chlorate reductions were most prominent in samples collected from LVWPS-A2-MW01B, with a final concentration of 30 μg/L compared to a baseline concentration of 5,200 μg/L. Although TOC concentrations were not elevated in samples collected from the LVWPS-A2-MW01A/B cluster, groundwater geochemical data indicate a slight shift

from aerobic to anaerobic conditions in this vicinity following the third injection event, which may be related to overall reducing conditions present in the vicinity of the injection well transect.

7.7.2.2 Chlorate in the UMCf

Chlorate concentrations in groundwater were measured during baseline and ranged from 260 µg/L to 18,000 µg/L in the UMCf. The highest baseline chlorate concentration was measured in the groundwater sample collected from LVWPS-U2-MW09, which is located more than 50 feet downgradient of the Zone 2 injection well transect. In general, chlorate concentration trends followed a similar or better reducing pattern as the perchlorate concentration trends throughout the Pilot Study timeframe (discussed in Section 7.7.1.2). Noteworthy chlorate results from the Pilot Study are summarized below.

- Chlorate concentration reductions of greater than 99 percent were observed in samples collected from upgradient monitoring well LVWPS-U2-MW01 following the first injection event. Following the second injection event, chlorate concentration reductions of greater than 99 percent were observed in samples collected from upgradient monitoring wells LVWPS-U2-MW01 and LVWPS-U2-MW02 (Appendix L, Figures L.75 and L.76). The most prominent reduction was observed in the samples collected from LVWPS-U2-MW02, with the results from the final five sampling events indicating concentrations below sample detection limits compared to a baseline concentration of 8,300 µg/L. As previously explained, low effective porosity can cause the injectate solution to move farther from the injection points (both upgradient and downgradient) during injections, particularly when injecting under pressure.
- Results from samples collected from the two cross-gradient monitoring wells located approximately 12 feet from either end of the injection well transect (LVWPS-U2-MW04 and LVWPS-U2-MW05) indicated chlorate concentrations below detection limits in 21 of the 24 samples collected throughout the Pilot Study (Appendix L, Figures L.78 and L.79).
- Results from the groundwater samples collected from the two monitoring wells located approximately 25 feet downgradient of the injection well transect (LVWPS-U2-MW06 and LVWPS-U2-MW18) indicated greater concentration reductions than perchlorate (Appendix L, Figures L.80 and L.81). Although perchlorate concentration reductions were not observed in samples collected from LVWPS-U2-MW06, chlorate concentrations were reduced in every sampling event, with reductions of up to 47 percent following the second injection event (3,900 µg/L in Month 14 compared to a baseline concentration of 7,300 µg/L). Chlorate concentrations reduced by greater than 99 percent in samples collected from monitoring well LVWPS-U2-MW18, with concentrations less than sample detection limit of 24 µg/L during the last five sampling events of the Pilot Study (compared to a baseline concentration of 10,000 µg/L).
- Chlorate concentrations reduced by an average of 18 percent in the samples collected from monitoring well LVWPS-U2-MW09, which is located approximately 50 feet downgradient of the injection well transect (Appendix L, Figure L.84). The final chlorate concentration in the sample collected from LVWPS-U2-MW09 measured 14,000 µg/L, which represents a reduction of 22 percent compared to a baseline concentration of 18,000 µg/L. Although perchlorate concentration reductions were consistently observed in the samples collected from LVWPS-U2-MW14 (also 50 feet downgradient of the injection well transect), chlorate concentrations fluctuated for much of the Pilot Study and did not indicate concentration reductions (Appendix L, Figure L.83). This lack of reduction in chlorate concentrations in the samples collected from LVWPS-U2-MW14 was likely due to an uncharacteristically low concentration in the sample collected during baseline that was being used for comparison purposes. Lastly, similar to perchlorate, chlorate concentrations did not reduce in samples collected from LVWPS-U2-MW08, which was likely due to the location of this monitoring well and the northeastern groundwater flow direction within the western side of the study area that likely results in groundwater migrating into the Zone 2 study area that does not pass through the biologically active zone near the injection well transect (**Figure 7c**) (Appendix L, Figure L.82).

- Groundwater samples were collected from two monitoring wells located approximately 100 feet downgradient of the injection well transect (LVWPS-U2-MW12 and LVWPS-U2-MW17) and one monitoring well located approximately 200 feet downgradient of the injection well transect (LVWPS-MW223C) (Appendix L, Figures L.85 through L.87). As with perchlorate, the most prominent reduction in chlorate concentrations was observed in samples collected from LVWPS-MW223C, which indicated a reduction from a baseline concentration of 7,700 μg/L to less than the sample detection limit of 24 μg/L during the final two sampling events (Months 16 and 18). A 92 percent reduction in chlorate concentrations was also observed in the Month 1 sample collected from LVWPS-U2-MW17, which correlates with the increase in TOC concentrations indicating the arrival of the injectate solution. Although chlorate concentrations increased following the concentration low observed in the Month 1 sample collected from LVWPS-U2-MW17, an average reduction of 36 percent was sustained throughout the remainder of the Pilot Study, with subsequent sampling events indicating concentrations ranging from 3,900 μg/L to 9,900 μg/L. Lastly, chlorate concentration reductions of up to 63 percent were observed in samples collected from LVWPS-U2-MW12, with a final concentration of 4,400 μg/L compared to a baseline concentration of 12,000 μg/L.

7.7.3 Nitrate

As discussed earlier in this report, nitrate concentrations were evaluated during the Pilot Study because it is the most likely competing electron acceptor as well as a consumer of organic carbon substrate. Nitrate concentrations during the Pilot Study are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.28 through L.87). Nitrate results from the Pilot Study for the alluvium and UMCf are summarized in Sections 7.7.3.1 and 7.7.3.2, respectively.

7.7.3.1 Nitrate in the Alluvium

Nitrate concentrations in groundwater were measured during baseline and ranged from 9 mg/L to 22 mg/L in the alluvium, with results generally consistent in both the shallow and deep alluvium. The highest baseline nitrate concentration of 22 mg/L was measured in groundwater samples collected from deep alluvial monitoring well LVWPS-A2-MW04B, which is located in the immediate vicinity of the Zone 2 injection well transect, as well as several farther downgradient monitoring wells (i.e., LVWPS-A2-MW15B, LVWPS-A2-MW16A, LVWPS-A2-MW16B, LVWPS-MW209 and LVWPS-MW210B). In general, nitrate concentration trends followed a similar reducing pattern as the perchlorate and chlorate concentration trends throughout the Pilot Study timeframe (discussed in Sections 7.7.1.1 and 7.7.1.2). Noteworthy nitrate results from the Pilot Study are summarized below.

- Samples collected from all four cross-gradient monitoring wells exhibited nitrate concentration decreases during the Pilot Study (Appendix L, Figures L.35 through L.38). Similar to the perchlorate and chlorate concentration reductions, nitrate reductions were initially the greatest in samples collected from the LVWPS-A2-MW05A/B monitoring well cluster located on the eastern side of the injection well transect. Over time, nitrate concentrations reductions improved in the samples collected from LVWPS-A2-MW04B and monitoring well cluster LVWPS-A2-MW05A/B, with the majority of the samples indicating nitrate concentrations less than 1 mg/L following injections (compared to baseline concentrations ranging from 9 mg/L to 22 mg/L). Although nitrate concentrations reduced in samples collected from LVWPS-A2-MW04A, reductions were not as strong as those observed in samples collected from the other three cross-gradient monitoring wells.
- Samples collected from all seven monitoring wells located approximately 50 feet downgradient of the injection well transect (LVWPS-A2-MW08A, LVWPS-A2-MW08B, LVWPS-A2-MW08C, LVWPS-A2-MW09A, LVWPS-A2-MW09B, LVWPS-A2-MW14A, and LVWPS-A2-MW14B) exhibited nitrate concentration decreases during the Pilot Study (Appendix L, Figures L.39 through L.45). Nitrate concentration reductions initially ranged from 14 to greater than 99 percent during the Month 1 sampling

event following the first injection event. By the end of the Pilot Study, nitrate concentrations had reduced by an overall average of 53 percent, with samples from four monitoring wells (i.e., LVWPS-A2-MW08A, LVWPS-A2-MW08B, LVWPS-A2-MW08C, and LVWPS-A2-MW14A) consistently indicating nitrate concentrations less than 1 mg/L (compared to baseline concentrations ranging from 19 mg/L to 21 mg/L). One notable observation is that the nitrate concentrations in samples collected from monitoring well LVWPS-A2-MW14B and monitoring well cluster LVWPS-A2-MW09A/B did not reduce to low levels, whereas chlorate concentrations reduced to below detection limits following the third injection event in samples collected from both monitoring wells. As previously explained in Section 6.7.3, this phenomenon may be due to the range of microorganisms that are native to the aquifer, wherein there could be a preference for perchlorate and chlorate respiration that provides more energy compared to nitrate, even though nitrate uptake generally precedes the degradation of these other electron acceptors.

- Of the 10 monitoring wells located approximately 100 feet downgradient from the injection well transect, samples collected from seven monitoring wells indicated significant nitrate concentration reductions (i.e., monitoring well clusters LVWPS-A2-MW12A/B, LVWPS-A2-MW13A/B, and LVWPS-A2-MW17A/B/C), with reductions from an average baseline concentration of 17 mg/L to an average post-injection concentration of 8 mg/L post-injection (Appendix L, Figures L.46 through L.52). Although minimal perchlorate and chlorate concentration reductions were observed in samples collected from monitoring well cluster LVWPS-A2-MW11A/B/C, nitrate concentrations generally remained stable throughout the Pilot Study (Appendix L, Figures L.53 through L.55). As previously explained, response from the injections at this location was generally minimal because of the location of this monitoring well cluster being west of the paleochannel and not downgradient of the injection well transect based on a review of groundwater flow directions.
- Of the two monitoring well clusters located approximately 200 feet downgradient of the injection well transect, results of samples collected from LVWPS-MW223A, LVWPS-MW223B, and LVWPS-MW208B indicated periodic nitrate concentration reductions of greater than 97 percent during the Pilot Study (Appendix L, Figures L.56 through L.59). Although this high level of reduction was generally not sustained throughout the Pilot Study, an overall average reduction of 52 percent was attained following injections. The most sustained nitrate concentration reduction was observed in the samples collected from LVWPS-MW223B, with nitrate concentrations consistently reducing from a baseline concentration of 20 mg/L to a final Month 18 concentration of 0.3 mg/L.
- Noteworthy sample results from remaining monitoring wells located greater than 200 feet in either the cross-gradient or downgradient direction are summarized below.
    - Similar to perchlorate, samples collected from monitoring well clusters LVWPS-A2-MW15A/B and LVWPS-A2-MW16A/B, which are located west of the paleochannel and approximately 200 and 350 feet downgradient of the injection well transect, respectively, indicated overall nitrate concentration reductions generally averaging 10 percent (Appendix L, Figures L.60 through L.63). However, nitrate concentrations at the end of the Pilot Study were consistent with baseline concentrations.
    - Nitrate concentrations reduced an average of 24 percent and 41 percent in samples collected from monitoring wells LVWPS-MW209A and LVWPS-MW211, respectively, both of which are located more than 600 feet downgradient of the injection well transect (Appendix L, Figures L.68 and L.71). Although these reductions were notable, reductions were not as strong as the chlorate reductions, which ranged from 80 percent to greater than 99 percent during the last six months of the Pilot Study. The most notable nitrate concentration reduction was in the sample collected from LVWPS-MW211 shortly after the first injection event, with a nitrate concentration of 4.4 mg/L compared to a baseline concentration of 14 mg/L. Nitrate concentrations slowly increased for the remainder of the study, with a final Month 18 nitrate concentration of 11 mg/L.

- Lastly, nitrate concentrations in groundwater samples collected from upgradient monitoring wells screened in the alluvium generally remained stable for much of the Pilot Study, with concentrations ranging from 7.3 mg/L to 26 mg/L (Appendix L, Figures L.28 through L.34).

7.7.3.2 Nitrate in the UMCf

Nitrate concentrations in groundwater were measured during baseline and ranged from 0.27 mg/L to 18 mg/L in the UMCf. The highest baseline nitrate concentration of 18 mg/L was measured in the groundwater sample collected from LVWPS-U2-MW18, which is located 25 feet downgradient of the Zone 2 injection well transect. In general, nitrate concentration trends followed a similar reducing pattern as the perchlorate and chlorate concentration trends throughout the Pilot Study timeframe (discussed in Section 7.7.1.2 and 7.7.2.2). Noteworthy nitrate results from the Pilot Study are summarized below.

- Nitrate concentration reductions of greater than 99 percent were observed in samples collected from two of the three upgradient monitoring wells, namely, LVWPS-U2-MW01 and LVWPS-U2-MW02 (Appendix L, Figures L.75 and L.76). The most notable concentration reduction was observed in samples collected from LVWPS-U2-MW02, with concentrations reducing from a baseline concentration of 6 mg/L to less than 0.14 mg/L in the final sampling event. As previously explained, low effective porosity can cause the injectate solution to move farther from the injection points (both upgradient and downgradient) during injections, particularly when injecting under pressure.
- Samples collected from the two cross-gradient monitoring wells located approximately 12 feet from either end of the injection well transect (LVWPS-U2-MW04 and LVWPS-U2-MW05) indicated an average baseline concentration of 4.34 mg/L. Following injection, nitrate concentrations were consistently below 1 mg/L, with the majority of the samples indicating concentrations below detection limits throughout the Pilot Study (Appendix L, Figures L.78 and L.79).
- Results from the groundwater samples collected from the two monitoring wells located approximately 25 feet downgradient of the injection well transect (LVWPS-U2-MW06 and LVWPS-U2-MW18) indicated variable nitrate concentration trends (Appendix L, Figures L.80 and L.81). Although chlorate concentration reductions were observed in samples collected from LVWPS-U2-MW06, nitrate concentrations generally remained stable, with an overall average of 11 mg/L. Nitrate concentrations reduced by greater than 98 percent, with concentrations less than 0.43 mg/L (compared to a baseline concentration of 18 mg/L) in samples collected from monitoring well LVWPS-U2-MW18 during the last six sampling events of the Pilot Study.
- Nitrate concentration reductions were observed in samples collected from two of the three monitoring wells located approximately 50 feet downgradient of the injection well transect (i.e., LVWPS-U2-MW08 and LVWPS-U2-MW14) (Appendix L, Figures L.82 and L.83). Despite minimal perchlorate and chlorate concentration reductions, nitrate concentrations reduced by approximately 40 percent following injections in samples collected from LVWPS-U2-MW08 (average of 10.3 mg/L compared to a baseline of 17 mg/L). Nitrate concentration trends almost mirrored perchlorate concentration trends in samples collected from LVWPS-U2-MW14, with nitrate concentrations reducing by greater than 99 percent during Months 11 and 12 (concentrations of less than 0.081 mg/L compared to a baseline concentration of 17 mg/L). Despite the small decreases observed in perchlorate and chlorate concentrations, nitrate concentrations did not reduce in samples collected from LVWPS-U2-MW09 (Appendix L, Figure L.84).
- Groundwater samples were collected from two monitoring wells located approximately 100 feet downgradient of the injection well transect (LVWPS-U2-MW12 and LVWPS-U2-MW17) and one monitoring well located approximately 200 feet downgradient of the injection well transect (LVWPS-MW223C) (Appendix L, Figures L.85 through L.87). As with perchlorate and chlorate, the most prominent reduction in nitrate concentrations was observed in samples collected from LVWPS-MW223C, which indicated an average reduction of 50 percent from a baseline concentration of 14 mg/L to an average post-injection concentration of 7.1 mg/L. Also similar to perchlorate and chlorate, a reduction of greater

than 99 percent in nitrate concentrations was observed in the Month 1 sample collected from LVWPS-U2-MW17 (less than 0.14 mg/L compared to a baseline concentration of 11 mg/L), which correlates with the increase in TOC concentrations indicating the arrival of the injectate solution. Following this initial substantial decrease in Month 1, nitrate concentrations generally rebounded to concentrations slightly above baseline concentrations. Lastly, nitrate concentration reductions averaged approximately 20 percent in samples collected from LVWPS-U2-MW12 following injections, with concentrations ranging from 13 mg/L to 16 mg/L compared to a baseline concentration of 18 mg/L.

7.7.4 Total Organic Carbon

As previously explained, TOC was analyzed throughout the Pilot Study to monitor changes in concentrations after injections compared to baseline pre-injection concentrations to track the carbon substrate injectate in the groundwater and to be used as an indicator to determine the appropriate timing for reinjection activities. TOC concentrations during the Pilot Study are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.28 through L.87. TOC results from the Pilot Study for the alluvium and UMCf are summarized in Sections 7.7.4.1 and 7.7.4.2. respectively.

7.7.4.1 TOC in the Alluvium

The initial baseline groundwater sampling event performed in October 2020 indicated that TOC concentrations were less than 2 mg/L in the samples collected from the alluvial monitoring wells located throughout the Zone 2 study area. Noteworthy TOC results from the Pilot Study are summarized below.

- TOC concentrations did not increase in samples collected from upgradient monitoring wells (Appendix L, Figures L. 28 through L.34). Transport of organic carbon in upgradient areas was not expected given the more transmissive nature of the alluvial sediments compared to the UMCf (i.e., injectate solution would not be expected to travel as far upgradient during injection activities).
- Samples collected from all four cross-gradient monitoring wells exhibited substantial increases in TOC concentrations during the Pilot Study (Appendix L. Figures L.35 through L.38). TOC concentrations were sustained above baseline concentrations in samples collected from LVWPS-A2-MW04B and monitoring well cluster LVWPS-A2-MW05A/B during all sampling events following injections, with an overall average post-injection TOC concentration of 110 mg/L compared to a baseline average concentration of 1.2 mg/L. Following the first injection event, TOC concentrations increased in samples collected from LVWPS-A2-MW04B and monitoring well cluster LVWPS-A2-MW05A/B, with TOC concentrations of up to 280 mg/L. Even greater TOC concentrations were observed following the second injection, with TOC concentrations detected as high as 1,800 mg/L in the sample collected from LVWPS-A2-MW05B during Month 5. Although relatively minor, slight increases in TOC concentrations began to be observed in samples collected from monitoring well LVWPS-A2-MW04A, which increased from a baseline concentration of 1.7 mg/L to 5.2 mg/L following the second injection event. This trend continued with a TOC concentration as high as 44 mg/L in the sample collected from LVWPS-A2-MW04A immediately following the third injection event. During the last sampling event, which was approximately eight months after the third injection event, TOC concentrations remained slightly above baseline in all four monitoring wells, with the highest TOC concentration of 25 mg/L observed in the final sample collected from LVWPS-A2-MW05B.
- Samples collected from five of the seven monitoring wells located approximately 50 feet downgradient of the injection well transect (LVWPS-A2-MW08A, LVWPS-A2-MW08B, LVWPS-A2-MW08C, LVWPS-A2-MW14A, and LVWPS-A2-MW14B) exhibited TOC concentration increases notably above baseline concentrations, with the maximum TOC concentration in samples collected from each well ranging from 7.4 mg/L to 230 mg/L compared to an average baseline concentration of 1.7 mg/L (Appendix L, Figures L.39 through L.45). TOC concentrations were sustained above baseline concentrations throughout the Pilot Study following injections in samples collected from LVWPS-A2-MW08C and LVWPS-A2-MW14A. TOC concentrations were elevated above baseline concentrations in the majority of samples collected

from monitoring wells LVWPS-A2-MW08A and LVWPS-A2-MW08B (ranging from 1.9 mg/L to 140 mg/L). These elevated TOC concentrations generally correlate with perchlorate and chlorate reductions, which were significant in samples collected from these five monitoring wells. Lastly, TOC concentration increases were not observed in samples collected from monitoring well cluster LVWPS-A2-MW09A/B. Despite the lack of TOC concentration increases, perchlorate concentration reductions ranging from 6 percent to 72 percent when compared to baseline concentrations were observed in samples collected from this monitoring well cluster. This is likely due to treated groundwater from upgradient locations migrating into the vicinity of this well cluster.

- TOC concentrations notably increased in samples collected from seven of the ten monitoring wells located approximately 100 feet downgradient from the injection well transect (i.e., monitoring well clusters LVWPS-A2-MW12A/B, LVWPS-A2-MW13A/B, and LVWPS-A2-MW17A/B/C) (Appendix L. Figures L.46 through L.52). The greatest increase in TOC concentrations was observed in the samples collected from monitoring wells LVWPS-A2-MW12A and LVWPS-A2-MW12B, with TOC concentrations increasing from an average baseline concentration of 1.7 mg/L to as high as 140 mg/L and 45 mg/L, respectively. These TOC concentration increases correlate with substantial perchlorate and chlorate concentration decreases of greater than 99 percent in samples collected from the LVWPS-A2-MW14A/B monitoring well cluster. Although sporadic, TOC concentrations increased significantly in samples from monitoring wells LVWPS-A2-MW13A and LVWPS-A2-MW13B, with TOC concentrations increasing from an average baseline concentration of 1 mg/L to as high as 84 mg/L and 32 mg/L, respectively. TOC concentrations were initially elevated after the first injection event in the sample collected from LVWPS-A2-MW13B (concentration of 32 mg/L compared to baseline concentration of 1.2 mg/L), which correlates to the initial decreases of both perchlorate and chlorate concentrations by greater than 98 percent following the first injection event. TOC concentrations significantly increased for the first time in samples collected from LVWPS-A2-MW13A during the Month 5 sampling event (concentration of 84 mg/L compared to a baseline concentration of 0.8 mg/L). This increase in TOC concentration also correlates with perchlorate and chlorate reductions, which reduced by 94 percent and 96 percent, respectively, during the Month 5 sampling event. Although not at the levels observed in samples collected from monitoring well clusters LVWPS-A2-MW12A/B and LVWPS-A2-MW13A/B, TOC concentrations increased in samples collected from monitoring wells LVWPS-A2-MW17A, LVWPS-A2-MW17B, and LVWPS-A2-MW17C to as high as 4.1 mg/L, 10 mg/L, and 62 mg/L, respectively, compared to an average baseline concentration of 1.5 mg/L. Similarly, perchlorate concentration reductions were primarily observed in samples from LVWPS-A2-MW17B and LVWPS-A2-MW17C in this well cluster, which correlates with the highest concentrations of TOC. TOC concentration increases were not observed in samples collected from the monitoring well cluster LVWPS-A2-MW11A/B/C (Appendix L, Figures L.53 through L.55), which is not unexpected due to this monitoring well cluster being located west of the paleochannel and not downgradient of the injection well transect based on a review of groundwater flow directions presented in **Figures 7a and 7b**.
- Of the two monitoring well clusters located approximately 200 feet downgradient of the injection well transect, TOC concentrations increased in samples collected from LVWPS-MW223A, LVWPS-MW223B, and LVWPS-MW208B, with increases from an average baseline concentration of 1.4 mg/L to as high as 11 mg/L, 30 mg/L, and 11 mg/L, respectively (Appendix L, Figures L.56 through L.59). Perchlorate concentrations also reduced in samples collected from these wells.
- TOC concentrations did not increase in samples collected from monitoring wells located greater than 200 feet in either the cross-gradient or downgradient direction (Appendix L, Figures L.60 through L.74). Despite the lack of TOC concentration increases, perchlorate and chlorate concentration reductions were observed in samples collected from these downgradient monitoring wells, which indicates the likely migration of treated groundwater from upgradient locations into this downgradient vicinity.

7.7.4.2 TOC in the UMCf

The initial baseline groundwater sampling event performed in October 2020 indicated that TOC concentrations were less than 1.5 mg/L in the samples collected from the UMCf monitoring wells located throughout the Zone 2 study area. Noteworthy TOC results from the Pilot Study are summarized below.

- Samples collected from the two cross-gradient monitoring wells located approximately 12 feet from either end of the injection well transect (LVWPS-U2-MW04 and LVWPS-US2-MW05) indicated elevated TOC concentrations above baseline concentrations throughout the Pilot Study (Appendix L, Figures L.78 and L.79). Specifically, TOC concentrations increased from an average baseline concentration of 0.34 mg/L to concentrations of 10 mg/L and 1,100 mg/L in samples collected from LVWPS-U2-MW04 and LVWPS-U2-MW05, respectively, after the first injection event. Concentrations increased to as high as 1,500 mg/L in the sample collected from LVWPS-U2-MW04 after the second injection event. During the final sampling event, TOC concentrations were 180 mg/L and 29 mg/L in samples collected from LVWPS-U2-MW04 and LVWPS-U2-MW05, respectively. This indicates substantial organic carbon was still present in the vicinity of the injection wells approximately eight months after the second injection event. These results correlate with perchlorate and chlorate concentrations, which were both regularly detected below sample detection limits during the Pilot Study.
- Of the two monitoring wells located approximately 25 feet downgradient of the injection well transect, TOC concentrations increased to as high as 530 mg/L in the sample collected from LVWPS-U2-MW18 approximately 3 months after the second injection event (compared to a baseline concentration of 1.3 mg/L), while no TOC concentration increases were observed in the samples collected from monitoring well LVWPS-U2-MW06 during the Pilot Study (Appendix L, Figures L.80 and L.81). Although perchlorate concentration reductions of up to 48 percent were observed in samples collected from LVWPS-U2-MW18 after the first injection event, TOC concentrations only slightly increased from a baseline concentration of 1.3 mg/L to a Month 4 concentration of 2.4 mg/L. Following the second injection event in which TOC concentrations increased to 530 mg/L in samples collected from LVWPS-U2-MW18, both perchlorate and chlorate concentrations decreased to below detection limits. The final Month 18 sampling event indicated a TOC concentration of 39 mg/L in the sample collected from LVWPS-U2-MW18, which indicates that organic carbon remained elevated approximately eight months after the second injection event. The increase in TOC concentrations in groundwater samples collected from LVWPS-U2-MW18 also correlated with an increase in perchlorate reductase enzyme and biomass populations in this vicinity (discussed in Section 7.7.7).
- Following the second injection event, TOC concentrations increased from a baseline concentration of 0.78 mg/L to a concentration of 34 mg/L in the sample collected during the Month 11 sampling event from monitoring well LVWPS-U2-MW14, which was located approximately 50 feet downgradient of the injection well transect (Appendix L, Figure L.83). TOC concentrations quickly decreased to 2.9 mg/L in the Month 12 sampling event and generally remained at this level for the remainder of the Pilot Study. This TOC increase correlates well with the decreases in perchlorate and chlorate concentrations observed during the Month 12 sampling event. Although TOC concentrations remained low during the final sampling events of the Pilot Study, perchlorate concentrations remained reduced by 55 percent in the final sampling event. No TOC concentration increases were observed in the other two monitoring wells located approximately 100 feet downgradient of the injection well transect (i.e., LVWPS-U2-MW08 and LVWPS-U2-MW09) (Appendix L, Figures L.82 and L.84).
- Groundwater samples were collected from two monitoring wells located approximately 100 feet downgradient of the injection well transect (LVWPS-U2-MW12 and LVWPS-U2-MW17) and one monitoring well located approximately 200 feet downgradient of the injection well transect (LVWPS-MW223C) (Appendix L, Figures L.85 through L.87). TOC concentrations initially increased in the sample collected from LVWPS-U2-MW17 from a baseline concentration of 0.66 mg/L to 6.1 mg/L, which correlates to a 60 percent reduction in perchlorate and a 92 percent reduction in chlorate concentrations

also observed during Month 1. No notable TOC concentration increases were observed in samples collected from monitoring wells LVWPS-U2-MW12 or LVWPS-MW223C.

- TOC concentrations slightly increased from a baseline concentration of 0.36 mg/L to 2.2 mg/L in the sample collected from upgradient monitoring well LVWPS-U2-MW01 during the third month following the initial injection event, which correlates with the timing of the perchlorate and chlorate concentration reductions (Appendix L, Figure L.75). TOC concentrations also increased from a baseline concentration of 0.64 mg/L to 310 mg/L in the sample collected from upgradient monitoring well LVWPS-U2-MW02 after the second injection event, which also correlates to perchlorate and chlorate concentration decreases (Appendix L, L.76). As previously explained, low effective porosity can cause the injectate solution to move farther from the injection points (both upgradient and downgradient) during injections, particularly when injecting under pressure.

7.7.5 Collective Result for Primary Parameters

As described in Sections 7.7.1 through 7.7.4, the results of the primary parameters of perchlorate, chlorate, nitrate, and TOC demonstrate that bioremediation processes occurred within the shallow and deep alluvium as well as the UMCf. Results show that in areas where groundwater samples indicated an increase in TOC concentrations, reductions were also generally observed in perchlorate, chlorate, and nitrate concentrations. Perchlorate concentrations in groundwater were reduced to below the PRG of 15 μg/L in multiple samples over several sampling events in both the shallow and deep alluvium and the UMCf. In several instances, groundwater samples collected from downgradient monitoring wells also had notable concentration reductions of perchlorate and chlorate despite minimal changes in TOC concentrations, which is likely due to downgradient movement of treated groundwater migrating from the injection well transect. Lastly, substantial chlorate degradation was observed in the alluvium, which in some cases was greater and more widespread than the perchlorate concentration reductions. These differences may be attributed to the elevated groundwater flow rates, which may not allow sufficient residence time for complete degradation of perchlorate but does allow for complete chlorate degradation.

7.7.6 Additional Chemical and Geochemical Evaluation

This section provides a summary of the additional data collected during the Pilot Study from the Zone 2 study area. This includes DO, ORP, sulfate, and sulfide, as well as the geochemical relevance of each parameter in relation to perchlorate biodegradation. During the Pilot Study, groundwater samples were also collected from three clustered well locations within Zone 2 (namely, LVWPS-A2-MW02A/B, LVWPS-U2-MW02, LVWPS-A2-MW12A/B, LVWPS-U2-MW12, and LVWPS-MW223A/B/C) and analyzed for an extended suite of parameters as described in Section 5.7. As a result, a discussion of metals, pH, alkalinity, TDS, methane, total nitrogen, phosphorus, hexavalent chromium, and VFAs is presented to discuss their significance on the Pilot Study findings. Results for all parameters discussed herein are presented in the comprehensive data tables provided in Appendix J, Tables J.1 and J.2. DO, ORP, and sulfate concentrations during the Pilot Study are graphically depicted in Appendix L, Figures L.28 through L.87. The significance of these additional parameters was previously explained in Section 6.7.6, and therefore, have not been reiterated herein.

7.7.6.1 Dissolved Oxygen

Baseline readings prior to injections indicated a generally aerobic aquifer with DO readings averaging approximately 5.14 mg/L and ranging from 1.55 mg/L to 7.60 mg/L in the alluvium (similar ranges for both the shallow and deep intervals). Following the first injection event, DO concentrations decreased in the groundwater samples collected from all 22 alluvial monitoring wells located less than 250 feet downgradient of the Zone 2 injection well transect, with an overall average DO concentration of 1.85 mg/L. Of these 22 downgradient alluvial monitoring wells, DO concentrations routinely decreased to below 0.5 mg/L in groundwater samples collected from 15 monitoring wells, a change that is indicative of strongly reducing conditions. These reductions in DO concentrations indicated that reducing conditions were rapidly established following injections. These anaerobic conditions became stronger following the second injection event, with an overall average DO concentration of 0.67 mg/L and samples collected from 18 alluvial monitoring wells frequently indicating DO concentrations less than 0.5 mg/L. These strongly reducing conditions continued following the third injection event and through the completion of the Pilot Study, with DO concentrations routinely detected below 0.5 mg/L in samples collected from 21 alluvial monitoring wells and an overall average DO concentration of 0.96 mg/L. The anaerobic conditions that were created in both the shallow and deep alluvium during the Pilot Study correlate to significant perchlorate concentration reductions in samples collected from downgradient monitoring wells. One notable finding was that despite other parameter results indicating the need for the next injection event (i.e., perchlorate concentration increases and/or TOC concentration decreases), DO concentrations generally remained consistently decreased following each injection event (i.e., minimal rebound in DO concentrations were observed in the latter months following an injection event). For example, the average DO concentration in the samples collected from the 22 downgradient alluvial monitoring wells during the final sampling event (approximately 8 months after the third injection event) was 0.76 mg/L, which was indicative of reducing conditions and substantially below the average baseline concentration of 5.14 mg/L.

Similar initial aerobic conditions were present in the UMCf with DO concentrations averaging approximately 3.5 mg/L and ranging from 0.9 mg/L to 8.1 mg/L during baseline. Following the first injection event, DO concentrations decreased in groundwater samples collected from nine of the 10 UMCf monitoring wells located less than 200 feet downgradient of the Zone 2 injection well transect, with an overall average DO concentration of 1.92 mg/L. Of these 10 downgradient UMCf monitoring wells, DO concentrations routinely decreased to below 0.5 mg/L in groundwater samples collected from three monitoring wells, a change that is indicative of strongly reducing conditions in these areas. This response was much slower compared to the Zone 2 alluvium due to the low permeability and low groundwater flow rates within the Zone 2 UMCf. These anaerobic conditions became slightly stronger following the second injection event, with an overall average DO concentration of 1.71 mg/L and samples collected from seven UMCf monitoring wells periodically indicating DO concentrations less than 0.5 mg/L. DO concentrations also decreased in to less 0.5 mg/L in multiple samples collected from upgradient monitoring well LVWPS-U2-MW02, which correlates to arrival of the injectate solution as evidenced by an increase in TOC concentrations. In general, the anaerobic conditions that were created in the UMCf during the Pilot Study correlate to perchlorate concentration reductions in samples collected from downgradient monitoring wells.

As previously stated in Section 6.7.6.1, DO can be a useful indicator during the initial 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 less organic carbon that gets transported to downgradient locations. As a result, DO is a good indicator parameter to be used for evaluating the influence of injections through the creation and sustainment of anaerobic conditions but is not likely to be the foremost indicator for evaluating the timing of additional injection events.

7.7.6.2 Oxidation-Reduction Potential

During the baseline sampling event in October 2020, ORP measurements collected from monitoring wells in the alluvium averaged 73.2 mV, which is generally consistent with aerobic conditions indicated by the DO concentrations within the Zone 2 study area prior to injections. Following the first injection event, ORP measurements indicated a shift to anaerobic conditions, with an overall average ORP measurement of -57 mV in the groundwater samples collected from all 22 alluvial monitoring wells located less than 250 feet downgradient of the Zone 2 injection well transect. Of these 22 downgradient alluvial monitoring wells, the ORP measurements routinely decreased to less than -50 mV in groundwater samples collected from 14 UMCf monitoring wells and less than -200 mV in groundwater samples collected from nine UMCf monitoring wells, a change that is indicative of strongly reducing conditions. These substantial reductions in ORP measurements indicated that reducing conditions were rapidly established following injections. As previously demonstrated with the DO concentration trends, ORP measurements continued to decrease following the second injection event, with an overall average ORP measurement of -143 mV and samples collected from 17 monitoring wells frequently indicating ORP measurements less than -50 mV and samples collected from 12 monitoring wells indicating ORP measurements less than -200 mV. These strongly reducing conditions continued following the third injection event and through the completion of the Pilot Study, with ORP measurements routinely detected below -50 mV in samples collected from 15 monitoring wells and below -200 mV in samples collected from eight monitoring wells. The overall average ORP measurement following the third injection event was -85.1 mV, which is indicative of slightly more anaerobic conditions than what was observed following the first injection event but less anaerobic compared to the conditions after the second injection event. This is likely due to the overall steady increase in ORP measurements towards the end of the Pilot Study due to the slow depletion of organic carbon from the last injection event approximately eight months earlier. Overall, the anaerobic conditions that were created in both the shallow and deep alluvium during the Pilot Study correlate to significant perchlorate concentration reductions and low DO concentrations observed in samples collected from downgradient monitoring wells.

During the baseline sampling event ORP measurements collected from wells installed in the UMCf averaged 58.3 mV which is generally consistent with aerobic conditions.

Similar to the alluvium, the UMCf was aerobic prior to injections with ORP measurements averaging approximately 58.3 mV during baseline. Following the first injection event, ORP measurements decreased in groundwater samples collected from seven of the 10 UMCf monitoring wells located less than 200 feet downgradient of the Zone 2 injection well transect, with an overall average ORP measurement -28.7 mV, a change that is indicative of strongly reducing conditions in these areas. Of these 10 downgradient UMCf monitoring wells, ORP measurements were periodically less than -50 mV in groundwater samples collected from seven monitoring wells and less than -200 mV in groundwater samples collected from two monitoring wells. As previously explained in Section 7.7.6.1, this response was much slower compared to the Zone 2 alluvium due to the low permeability and low groundwater flow rates within the Zone 2 UMCf. These anaerobic conditions became slightly stronger following the second injection event, with an overall average ORP measurement of -84 mV. Samples collected from six UMCf monitoring wells periodically indicated ORP measurements less than -50 mV, while samples collected from four UMCf monitoring wells periodically indicated ORP measurements less than -200 mV. ORP measurements also substantially reduced in multiple samples collected from upgradient monitoring wells LVWPS-U2-MW01 and LVWPS-U2-MW02. In general, the anaerobic conditions that were created in the UMCf during the Pilot Study correlate to perchlorate concentration reductions in samples collected from downgradient monitoring wells.

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 Pilot Study, as inferred from ORP readings.

7.7.6.3 Sulfate and Sulfide

Baseline sulfate concentrations averaged approximately 2,059 mg/L in the groundwater samples collected from the monitoring wells screened in the alluvium within the Zone 2 study area. In general, groundwater at downgradient monitoring wells exhibited relatively stable sulfate concentrations during the Pilot Study, with the overall average sulfate concentrations in each event ranging from 1,755 mg/L to 2,245 mg/L. Of the 22 monitoring wells located less than 250 feet downgradient of the Zone 2 injection well transect, samples collected from six monitoring wells indicated notable sulfate concentration reductions. The most significant sulfate concentration reduction was observed in groundwater samples collected from LVWPS-A2-MW05B, which indicated sulfate concentrations as low as 1.4 mg/L compared to a baseline concentration of 2,000 mg/L. Sulfate concentrations remained reduced by greater than 70 percent throughout the majority of the Pilot Study in samples collected from this well. Significant sulfate reductions were also observed in samples collected from LVWPS-A2-MW12A and LVWPS-A2-MW14A, which reduced from baseline concentrations greater than 2,000 mg/L to concentrations as low as 140 mg/L and 2.6 mg/L, respectively. Although these reductions were significant, sulfate concentrations returned to baseline concentrations during the last five sampling events in samples collected from both monitoring wells. Significant TOC concentration increases were observed in samples collected from all three of the monitoring wells with significant sulfate reductions. However, TOC concentrations also significantly increased in samples from other monitoring wells that did not observe sulfate reductions (i.e., LVWPS-A2-MW04A, LVWPS-A2-MW05A, LVWPS-A2-MW08A, LVWPS-A2-MW08B, LVWPS-A2-MW212B, and LVWPS-A2-MW217C).

In the groundwater samples collected from the Zone 2 monitoring wells screened in the UMCf, baseline sulfate concentrations averaged approximately 2,062 mg/L. In general, groundwater at downgradient monitoring wells exhibited relatively stable sulfate concentrations during the Pilot Study, with the overall average sulfate concentrations in each event ranging from 1,731 mg/L to 2,054 mg/L. Notable sulfate concentration decreases were observed in groundwater samples collected from upgradient well LVWPS-U2-MW02 and downgradient well LVWPS-U2-MW05. Specifically, sulfate concentrations decreased from a baseline concentration of 1,800 mg/L to as low as 410 mg/L in samples collected from upgradient monitoring well LVWPS-U2-MW02 following the second injection event. Sulfate concentrations also decreased in samples collected from downgradient monitoring well LVWPS-U2-MW05, with concentrations decreasing from a baseline concentration of 1,300 mg/L to as low as 0.57 mg/L during Month 8 of the Pilot Study.

Sulfide was monitored at one upgradient monitoring well cluster (LVWPS-A2-MW02A/B; LVWPS-U2-MW02) and two downgradient monitoring well clusters (LVWPS-A2-MW12A/B; LVWPS-U2-MW12 and LVWPS-MW223A/B/C) within the Zone 2 study area. Although limited samples were collected, sulfide was only detected in samples collected from monitoring well cluster LVWPS-A2-MW12A/B. Sulfide was detected in multiple samples collected from LVWPS-A2-MW12A at low concentrations ranging from 0.1 to 2 mg/L, which was expected given the sulfate concentration reductions observed in the samples collected from this well. Sulfide was only detected once in samples collected from LVWPS-A2-MW12B at a concentration of 0.4 mg/L.

Although sulfate concentrations significantly reduced in three alluvium and two UMCf monitoring wells within the Zone 2 study area, the overall sulfate results suggest that sulfate reduction is not persistent throughout the Zone 2 Study Area. The limited sulfate reduction observed in the Zone 2 study area is consistent with the results of previous ISB studies performed at NERT and other study areas as part of this Pilot Study, which suggests that the potential negative impacts of sulfate biodegradation in this high sulfate environment may be minimized and/or controlled during implementation of perchlorate bioremediation due to the employment of the slow-release carbon substrate. Additionally, in samples collected from monitoring wells that indicated significant sulfate reduction, neither perchlorate nor chlorate reduction was hindered.

7.7.6.4 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. To monitor for potential metals mobilization, dissolved metals were analyzed during baseline and periodically during the Pilot Study within the Zone 2 study area at one upgradient monitoring well cluster (LVWPS-A2-MW02A/B; LVWPS-U2-MW02) and two downgradient monitoring well clusters (LVWPS-A2-MW12A/B; LVWPS-U2-MW12 and LVWPS-MW223A/B/C). This section presents an evaluation of arsenic, iron, and manganese groundwater concentrations during the Pilot Study.

7.7.6.4.1 Arsenic

Baseline dissolved arsenic concentrations ranged from 17 µg/L to 61 µg/L in the Zone 2 study area (both alluvium and UMCf). Following injections, arsenic concentrations in groundwater generally remained stable except for the increases observed in the samples collected from shallow alluvial monitoring well LVWPS-A2-MW12A and UMCf monitoring well LVWPS-U2-MW02. Arsenic concentrations increased in samples collected from LVWPS-A2-MW12A from a baseline concentration of 39 µg/L to a high of 550 µg/L approximately four months after the first injection event. However, arsenic concentrations subsequently reduced, with a final concentration in Month 18 of 10 μg/L, which was less than the baseline concentration. A similar trend was observed in arsenic concentrations in samples collected from LVWPS-U2-MW02, which exhibited an arsenic concentration increase from a baseline concentration of 17 μg/L to a high concentration of 390 μg/L approximately two months after the second injection event. Arsenic concentrations reduced during the remaining sampling events, with a concentration of 28 μg/L in the final sample collected from LVWPS-U2-MW02. As explained in Section 6.7.6.4.1, arsenic is sometimes released in the saturated subsurface when reducing conditions are created following the injection of a carbon substrate. However, under prolonged reducing conditions, particularly in the presence of sulfate and even minimal sulfide production, arsenic tends to return to a non-soluble state. Based on these results, arsenic release and mobilization of arsenic are highly unlikely to be a secondary issue during the implementation of ISB using EVO as the carbon substrate, which is a similar conclusion drawn from the results of the Zones 1 and 3 study areas.

7.7.6.4.2 Iron

Baseline concentrations of dissolved iron ranged from less than 0.030 mg/L to 0.071 mg/L in both the alluvium and UMCf within the Zone 2 study area. Following injections, groundwater dissolved iron concentrations slightly increased but generally continued to remain low in both the alluvium and UMCf. The highest detections of iron in the alluvium and UMCf were 2.6 mg/L (LVWPS-A2-MW12A) and 2.3 mg/L (LVWPS-U2-MW02), respectively. These concentrations generally decreased as the Pilot Study progressed with the final sampling event indicating dissolved iron concentration of 1.6 mg/L in the sample collected from alluvial monitoring well LVWPS-A2-MW12A and less than 0.019 mg/L in the sample collected from UMCf monitoring well LVWPS-U2-MW02. Ferrous iron measurements also slightly increased in samples collected from alluvial monitoring wells LVWPS-A2-MW12A and LVWPS-A2-MW12B with concentration detections of up to 2.5 mg/L and 2 mg/L, respectively. Once oxidizing conditions return, following the consumption of residual organic carbon, ferrous iron is likely to precipitate in the groundwater at these relatively low concentrations.

7.7.6.4.3 Manganese

Baseline dissolved manganese concentrations in groundwater measured up to 0.013 mg/L in the alluvium and up to 0.65 mg/L in the UMCf. Following injections, manganese concentrations increased in groundwater samples collected from both the alluvium and UMCf. Specifically, the highest manganese concentration increase was observed in the samples collected from downgradient shallow alluvial monitoring well LVWPS-A2-MW12A, which increased from a baseline concentration of less than 0.010 mg/L to 12 mg/L following the first injection event. Manganese concentrations decreased throughout the remainder of the Pilot Study, with a concentration of 0.37 mg/L in the final sample collected from LVWPS-A2-MW12A. In the UMCf, the highest manganese concentration increase was observed in the samples collected from upgradient UMCf monitoring well LVWPS-U2-MW02, which increased from a baseline concentration of 0.65 mg/L to 3.3 mg/L following the second injection event. Manganese concentrations decreased throughout the remainder of the Pilot Study, with a concentration of 0.39 mg/L in the final sample collected from LVWPS-U2-MW02. Although manganese concentrations slightly increased in samples collected from other Zone 2 alluvium and UMCf monitoring wells, similar concentration decreases occurred throughout the Pilot Study. Based on these results, the manganese increases followed by decreasing trends indicate that manganese solubilization is contained within the Zone 2 study area and does not appear to be mobilizing downgradient.

7.7.6.5 Other Parameters

A suite of several other parameters was periodically analyzed during the Pilot Study. A summary of these parameters and their significance is presented below. With the exception of pH, which was sampled at all wells during all events, these other parameters were only analyzed in one upgradient monitoring well cluster (LVWPS-A2-MW02A/B; LVWPS-U2-MW02) and two downgradient monitoring well clusters (LVWPS-A2-MW12A/B;

LVWPS-U2-MW12 and LVWPS-MW223A/B/C). Results for each parameter are presented in the comprehensive data tables provided in Appendix J, Tables J.1 and J.2.

- Groundwater pH is an environmental factor that can affect microbial activity, with most species of microorganisms generally preferring a neutral pH between 5.5 and 8.5 standard units. During baseline sampling, groundwater pH ranged from 6.13 to 7.86 standard units. In general, groundwater pH remained within the ideal range of 5.5 to 8.5 during the Pilot Study, with an overall average pH after injections of 7.07 standard units, with only seven of the more than 1,000 samples collected having a pH outside the ideal range.
- Baseline alkalinity values in groundwater within the Zone 2 study area ranged from 75 mg/L to 180 mg/L in samples collected from both the alluvium and UMCf. During the Pilot Study, results from the groundwater samples collected from alluvial monitoring wells LVWPS-A2-MW12A, LVWPS-A2-MW12B and LVWPS-MW223B and UMCf monitoring well LVWPS-U2-MW02 indicated significant increases in alkalinity levels compared to baseline concentrations. The highest increase observed in the alluvium was from samples collected from LVWPS-A2-MW12A, which increased from a baseline concentration of 110 mg/L to a high of 1,400 mg/L after the second injection event. Samples collected from UMCf monitoring well LVWPS-U2-MW02 indicated the highest concentration increase in the UMCf, increasing from a baseline concentration of 75 mg/L to 1,300 mg/L following the second injection event. These increases in groundwater alkalinity of more than twice the baseline concentrations indicated that biodegradation is occurring in groundwater. As previously discussed in Section 7.7.1, samples from these monitoring wells also indicated substantial groundwater perchlorate concentration decreases during the Pilot Study.
- TDS concentrations in groundwater ranged from 550 to 6,600 mg/L throughout the Pilot Study. Although these are relatively high concentrations, the Pilot Study (similar to the bench-scale study) indicated that TDS concentrations at these levels did not hinder microbial activity and perchlorate biodegradation.
- Methane was periodically evaluated during the Pilot Study as an additional indicator of the level of reducing conditions that were established following carbon substrate injections. Methane was not detected during the baseline sampling event. During the Pilot Study, methane concentrations were detected above baseline concentrations in samples from several locations, with the maximum concentrations observed in the alluvium of 23 mg/L in samples collected from monitoring well LVWPS-A2-MW12A and in the UMCf of 11 mg/L in the sample collected from monitoring well LVWPS-U2-MW02. The higher methane concentrations detected in groundwater samples collected from LVWPS-A2-MW12A and LVWPS-U2-MW02 can be linked to high TOC concentrations and highly reducing conditions present in these vicinities following injections. Methane present in the saturated alluvium or UMCf is likely to get rapidly oxidized into carbon dioxide in the more porous and likely highly oxygenated unsaturated zone above it.
- Total nitrogen concentrations in groundwater ranged from 7.5 mg/L to 23 mg/L during the baseline sampling event. During the Pilot Study, total nitrogen concentrations in groundwater collected from downgradient monitoring wells generally decreased when compared to baseline concentrations. For example, total nitrogen at LVWPS-A2-MW12A reduced from a baseline concentration of 20 mg/L to 0.74 mg/L in June 2022. The decrease in total nitrogen is likely the result of denitrification that was actively occurring in the groundwater as described in Section 7.7.3.1. Despite the reductions of total nitrogen, high nitrate concentrations in area groundwater combined with the efforts of four bench-scale studies and three field treatability/pilot studies indicate that there is sufficient nitrogen present in the groundwater and therefore, should not be a limiting nutrient for bioremediation.
- Phosphorus in groundwater was monitored during the Pilot Study because a phosphate solution was added to the injectate mixture during the first injection event to serve as a macronutrient for reduced acclimation time for the onset of perchlorate biodegradation. Similar to the results from the other study areas, results indicated that the addition of the phosphate solution resulted in transient localized

increases in total phosphorus concentrations when compared to baseline concentrations, but concentrations quickly returned to at or below baseline concentration levels. 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 Pilot Study location, with baseline concentrations ranging from 6.98 μg/L to 45.4 μg/L. Hexavalent chromium concentrations decreased in samples collected from downgradient alluvium well clusters LVWPS-A2-MW12A/B and LVWPS-MW223A/B and all three UMCf monitoring wells sampled (LVWPS-MW223C, LVWPS-U2-MW02, and LVWPS-U2-MW12). Of these, concentrations reduced to below the sample detection limit of 0.150 μg/L in samples collected from LVWPS-A2-MW12A, LVWPS-A2-MW12B, LVWPS-MW223B, and LVWPS-U2-MW02.
- Volatile fatty acids were periodically analyzed at select downgradient wells to get an assessment of the acids produced during hydrolysis of the long-chain fatty acids of EVO. Acetic acid, formic acid, and propionic acid were detected in isolated sampling events performed post-injections during the Pilot Study. The most notable of three VFAs detected was acetic acid, which was detected as high as 620 mg/L in samples collected from LVWPS-U2-MW02 following the second injection event. Acetic acid was detected as high as 340 mg/L in samples from the alluvium (i.e., LVWPS-A2-MW12A). Generally, a flux of injectate that is introduced into groundwater that results in a changed microbial community and rapidly modified geochemical conditions that are reducing would likely result in the creation of measurable quantities of VFAs from the fermentation of EVO.

7.7.7 Microbial Evaluation

Microbial sampling was included in the effectiveness monitoring program to examine the microbial response to carbon substrate injections. As part of this microbial evaluation, Bio-Trap® samplers were deployed in one upgradient monitoring well cluster (LVWPS-A2-MW01A/B; LVWPS-U2-MW01), one downgradient alluvium well cluster (LVWPS-A2-MW14A/B) and two alternating UMCf monitoring wells (LVWPS-U2-MW06 and LVWPS-U2-MW18). Bio-Trap® samplers were deployed during the pre-injection baseline sampling event and two post-injection events (approximately 10 and 16 months following the first injection event). This section presents a summary of this microbial evaluation for Zone 2. Complete analytical results for the microbial analyses performed during the Pilot Study are provided in Appendix J, Table J.3; microbial laboratory data reports are provided in Appendix N. A description of Bio-Trap® sampling and analysis is provided in Section 6.7.7.

7.7.7.1 Analysis of Microbial Results

Results of the baseline microbial sampling indicated that a robust microbial population was present in the vicinity in groundwater in Zone 2 prior to the injection events. Although the perchlorate reductase enzyme was present at a population of less than 2.5×10^2 cells per bead in the shallow and deep alluvium and UMCf, the overall biomass populations during baseline ranged from 6.2×10^4 cells per bead to 1.13×10^5 cells per bead. PLFA analysis on community structure indicated that an average of 70 percent of the bacterial population belonged to the proteobacteria group. The decreased permeability ratio was 0.00 in all samples collected from all alluvium and UMCf monitoring wells during baseline sampling, which indicates negligible toxicity to the native microorganisms prior to injections. On the other hand, the ratios for slow growth ranged from 0.8 to 3.34, which indicates low availability of carbon as a food source for native microorganisms in the Zone 2 study area prior to injections.

Following injections into the Zone 2 alluvium, the perchlorate reductase enzyme increased by two orders of magnitude to a concentration of 2.07×10^4 cells per bead in samples collected from shallow alluvial monitoring well LVWPS-A2-MW14A and by one order of magnitude to a concentration of 5.3×10^3 cells per bead in samples collected from deep alluvial monitoring well LVWPS-A2-MW14B. As expected, perchlorate reductase generally remained below 2.5x10^2 cells per bead in samples collected from upgradient monitoring wells LVWPS-A2-MW01A and LVWPS-A2-MW01B during the Pilot Study.

Proteobacteria percentages continued to remain at an average of 70 percent of the microbial population. The percentage of firmicutes increased from 2.46 percent to 21.4 percent in the sample collected from LVWPS-A2-MW14A following the second 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. Finally, the decreased permeability rations remained at 0.00 in all samples, while the slowed growth ratios notably decreased in samples collected from the downgradient alluvium well cluster LVWPS-A2-MW14A/B, which indicates that a conducive environment was created through the availability of a carbon source that was supportive of enhanced microbial growth. Overall, the microbial response in samples collected from the downgradient alluvium correlate with the reduction in perchlorate concentrations and the increase in TOC concentrations.

Despite the baseline Bio-trap® being installed in downgradient UMCf monitoring well LVWPS-U2-MW06, the first Bio-trap® following injections was installed in downgradient monitoring well LVWPS-U2-MW18. This change was made due to the lack of perchlorate concentration reductions observed in samples collected from LVWPS-U2-MW06 following the first injection event compared to the average 39 percent reduction in samples collected from LVWPS-U2-MW18. Following injections, the perchlorate reductase enzyme increased by two orders of magnitude to a concentration of 1.02x10^4 cells per bead in the sample collected from UMCf monitoring well LVWPS-U2-MW18. This sample also indicated the highest proportion of proteobacteria within the Zone 2 area at 88 percent as well as a low slowed growth ratio (less than 1.0) and a decreased permeability of 0.0. Because of the slightly improved perchlorate degradation response following the second injection event, the final Bio-trap® sampler was installed in downgradient UMCf monitoring well LVWPS-U2-MW06. Although the perchlorate reductase enzyme did not increase in this sample, the overall biomass increased by one order of magnitude to 1.07x10^5 cells per bead. The sample collected from monitoring well LVWPS-U2-MW06 also indicated an increase in firmicutes and a decrease in the slowed growth ratio, which suggested a conducive environment for microbial growth. As expected, perchlorate reductase remained below 2.5x10^2 cells per bead in samples collected from upgradient monitoring well LVWPS-U2-MW01 during the Pilot Study.

7.8 ZONE 2 SUMMARY

The results summarized herein for Zone 2 provided sufficient data to meet the objectives of the Pilot Study and will support evaluation of ISB as a potential component of the NERT final remedy in the forthcoming OU-3 FS. The fulfillment of the study objectives is described below and provided in tabular format in the performance criteria tables provided as Appendix O.

- Objective 1 – Determine if ISB can effectively create a biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater within a main, deep oriented paleochannel located upgradient of the Wash, which will be important data to evaluate in the FS because targeting such paleochannels will most likely be a key component of the final remedy. Data collected indicate the following:
    - A biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater was created along and downgradient of the Zone 2 alluvium injection well transect. Groundwater perchlorate concentrations of less than the 15 μg/L PRG for perchlorate were achieved in samples collected from both the shallow and deep alluvium, with DO concentrations in the alluvium throughout the Zone 2 study area indicating a substantial shift from aerobic conditions to anaerobic conditions post-injection (baseline average of 5.14 mg/L to less than 1 mg/L in majority of samples collected post-injection).
    - Within the Zone 2 UMCf, a biologically active zone was also created that resulted in remediation of perchlorate- and chlorate-contaminated groundwater upgradient, along, and downgradient of

the Zone 2 UMCf injection well transect. Groundwater perchlorate concentrations of less than the 15 μg/L PRG for perchlorate were achieved in samples collected from two upgradient UMCf monitoring wells and two cross-gradient UMCf monitoring wells. DO concentrations also routinely decreased to below 0.5 mg/L, a change that is indicative of strongly reducing conditions in these areas. The downgradient effect from injections into the UMCf was not as widespread as the alluvium, which was expected due to the lower groundwater flow rates within the Zone 2 UMCf and the short duration of the Pilot Study. However, perchlorate concentration reductions of greater than 99 percent were achieved in samples collected from three downgradient monitoring wells located from 25 feet to 200 feet downgradient of the injection well transect.

- Objective 2 – Verify ISB effectiveness and injectate distribution in large, saturated thicknesses of alluvium, which are up to three times greater within the Zone 2 study area than has been evaluated in previous treatability studies. Data collected indicate the following:
    - During injections, the injectate solution, tagged with rhodamine dye, appeared in samples collected from all four dose-response monitoring wells screened in the shallow and deep alluvium (LVWPS-A2-DR01A, LVWPS-A2-DR01B, LVWPS-A2-DR02A, and LVWPS-A2-DR02B) and all four alluvial cross-gradient monitoring wells (LVWPS-A2-MW04A, LVWPS-A2-MW04B, LVWPS-A2-MW05A, and LVWPS-A2-MW05B). These results indicate that the injectate was distributed both horizontally and vertically in the subsurface, despite the large, saturated thickness of the alluvium. Observation of the injectate/dye solution in the cross-gradient monitoring wells also confirmed that the targeted ROI of 17.5 feet was attainable for the alluvium, which confirmed that a 35-foot well spacing was adequate in this alluvial setting.
    - Significant reductions in perchlorate and chlorate concentrations were observed in both the shallow and deep alluvium, with slightly better results in the treatment intervals with the lower groundwater flow velocities, which allowed for more residence time to complete perchlorate biodegradation. For example, samples collected from the downgradient shallow alluvial monitoring well LVWPS-A2-MW14A indicated an overall Pilot Study average perchlorate concentration reduction of 98 percent when compared to baseline concentrations. However, samples collected from the deep alluvial monitoring well LVWPS-A2-MW14B indicated an overall Pilot Study average perchlorate concentration reduction of 20 percent when compared to baseline concentrations. This result correlates with the difference in groundwater flow rates between the shallow and deep alluvium at this location, which were approximately 4 ft/day and 88 ft/day, respectively. Despite the high groundwater flow rate of 88 ft/day, chlorate concentrations were reduced in samples collected from deep alluvial monitoring well LVWPS-A2-MW14B, which is a valuable data point as it indicates that flow rates at these levels may not allow sufficient residence time for complete degradation of perchlorate but does allow for complete chlorate degradation. Lastly, samples collected from deep alluvial monitoring well LVWPS-A2-MW08C indicated several perchlorate concentration detections less than the PRG of 15 μg/L and an overall average perchlorate concentration reduction of 94 percent, despite a high groundwater flow rate of approximately 33 ft/day (a similar groundwater flow rate to the first Groundwater Bioremediation Treatability Study; see ***Table 1*** herein for summary). This result indicates that although a flow rate of 88 ft/day in LVWPS-A2-MW14B was likely too rapid to allow for sufficient residence time for perchlorate biodegradation, a high groundwater flow rate of 33 ft/day in LVWPS-A2-MW08C did not hinder complete biodegradation of perchlorate. As a result of the variability, the design of a full-scale ISB remedy would be significantly different than the compact Pilot Study design, and if selected as a component of the NERT final remedy, the injection well design could potentially include multiple injection well transects and/or varying injection frequencies depending on the groundwater flow rate of the targeted formation to achieve a more uniform biologically active treatment zone to maximize perchlorate biodegradation.

- Objective 3 – Determine if synergistic effects occur when both alluvium and UMCf are injected with carbon substrate; combined remediation of these two units has not been evaluated to-date. Data collected indicate the following:
    - The tracer study results indicated the presence of the UMCf-injected fluorescein in the overlying alluvium as well as the alluvium-injected rhodamine in the underlying UMCf.
        - As noted in Section 7.6.3.2, during injection activities, fluorescein appeared in both deep alluvial dose-response monitoring wells LVWPS-A2-DR01B and LVWPS-A2-DR02B, which illustrates the connectivity of the alluvium and the UMCf due to faulting and the deep alluvial paleochannel within Zone 2 compared to Zone 1 UMCf and Zone 3 UMCf-cg injections that did not observe injectate solution in the alluvium dose-response monitoring wells using the same injection protocols.
        - Once the fluorescein dye migrated into the alluvium along preferential flow pathways including faults, fractures, and/or the incised paleochannel in the UMCf, the dye rapidly flowed downgradient within the alluvium. Fluorescein was detected in samples collected approximately 1 month after dye injection from three monitoring wells screened in the deep alluvium located up to 100 feet cross-gradient and downgradient of the injection well transect (i.e., LVWPS-A2-MW04B, LVWPS-A2-MW08C, and LVWPS-A2-MW13B). Fluorescein continued to be detected in groundwater samples collected from select downgradient monitoring wells for up to six months after the first injection event, which suggests that there is a continued flux of groundwater from the UMCf to the alluvium.
        - Both rhodamine and fluorescein were detected in samples collected from monitoring wells LVWPS-U2-MW12 and LVWPS-U2-MW17, which were located approximately 100 feet downgradient of the injection well transect and screened in the UMCf. The arrival of fluorescein and rhodamine dyes together at these downgradient monitoring locations illustrates the varied vertical gradients ranging from 0.01 ft/ft upward to 0.03 ft/ft downward and cross-connecting flow pathways between the alluvium and UMCf within Zone 2.
    - Perchlorate concentrations reduced in samples collected from UMCf monitoring wells LVWPS-U2-MW12 and LVWPS-U2-MW17 within the first month following injections, despite being located approximately 100 feet downgradient of the injection well transect. This result was unexpected given the average estimated groundwater flow rate from borehole dilution testing performed in Zone 2 UMCf monitoring wells was approximately 0.2 ft/day. Using this groundwater flow rate, it should have taken an estimated 500 days for the injectate and/or treated groundwater to reach these far downgradient locations. Although preferential flow pathways may exist in the UMCf from the injection well transect to this location, both rhodamine and fluorescein were detected in the Month 1 samples from these monitoring wells. As previously stated, the arrival of both fluorescein rhodamine together indicates that injections into the overlying alluvium likely impacted/improved the degradation response observed in the UMCf at this downgradient location. This observation indicates that dual treatment in both the alluvium and UMCf may result in more mass being treated over time and/or improved use of the injected carbon substrate in both the alluvium and UMCf.
- Objective 4 – Evaluate injectate distribution in a dual-nested injection well configuration within the alluvium (previously only tested in single/paired injection wells) because nested injection wells can be a cost-effective option for large, saturated thicknesses as opposed to multiple separate injection wells. Data collected indicate the following:
    - Injections were performed in both the shallow and deep treatment interval within each nested injection well cluster at the same time, with the injection rates adjusted so that each injection well within a cluster would finish the injection process at generally the same time interval. The goal of

performing injections in this manner was to achieve relatively even subsurface distribution within the long-screened intervals of the nested injection wells while also attempting to account for variability and non-uniform groundwater flow and lithology. As explained above associated with fulfillment of Objective 2, the injectate solution, tagged with Rhodamine WT dye, appeared in samples collected from all four dose-response monitoring wells screened in the shallow and deep alluvium and all four alluvial cross-gradient monitoring wells. This indicates that the injectate was distributed both vertically and horizontally using dual-nested injection wells and did not preferentially go into one interval over the other.

- In addition to observing the injectate solution in both the shallow and deep intervals in the downgradient dose-response monitoring wells, significant reductions in perchlorate and chlorate concentrations were observed in both the shallow and deep alluvium, including the reduction of perchlorate concentrations to less than the 15 μg/L PRG in both treatment intervals.
- Nested injection wells provide an additional benefit of allowing application of carbon substrate at different frequencies and doses for various depth intervals at the same location, depending on depth-specific variables, such as contaminant concentrations, effective porosity, and groundwater flow velocity. For example, in a full-scale application, there may be a situation where one treatment interval may require more frequent injections than another depth interval at the same location due to different groundwater flow rates as a result of subsurface heterogeneity. Therefore, nested injection wells could potentially help minimize the quantity of carbon substrate injected by optimizing dosing for discrete treatment intervals. It should be noted that this Pilot Study did not evaluate injections into only one interval of an injection well and not the other. While this will not impede evaluation of ISB as part of the OU-3 FS, if ISB is selected as a component of the final remedy, this approach would need to be tested to ensure that appropriate vertical distribution could be achieved.

- Objective 5 – Evaluate implementation of single injection wells in the UMCf, which is a contrast to the Zone 1 and Zone 3 implementation in the UMCf and UMCf-cg that evaluated both dual-nested and triple-nested injection wells. Data collected indicate the following:
  - During injection activities in Zone 2 UMCf, fluorescein-tagged carbon substrate solution was observed in samples collected from both dose-response monitoring wells screened in the UMCf (LVWPS-U2-DR01, LVWPS-U2-DR02) and one cross-gradient monitoring well located approximately 12 feet from the injection well transect (LVWPS-U2-MW05). Although fluorescein was not detected in groundwater collected from cross-gradient monitoring well LVWPS-U2-MW04 using the field fluorimeter during injection activities, fluorescein was detected in the charcoal sampler collected from LVWPS-U2-MW04 during the first effectiveness monitoring sampling event. Furthermore, an increase in TOC (a proxy for arrival of carbon substrate solution discussed in Section 7.7.4.2) was observed in groundwater collected from LVWPS-U2-MW04, which confirmed that the target ROI of 12.5 feet was adequate within the UMCf.
  - Injection rates in Zone 2 UMCf averaged approximately 2 gpm with sustained pressures that averaged approximately 30 psi. Overall, injection wells screened in the Zone 2 UMCf indicated decreased injection capacity compared to the injection wells in Zones 1 and 3. In general, sustained injection pressures were higher in the injection wells located within the eastern portion of the Zone 2 injection well transect, where the saturated thickness of unconsolidated UMCf is the thinnest. This resulted in three of the 12 injection wells screened in Zone 2 UMCf (i.e., LVWPS-U2-IW06, LVWPS-U2-IW07, and LVWPS-IW10) not accepting the targeted injection volumes at the permissible maximum injection pressure of 45 psi. The saturated thickness of the unconsolidated UMCf (and therefore the length of the injection well screens) was shorter in these areas and the observed geology in these intervals included a larger proportion of strongly cemented material, which was likely the reason for the decreased injection capacity. If ISB is

selected as a component of the NERT final remedy, pre-design investigations could be performed to collect data for final design and optimization of injection wells, resulting in improved injectate delivery.

- Objective 6 – Verify that ISB implementation and operational components within the alluvium are in line with previous studies or if variations are required based on the large, saturated alluvium targeted, with particular focus on carbon substrate distribution, evaluation of optimal chase water quantities, and injection frequencies required to maintain a biologically active zone for perchlorate and chlorate biodegradation. Data collected indicate the following:
    - Even though the alluvium targeted in this Pilot Study contains a larger saturated alluvium than previously evaluated in other treatability studies, the implementation and operational components related to injection activities into the alluvium are similar to previous studies. This finding adds to NERT's growing knowledgebase of ISB implementation experience.
    - Injection rates and pressures into the alluvium were similar to previous treatability studies that targeted the alluvium. During the first injection event, injection rates into the alluvium averaged approximately 13 gpm with average sustained pressures of approximately 2 psi. At nine of the eighteen alluvial injection wells, sustained pressures of 0 psi were measured throughout the injection event, even at injection rates of up to 23 gpm. By the third injection event, the sustained injection pressures averaged 13 psi, which indicated an increase in injection pressure compared to the first and second injection events. As previously explained in Section 7.3, this small increase in injection pressure is expected with periodic carbon substrate injections. Specifically, as multiple injection events are performed, injection well screens and surrounding filter packs can sometimes accumulate biomass, inorganic precipitates, and/or EVO breakdown compounds (such as oleate). This phenomenon can result in changes to the injectability (i.e., increases in injection pressures required for subsurface distribution and/or decrease in achievable injection rates) and may require injection well maintenance measures to promote injection well longevity and ensure successful long-term operation of ISB. This operational component of implementing ISB has been evaluated as part of the SWF Area Bioremediation Treatability Study (Tetra Tech, 2019b; Tetra Tech, 2022), which will provide valuable data for the forthcoming FS in evaluating the long-term viability and operational considerations of a full-scale ISB remedy. Although a trend of slightly increasing injection pressures was observed during the second and third injection events, all injection wells continued to accept their designed volumes of injectate solution at reasonable injection rates and pressures during all injection events. No injection well maintenance was required during this Pilot Study.
    - Operationally, the primary component in the injection procedures that was different from previous studies was the nested well configuration evaluated in this Pilot Study. As explained above in the discussion regarding Objective 4, injections were performed in both the shallow and deep treatment intervals within each nested injection well cluster at the same time and at generally similar injection rates in an effort to achieve relatively even subsurface distribution within the large thickness of saturated alluvium and account for variability and non-uniform groundwater flow and lithology. The Zone 2 results indicated good vertical distribution within the large thickness of saturated alluvium and therefore, provided valuable data for the effectiveness and implementability evaluation of an ISB remedy in the forthcoming FS.
    - As described in Section 7.3.1, the results from the dose-response monitoring related to the dye injections indicated an average effective porosity of approximately 6 percent, which resulted in no changes to the distribution water requirements from the design. Because the quantity of distribution water directly impacts not only the effectiveness from an injectate distribution standpoint but also the implementability and costs due to the direct relationship to the injection

duration, this was an important data point for the forthcoming FS when evaluating the effectiveness, implementability, and cost of an injection remedy into the alluvium.

- The injection frequency varied during the Pilot Study, with the second injection performed approximately four months after the first injection event and the third injection event performed approximately six months after the second injection event. During the final sampling event of the Pilot Study, samples collected from one cross-gradient and two downgradient monitoring wells (LVWPS-A2-MW05A, LVWPS-A2-MW12A and LVWPS-A2-MW14B) continued to indicate perchlorate concentrations below the PRG of 15 μg/L despite the sampling event being performed eight months after the final injection event. This indicates that the injectate can last for extended periods of time in some areas with groundwater flow rates generally less than 10 ft/day. In areas where higher groundwater flow velocities were present, such as LVWPS-A2-MW08C with an estimated groundwater flow rate of 33 ft/day, perchlorate concentrations generally remained reduced below PRGs for approximately 7 months following the third injection event. Areas with even greater flow rates (generally greater than 50 ft/day), perchlorate concentrations were reduced but not to levels below the PRG. Lastly, performing injections into the saturated alluvium over three injection events was shown to gradually increase the length of time that perchlorate concentrations remaining reduced to below PRGs in select locations. This is likely due to the choice of EVO as a carbon substrate, which because of its chemical properties, tends to gradually coat the soil grains along the injection well transect, creating a more uniform treatment barrier over time. This observation was also observed in the SWF Area Bioremediation Treatability Study, with injection frequencies reducing over time (Tetra Tech, 2019b). In conclusion, the injection frequency in the alluvium for full-scale operations, if ISB is selected as a component of the NERT final remedy, will vary depending on location based on groundwater flow rates in the vicinity of treatment and the extent of heterogeneity of the subsurface.
- An additional operational factor to consider in application of ISB to large, saturated thicknesses of alluvium is the required volume of extracted groundwater to support high injection rates. To maximize vertical distribution of the injectate solution, each individual injection well within the nested injection well configuration received injectate solution simultaneously, with sustainable injection rates of up to 23 gpm at alluvial injection wells at relatively low injection pressures. Therefore, a single dual-nested injection well location could potentially accept an overall injection rate of up to 50 gpm, possibly more depending on the screen length. Six extraction wells (five newly installed 6-inch monitoring wells and one existing 4-inch monitoring well) were utilized during the Pilot Study to achieve a total extraction rate of approximately 300 gpm (Appendix D). The source and supply rate of the water used for injections at full-scale, if ISB is selected as part of the final remedy, will be an important design consideration to maximize injection rates and therefore minimize overall operational costs.

8.0 ZONE 3 SUMMARY AND EVALUATION OF RESULTS

The focus of the Zone 3 study area was to evaluate bioremediation within the coarse-grained facies of the UMCf, referred to as the UMCf-cg, which has not been evaluated in either previous or on-going treatability studies. This lithological unit was encountered within the eastern portion of the Pilot Study area with depths of up to 235 feet bgs due to faulting adjacent to the bedrock outcrop. Application of ISB within the UMCf-cg in Zone 3 not only provides data on effectiveness and implementability of ISB within the UMCf-cg, but also allows for direct comparison of the effectiveness and implementability of ISB in the UMCf encountered within the Zone 1 study area (discussed in Section 6.0).

This section summarizes the Zone 3 objectives, study design, injection activities, geology, hydrogeology, and effectiveness monitoring results.

8.1 OBJECTIVES

Evaluation of ISB within a zone that only focuses on the UMCf-cg, namely Zone 3, allowed for assessment of the following specific objectives as previously outlined in the Work Plan Addendum (Tetra Tech, 2019).

- Determine if ISB can effectively create a biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater within the UMCf-cg and compare the effectiveness with respect to variations in lithology between the UMCf within Zone 1 (discussed in Section 6.0) and UMCf-cg within Zone 3.
- Evaluate ISB implementation and operational components within the UMCf-cg, including injection protocols, achievable injection rates, subsurface distribution of injectate, injection well spacing, and construction methods.
- Determine whether remediation in the UMCf-cg in an area with elevated contaminant concentrations in groundwater and a known upward gradient has an effect on contaminant concentrations in the overlying alluvium groundwater, and if so, whether the effect differs depending on the UMCf lithology (comparison of results from Zones 1 and 3). These data can be used to evaluate the potential effectiveness of remediation of small areas of elevated concentrations in the UMCf-cg with respect to achieving long-term remedial goals for OU-3.
- Determine the approximate length of time that ISB could be expected to affect concentrations in the UMCf-cg and the resulting injection frequency required to maintain these concentration reductions.
- Evaluate if dual-nested injection wells are effective in delivering substrate to large, saturated thicknesses of the UMCf-cg because nested injection wells can be a cost-effective option compared to multiple separate injection wells.

8.2 PILOT STUDY LAYOUT AND WELL DESIGN

Both injection and monitoring wells were installed in the Zone 3 study area as described in Section 5.4. The layout of the injection well transect and monitoring well network was designed to collect data for evaluation of the Zone 3 objectives. **Figure 8** presents the layout of the Zone 3 injection well transect and monitoring well network. Well construction details and soil boring logs for all injection and monitoring wells are provided in Appendix B.

8.2.1 Injection Wells

As presented in the Work Plan Addendum, the injection well transect within the Zone 3 study area was designed to be approximately 200-feet long, consist of eight injection wells spaced approximately 25 feet apart and screened within the UMCf-cg, and oriented perpendicular to groundwater flow. The Zone 3 injection well transect is situated immediately west of the bedrock outcrop and approximately 200 feet east of the Zone 2 study area.

This location was selected based on Phase 1 pre-design data that indicated perchlorate was present in groundwater within the UMCf-cg in a fault zone adjacent to the bedrock outcrop, while ensuring sufficient distance from the Zone 2 study area to avoid overlapping zones. Full design details related to general location and injection well spacing are summarized in the Work Plan Addendum (Tetra Tech, 2019).

An Initial pilot boring installation phase was performed to determine optimal placement of the Zone 3 injection well transect due to the high level of site heterogeneity. Six pilot borings (LVWPS-U3-MW01B through LVWPS-U3-MW06B) were installed in an approximate 300-foot staggered row situated perpendicular to groundwater flow and near existing monitoring well cluster LVWPS-MW222. Pilot borings were installed on approximately 50-foot centers. Each pilot boring was drilled to a depth of up to 175 feet bgs, terminated at the top of the bedrock and subsequently converted to a 4-inch, Schedule 80 PVC monitoring well and screened with 4-inch diameter slotted PVC well screen in the deepest portion of the unconsolidated UMCf-cg. Following well construction and development, groundwater samples were collected and analyzed for perchlorate and chlorate to determine contaminant distribution along the pilot boring transect. Additionally, slug testing and NMR logging were performed to further delineate localized preferential flow pathways. These results were used to select the location of the 200-foot-long injection well transect, which ultimately was situated in an area with the highest groundwater perchlorate and chlorate concentrations in the UMCf-cg as well as the most heterogeneous portion of the investigated pilot boring area. All of the monitoring wells installed as part of the pilot boring phase ultimately became part of the effectiveness monitoring program for the Pilot Study, except LVWPS-U3-MW04B (installed on the far western boundary of the Zone 3 study area).

Following completion of the pilot boring installation and testing, the eight Zone 3 injection wells were installed in either a single, dual-nested well, or triple-nested configuration (multiple separately screened injection wells installed within the same borehole). The screen length and type of well installed varied to target the large, saturated thickness of the unconsolidated UMCf-cg that contained elevated perchlorate and chlorate concentrations in groundwater. The injection well depth for the one single injection well was 115 feet bgs. Each nested pair of the four dual-nested injection wells averaged 113 feet bgs for the shallow UMCf-cg (designated as "A" wells) and 148 feet bgs for the deep UMCf-cg (designated as "B" wells). Each nested pair of the three dual-nested injection wells averaged 111 feet bgs for the shallow UMCf-cg (designated as "A" wells), 143 feet bgs for the deep UMCf-cg (designated as "B" wells), and 175 feet bgs for the deepest UMCf-cg (designated as "C" wells). Injection well screened intervals were selected to target the impacted portion of the unconsolidated UMCf-cg which varied in thickness from 35 to 90 feet. Injection well construction details, including total depths and screened intervals, are provided in Table B.1.

8.2.2 Effectiveness Monitoring Wells

Twelve monitoring well clusters were installed throughout the Zone 3 study area at varying distances upgradient and downgradient from the injection well transect to provide an effective monitoring well network to meet the detailed study objectives and determine remediation effectiveness following ISB injections. The effectiveness monitoring well layout consisted of monitoring wells located in clusters at two upgradient and ten downgradient locations within the Zone 3 study area. Monitoring well cluster LVWPS-MW212C/D, which was installed as part of Phase 1 pre-design activities, was also incorporated into the effectiveness monitoring program, and is included in the 12 locations. The names of Zone 3 monitoring wells screened in the alluvium included an "LVWPS-A3" prefix, while Zone 3 monitoring wells screened in the UMCf-cg included an "LVWPS-U3" prefix. Due to the large saturated thickness of the UMCf-cg in Zone 3, the monitoring well names also included a suffix of either an "A", "B", or "C", which indicated wells screened in the shallow, deep, or deepest UMCf-cg, respectively. Additional details regarding the monitoring well layout are noted as follows:

- Two monitoring well clusters (consisting of one monitoring well screened in the alluvium and two monitoring wells screened in different intervals within the UMCf-cg) were installed approximately 55 and 60 feet upgradient from the injection well transect to determine the contaminant concentrations in groundwater migrating through the injection well transect and refine the mass flux entering the Zone 3 study area.

- Ten downgradient monitoring well locations were included in the effectiveness monitoring program to monitor ISB effectiveness and estimate the zone of influence of the carbon substrate following injections in the Zone 3 study area. These 10 monitoring well locations were positioned throughout the study area at varying distances between approximately 25 and 150 feet downgradient of the injection well transect and positions both directly in line and off-set from the individual injection wells to evaluate remediation with respect to the heterogeneity and preferential flow paths. These 10 monitoring well clusters included a total of 23 monitoring wells, which consisted of the installation of 19 new monitoring wells and incorporation of the four pilot boring wells. In addition, approximately four months after the first injection event, existing monitoring wells LVWPS-MW212C and LVWPS-MW212D, which are located approximately 250 feet downgradient of the injection well transect, were incorporated into the monitoring program to allow for monitoring farther downgradient based on the effectiveness monitoring results (discussed in Section 8.7.1.1.2). Due to the large, saturated thickness of the targeted unconsolidated UMCf-cg within the Zone 3 study area, seven of the 10 monitoring locations included two monitoring wells screened in different intervals within the unconsolidated UMCf-cg. In addition, five of the 10 monitoring locations included one monitoring well screened within the alluvium to monitor for potential reductions in the alluvium from injections into the underlying UMCf-cg.
- In addition to the 12 effectiveness monitoring well clusters listed above, two clusters of dose-response monitoring wells consisting of three monitoring wells each, were installed immediately downgradient of the injection well transect (less than 5 feet away) to support the tracer dye study presented in Section 5.4.3 of the Work Plan Addendum. The dose-response monitoring well cluster within the western half of the study area included two dose-response monitoring wells (LVWPS-U3-DR01A and LVWPS-U3-DR01B) screened in the UMCf-cg across the same depth intervals as the nearby injection wells and one dose-response monitoring well screened in the overlying alluvium (LVWPS-A3-DR01) to evaluate if injectate was entering the alluvium in the immediate vicinity of the injection well transect. Due to the large, saturated thickness encountered along the eastern side of the Zone 3 study area, the eastern most dose-response monitoring well cluster consisted of three dose-response monitoring wells (LVWPS-U3-DR01A/B/C), all of which were screened in the UMCf-cg across the same depth intervals as the nearby triple-nested injection wells.

8.3 ZONE 3 INJECTIONS

As presented in Section 5.5, two carbon substrate injection events were performed as part of Zone 3 Pilot Study activities. The following sections provide details of the two injection events conducted at Zone 3 injection wells screened in the unconsolidated UMCf-cg. Injection summary tables including injection volumes, flow rates, and pressures for each injection well are provided in Appendix D. As described in Section 5.7.1, the five extraction wells installed in the alluvium outside of the remediation zones (**Figure 5**) during Phase 2 were sampled during the baseline sampling event in September/October 2020 prior to the first injection event and on a quarterly basis thereafter to determine contaminant concentrations in monitoring wells used for extraction operations during injections. Data for all parameters for groundwater samples collected from extraction wells are presented in the comprehensive data tables provided in Appendix J, Table J.1. Field logs from all groundwater sampling events are provided in Appendix I and the DVSR is provided in Appendix K.

8.3.1 Injection Details

The first injection event in Zone 3 was performed from December 16 to December 18, 2020. A brief step-rate injection test using extracted groundwater only was performed prior to initiating carbon substrate injections. The step-rate injection test indicated that the target initial injection rate of 5 gpm was possible at relatively low sustained pressures (up to a maximum of 12 psi).

During the first injection event, approximately 31,500 gallons of carbon substrate solution were injected into the Zone 3 injection wells. The solution consisted of approximately 6,305 gallons of EOS® PRO, 44 gallons of glycerin, 40 gallons of phosphate solution, 80 pounds of sodium sulfite, and 25,259 gallons of injectate dilution water (extracted groundwater from nearby extraction wells). In addition, fluorescein dye was added to the carbon substrate solution to achieve a target concentration of 400 ppb. As summarized in the tables in Appendix D, the quantities of EOS® PRO varied between injection wells based on the screen lengths and thickness of the targeted formation at each injection location. Upon completion of carbon substrate injections, approximately 14,000 gallons of water were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to refine the effective porosity values and recalculate the corresponding distribution water quantities for the program. These results indicated that the field-determined effective porosity was less than originally estimated during the design for the Zone 3 UMCf-cg, with a revised calculated effective porosity of one percent in the shallow UMCf-cg from 88-110 feet bgs, two percent in the deep UMCf-cg from 110-150 feet bgs, and three percent in the deepest UMCf-cg from 150 to 175 feet bgs. As a result, the Zone 3 UMCf-cg distribution water volumes were proportionately reduced using the new porosity estimates. Where the effective porosity resulted in a small volume of designed distribution water in the shallow UMCf-cg, a minimum of six borehole volumes was used to calculate the volume of distribution water. During injections, both flow rate and pressure were measured at each injection well. Injection rates averaged approximately 4 gpm while sustained pressures generally averaged 12 psi. In general, sustained injection pressures observed were higher in the eastern portion of the transect, which is consistent with the higher proportion of fine-grained UMCf interbedded with the UMCf-cg observed during drilling and the lower hydraulic conductivity of the monitoring wells in this area (discussed in Sections 8.4 and 8.5). Sixteen of the 18 injection wells received their targeted volume of carbon substrate solution during the first injection event. Two injection wells in the easternmost injection well cluster LVWPS-U3-IW08A and LVWPS-U3-IW08B indicated dwindling injection flow rates at sustained pressures of 35 psi towards the end of the carbon substrate injection period and therefore, did not reach their designed targets.

The second injection event in Zone 3 was performed from October 22 to October 24, 2021, approximately 10 months after the first injection event. The timing of the second injection event was based on the beginning of perchlorate, chlorate, and nitrate concentration rebounds in conjunction with a decrease in TOC concentrations to near baseline conditions in samples collected from key monitoring wells (further discussed in Section 8.7). During the second injection event, approximately 22,800 gallons of carbon substrate solution comprising 4,829 gallons of EOS® PRO, 40 gallons of glycerin, 23 pounds of sodium sulfite, and 19,020 gallons of injectate dilution water (extracted groundwater from nearby extraction wells) were injected into Zone 3 injection wells. The quantity of EOS® PRO was approximately 85 percent of that used in the first injection event. The objective of reducing the EOS® PRO 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 carbon substrate injections, a total of 18,598 gallons of water were injected into the injection wells to optimize the distribution of carbon substrate both within the injection well transect and in the vicinity of the injection area. This higher volume of distribution water during the second injection event (compared to the first event) was selected to maintain an overall injection volume of approximately one pore volume at each injection well, despite the lower target carbon substrate solution volume (85 percent of the first injection event). Results from groundwater samples collected from extraction wells prior to the second injection event indicated a slightly elevated average perchlorate concentration of 4,540 μg/L compared to the average perchlorate concentration of 2,900 μg/L measured prior to the first injection event. Therefore, the concentration of perchlorate in the injectate solution and follow-up distribution water during the second injection event may have been higher than the previous injection event.

During the second injection event, injection rates averaged approximately 3 gpm while sustained pressures generally averaged 16 psi. Fifteen of the 18 injection wells received their targeted volume of carbon substrate solution during the second event. As with the first injection event, the exception was triple nested injection well LVWPS-U3-IW08A/B/C, where injection flow rates reduced to an average of approximately 1 gpm at the maximum allowable injection pressure of 45 psi. Injection rates improved during injection of follow up distribution water and those designed targets were met. This difference in injection well performance between the carbon substrate solution and the distribution water has been observed during previous ISB applications and is likely related to the difference in viscosity between the two injectate fluids. Although a reduction in injection well performance was observed at LVWPS-U3-IW08A/B/C during the second injection event, the average hydraulic conductivity of the UMCf-cg measured during post-injection slug testing in monitoring wells LVWPS-U3-MW03B and LVWPS-U3-MW03C, which are located 25 feet downgradient of this injection well cluster, was similar to baseline conditions. This result suggests the apparent decrease in permeability was limited to the immediate vicinity of the injection wells.

8.3.2 Hydraulic Response

The injections into Zone 3 injection wells were under pressure, which resulted in a visible rise in hydraulic head in surrounding monitoring wells. Transducers were installed in monitoring wells LVWPS-U3-MW03A, LVWPS-U3-MW09, and LVWPS-U3-MW13A, all of which are located approximately 25 feet downgradient of the injection well transect. Transducer data collected indicated a rise in hydraulic head ranging from approximately 8 feet to 14 feet in the shallow UMCf-cg. The response increased towards the east, with increasing proximity to the bedrock outcrop. A rise in hydraulic head of approximately 18 feet was observed in monitoring wells screened in the deeper UMCf-cg (LVWPS-U3-MW03B, LVWPS-U3-MW03C, and LVWPS-U3-MW13B) during the first injection event. The significant rise in hydraulic head observed in downgradient monitoring wells screened in the UMCf-cg indicates a low effective porosity, which was confirmed through dye sampling in the dose-response monitoring wells and subsequent recalculation of effective porosity as described in Section 5.5.1. This hydraulic response was weaker than that observed in Zone 1 UMCf, where dye-tagged water rose to ground surface elevations at some monitoring locations (discussed in Section 6.3.3). The weaker response in Zone 3 was expected based the more permeable nature of the UMCf-cg in Zone 3 compared to the UMCf in Zone1.

8.4 ZONE 3 GEOLOGY

Data from the soil boring and monitoring well installation activities were compiled to provide a description of the geology for the Zone 3 study area. A geologic cross-section of Zone 3 is presented on **Figure 10c**. Bedrock outcrops in the eastern portion of the study area adjacent to Zone 3 as a result of historical faulting in the area, which influences groundwater flow in the area. The lithology encountered during drilling suggests that the bedrock outcrop on the eastern side of the Pilot Study area is part of a fault-bounded block and that unconsolidated valley-fill sediments of the alluvium and UMCf were deposited on the western, down-dropped portions of the fault zone.

Within the Zone 3 study area, the alluvium ranges from silty sand to sandy gravel with minor lenses of sandy silt that extends to approximately 80 feet bgs. In general, the alluvium in Zone 3 is more homogenous than the alluvium present within the Zone 1 and Zone 2 study areas. A small paleochannel filled with coarser sediments is present in the vicinity of injection well LVWPS-U3-IW04A/B and appears to have migrated to the east over time, similar to the larger paleochannel present in the Zone 2 study area (discussed in Section 7.4). Near the bedrock outcrop in the Zone 3 study area, the UMCf coarsens and is interbedded with a wedge of alluvial fan material, which likely represents coarse-grained facies of the UMCf (UMCf-cg). The UMCf-cg consists of silty sand with up to 10 percent angular to subangular gravel interbedded with fine-grained UMCf. These gravels are commonly angular carbonate clasts, suggesting the sediments originated locally from the Horse Springs formation, which is mapped as carbonates and calcareous siltstone/shale where it outcrops in the Pilot Study area (Bell and Smith, 1980). In general, the deepest portions of the UMCf-cg in Zone 3 tend to be coarser with higher proportions of sand and gravel compared to the shallower UMCf-cg, which typically contains a higher proportion of fine-grained UMCf. In addition, the UMCf-cg in the vicinity of nested injection wells LVWPS-U3-IW05, LVWPS-U3-IW06, and

LVWPS-U3-IW07 tends to be interbedded with relatively more fine-grained UMCf layers compared to the rest of the Zone 3 injection well transect.

In the eastern portion of the Pilot Study area, bedrock was encountered below the UMCf-cg. Bedrock encountered at depth was primarily sandstone and siltstone, which is consistent with mapped lithologies of the Horse Springs formation (Plume, 1989). The depth to bedrock, which ranges from approximately 100 feet bgs to 235 feet bgs, is likely fault controlled as shown on **Figure 10c**. Faulting adjacent to the bedrock outcrop has resulted in deep, unconsolidated UMCf-cg up to 235 feet bgs on the western, down-dropped side of the fault zone. As a result, the saturated thickness of the UMCf/UMCf-cg in the Zone 3 study area ranges from approximately 45 feet near injection well LVWPS-U3-IW01 to more than 95 feet near injection well LVWPS-U3-IW08A/B/C.

8.5 ZONE 3 HYDROGEOLOGY

As discussed in Section 8.4, Zone 3 is located in the eastern portion of the Pilot Study area adjacent to the bedrock outcrop. The hydrogeology of the Zone 3 area is controlled by geologic structures, specifically the bedrock outcrop and the deep fault zone underlying Zone 3. This bedrock outcrop forms a hydrogeologic barrier to flow due to the significantly lower hydraulic conductivity of the consolidated bedrock materials relative to the unconsolidated alluvial and UMCf-cg sediments. As a result, the primary groundwater flow direction tends to be around the bedrock outcrop, paralleling the contact of the bedrock with the unconsolidated sediments of the alluvium and UMCf-cg. Although the Zone 3 fault likely affects groundwater flow at depth, the fault does not appear to propagate into the UMCf-cg sediments due to their unconsolidated nature. Because of this, the Zone 3 fault does not appear to have the same clear effects on groundwater flow and cross-connections between the UMCf-cg and the alluvium that the faulting has within the Zone 2 study area (discussed in Section 7.5). Some migration of water from the UMCf-cg is still expected due to the possibility of discharge from the UMCf-cg into the overlying alluvium in the vicinity of the small paleochannel that crosses the injection well transect in the vicinity of nested injection well LVWPS-U3-IW04A/B (**Figure 10c**).

Figure 8 includes a groundwater potentiometric surface of the unconsolidated UMCf-cg in Zone 3 during baseline sampling in October 2020. As with the alluvium, the groundwater flow within the UMCf-cg roughly parallels the bedrock outcrop, with a calculated average north-northwest hydraulic gradient of 0.005 ft/ft in the vicinity of the Zone 3 injection well transect. Downgradient of the injection well transect, groundwater flow turns to the north-northeast around the bedrock outcrop. Groundwater levels were gauged on a quarterly basis during the Pilot Study, and these subsequent synoptic groundwater level gauging events performed during the effectiveness monitoring period indicated groundwater flow direction generally remained consistent over time with the baseline October 2020 conditions. Depth to water measurements are provided in Table I.1 in Appendix I.

As discussed in Section 8.1, one of the objectives of the Pilot Study in Zone 3 was to determine whether remediation in the UMCf-cg in an area with upward vertical gradients has an effect on contaminant concentrations in the overlying alluvium groundwater. Based on the available Phase 1 pre-design data collected from monitoring well cluster LVWPS-MW222A/B/C, the vertical gradient between the alluvium and UMCf-cg was expected to be upward, similar to Zone 1. However, analysis of the groundwater elevations of the Zone 3 monitoring well network installed during Phase 2 activities indicated that the magnitude of the vertical gradients between the alluvium and the UMCf-cg is generally small and downward, ranging from about 0.001 ft/ft to 0.014 ft/ft. These relatively weak vertical gradients are reflective of reasonably good connections between the various lithological units. Vertical gradients within the UMCf-cg varied from weakly upward to weakly downward, with the greatest upward gradient of 0.041 ft/ft observed in the deep UMCf-cg adjacent to the Zone 3 fault and the bedrock outcrop at LVWPS-MW222.

8.6 ZONE 3 HYDROGEOLOGICAL EVALUATION

As previously explained in Section 5.6, an aquifer testing program was implemented to obtain information regarding aquifer hydraulic conductivity, groundwater flow velocity, and total and effective porosity in the Pilot Study area. Additionally, a fluorescein dye was injected during the first Zone 3 injection event and samples collected post-injection to periodically monitor for the presence of dye. This additional dye data aided in the evaluation of study objectives including ROI of the injection wells, travel times of the injectate/dye, upflux from the UMCf-cg into the overlying alluvium, and the effective porosity of the formation near the injection well transect. This section summarizes the results from the aquifer testing activities (i.e., NMR logging, borehole dilution testing, slug testing, long-term transducer data downloads, and tracer dye study) performed in the Zone 3 study area during the Pilot Study. The supporting summary memos for the tracer study, NMR logging, borehole dilution testing, and slug testing are presented in Appendices C, E, F, and G, respectively.

8.6.1 Nuclear Magnetic Resonance Logging Results

NMR logging, which was described in Section 5.6.1, was performed in each of the six pilot monitoring wells within Zone 3 to further delineate localized preferential flow pathways within the Pilot Study areas prior to selecting the final placement of the Zone 3 injection well transect. The high-resolution estimates of hydraulic conductivity were compared to the lithologic logs and aquifer testing results for each pilot boring to assess the possibility of preferential flow. Results from NMR logging are presented in Appendix E. Although the transition is not as distinct as the alluvium-UMCf contact in Zone 1, the NMR profiles clearly indicate the transition from alluvium to UMCf-cg in Zone 3. The water content increased at the UMCf-cg contact to approximately 30-45 percent, reflecting the increased proportion of clay and associated capillary water content in the UMCf-cg relative to the alluvium. These lower water content measurements in the UMCf-cg in Zone 3 compared to the water content of greater than 50 percent in Zone 1 are consistent with the logged lithology of this coarser grained facies of the UMCf. Average mobile porosities (similar to effective porosity) measured in the UMCf-cg at Zone 3 pilot borings was 5 percent. This estimate of mobile porosity in Zone 3 from NMR logging was higher than the effective porosity of approximately 2 percent calculated at the dose-response monitoring wells during injection activities as part of the tracer study (discussed in Section 8.6.4). Unlike the results from Zone 1 pilot borings, the NMR data for Zone 3 do appear to better reflect the logged formation, and the NMR estimates of hydraulic conductivity generally agreed with estimates derived using slug testing within an order of magnitude.

8.6.2 Borehole Dilution Testing Results

Using the procedures presented in Section 5.6.2 and Appendix F, single-borehole dilution tests were performed in seven monitoring wells screened in the UMCf-cg (LVWPS-U3-MW03A/B/C, LVWPWS-U3-MW10A/B, and LVWPS-U3-MW13A/B) and one monitoring well screened in the alluvium (LVWPS-A3-MW10) to evaluate groundwater flow velocities in the Zone 3 study area. Groundwater flow rates at alluvial monitoring well LVWPS-A3-MW10 measured 14 feet/day, which is similar to other flow rates observed in the alluvium in the southern portion of Pilot Study area (i.e., not in the immediate vicinity of the Wash). The average groundwater flow rate in the shallow UMCf-cg in the Zone 3 study area was determined to be approximately 0.1 ft/day, based on single-borehole dilution tests in wells LVWPS-U3-MW03A, LVWPWS-U3-MW10A, and LVWPS-U3-MW13A. The calculated flow velocities for the shallow UMCf-cg in the Zone 3 were similar to those measured in the shallow UMCf in Zone 1. The groundwater flow rate in the deeper UMCf-cg at these same monitoring well clusters was more variable, ranging from 0.02 ft/day to 0.7 ft/day. The highest groundwater flow velocities were measured at monitoring wells LVWPS-U3-MW03B and LVWPS-U3-MW03C, which are in the easternmost downgradient portion of the Zone 3 study area adjacent to the bedrock outcrop where secondary porosity may exist due to faulting (**Figure 8**). Groundwater flow velocity ranges calculated from Phase 2 borehole dilution testing are comparable to those calculated using the baseline slug test hydraulic conductivity and effective porosity estimates from the tracer study, which ranged from 0.06 to 0.7 ft/day. A complete summary of the borehole dilution tests and results is provided in Appendix F.

8.6.3 Slug Tests

Using the procedures described in Section 5.6.3 and Appendix G, slug tests were performed in several phases during Phase 2 implementation to estimate location-specific aquifer hydraulic conductivity within the Zone 3 study area. Appendix G presents results from the slug testing events conducted as part of Phase 2 of the Pilot Study.

The first slug testing event was performed from March 2 to March 3, 2020 to test the six newly installed pilot boring monitoring wells prior to final selection of the Zone 3 injection well transect location, as discussed in Section 8.2.1. Based on slug testing of the pilot boring monitoring wells, the hydraulic conductivity of the UMCf-cg ranged from 0.2 ft/day in monitoring well LVWPS-U3-MW01B to 4.3 ft/day in monitoring well LVWPS-U3-MW03B, with an average hydraulic conductivity of approximately 1.3 ft/day. In general, the estimated hydraulic conductivity of the UMCf-cg measured at the six pilot borings increased from west to east, with increasing proximity to the bedrock outcrop. The final location of the Zone 3 injection well transect, which was situated to be upgradient from LVWPS-U3-MW03B and LVWPS-U3-MW06B where the highest hydraulic conductivities were observed, was in part selected based on these pilot boring slug test results.

After installation of the Zone 3 effectiveness monitoring well network, slug testing was performed at all newly installed monitoring wells in two mobilizations on June 21 to June 24, 2020 and October 29 to October 30, 2020. This baseline slug testing event indicated an average estimated hydraulic conductivity of the shallow UMCf-cg in Zone 3 of 1.4 ft/day based on the results of tests at monitoring wells with mid-screen depths of between approximately 88 and 110 feet bgs. This estimated hydraulic conductivity for the shallow UMCf-cg is similar to the hydraulic conductivity of the UMCf in Zone 1. In contrast, baseline slug testing indicated an average estimated hydraulic conductivity of 3.3 ft/day and ranging from 0.5 ft/day to 17 ft/day for the deeper UMCf-cg, based on results from monitoring wells screened between approximately 110 and 175 feet bgs. The more variable hydraulic conductivities observed in Zone 3 compared to Zone 1 likely relate to the heterogeneity of the UMCf-cg shown on **Figure 10c**. The highest hydraulic conductivities estimated for the UMCf-cg of 10 ft/day and 17 ft/day were measured in the western portion of the Zone 3 study area at monitoring wells LVWPS-U3-MW09 and LVWPS-U3-MW10B, respectively, where the UMCf-cg tends to be coarser with fewer fine-grained beds.

Following carbon substrate injections, slug tests were performed periodically throughout the Pilot Study to examine subsurface conductivity changes following carbon substrate injections. Three post-injection slug testing events were performed on seven Zone 3 monitoring wells in June/July 2021, January 2022, and June/July 2022. The mean hydraulic conductivities observed during post-injection testing were within the same order of magnitude as the baseline hydraulic conductivities for six of the seven monitoring wells evaluated post-injection. However, monitoring well LVWPS-U3-MW09, which was located within approximately 25 feet downgradient of the injection well transect in Zone 3, indicated a decreasing trend in post-injection hydraulic conductivity from approximately 10 ft/day during baseline slug testing to 0.1 ft/day during the third and final post-injection slug testing event. Although post-injection hydraulic conductivity values indicated decreases at one location, the injection rates during the second injection event performed in Zone 3 did not show comparable decreases. LVWPS-U3-MW09 was located within the ROI of the carbon substrate injections, with results from groundwater sampling indicating an increase in TOC concentrations following injections confirming the arrival of carbon substrate solution. All other monitoring wells downgradient of the injection well transects experienced no significant change in hydraulic conductivity.

8.6.4 Dye Results

As presented in Section 5.6.5, the Pilot Study design included injection of fluorescein dye during the first Zone 3 injection event and periodic monitoring to provide data to evaluate tracer study objectives including the ROI of injection wells, travel times of the injectate/dye, upflux from the UMCf-cg to the overlying alluvium, and the effective porosity of the formation near each injection well transect. The tracer dye monitoring program included qualitative (i.e., presence/absence) analysis of charcoal samplers that were installed in monitoring wells during injection activities and between effectiveness monitoring events, as well as quantitative analysis of tracer dye concentration in groundwater samples. If tracer dye was detected in the charcoal sampler, indicating the arrival of tracer dye at the monitoring location, the groundwater sample collected from that same monitoring well location was then analyzed to determine the dye concentration in the groundwater. This two-step analysis process allowed for presence/absence dye analysis at all monitoring locations and also permitted quantitative analysis where the dye was found to be present. A complete discussion of the dye study, including dye analytical results, is provided in Appendix C.

During injection activities, the fluorescein-tagged carbon substrate solution appeared in samples collected from all five dose-response monitoring wells screened in the UMCf-cg (LVWPS-U3-DR01A, LVWPS-U3-DR01B, LVWPS-U3-DR02A, LVWPS-U3-DR02B, and LVWPS-U3-DR02C). As described in Section 5.5.1, real-time dye concentration data collected from the dose-response monitoring wells during the active carbon substrate injections were used to estimate the effective porosity of the UMCf-cg in Zone 3. These results indicated that the field-determined effective porosity was less than originally estimated during the design of injection quantities for the Zone 3 UMCf-cg, with revised calculated effective porosities for the shallow UMCf-cg (88-110 feet bgs) and deep UMCf-cg (110-150 feet bgs) and deepest UMCf-cg (150 – 175 feet bgs) of 1 percent, 2 percent, and 3 percent, respectively. Fluorescein was observed within one week of injection activities in samples collected from monitoring wells LVWPS-U3-MW03B, LVWPS-U3-MW03C, LVWPS-U3-MW09, and LVWPS-U3-MW13B, which were all located approximately 25 feet downgradient of the injection well transect. Fluorescein was not observed in samples collected from LVWPS-U3-MW03A or LVWPS-U3-MW13A, which were screened in the shallow UMCf-cg at these same locations.

Migration of fluorescein downgradient was faster in the UMCf-cg compared to the UMCf, with fluorescein detected in charcoal samplers collected from monitoring wells up to 150 feet downgradient of the injection well transect during the first month after injection of the tracer dye. Fluorescein dye may have migrated farther than 150 feet, but the monitoring well network was not optimized to detect movement of fluorescein greater than 150 feet downgradient. Groundwater velocities calculated from tracer peaks were faster than those estimated for the UMCf in Zones 1 and 2, and typically groundwater velocities ranged from less than 0.2 ft/day to 2 ft/day. Fluorescein generally migrated quicker in the deep UMCf-cg with respect to the varying depths in the UMCf-cg. For example, samples collected from monitoring well cluster LVWPS-U3-MW10A/B, which was located approximately 100 feet downgradient of the injection well transect, indicated fluorescein detections in groundwater from deep UMCf-cg monitoring well LVWPS-U3-MW10B approximately 2 months after injection. For comparison, fluorescein was not detected in samples collected from shallow monitoring well LVWPS-U3-MW10A until approximately 4 months after the injection event. These dye monitoring results for groundwater at monitoring well cluster LVWPS-U3-MW10A/B suggests groundwater flow rates of approximately 1 ft/day in the UMCf-cg, which is higher than the estimated flow velocities from borehole dilution testing of approximately 0.1 ft/day. This difference may in part reflect the difference between flow at the natural gradient of the aquifer during borehole dilution testing compared to the tracer study results, which would be influenced by pressurized injection of fluorescein-tagged injectate solution.

Lastly, fluorescein generally did not migrate into the overlying alluvium, which is consistent with the weak, downward vertical gradient between the alluvium and the UMCf-cg in the Zone 3 study area (discussed in Section 8.5). Fluorescein was detected in samples collected from one Zone 3 monitoring well screened in the alluvium, namely, LVWPS-A3-MW12, which was located approximately 150 feet downgradient of the injection well transect. The relatively weak vertical gradients are reflective of reasonably good connections between the various lithological units. Therefore, localized migration into the alluvium near LVWPS-A3-MW12 is consistent with the erosional contact and the lack of barriers to flow between the alluvium and the UMCf-cg.

8.7 EFFECTIVENESS MONITORING RESULTS

As explained in Section 5.7, groundwater samples were collected on a monthly and bimonthly basis and analyzed for a variety of constituents to evaluate the aquifer's response related to ISB injections into the UMCf-cg in the Zone 3 study area. 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 these parameters. Because perchlorate is the primary chemical constituents associated with this Pilot Study, Section 8.7.1 presents a detailed discussion of the perchlorate degradation response, an estimate of perchlorate distribution, and an estimate of perchlorate mass destroyed during the Pilot Study. Other significant constituents, including chlorate, nitrate, and TOC, are discussed in Sections 8.7.2 through 8.7.4, with a collective summary of these primary parameters results presented in Section 8.7.5. Additional parameters, including DO, ORP, pH, sulfate, sulfide, metals, and methane, have also been evaluated and are discussed in Section 8.7.6, while an evaluation of the groundwater microbial analytical results is provided in Section 8.7.7. Data for all parameters are presented in the comprehensive data tables provided in Appendix J, Tables J.1 through J.3. Data for perchlorate, chlorate, nitrate, TOC, arsenic, phosphorus, DO, and ORP are depicted graphically in individual well trend profiles provided in Appendix L, Figures L.88 through L.119. Field logs from all groundwater sampling events are provided in Appendix I and the DVSR is provided in Appendix K.

8.7.1 Perchlorate

Perchlorate concentrations in groundwater were evaluated throughout the study to monitor concentration changes by comparing the baseline (pre-injection) sampling event results to those from subsequent sampling events performed following each of the two injection events into the UMCf-cg within the Zone 3 study area. This monitoring program included monitoring wells located at significant distances downgradient of the injection well transect, where concentration reductions may be minimal due to the limited study duration and short injection well transect length that likely results in migration of groundwater into the study area that did not pass directly through the biologically active zone. As such, this limits the extent of farther downgradient treatment that can be observed as part of this small-scale Pilot Study. Evaluations of the perchlorate degradation response, perchlorate distribution throughout the Zone 3 study area, and estimates of perchlorate mass removal are presented in the subsequent sections. Perchlorate concentration data collected from the Zone 3 study area are summarized in Appendix J, Tables J.1 and J.7 and graphically depicted in Appendix L, Figures L.88 through L.119 **Figures 16a-c through 18a-c** present perchlorate plume interpretations for the shallow, deep, and deepest extents of the UMCf-cg, respectively, within the Zone 3 study area, which are discussed in Section 8.7.1.2.

8.7.1.1 Perchlorate Degradation Response

This section provides a summary of the baseline conditions and subsequent perchlorate degradation response that was observed following each of the two injection events that were summarized in Section 8.3. Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages. ***Table 7*** summarizes the average and maximum perchlorate concentration changes in groundwater observed in monitoring wells located upgradient and downgradient of the injection well transect throughout the study duration. Analytical data used in the calculations for concentration changes during the Pilot Study are presented in Appendix J, Table J.1. A detailed summary of percentage change in perchlorate concentrations compared to baseline concentrations for all Zone 3 monitoring wells is provided in Appendix J, Table J.7.

Table 7 Zone 3 Perchlorate Concentration Changes During Pilot Study

Sampling Event	Event Description	Monitoring Well Location							
		55 to 60 Feet Upgradient of Injection Well Transect		25 Feet Downgradient of Injection Well Transect		50 to 100 Feet Downgradient of Injection Well Transect		150 to 250 Feet Downgradient of Injection Well Transect	
		No. of Wells = 4		No. of Wells = 6		No. of Wells = 9[1]		No. of Wells = 4[2]	
		Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
After Injection Event 1	Month 1	4%	-7%	-49%	-99%	-31%	-99%	-42%	-68%
	Month 2	2%	-7%	-45%	-99%	-21%	-99%	-56%	-86%
	Month 3	-9%	-20%	-44%	-99%	-6%	-99%	-62%	-86%
	Month 4	-8%	-18%	-47%	-99%	-25%	-99%	-37%	-99%
	Month 6	-10%	-13%	-46%	-99%	-2%	-99%	-18%	-83%
	Month 8	1%	-8%	-39%	-99%	-6%	-99%	-13%	-84%
After Injection Event 2	Month 11	-29%	-48%	-69%	-99%	-19%	-99%	-51%	-88%
	Month 12	-8%	-13%	-64%	-99%	-11%	-99%	-18%	-84%
	Month 13	-18%	-33%	-59%	-99%	-33%	-99%	-25%	-85%
	Month 14	-14%	-20%	-69%	-99%	2%	-99%	-10%	-84%
	Month 16	-14%	-20%	-55%	-99%	-6%	-99%	-19%	-83%
	Month 18	-14%	-20%	-51%	-99%	-8%	-99%	-7%	-84%

Notes:
1. The baseline perchlorate concentration measured in groundwater collected from monitoring well LVWPS-U3-MW05B was an outlier of 9.4 µg/L, which resulted in anomalously high reports of calculated percent change from baseline. Therefore, results for LVWPS-U3-MW05B have been excluded.
2. During the first three months of monitoring, only two monitoring wells LVWPS-U3-MW12A and LVWPS-U3-MW12B, which are located 150 feet downgradient of the injection well transect, are included. Based on the effectiveness monitoring results indicating concentration reductions in samples collected from monitoring wells located 150 feet downgradient, monitoring wells LVWPS-MW212C and LVWPS-MW212D, which are located approximately 250 feet downgradient of the injection well transect, were added to the effectiveness monitoring network.
3. Percentage change in perchlorate concentration is calculated relative to the pre-injection baseline groundwater sampling event in September/October 2020 (labeled as event BL04 in Appendix J, Table J.1). Increases in perchlorate concentrations relative to baseline concentrations are represented as positive percentages, while decreases in perchlorate concentrations relative to baseline concentrations are represented as negative percentages.
4. The calculation for average concentration change accounts for both increases and decreases in concentrations compared to baseline.
5. The maximum change shown is the most significant reduction in concentration compared to baseline concentrations and is represented by the most negative percentage calculated.

8.7.1.1.1 Baseline Groundwater Results

Groundwater samples were collected from monitoring wells screened in the alluvium and both the shallow and deep UMCf-cg in September/October 2020 as part of baseline sampling activities. Perchlorate concentrations in groundwater ranged from 78 μg/L to 200 μg/L in the alluvium, 9.4 μg/L to 15,000 μg/L in the shallow UMCf-cg, 350 μg/L to 8,400 μg/L in the deep UMCf-cg, and 3,800 μg/L to 6,100 μg/L in the deepest portions of the UMCf-cg (generally from 150 to 175 feet bgs). The highest detection of 15,000 μg/L was measured in a groundwater sample collected from LVWPS-U3-MW08A, which is located approximately 60 feet upgradient from the injection well transect and screened in the UMCf-cg from approximately 118 to 143 feet bgs.

8.7.1.1.2 Perchlorate Degradation Response Following Injection Event 1

Following completion of the first injection event in December 2020, groundwater sampling was performed monthly for the first four months and then reduced to bimonthly sampling until the second injection event in October 2021. This resulted in groundwater sampling events being conducted during Months 1, 2, 3, 4, 6, and 8 following the first injection event. Groundwater samples were collected from all Zone 3 monitoring wells screened in both the alluvium and shallow/deep UMCf-cg (as described in Section 8.2.2) to monitor for potential contaminant concentration reductions resulting from ISB injections into the UMCf-cg within the Zone 3 study area. Results following the first injection event are summarized below.

- Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW01B, which is located approximately 60 feet cross-gradient of the Zone 3 injection well transect, were similar to the baseline concentration of 2,000 μg/L, ranging from 1,900 μg/L to 2,400 μg/L following the first injection event (Appendix L, Figure L.92). Similarly, perchlorate concentrations in the samples collected from the upgradient monitoring wells screened in the UMCf-cg and located approximately 60 feet upgradient from the injection well transect also remained relatively stable following the first injection event (Appendix L, Figures L.88 through L.91). For example, the perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW07A ranged from 220 μg/L to 300 μg/L compared to the baseline concentration of 250 μg/L, and the perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW07B ranged from 4,400 μg/L to 4,900 μg/L compared to the baseline concentration of 4,800 μg/L. Lastly, results from the samples collected from upgradient monitoring wells LVWPS-U3-MW08A and LVWPS-U3-MW08B indicated an overall average concentration reduction of 8 percent, with slight decreases periodically observed. Overall, results from samples collected outside of the Zone 3 study area indicate a relatively stable environment, with only minor natural fluctuations in perchlorate concentrations. Unlike the Zone 1 study area, significant perchlorate concentration reductions were not observed in the samples collected from the upgradient monitoring wells screened in the UMCf-cg. This is likely due to the presence of the slightly more permeable UMCf-cg within the Zone 3 study area, which resulted in less movement upgradient when injecting under pressure.
- Samples collected from three of the six monitoring wells located approximately 25 feet downgradient of the injection well transect (LVWPS-U3-MW03B, LVWPS-U3-MW09, and LVWPS-U3-MW13B) exhibited perchlorate concentration decreases of greater than 97 percent during the Month 1 post-injection sampling event when compared to baseline concentrations and were consistently greater than 90 percent throughout all sampling events performed following the first injection event (Appendix L, Figures L.93 through 98). Additionally, perchlorate concentrations in samples from all three monitoring wells reduced to below the 15 μg/L PRG over multiple sampling events. Concentration trends for these wells are described below:
    - Perchlorate concentrations in samples collected from LVWPS-U3-MW03B reduced from a baseline concentration of 3,800 μg/L to 100 μg/L during Month 1. Following the Month 1 sampling event, perchlorate concentrations fluctuated up to 430 μg/L before reducing to less than the sample detection limit of 0.31 μg/L prior to the second injection event.

    - Perchlorate concentrations in samples collected from LVWPS-U3-MW09 reduced from a baseline concentration of 3,500 µg/L to 14 µg/L during Month 1. Following the initial Month 1 sampling event, perchlorate concentrations fluctuated up to 130 µg/L before reducing to less than the sample detection limit of 0.31 µg/L prior to the second injection event.
    - Perchlorate concentrations in samples collected from LVWPS-U3-MW13B reduced from a baseline concentration of 350 µg/L to less than the sample detection limit of 0.31 µg/L following the first injection event, with this level of reduction sustained through Month 6. During the Month 8 sampling event (immediately prior to the second injection event), the perchlorate concentration slightly rebounded to 48 µg/L.
- Results from the samples collected from the other three monitoring wells screened in both the shallow and deep UMCf-cg located within these well clusters (namely, LVWPS-U3-MW03A, LVWPS-U3-MW03C, and LVWPS-U3-MW13A) indicated perchlorate concentration fluctuations and/or minimal concentration decreases following the first injection event, with samples collected from LVWPS-U3-MW03C showing perchlorate concentration increases. Specifically, perchlorate concentrations in groundwater samples collected from shallow monitoring wells LVWPS-U3-MW03A and LVWPS-U3-MW13A following the first injection event averaged 3,867 µg/L and 3,133 µg/L compared to baseline concentrations of 3,900 µg/L and 3,300 µg/L, respectively. In contrast, perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW03C ranged from 4,800 µg/L to 8,100 µg/L following the first injection event compared to a baseline concentration of 4,900 µg/L. The variability in the concentration reductions observed at well clusters located approximately 25 feet downgradient of the injection well transect illustrate the higher hydraulic conductivity and effective porosity of the coarser materials in the deeper UMCf-cg discussed in Sections 8.4 and 8.5.
- Groundwater samples were collected at the four monitoring wells located approximately 50 feet downgradient of the injection well transect and screened in the shallow or deep UMCf-cg (LVWPS-U3-MW02A, LVWPS-U3-MW02B, LVWPS-U3-MW06A, and LVWPS-U3-MW06B; Appendix L, Figures L.99 through L.102). Perchlorate concentrations in the Month 1 sample collected from LVWPS-U3-MW02B decreased to 190 µg/L (representing a 98 percent reduction when compared to a baseline concentration of 8,400 µg/L). The reduction in perchlorate correlates with the arrival of the injectate as indicated by the slight increase in TOC concentration during this same event (further discussed in Section 8.7.4). Although perchlorate concentrations in samples collected from LVWPS-U3-MW02B continued to be reduced when compared to baseline, the reductions were lower in the Months 2 through 8 sampling events, ranging from 14 percent to 32 percent (or concentrations of 5,700 µg/L to 7,200 µg/L). Perchlorate concentration reductions of approximately 37 percent also occurred in the groundwater samples collected from LVWPS-U3-MW02A and LVWPS-U3-MW06A during the Month 1 post-injection sampling event. Some reduction was generally sustained in the samples collected from LVWPS-U3-MW02A during the eight months following the first injection event, with concentrations ranging from 1,900 µg/L to 2,800 µg/L compared to the baseline concentration of 3,000 µg/L. However, perchlorate concentrations in samples collected from LVWPS-U3-MW06A quickly returned to baseline concentrations in Month 2 (9,400 µg/L compared to a baseline concentration of 9,500 µg/L) and then subsequently increased during Months 3 through 8 to concentrations ranging from 11,000 µg/L to 15,000 µg/L. Perchlorate concentrations fluctuated and slightly increased in samples collected from LVWPS-U3-MW06B over the first eight months of sampling, ranging from 680 µg/L to 1,500 µg/L compared to a baseline concentration of 630 µg/L. Monitoring wells LVWPS-U3-MW06A and LVWPS-U3-MW06B are located downgradient of the portion of the injection well transect that includes wells screened in the UMCf-cg that is interbedded with the highest proportion of fine-grained UMCf. Therefore, the variability in the concentration reductions observed in samples collected from well clusters located approximately 50 feet downgradient of the injection well transect (i.e., stronger response in LVWPS-U3-MW02A/B compared to LVWPS-U3-MW06A/B) likely illustrate the heterogeneity of the UMCf-cg within the Zone 3 study area shown on **Figure 10c**. This heterogeneity

results in variability in the transport of the injectate, which in turn is reflected in the variation in geochemical response and perchlorate biodegradation levels at downgradient locations.

- Eight monitoring wells screened in the shallow or deep UMCf-cg and located approximately 75 to 150 feet downgradient of the injection well transect (LVWPS-U3-MW05B, LVWPS-U3-MW10A, LVWPS-U3-MW10B, LVWPS-U3-MW11A, LVWPS-U3-MW11B, LVWPS-U3-MW11C, LVWPS-U3-MW12A, and LVWPS-U3-MW12B) were also sampled following the first injection event (Appendix L, Figures L.103 through L.110). Of these, results from groundwater samples collected from LVWPS-U3-MW10A and LVWPS-U3-MW10B indicated perchlorate concentration reductions of greater than 99 percent when compared to baseline concentrations, with the majority of the sample results indicating concentrations below PRGs. Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW10A ranged from less than the sample detection limit of 0.31 μg/L to 160 μg/L following the first injection event compared to a baseline concentration of 2,600 μg/L, while perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW10B ranged from less than the sample detection limit of 0.31 μg/L to 0.69 μg/L following the first injection event compared to a baseline concentration of 3,200 μg/L. Results also indicated significant perchlorate concentration reductions in samples collected from LVWPS-U3-MW12B, with perchlorate concentrations reducing from 6,000 μg/L to 1,900 μg/L (representing an approximate 68 percent reduction) during the first month following injections. Those concentration reductions continued to improve over time, with reductions of greater than 99 percent and concentrations as low as 7.6 μg/L (below the PRG of 15 μg/L) during Month 4. Perchlorate concentration reductions were minimal in the samples collected from LVWPS-U3-MW11A, LVWPS-U3-MW11B, LVWPS-U3-MW11C, and LVWPS-U3-MW12A. The lack of significant reductions observed in samples collected from the LVWPS-U3-MW11A/B/C monitoring well cluster was not unexpected given its location along the eastern edge of the Zone 3 study area and is likely influenced by groundwater migrating into the Zone 3 study area that does not pass through the biologically active treatment zone in the vicinity of the injection well transect. The stronger response observed at LVWPS-U3-MW12B compared to LVWPS-U3-MW12A is likely due to the higher hydraulic conductivity of the deep UMCf-cg compared to the shallow UMCf-cg, as discussed in Section 8.6.3.
- The farthest downgradient monitoring well cluster LVWPS-MW212C and LVWPS-MW212D (located approximately 250 feet downgradient) was added to the Zone 3 effectiveness monitoring network during Month 4 to provide data farther downgradient of the injection well transect than was initially anticipated to be needed within the short Pilot Study timeframe. However, the first sampling of this well during Month 4 indicated slight concentration reductions in the samples collected from both wells of approximately 12 to 14 percent reductions, with concentrations of 6,700 μg/L and 6,000 μg/L when compared to baseline concentrations of 7,800 μg/L and 6,800 μg/L, respectively (Appendix L, Figures L.111 and L.112). These perchlorate reductions continued during the Month 6 sampling event, with reductions of up to 21 percent and perchlorate concentrations of 6,200 μg/L and 5,900 μg/L in samples collected from LVWPS-MW212C and LVWPS-MW212D, respectively. Perchlorate concentrations returned to close to baseline concentrations during the Month 8 sampling event. Reductions observed this far downgradient of the injection well transect in a short timeframe following the first injection event are consistent with the groundwater flow velocities of approximately 1 ft/day and rapid migration of fluorescein dye downgradient in portions of the Zone 3 study area, as discussed in Section 8.6.4. These perchlorate reductions observed approximately 250 feet downgradient of the Zone 3 injection well transect combined with the lack of significant perchlorate reductions in samples collected from the LVWPS-U3-MW11A/B/C monitoring well cluster located 100 feet downgradient discussed above illustrate the preferential flow pathways and heterogeneity in hydrogeology of the UMCf-cg in Zone 3.
- No perchlorate concentration reductions were observed in the alluvium within the Zone 3 study area (Appendix L, Figures L.113 through L.119). This was not unexpected given the low baseline concentrations in the alluvium and the relatively weak, downward vertical gradient between the alluvium

and the UMCf-cg in the Zone 3 study area (discussed in Section 8.5), which resulted in limited preferential flow pathways between the alluvium and the UMCf-cg.

8.7.1.1.3 Perchlorate Degradation Response Following Injection Event 2

Following completion of the second injection event in October 2021, groundwater sampling was performed monthly for the first four months and then reduced to bimonthly sampling until completion of the Pilot Study's 18-month monitoring program. This resulted in groundwater sampling events being conducted during Months 11, 12, 13, 14, 16, and 18. Results following the second injection event are described below.

- Following the second injection event, perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW01B, which is located approximately 60 feet cross-gradient of the Zone 3 injection well transect, ranged from 2,100 μg/L to 3,100 μg/L (higher than the baseline concentration of 2,000 μg/L; Appendix L, Figure L.92). Although perchlorate concentrations in samples collected from the upgradient monitoring wells screened in the UMCf-cg remained relatively stable following the first injection event, samples collected from all four upgradient monitoring wells (LVWPS-U3-MW07A, LVWPS-U3-MW07B, LVWPS-U3-MW08A, and LVWPS-U3-MW08B) during the first month following the second injection event indicated perchlorate concentration reductions ranging from 20 percent to 48 percent (Appendix L, Figures L.88 through L.91). However, these upgradient reductions were not sustained as concentrations generally remained similar to baseline concentrations throughout the remainder of the Pilot Study. Unlike the Zone 1 study area, significant perchlorate concentration reductions were not observed in the samples collected from the upgradient monitoring wells screened in the UMCf-cg. This is likely due to the presence of the slightly more permeable UMCf-cg within the Zone 3 study area, which resulted in less movement upgradient when injecting under pressure.
- Perchlorate concentration reductions improved following the second event in the samples collected from the six monitoring wells located approximately 25 feet downgradient of the injection well transect, with perchlorate concentration reductions observed in samples collected from five of the six monitoring wells (Appendix L, Figures L.93 through 98). Perchlorate concentration reductions remained greater than 99 percent in the samples collected from LVWPS-U3-MW03B and LVWPS-U3-MW09, with concentrations ranging from less than the sample detection limit of 0.31 μg/L to 18 μg/L during all six sampling events. Although perchlorate concentration reductions were also greater than 99 percent and concentrations were below the PRG in samples collected from LVWPS-U3-MW13B during multiple sampling events following the second injection event, the perchlorate concentrations did periodically fluctuate (ranging from 0.92 μg/L to 300 μg/L), compared to the more sustained reduction observed following the first injection event. Perchlorate concentration reductions were observed for the first time in samples collected from both LVWPS-U3-MW03A and LVWPS-U3-MW03C following the second injection event, with perchlorate concentration reductions of up to 64 percent and 96 percent, respectively. These reductions were sustained for the majority of the sampling events, which indicates that a more complete biologically active zone likely developed following the second injection event. Specifically, perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW03A ranged from 1,200 μg/L to 3,000 μg/L following the second injection event compared to a baseline concentration of 3,300 μg/L and perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW03C ranged from 190 μg/L to 2,700 μg/L following the second injection event compared to a baseline concentration of 4,900 μg/L.
- Groundwater samples collected from the four monitoring wells located approximately 50 feet downgradient of the injection well transect and screened in the shallow or deep UMCf-cg (LVWPS-U3-MW02A, LVWPS-U3-MW02B, LVWPS-U3-MW06A, and LVWPS-U3-MW06B) indicated similar results to the response following the first injection event (Appendix L, Figures L.99 through 102). Perchlorate concentrations in groundwater samples collected from LVWPS-U3-MW02A and LVWPS-U3-MW02B were reduced by 30 percent and 60 percent, respectively, immediately following the second injection

event. These reductions generally remained in this range in the samples collected from LVWPS-U3-MW02A and LVWPS-U3-MW02B during the eight months following the second injection event. Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW02A ranged from 1,500 μg/L to 2,400 μg/L following the second injection event but returned to the baseline concentration of 3,000 μg/L during the final sampling event. Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW02B ranged from 3,400 μg/L to 6,100 μg/L following the second injection event compared to a baseline concentration of 8,400 μg/L. Perchlorate concentrations did not reduce in the samples collected from LVWPS-U3-MW06A or LVWPS-U3-MW06B, which is likely due to the significant preferential flow path located to the west of this well cluster. As discussed previously, monitoring wells LVWPS-U3-MW06A and LVWPS-U3-MW06B are located downgradient of the portion of the injection well transect screened in UMCf-cg interbedded with the highest proportion of fine-grained UMCf. In addition, the highly variable hydraulic conductivities of the UMCf-cg within Zone 3 likely results in preferential flow to the west of monitoring well cluster LVWPS-U3-MW06A/B.

- Results from the sampling of the eight monitoring wells located approximately 75 to 150 feet downgradient of the injection well transect following the second injection event were also similar to the first injection event (Appendix L, Figures L.103 through 110).
  - Perchlorate concentration reductions of greater than 99 percent when compared to baseline concentrations, with the majority of the sample results indicating concentrations below the PRG, continued to be observed in the samples collected from LVWPS-U3-MW10A and LVWPS-U3-MW10B. Perchlorate concentration reductions were stronger in samples collected from the deeper monitoring well LVWPS-U3-MW10B, with concentrations ranging from less than the sample detection limit of 0.31 μg/L to 0.92 μg/L (sustained through the end of the Pilot Study) whereas perchlorate concentrations in samples collected from the shallower monitoring well LVWPS-U3-MW10A began to rebound slightly, increasing from less than the sample detection limit of 0.31 μg/L immediately following the second injection event to 2,100 μg/L during the final sampling event. These results are consistent with the TOC concentrations in samples collected from these monitoring wells, which remained elevated in the deeper monitoring well LVWPS-U3-MW10B following the second injection event, steadily trending from 330 mg/L to 2.7 mg/L from Month 11 to Month 18, whereas TOC concentrations in samples collected from the shallower monitoring well LVWPS-U3-MW10A were elevated to 15 mg/L immediately after the second injection event, but quickly returned to baseline concentrations below 2 mg/L.
  - Results also indicated significant perchlorate concentration reductions in samples collected from monitoring well LVWPS-U3-MW12B of greater than 83 percent, with concentrations ranging from 710 μg/L to 1,000 μg/L following the second injection event compared to a baseline concentration of 6,000 μg/L. Perchlorate concentration reductions were periodically observed in the samples collected from LVWPS-U3-MW11A, LVWPS-U3-MW11B, and LVWPS-U3-MW11C, with the Month 13 sampling event indicating concentration reductions ranging from 26 percent to 91 percent in samples collected from the three wells at this location (concentrations ranging from 870 μg/L to 3,900 μg/L compared to baseline concentrations ranging from 4,100 μg/L to 10,000 μg/L). As previously explained, given the location of this well cluster along the eastern edge of the Zone 3 study area, it is likely primarily influenced by groundwater migrating into the Zone 3 study area that does not pass through the biologically active treatment zone in the vicinity of the injection well transect. However, the reductions observed during the Month 13 sampling event do correlate with an increase in TOC concentrations in samples collected from this location (Month 13 TOC concentration of 6.8 mg/L compared to baseline concentration of 0.42 mg/L). This increase in TOC concentrations indicates a brief influence from the injections approximately 3 months after the second injection event. However, the regular transport of untreated perchlorate-laden water that moves towards this monitoring well over time impacts concentrations because

this location does not continue to receive carbon-rich water because it is not directly downgradient on the injection well transect under the natural groundwater flow regime. As a result, perchlorate concentrations in samples collected from these wells generally increased to close to baseline conditions during the final sampling event of the Pilot Study.

- Groundwater samples collected from monitoring wells LVWPS-MW212C and LVWPS-MW212D (located approximately 250 feet downgradient of the injection well transect) continued to indicate perchlorate concentration reductions, with improved reductions following the second injection event compared to first injection event (Appendix L, Figures L.111 and L.112). Perchlorate concentrations reduced during the first month following the second injection event in samples collected from LVWPS-MW212C and LVWPS-MW212D, with perchlorate concentrations of 3,900 μg/L and 3,700 μg/L compared to baseline concentrations of 7,800 μg/L and 6,800 μg/L, respectively. Perchlorate concentrations in samples collected from LVWPS-MW212C fluctuated but remained reduced for the remainder of the Pilot Study, with reductions of up to 60 percent during the Month 16 sampling event. Perchlorate concentrations slightly increased during remaining events in samples collected from LVWPS-MW212D but remained reduced by 12 percent to 19 percent, with concentrations ranging from 5,500 μg/L to 6,000 μg/L compared to the baseline concentration of 6,800 μg/L. Concentration reductions observed in these samples in a relatively short timeframe following the second injection event are indicative of likely preferential flow paths within the Zone 3 study area in the vicinity of the LVWPS-MW212C/D cluster. However, strong reductions were not expected to be observed in the vicinity of this monitoring well cluster due to the significant distance of 250 feet downgradient of the short injection well transect, which likely results in migration of groundwater into this vicinity that did not pass directly through the biologically active zone.
- In general, perchlorate concentration reductions were not observed in the alluvium within the Zone 3 study area following the second injection event, which was not unexpected given the generally small and downward vertical gradient present within the Zone 3 study area (as discussed in Section 8.5). However, perchlorate concentrations did exhibit a decreasing trend in samples collected from monitoring well LVWPS-A3-MW12, which is located 150 feet downgradient of the injection well transect, reducing from a baseline concentration of 200 μg/L to a final Month 18 concentration of 89 μg/L (Appendix L, Figure L.119). This concentration decrease correlates with the dye results, which indicated the presence of fluorescein (and therefore, injectate solution) in samples collected from alluvial monitoring well LVWPS-A3-MW12.

8.7.1.2 Estimate of Perchlorate Distribution

Figures 16a-c through 18a-c present perchlorate plume isoconcentration contour interpretations during the Pilot Study for the shallow UMCf-cg present from 88 to 110 feet bgs, deep UMCf-cg present from 110 to 150 feet bgs, and the deepest UMCf-cg present from 150 to 175 feet bgs within the Zone 3 study area, respectively. The baseline event in October 2020 is intended to represent pre-injection perchlorate concentrations in groundwater within the vicinity of the Zone 3 study area, followed by depictions of subsequent sampling events post-injection. These comparisons show reductions in perchlorate concentrations in the immediate vicinity of the injection well transect with reductions extending between 50 and more than 150 feet downgradient of the injection well transect depending on the UMCf-cg interval (i.e., shallow, deep, deepest). As illustrated in the isoconcentration maps on **Figures 16a-c through 18a-c**, a biologically active treatment zone was created following each injection event, with perchlorate concentrations in groundwater within all three UMCf-cg zones reduced to concentrations below the PRG of 15 μg/L at multiple locations.

Following the first injection event, reductions in perchlorate concentrations within the shallow UMCf-cg were limited to within approximately 25 feet of the injection well transect in the eastern portion of the Zone 3 study area but extended 100 feet downgradient of the injection well transect in the western portion of the Zone 3 study area (**Figures 16a-c**). Following the second injection event, perchlorate concentration reductions were observed farther downgradient, with reductions expanding to approximately 100 feet downgradient in the eastern portion of the Zone 3 study area. These results are consistent with the lithology and hydrogeology of the shallow UMCf-cg discussed in Sections 8.4 through 8.6. The shallow UMCf-cg in Zone 3 tends to be finer than deeper portions of the UMCf-cg, with higher proportions of interbedded fine-grained UMCf. Furthermore, the UMCf-cg in the vicinity of the eastern portion of the injection well transect (e.g., LVWPS-U3-IW05, LVWPS-U3-IW06, and LVWPS-U3-IW07) tends to be interbedded with relatively more fine-grained UMCf layers compared to the rest of the Zone 3 injection well transect. Additionally, the estimated groundwater flow rates in the shallow UMCf-cg were higher in the western portion of the Zone 3 study area at 0.1 ft/day compared to the eastern portion at 0.05 feet/day (Appendix F). Based on these groundwater flow rates, influence from ISB would be expected to be observed approximately 28 to 56 feet downgradient under the natural gradient of the formation by the end of the 18-month Pilot Study. However, migration of fluorescein downgradient was faster than the velocities estimated through borehole dilution testing would suggest, with fluorescein detected in samples collected from shallow monitoring well LVWPS-U3-MW10A located approximately 100 feet downgradient of the injection well transect approximately four months after the first injection event. These dye monitoring results suggest groundwater flow rates of approximately 1 ft/day in the shallow UMCf-cg. This may in part reflect the difference between flow at the natural gradient of the aquifer during borehole dilution testing compared to the tracer study results, which would be influenced by pressurized injection of fluorescein-tagged injectate solution.

Reductions in perchlorate concentrations within the deep and deepest UMCf-cg extended farther than the shallow UMCf-cg, with reductions observed at least 250 feet downgradient of the injection well transect in the western portion of the Zone 3 study area (**Figures 17a-c and 18a-c**). These results are consistent with the lithology and hydrogeology of the deeper UMCf-cg discussed in Sections 8.4 through 8.6. The deeper UMCf-cg in the Zone 3 study area tends to be coarser with a higher hydraulic conductivity than the shallower portions of the UMCf-cg. The groundwater flow rates estimated in the deeper UMCf-cg were more variable than the shallow UMCf-cg, ranging from 0.02 ft/day to 0.7 ft/day. Based on these groundwater flow rates, influence from ISB would be expected to be observed approximately 11 to 390 feet downgradient under the natural gradient of the formation by the end of the 18-month Pilot Study. However, similar to the shallow UMCf-cg, migration of fluorescein downgradient was faster than the velocities estimated through borehole dilution testing would suggest, with fluorescein detected in samples collected from monitoring well LVWPS-U3-MW10B screened in the deep UMCf-cg approximately two months after the first injection event. These dye monitoring results suggest groundwater flow rates of approximately 2 ft/day in the deep UMCf-cg. As discussed above, this difference may be due to the flow at the natural gradient of the aquifer during borehole dilution testing compared to the tracer study results, which would be influenced by pressurized injection of fluorescein-tagged injectate solution.

As described in Section 8.7.1.1 and depicted on **Figures 16a-c through 18a-c**, the response following the second injection event resulted in the greatest perchlorate concentration reductions. Some areas within the treatment zone had less reduction in perchlorate concentrations, which is likely due to the heterogeneous nature of the subsurface, localized preferential flow paths due to secondary porosity generated by faulting, and groundwater migrating into the Zone 3 study area that did not flow through the relatively short injection well transect. While acknowledging that the design of the Pilot Study was compact and specific to meet the study objectives, the design of a full-scale remedy would be significantly different, and if selected as a component of the NERT final remedy, the injection well transect would likely extend across a much larger distance and potentially include multiple injection well transects to achieve a more uniform biologically active treatment zone.

8.7.1.3 Estimation of Perchlorate Mass Removal

The mass flux of perchlorate passing through the Zone 3 study area was estimated for baseline and subsequent post-injection sampling events using the methods previously described in Section 6.7.1.3 to determine the reduction in perchlorate mass following injections. The resultant estimates for flux of perchlorate mass removed and perchlorate mass removed for each sampling event are provided in Appendix M, Table M.1. Using this calculation process, an estimated total of 86 pounds of perchlorate was destroyed from the groundwater in the

Zone 3 study area during the Pilot Study. It is estimated that of the 86 pounds of perchlorate destroyed, approximately 0.5 pounds of perchlorate were destroyed in the overlying alluvium, with the remaining 85.5 pounds of perchlorate destroyed in the UMCf-cg. When comparing the mass destroyed within the Zone 3 UMCf-cg to the mass destroyed in the UMCf in the Zones 1 and 2 study areas, the mass destroyed in the Zone 3 UMCf-cg was more than both areas combined (i.e., 86 pounds in Zone 3 compared to 52 pounds in Zone 2 and 25 pounds in Zone 1).

8.7.2 Chlorate

Chlorate is present in groundwater within the Zone 3 study area at concentrations that are often slightly higher than those of perchlorate. As previously explained, chlorate is also amenable to anaerobic biodegradation, similar to perchlorate. Chlorate concentrations are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.88 through L.119.

Chlorate concentrations in groundwater were measured during baseline and ranged from 150 μg/L to 270 μg/L in the alluvium, less than 10 μg/L to 16,000 μg/L in the shallow UMCf-cg, 550 μg/L to 22,000 μg/L in the deep UMCf-cg, and 7,100 μg/L to 13,000 μg/L in the deepest portions of the UMCf-cg (generally from 150 to 175 feet bgs). The highest baseline chlorate concentration of 22,000 μg/L was measured in the groundwater sample collected from upgradient monitoring well LVWPS-U3-MW08A, which was screened in the UMCf-cg from approximately 118 to 143 feet bgs. In general, chlorate concentration trends followed a similar reducing pattern as the perchlorate concentration trends throughout the Pilot Study timeframe (discussed in Section 8.7.1). Noteworthy chlorate results from the Pilot Study are summarized below.

- Chlorate concentrations in the groundwater samples collected from monitoring well LVWPS-U3-MW01B, which is located approximately 60 feet cross-gradient of the Zone 3 injection well transect, exhibited an increasing trend throughout the Pilot Study, with concentrations ranging from 2,100 μg/L to 4,600 μg/L compared to a baseline concentration of 1,800 μg/L (Appendix L, Figure L.92). However, samples collected from all four of the upgradient monitoring wells (LVWPS-U3-MW07A, LVWPS-U3-MW07B, LVWPS-U3-MW08A, and LVWPS-U3-MW08B) indicated an average chlorate concentration reduction of approximately 20 percent over the duration of the Pilot Study (Appendix L, Figures L.88 through 91). Unlike the Zone 1 study area, significant increases in TOC concentrations and simultaneous decreases in perchlorate and chlorate concentrations were not observed in the samples collected from the upgradient monitoring wells screened in the UMCf-cg. Although the effective porosity of the UMCf-cg was determined to be lower than expected (as described in Section 8.3), the slightly more permeable UMCf-cg likely resulted in less movement of the injecate solution upgradient when injecting under pressure. Therefore, the reductions are likely not a result of injection activities.
- Groundwater samples collected from all six monitoring wells located approximately 25 feet downgradient of the injection well transect (LVWPS-U3-MW03A, LVWPS-U3-MW03B, LVWPS-U3-MW03C, LVWPS-U3-MW09, LVWPS-U3-MW13A, and LVWPS-U3-MW13B) exhibited chlorate concentration decreases during the Pilot Study (Appendix L, Figures L.93 through 98).
  - Similar to perchlorate, results from the samples collected from three of the monitoring wells (LVWPS-U3-MW03B. LVWPS-U3-MW09, and LVWPS-U3-MW13B) indicated chlorate concentration reductions of greater than 99 percent during the Month 1 post-injection sampling event when compared to baseline concentrations, with results in the majority of the remaining sampling events indicating chlorate concentrations below sample detection limits. Chlorate concentrations in samples collected from these monitoring wells ranged from less than the sample detection limit of 10 μg/L to 93 μg/L following the first injection event. Following the second injection event, chlorate concentrations in samples collected from monitoring wells LVWPS-U3-MW03B and LVWPS-U3-MW09 generally remained less than the sample detection limit of 24 μg/L, with these concentrations sustained during the final Month 18 sampling event

(compared to baseline concentrations of 13,000 μg/L and 6,100 μg/L, respectively). Chlorate concentrations in samples collected from monitoring well LVWPS-U3-MW13B fluctuated following the second injection event, with concentrations ranging from less than the sample detection limit of 24 μg/L to 450 μg/L and a final perchlorate concentration of 190 μg/L (compared to a baseline concentration of 550 μg/L).

  - Although perchlorate concentrations did not initially reduce in samples collected from LVWPS-U3-MW03C following the first injection event, chlorate concentrations did decrease, with chlorate reductions of up to 64 percent during the Month 1 sampling event. During the four months following the second injection event, these reductions in samples collected from LVWPS-U3-MW03C improved, with chlorate reductions of greater than 95 percent (concentrations ranging from less than the sample detection limit of 24 μg/L to 600 μg/L when compared to the baseline concentration of 12,000 μg/L). During the final two sampling events, chlorate concentrations increased slightly to 2,400 μg/L and 1,200 μg/L, which still represent reductions ranging from 80 percent to 90 percent reductions compared to baseline concentrations.
  - Like perchlorate, chlorate was also reduced in samples collected from the remaining two monitoring wells located approximately 25 feet downgradient (LVWPS-U3-MW03A and LVWPS-U3-MW13A) following the second injection event, with reductions of up to 44 percent when compared to baseline after approximately 13 months of monitoring. During the final six months of the Pilot Study, chlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW03A ranged from 2,500 μg/L to 3,700 μg/L compared to a baseline concentration of 4,500 μg/L, while chlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW13A ranged from 4,100 μg/L to 5,900 μg/L compared to a baseline concentration of 7,200 μg/L. As previously explained in Section 8.7.1.2, these reductions indicate that a more complete biologically active zone was likely developed following the second injection event and illustrate the extended time required to influence the finer grained, lower hydraulic conductivity portions of the shallow UMCf-cg in the Zone 3 study area.

- Groundwater samples collected from the four monitoring wells located approximately 50 feet downgradient of the injection well transect and screened in the shallow or deep UMCf-cg (LVWPS-U3-MW02A, LVWPS-U3-MW02B, LVWPS-U3-MW06A, and LVWPS-U3-MW06B) indicated a similar result following both injection events (Appendix L, Figures L.99 through 102). The chlorate concentration in the groundwater sample collected from LVWPS-U3-MW02B during the Month 1 sampling event was reduced by approximately 97 percent (370 μg/L compared to a baseline concentration of 12,000 μg/L). This chlorate reduction correlates with a significant decrease in perchlorate concentrations and the arrival of the injectate solution indicated by an increase in TOC concentrations (TOC concentration during Month 1 of 14 mg/L compared to baseline concentration of 2.1 mg/L). Chlorate concentration reductions continued through the remaining Pilot Study events but were notably lower ranging from 17 percent to 44 percent following the second injection event, with concentrations ranging from 6,700 μg/L to 10,000 μg/L. One notable difference when compared to perchlorate concentration trends in the Zone 3 study area was the lack of reduction in chlorate concentrations in the samples collected from LVWPS-U3-MW02A, which is likely due to an uncharacteristically low concentration in the sample collected during baseline that was being used for comparison purposes. Lastly, similar to perchlorate, chlorate concentrations did not reduce in samples collected from monitoring wells LVWPS-U3-MW06A or LVWPS-U3-MW06B, which is likely due to the finer-grained nature of the sediments in the upgradient portion of the injection well transect and the significant preferential flow path located to the west of this well cluster.
- Results from the sampling of the eight monitoring wells located approximately 75 to 150 feet downgradient of the injection well transect were similar to perchlorate, with chlorate concentration reductions of greater than 99 percent occurring in samples collected from LVWPS-U3-MW10A and LVWPS-U3-MW10B (Appendix L, Figures L.103 through 110). As with perchlorate concentrations,

chlorate concentration reductions were stronger in samples collected from the deeper monitoring well LVWPS-U3-MW10B, with concentrations measuring less than the sample detection limit of 24 μg/L for the entire duration of the Pilot Study with the exception of immediately before and after the second injection event. Chlorate concentrations in samples collected from the shallower monitoring well LVWPS-U3-MW10A also reduced to below the sample detection limit of 24 μg/L during multiple sampling events but began to rebound approximately three months following the second injection, with concentrations slowly increasing from less than the sample detection limit of 24 μg/L to 1,600 μg/L during the final sampling event. As discussed in Section 8.7.1.1.3 and 8.7.4, these results are consistent with the TOC concentrations in samples collected from these monitoring wells. Chlorate concentrations also reduced significantly in samples collected from LVWPS-U3-MW12B, with concentration reductions ranging from 47 percent to 80 percent (concentrations ranging from 980 μg/L to 2,600 μg/L compared to a baseline concentration of 4,900 μg/L). Results also indicated periodic reductions in chlorate concentrations in samples collected from LVWPS-U3-MW11A, LVWPS-U3-MW11B, and LVWPS-U3-MW11C, with the Month 13 sampling event indicating concentration reductions ranging from 18 percent to 96 percent (concentrations ranging from 590 μg/L to 5,800 μg/L compared to baseline concentrations ranging from 7,100 μg/L to 16,000 μg/L). As previously explained, the LVWPS-U3-MW11A/B/C monitoring well cluster is located along the eastern edge of the Zone 3 study area and likely primarily influenced by groundwater migrating into the Zone 3 study area that does not pass through the injection well transect.

- Groundwater results from the samples collected from monitoring wells LVWPS-MW212C and LVWPS-MW212D (located approximately 250 feet downgradient of the injection well transect) indicated fluctuating chlorate concentration reductions throughout the Pilot Study, with reductions of up to 55 percent and 32 percent, respectively. (Appendix L, Figures L.111 and 112). Specifically, chlorate concentrations reduced from a baseline concentration of 11,000 μg/L to a low of 5,000 μg/L and 7,500 μg/L in samples collected from LVWPS-MW212C and LVWPS-MW212D, respectively. Concentration reductions observed in these samples in a relatively short timeframe following injections indicated likely preferential flow paths within the Zone 3 study area in the vicinity of the LVWPS-MW212C/D cluster.
- In general, minimal chlorate concentration reductions were observed in the samples collected from the wells screened in the alluvium, with one exception in the sample collected during Month 12 from LVWPS-A3-MW11 indicating a chlorate concentration reduction of 83 percent when compared to baseline concentrations (Appendix L, Figures L.113 through L.119).

8.7.3 Nitrate

As discussed earlier in this report, nitrate concentrations were evaluated during the Pilot Study because it is the most likely competing electron acceptor as well as a consumer of organic carbon substrate. Nitrate concentrations during the Pilot Study are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.88 through L.119).

Groundwater nitrate concentrations generally ranged from 3 mg/L to 14 mg/L during baseline sampling. Nitrate concentration reductions followed a similar reducing pattern as perchlorate and chlorate concentrations throughout the Pilot Study timeframe (discussed in Sections 8.7.1 and 8.7.2). Noteworthy nitrate results from the Pilot Study are summarized below.

- Minimal nitrate concentration reductions were observed in the samples collected from upgradient monitoring wells screened in the UMCf-cg (Appendix L, Figures L.88 through L.91) or in monitoring wells located throughout the Zone 3 study area screened in the alluvium (Appendix L, Figures L.113 through L.119).
- During the month immediately following the first injection event, nitrate concentrations reduced in samples collected from four of the six monitoring wells located approximately 25 feet downgradient of the injection well transect, with nitrate concentrations reduced to less than 1 mg/L in all of the samples collected from

LVWPS-U3-MW03B, LVWPS-U3-MW09, and LVWPS-U3-MW13B throughout the Pilot Study (Appendix L, Figures L.93 through L.98). Although nitrate concentrations only marginally reduced in samples collected from LVWPS-U3-MW03C following the first injection event, reductions substantially improved following the second injection event, with concentrations ranging from 0.020 mg/L to 0.48 mg/L (reductions of greater than 94 percent) during the first six months of monitoring following the second injection event. Nitrate concentration reductions in samples collected from monitoring wells LVWPS-U3-MW03A and LVWPS-U3-MW13A were minimal illustrating the extended time required to influence the finer grained, lower hydraulic conductivity portions of the shallow UMCf-cg in the Zone 3 study area.

- Groundwater samples collected from the four monitoring wells located approximately 50 feet downgradient of the injection well transect and screened in the shallow or deep UMCf-cg indicated minimal reductions in nitrate concentrations during the Pilot Study (Appendix L, Figures L.99 through L.102). Similar to perchlorate and chlorate, one notable exception was the 97 percent nitrate concentration reduction observed in the sample collected from LVWPS-U3-MW02B during the Month 1 sampling event following the first injection event, which was the same event that indicated an increase in the TOC concentration signaling the arrival of the injectate solution. During the Month 1 sampling event, the nitrate concentration reduced to 0.29 mg/L compared to a baseline concentration of 10 mg/L. Nitrate concentrations generally returned to baseline concentrations for the remainder of the Pilot Study, with concentrations ranging from 7.3 mg/L to 10 mg/L.
- Nitrate concentration reductions observed in the samples collected from the eight monitoring wells located approximately 75 to 150 feet downgradient of the injection well transect were similar to perchlorate and chlorate, with nitrate concentrations reducing to below 0.11 mg/L in all of the samples collected from LVWPS-U3-MW10A and LVWPS-U3-MW10B throughout the Pilot Study, with the exception of the final samples collected from LVWPS-U3-MW10A, which began to rebound slightly to 2.2 mg/L (Appendix L, Figures L.103 through L.110). Nitrate concentrations also reduced significantly in samples collected from LVWPS-U3-MW12B, with an average post-injection concentration of 1.4 mg/L compared to a baseline concentration of 6.6 mg/L. Results also indicated periodic reductions in nitrate concentrations in the samples collected from LVWPS-U3-MW11A, LVWPS-U3-MW11B, and LVWPS-U3-MW11C, with the Month 13 sampling event indicating concentration reductions ranging from 18 percent to 69 percent (concentrations ranging from 1.6 mg/L to 7.0 mg/L compared to baseline concentrations ranging from 5.2 mg/L to 9.8 mg/L).
- As with perchlorate and chlorate, samples collected from monitoring wells LVWPS-MW212C and LVWPS-MW212D (located approximately 250 feet downgradient of the injection well transect) also indicated periodic nitrate concentration reductions (Appendix L, Figures L.111 and L.112). The most predominant reductions were observed in the samples collected from LVWPS-MW212C, with concentrations ranging from 3.3 mg/L to 3.6 mg/L in three sampling events compared to a baseline concentration of 8.4 mg/L. As previously stated, the reductions in nitrate concentrations at this far downgradient location are likely due to preferential flow pathways in this vicinity.

8.7.4 Total Organic Carbon

As previously explained, TOC was analyzed throughout the Pilot Study to monitor changes in concentrations after injections compared to baseline pre-injection concentrations to track the carbon substrate injectate in the groundwater and used as an indicator to determine the appropriate timing for reinjection activities. TOC concentrations during the Pilot Study are summarized in Appendix J, Table J.1 and graphically depicted in Appendix L, Figures L.88 through L.119.

The initial baseline groundwater sampling event performed in October 2020 indicated that TOC concentrations were generally less than 1 mg/L throughout the Zone 3 study area with a few isolated exceptions. Noteworthy TOC results from the Pilot Study are summarized below.

- No significant increase in TOC concentrations was observed in upgradient monitoring wells screened in the UMCf-cg (Appendix L, Figures L.88 through L.91) or monitoring wells located throughout the Zone 3 study area screened in the alluvium (Appendix L, Figures L.113 through L.119).
- During the first monthly groundwater sampling event following the first injection event, TOC concentrations significantly increased from an average of 0.4 mg/L to an average of 142 mg/L in groundwater samples collected from three of the six monitoring wells located approximately 25 feet downgradient of the injection well transect (namely, LVWPS-U3-MW03B, LVWPS-U3-MW09, and LVWPS-U3-MW13B; Appendix L, Figures L.93 through L.98). These TOC concentration increases generally coincided with rapid decreases in perchlorate and chlorate concentrations, which continues to demonstrate the biochemical relevance between this indicator parameter and perchlorate biodegradation soon after the first injection event. TOC concentrations remained significantly greater than baseline concentrations in samples collected from these three monitoring wells for approximately 4 months following the first injection event, which is similar to the TOC concentration trends observed in the results from the UMCf within the Zone 1 study area. During the sampling event performed in Month 6 following the first injection event, TOC concentrations notably decreased to an average of 6.3 mg/L in samples collected from these three monitoring wells. The sampling event performed in Month 8, prior to the second injection event, indicated TOC concentrations were approximately 2.7 mg/L in samples collected from these same three monitoring wells, which was close to the average baseline concentration and signaled the need for a second injection event. Although perchlorate concentrations remained significantly below baseline concentrations, this decrease in TOC concentration was associated with an observable increase in the perchlorate concentration in the sample collected from LVWPS-U3-MW13B. No notable TOC concentration increases were reported in samples collected from the remaining three downgradient monitoring wells located approximately 25 feet downgradient (i.e., LVWPS-U3-MW03A, LVWPS-U3-MW03C, and LVWPS-U3-MW13A). These results illustrate that the carbon substate solution traveled farther downgradient within the coarser-grained, higher hydraulic conductivity subsurface materials of the deeper UMCf-cg.
- TOC concentration increases were also observed in the samples collected from four monitoring wells located 100 to 150 feet downgradient of the injection well transect (LVWPS-U3-MW10A, LVWPS-U3-MW10B, LVWPS-U3-MW12A, and LVWPS-U3-MW12B), with concentrations increasing from less than 1 mg/L during baseline to concentrations ranging from 3.7 to 310 mg/L following the first injection event (Appendix L, Figures L.103 through L.110). In general, these TOC concentration increases were not sustained for as long as the increases observed in the samples collected from the monitoring wells located closer to the injection well transect but were sustained for approximately 4 months in the samples collected from LVWPS-U3-MW10B. However, despite these decreases in TOC concentrations, perchlorate concentrations remained below the sample detection limit of 0.31 μg/L.
- The TOC data collected following the first injection event was used in the determination of the timing for the second injection event, as discussed in Section 8.3.1. Following the second injection event, notable increases in groundwater TOC concentrations were observed in samples collected from monitoring wells LVWPS-U3-MW03B, LVWPS-U3-MW03C, LVWPS-U3-MW09, LVWPS-U3-MW10A, LVWPS-U3-MW10B, LVWPS-U3-MW11A, and LVWPS-U3-MW13A with TOC concentrations ranging from 6.8 mg/L to 330 mg/L (Appendix L, Figures L.94 through L.97 and L.104 through L.106). Although an increase in TOC concentrations was not observed in samples collected from LVWPS-U3-MW03C following the first injection event, TOC concentrations increased significantly following the second injection event, with a TOC concentration of 110 mg/L immediately following the second injection event. One final noteworthy TOC concentration was the detection of TOC at 6.8 mg/L in the sample from LVWPS-U3-MW11A, which coincides with the temporary decrease in perchlorate, chlorate, and nitrate concentrations observed in samples from this well during the Month 13 sampling event.

- Similar to the results following the first injection event, TOC concentrations generally remained elevated for approximately 4 months following the second injection event in samples collected from LVWPS-U3-MW09 and LVWPS-U3-MW10B (Appendix L, Figures L.96 and L.105). During the final sampling event of the Pilot Study (approximately 8 months following the second injection event), the highest TOC concentration detected was 2.7 mg/L in the sample collected from LVWPS-U3-MW10B. For comparison, the Zone 1 study area included TOC concentrations as high as 38 mg/L during the final sampling event. This result was not unexpected given that the UMCf-cg is slightly more transmissive, which may result in a more rapid depletion of organic carbon compared to the UMCf.

The TOC concentration data collected over the 18-month study provides valuable information to determine the longevity of the EVO and potential injection frequencies if ISB is selected as a component of the NERT final remedy. The data also confirm the presence of low effective porosity and significant preferential flow paths within the Zone 3 shallow and deep UMCf-cg, as indicated by increased TOC concentrations in samples collected from monitoring wells located more than 100 feet downgradient of the injection well transect within the first month following each injection event. Lastly, although notable TOC concentration increases were present in samples collected from nine different monitoring wells within the Zone 3 study area, perchlorate concentrations decreased in samples collected from other downgradient monitoring wells (such as LVWPS-MW212C and LVWPS-MW212D) that did not show TOC concentration increases. This finding indicates the likely downgradient movement of treated groundwater migrating from the injection well transect, a phenomenon that is commonly observed in transect-based bioremediation.

8.7.5 Collective Result for Primary Parameters

As described in Sections 8.7.1 through 8.7.4, the results of the primary parameters of perchlorate, chlorate, nitrate, and TOC demonstrate that bioremediation of perchlorate occurred within both the shallow, deep, and deepest portions of the UMCf-cg in the Zone 3 study area. Results show that in areas where groundwater samples indicated an increase in TOC concentrations, reductions were also observed in perchlorate, chlorate, and nitrate concentrations. In these areas, perchlorate concentrations in groundwater were reduced to below the PRG of 15 μg/L in multiple samples over several sampling events. Groundwater samples collected from other downgradient monitoring wells also had notable concentration reductions of perchlorate despite minimal changes in TOC concentrations, likely due to flow of treated groundwater from upgradient areas. Although contaminant concentration reductions and TOC concentration increases were observed in the upgradient UMCf monitoring wells within the Zone 1 study area, similar reductions were not observed in the upgradient UMCf-cg monitoring wells within the Zone 3 study area. This dissimilarity in results between the two study areas highlights a difference in the injectate distribution patterns between the UMCf and the UMCf-cg. Additionally, no effects from the injections were observed in the overlying alluvium, which indicates that minimal upflux into the overlying alluvium occurred during the Pilot Study within the Zone 3 study area or the baseline alluvial concentrations within the Zone 3 study area were too low to observe any discernable change due to upward migration of the injectate solution and/or treated groundwater.

8.7.6 Additional Chemical and Geochemical Evaluation

This section provides a summary of the additional data collected during the Pilot Study from the Zone 3 study area. This includes DO, ORP, sulfate, and sulfide, as well as the geochemical relevance of each parameter in relation to perchlorate biodegradation. During the Pilot Study, groundwater samples were also collected from three clustered monitoring well locations within the Zone 3 study area (LVWPS-A3-MW02, LVWPS-U3-MW02A/B, LVWPS-A3-MW07, LVWPS-U3-MW07A/B, LVWPS-A3-MW12, and LVWPS-U3-MW12A/B) for analysis of an extended suite of parameters as described in Section 5.7. As a result, a discussion of metals, pH, alkalinity, TDS, methane, total nitrogen, phosphorus, hexavalent chromium, and VFAs is also presented to discuss their significance on the Pilot Study findings. Results for all parameters discussed herein are presented in the comprehensive data tables provided in Appendix J, Tables J.1 and J.2. DO, ORP, and sulfate concentrations during the Pilot Study are graphically depicted in Appendix L, Figures L.88 through L.119. The significance of these additional parameters was previously explained in Section 6.7.6, and therefore, have not been reiterated herein.

8.7.6.1 Dissolved Oxygen

Baseline readings prior to injections indicated a generally aerobic aquifer with DO readings averaging approximately 3.97 mg/L and ranging from 0.99 to 8.50 mg/L. Following the first injection event, DO concentrations decreased in groundwater samples collected from the majority of the monitoring wells within the Zone 3 study area, with an average DO concentration of 2.38 mg/L in the Month 1 sampling event following the first injection event. During the Month 1 sampling event, samples collected from seven downgradient monitoring wells screened in the UMCf-cg (namely, LVWPS-U3-MW02B, LVWPS-U3-MW03B, LVWPS-U3-MW03C, LVWPS-U3-MW09, LVWPS-U3-MW10A, LVWPS-U3-MW10B, and LVWPS-U3-MW13B) indicated DO concentrations less than 1.0 mg/L, with samples from LVWPS-U3-MW02B, LVWPS-U3-MW03B, LVWPS-U3-MW03C, and LVWPS-U3-MW13B indicated DO concentrations less than 0.5 mg/L. These reductions in DO concentrations indicated that reducing conditions were rapidly established following injections. Despite other parameter results indicating the need for the second injection event (i.e., perchlorate concentration increases and/or TOC concentration decreases), DO concentrations generally remained consistently decreased during all sampling events after the first injection event, with no notable return to aerobic conditions (i.e., DO concentrations prior to the second injection were less than 0.5 mg/L in samples from five monitoring wells and less than 1.0 mg/L in samples from 11 monitoring wells). Therefore, similar to Zone 1, the Zone 3 results indicate that DO is a good indicator for evaluating the influence of injections through the creation and sustainment of anaerobic conditions but is not likely to be the foremost indicator for evaluating the timing of additional injection events.

Following the second injection event in October 2021, field readings for DO continued to indicate a generally reducing environment at many locations, with DO concentrations routinely reduced to less than 1.0 mg/L in groundwater samples collected from 15 of the 20 downgradient monitoring wells screened within the UMCf-cg within the Zone 3 study area. Other notable DO concentration decreases to less than 1.0 mg/L were observed in groundwater samples collected from alluvial monitoring wells LVWPS-A3-MW10 and LVWPS-A3-MW12, which are located approximately 100 to 150 feet downgradient of the injection well transect. Despite not observing significant decreases in contaminant concentrations, these DO concentration decreases in samples collected from the alluvium indicate limited upflux of treated groundwater from the UMCf-cg into the overlying alluvium in the Zone 3 study area. However, insufficient organic carbon appears to be available for the microorganisms to begin perchlorate biodegradation in the overlying alluvium.

As previously explained, DO is a useful indicator during the initial 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 less organic carbon that gets transported to downgradient locations. As a result, DO is a valuable indicator parameter to be used for evaluating the influence of injections through the creation and sustainment of anaerobic conditions but is not likely to be the foremost indicator for evaluating the timing of additional injection events.

8.7.6.2 Oxidation-Reduction Potential

During the baseline sampling event in October 2020, ORP measurements collected from groundwater in the UMCf-cg averaged 62.9 mV, which is generally consistent with aerobic conditions indicated by the DO concentrations within the Zone 3 study area prior to injections. Immediately following the first injection event, ORP measurements in monitoring wells screened in the UMCf-cg significantly decreased to an average of -53.8 mV, which indicated a shift towards anaerobic conditions. Strongly negative ORP measurements of less than approximately–- 200 mV were measured in samples from monitoring wells where an increase in TOC concentration was also observed (i.e., LVWPS-U3-MW03B, LVWPS-U3-MW03C, LVWPS-U3-MW09, LVWPS-U3-MW10A, LVWPS-U3-MW10B, and LVWPS-U3-MW13B).

ORP measurements following the second injection event continued to indicate generally anaerobic conditions, with an overall average ORP value of -43 mV measured throughout all sampling events after the second injection event. Additionally, although ORP measurements in samples collected from monitoring wells LVWPS-U3-MW02A and LVWPS-U3-MW02B were not negative following the second injection event, perchlorate concentrations did reduce in multiple sampling events in the samples collected at these locations following the second injection event. As with DO, ORP measurements in the samples collected from alluvial monitoring wells LVWPS-A3-MW10 and LVWPS-A3-MW12, which are located approximately 100 to 150 feet downgradient of the injection well transect, indicated either anaerobic or substantially reduced values when compared to baseline. As previously explained, despite not observing significant decreases in contaminant concentrations, these ORP reductions in samples collected from the alluvium indicate that limited discharge of treated groundwater from the UMCf-cg into the overlying alluvium is likely occurring within the Zone 3 study area.

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 Pilot Study, as inferred from ORP readings. However, during some sampling events, redox measurements did not correlate well with the supporting data from other analytes.

8.7.6.3 Sulfate and Sulfide

Baseline sulfate concentrations averaged approximately 1,835 mg/L in the groundwater samples collected from the monitoring wells screened in the UMCf-cg within the Zone 3 study area. In general, groundwater at downgradient monitoring wells exhibited relatively stable sulfate concentrations during the Pilot Study, with the overall average sulfate concentrations in each event ranging from 1,561 mg/L to 1,937 mg/L. Significant sulfate concentration reductions were noted in samples collected from monitoring wells LVWPS-U3-MW09 and LVWPS-U3-MW10B, with decreases from greater than 1,300 mg/L in baseline to a Pilot Study low concentration of 1.9 and 3.6, respectively. Sulfate concentrations began increasing towards the end of the Pilot Study, with concentrations of 400 mg/L and 290 mg/L in the final samples collected from monitoring wells LVWPS-U3-MW09 and LVWPS-U3-MW10, respectively.

Sulfide was monitored at one upgradient monitoring well cluster (LVWPS-A3-MW07, LVWPS-U3-MW07A and LVWPS-U3-MW07B) and two downgradient monitoring well clusters (LVWPS-A3-MW02, LVWPS-U3-MW02A, LVWPS-U3-MW02B, LVWPS-A3-MW12, LVWPS-U3-MW12A, and LVWPS-U3-MW12B). Although limited samples were collected, sulfide was not detected in any samples collected from the Zone 3 study area during the Pilot Study.

Although sulfate concentrations significantly reduced in samples collected from LVWPS-U3-MW09 and LVWPS-U3-MW10B, sulfate concentrations only slightly reduced in samples collected from remaining downgradient UMCf-cg monitoring wells that also had increased TOC concentrations. These overall sulfate results suggest that sulfate reduction is not persistent throughout the Zone 3 study area, which is consistent with the results from the Zone 1 study area (discussed in Section 6.7.6) and previous ISB studies performed at NERT. This data can be useful for full-scale remedy evaluation because the data suggests the potential negative impacts of sulfate biodegradation in this high sulfate environment may be minimized and/or controlled during implementation of in-situ bioremediation. Therefore, even with the significant heterogeneity, high percentage of fines in the UMCf/UMCf-cg, and lower groundwater flow velocities compared to the alluvium, there does not appear to be sufficient residence time (nor highly reducing conditions) for sulfate reduction to occur biologically.

8.7.6.4 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. To monitor for potential metals mobilization, dissolved metals were analyzed during baseline and periodically during the Pilot Study within the Zone 3 study area at one upgradient monitoring well cluster (LVWPS-A3-MW07; LVWPS-U3-MW07A/B) and two downgradient monitoring well clusters (LVWPS-A3-MW02; LVWPS-U3-MW02A/B and LVWPS-A3-MW12; LVWPS-U3-MW12A/B). This section presents an evaluation of arsenic, iron, and manganese groundwater concentrations during the Pilot Study.

8.7.6.4.1 Arsenic

Baseline dissolved arsenic concentrations ranged from 25 µg/L to 60 µg/L. Following injections, arsenic concentrations in groundwater generally remained stable except for the transient increases observed in the samples collected from UMCf-cg monitoring well LVWPS-U3-MW12B of up to 150 µg/L following the first injection event. However, concentrations generally followed a reducing trend following the second injection event, with an arsenic concentration of 100 µg/L during the final sampling event in June 2022. Despite this increase in arsenic concentration, arsenic increases were not observed in samples collected from other downgradient monitoring wells. Therefore, arsenic release and mobilization are unlikely to be a secondary issue during the implementation of ISB using EVO as the carbon substrate, which is a similar conclusion drawn from the results of the Zones 1 and 2 study areas.

8.7.6.4.2 Iron

Baseline concentrations of dissolved iron were less than 0.19 mg/L. During the study, groundwater concentrations for dissolved iron generally continued to remain low, with the highest detection of dissolved iron at 0.35 mg/L in a sample collected from LVWPS-U3-MW12A. However, this relatively minor increase in concentration was short-lived, with a dissolved iron concentration of 0.058 mg/L in the final sample collected from LVWPS-U3-MW12A. The lack of iron mobilization is further supported by field measurements of ferrous iron, which was only periodically detected in samples collected from LVWPS-U3-MW02A and LVWPS-U3-MW07A.

8.7.6.4.3 Manganese

Baseline dissolved manganese concentrations in groundwater measured up to 0.23 mg/L. Following injections, manganese concentrations slightly increased in groundwater samples collected from LVWPS-U3-MW02B, LVWPS-U3-MW12A, and LVWPS-U3-MW12B, with the highest concentration detected in each well of 1.1 mg/L, 1.2 mg/L, and 3.3 mg/L, respectively. Manganese concentrations decreased over time during the Pilot Study, with concentrations of 0.024 mg/L, 0.11 mg/L and 1.5 mg/L in the final samples collected from LVWPS-U3-MW02B, LVWPS-U3-MW12A, and LVWPS-U3-MW12B, respectively. The minor transient increases followed by decreasing trends indicate that manganese solubilization is contained within the Zone 3 study area and does not appear to be migrate downgradient.

8.7.6.5 Other Parameters

A suite of several other parameters was periodically analyzed during the Pilot Study. A summary of these parameters and their significance is presented below. With the exception of pH, which was sampled at all wells during all events, these other parameters were only analyzed in one upgradient monitoring well cluster (LVWPS-A3-MW07; LVWPS-U3-MW07A/B) and two downgradient monitoring well clusters (LVWPS-A3-MW02; LVWPS-U3-MW02A/B and LVWPS-A3-MW12; LVWPS-U3-MW12A/B). Results for each parameter are presented in the comprehensive data tables provided in Appendix J, Tables J.1 and J.2.

- Groundwater pH is an environmental factor that can affect microbial activity, with most species of microorganisms generally preferring a neutral pH between 5.5 and 8.5 standard units. During baseline sampling, groundwater pH ranged from 6.92 to 8.49 standard units. In general, groundwater pH remained within the ideal range during the Pilot Study, with an overall average pH after injections of 7.38 standard units.

- Baseline alkalinity values in groundwater within the Zone 3 study area ranged from 54 mg/L to 94 mg/L. During the Pilot Study, results from the groundwater samples collected from monitoring well LVWPS-U3-MW12B showed considerable increases in alkalinity concentrations following the injections, with concentrations of up to 250 mg/L compared to the baseline concentration of 72 mg/L. Groundwater results from the samples collected from monitoring wells LVWPS-A3-MW12, LVWPS-U3-MW02B, and LVWPS-U3-MW12A also indicated slight increases of up to 130 mg/L during periodic sampling events following injections. Increases in groundwater alkalinity at these levels compared to baseline concentrations indicated that groundwater is undergoing biodegradation. As previously discussed in Section 8.7.1, samples from these monitoring wells also indicated substantial groundwater perchlorate concentration decreases during the Pilot Study.
- TDS concentrations in groundwater ranged from 1,800 to 5,900 mg/L throughout the Pilot Study. Although these are relatively high concentrations, the Pilot Study (similar to the bench-scale study [Tetra Tech, 2019a]) indicated that TDS concentrations at these levels did not hinder microbial activity and perchlorate biodegradation.
- Methane was periodically evaluated during the Pilot Study as an additional indicator of the level of reducing conditions that were established following carbon substrate injections. Methane was not detected during the baseline sampling event. During the Pilot Study, methane concentrations were detected above baseline concentrations in samples from several locations, with the maximum observed concentration of 13 mg/L in the sample collected from monitoring well LVWPS-U3-MW12B. Generally, when methane is created, it is produced at the depth at which groundwater is undergoing bioremediation and is oxidized rapidly as it rises in the UMCf-cg or into the overlying sandy and gravelly alluvium because of the more aerobic conditions present in these zones. This oxidizing process was confirmed based on the results of the samples collected from the monitoring wells screened in the overlying alluvium and shallow UMCf-cg. Specifically, samples collected from shallow UMCf-cg monitoring well LVWPS-U3-MW12A indicated a methane concentration of 1.1 mg/L, while the samples collected from the alluvial monitoring well LVWPS-A3-MW12 indicated a methane concentration of 2.5 mg/L. Additionally, it is likely to be further rapidly oxidized into carbon dioxide in the upper unsaturated alluvium.
- Total nitrogen concentrations in groundwater ranged from 5.8 mg/L to 12 mg/L during the baseline sampling event. Following injections, total nitrogen concentrations in groundwater generally remained the same, with the exception of decreases observed in samples collected from LVWPS-U3-MW12B (baseline concentration of 7.4 mg/L, followed by post-injection concentrations ranging from 1.3 mg/L to 3.3 mg/L). The decrease in total nitrogen is likely the result of denitrification that was actively occurring in the groundwater as described in Section 8.7.3. Despite the reductions of total nitrogen, high nitrate concentrations in area groundwater combined with the efforts of four bench-scale studies and three field treatability/pilot studies indicate that there is sufficient nitrogen present in the groundwater and therefore, should not be a limiting nutrient for bioremediation.
- Phosphorus in groundwater was monitored during the Pilot Study because a phosphate solution was added to the injectate mixture during the first injection event to serve as a macronutrient for reduced acclimation time for the onset of perchlorate biodegradation. Similar to the results from the other study areas, results indicated that the addition of the phosphate solution resulted in transient localized increases in total phosphorus concentrations when compared to baseline concentrations, but concentrations quickly returned to at or below baseline concentration levels. This indicates that the augmented phosphorus was likely consumed 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 Pilot Study location, with baseline concentrations ranging from 15.3 μg/L to 31.5 μg/L. Periodic concentration decreases were observed in samples collected from all monitoring wells sampled. Hexavalent chromium concentrations significantly decreased in samples collected from LVWPS-U3-MW12B, decreasing from a

baseline concentration of 27.7 μg/L to below the sample detection limit of 0.150 μg/L in the final sample collected from this monitoring well.

- Volatile fatty acids were periodically analyzed at select downgradient wells to get an assessment of the acids produced during hydrolysis of the long-chain fatty acids of EVO. Acetic acid, butyric acid, and formic acid were detected in isolated sampling events performed post-injections during the Pilot Study; however, groundwater concentrations were generally low ranging from 2.6 mg/L to 6.3 mg/L. Most of the VFAs that are produced from EVO get converted into hydrogen and are consumed by the native microorganisms.

8.7.7 Microbial Evaluation

Microbial sampling was included in the effectiveness monitoring program to examine the microbial response to carbon substrate injections. As part of this microbial evaluation, Bio-Trap® samplers were deployed in one upgradient well cluster (LVWPS-U3-MW08A and LVWPS-U3-MW08B) and one downgradient well cluster (LVWPS-U3-MW13A and LVWPS-U3-MW13B) during the pre-injection baseline sampling event and two post-injection events (approximately 10 and 16 months following the first injection event). This section presents a summary of this microbial evaluation for Zone 3. Complete analytical results for the microbial analyses performed during the Pilot Study are provided in Appendix J, Table J.3; microbial laboratory data reports are provided in Appendix N. A description of Bio-Trap® sampling and analysis is provided in Section 6.7.7.

8.7.7.1 Analysis of Microbial Results

Results of the microbial sampling prior to injections indicated a robust microbial population was present in the groundwater in the vicinity of Zone 3 prior to injections. Although the perchlorate reductase enzyme was present at a population of less than 2.5×10^2 cells per bead, the overall biomass populations during baseline were greater than 8.16×10^4 cells per bead in both the shallow and deep UMCf-cg. PLFA analysis on community structure indicated that more than 50 percent of the bacterial population belonged to the proteobacteria group. As previously explained in Section 6.7.7.1, the proteobacteria represent a wide variety of anaerobic and aerobic microorganisms that are capable of adapting quickly to changes in the environment, such as the addition of a carbon substrate. As a result, this high percentage of proteobacteria harbors well for the potential bioremediation of perchlorate once a carbon substrate is injected into the subsurface. Other notable baseline results include the decreased permeability ratios of 0.0 in the samples collected from all four monitoring wells, which indicates that there are no signs of toxicity to the native microorganisms in the subsurface prior to injections. On the other hand, the ratios for slow growth ranged from 1.03 to 2.07, which indicated the low availability of carbon as a food source for native microorganisms in the Zone 3 study area prior to injections.

Following injections and approximately a year after the initial injection event, the perchlorate reductase enzyme increased by one order of magnitude (increase from 10^2 to 10^3) in the sample collected from monitoring wellLVWPS-U3-MW08B. Additionally, the perchlorate reductase enzyme increased by two orders of magnitude (increase from 10^2 to 10^4) in the sample collected from LVWPS-U3-MW13B and three orders of magnitude (increase from 10^2 to 10^5) in the sample collected from LVWPS-U3-MW08A. No increases were observed in perchlorate reductase in samples collected from monitoring well LVWPS-U3-MW13A.

This indicates an increase in the perchlorate-degrading capability of the microorganisms in the aquifer following the addition of a carbon substrate. The PLFA analysis indicated that percentage of proteobacteria increased to greater than 80 percent in samples collected from LVWPS-U3-MW08A and LVWPS-U3-MW08B and remained greater than 50 percent in all other samples following injections. The most significant increase in firmicutes was noted in the sample collected from LVWPS-U3-MW13A, which increased from 3.17 percent to 12.86 percent following the first injection event. This increase indicated the growth of bacteria that can ferment the injected EVO and its daughter products into hydrogen for utilization by the microbes belonging to the proteobacteria group for the reduction of perchlorate.

Lastly, the ratios for slowed growth decreased in the samples collected from the downgradient monitoring wells (LVWPS-U3-MW13A and LVWPS-U3-MW13B) following injections but remained stable or increased in samples collected from the upgradient monitoring wells (LVWPS-U3-MW08A and LVWPS-U3-MW08B), which was unexpected considering the proliferation of the microbial biomass population at these upgradient locations. The decrease in the slow growth ratios in the samples from the downgradient monitoring wells indicates the strong availability of carbon for microbial consumption. The ratios for decreased permeability remained 0.0 in samples from all monitoring wells except LVWPS-U3-MW13B, which only slightly increased from 0.0 to 0.11, which indicates little toxicity to native microorganisms throughout the period of the study.

8.8 ZONE 3 SUMMARY

The results summarized herein for Zone 3 provide sufficient data to meet the objectives of the Pilot Study and will support evaluation of ISB as a potential portion of the final remedy in the forthcoming OU-3 FS. The fulfillment of the study objectives is described below and provided in tabular format in the performance criteria tables provided as Appendix O.

- Objective 1 – Determine if ISB can effectively create a biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater within the UMCf-cg and compare the effectiveness with respect to variations in lithology between the UMCf within Zone 1 (discussed in Section 6.0) and UMCf-cg within Zone 3. Data collected indicate the following:
    - A biologically active zone for remediation of perchlorate- and chlorate-contaminated groundwater was created downgradient of the injection well transect in Zone 3. Groundwater perchlorate concentrations of less than 0.31 μg/L were achieved in samples collected from all targeted depths of the UMCf-cg. Although a biologically active zone was created, the injectate travelled along preferential flow paths throughout the faulted-UMCf-cg, which resulted in greater contaminant concentration reductions in the western portion of the Pilot Study area. As previously explained in the summary of the other study areas, if ISB were selected as a component of the NERT final remedy, the injection well transect would likely extend the entire width of the targeted groundwater plume or include multiple rows of injection well transects throughout the length of the groundwater plume. This would substantially improve distribution throughout the preferential flow paths that exist in the UMCf-cg as opposed to just those that existed near the 200-foot injection well transect, which was designed specifically on a scale to evaluate study objectives in the Zone 3 study area.
    - Overall, the ISB injections into the Zone 3 study area were more effective (i.e., greater subsurface distribution of injectate) than the ISB injections into the Zone 1 study area. The difference in effectiveness relates directly to the difference in the lithology within each of the zones (i.e., UMCf and UMCf-cg). Although ISB was effective in the Zone 1 UMCf, hydrogeologic controls on groundwater flow resulted in a more pronounced preferential flow path through the faulted UMCf and into the overlying alluvium downgradient of the injection well transect. Additionally, slug test results indicated that the UMCf-cg had a higher hydraulic conductivity in the western portion of the Zone 3 study area compared to the slightly lower hydraulic conductivities in the UMCf present in Zone 1. This higher hydraulic conductivity in the UMCf-cg resulted in improved lateral downgradient distribution of the injectate compared to the distribution within the UMCf within the Zone 1 study area that was primarily associated with preferential flow pathways. Lastly, the injectate solution did not travel upgradient from the injection well transect in the Zone 3 study area like it did in the Zone 1 study area. This lack of upgradient distribution was likely due to the coarser-grained UMCf-cg in the Zone 3 area compared to the UMCf in the Zone 1 study area, which is an important data point for the forthcoming FS when evaluating the implementability and cost of an injection remedy into the UMCf-cg.

- Objective 2 – Evaluate ISB implementation and operational components within the UMCf-cg, including injection protocols, achievable injection rates, subsurface distribution of injectate, injection well spacing, and construction methods. Data collected indicate the following:
  - As with other study areas with injections into nested injection wells, the injection protocol included performed injections into all treatment intervals within each nested injection well cluster at the same time, with the injection rates adjusted so that each injection well within a cluster would finish the injection process at generally the same time interval. The goal of performing injections in this manner was to achieve relatively even subsurface distribution within the long-screened intervals of the nested injection well while also attempting to account for variability and non-uniform groundwater flow and lithology. As explained in Section 8.6.4, the injectate solution, tagged with fluorescein dye appeared in samples collected from all four dose-response monitoring wells screened in the shallow and deep UMCf-cg. This indicates that the injections were successful in vertically distributing the injectate in both the shallow and deep UMCf-cg using this injection method with the dual-nested injection wells and did not preferentially go into one interval over the other.
  - The study generated a substantial dataset related to achievable injection rates and pressures, with average injection rates of 4 gpm and injection pressures of 12 psi during the first injection event and 3 gpm and 16 psi during the second injection event. Due to the preferential flow paths of the subsurface, it is important to maintain relatively low injection rates and pressures to minimize distribution primarily along those paths and instead achieve more evenly distributed injectate around the injection well transect thereby creating a more uniform biologically active zone.
  - As described in Section 8.3.1 (and similar to the injections into the UMCf in Zones 1 and 2), the dose-response monitoring related to the dye injections indicated a significantly lower mobile (effective) porosity compared to the values estimated using the data collected during pre-design activities. This lower effective porosity resulted in a reduction in distribution water requirements in the UMCf-cg, which is an important data point for the forthcoming FS when evaluating the implementability and cost of an injection remedy into the UMCf.
  - Lastly, an injection well spacing of 25 feet, resulting in an injection ROI of 12.5 feet, was determined to be reasonable for the lithology present within the study area based on the overall response to the injections into the UMCf-cg within Zone 3. This finding adds to NERT's growing knowledgebase of ISB implementation experience and the operational data collected during this study provides important information for evaluation of a full-scale ISB remedy in the UMCf-cg and the scale-up requirements related to injection quantities, rates/pressures, and durations.
- Objective 3 – Determine whether remediation in the UMCf-cg in an area with elevated perchlorate and chlorate concentrations in groundwater and a known upward gradient has an effect on contaminant concentrations in the overlying alluvium groundwater, and if so, whether the effect differs depending on UMCf lithology (comparison of results from Zones 1 and 3). Data collected indicate the following:
  - Although fluorescein injected in the UMCf was observed in the overlying alluvium during the Pilot Study in Zone 1, fluorescein was only minimally detected in one alluvial monitoring well, namely, LVWPS-A3-MW12, which was located approximately 150 feet downgradient of the injection well transect in Zone 3. Additionally, perchlorate concentrations exhibited an overall decreasing trend in samples collected from LVWPS-A3-MW12, reducing from a baseline concentration of 200 μg/L to a final Month 18 concentration of 89 μg/L. However, other than the relatively small response in samples collected from the LVWPS-A3-MW12 location, perchlorate concentration decreases, or TOC concentration increases were generally not observed in samples collected from other monitoring wells screened in the alluvium in the Zone 3 study area. As noted in Section 8.5, analysis of the groundwater elevations following the Phase 2 well installation in the Zone 3 study

area indicated that the magnitude of the vertical gradients between the alluvium and UMCf-cg were generally small and downward, ranging from 0.001 ft/ft to 0.014 ft/ft. As a result, it was expected that the alluvium in the Zone 3 study area would not be significantly impacted by the injections into the underlying UMCf-cg.

- Objective 4 – Determine the approximate length of time that ISB could be expected to affect concentrations in the UMCf-cg and the resulting injection frequency required to maintain these concentration reductions. Data indicate the following:
  - Treatment effectiveness is directly related to groundwater flow within the UMCf-cg that is governed by a variety of unique location-specific hydrogeologic variables. Preferential flow can occur along secondary porosity generated by faulting, along bedding planes within the UMCf-cg, and within laterally discontinuous beds of coarser sediments. In addition, the depth of the UMCf-cg contact with the alluvium varies, especially where alluvial paleochannels are eroded into the surface of the UMCf-cg. In general, groundwater flow through primary porosity under natural gradients is likely faster in the UMCf-cg than the UMCf (as in Zone 1), particularly in the most coarse-grained, highest hydraulic conductivity portions of the UMCf-cg in the western part of Zone 3.
  - Following injections, the injectate solution was immediately transported downgradient along preferential flow paths to select monitoring wells, while also slowly migrating in the subsurface via natural groundwater flow. Samples collected from multiple locations within the Zone 3 study area indicated perchlorate concentrations below the PRG of 15 μg/L, with some areas indicating sustained reductions below the PRG for the entire duration of Pilot Study following the initial injection event (such as LVWPS-U3-MW10B). These results indicate that the injection frequency could likely be increased to greater than the ten-month frequency evaluated in the Pilot Study; however, there are many site-specific variables (i.e., preferential flow pathways, subsurface heterogeneity, injection well design, and RAOs) that may influence injection frequency if ISB were selected as a component of the NERT final remedy.
- Objective 5 – Evaluate if dual-nested injection wells are effective in delivering substrate to large, saturated thicknesses of the UMCf-cg because nested injection wells can be a cost-effective option as opposed to multiple separate injection wells. Data collected indicated the following:
  - Installation of nested wells as opposed to single clustered injection wells resulted in significant cost savings of approximately 30 percent per well for the dual nested configuration and 40 percent per well for the triple nested configuration.
  - During active injections, the injectate solution was observed in both sets of shallow, deep, and deepest dose-response monitoring wells located immediately downgradient of the injection wells. These results indicate that the injectate was distributed both horizontally and vertically in the subsurface, despite the large, saturated thickness of the UMCf-cg.
  - Injectate solution was observed in all depth intervals within the UMCf-cg as evidenced by TOC concentration increases in samples collected from monitoring wells screened as shallow as 83 to 108 feet bgs and as deep as 151 to 176 feet bgs. These data indicate that both dual- and triple-nested well configurations can effectively distribute the injectate in both horizontal and vertical directions.

9.0 LONG-TERM MONITORING OF THE PILOT STUDY AREA

This section presents the results of the long-term monitoring of the Pilot Study area including evaluation of trends in groundwater elevations and contaminant concentrations in the vicinity of the remediation zones but outside the influence of ISB.

9.1 LONG-TERM GROUNDWATER LEVEL MONITORING

As described in Section 5.6.4, transducers were installed in 15 monitoring wells within four monitoring well cluster locations, which included LVWPS-MW201A/B, LVWPS-MW206A/B/C/D/E, LVWPS-MW210A/B/C/D/E, and LVWPS-MW222A/B/C during Phase 1 pre-design activities to monitor water levels during the Pilot Study. These same 15 monitoring wells remained instrumented during Phase 2 activities. Results of the transducer data collection and evaluation are presented in Appendix H.

The transducer data were corrected for barometric pressure and compared to the surface water elevation data from the nearby Bostick Weir gauging station (USGS 09419747 LV Wash Abv Bostick Weir Nr Henderson, NV). The comparison indicated that many of the monitoring wells were visibly influenced by water levels in the Wash, showing daily groundwater elevation changes that corresponded closely to the Wash surface water elevation changes. The response of groundwater elevation to water levels in the Las Vegas Wash is not surprising because the instrumented well clusters are located less than 500 feet from the Las Vegas Wash. Some of the deeper monitoring wells screened in the UMCf/UMCf-cg such as LVWPS-MW201B did not show daily changes that match the surface water elevations in the Wash. However, when the Wash surface water elevation increases significantly (i.e., by more than 0.5 feet), there was a corresponding increase in groundwater elevation at LVWPS-MW201B approximately 1 day later. While the UMCf screened by LVPWS-MW201B was not transmissive enough to detect the daily fluctuations in water level, the increased head in the upper portion of the aquifer was eventually transmitted to the lower portion. Data from monitoring well cluster LVWPS-MW222A/B/C, which included three monitoring wells screened in the UMCf-cg, also indicated that groundwater elevations did not visibly respond to daily surface water elevation changes in the Wash, likely due to the greater distance of this monitoring well cluster from the Wash (i.e., approximately 1,000 feet).

The groundwater elevation data indicated a response within a few hours at monitoring wells screened in the alluvium and shallow UMCf/UMCf-cg following precipitation events of greater than 0.25 inches. In contrast, groundwater elevations measured at many monitoring wells screened in the deeper UMCf/UMCf-cg and semi-consolidated UMCf (LVWPS-MW201B, LVWPS-MW206D/E, LVWPS-MW222C) indicated only a weak and/or delayed response approximately 24 hours following precipitation events.

The long-term water level monitoring also showed the hydraulic response to injection and extraction activities associated with the Pilot Study. The LVWPS-MW206A/B/C/D/E monitoring well cluster was the closest instrumented well cluster to the Zone 1 study area. During the first injection event, water level rises of approximately 0.7 feet and 3 feet were observed at monitoring wells LVWPS-MW206D and LVWPS-MW206E, respectively. Although the LVWPS-MW206A/B/C/D/E monitoring well cluster is located approximately 275 feet away from the Zone 1 injection well transect, the observable pressure response in the deeper UMCf monitoring wells LVWPS-MW206D/E is not unusual given the strong hydraulic response to injections in the immediately vicinity of the Zone 1 study area (discussed in more detail in Section 6.3.3). A visible response to Zone 2 injection activities was not observed at the LVWPS-MW206A/B/C/D/E monitoring well cluster. However, monitoring well LVWPS-MW206B was used as an extraction well during injection activities, so any effects from Zone 2 alluvial injections would be masked by the drawdown associated with extraction activities. During the first injection event, a drawdown of approximately 3 feet was observed at LVWPS-MW206B at an average extraction flow rate of 56 gpm. (Table D.1 in Appendix D). Additionally, all three monitoring wells at the LVWPS-MW222A/B/C monitoring well cluster (located approximately 100 feet away) were visibly influenced by the Zone 3 injection events in December 2020 and October 2021. The largest responses to injection activities were observed in the two deepest monitoring wells LVWPS-MW222B/C, where a rise of approximately 2 to 3 feet was observed during active injections.

Lastly, groundwater elevation data collected from monitoring well cluster LVWPS-MW222A/B/C generally indicated consistent upward vertical gradients within the UMCf-cg in the vicinity of Zone 3. However, during the second half of 2021, groundwater levels in the two shallower monitoring wells LVWPS-MW222A and LVWPS-MW222B became approximately equal, indicating little to no upward vertical gradient at that time. This change in gradient is unlikely to be associated with Pilot Study activities because the change started prior to the second Zone 3 injection event. The vertical gradient measured at this location in March 2022 had returned to baseline conditions.

9.2 LONG-TERM GROUNDWATER CONCENTRATION MONITORING

As described in Section 5.7.1, an effectiveness monitoring program was implemented to evaluate the effectiveness of ISB through monitoring changes in both groundwater contaminants and geochemical parameters following injection events. In addition to groundwater samples being periodically collected from monitoring wells located within the Pilot Study treatment zones, the effectiveness monitoring network also included select extraction and monitoring wells located at significant distances cross-gradient and/or upgradient of the injection well transects, where ISB impacts were anticipated to be minimal. Evaluation of groundwater analytical data collected from these wells provides insight into long-term groundwater concentrations trends in the general vicinity of the Pilot Study but in areas outside of the influence of ISB. This section provides a discussion of these long-term groundwater concentration trends, with data presented in the comprehensive data tables provided in Appendix J, Tables J.1 and J.2 and select data depicted graphically in individual well trend profiles provided in Appendix L. Field logs from all groundwater sampling events are provided in Appendix I and the DVSR is provided in Appendix K.

9.2.1 Long-Term Groundwater Concentrations in the Alluvium

As described in Section 5.4.3, the Pilot Study design incorporated extraction wells installed within the general Pilot Study area to be used as the water source during injection activities. These extraction wells were screened in the alluvium and installed in cross-gradient locations outside of the treatment zones to minimize potential hydraulic influence of extraction activities on concurrent injections within the treatment zones (**Figure 5**). Groundwater samples were collected from these extraction wells on a quarterly basis during the 18-month Pilot Study monitoring period. In addition to the extraction wells, alluvial monitoring wells located upgradient of the Zone 2 study area (namely, LVWPS-A2-MW01A/B, LVWPS-A2-MW02A/B, LVWPS-A2-MW03A/B, and LVWPS-MW224A; **Figures 5** and **7a-c**) were also sampled on a monthly or quarterly basis during the 18-month Pilot Study. As a result, groundwater analytical data from samples collected from these extraction and monitoring wells can be used to evaluate long-term groundwater concentrations trends within the alluvium in areas outside of the influence of ISB injections.

In general, groundwater analytical data from samples collected from extraction and monitoring wells screened in the alluvium in areas outside of the influence of ISB injections indicate relatively stable concentration trends throughout the duration of the 18-month Pilot Study. Results from the long-term monitoring performed in the alluvium in areas outside of the influence of ISB injections are summarized below.

- As shown in Appendix L, Figures L.120 through L.124, groundwater analytical data from samples collected from extraction wells LVWPS-EW01 through LVWPS-EW05 suggest that groundwater concentration trends for perchlorate, chlorate and nitrate in the alluvium in areas outside of the influence of ISB injections fluctuated but remained relatively stable throughout the duration of the Pilot Study. Perchlorate concentrations in groundwater samples collected from all five extraction wells throughout the Pilot Study ranged from 2,500 μg/L to 3,500 μg/L, with the exception of the perchlorate concentration in the sample collected LVWPS-EW03 in September 2021, which measured 9,600 μg/L but subsequently reduced to 2,900 μg/L. Chlorate concentrations in groundwater samples collected from the five extraction wells were more variable than the perchlorate concentrations, ranging from 1,900 μg/L to 14,000 μg/L. In general, chlorate concentrations were higher in groundwater samples collected from monitoring wells LVWPS-EW01 and LVWPS-EW05, ranging from 7,400 μg/L to 14,000 μg/L and averaging approximately 11,000 μg/L. In contrast, chlorate concentrations in groundwater samples collected from LVWPS-EW02, LVWPS-EW03 and LVWPS-EW04 ranged from 1,900 μg/L to 7,200 μg/L and averaged approximately 5,000 μg/L. Nitrate concentrations in groundwater samples collected from all five monitoring wells throughout the Pilot Study ranged from 14 mg/L to 30 mg/L.

- As presented in Section 7.7.1, perchlorate concentrations in samples collected from upgradient monitoring wells generally ranged from 1,100 μg/L to 4,200 μg/L (Appendix L, Figures L.28 through L.34). The highest upgradient perchlorate concentrations were generally observed in groundwater samples collected from monitoring wells LVWPS-A2-MW02A/B, which are centrally located upgradient of the injection well transect (**Figures 7a and 7b**). In general, upgradient perchlorate concentrations remained consistent in samples collected from each monitoring well throughout the Pilot Study. Although perchlorate concentrations remained generally consistent, chlorate concentration reductions of up to 71 percent and 99 percent were observed in samples collected from upgradient monitoring wells LVWPS-A2-MW01A and LVWPS-A2-MW01B, respectively, following the third injection event (Appendix L, Figures L.29 and L.30). Chlorate reductions were most prominent in samples collected from LVWPS-A2-MW01B, with a final concentration of 30 μg/L compared to a baseline concentration of 5,200 μg/L. Although TOC concentrations were not elevated in samples collected from the LVWPS-A2-MW01A/B cluster, groundwater geochemical data indicate a slight shift from aerobic to anaerobic conditions in this vicinity following the third injection event, which may be related to overall reducing conditions present in the vicinity of the injection well transect. Lastly, nitrate concentrations in groundwater samples collected from upgradient monitoring wells screened in the alluvium generally remained stable for much of the Pilot Study, with concentrations ranging from 7.3 mg/L to 26 mg/L (Appendix L, Figures L.29 through L.34).
- Groundwater samples collected from upgradient monitoring well LVWPS-MW224A indicated a baseline perchlorate concentration of 2,300 µg/L, followed by relatively stable concentrations ranging from 1,900 µg/L to 2,700 µg/L during subsequent sampling events (Appendix L, Figure L.28). Chlorate and nitrate concentrations also remained relatively stable throughout the 18-month Pilot Study, with chlorate concentrations ranging from 2,700 µg/L to 3,700 µg/L compared to the baseline concentration 2,900 µg/L and nitrate concentrations ranging from 9.6 mg/L to 14 mg/L compared to a baseline concentration of 11 mg/L.

9.2.2 Long-Term Groundwater Concentrations in the UMCf/UMCf-cg

Groundwater samples collected on a monthly basis from monitoring wells LVWPS-U1-MW03B and LVWPS-U3-MW01B were used to provide insight on long-term groundwater concentration trends within the UMCf and UMCf-cg in areas outside of the influence of ISB injections. Monitoring well LVWPS-U1-MW03B is screened in the deep UMCf approximately 60 feet cross-gradient of the Zone 1 injection well transect and outside of the influence of ISB injections (**Figure 6**), while monitoring well LVWPS-U3-MW01B is screened in the shallow UMCf-cg approximately 60 feet cross-gradient of the Zone 3 injection well transect (**Figure 8**). Data collected from monitoring wells screened in the UMCf and located upgradient of Zones 1 and 2 cannot be used in this evaluation due to ISB injections impacting several upgradient monitoring wells during the Pilot Study (e.g., LVWPS-U1-MW06A/B, LVWPS-U1-MW07, LVWPS-U2-MW01, and LVWPS-U2-MW02) as discussed in Sections 6.7.1 and 7.7.1. However, data collected from monitoring wells screened in the UMCf-cg and located upgradient of Zone 3 can be used in this evaluation because their location is outside the influence of the ISB injections.

In general, groundwater analytical data from samples collected from monitoring wells screened in the UMCf/UMCf-cg in areas outside of the influence of ISB injections indicate relatively stable concentration trends throughout the duration of the 18-month Pilot Study. Results from the long-term monitoring performed in the UMCf/UMCf-cg in areas outside of the influence of ISB injections are summarized below.

- Groundwater samples were collected from monitoring well LVWPS-U1-MW03B in September/October 2020 as part of baseline sampling activities and throughout the 18-month Pilot Study. Perchlorate concentrations in groundwater measured 4,300 μg/L, which is aligned with the range of perchlorate concentrations of 1,700 μg/L to 7,100 μg/L detected in groundwater collected from other Zone 1 monitoring wells screened in the deep UMCf during the baseline sampling event, as discussed in Section 6.7.1.1.1. Perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U1-MW03B during subsequent monitoring events ranged from 5,000 μg/L to 6,300 μg/L, which represent perchlorate concentration increases of 16 percent to 47 percent compared to the baseline concentration of 4,300 μg/L (Appendix L, Figure L.4). In contrast, chlorate and nitrate concentrations remained relatively stable throughout the 18-month Pilot Study.
- Monitoring well LVWPS-U3-MW01B is screened in the shallow UMCf-cg approximately 60 feet cross-gradient of the Zone 3 injection well transect (**Figure 8**). Groundwater samples were collected from monitoring well LVWPS-U3-MW01B in September/October 2020 as part of baseline sampling activities and throughout the 18-month Pilot Study. Perchlorate concentrations in groundwater samples collected from LVWPS-U3-MW01B ranged from 1,900 μg/L to 3,100 μg/L compared to a baseline concentration of 2,000 μg/L (Appendix L, Figure L.92). Chlorate concentrations exhibited an increasing trend throughout the Pilot Study, with concentrations ranging from 2,100 μg/L to 4,600 μg/L compared to a baseline concentration of 1,800 μg/L (Appendix L, Figure L.92). Similarly, nitrate concentrations steadily increased during the Pilot Study from a baseline concentration of 0.24 mg/L to 2.9 mg/L. Although chlorate and nitrate concentrations increased during the Pilot Study at LVWPS-U3-MW01B, the concentrations did not exceed typical concentrations of these parameters in groundwater within the UMCf-cg within Zone 3.
- As presented in Section 8.7.1, perchlorate concentrations in the samples collected from the monitoring wells screened in the UMCf-cg and located approximately 60 feet upgradient from the Zone 3 injection well transect also remained relatively stable throughout the Pilot Study (Appendix L, Figures L.88 through L.91). For example, the perchlorate concentrations in groundwater samples collected from monitoring well LVWPS-U3-MW07A ranged from 150 μg/L to 300 μg/L compared to the baseline concentration of 250 μg/L, and perchlorate concentrations in samples collected from monitoring well LVWPS-U3-MW07B ranged from 4,100 μg/L to 4,900 μg/L compared to the baseline concentration of 4,800 μg/L. Perchlorate concentrations in groundwater samples collected from LVWPS-U3-MW08A and LVWPS-U3-MW08B during the first month following the second injection event indicated perchlorate concentration reductions ranging from 20 percent to 48 percent, respectively. However, perchlorate concentrations increased to levels similar to baseline concentrations throughout the remainder of the Pilot Study. Chlorate concentrations in samples collected from all four of the upgradient monitoring wells indicated an average chlorate concentration reduction of approximately 20 percent over the duration of the Pilot Study. However, significant increases in TOC concentrations were not observed in the samples, and therefore, these reductions are likely not a result of injection activities (as discussed in Section 8.7.2). Lastly, nitrate concentrations indicated an average nitrate concentration increase of 6 percent over the duration of the Pilot Study. Overall, results from samples collected upgradient of the Zone 3 study area indicate a relatively stable environment, with only minor natural fluctuations in perchlorate, chlorate, and nitrate concentrations.

10.0 SURFACE WATER MONITORING

As explained in Section 5.7.2, surface water samples were collected from strategic locations within the Wash on a monthly basis during the Pilot Study to evaluate if the injectate solution tagged with tracer dye migrated into the Wash during the Pilot Study timeframe. Although reducing perchlorate and chlorate concentrations in surface water was not an objective of this Pilot Study, the surface water sampling program included perchlorate, chlorate and TOC to evaluate perchlorate and chlorate concentration trends and potential increases in TOC concentrations following injections. As part of the on-going monthly surface water sampling, surface water samples were already being collected on a monthly basis from three transect locations within the Wash that are located downgradient of the Pilot Study area between Historical Lateral and Homestead Weirs, namely LVW5.3, LVW4.75, and LVW4.2. In addition to these three transect locations, surface water samples were also collected for dye analysis from three additional locations along the southern bank of the Wash (i.e., LVWPS4.4, LVWPS4.8, and LVWPS4.9; shown on **Figure 9**). As explained in Section 5.7.2, an attempt was made to collect a sample from the LVW 5.1 area, but samples were not able to be collected due to access issues. Data for perchlorate, chlorate, TDS, and TOC are presented in the comprehensive data tables provided in Appendix J, Table J.8, while dye analytical data is presented in Appendix C, Table C.2.

A baseline sampling event was performed to determine the presence of dye prior to injections. Baseline results indicated that Rhodamine WT was not detected in surface water samples within the Wash. Fluorescein was detected at two of the six locations with fluorescein detected at up to 0.053 ppb. Following injections, although rhodamine was not detected in any surface water samples, fluorescein was detected at notable concentrations above background in surface water samples collected from three locations (i.e., LVW4.75-1, LVWPS4.8, and LVWPS4.9) in January and February 2021. Specifically, fluorescein was first detected at 0.218 ppb (approximately four times greater than background concentrations) in the sample collected from LVW4.75-1 in January 2021. In February 2021, fluorescein was detected at slightly greater concentrations in samples collected from LVWPS-4.75-1, LVWPS4.8, and LVWPS4.9, with fluorescein concentrations ranging from 0.313 ppb to 0.444 ppb (approximately six to eight times background concentrations). As shown in Figure 9, these locations are in the immediate vicinity of the Calico Ridge Weir, which is in line with historical data collected that indicates that groundwater discharge is likely occurring immediately downstream of the Calico Ridge Weir.

The detection of fluorescein in the Wash in this area is likely from the injections into the UMCf in the Zone 1 study area. As noted in Section 6.6.4, fluorescein dye rapidly migrated downgradient of the Zone 1 injection well transect and into the alluvium along preferential flow pathways likely including faults, fractures, and/or incised paleochannels in the UMCf. Fluorescein was detected in charcoal samplers collected approximately 1 month after dye injection from three downgradient monitoring wells screened in the alluvium, namely, LVWPS-A1-MW09, LVWPS-A1-MW10, and LVWPS-MW217A, which were located 100 to 150 feet downgradient of the Zone 1 injection well transect. Once the dye entered the alluvium, the dye rapidly traveled more than 1,300 feet within the first month, as indicated by detection of fluorescein in samples collected from LVWPS-MW210B (location shown on **Figure 5**), which is the farthest downgradient monitoring well within the Pilot Study area. This rapid rate of travel in the alluvium was expected given that the Phase 1 borehole dilution test results indicated alluvial groundwater flow velocities of greater than 90 ft/day in areas adjacent to the Wash. As a result, it is highly likely that the fluorescein detected above background concentrations in the Wash was from the Zone 1 UMCf injections, which shows that the Zone 1 UMCf ultimately discharges into the ancestral fluvial deposits and then to the Wash itself within the Pilot Study area.

Rhodamine WT was not detected in the Wash downgradient of the Pilot Study area. Groundwater within Zone 2 alluvium where rhodamine dye was injected likely flows even further east, parallel to the Wash within the ancestral fluvial deposits before discharging into the Wash outside of the Pilot Study area. Therefore, the rhodamine dye injected into Zone 2 alluvium may have been observable farther downstream of the Pilot Study area.

Although limited surface water sampling was periodically conducted downgradient from the study area, reducing perchlorate and chlorate concentrations in surface water was not an objective of this Pilot Study. However, the data was evaluated to determine if there were any concentration trends within the samples collected from the Wash following the injections performed as part of the Pilot Study. In general, perchlorate and chlorate concentrations within the Wash fluctuated throughout the Pilot Study, with no distinct concentration reductions below historical concentrations following injections. Slightly decreasing concentration trends were periodically observed for both perchlorate and chlorate following injections when compared overall concentration trends upstream of Calico Ridge Weir (showing upward trends in some areas). However, sufficient data was not collected during this short-term Pilot Study that included relatively small injection transects to determine effects from injections within the Wash.

Lastly, TOC was monitored throughout the Pilot Study to monitor for potential TOC increases in the Wash following injections. TOC concentrations were measured during baseline at concentrations generally less than 5.0 mg/L and generally remained at these levels following injections. One notable exception was the significant increases in TOC concentrations during the July 2021 sampling event, with concentrations ranging from 13 mg/L to 33 mg/L in all samples collected from LVW4.2-1 through LVW5.3-1, which includes areas both upstream and downstream of the Pilot Study area. During this sampling event, perchlorate concentrations were also unusually high at multiple locations within the Wash. Per the *2021 Semi-Annual Performance Memorandum* (Ramboll, 2022), it was concluded that these increases were potentially associated with Fourth of July fireworks and a low-intensity rain event throughout the Las Vegas Valley from July 12 to July 13, 2021.

11.0 SUMMARY OF KEY FINDINGS

This section presents the overall findings of the Pilot Study and provides cost considerations for future implementation of this technology by NERT if selected as part of the final remedy.

11.1 PILOT STUDY SUMMARY

As explained in Section 1.1, the purpose of the Pilot Study was to collect data needed to evaluate the key FS criteria (effectiveness, implementability, and cost) and gather additional data in this complex geologic setting to inform the forthcoming FS evaluation of ISB as a potential component to the NERT final remedy. This Pilot Study was carefully designed to assess certain components of an ISB approach not previously evaluated by NERT, which included application of ISB in areas with significant geological heterogeneity, large and deep paleochannels, fault-zone channels, large saturated thicknesses of alluvium, UMCf, and UMCf-cg, and perchlorate and chlorate at concentrations and depths greater than previously evaluated. The design of three separate Pilot Study zones (referred to herein as Zones 1, 2, and 3) was determined based solely on the defined Pilot Study objectives and therefore, likely differs from the objectives of a full-scale remedial design if ISB was selected as a component of NERTs final remedy. Likewise, implementation of the ISB technology would be focused and designed to achieve NERT's specific RAOs, as opposed to the Pilot Study objectives. As a result, data collected and lessons learned during the Pilot Study are meant to inform the FS and should not be construed as a final determination of the appropriateness of the ISB technology and/or its application to the NERT RI Study Area.

The Pilot Study was divided into two distinct phases, which afforded the Trust the opportunity to evaluate newly available data to determine the optimal strategy for the final pilot study design. Phase 1, which was conducted from March 2018 through January 2019, collected valuable information that significantly expanded the understanding of the lithology, hydrogeology, and contaminant distribution in the Pilot Study area and informed the conceptual site model near the Wash, which will benefit the Trust's overall RI/FS implementation strategy. Based on the findings from Phase 1, the Work Plan Addendum was prepared to refine the Phase 2 Pilot Study objectives and inform the final Phase 2 Pilot Study design. The Work Plan Addendum was approved by NDEP on December 11, 2019 and implementation and performance of Phase 2 of the Pilot Study as detailed in this report was completed consistent with the approved Work Plan Addendum.

Through the performance of this Pilot Study, sufficient data was collected to meet the overall study objective to demonstrate and evaluate the effectiveness and implementability of ISB in a geologically complex area where perchlorate-contaminated groundwater is migrating into the Wash. Based on the data collected during the Phase 1 pre-design investigation and using the results, findings, and lessons learned from previous and on-going treatability studies, the design for this Pilot Study was refined to assess three distinct, separate, smaller zones within the Pilot Study area (i.e., Zones 1, 2, and 3). This refinement allowed for the collection of a substantial dataset that would not only fulfill the overall study objective but also satisfy a more focused, zone-specific set of objectives to maximize the usefulness of the data collected with respect to effectiveness and implementability for particular lithologies within OU-3 (i.e., alluvium, UMCf, and UMCf-cg).

Expanding on the results presented in Sections 6 through 8, this section presents a summary of the overall key Pilot Study results and conclusions with regard to the success of the Pilot Study in treating perchlorate-contaminated groundwater as well as a summary of the key findings from the dye tracer study. More detailed discussions of the fulfillment of the zone-specific objectives for Zones 1, 2, and 3 were provided in Sections 6.8, 7.8, and 8.8, respectively.

The data collected during this Pilot Study, along with data collected during other ISB treatability studies summarized in **Table 1,** will be evaluated as part of the forthcoming OU-3 FS.

11.1.1 Main Findings and Conclusions of the Pilot Study

Overall, groundwater within the Pilot Study area was amenable to biodegradation of perchlorate, chlorate, and nitrate. As demonstrated in this Pilot Study, periodic injection of EVO and amendments created biologically active treatment zones in all three lithologies evaluated, which is necessary for effective and continual perchlorate and chlorate biodegradation in the groundwater. The main findings and conclusions presented below draw upon the substantial data collected during the Pilot Study. Additionally, performance criteria tables that summarize key performance criteria, metrics, confirmation methods, and performance demonstration are provided in Appendix O.

- Perchlorate, chlorate, and nitrate degradation was initiated rapidly following carbon substrate injections into the alluvium, UMCf, and UMCf-cg through the creation of a biologically active zone. These biologically active zones were sustained over multiple injection events during the 18-month Pilot Study (three injection events in the alluvium and two injection events in the UMCf and UMCf-cg).
- The Pilot Study demonstrated the ability of ISB using a slow-release carbon substrate (EVO) to biodegrade perchlorate to concentrations below the PRG of 15 µg/L in groundwater samples collected from several monitoring well locations within the alluvium, UMCf, and UMCf-cg.
- Denitrification (nitrate biodegradation) occurred rapidly and generally preferentially compared to perchlorate and chlorate biodegradation. However, in some instances, nitrate concentrations did not reduce as much as perchlorate and chlorate, which may be due to the range of microorganisms that are native to the aquifer. Native microorganisms may prefer perchlorate and chlorate respiration, which provides more energy compared to nitrate respiration, even though nitrate uptake generally precedes the degradation of these other electron acceptors. 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.
- Although significant reductions in perchlorate and chlorate concentrations were observed in both the shallow and deep alluvium, slightly better results were observed in intervals with lower groundwater flow velocities, which allowed for more residence time to complete both perchlorate and chlorate biodegradation. In select treatment intervals with high groundwater flow rates, chlorate concentration reductions were greater than perchlorate concentration reductions. This is a valuable data point as it indicates higher flow rates may not allow sufficient residence time for complete degradation of perchlorate but does allow for complete chlorate degradation. As a result of the heterogeneity of the subsurface and the variability in groundwater flow rates, if ISB is selected as a component of the NERT final remedy, the injection well design may potentially include multiple injection well transects and/or varying injection frequencies depending on the groundwater flow rate of the targeted formation to achieve a more uniform biologically active treatment zone that could enhance and maximize perchlorate biodegradation to increase residence times.
- The Pilot Study results indicated that approximately 1,810 pounds of perchlorate were destroyed during the 18-month Pilot Study time frame. The perchlorate mass destroyed by zone is as follows: 1) Zone 1 – 74 pounds (49 pounds in the alluvium and 25 pounds in the UMCf); 2) Zone 2 – 1,650 pounds (1,598 pounds in the alluvium and 52 pounds in the UMCf); and 3) Zone 3 – 86 pounds (0.5 pounds in the alluvium and 85.5 pounds in the UMCf-cg). These results demonstrate that more mass was destroyed in the UMCf-cg within the Zone 3 study area compared to the UMCf in Zones 1 and 2 combined.
- During active injections into the Zone 2 UMCf, UMCf-injected fluorescein was observed in dose response monitoring wells screened in the overlying alluvium. In contrast, Zone 1 UMCf and Zone 3 UMCf-cg injections did not result in any migration of injectate solution into the alluvial dose-response monitoring wells using the same injection protocols. In addition, Zone 2 results downgradient of the injection well transect indicated the presence of the UMCf-injected fluorescein in the overlying alluvium as well as the alluvium-injected rhodamine in the underlying UMCf, which further demonstrates the connectivity of the alluvium and the UMCf due to faulting and the deep alluvial paleochannel within Zone 2. Both rhodamine

and fluorescein were detected in samples collected from UMCf monitoring wells located approximately 100 feet downgradient from the injection well transect, which illustrates the varied upward and downward vertical gradients and cross-connecting flow pathways between the alluvium and UMCf within Zone 2. This observation coupled with perchlorate concentration reductions observed in farther downgradient locations than expected based on groundwater flow rates within the UMCf indicates that dual treatment in both the alluvium and UMCf may result in more mass being treated over time and/or improved use of the injected carbon substrate in both the alluvium and UMCf in lithological situations similar to Zone 2.

- The ISB injections into the UMCf-cg within the Zone 3 study area were more effective (i.e., greater subsurface distribution of injectate) than the ISB injections into the UMCf within the Zone 1 study area. The difference in effectiveness relates directly to the difference in the lithology within each zone (i.e., UMCf and UMCf-cg). Although ISB was effective in the Zone 1 UMCf where injectate was distributed, hydrogeologic controls on groundwater flow resulted in a more pronounced preferential flow pathways through the faulted UMCf and into the overlying alluvium downgradient of the injection well transect. Additionally, slug tests results indicated that the UMCf-cg had a higher hydraulic conductivity in the western portion of the Zone 3 study area compared to the slightly lower hydraulic conductivities in the UMCf present in Zone 1. This higher hydraulic conductivity resulted in improved lateral downgradient distribution of the injectate in the Zone 3 UMCf-cg compared to the distribution within Zone 1, which was primarily associated with preferential flow pathways. Lastly, the injectate solution did not travel upgradient from the injection well transect in the Zone 3 study area like it did in the Zone 1 study area. This lack of upgradient distribution was likely due to the coarser-grained UMCf-cg in the Zone 3 area, which allowed injectate to migrate more readily downgradient without pressure build-up resulting in upgradient distribution of injectate as was observed in the Zone 1 study area.
- 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 in the alluvium, UMCf, and/or UMCf-cg.
- In alignment with the results from previous ISB treatability studies, performing periodic injections into the injection wells over time was shown to gradually increase the overall biodegradation in groundwater following subsequent events. A likely reason for this improved degradation observation was the use of EVO, which because of its chemical characteristics, tends to gradually coat the soil grains along the transect width, thereby attaching to more of the subsurface and creating a uniform barrier over time.
- The ability of alluvium, UMCf, and UMCf-cg to accept multiple substrate injections indicates that ISB can be a feasible long-term option for groundwater in all lithological units. Over the course of the Pilot Study, injection pressures only gradually increased from an approximate average of 2 psi to 13 psi during the three injection events performed in the alluvium. Similar to the alluvium, the injection pressures within the second injection event into the UMCf and UMCf-cg only slightly increased compared to the injection pressures during the first injection event (i.e., Zone 1 – 11 psi in the first injection event and 7 psi in the second injection event; Zone 2 – 30 psi in the first injection event and 34 psi in the second injection event; Zone 3 – 12 psi in the first injection event and 16 psi in the second injection event). Slightly higher injection pressures during subsequent injections are common and expected with ISB as a normal response to the growth of perchlorate-reducing biomass on the subsurface media (i.e., injection well screens/filter pack and/or the surrounding formation). However, no injection well maintenance was required during the Pilot Study, indicating that the subsurface continues to be amenable to periodic injections of EVO. Periodic injection well maintenance could be required to maintain long-term injectability into the subsurface if ISB is selected as a component to the NERT final remedy. This operational component of implementing ISB has been evaluated as part of the SWF Area Bioremediation Treatability Study (Tetra Tech, 2019b; Tetra Tech, 2022), which reinforces the conclusion that if designed properly, in conjunction with an injection well maintenance program, ISB can be designed and implemented long-term

within the lithologies present within the NERT RI Study Area. This data will be valuable in evaluating the long-term viability and operational considerations of a full-scale ISB remedy in the forthcoming FS.

- During injections in the Zone 2 study area, both tracer dye and increased TOC concentrations indicating the presence of carbon substrate were observed in all six alluvial and UMCf cross-gradient monitoring wells. These results indicate that the injectate was distributed both horizontally and vertically in the subsurface and confirmed that the targeted ROI of 17.5 feet for the alluvium and 12.5 feet for the UMCf was attainable for both lithologies. These data can be used to evaluate a full-scale ISB remedy in the forthcoming FS with respect to effectiveness, implementability, and cost (i.e., how many injection wells are required in an ISB remedy for the various lithologies).
- Installation of nested wells as opposed to single clustered injection wells resulted in significant cost savings of approximately 30 percent per well for the dual nested configuration and 40 percent per well for the triple nested configuration. During active injections, the injectate solution was observed in the dose-response monitoring wells located immediately downgradient of the injection wells, which indicated that the injectate was distributed both horizontally and vertically in the subsurface, despite the large, saturated thickness of the alluvium, UMCf, or UMCf-cg targeted. Increases in TOC concentrations were also observed in both the shallow and deep alluvium as well as the shallow and deep portions of the UMCf and UMCf-cg. These results indicate that both dual- and triple-nested well configurations can effectively distribute the injectate in both horizontal and vertical directions. Nested injection wells may also provide an additional benefit of allowing application of carbon substrate at different frequencies and doses for various depth intervals at the same location, depending on depth-specific variables, such as contaminant concentrations, effective porosity, and groundwater flow velocity.

11.1.2 Main Findings and Conclusions of the Dye Tracer Study

As presented in Section 5.6.5, tracer dyes were injected and monitored during the Pilot Study to provide additional data to aid in the evaluation of study objectives as well as key ISB design criteria such as injection well spacing, injection quantities (based in part on the effective porosity of the target formation), groundwater velocity, and synergistic effects of concurrent treatment of the alluvium and UMCf. Although a detailed analysis of the dye study is provided in Appendix C, a summary of the key findings in terms of how the objectives of the dye study were successfully achieved are provided below.

- Objective 1 – Assess the ROI of the injections in the alluvium and UMCf. Data collected indicate the following:
  - This objective was met through monitoring the nearby cross-gradient monitoring wells (located on either end of the Zone 2 injection well transect) both during and after the first injection event. Results indicated that samples collected from all cross-gradient monitoring wells screened in both the alluvium and UMCf observed dye tracer in either field groundwater samples collected during injections and/or charcoal/groundwater samples collected following the injections. Additionally, results of the samples collected from all cross-gradient monitoring wells indicated decreases in groundwater perchlorate concentrations after injections. These data confirm that the ROI was equal to, if not larger than, the designed ROI calculated from baseline aquifer data (i.e., 17.5 feet in the alluvium and 12.5 feet in the UMCf). As a result, the injection spacing used in the Pilot Study was appropriate for the lithology.
- Objective 2 – Estimate effective porosity of the formation near each injection well transect. Data collected indicate the following:
  - This objective was accomplished by evaluating the dose-response data collected during active injections. In the alluvium, the effective porosity was in the range originally anticipated based on aquifer data collected during the design phase (approximately 6 percent). In the UMCf and UMCf-cg, the effective porosity ranged from approximately 1 to 3 percent, which is less than the original

conservative estimate used for distribution water calculations during the design phase. These lower effective porosity results indicated that less distribution water was required and therefore, a field modification was made to decrease the follow-up distribution water volumes, which as previously stated is beneficial information for future remedy evaluation in the forthcoming FS.

- Objective 3 – Evaluate travel times of the injectate/dye. Data collected indicate the following:
  - This objective was achieved in the alluvium by collecting samples from downgradient monitoring wells and analyzing for dye tracer over the course of six months following the first injection event.
    - In the Zone 2 alluvium, the shortest travel time to the Wash (located approximately 850 feet downgradient) was 15 days, which equates to an average of 57 ft/day. However, Zone 2 alluvium groundwater velocities calculated using the tracer peaks rather than the leading edge have typically resulted in groundwater velocities ranging from less than 1 ft/day to approximately 13 ft/day.
    - Data from the monitoring wells screened in the UMCf and/or UMCf-cg within Zones 1, 2, and 3 demonstrate the heterogeneity within these units. Travel times within Zone 1 and Zone 2 UMCf indicate a groundwater flow velocity of approximately 0.3 ft/day. Zone 3 UMCf-cg groundwater velocities calculated from tracer peaks were faster than those estimated for the UMCf, with groundwater velocities ranging from less than 0.2 ft/day to 2 ft/day.
- Objective 4 – Determine whether groundwater from the UMCf discharges into the alluvium and vice versa. Data collected indicate the following:
  - This objective was met by monitoring the alluvium for fluorescein, which was only injected into the UMCf and the UMCf for rhodamine, which was only injected in the alluvium. The dye tracer results indicate that groundwater from the UMCf discharges into the alluvium (upflux), as confirmed by detections of the UMCf-injected fluorescein in samples collected from downgradient alluvial monitoring wells located within Zones 1, 2, and 3. Furthermore, small detections of rhodamine, which was only injected into the alluvium, were present in the underlying Zone 2 UMCf in Zone 2, suggesting that some degree of downflux is also occurring.

11.2 PRELIMINARY COST CONSIDERATIONS FOR FULL-SCALE ISB

As summarized in Sections 6.8, 7.8, 8.8, and 10.1 of this report, the Pilot Study results have generated a substantial data set and provided valuable information with respect to the effectiveness and implementability of an ISB remedy for evaluation in the forthcoming FS. At the direction of NDEP, and in accordance with the NDEP-approved Work Plan Addendum the data have been used to develop preliminary cost considerations for potential full-scale implementation of an ISB system if selected as a component to the NERT final remedy. A summary of the preliminary cost considerations for full-scale ISB is provided in Appendix P.

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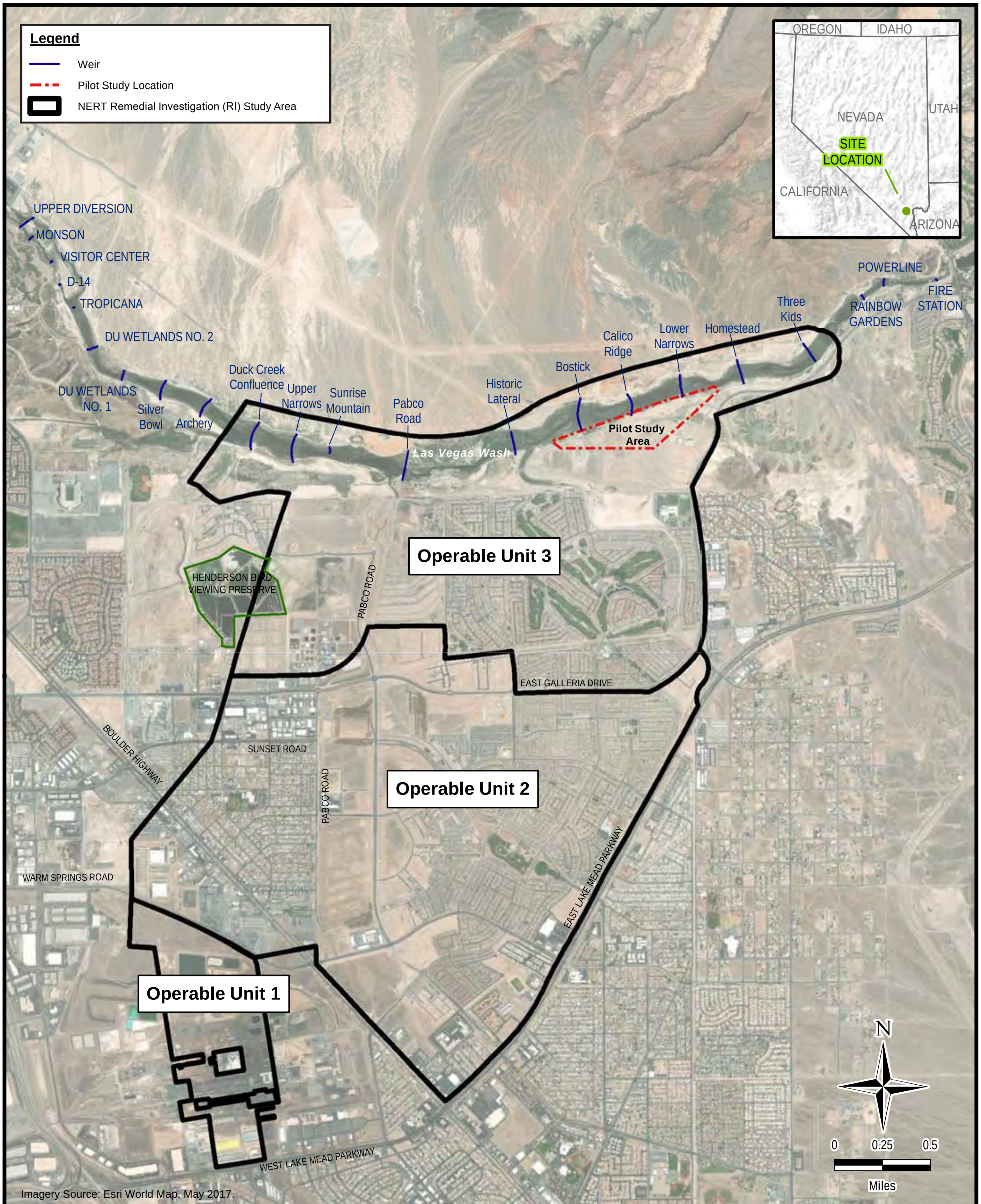
Figures



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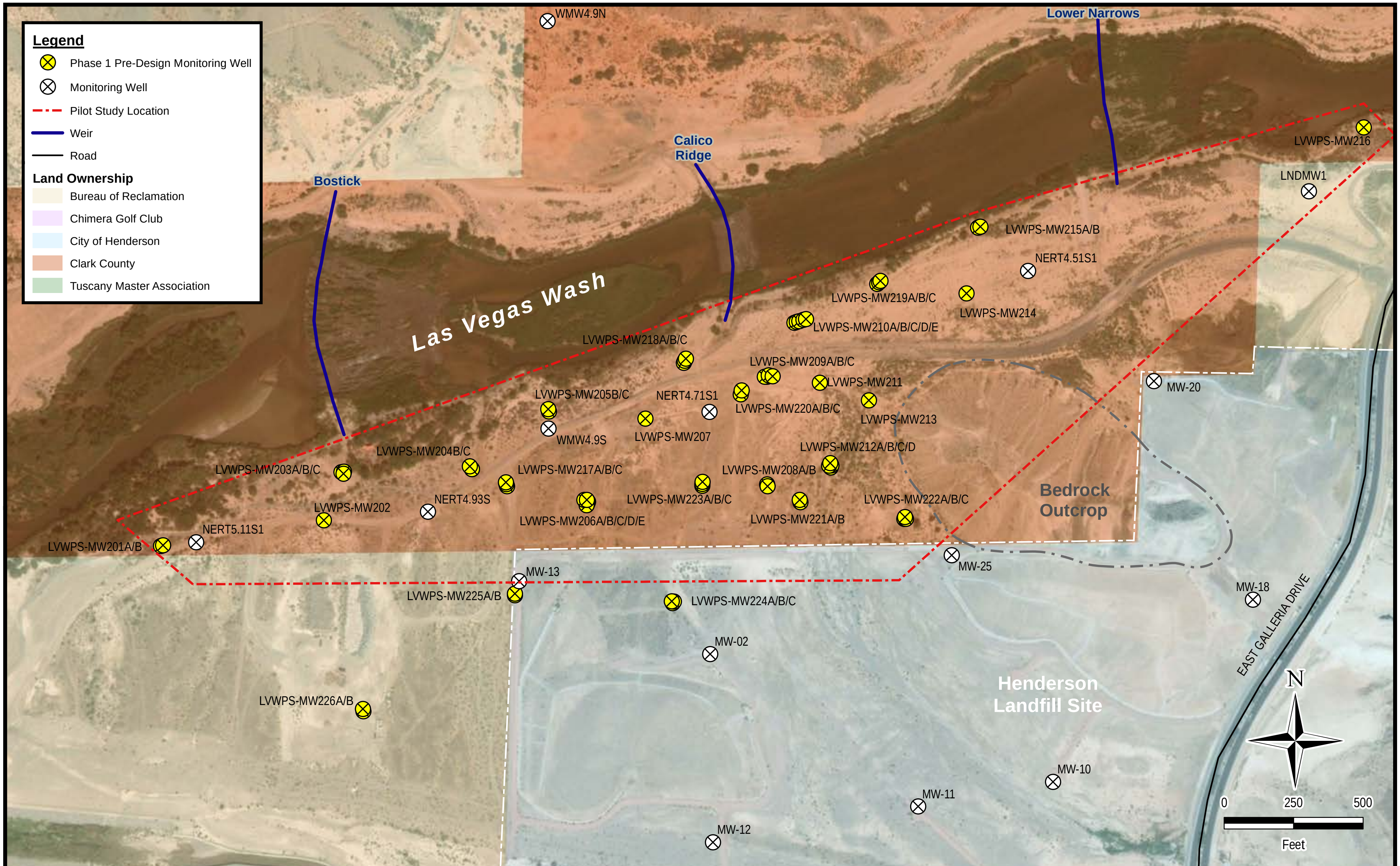
NEVADA ENVIRONMENTAL RESPONSE TRUST

LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

STUDY AREA OVERVIEW

PROJECT NO.:	117-7502019-M19-01
DATE:	JUNE 12, 2024
DESIGNED BY:	WG

Figure No.
1



Notes:
1. Phase 1 monitoring wells that were used to initially characterize the pilot study area and finalize the design are shown here. Well infrastructure installed as part of Phase 2 is provided in Figures 5 through 8.
2. Imagery Source: Esri World Map, August 2022.

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LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PILOT STUDY LOCATION

PROJECT NO.:	117-7502019-M19-01
DATE:	APRIL 12, 2023
DESIGNED BY:	WG
Figure No.	2

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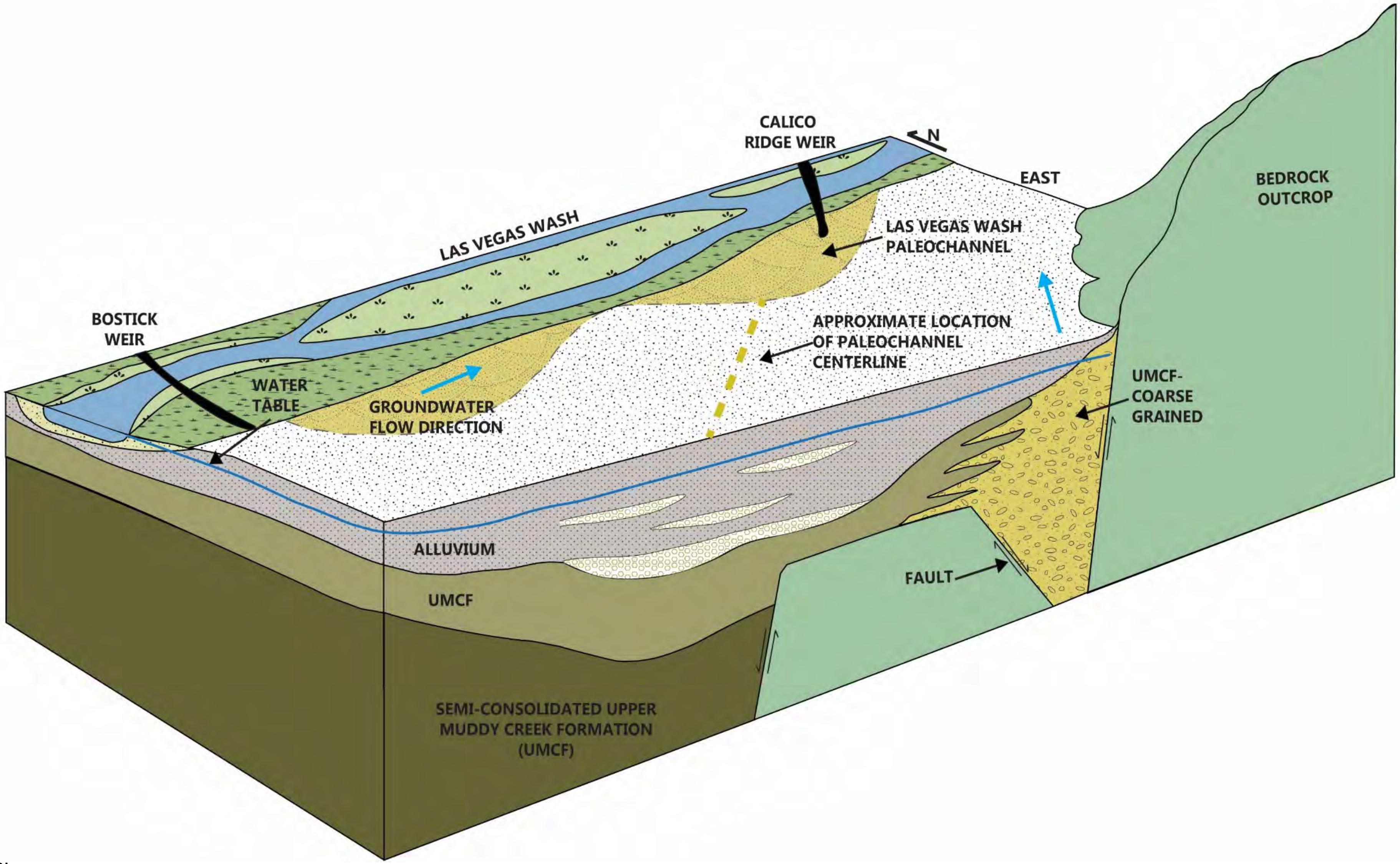

Notes:
1. Diagram is conceptual and is not to scale.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

CONCEPTUAL BLOCK DIAGRAM

Project No.:117-7502019-M19-01
Date: MAY 4, 2023
Designed By: JD
Figure No.
3

Notes:
1. Phase 1 monitoring wells that were used to initially characterize the pilot study area and finalize the design are shown here. Well infrastructure installed as part of Phase 2 is provided in Figures 5 through 8.
2. Imagery Source: Esri World Map, August 2022.

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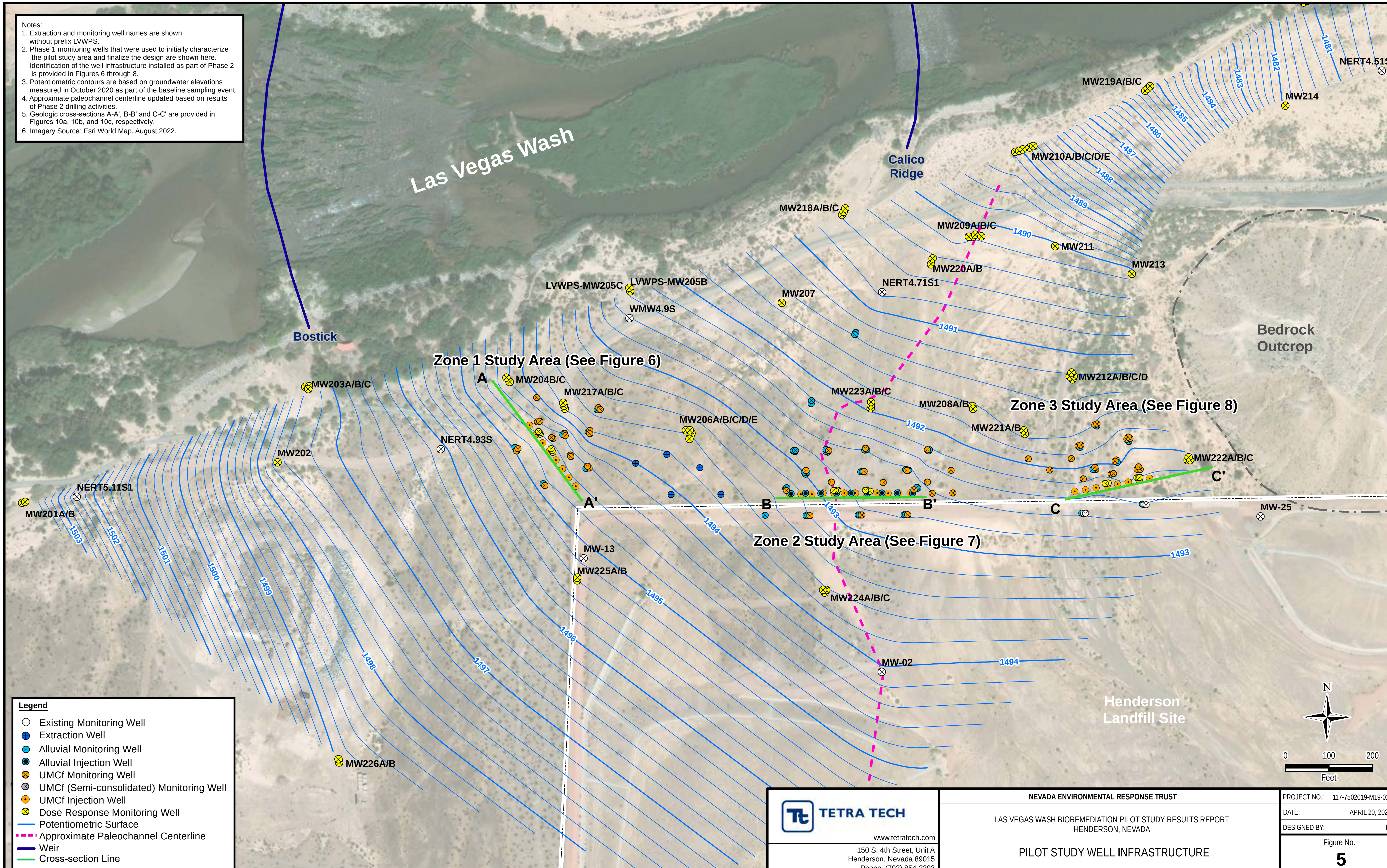
NEVADA ENVIRONMENTAL RESPONSE TRUST

LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PILOT STUDY DESIGN

PROJECT NO.:	117-7502019-M19-01
DATE:	APRIL 12, 2023
DESIGNED BY:	ACC
Figure No.	4



Notes:
1. Extraction and monitoring well names are shown without prefix LVWPS.
2. Phase 1 monitoring wells that were used to initially characterize the pilot study area and finalize the design are shown here. Identification of the well infrastructure installed as part of Phase 2 is provided in Figures 6 through 8.
3. Potentiometric contours are based on groundwater elevations measured in October 2020 as part of the baseline sampling event.
4. Approximate paleochannel centerline updated based on results of Phase 2 drilling activities.
5. Geologic cross-sections A-A', B-B' and C-C' are provided in Figures 10a, 10b, and 10c, respectively.
6. Imagery Source: Esri World Map, August 2022.

Legend
- Existing Monitoring Well
- Extraction Well
- Alluvial Monitoring Well
- Alluvial Injection Well
- UMCf Monitoring Well
- UMCf (Semi-consolidated) Monitoring Well
- UMCf Injection Well
- Dose Response Monitoring Well
- Potentiometric Surface
- Approximate Paleochannel Centerline
- Weir
- Cross-section Line

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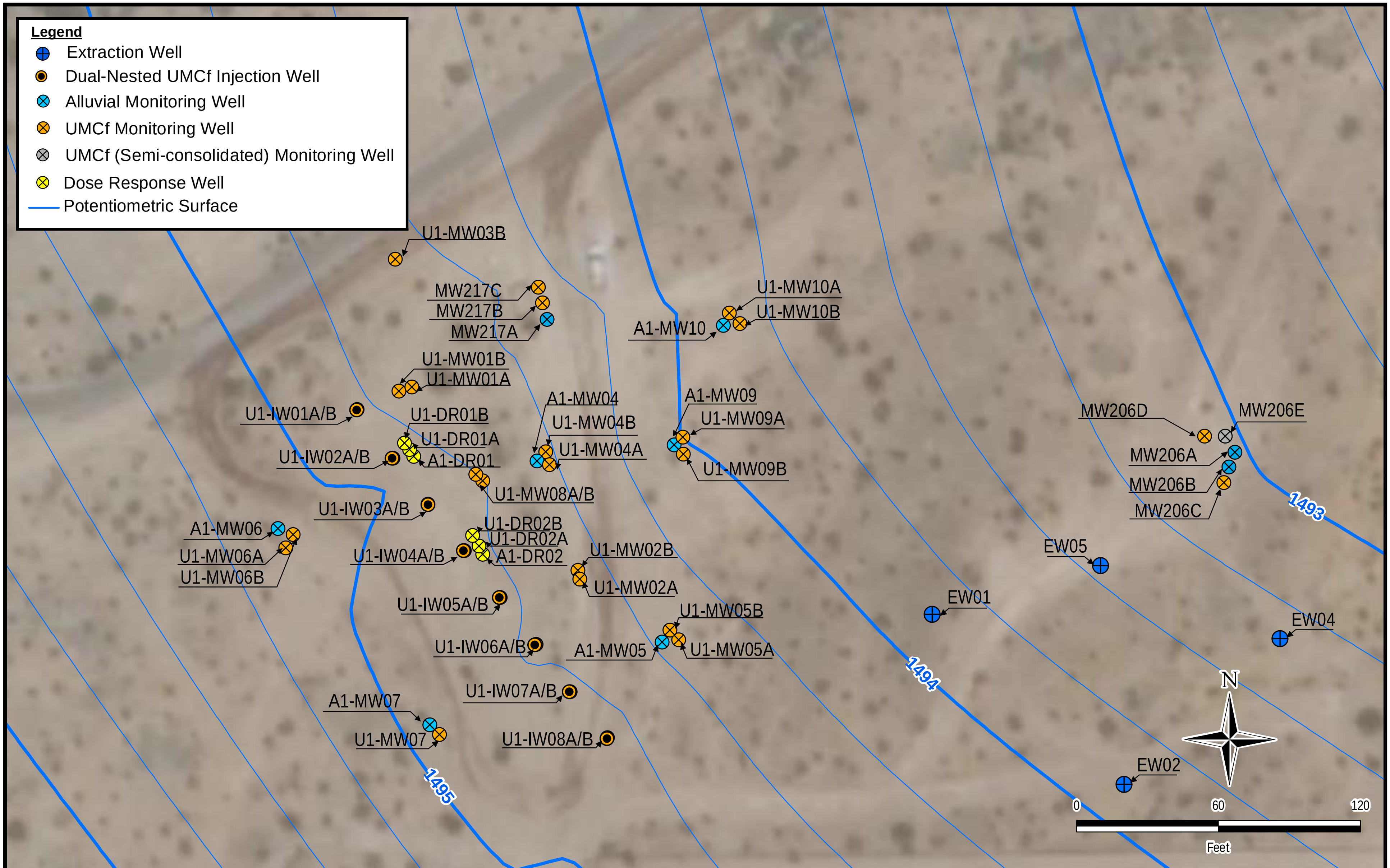
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PILOT STUDY WELL INFRASTRUCTURE

PROJECT NO.:	117-7502019-M19-01
DATE:	APRIL 20, 2023
DESIGNED BY:	DS
Figure No.	5

D:\NERT\M19\MXD\Figure 5 MW Network_v2.mxd



Notes:

1. Monitoring and injection well names are shown without prefix LVWPS.
2. Depth to water measurements collected in October 2020. Wells screened in the UMCf/UMCf-cg with mid-screen depths of approximately 60' to 90' below the water table were used to generate groundwater contours.

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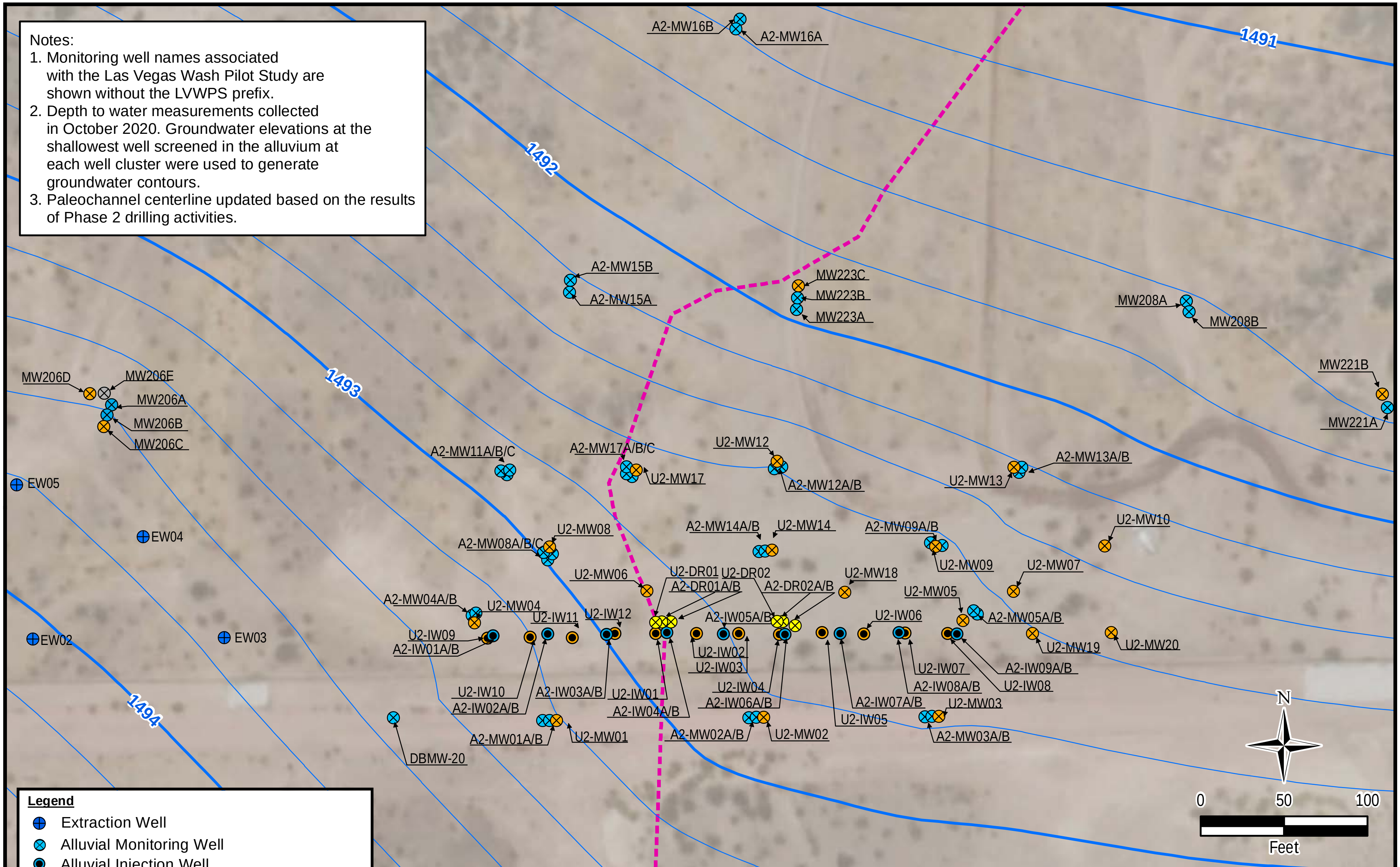
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

ZONE 1 WELL LAYOUT AND GROUNDWATER POTENTIOMETRIC CONTOURS FOR THE UMCF

PROJECT NO.:	117-7502019-M19-01
DATE:	OCTOBER 22, 2020
DESIGNED BY:	ES

Figure No.
6

C:\Users\ELLYN.SWENSON\LVW Monitoring Well Installation Figures\BL04 Groundwater Contours\Zone1_UMCfContours_1021.mxd



Notes:
1. Monitoring well names associated with the Las Vegas Wash Pilot Study are shown without the LVWPS prefix.
2. Depth to water measurements collected in October 2020. Groundwater elevations at the shallowest well screened in the alluvium at each well cluster were used to generate groundwater contours.
3. Paleochannel centerline updated based on the results of Phase 2 drilling activities.

Legend

- Extraction Well
- Alluvial Monitoring Well
- Alluvial Injection Well
- UMCf Monitoring Well
- UMCf (Semi-consolidated) Monitoring Well
- UMCf Injection Well
- Dose Response Well
- Potentiometric Surface
- Paleochannel Centerline

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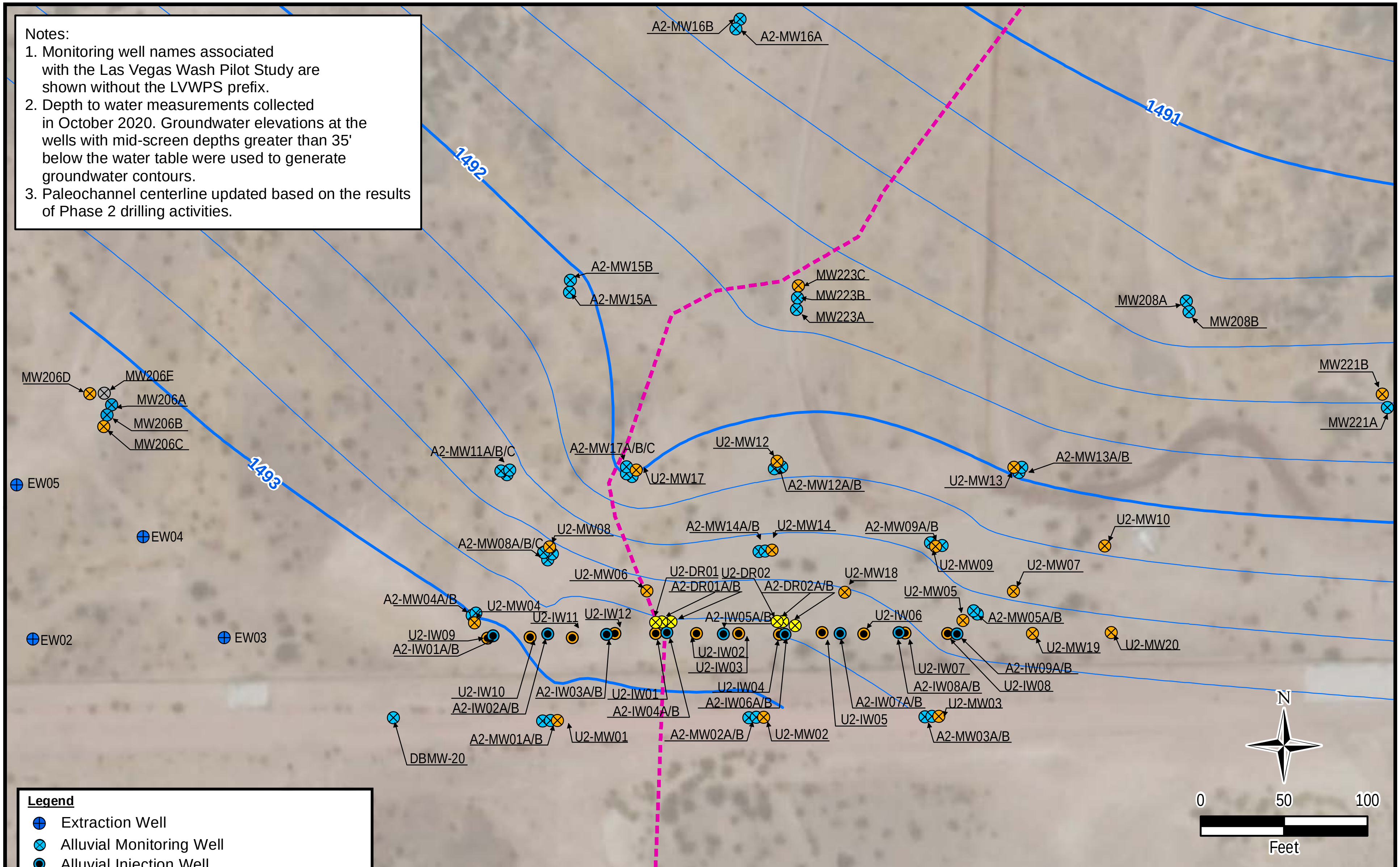
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

ZONE 2 WELL LAYOUT AND GROUNDWATER POTENTIOMETIC CONTOURS FOR THE SHALLOW ALLUVIUM

PROJECT NO.: 117-7502019-M19-01
DATE: OCTOBER 26, 2020
DESIGNED BY: ES

Figure No.
7a

C:\Users\ELLYN.SWENSON\LVW Monitoring Well Installation Figures\BL04 Groundwater Contours\Zone2_Contours_ShallowestQal_1019.mxd



Notes:
1. Monitoring well names associated with the Las Vegas Wash Pilot Study are shown without the LVWPS prefix.
2. Depth to water measurements collected in October 2020. Groundwater elevations at the wells with mid-screen depths greater than 35' below the water table were used to generate groundwater contours.
3. Paleochannel centerline updated based on the results of Phase 2 drilling activities.

Legend

- Extraction Well
- Alluvial Monitoring Well
- Alluvial Injection Well
- UMCf Monitoring Well
- UMCf (Semi-consolidated) Monitoring Well
- UMCf Injection Well
- Dose Response Well
- Potentiometric Surface
- Paleochannel Centerline

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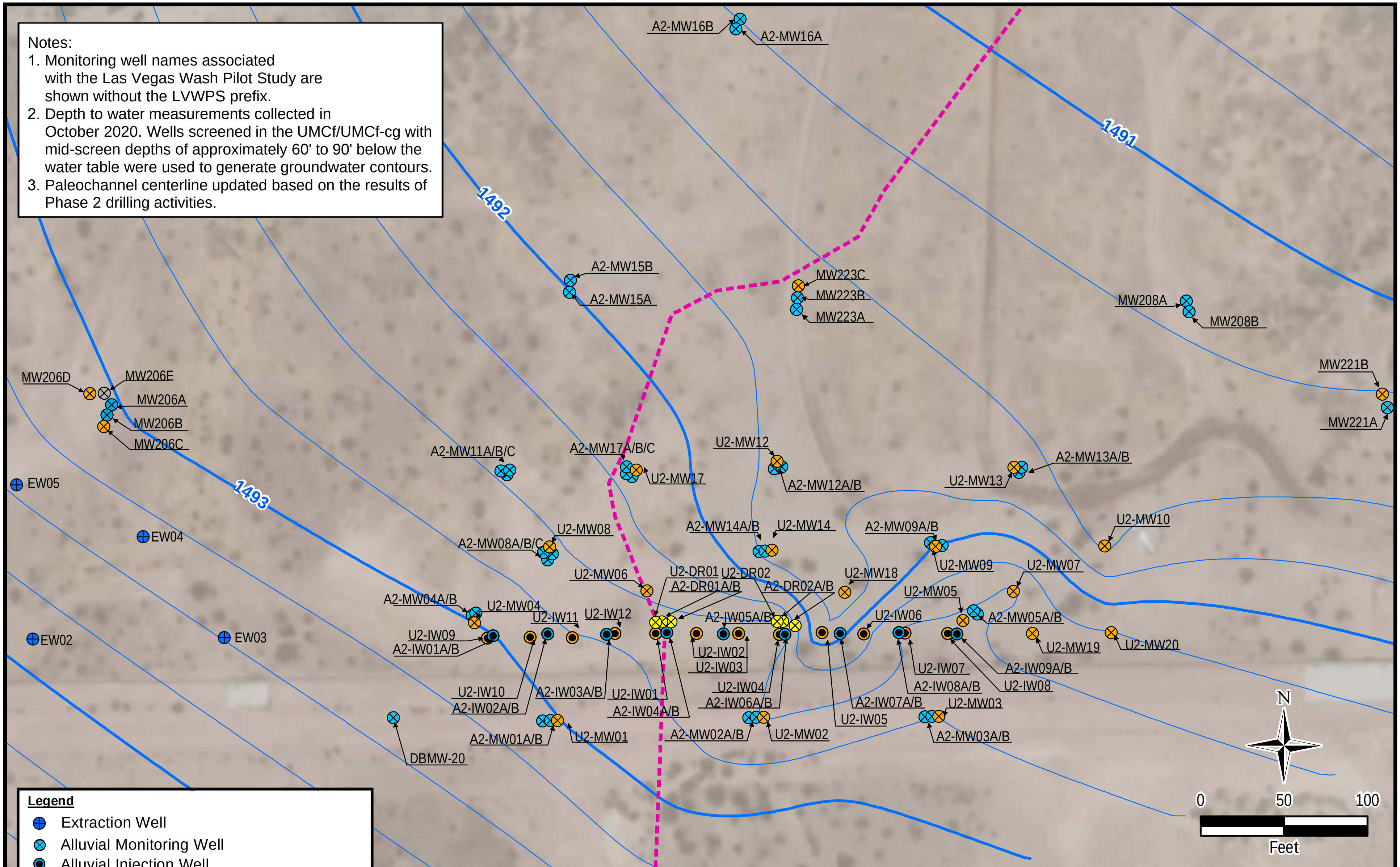
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT

HENDERSON, NEVADA

ZONE 2 WELL LAYOUT AND GROUNDWATER POTENTIOMETIC CONTOURS FOR THE DEEP ALLUVIUM

PROJECT NO.:	117-7502019-M19-01
DATE:	OCTOBER 26, 2020
DESIGNED BY:	ES
Figure No.	**7b**

C:\Users\ELLYN.SWENSON\LVW Monitoring Well Installation Figures\BL04 Groundwater Contours\Zone2_Contours_DeepQal_1019.mxd



Legend

- Extraction Well
- Alluvial Monitoring Well
- Alluvial Injection Well
- UMCf Monitoring Well
- UMCf (Semi-consolidated) Monitoring Well
- UMCf Injection Well
- Dose Response Well
- Potentiometric Surface
- Paleochannel Centerline

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LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
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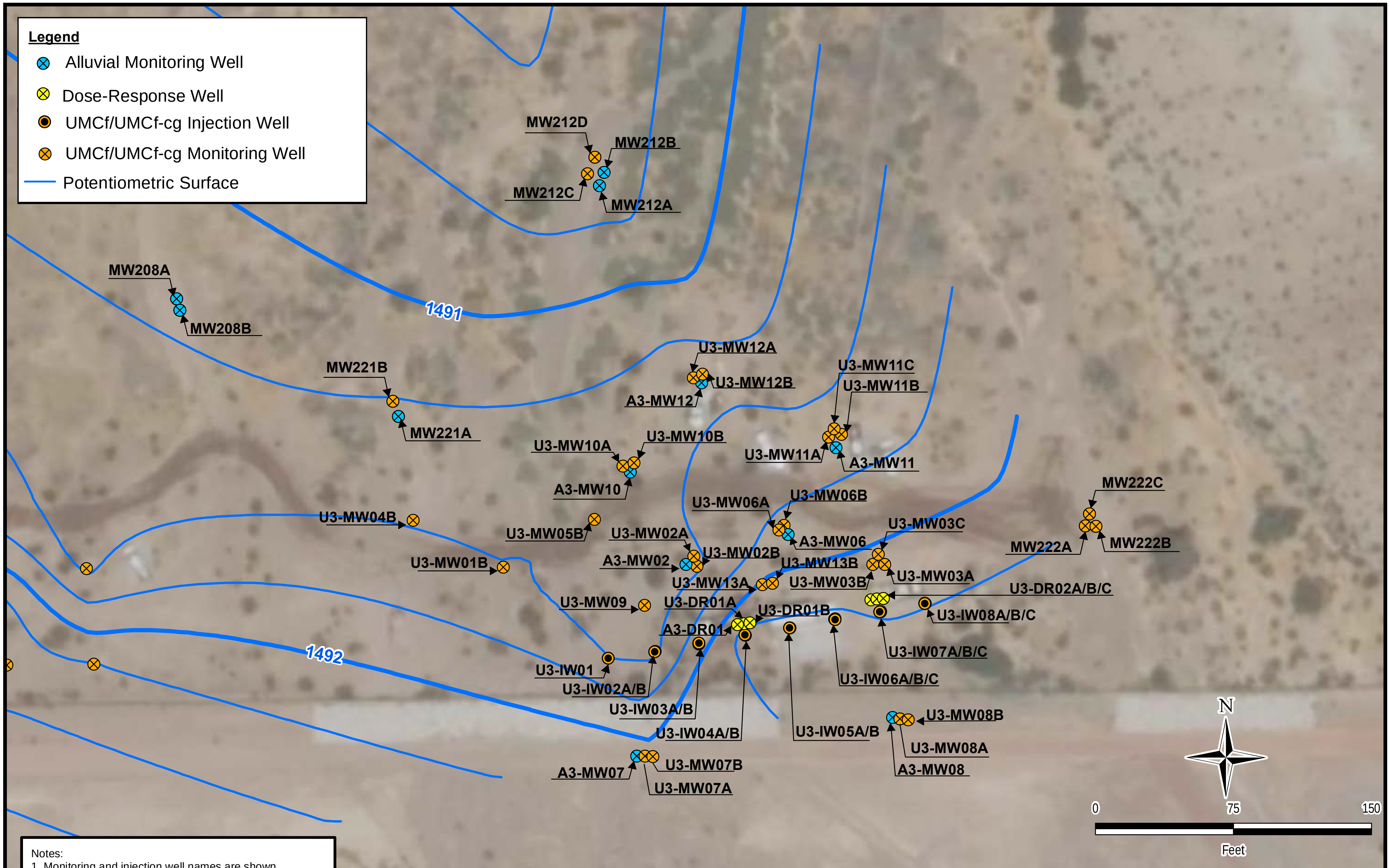
ZONE 2 WELL LAYOUT AND GROUNDWATER POTENTIOMETRIC CONTOURS FOR THE UMCF

PROJECT NO.:	117-7502019-M19-01
DATE:	OCTOBER 26, 2020
DESIGNED BY:	ES

Figure No.
7c



C:\Users\ELLYN.SWENSON\LVW Monitoring Well Installation Figures\BL04 Groundwater Contours\Zone3_Contours_UMCf_1021.mxd

Notes:
1. Monitoring and injection well names are shown without prefix LVWPS.
2. Depth to water measurements collected in October 2020. Wells screened in the UMCf/UMCf-cg with mid-screen depths of approximately 60' to 90' below the water table were used to generate groundwater contours. In addition, the groundwater elevation at LVWPS-A3-MW08, which is screened in the alluvium, was also used due to the deep alluvium-UMCf-cg contact at that location.

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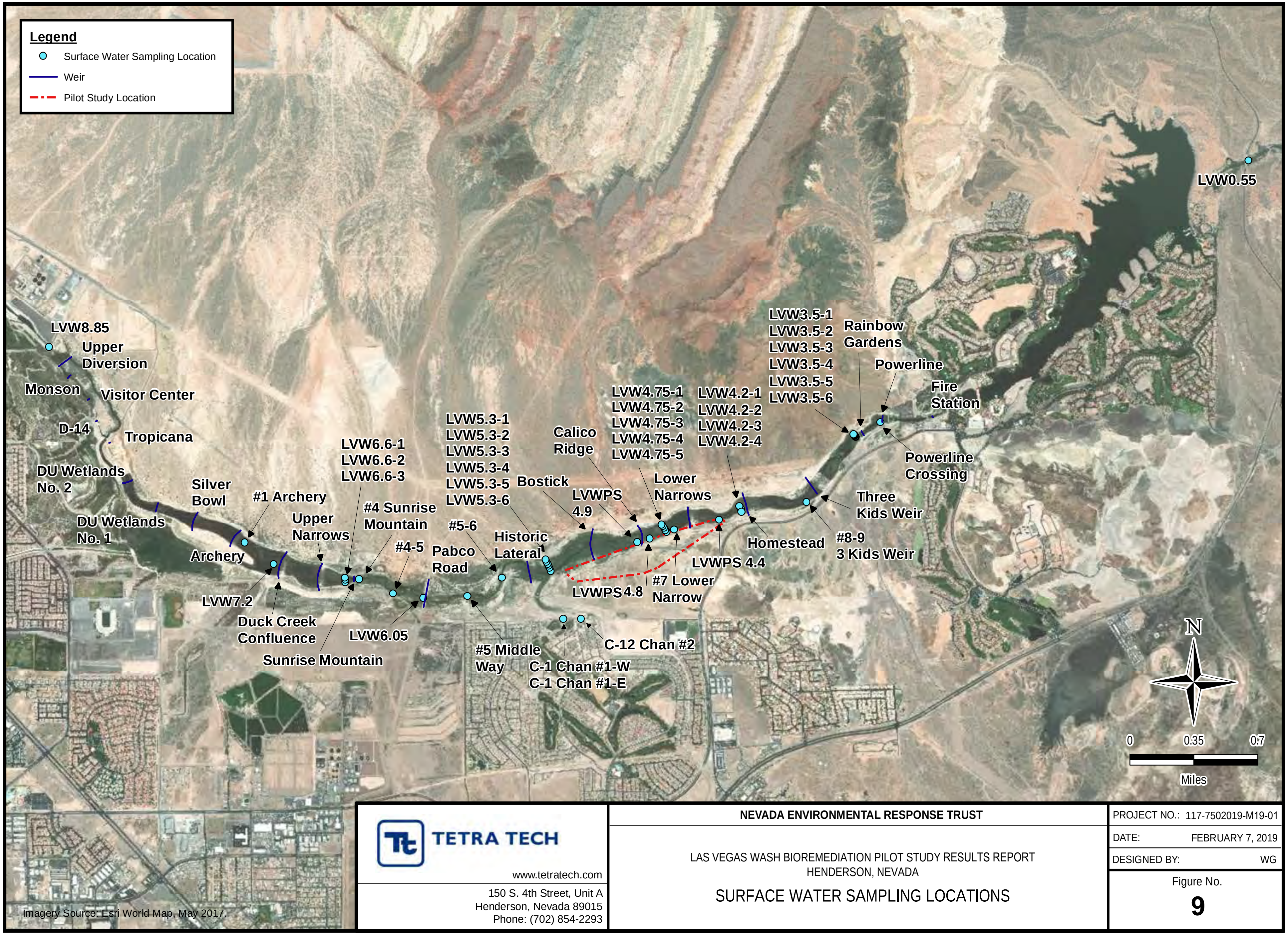
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

ZONE 3 WELL LAYOUT AND GROUNDWATER POTENTIOMETRIC CONTOURS FOR THE UMCF-CG

PROJECT NO.:	117-7502019-M19-01
DATE:	OCTOBER 22, 2020
DESIGNED BY:	ES
Figure No.	8



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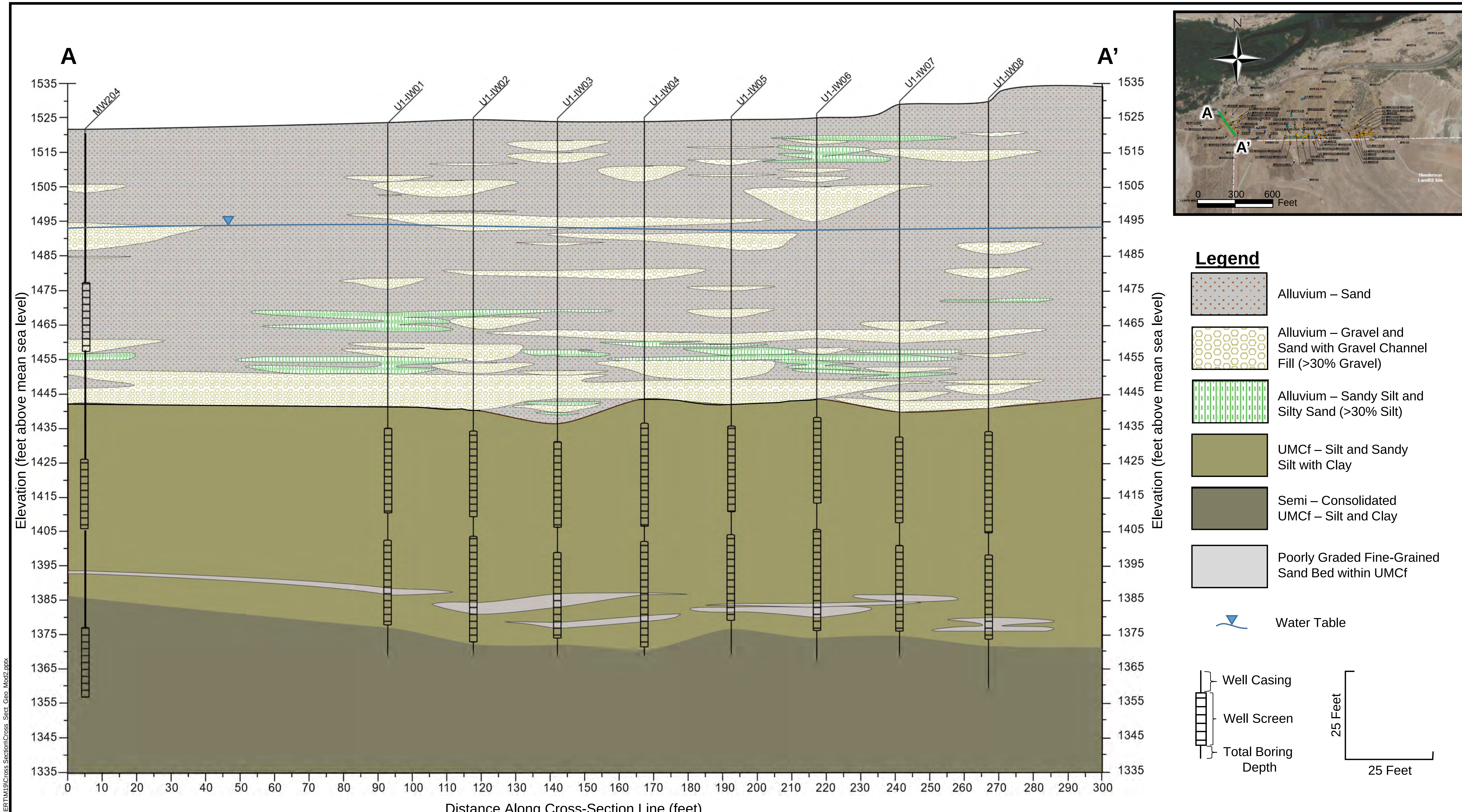
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

SURFACE WATER SAMPLING LOCATIONS

PROJECT NO.:	117-7502019-M19-01
DATE:	FEBRUARY 7, 2019
DESIGNED BY:	WG

Figure No.
9



Notes:
IW – Injection Well
MW – Monitoring Well
UMCf – Upper Muddy Creek formation
1. Well names are shown within the prefix “LVWPS-”.
2. Semi-consolidated Upper Muddy Creek formation contact represents the depth of the first occurrence of more cemented and consolidated material. Degree of cementation and consolidation varies with depth.
3. Monitoring well cluster LVWPS-MW204 includes three wells in separate borings including LVWPS-MW204, LVWPS-MW204B, and LVWPS-MW204C.
4. Each injection well location includes two nested wells screened separately within the same borehole.

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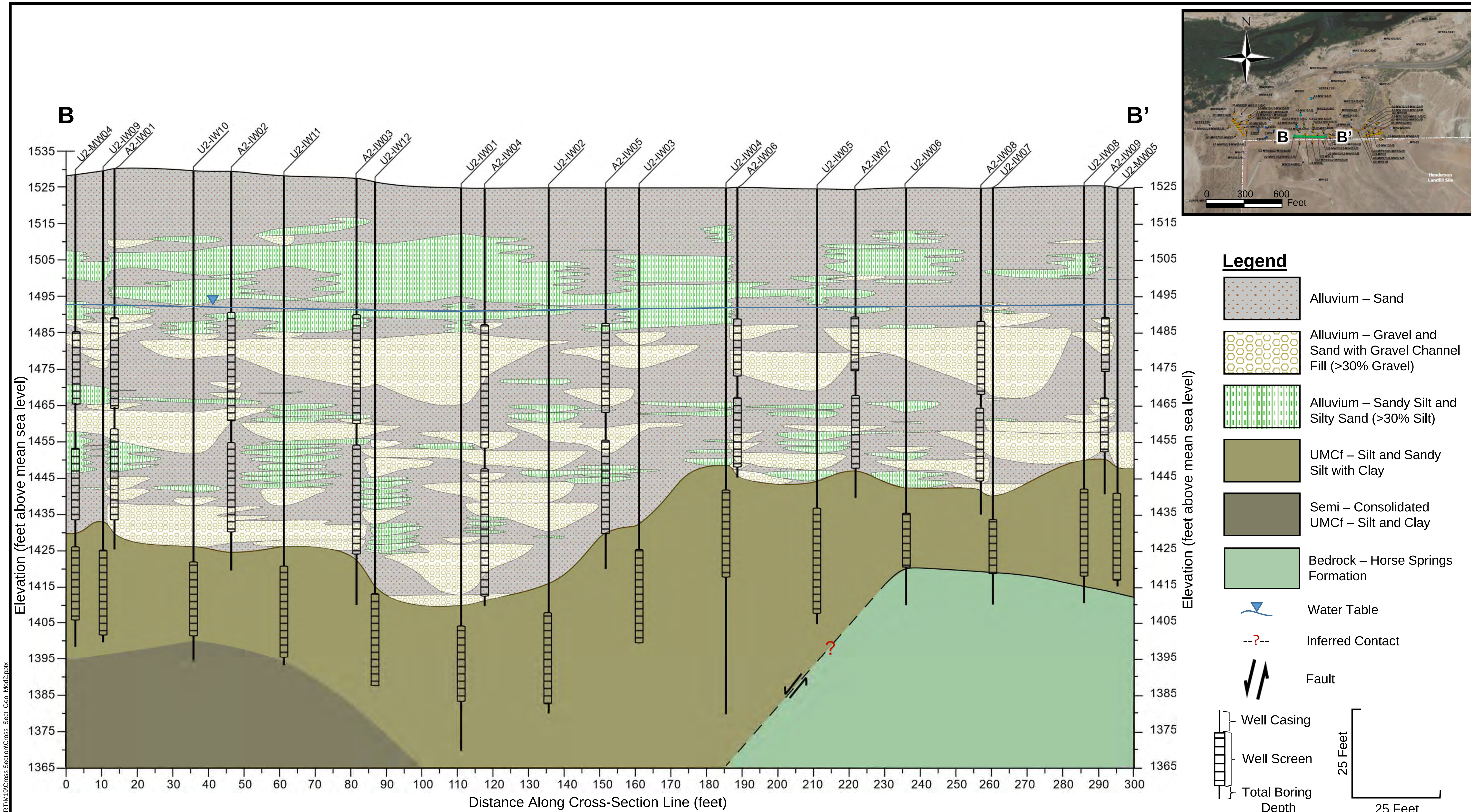
HENDERSON, NEVADA

GEOLOGIC CROSS SECTION ALONG THE ZONE 1 INJECTION WELL TRANSECT

Project No.: 117-7502019-M19-01
Date: APRIL 15, 2023
Designed By: MRB
Figure No. 10a



Notes:
IW – Injection Well
MW – Monitoring Well
UMCf – Upper Muddy Creek formation
1. Well names are shown within the prefix "LVWPS-".
2. Semi-consolidated Upper Muddy Creek formation contact represents the depth of the first occurrence of more cemented and consolidated material. Degree of cementation and consolidation varies with depth.
3. Each injection well location screened in the alluvium includes two nested wells screened separately within the same borehole.

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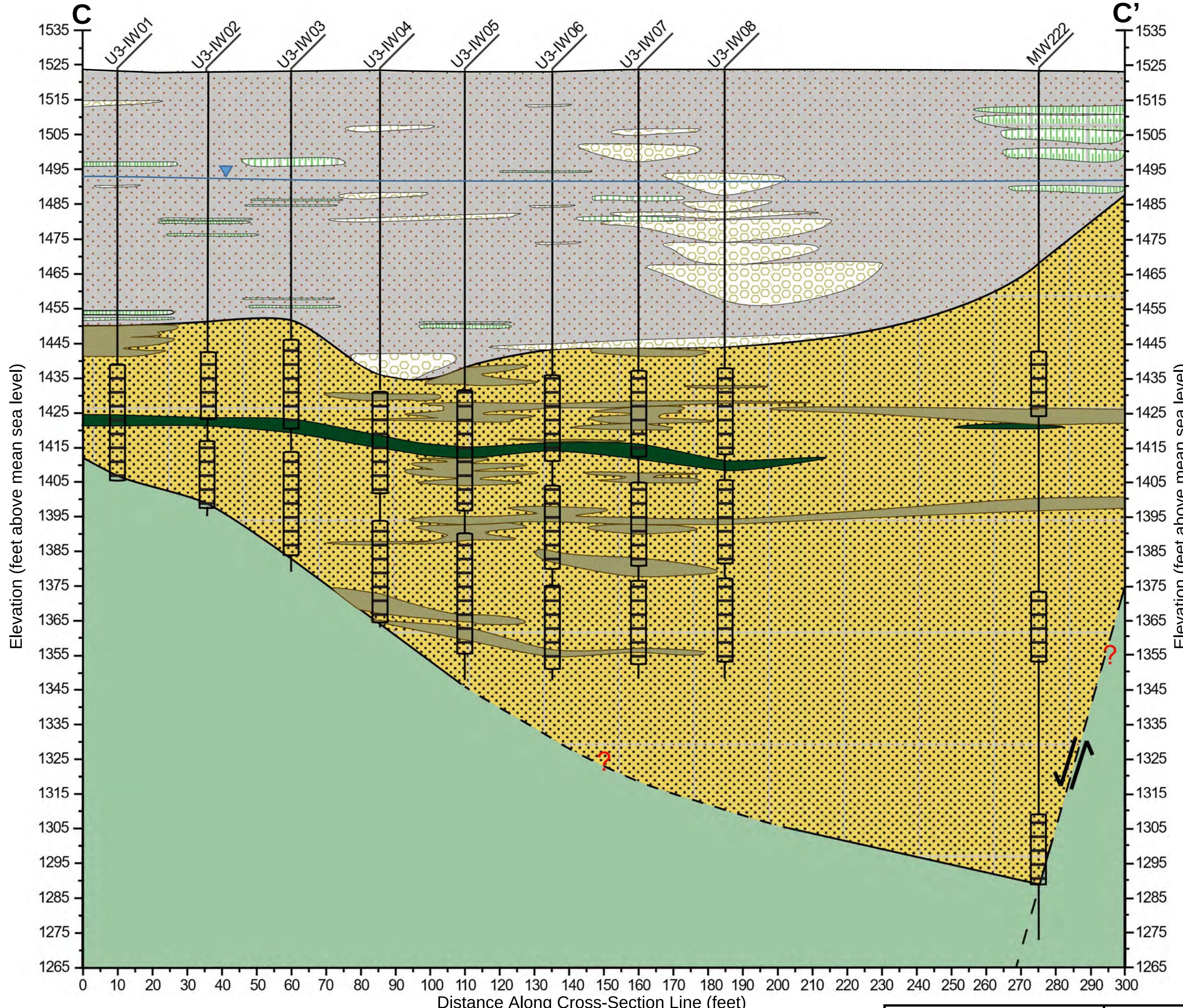
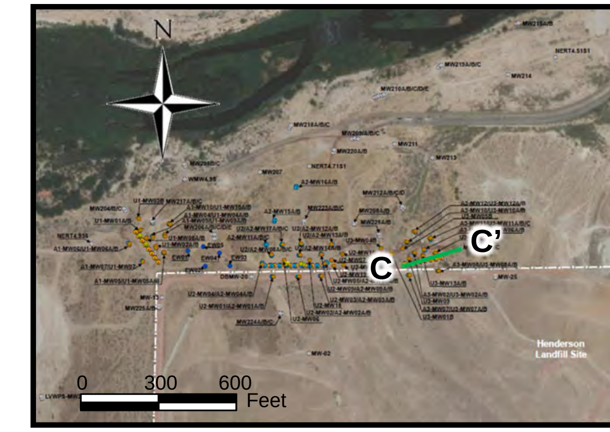
GEOLOGIC CROSS SECTION ALONG THE ZONE 2 INJECTION WELL TRANSECT

Project No.:	117-7502019-M19-01
Date:	APRIL 15, 2023
Designed By:	MRB
Figure No.	10b





Legend

- Alluvium – Sand
- Alluvium – Gravel and Sand with Gravel Channel Fill (>30% Gravel)
- Alluvium – Sandy Silt and Silty Sand (>30% Silt)
- UMCf – Silt and Sandy Silt with Clay
- Silty Sand with Minor Gravel – Coarse – Grained Facies of UMCf
- UMCf – Organic – Rich Silt and Clay
- Bedrock – Horse Springs Formation
- Water Table
- --?-- Inferred Contact
- Fault
- Well Casing
- Well Screen
- Total Boring Depth

30 Feet

30 Feet

Notes:
IW – Injection Well
MW – Monitoring Well
UMCf – Upper Muddy Creek formation
1. Well names are shown within the prefix "LVWPS-".
2. Monitoring well cluster LVWPS-MW222 includes three wells in separate borings including LVWPS-MW222A, LVWPS-MW222B, and LVWPS-MW222C.
3. With the exception of LVWPS-U3-IW01, each injection well location includes either two or three nested wells screened separately within the same borehole.

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LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
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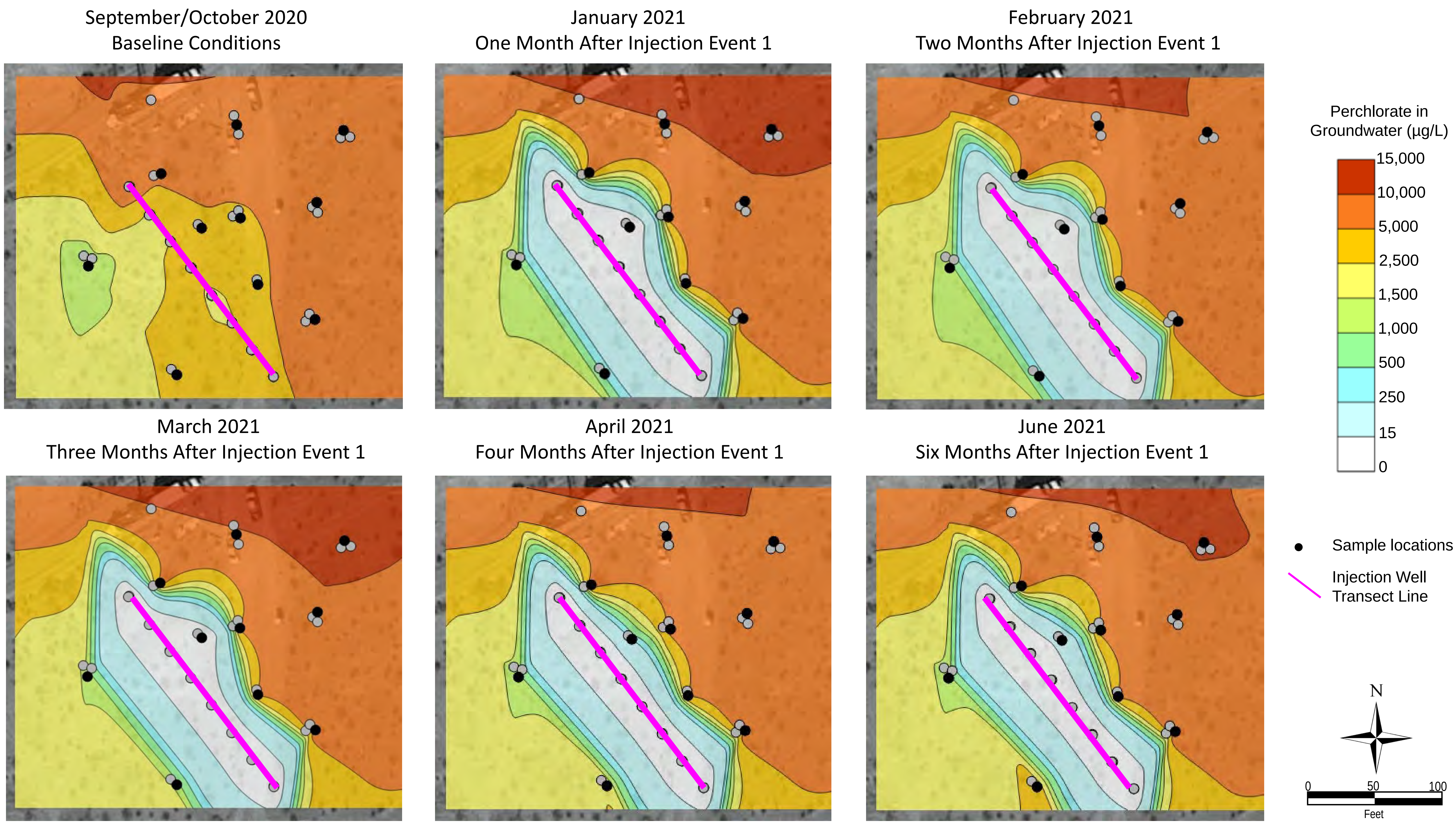
GEOLOGIC CROSS SECTION ALONG THE ZONE 3 INJECTION WELL TRANSECT

Project No.:	117-7502019-M19-01
Date:	APRIL 15, 2023
Designed By:	MRB
Figure No.	10c

\\tte134fs1\GEOSUP\VOL1\Projects\Data\NERT\M19\Cross Section\Cross_Sect_Geo_Mod2.pptx



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow UMCf between approximately 90 and 120 feet below ground surface. Monitoring and injection well names are provided on Figure 6.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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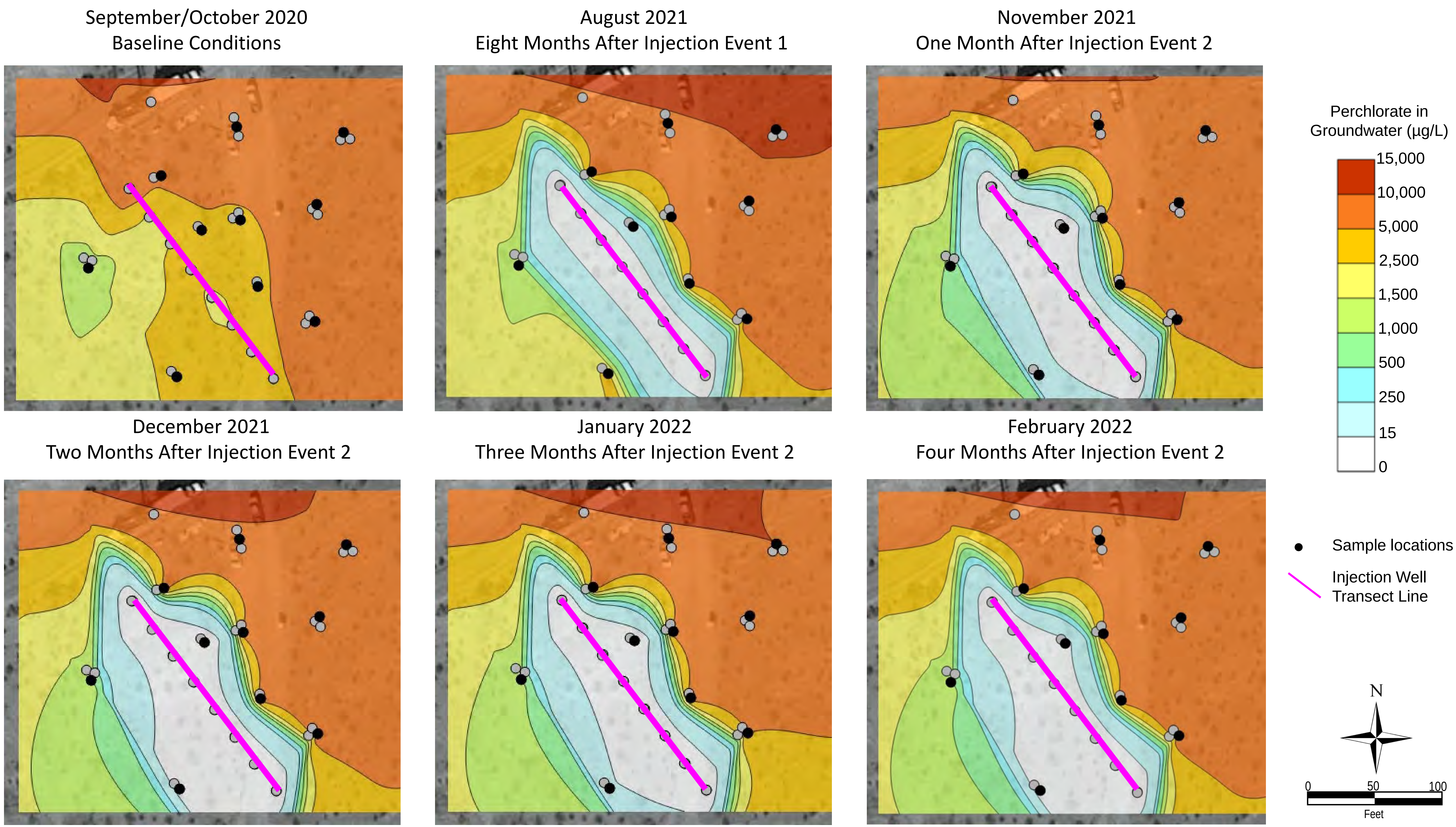
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 1 SHALLOW UMCF

Project No.: 117-7502019-M19-01
Date: June 17, 2024
Designed By: KRG
Figure No.
11A



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow UMCf between approximately 90 and 120 feet below ground surface. Monitoring and injection well names are provided on Figure 6.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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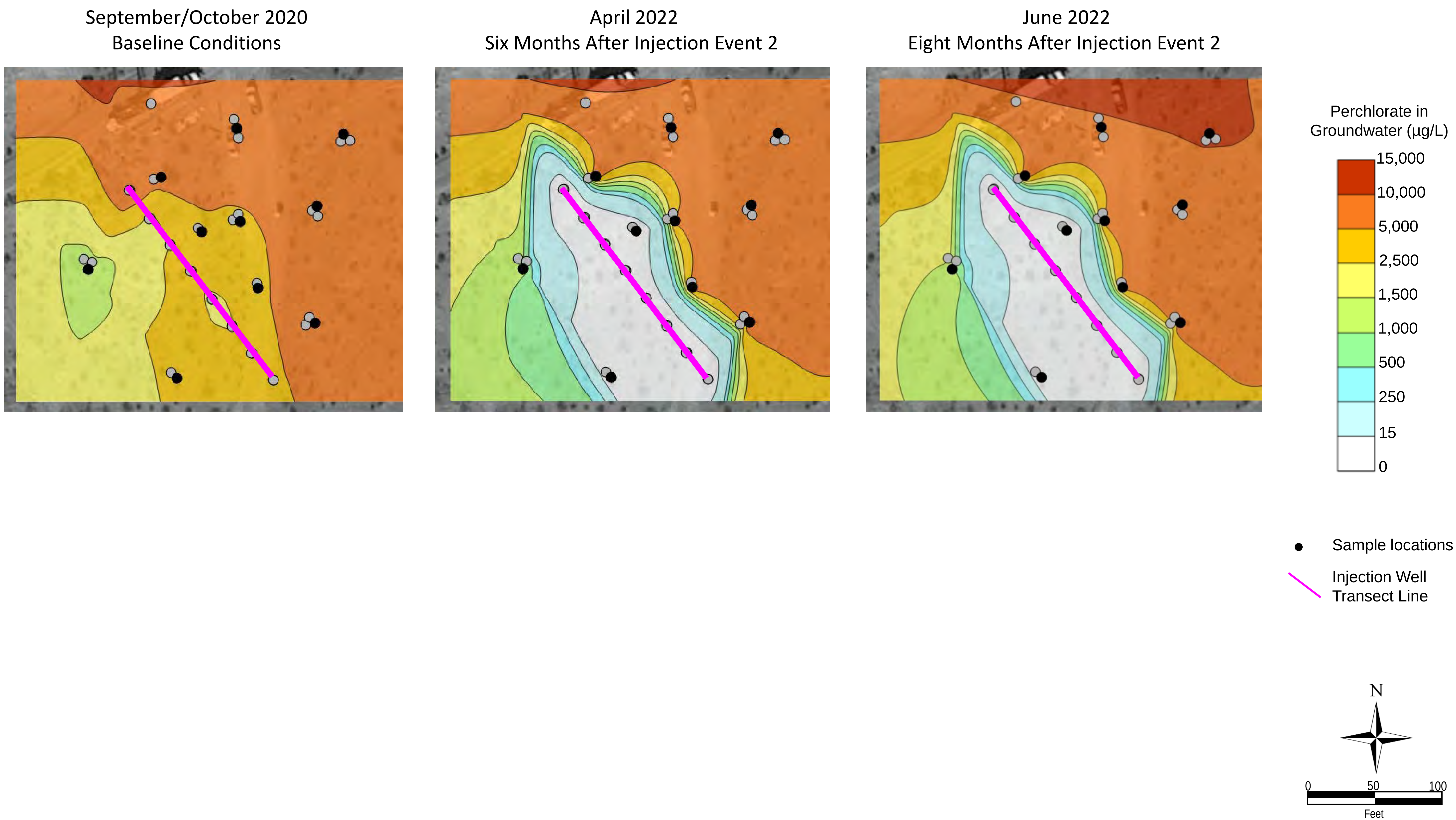
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 1 SHALLOW UMCF

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	**11B**

\\tts134fs1\GEOSUPVOL1\PROJECTS\DATA\NERT\M11\ppt_Figs\2020\Annual Report EVS Figures 2020_v1.5.pptx



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow UMCf between approximately 90 and 120 feet below ground surface. Monitoring and injection well names are provided on Figure 6.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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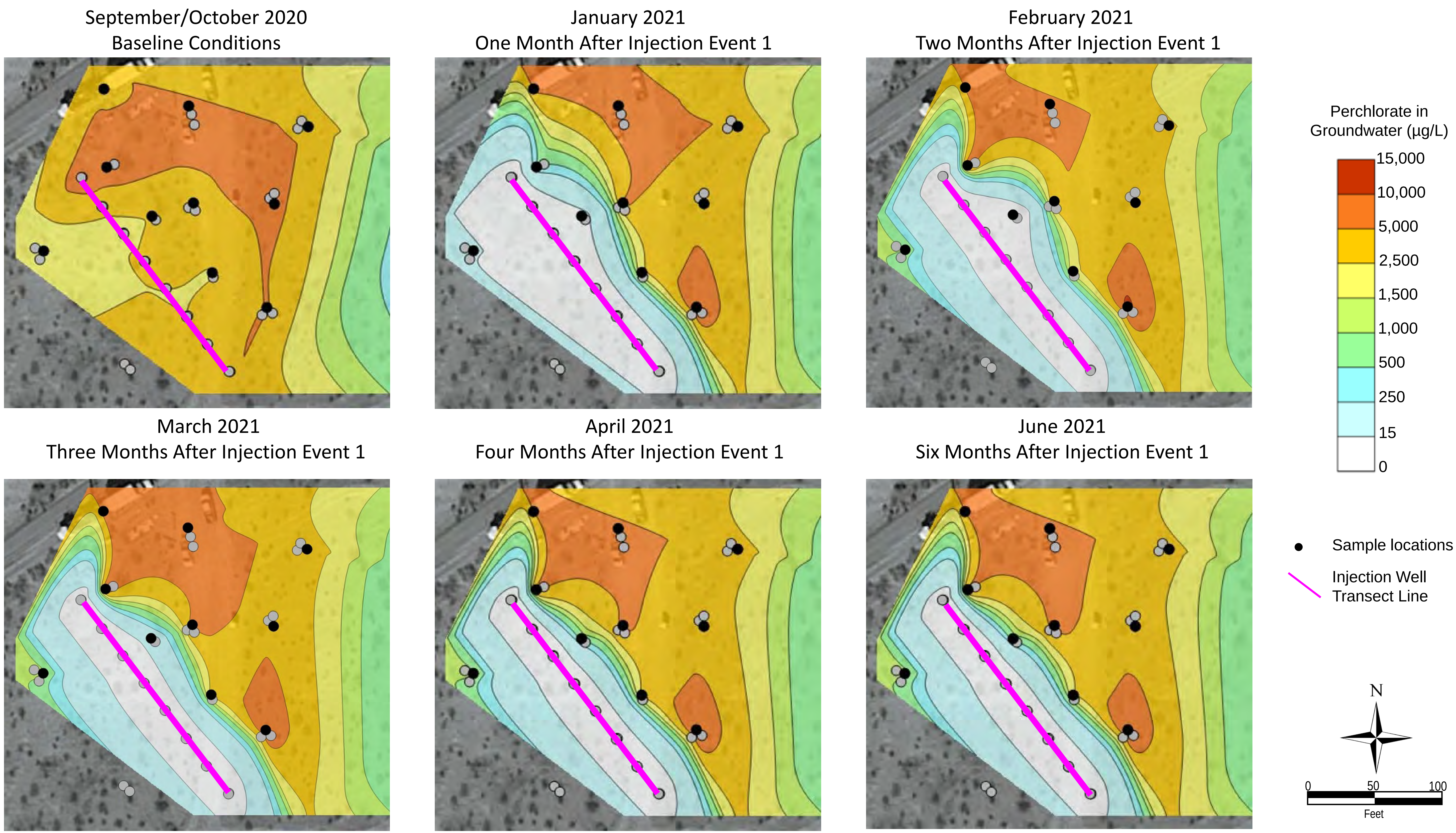

Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep UMCf between approximately 120 and 150 feet below ground surface. Monitoring and injection well names are provided on Figure 6.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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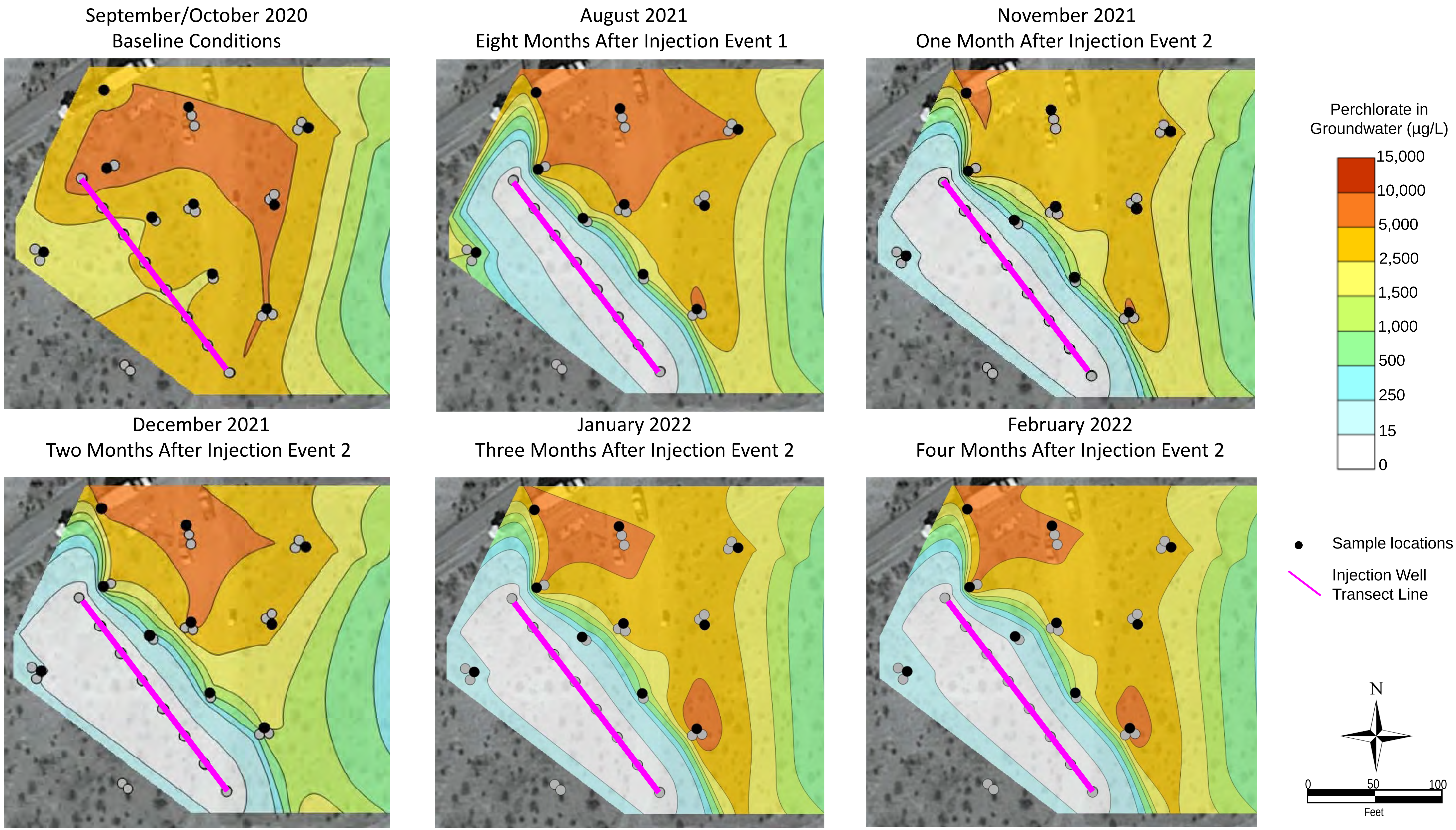
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 1 DEEP UMCF

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	12A



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep UMCf between approximately 120 and 150 feet below ground surface. Monitoring and injection well names are provided on Figure 6.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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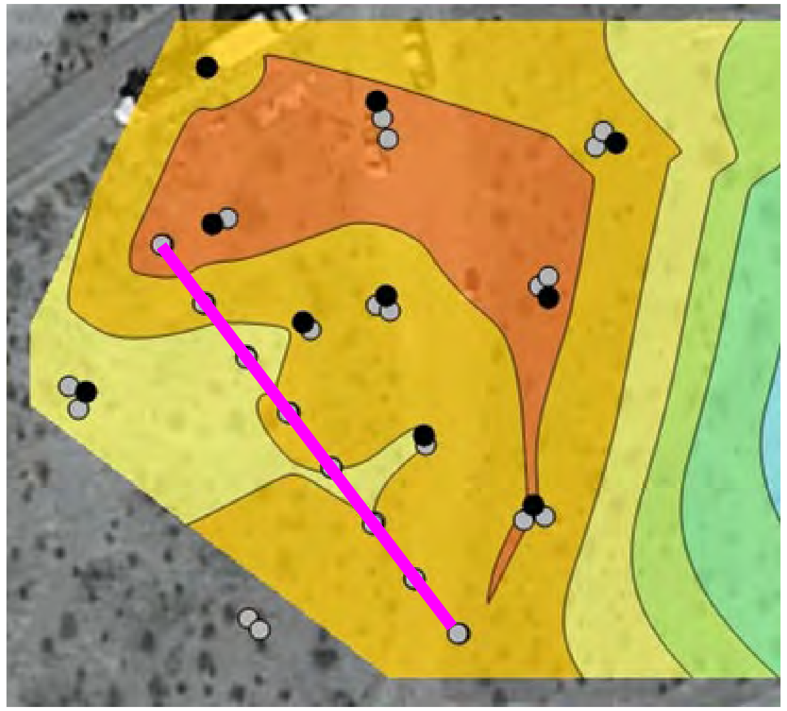
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 1 DEEP UMCF

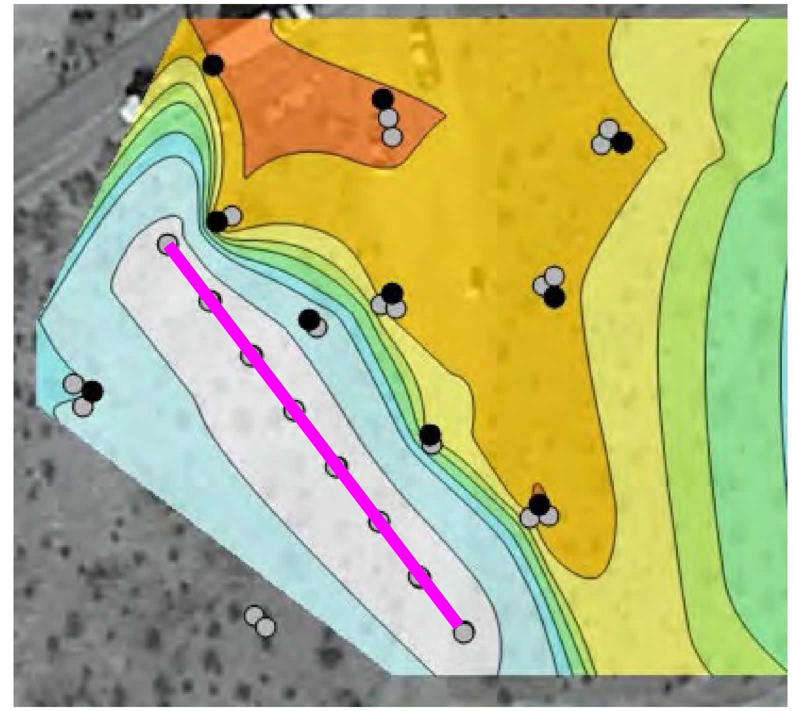
Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	12B

\\tts134fs1\GEOS\UP\VOL1\PROJECTS\DATA\NERT\M11\ppt_Figs\2020\Annual Report EVS Figures 2020_v1.5.pptx

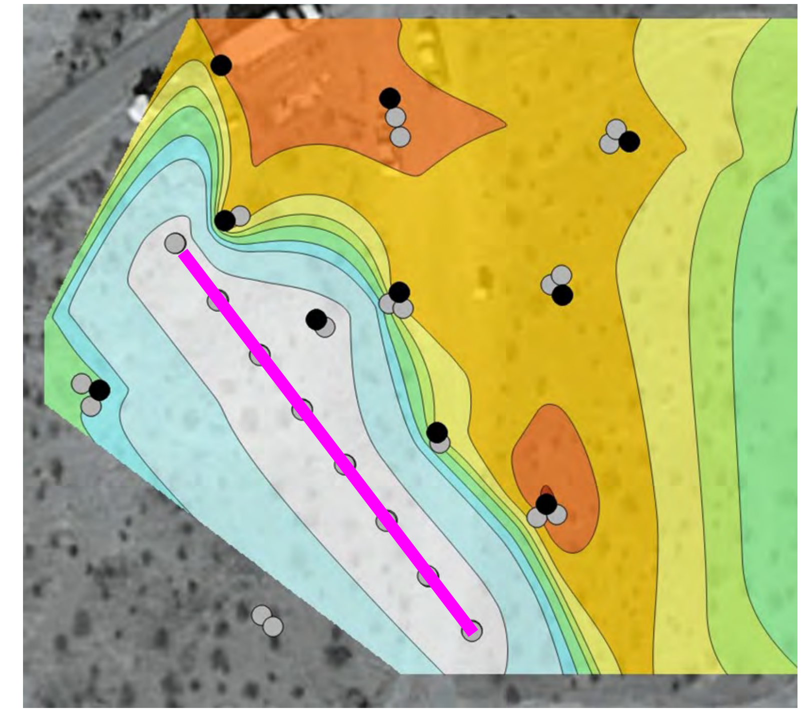
September/October 2020
Baseline Conditions

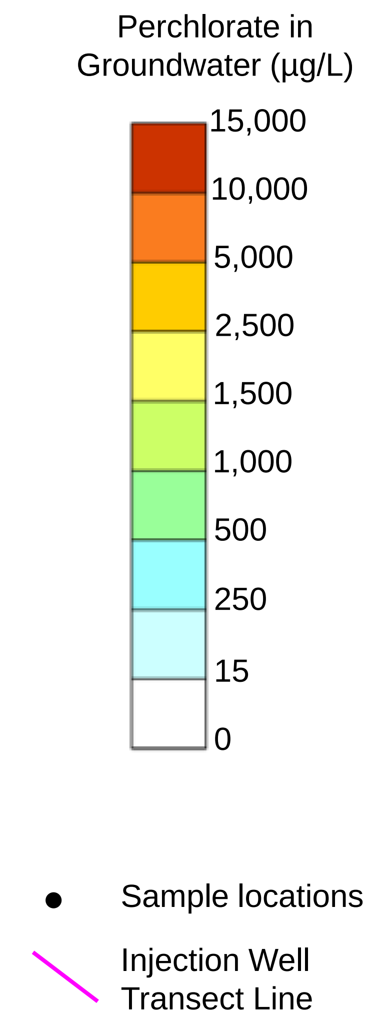


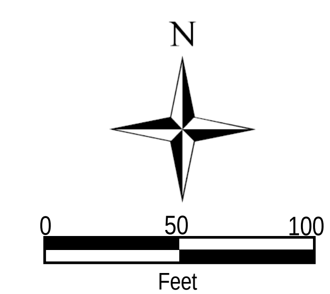
April 2022
Six Months After Injection Event 2



June 2022
Eight Months After Injection Event 2







Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep UMCf between approximately 120 and 150 feet below ground surface. Monitoring and injection well names are provided on Figure 6.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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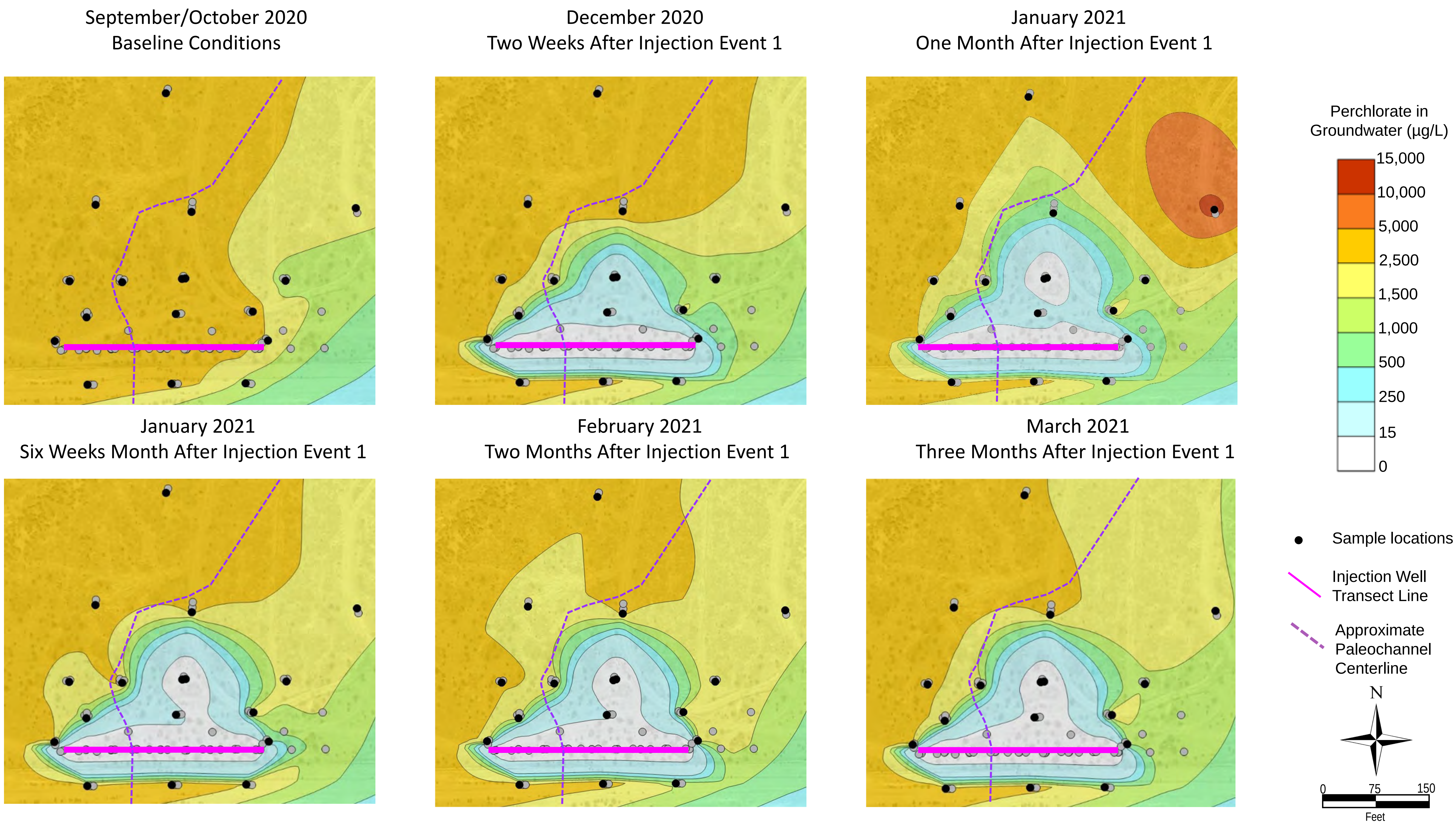
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 1 DEEP UMCF

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	12C



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow alluvium between approximately 30 and 70 feet below ground surface. Monitoring and injection well names are provided on Figures 7a – 7c.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020, April 2021, and October 2021. Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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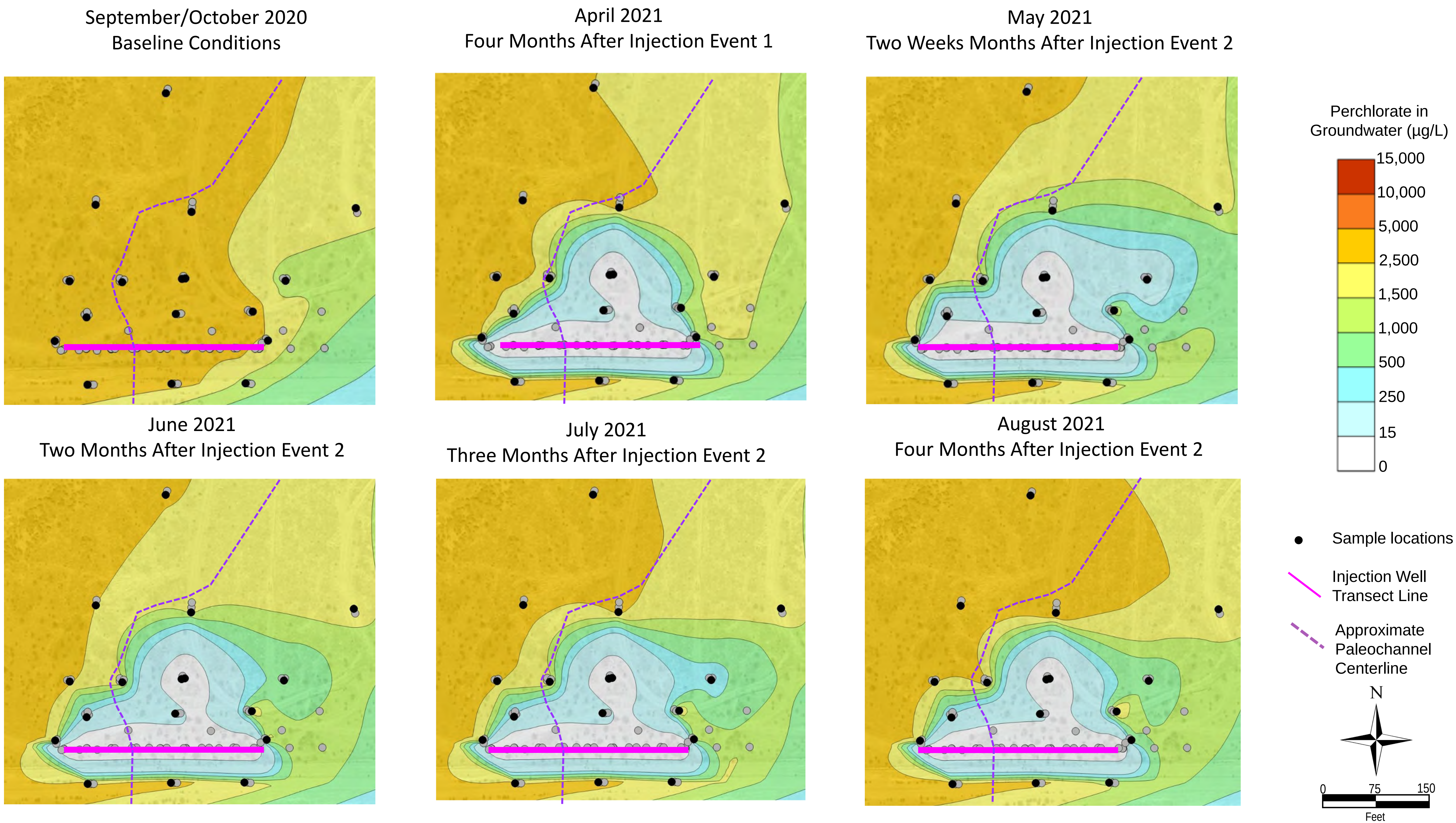
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 SHALLOW ALLUVIUM

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	13A

\\tts134fs1\GEOSUPVOL1\PROJECTS\DATA\NERT\M11\ppt_Figs\2020\Annual Report EVS Figures 2020_v1.5.pptx



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow alluvium between approximately 30 and 70 feet below ground surface. Monitoring and injection well names are provided on Figures 7a – 7c.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020, April 2021, and October 2021. Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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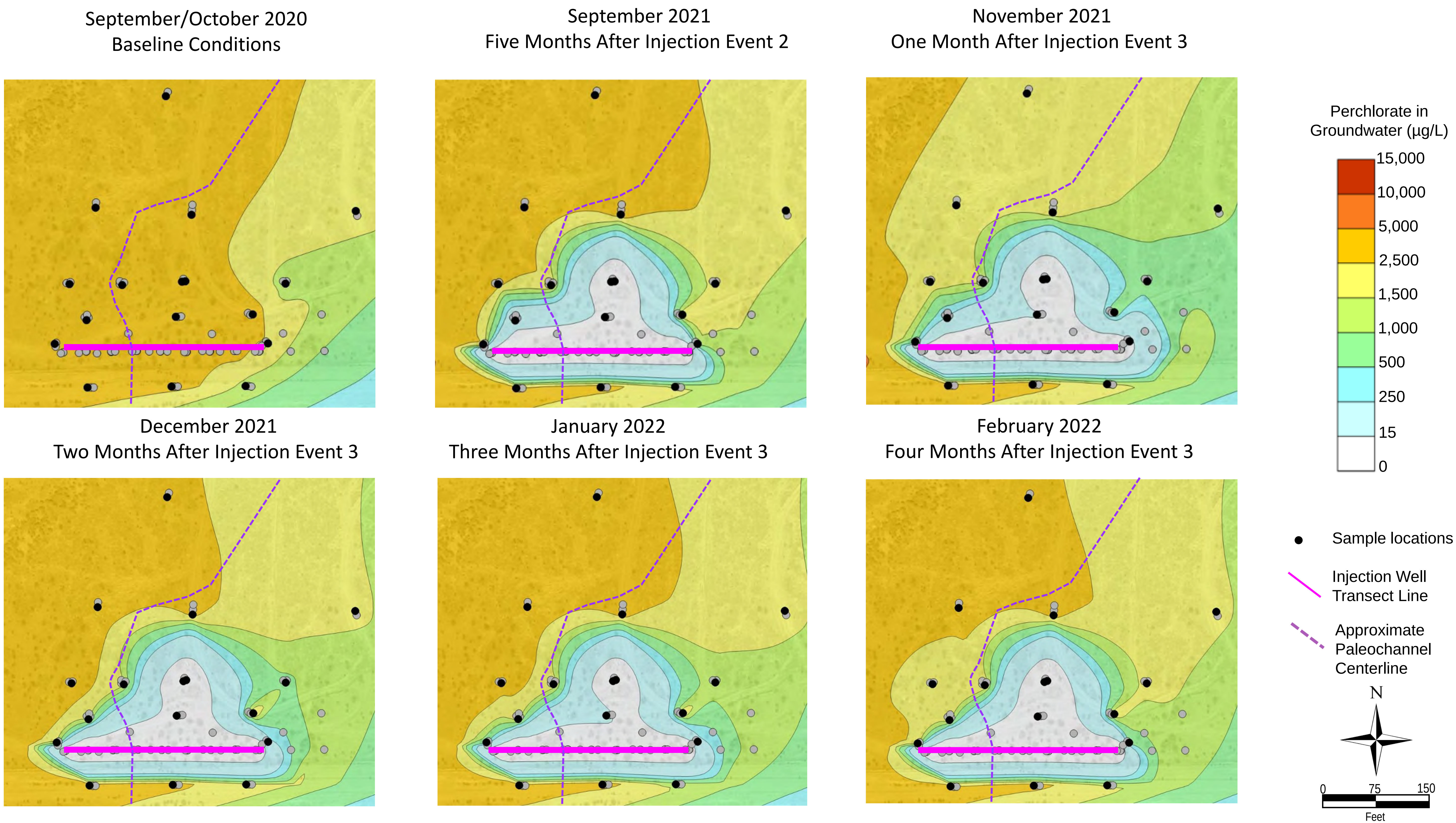
PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 SHALLOW ALLUVIUM

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	13B



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow alluvium between approximately 30 and 70 feet below ground surface. Monitoring and injection well names are provided on Figures 7a – 7c.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020, April 2021, and October 2021. Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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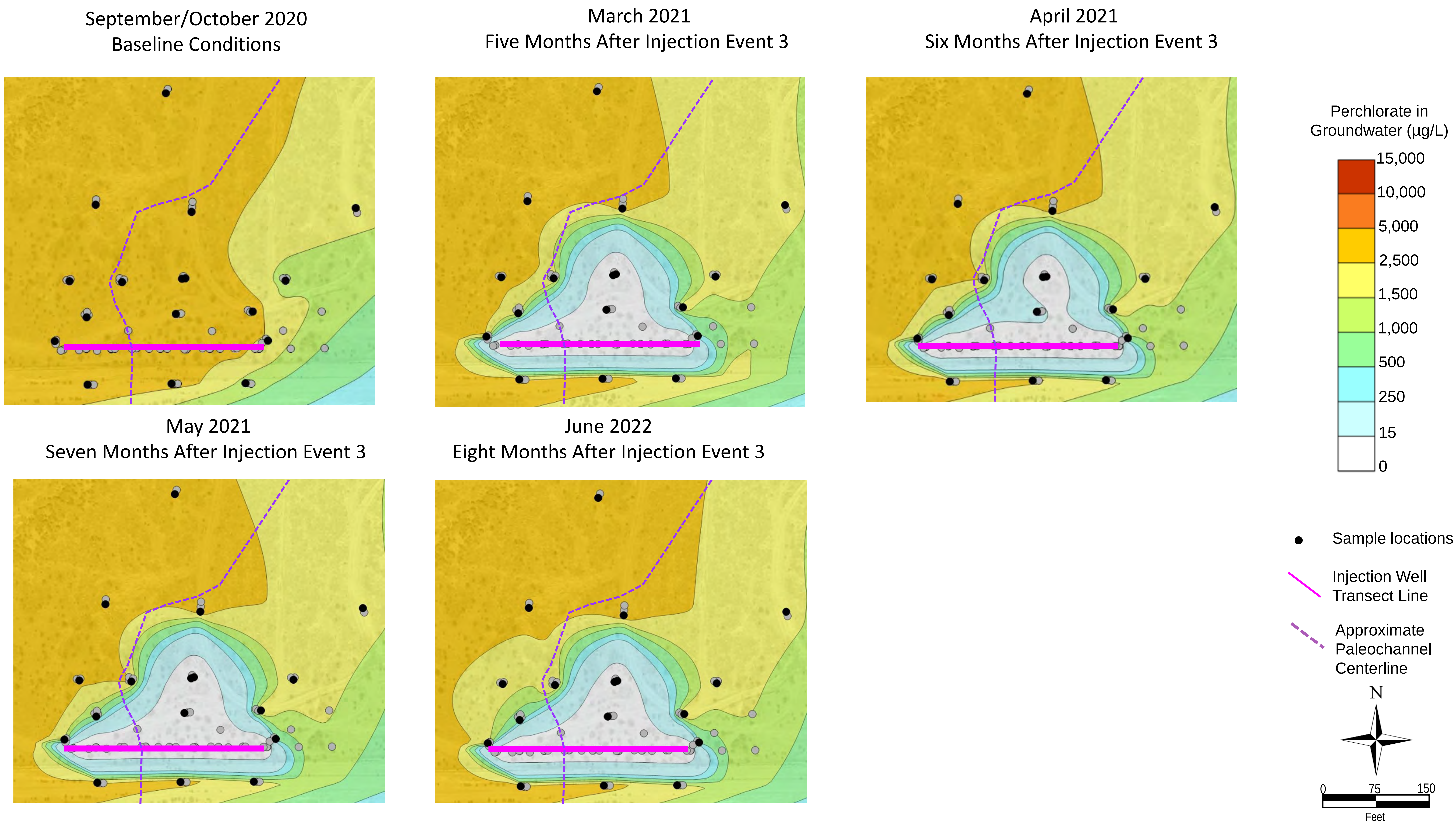
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 SHALLOW ALLUVIUM

Project No.: 117-7502019-M19-01
Date: June 17, 2024
Designed By: KRG

Figure No.
13C



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow alluvium between approximately 30 and 70 feet below ground surface. Monitoring and injection well names are provided on Figures 7a – 7c.
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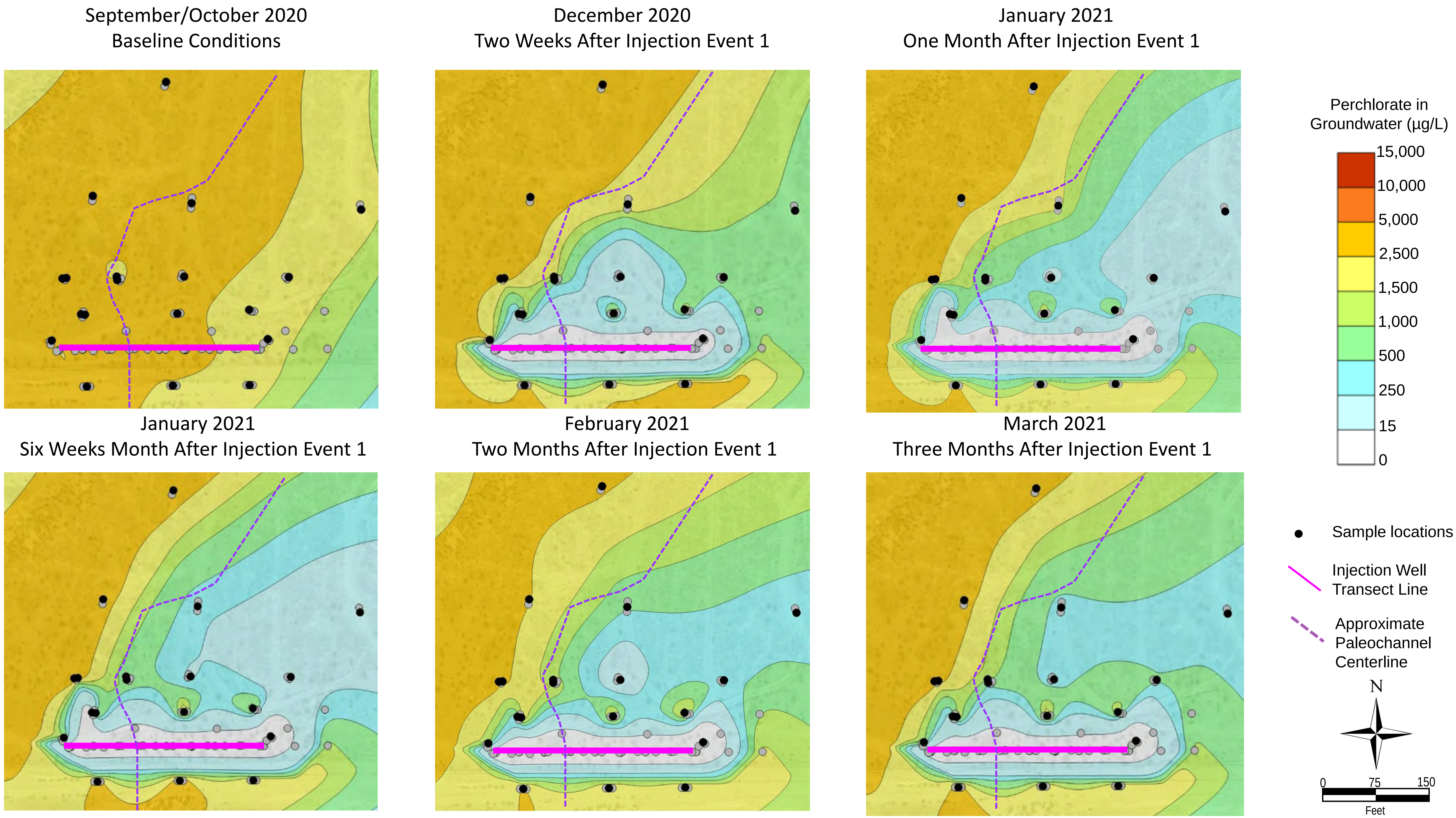
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 SHALLOW ALLUVIUM

Project No.: 117-7502019-M19-01
Date: June 17, 2024
Designed By: KRG
Figure No. **13D**

\\tts134fs1\GEOSUPVOL1\PROJECTS\DATA\NERT\M11\ppt_Figs\2020\Annual Report EVS Figures 2020_v1.5.pptx



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep alluvium between approximately 70 and 115 feet below ground surface. Monitoring and injection well names are provided on Figures 7a – 7c.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020, April 2021, and October 2021. Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 DEEP ALLUVIUM

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	14A

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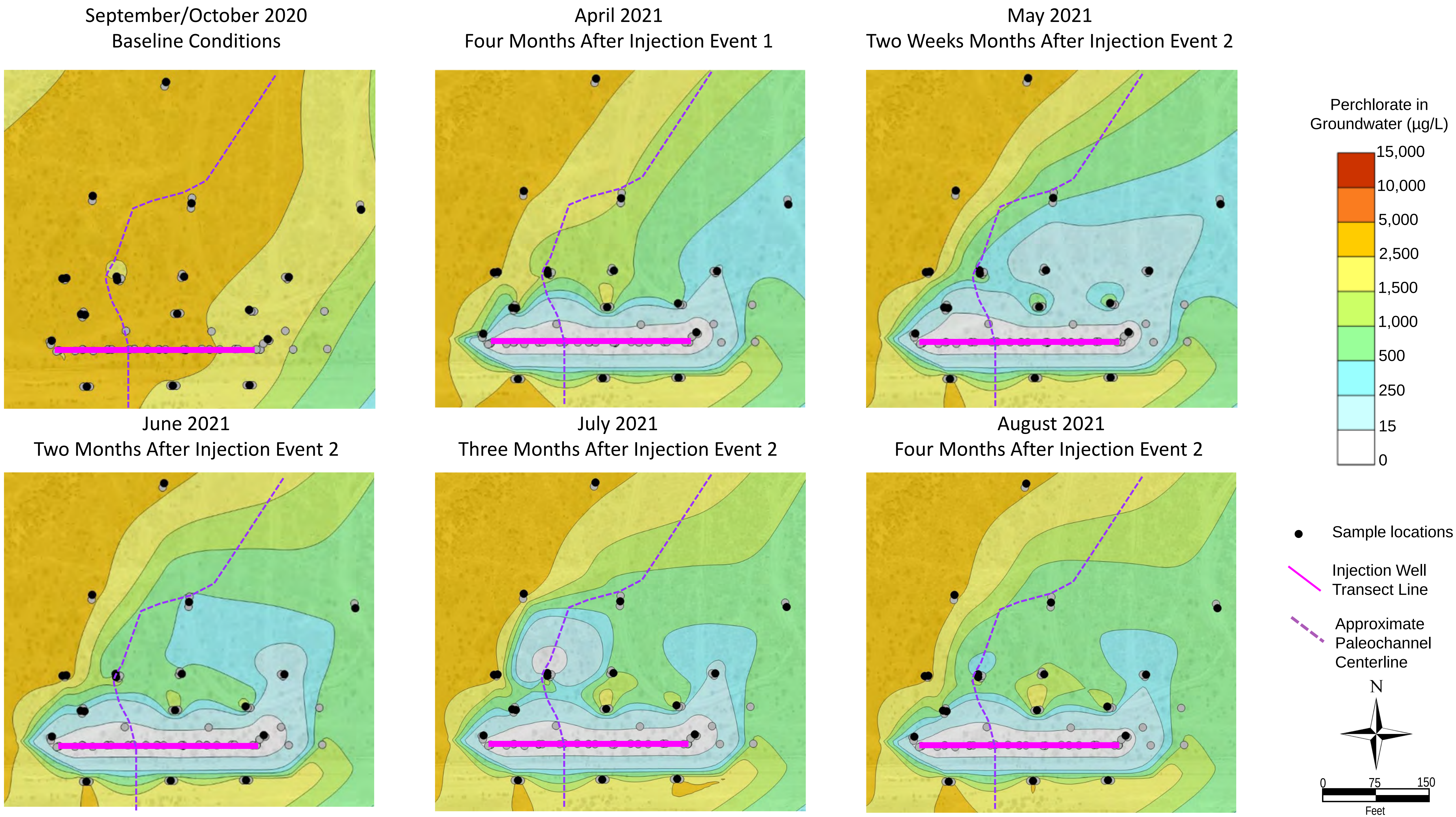

Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep alluvium between approximately 70 and 115 feet below ground surface. Monitoring and injection well names are provided on Figures 7a – 7c.
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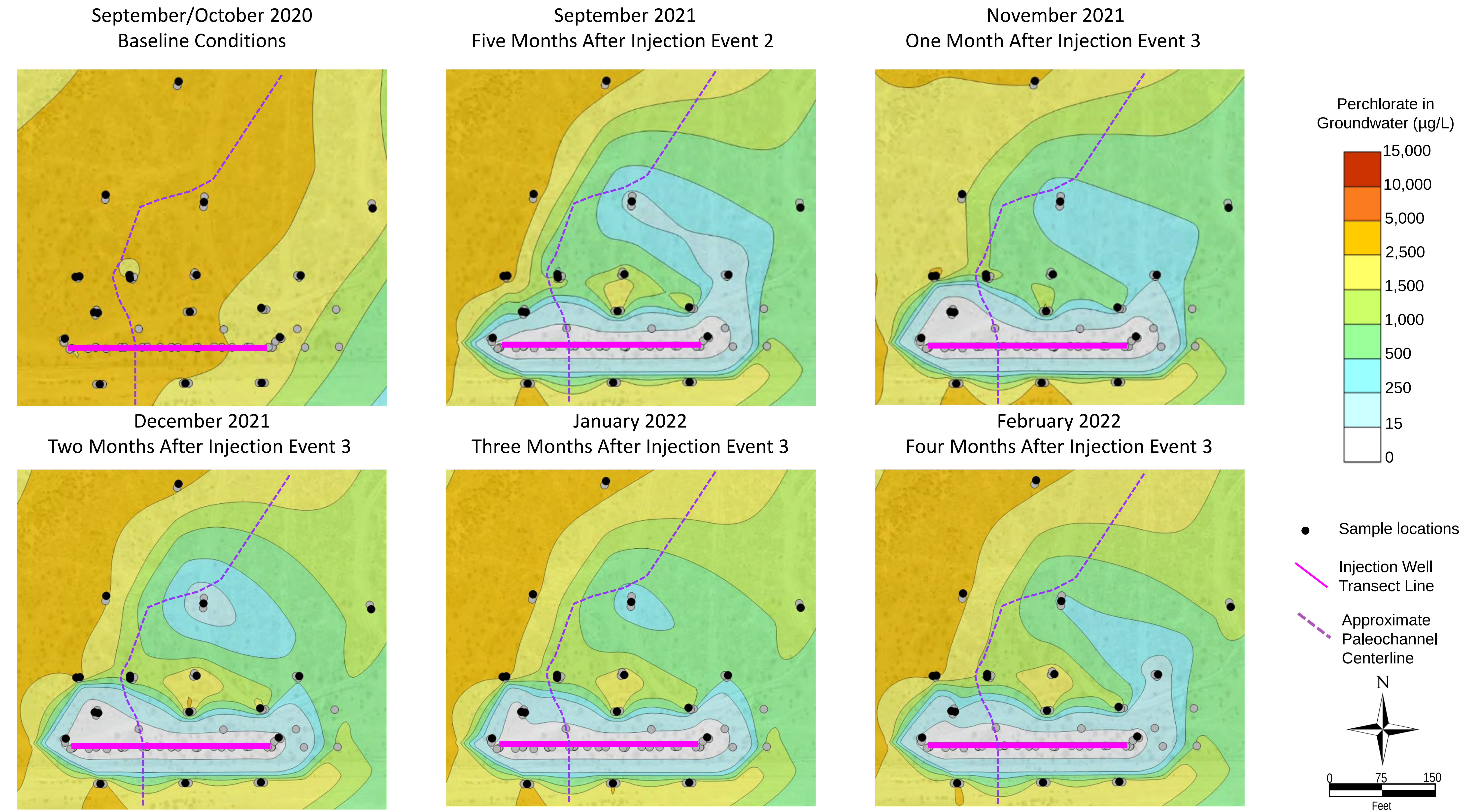
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 DEEP ALLUVIUM

Project No.: 117-7502019-M19-01
Date: June 17, 2024
Designed By: KRG
Figure No.
14B



Notes:

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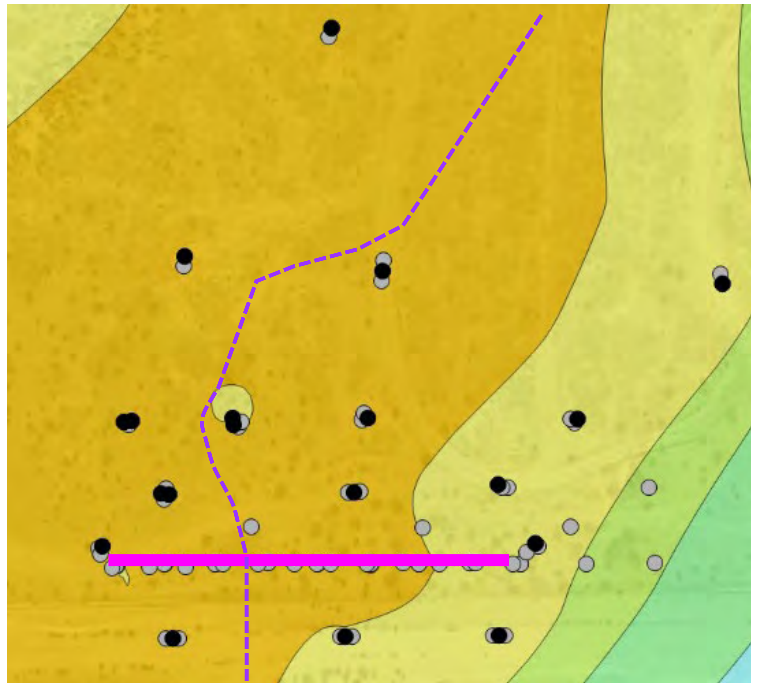
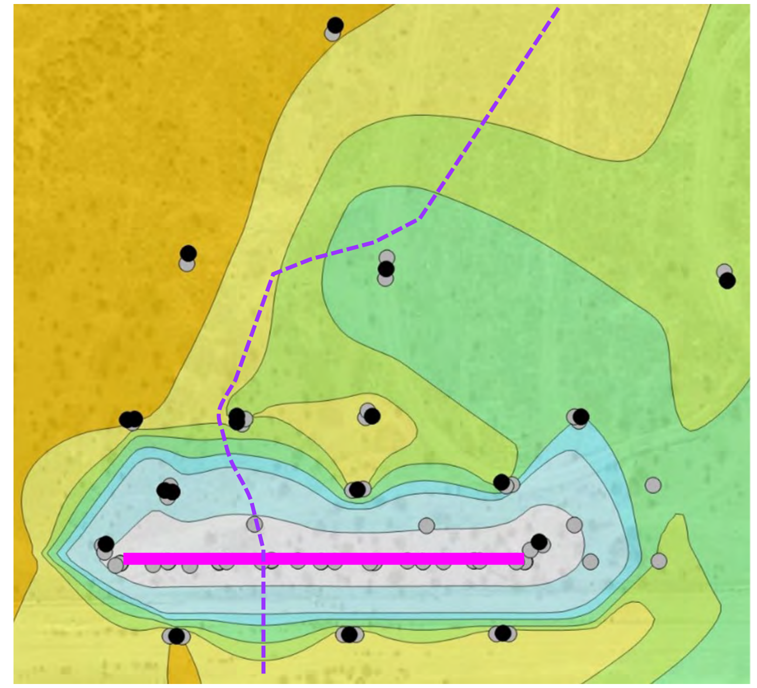
PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 DEEP ALLUVIUM

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	14C

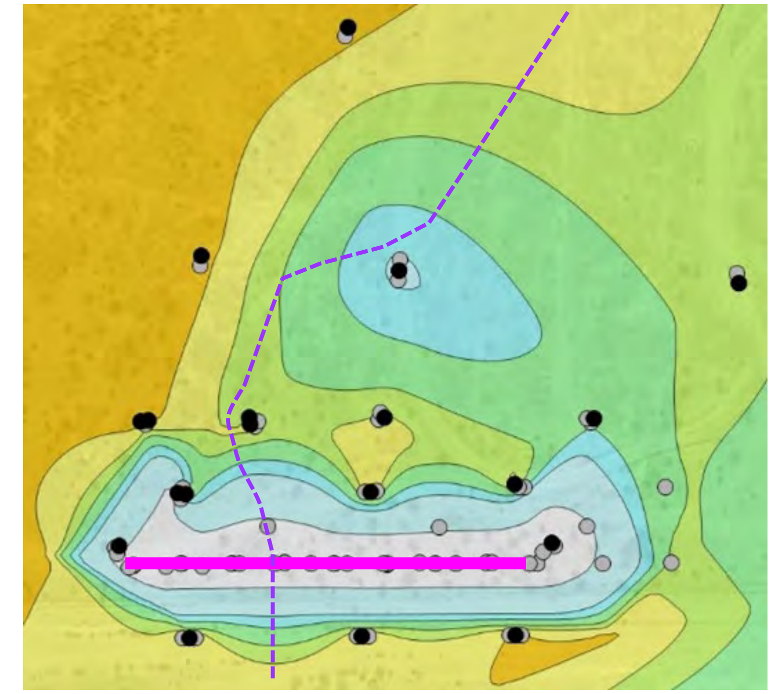
September/October 2020
Baseline Conditions



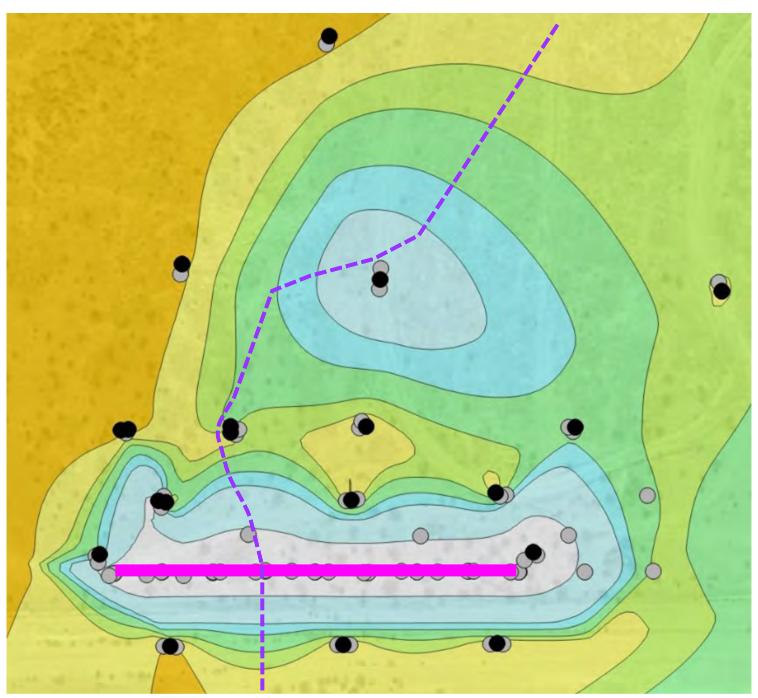
March 2021
Five Months After Injection Event 3



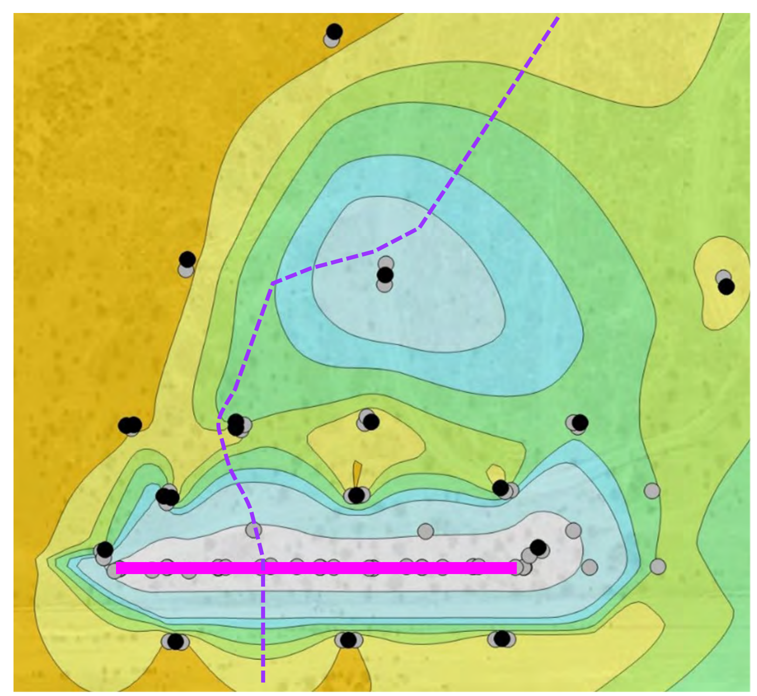
April 2021
Six Months After Injection Event 3

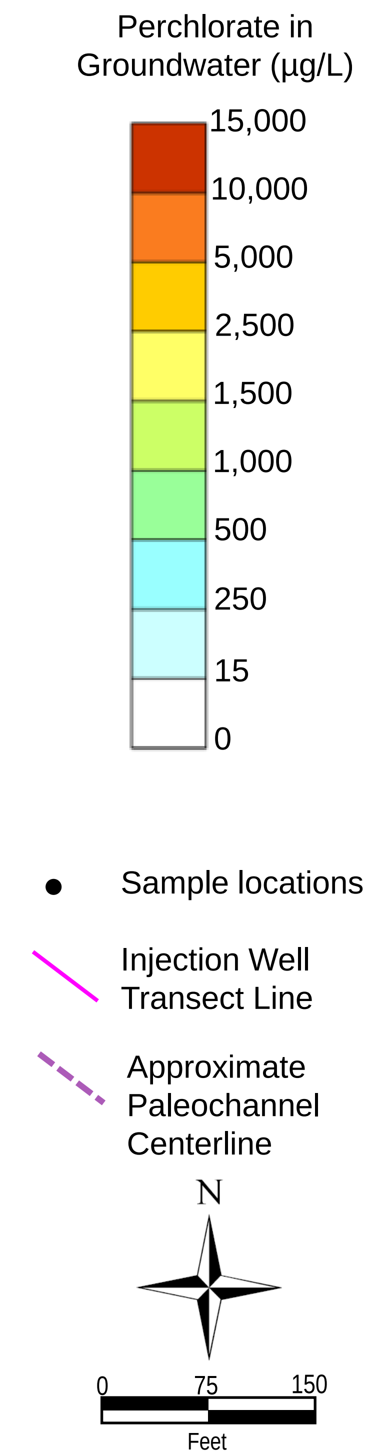


May 2021
Seven Months After Injection Event 3



June 2022
Eight Months After Injection Event 3





Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep alluvium between approximately 70 and 115 feet below ground surface. Monitoring and injection well names are provided on Figures 7a – 7c.
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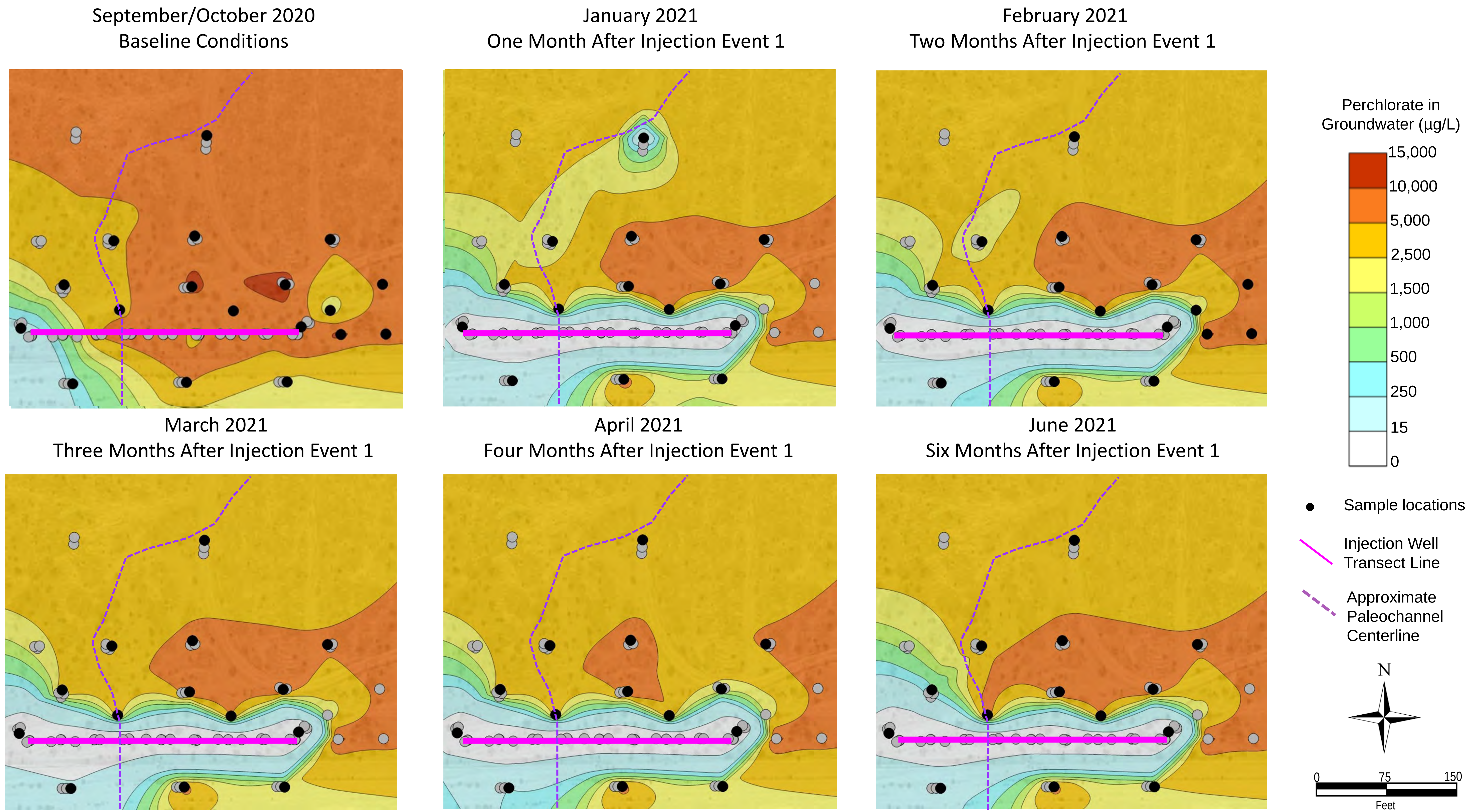
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 DEEP ALLUVIUM

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	14D



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the UMCf between approximately 95 and 140 feet below ground surface. Monitoring and injection well names are provided on Figures 7a-7c.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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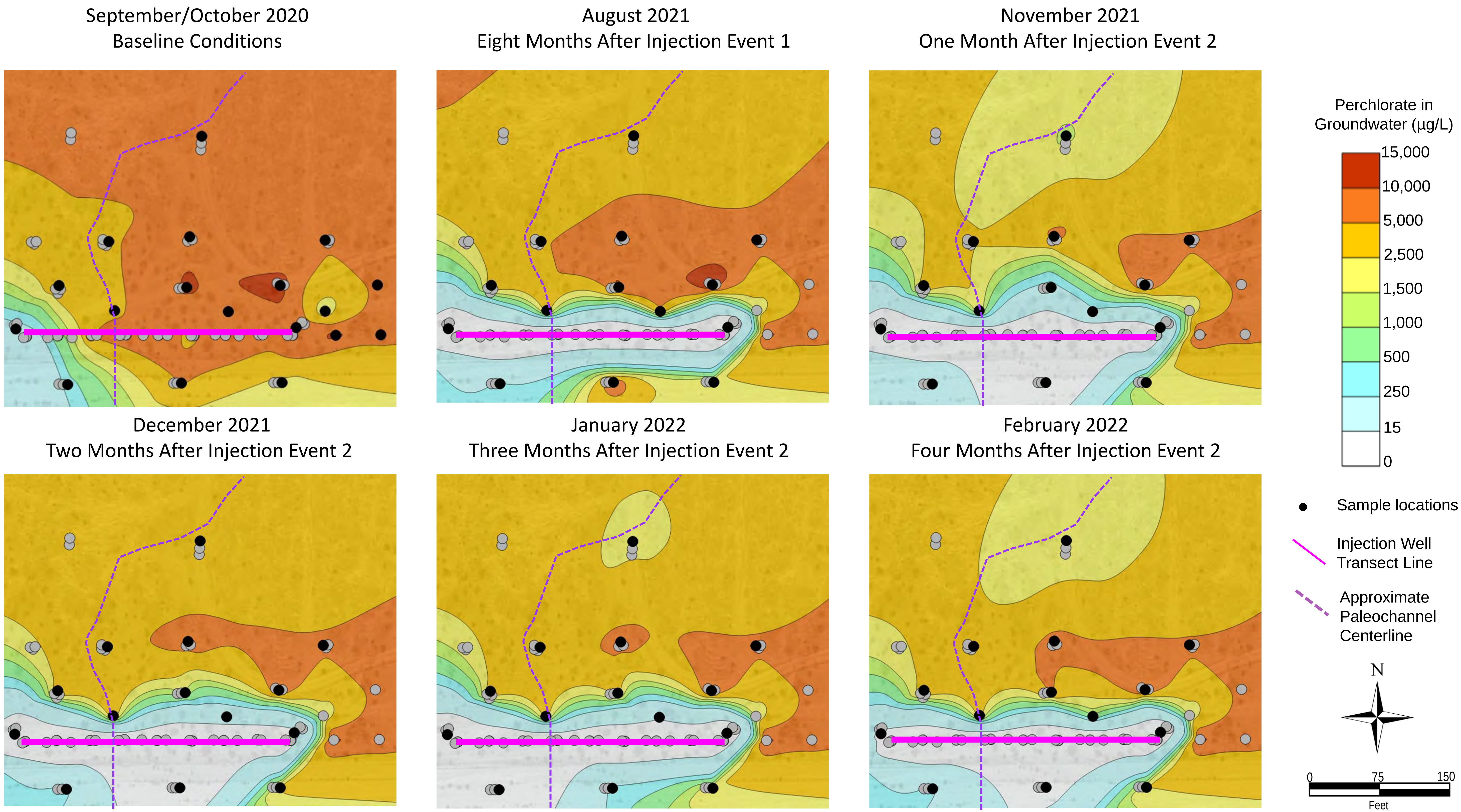
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 UMCF

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	15A



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the UMCf between approximately 95 and 140 feet below ground surface. Monitoring and injection well names are provided on Figures 7a-7c.
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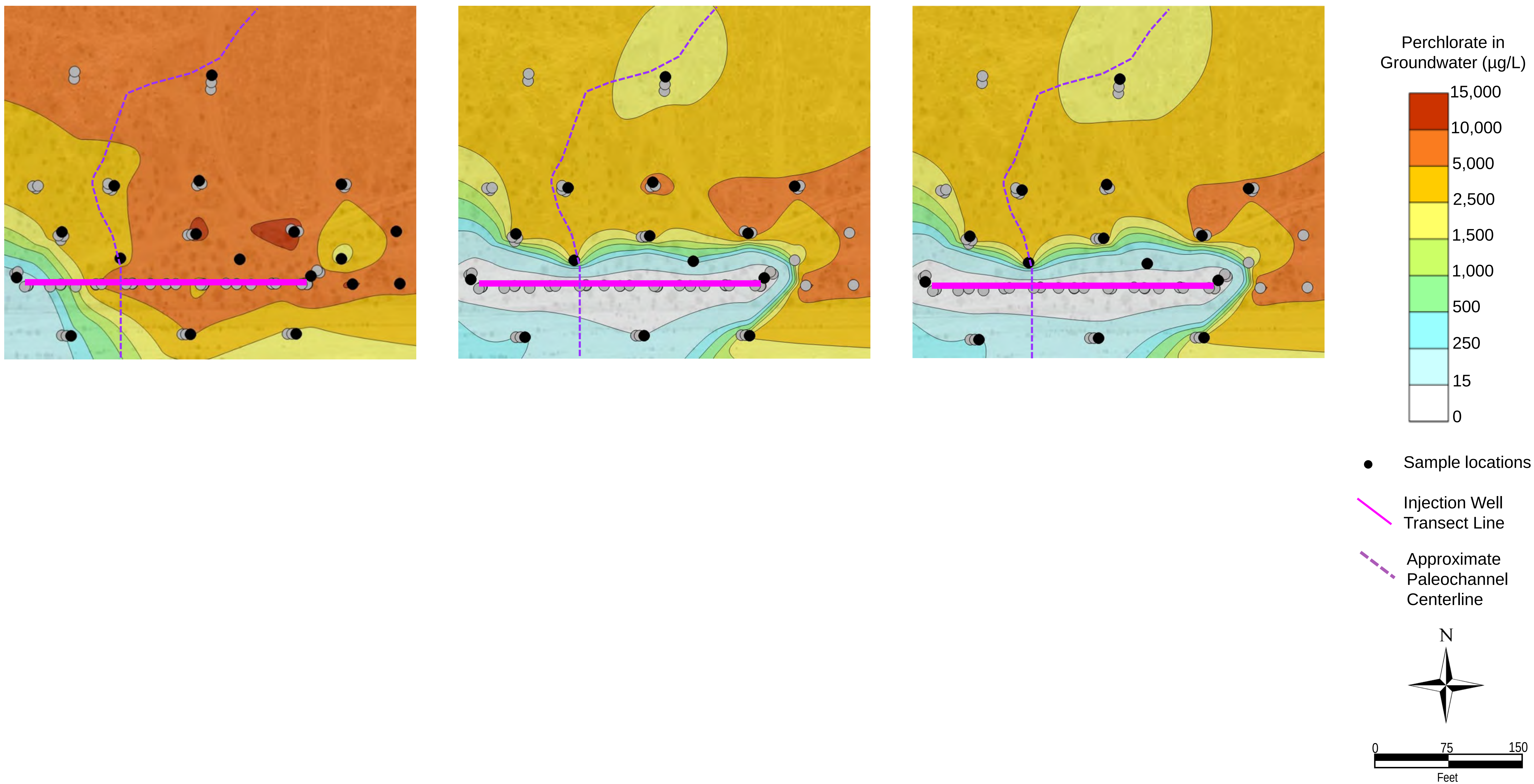
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 UMCF

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	15B

September/October 2020 Baseline Conditions	April 2022 Six Months After Injection Event 2	June 2022 Eight Months After Injection Event 2



Notes:

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HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 2 UMCF

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	15C

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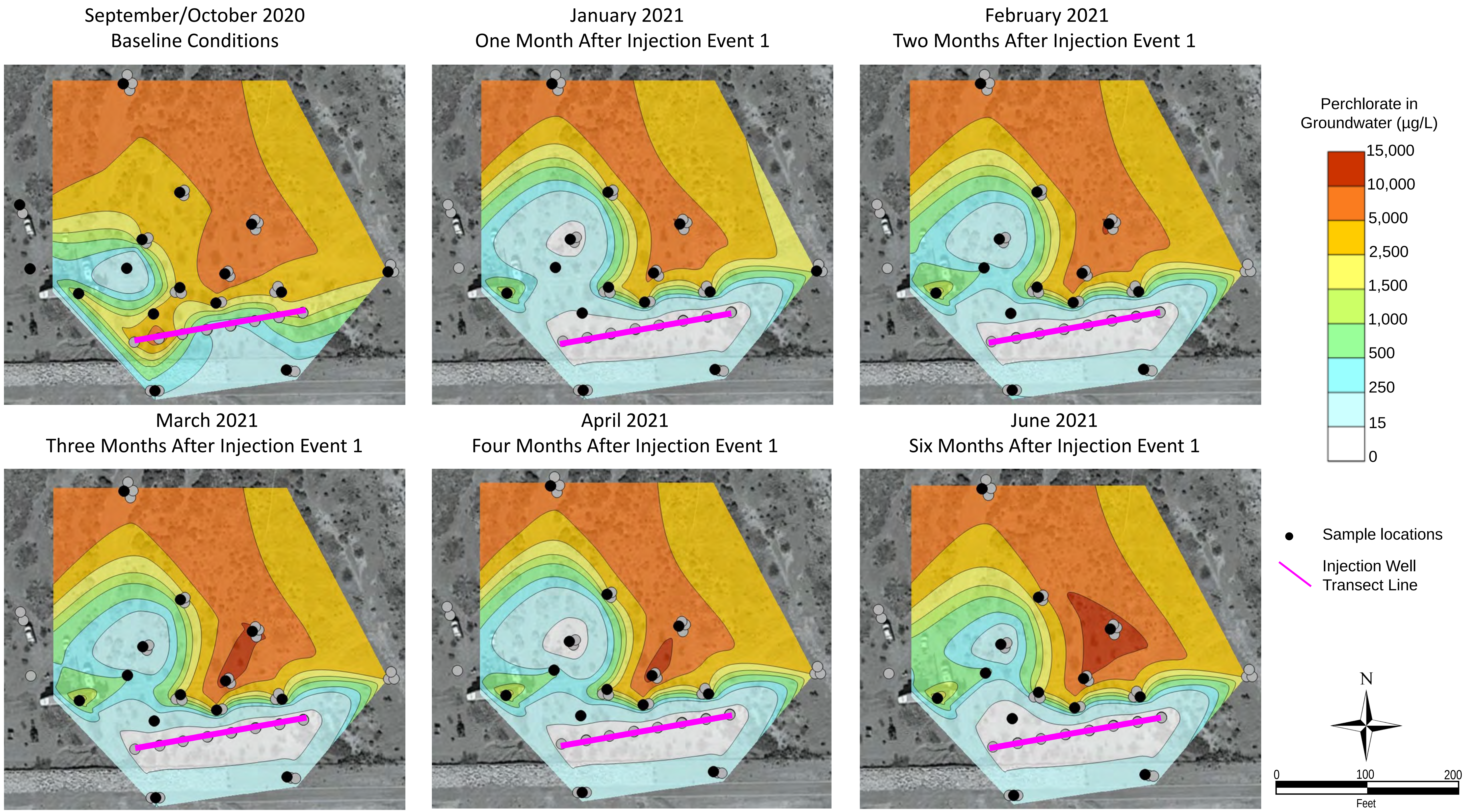

Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow UMCf-cg between approximately 80 and 110 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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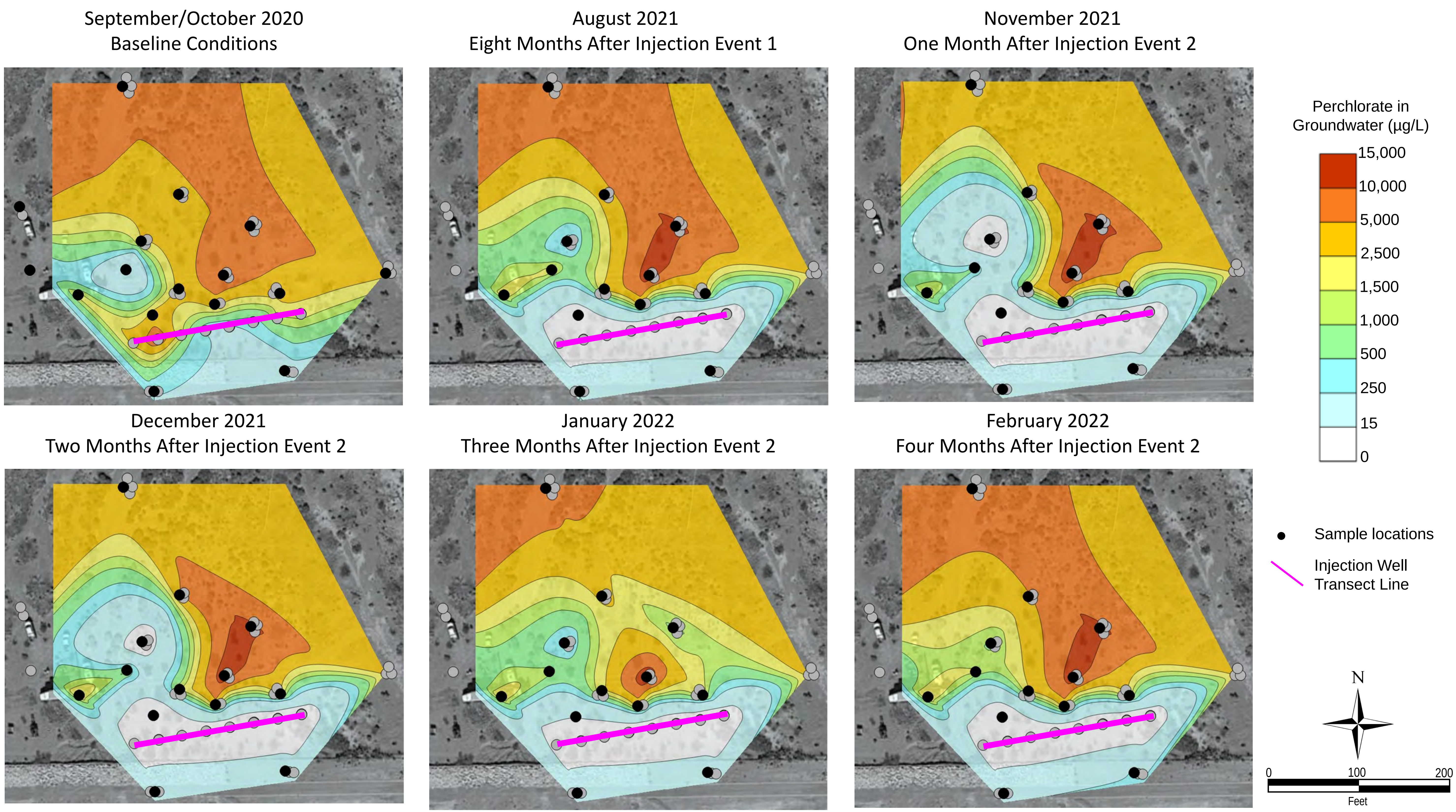
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 3 SHALLOW UMCF-CG

Project No.: 117-7502019-M19-01
Date: June 17, 2024
Designed By: KRG
Figure No. 16A



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow UMCf-cg between approximately 80 and 110 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 3 SHALLOW UMCF-CG

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	16B

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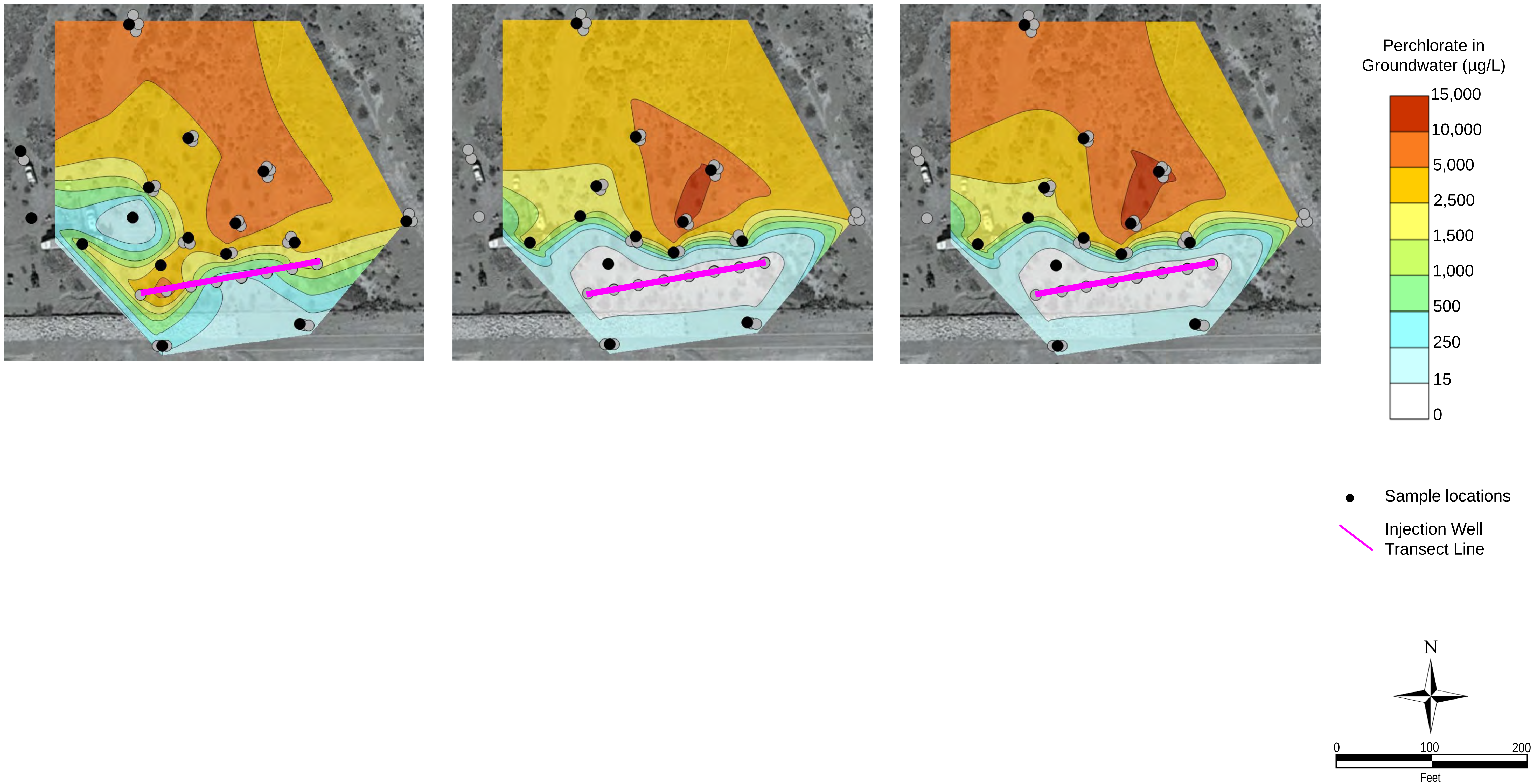
September/October 2020
Baseline Conditions

April 2022
Six Months After Injection Event 2

June 2022
Eight Months After Injection Event 2



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the shallow UMCf-cg between approximately 80 and 110 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
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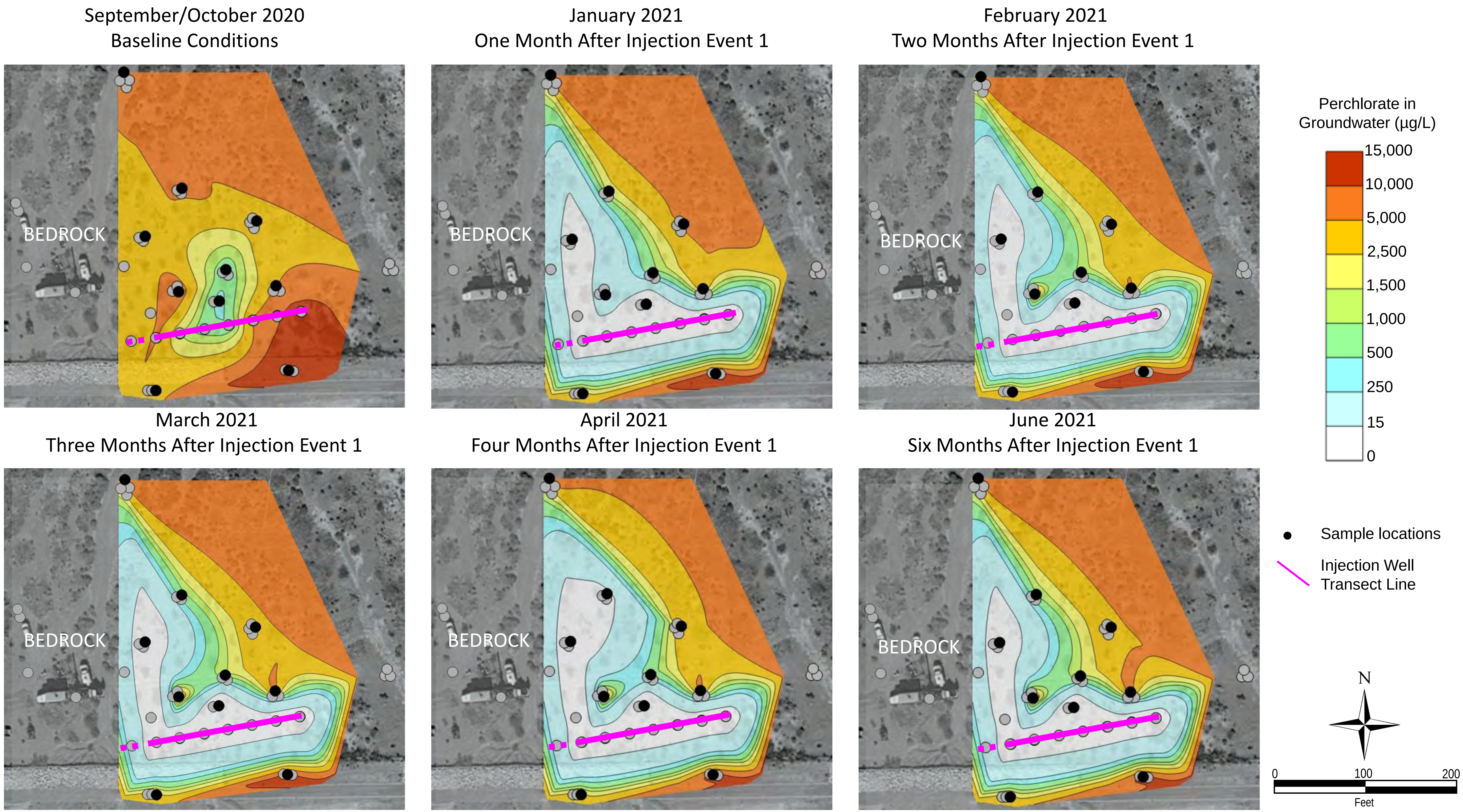
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 3 SHALLOW UMCF-CG

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	16C



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep UMCf-cg between approximately 110 and 150 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
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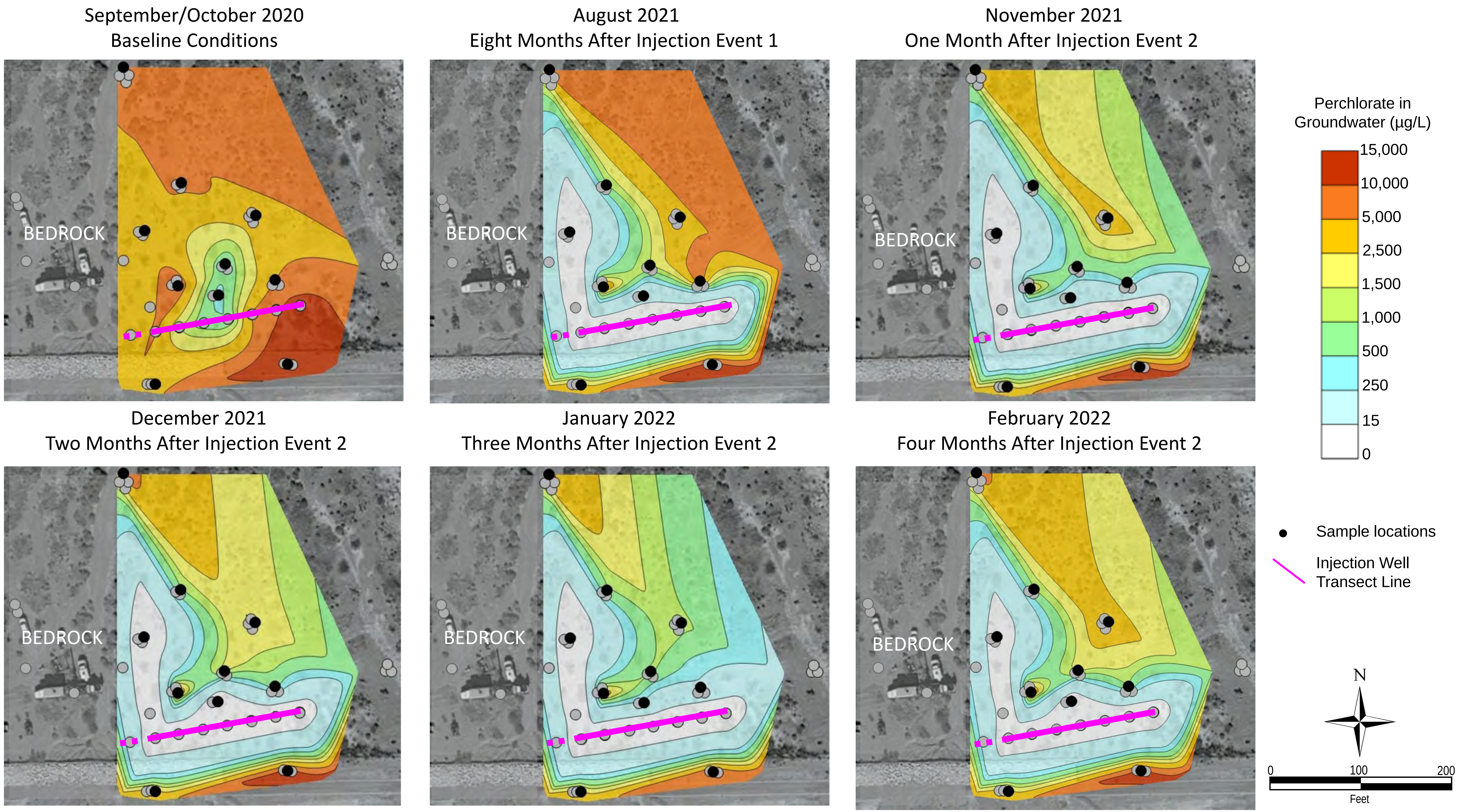
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 3 DEEP UMCF-CG

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	17A



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep UMCf-cg between approximately 110 and 150 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
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Project No.: 117-7502019-M19-01
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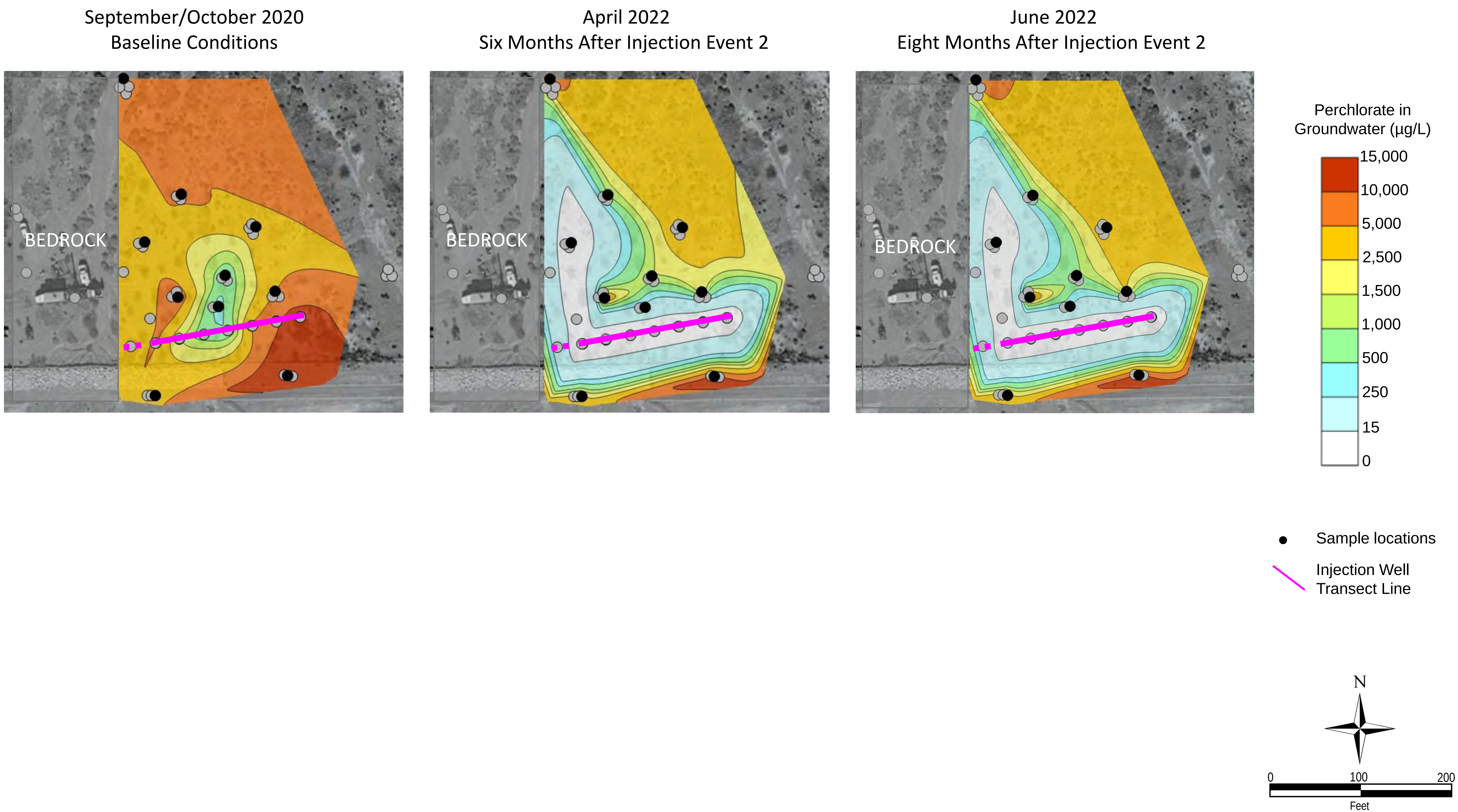
Figure No.
17B



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deep UMCf-cg between approximately 110 and 150 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
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Project No.:	117-7502019-M19-01
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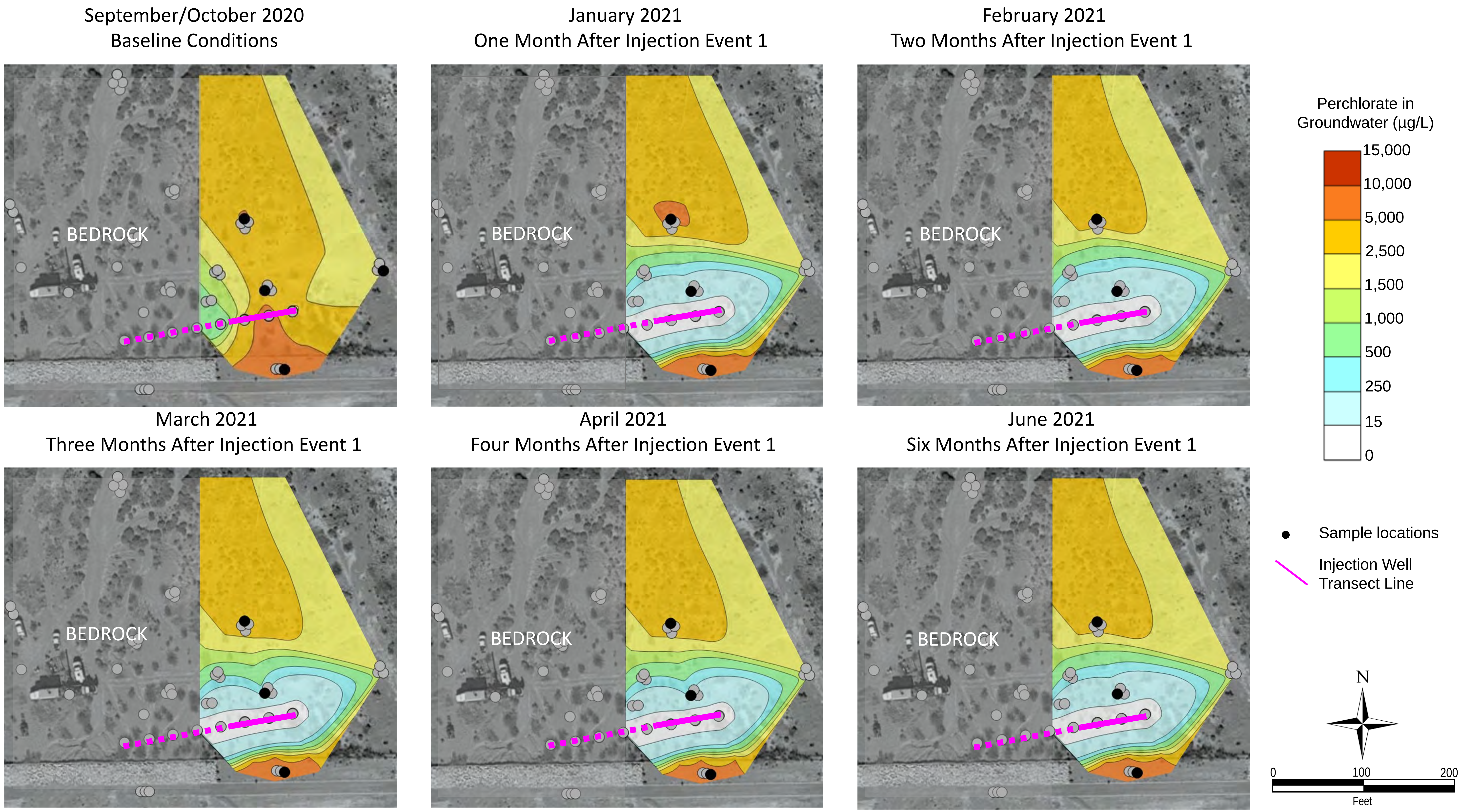
Figure No.	17C



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deepest UMCf-cg between approximately 150 and 175 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
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HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 3 DEEPEST UMCF-CG

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	18A

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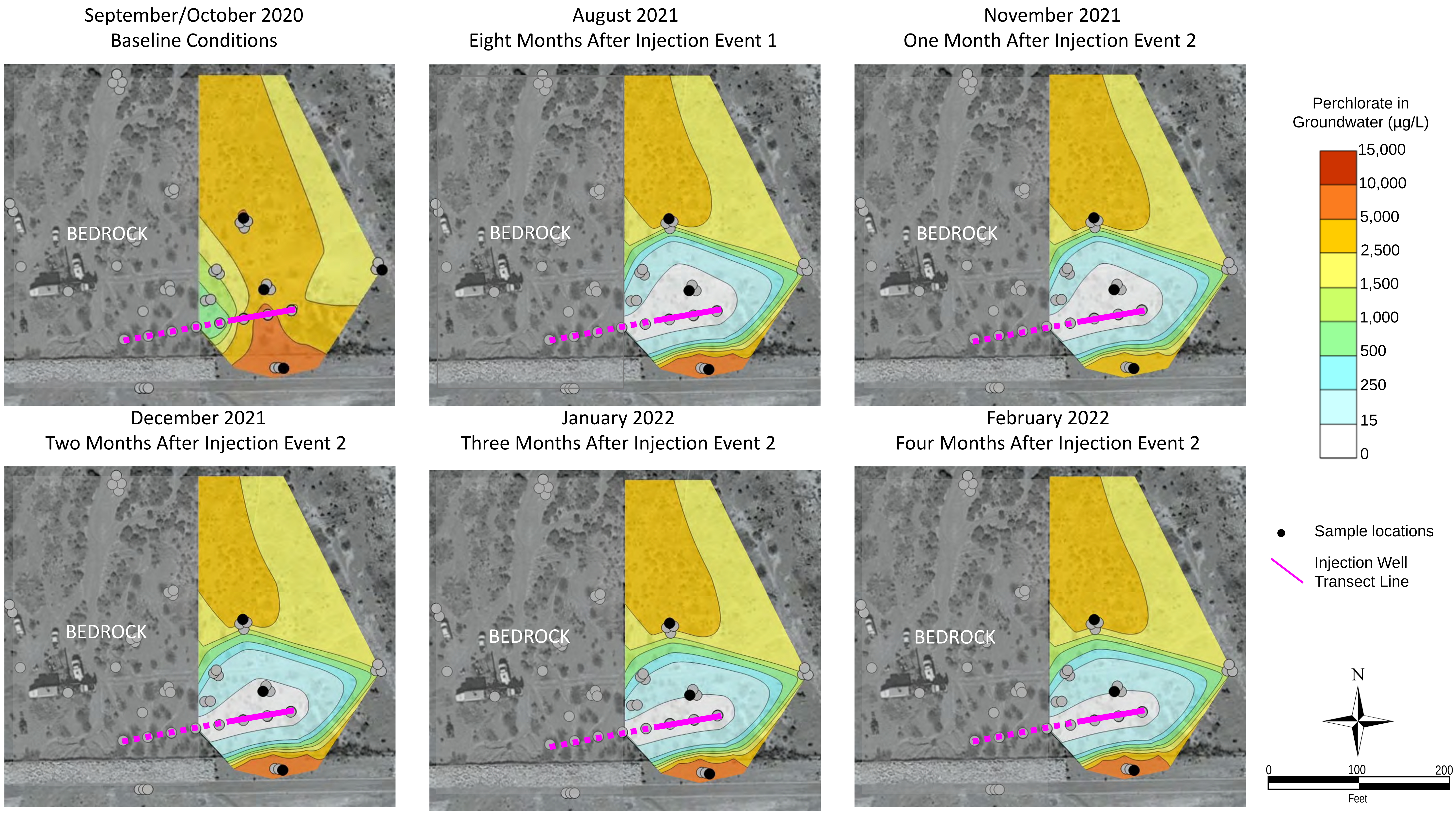

Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deepest UMCf-cg between approximately 150 and 175 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
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ZONE 3 DEEPEST UMCF-CG

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	18B

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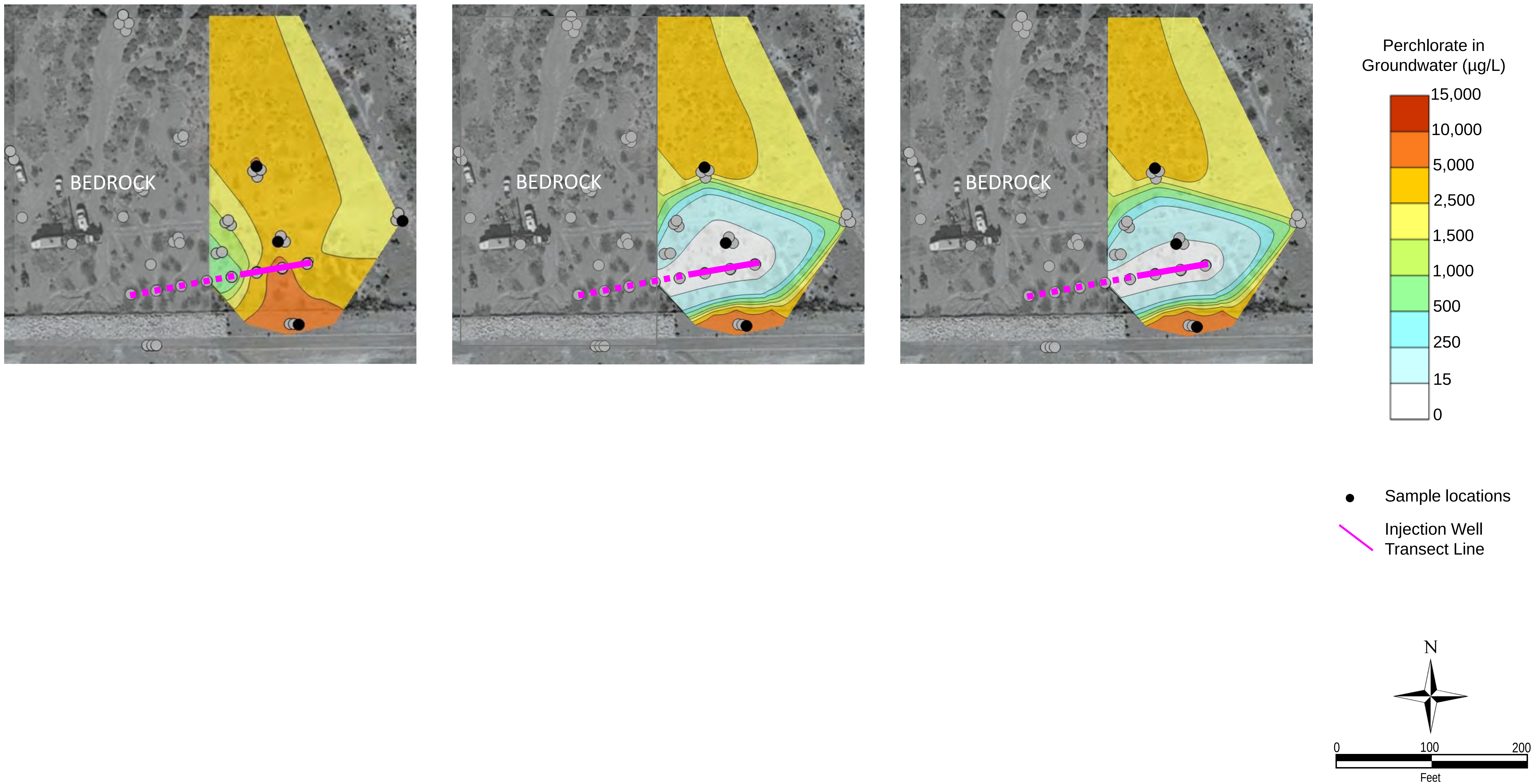
September/October 2020
Baseline Conditions

April 2022
Six Months After Injection Event 2

June 2022
Eight Months After Injection Event 2



Notes:

1. Each image represents an interpolated perchlorate concentration plume based on the concentrations in groundwater at monitoring wells screened in the deepest UMCf-cg between approximately 150 and 175 feet below ground surface. Monitoring and injection well names are provided on Figure 8.
2. Baseline concentrations presented from September/October 2020 are representative of pre-injection conditions. Injection events occurred in December 2020 and October 2021.Images presented in this figure represent groundwater sampling events that occurred following each injection event for the duration of the Pilot Study.

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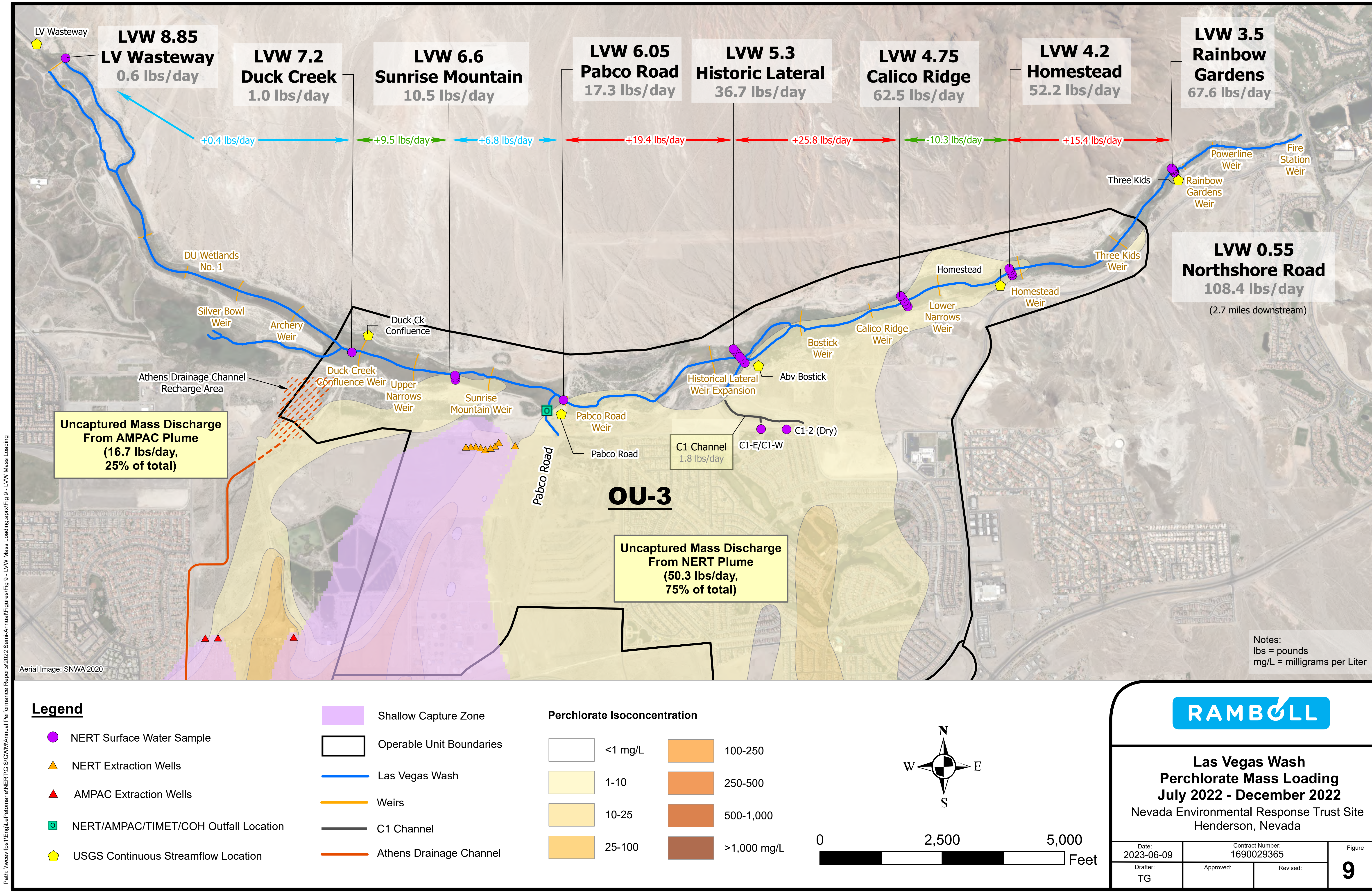
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE
LAS VEGAS WASH BIOREMEDIATION PILOT STUDY RESULTS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER
ZONE 3 DEEPEST UMCF-CG

Project No.:	117-7502019-M19-01
Date:	June 17, 2024
Designed By:	KRG
Figure No.	18C

\\tts134fs1\GEOSUPVOL1\PROJECTS\DATA\NERT\M11\ppt_Figs\2020\Annual Report EVS Figures 2020_v1.5.pptx

Attachment 1


LV Wasteway
LVW 8.85
LV Wasteway
0.6 lbs/day
LVW 7.2
Duck Creek
1.0 lbs/day
LVW 6.6
Sunrise Mountain
10.5 lbs/day
LVW 6.05
Pabco Road
17.3 lbs/day
LVW 5.3
Historic Lateral
36.7 lbs/day
LVW 4.75
Calico Ridge
62.5 lbs/day
LVW 4.2
Homestead
52.2 lbs/day
LVW 3.5
Rainbow
Gardens
67.6 lbs/day
+0.4 lbs/day
+9.5 lbs/day
+6.8 lbs/day
+19.4 lbs/day
+25.8 lbs/day
-10.3 lbs/day
+15.4 lbs/day
Powerline Weir
Fire Station Weir
Three Kids
Rainbow Gardens Weir
LVW 0.55
Northshore Road
108.4 lbs/day
(2.7 miles downstream)
Three Kids Weir
Homestead
Homestead Weir
Lower Narrows Weir
Calico Ridge Weir
Bostick Weir
Abv Bostick
Historical Lateral Weir Expansion
DU Wetlands No. 1
Silver Bowl Weir
Archery Weir
Duck Ck Confluence
Duck Creek Confluence Weir
Upper Narrows Weir
Sunrise Mountain Weir
Pabco Road Weir
Pabco Road
Athens Drainage Channel Recharge Area
C1-2 (Dry)
C1-E/C1-W
C1 Channel
1.8 lbs/day
Uncaptured Mass Discharge From AMPAC Plume (16.7 lbs/day, 25% of total)
Pabco Road
OU-3
Uncaptured Mass Discharge From NERT Plume (50.3 lbs/day, 75% of total)
Aerial Image: SNWA 2020
Notes:
lbs = pounds
mg/L = milligrams per Liter
Legend
NERT Surface Water Sample
NERT Extraction Wells
AMPAC Extraction Wells
NERT/AMPAC/TIMET/COH Outfall Location
USGS Continuous Streamflow Location
Shallow Capture Zone
Operable Unit Boundaries
Las Vegas Wash
Weirs
C1 Channel
Athens Drainage Channel
Perchlorate Isoconcentration
<1 mg/L
1-10
10-25
25-100
100-250
250-500
500-1,000
>1,000 mg/L
N
W
E
S
0
2,500
5,000
Feet
RAMBOLL
Las Vegas Wash
Perchlorate Mass Loading
July 2022 - December 2022
Nevada Environmental Response Trust Site
Henderson, Nevada
Date:
2023-06-09
Contract Number:
1690029365
Figure
9
Drafter:
TG
Approved:
Revised:
Path: \\wcevlfps1\Eng\LePetomane\NERT\GIS\GWM\Annual Performance Reports\2022 Semi-Annual\Figures\Fig 9 - LVW Mass Loading.aprx\Fig 9 - LVW Mass Loading