Seep Well Field Area Bioremediation Treatability Study

2019 Annual Progress Report

Nevada Environmental Response Trust Site
Henderson, Nevada

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LIST OF ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
AOI	area of interest
BWPC	Bureau of Water Pollution Control
DO	dissolved oxygen
DVSR	Data Validation Summary Report
EVO	emulsified vegetable oil
FS	Feasibility Study
gpm	gallons per minute
ISB	in-situ bioremediation
MBTs	Molecular biology tools
mg/kg	milligrams per kilogram
µg/L	micrograms per liter
mg/L	milligrams per liter
mV	millivolts
NDEP	Nevada Division of Environmental Protection
NERT or Trust	Nevada Environmental Response Trust
NMR	nuclear magnetic resonance
ORP	oxidation-reduction potential
PLFA	phospholipid fatty acids
PRG	Preliminary Remediation Goal
psi	pounds per square inch
QA/QC	quality assurance/quality control
SESI	SESI Consulting Engineers Company
Site	Nevada Environmental Response Trust site, Clark County, Nevada
SRB	sulfate-reducing bacteria
SWF	Seep Well Field
Tetra Tech	Tetra Tech, Inc.
TOC	total organic carbon
UIC	Underground Injection Control
UMCf	Upper Muddy Creek formation
UNLV	University of Nevada at Las Vegas

CERTIFICATION

Seep Well Field Area Bioremediation Treatability Study 2019 Annual Progress Report

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

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

Office of the Nevada Environmental Response Trust

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

Not Individually, but Solely
as President of the Trustee

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

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

Title: Solely as President and not individually

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

Date: 9/4/2020

CERTIFICATION

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

Description of Services Provided: Prepared Seep Well Field Area Bioremediation Treatability Study 2019 Annual Progress Report

September 4, 2020

Kyle Hansen, CEM
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Tetra Tech, Inc.

Date

Nevada CEM Certificate Number: 2167
Nevada CEM Expiration Date: September 18, 2022

1.0 INTRODUCTION

At the direction of the Nevada Environmental Response Trust (NERT or Trust), Tetra Tech, Inc. (Tetra Tech) has prepared this *Seep Well Field Area Bioremediation Treatability Study 2019 Annual Progress Report* for the NERT site (Site), located in Clark County, Nevada (Figure 1). This report is being submitted to the Nevada Division of Environmental Protection (NDEP) under the Interim Consent Agreement effective February 14, 2011. This Annual Progress Report, which covers the period of November 2018 through December 2019 (referred to herein as the reporting period), provides a summary of the activities performed, presents the data collected, and discusses the results associated with the on-going extension of the Seep Well Field (SWF) Area Bioremediation Treatability Study. This treatability study extension was implemented consistent with the NDEP-approved *Treatability/Pilot Study Modification No. 6 – Seep Well Field Area Bioremediation Treatability Study* (Modification No. 6) (Tetra Tech, 2018).

1.1 BACKGROUND

The SWF Area Bioremediation Treatability Study, which began in 2017, was implemented to evaluate and demonstrate the effectiveness of using in-situ bioremediation (ISB) to reduce the flux of perchlorate mass in groundwater that is migrating towards the Las Vegas Wash and not currently being captured by the existing extraction well network known as the SWF. As part of this treatability study, 25 injection wells were installed in a transect-orientation generally perpendicular to groundwater flow, with monitoring wells installed at varying distances upgradient, between, and downgradient of the injection wells (Figure 2). Following well installation, carbon substrate injections performed from 2017 – 2018 provided a sustained reducing environment in the subsurface and created a biologically active zone necessary for effective and continual perchlorate and chlorate biodegradation. Effectiveness monitoring results indicated that groundwater in this area is amenable to biodegradation of perchlorate, chlorate, and nitrate, including a reduction in perchlorate concentrations to less than the perchlorate Preliminary Remediation Goal (PRG) of 15 micrograms per liter (μg/L) in groundwater samples collected from several monitoring wells. Complete results of the treatability study through October 2018 were presented in the *Seep Well Field Area Bioremediation Treatability Study Results Report* (Results Report) (Tetra Tech, 2019a).

Because the SWF Area Bioremediation Treatability Study demonstrated that ISB can be effective at reducing perchlorate concentrations in groundwater and has already had multiple injection events performed within the area, it was recommended that this treatability study be continued to evaluate long-term operation and maintenance requirements. As part of the long-term operation and maintenance components of the ISB technology, the study extension will evaluate injection frequencies, injection well pressures and flow rates over time, and injection well maintenance requirements to sustain injectability into the subsurface. This information will be important in the remedy alternatives evaluation to be conducted as part of the forthcoming feasibility study (FS), as it is not only important to determine if the alternative can be technically and cost effective at achieving the remedial action objectives, but also equally important to evaluate and optimize key components of the alternative that will make it successful with regards to both implementation and long-term operation and maintenance and the costing thereof integral to the FS. This study extension was detailed in Modification No.6, which was approved by NDEP on December 14, 2018.

1.2 OBJECTIVES

The overall purpose of extending the SWF Area Bioremediation Treatability Study is to develop a more thorough understanding of the key design considerations and operation and maintenance components as they relate to potential long-term applications of ISB at the NERT site. Specifically, the objectives of the study extension are:

- Evaluate the injection frequency and required injectate quantities for long-term ISB operation, with injectate quantities of carbon substrate, nutrients, and distribution water assessed over time to provide optimal dosing that sustains the reducing conditions required for ISB of perchlorate and chlorate in groundwater.
- Develop a more in-depth understanding of long-term operation and maintenance requirements of injection well networks associated with ISB systems at the NERT site related to evaluation of:
    - Impacts of biological activity and biomass accumulation on the injectability of carbon substrate into the injection wells through evaluation of injection pressures and flows.
    - Injection well maintenance requirements, including maintenance frequency and optimal techniques, to maintain long-term injectability.
    - Costs associated with long-term operation and maintenance of ISB systems.

Data collected as part of this treatability study extension will be incorporated into the FS to provide information with respect to effectiveness, operational requirements, and associated costs to ensure the long-term viability of ISB should it be selected as part of the final remedy.

1.3 REPORT ORGANIZATION

This report is organized as follows:

- **Introduction (Section 1.0):** Provides a brief background of the study, the primary objectives of this treatability study extension, and organization of this report.
- **Routine Operations (Section 2.0):** Presents a summary of the injection activities implemented within the study area during this reporting period to maintain the ISB system for continued reduction of perchlorate- and chlorate-contaminated groundwater.
- **Periodic Maintenance (Section 3.0):** Summarizes the activities performed during this reporting period that are associated with injection well maintenance and evaluates the results of these maintenance activities.
- **Effectiveness Monitoring (Section 4.0):** Provides an overview of the effectiveness monitoring program and summarizes the chemical, geochemical, microbial, and hydrogeological data collected during this reporting period.
- **Summary of Key Findings and Future Activities (Section 5.0):** Presents the overall findings of data collected during this reporting period, a preliminary cost evaluation, and a summary of future activities planned for the on-going extension of the SWF Area Bioremediation Treatability Study.
- **References (Section 6.0):** Lists the documents referenced in this report.

2.0 ROUTINE OPERATIONS

The primary operational component associated with the SWF Area ISB system is injection of a carbon donor into the subsurface to maintain reducing conditions for remediation of perchlorate- and chlorate-contaminated groundwater. As a result, a total of five injection events have been performed since the SWF Area Bioremediation Treatability Study began in 2017; three of which were performed under the original treatability study scope of work and were summarized in the Results Report (Tetra Tech, 2019a). All injection events have been performed by Cascade Technical Services (Cascade) under Tetra Tech oversight and direction. This section provides a summary of the injection activities that were performed during this reporting period, noted as Injection Event 4 and Injection Event 5. The overall injection system and framework for the two injection events in 2019 followed the general protocols and procedures for the prior events in 2017 and 2018 unless otherwise noted.

2.1 INJECTION EVENT 4

The fourth injection event was performed from January 21 through February 10, 2019. Injections were performed using Cascade's custom-built injection platform that was equipped with variable high-speed multi-stage centrifugal pumps, injection/extraction hosing, meters, valves, and fittings coupled with two 16,400-gallon frac tanks, which was the same general process and equipment used during previous injection events at the SWF Treatability Study.

To briefly restate the overall basis for determining the carbon substrate and distribution water requirements, prior to the first injection event in 2017, several criteria were considered when determining the initial injection quantities. These included a review of stoichiometric requirements, results and findings from the University of Nevada at Las Vegas (UNLV) laboratory bench-scale studies including oil adsorption tests, results and findings from previous NERT treatability studies (both laboratory and field), literature case studies (emulsified vegetable oil [EVO] adsorption reports in particular), established industry protocol documents, prior experience of Tetra Tech designers, and discussions with EOS Remediation (the manufacturer of the selected EVO product). With this background information and criteria, an oil retention ratio was ultimately employed as the governing criterion for the selection of EVO quantities during the first injection event. As part of the injection design process, varying injection quantities were then used during the first three injection events to arrive at an optimal injection quantity. Based on the effectiveness monitoring results, it was determined that the quantities injected during the third injection event, which were approximately 85 percent of the carbon substrate that was injected during the first injection event, resulted in robust perchlorate and chlorate treatment and the sustainment of reducing conditions. Therefore, the quantities injected during the fourth injection event included a total of 16,752 gallons of EOS® PRO, 368 gallons of glycerin, 120 gallons of phosphate solution, and 300 pounds of sodium sulfite. Glycerin was added to the injectate solution to serve as an immediate source of organic carbon due to the relatively high groundwater flow velocities coupled with high nitrate and chlorate concentrations. 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 as an oxygen scavenger to remove dissolved oxygen chemically and prevent aerobic microbial growth in the formation to the extent possible.

In addition to the carbon source and amendments, water was required for both dilution of the injectate solution and subsequent injections of water to optimize the distribution of carbon substrate within the vicinity of the injection area. The water source selected for injections was extracted groundwater, which was the same water source as previous injection events. During this process, groundwater was extracted via submersible pumps placed in five upgradient monitoring wells (SWFTS-MW08A, SWFTS-MW11, SWFTS-MW12, SWFTS-MW13, and SWFTS-MW17) and transferred to the two 16,400-gallon frac tanks for use during injection operations. The carbon substrate solution was diluted at a ratio of 1:4 parts of EOS® PRO:water, which resulted in a total of approximately 67,008 gallons of dilution water being added to the injectate solution. Following injections of carbon substrate and amendments, approximately 275,725 gallons of extracted groundwater were injected as distribution water.

The injection process involved collecting extracted groundwater in the frac tanks until the targeted water quantity was achieved for each batch. The required quantities of EOS®, glycerin, phosphate solution, and sodium sulfite (based on the injectate solution recipe) were then added to the frac tank of extracted groundwater. The injectate solution was recirculated within the frac tank using a submersible pump to ensure mixture consistency prior to injections. Following preparation, the injectate solution was pumped from the frac tank to the injection wells via an injection manifold system that was connected to up to nine injection wells at a single time. Upon completion of substrate injections, distribution water was injected into the injection wells to optimize the distribution of carbon substrate within the vicinity of the injection area. During all injection operations, flow rate, pressure, and total quantities injected were measured at each injection well. As summarized in Appendix A, Tables A.1 through A.3, the quantities of the injectate solution and distribution water varied between injection wells based on the screen lengths and thickness of the targeted formation at each injection location. Following completion of the injections, the frac tanks were cleaned, and all equipment was dismantled and removed from the Site.

During the fourth injection event, measurements of flow rate and injection pressure at each injection well indicate that the average injection rate was approximately 7 gallons per minute (gpm) while sustained injection pressures generally averaged 24 pounds per square inch (psi). Two of the 25 injection wells (namely, SWFTS-IW13B and SWFTS-IW19) did not accept injectate additions at 35 psi, which is the maximum permissible pressure established in NERT's Underground Injection Control (UIC) injection permit. As a result, injection quantities targeted for those wells were distributed into nearby injection wells. It should be noted that injection pressures in injection well SWFTS-IW13B exhibited a gradual upward trend over the first three injection events (including pressures up to the maximum threshold of 35 psi), and therefore, it was expected that this injection well might require maintenance. However, increasing injection pressures were not previously observed at injection well SWFTS-IW19, where injection rates in the third injection event were observed to have consistent flows that exceeded 6 gpm at approximately 10 psi. Based on the observations during the fourth injection event, these two injection wells were identified or maintenance in the *Proposed Well Maintenance Activities Technical Memorandum* (referred to herein as Well Maintenance Technical Memorandum) (Tetra Tech, 2019b). Discussion of maintenance activities is presented in Section 3.4.

2.2 INJECTION EVENT 5

The fifth injection event was performed from September 30 through October 25, 2019. Injections were performed following the same protocol for the previous injection events and included the same general quantities described in Section 2.1. Specifically, the injectate solution for the fifth injection event included a total of 16,927 gallons of EOS® PRO, 385 gallons of glycerin, 120 gallons of phosphate solution, 300 pounds of sodium sulfite, and 67,650 gallons of extracted groundwater for dilution of the substrate. Following injections of carbon substrate and amendments, approximately 325,549 gallons of extracted groundwater was injected as distribution water. This was slightly more distribution water than used during the fourth injection event primarily because of the successful injection well maintenance performed prior to the fifth injection event (as discussed in Section 3.4), which facilitated the addition of distribution water in several wells (such as SWFTS-IW19) that previously did not require distribution water since injection was not possible.

Prior to the start of the fifth injection event, a short water injection test was performed to determine effectiveness of injection well maintenance activities conducted in September 2019 (results discussed in more detail in Section 3.4). The fifth carbon substrate injection event began following completion of the water injection test. As summarized in Appendix A, Tables A.4 through A.7, the quantities of the injectate solution and distribution water varied between injection wells based on the screen lengths and thickness of the targeted formation at each injection location. During all injection operations, flow rate, pressure, and total quantities injected were measured at each injection well. These measurements indicated that the average injection rate was approximately 8.1 gpm while the average sustained pressure was 22 psi. Only one of the 25 injection wells (namely, SWFTS-IW13B) did not accept injectate at the maximum permissible pressure of 35 psi despite injection well maintenance efforts performed prior to the fifth injection event (discussed in more detail in Section 3.4). As a result, targeted injection quantities for this injection well were distributed into nearby injection wells. It should be noted that injection well SWFTS-IW19, which was unable to receive injectate during the fourth injection event, was successfully restored during injection well maintenance activities performed (as described in Section 3.4), and therefore, received the targeted injection quantity.

In addition to recording injection rates and quantities, the specific gravity of the injectate solution was also periodically measured during the injections to confirm that the solution was being injected as a consistent mixture throughout the injection process. Specific gravity measurements have also been provided in Appendix A, Tables A.8 and A.9.

Lastly, it should be noted that the cumulative daily injection quantities during the first part of the injection event, which focused on the carbon substrate injections, were lower than previous injection events. This resulted from field modifications and equipment adjustments required during the injection event. The effects of the lower daily injection volumes on substrate distribution and hydraulic response will be evaluated throughout subsequent monitoring events that are scheduled to occur in 2020.

2.3 EVALUATION OF INJECTION FREQUENCY

As previously described in Section 1.2, one of the objectives of the treatability study extension is to evaluate the injection frequency and required injectate quantities for long-term ISB operation to provide optimal dosing that sustains the reducing conditions required for ISB of perchlorate and chlorate in groundwater, as well as to evaluate requirements for long term O&M resources and costs for this technology application. Injection protocol requirements are an important design consideration for the creation and maintenance of adequate anaerobic conditions for sustained perchlorate bioremediation. Generally, injection frequency and carbon substrate requirements for ISB systems can vary over the operational time frame, particularly with passive systems that involve the periodic injection of slow-release carbon substrates, such as EVO, which tend to adsorb and persist in the saturated subsurface over time. Therefore, the injection frequency and required carbon substrate quantities are key long-term operation and maintenance components that determine both remedy effectiveness and associated cost to maintain the remedial system.

To date, a total of five injection events have been performed since 2017. ***Table 1*** presents an overview of the injection events over time since the treatability study began.

Table 1 Injection Frequency Over Time

Injection Events	Months Between Injection Events
Event 1 to 2	4
Event 2 to 3	4
Event 3 to 4	7
Event 4 to 5	8

As observed in ***Table 1***, the injection frequency has decreased over time (i.e., more months in between injection events) while still sustaining a biologically active zone that is degrading substantial perchlorate and chlorate in groundwater based on the effectiveness monitoring results described in Section 4.0. This is an indication that the span between injection events could be extended considerably over time, provided other conditions such as hydraulic conditions and contaminant flux from upgradient locations remain fairly consistent. Decreasing the injection frequency over time while maintaining remedial effectiveness has also resulted in a reduction in sampling frequency and associated analytes. Over the period of this study extension, the injection frequency, potential adjustments to injection quantities, and groundwater sampling frequency and parameters will continue to be evaluated as part of ISB system optimization.

3.0 PERIODIC MAINTENANCE

While ISB implemented through periodic injections of a slow-release substrate is generally considered a passive remedy, there are intermittent active processes involved with implementation over time, and therefore some degree of injection well maintenance will be necessary should ISB be selected as part of the final remedy(USEPA, 2013). Due to periodic injections of the slow-release carbon substrate and amendments, both perchlorate-degrading biomass and solids precipitation are expected to develop, which may result in some biomass or chemical precipitate accumulations within the injection wells and surrounding filter pack resulting in localized permeability reductions. As a result, injection wells that periodically encounter permeability reduction due to buildup of biomass and/or inorganic precipitates (as indicated by injection pressure fluctuations) commonly need occasional physical and/or chemical well maintenance. Project stakeholders have raised concerns over potential reduction in injection well efficiency and aquifer permeability in the vicinity of the injection wells due to biomass and chemical precipitate accumulation. As a result, this study extension will evaluate these concerns and associated maintenance requirements to maintain long-term injectability.

This section presents an overview of biomass and inorganic precipitates that are typically observed in injection wells associated with ISB systems. This section also includes a summary and results of the injection well maintenance activities performed in 2019, which included video logging, analysis of the water and accumulated material from the injection wells, and injection well maintenance and associated aquifer testing. The 2019 injection well maintenance activities were performed in accordance Well Maintenance Memorandum.

3.1 OVERVIEW OF BIOMASS AND PRECIPITATES

Because injection wells are subject to periodic injection of EVO, nutrients, and distribution water, there are occasional accumulations of biomass and inorganic precipitates within the injection well screens and surrounding filter pack. Based on more than two decades of field ISB applications at various sites across the country, the accumulation of biomass and precipitates, particularly with passive systems, is generally observed to occur around the immediate vicinity of injection wells rather than in the broader surrounding aquifer formation. If accumulation of biomass and precipitates results in decreased injection well efficiency, conventional, established well maintenance techniques can be performed to maintain injectability if required. This section includes an overview of the typical biomass and precipitates encountered to provide a better understanding of their source, respective compositions, and the routine maintenance options that can be implemented to minimize impact to ISB operations and effectiveness, while simultaneously optimizing O&M costs.

For ISB to be successful, the growth and reproduction of microorganisms is an essential function to biodegrade perchlorate and other contaminants in the subsurface. The term biomass is used to represent native microorganisms and their colonies that grow and reproduce in response to the addition of a carbon substrate in ISB systems. Microorganisms may either be suspended in the groundwater or attached to the soil within the saturated soil matrix. In addition to microorganisms, biomass also includes external structural components such as exopolymers and polysaccharides. Some key things to note about biomass and the ISB approach that is employed for the SWF Area Bioremediation Treatability Study are provided below.

- Generally, anaerobic systems, such as the one being implemented for the SWF Area Bioremediation Treatability Study, have very low microbial cell yield and less overall cell mass compared to aerobic systems.
- A distinct advantage of the selected substrate, EVO, is that it hydrolyzes and ferments very gradually to provide useable carbon products for native microorganisms over a prolonged period, unlike quick release substrates, which do the opposite and require continual or much more frequent addition. Therefore, EVO results in less rapid biomass development.
- The addition of large quantities of distribution water moves the substrate away from the injection well screen and associated filter pack where biomass buildup could be more problematic.

- Biomass itself is eventually a source of carbon when cells lyse and tend to endogenously self-cannibalize over time, particularly when the added carbon substrate gets consumed.
- Finally, biomass is relatively easy to scour, scrape, and remove from the injection wells via common well maintenance techniques that can be periodically implemented such as well screen brushing, surging and bailing, hydrojetting, and/or the addition of mild acids (if required).

In addition to biomass growth, inorganic precipitates also can sometimes form within the injection well casings and surrounding filter pack during ISB operations. Precipitate formation results from natural groundwater cationic constituents, such as calcium, magnesium, and iron, that combine with carbonates that form as a result of biological activity and from an increase in alkalinity. It should be noted that this aquifer has relatively low iron compared to many other aquifers, an advantageous condition in that it avoids typical scaling and iron fouling issues. However, there are relatively high concentrations of calcium in groundwater (as high as 820 milligrams per liter [mg/L] within the treatability study area), which could result in the formation of calcium carbonate or calcium oleate precipitates. Some formation of calcium oleate may develop because oleate is a significant constituent of EVO. When these precipitates form in the vicinity of the injection well screens and surrounding filter pack, they can typically be removed by common well maintenance techniques (such as surging and bailing, brushing, and/or the addition of acidic agents to solubilize the chemical precipitates), particularly if they are softer and more malleable in nature and can be smeared easily with finger pressure as observed at this treatability study area.

3.2 INJECTION WELL VIDEO LOGGING

Prior to conducting injection well maintenance, video logging was performed on all injection wells to visually inspect for the presence of biomass and/or precipitates in the injection wells. Video logging of all injection wells was performed in July 2019 by Pacific Surveys (a subcontractor to Cascade Drilling) as directed by Tetra Tech to supplement the injection well evaluation process. Two cameras were utilized during the survey, each with different diameters. The higher resolution camera was approximately 1.75 inches in diameter and therefore, due to the size, provided minimal clearance when lowered into the 2-inch injection wells. Any slight deviation from vertical in the injection well casing would render the camera unable to pass and result in termination of the video log prior to reaching the desired depth. Therefore, a second lower resolution camera that was approximately 1-inch in diameter was used when necessary. A summary of the video log results and images from select injection wells are provided in Table B.1 and Figures B.1 – B.2 in Appendix B.

The video logs indicated that the upper portion of the water columns were generally clearer than the water deeper in the well screen. As expected, the degree of cloudiness or turbidity generally increased with depth in the injection well screens, indicating some settling of material within the well casing. Video logging also provided visual evidence of biomass (brown or other dark-colored) and/or chemical precipitates (white to buff) along some of the injection well casings and well screens. An important note is that in many cases, observation of biomass and chemical precipitates was not associated with reduced injectability. As an example, SWFTS-IW05 achieved injection rates of 17.8 gpm during the fourth injection event, despite the presence of biomass on the injection well casing and screen.

The video logging results indicated that only five of the 25 injection wells had accumulated material (noted as camera resting on soft material at the base of the injection well) that could be partially obstructing up 50 percent or more of the well screen (namely, SWFTS-IW08, SWFTS-IW12, SWFTS-IW13B, SWFTS-IW16A, and SWFTS-IW18). The light weight of the camera prevented it from passing through the soft material, but field observations indicated that a weighted bailer or surge block would likely have been able to pass through this material. A review of data collected during the fourth injection event at these five injection wells indicated that the highest injection rates to-date were observed in SWFTS-IW08, SWFTS-IW12, and SWFTS-IW16A, with average injection rates ranging from 8.5 to 11.1 gpm. Therefore, although soft material was present (likely dead biomass that is generally powdery and eventually consumes itself), it did not appear to inhibit injections during the fourth injection event. As a result, injection wells SWFTS-IW08, SWFTS-IW12, and SWFTS-IW16A were not selected for well maintenance testing. Injection well SWFTS-IW13B was selected for maintenance because it did not accept injections at the maximum allowable pressure; well SWFTS-IW18 was also selected for maintenance because of its observed increased injection pressure to injection rate ratio. The well maintenance program is discussed in greater detail in Section 3.4.

3.3 ANALYSIS OF INJECTION WELL WATER AND ACCUMULATED SOLIDS

As explained in Section 3.1, based on the nature of carbon injections, it is expected that some solids precipitation with slight accumulations will occur over time within some of the injection wells. These solids include biomass (active and dead cell mass and related microbial structural material), inorganic precipitates (such as calcium, magnesium, and iron carbonates), oleate (a major component of EVO), intermediate by-products of EVO hydrolysis, colloids, and fines. An evaluation of water and accumulated solids from the injection wells was performed, with samples collected and analyzed to determine the composition of the material in the injection wells as it relates to the carbon substrate injections, biomass growth, and interactions with the geochemical elements and minerals in the aquifer.

Prior to performing well maintenance activities, approximately two gallons of groundwater and accumulated solids were collected in September 2019 from injection wells SWFTS-IW02A, SWFTS-IW06A, SWFTS-IW13B, and SWFTS-IW19. These four injection wells were selected based on observations from the video logging and increases in the injection pressure to injection rate ratios observed during injection event 4, with the last two injections wells not accepting any injectate during the fourth injection event at the maximum permissible injection pressure of 35 psi. Samples were shipped to SESI Consulting Engineers Company (SESI) in Pine Brook, New Jersey, for specialized physical, chemical, and biological analyses, which are summarized in ***Table 2***.

Table 2 Summary Parameters Analyzed by SESI

Parameter	Purpose
Moisture content, volatile solids and ash	The appearance of oil droplets can indicate the presence of EVO. This also provides an indication of the level of solids content and relative of fraction of inorganic and organic solids.
Organic, inorganic, and total carbon	Inorganic carbon is an indicator of carbonate precipitates, while organic carbon can be an indicator of biomass and EVO.
Alkalinity	Alkalinity is an indicator of carbonate precipitates.
Major anions and cations in ash	Analytes used to characterize the major ion chemistry. For example, high levels of calcium, manganese, and iron can indicate carbonate or organic related precipitation.
Total Kjeldahl Nitrogen	These levels can be used to estimate total protein and microbial biomass.
Carbohydrate, fat, and protein	Results from these standard analyses for food products can be used to distinguish between biomass (carbohydrate and protein) and fat (EVO).

During sample collection, the material from the injection wells was observed to be largely in liquid form. SESI estimated that the percentage of total solids in the samples was less than 0.5 percent in all injection wells except for SWFTS-IW19, which had approximately 2.6 percent solids. Because this testing program was designed to focus on solids materials within the injection wells, the analytic results have limitations due to the limited solids content. Therefore, it was not possible to directly measure carbohydrates, proteins, fats, alkalinity, organic and inorganic carbon, and total Kjeldahl nitrogen on solids due to low sample yields; however, select analyses were run on the liquid phase. There were enough solids in the samples to analyze for volatile solids, ash, and major anions and cations. The low percentage of solids may infer a very strong indication that any accumulation of material within the injection well and surrounding filter pack is likely temporary and reversible, and that common well maintenance techniques are very likely to improve injectability.

Given the limitations of testing and the limited testing, only tentative deductions and broad conclusions can be reached as summarized below. The complete results of the analyses performed by SESI appear in Appendix C.

- Samples collected from injection wells SWFTS-IW02A and SWFTS-IW06A had a percentage of volatile solids between 33 and 37 percent, which indicated that the material in these wells are likely more inorganic in nature. Major cations and anions analysis indicates that this is primarily calcium in the form of carbonates. However, the results of inorganic analyses and organic carbon varied in these two wells. Specifically, results of the inorganic analyses indicated that the sample from SWFTS-IW06A had approximately 606 mg/L of inorganic carbon, which is considerably more than the inorganic carbon content from SWFTS-IW02A (less than 50 mg/L). The sample from SWFTS-IW06A also had the lowest organic carbon at 600 mg/L (compared to approximately 2,000 mg/L in SWFTS-IW02A). Therefore, taking these results into consideration, it appears that the material from injection well SWFTS-IW06A could have more inorganic material (such as calcium carbonate) than organic material (such as biomass), whereas SWFTS-IW02A likely has more organic content. In general, injections wells with limited inorganic material should be quite amenable to well maintenance using chemical treatment, though physical techniques could also be efficient due to the limited solids content. It may also be noted that the only injection well with a measurable fat content was SWFTS-IW02A, which had 5,300 mg/L of fat and is likely indicative of organic content from the injectate.
- Samples from the other two injection wells, SWFTS-IW13B and SWFTS-IW19, had a much higher percentage of volatile solids at approximately 94 percent in both samples. The analyses of major cations and anions indicated that over 80 percent of the metals in the samples from the SWFTS-IW19 was comprised of calcium, suggesting that the compound of predominance in this well could be those related to calcium. Based on this result, it is likely that this well could contain organic compounds such as calcium oleate (oleate is a major component of emulsified vegetable oil) as well as biomass due to the high volatile content of the solids from these wells. However, in addition to biomass and calcium oleate, the high sulfate concentrations in material from these two injection wells (470 mg/L and 702 mg/L for SWFTS-IW13B and SWFTS-IW19, respectively) also suggest that calcium sulfate or gypsum is present in this vicinity. The limited analyses of biochemical compounds such as fats, proteins, and carbohydrates, which are generally an indication of biomass, showed that the only injection wells that had significant carbohydrates were SWFTS-IW13B and SWFTS-IW19, though these were estimated to be present at low concentrations of 3,500 mg/L and 2,000 mg/L, respectively. Therefore, based on the available data, samples from these two injection wells appear to contain biomass, materials related to EVO such as oleate in the form of calcium oleate, as well as inorganic material in the form of calcium precipitates.
- When comparing these results to the injection pressure and flow rate ratios, injection wells with more abundant inorganic precipitates had higher pressure to flow rate ratios during injections (namely, SWFTS-IW-13B and SWFTS-IW19). However, in general, a correlation is not observed between higher total volumes of carbon substrate solution injected during the first five injection events with the presence of more inorganic precipitates.

Based on this information, it is likely that common injection well maintenance efforts could easily remove this material and likely ensure long-term viability of the injection well network. Removal effectiveness will continue to be evaluated during future maintenance events. No additional sampling of injection well solids is planned at this time.

3.4 INJECTION WELL MAINTENANCE

ISB systems that continue to operate over extended periods of time generally require periodic maintenance, which is typically required of all remediation systems (both in-situ and ex-situ). During the first 24 months of operations associated with the SWF Area Bioremediation Treatability Study, maintenance was not required for the injection wells. This was likely due to the judicious employment of a slow-release substrate, which releases carbon very gradually thereby preventing rapid biomass overgrowth, and the use of copious quantities of distribution water that flush the carbon substrate into the formation. However, during this reporting period (November 2018 through December 2019), an increase in injection pressures and subsequent decrease in injection rates were observed at select injection wells, including wells SWFTS-IW13B and SWFTS-IW19 that did not accept injectate during the fourth injection event at the maximum permissible injection pressure allowed by the Underground Injection Control permit. As a result, several field activities were performed to develop a more in-depth understanding of long-term maintenance requirements of injection well networks associated with ISB systems at the NERT site. This section provides an overview of the injection well selection process, the well maintenance activities that were performed in 2019, and the pre- and post-maintenance aquifer testing and injection data that were used to determine the effectiveness of the injection well maintenance. These well maintenance activities were performed in accordance the Well Maintenance Technical Memorandum.

3.4.1 Injection Well Selection

As described in the Well Maintenance Technical Memorandum, nine injection wells were selected based on the video logging survey and injection rates and pressures observed during the fourth injection event, as well as trends observed from all injection events to date. The selected injection wells generally had an injection pressure of around 25 – 35 psi accompanied by decreasing injection rates compared to previous injection events. The selected injection wells, screen lengths, and their respective injection pressure to injection rate ratios during the fourth injection event are summarized below in ***Table 3***. More detailed data are provided in Table A.10 of Appendix A.

Table 3 Injection Wells Selected for Well Maintenance

Well ID	Screen Length (ft)	Ratio (Injection Pressure to Injection Rate)
SWFTS-IW02A	10	5.8
SWFTS-IW06A	10	5.4
SWFTS-IW06B	5	10.8
SWFTS-IW09	20	7.4
SWFTS-IW10	20	7.8
SWFTS-IW11	20	5.6
SWFTS-IW13B	10	-----(1)
SWFTS-IW18	20	7.5
SWFTS-IW19	20	-----(1)

Notes:
ft – feet
(1) Injections were not performed during fourth event due to the inability to achieve flow at the maximum allowed injection pressure.

3.4.2 Injection Well Maintenance Activities

The first well maintenance effort was conducted on September 20 – 26, 2019, prior to the fifth carbon substrate solution injection event. The following three well maintenance techniques were selected as part of this first evaluation:

- Surge and bail
- Hydrojetting – use of high-pressure water with either fixed or rotating nozzles to remove any incrustation from well screens
- Combination of both surge and bail, and hydrojetting with the addition of chemicals.

To provide a good comparison of techniques and resulting outcome (i.e., improved injectability), three injection wells were selected for each well maintenance procedure. ***Table 4*** summarizes the injection wells and the respective selected maintenance method. Sections 3.4.2.1 through 3.4.2.3 provide additional details on the maintenance processes.

Table 4 Injection Well Maintenance Methods

Well ID	Ratio (Injection Pressure to Injection Rate)	Proposed Method
SWFTS-IW02A	5.80	Surge and Bail
SWFTS-IW06B	10.75	
SWFTS-IW09	7.37	
SWFTS-IW10	7.83	Hydrojetting
SWFTS-IW11	5.59	
SWFTS-IW19	-----[1]	
SWFTS-IW06A	5.43	Combination of surge and bail, and hydrojetting with chemicals
SWFTS-IW13B	-----[1]	
SWFTS-IW18	7.49	

Notes:
[1] Injections were not performed during fourth event due to the inability to achieve flow at the maximum allowed injection pressure.

3.4.2.1 Surge and Bail

This process started with a bailing phase to gently disturb the sand pack and begin to remove sediment, biomass, and/or precipitates that had settled in the injection well. After the injection well was cleared of solids to the total depth, a surge block was used to move biomass and/or precipitates from the filter pack into the well casing. The surge block was moved up and down the injection well screen interval and then removed, followed by a return to bailing to remove any solids brought into the well by the surging action. A brush was then used to further help dislodge any biomass and/or precipitates that may have remained on the injection well casing and screen. Bailing continued until the solids content in the water removed began to decrease. This surge and bail process was followed by purging the well using a submersible pump until the water was relatively clear. Several gallons of hydrant water were periodically added to the injection well to aid in solids removal, if required. Pumping continued until the volume of any added water and three-to-ten casing volumes of water had been removed from the injection well.

3.4.2.2 Hydrojetting

Prior to beginning the hydrojetting process, the well casing and screens were cleared via the surge and bail process previously described in Section 3.4.2.1. This initial process removed the bulk of the solids that had accumulated in the bottom of the injection well screen, and allowed access for the jetting tool to be applied to the entire well screen. After completion of the initial surge, brush, and bail steps, the hydrojetting process began, which consisted of injecting water via a specialized high-pressure jetting tool. The jetting tool was connected to a 350-gallon tote of hydrant water, and a pump was installed in the well vault of the injection well. This pump removed water from the well vault and discharged it to a 55-gallon drum during the hydrojetting process to ensure no jetting water or suspended solids overflowed from the well vault. During the jetting process, the high-pressure water was jetted outward at high velocity through the injection well screen and into the surrounding filter pack. The jetting tool was moved throughout the screened interval at a pace of 1 foot per minute to ensure treatment of the entire injection well screen. The total volume injected during the jetting process and total volume pumped from the well vault were recorded. Upon completion of jetting operations, the jetting tool was removed and the submersible pump was lowered into the injection well to continue pumping until, at a minimum, the volume of water removed was equal to the volume injected plus three-to-ten casing volumes of water.

3.4.2.3 Combination of Surge and Bail, Hydrojetting, and Chemical Addition

The combination of surge and bail, hydrojetting, and chemical addition used the step-by-step process of surge and bail redevelopment and hydrojetting (as described in Sections 3.4.2.1 and 3.4.2.2), followed by the addition of the chemicals. Acidic agents AQUA-CLEAR® MGA (dry blend of granular sulfamic acid and sodium chloride) and AQUA-CLEAR® AE (liquid blend of hydroxyacetic acid) were selected to support chemical well maintenance. The use of these products was requested as part of Modification 4 to the Long-Term UIC Permit GU07RL-51057, which was approved by the Bureau of Water Pollution Control (BWPC) on August 23, 2019. The volume of chemicals added to each injection well was calculated based on manufacturer guidelines and varied based on the screen length and volume of water within the well at the time of chemical addition.

For each injection well selected for the combination of well maintenance techniques, the injection well was initially surged, bailed, and hydrojetted as previously described in Sections 3.4.2.1 and 3.4.2.2. Following these activities, chemicals were added to the injection well via tremie pipe and then a surge block was used to move the chemically amended water into the filter pack. The chemical treatment was then allowed to sit overnight to allow the chemical(s) to act as a biocide and descaling agent. The pH of the groundwater within the injection well was monitored before and after the chemical addition by collecting pH measurements prior to the addition of the chemicals and at periodic intervals after the addition of the chemicals. Each injection well was then redeveloped using traditional surge, bail, and pump techniques. During this process, each injection well was surged and bailed to remove as much of the amended water and material from the injection well as feasible. This was followed by purging the injection well using a submersible pump until the water was relatively clear and pH returned to neutral, pre-maintenance levels. The volume of water added to each injection well during the well redevelopment process was recorded, and pumping continued until the volume of any added water and three-to-ten casing volumes of water had been removed from the well.

3.4.3 Pre- and Post-Maintenance Aquifer Testing and Data Collection

Specific capacity and injection testing were performed on injection wells as part of this effort to collect data to aid in the evaluation of injection well maintenance effectiveness. Pre- and post-maintenance specific capacity testing (short duration and low-rate) was performed during September 17 – 22, 2019, and during September 24 – 30, 2019, respectively. Prior to beginning the test, transducers were installed in each injection well to measure drawdown during testing and recovery. The specific capacity test then began by extracting groundwater at the lowest rate the pump could support, which was generally 0.25 gpm. The flow rate was then incrementally increased, provided that the injection well could support such pumping. Flow rates, drawdown, and water level recovery data were monitored throughout the test. During pre-maintenance testing, it was common for pumps to become clogged or for wells to go dry due to material present in the well. When either occurred, the test was terminated, and water levels were monitored during recovery. Complete details on field procedures are provided in Appendix D.

In addition, a short-term water injection test was performed on October 1 - 2, 2019, prior to the fifth carbon substrate injection event. This injection test included the injection of extracted groundwater water into each of the nine injection wells that received maintenance. During this water injection event, both injection pressures and rates were monitored and recorded.

3.4.4 Evaluation of Injection Well Maintenance Results

This section summarizes field observations of suspended solids during injection well maintenance activities, presents the results from the pre- and post-maintenance specific capacity testing, and evaluates the effectiveness of the injection well maintenance activities and improved injectability over time.

3.4.4.1 Visual Inspection of Suspended Solids During Well Development

During the initial surge/brush/bail activities conducted at each injection well, groundwater was typically light to dark grey and with an organic odor. Solids removed from the injection wells during maintenance included black organic fines and colloidal materials and/or white to yellowish-white inorganic precipitates. The black organic fines consisted of both active and dead biomass and fine-grained sand representative of the surrounding formation. In general, the inorganic precipitates were soft to firm with a malleable, soapy texture, and smeared easily with finger pressure, indicating the presence of calcium oleate (a breakdown product of EVO). At select injection wells, including SWFTS-IW13B, the inorganic precipitates were more brittle and reacted with HCl. As the bulk of the accumulated solids were cleared from the injection well casing and screens during maintenance activities, the groundwater removed commonly became relatively clear to light grey with only trace black organic fines and colloidal material.

3.4.4.2 Pre- and Post-Maintenance Aquifer Testing Results

As explained in Section 3.4.3, during specific capacity testing, the injection well was initially subjected to the lowest rate that the pump could support, typically 0.25 gpm. During pre-maintenance testing, even these low rates often resulted in excessive drawdown, a reduced number of steps completed, and relatively short pumping times for the step(s) completed. Since drawdown in the wells did not stabilize during the steps, typical methods of step and pumping test analysis could not be applied. Instead, specific capacity was calculated using drawdown at a selected time after the start of pumping to enable comparison between pre- and post-maintenance test results. Specific capacity, as a measure of well efficiency calculated by dividing the pumping rate by drawdown in the well, would be expected to increase after well maintenance. The post-maintenance specific capacity was greater than the pre-maintenance specific capacity for all injection wells tested. Post-maintenance, the injection wells were able to sustain higher pumping rates for longer times without inducing drawdown to the pump intake. These results indicate that well maintenance was successful in improving the efficiency of the wells. Complete results are provided in Appendix D.

While specific capacity can be a useful measure of potential well injectability, the best test of injectability is to actually perform injection testing. The next section compares injection rates and pressures before and after well maintenance to illustrate the effects of well maintenance on injectability.

3.4.4.3 Evaluation of Post-Maintenance Injectability

Following completion of the well maintenance field activities, injection pressures and flow rates were monitored and recorded during both a short-term water injection test and injection event 5, with results compared to previous injection events to evaluate increased injectability (in terms of reduced injection pressures and/or increased injection rates). Figure 3 presents a graphical depiction of the average sustained pressure to injection rate for each of the nine injection wells that received well maintenance.

As observed in Figure 3, eight of the nine injection wells selected for well maintenance demonstrated improved injectability. Injection well SWFTS-IW19, which did not accept injectate during the fourth injection event, substantially improved and exhibited an average injection rate of 10 gpm during injection event 5. The only injection well that did not demonstrate improved injectability was SWFTS-IW13B, which did not accept injectate during the fourth and fifth injection events. When comparing SWFTS-IW13B and SWFTS-IW19, a key difference between these two injection wells is length of the injection well screen. Specifically, injection well SWFTS-IW13B has a screen length of 10 feet compared to SWFTS-IW19, which has a screen length of 20 feet. Because

SWFTS-IW19 has a longer screened interval, it is open to a larger portion of the aquifer and would be therefore be expected to accept higher injection rates. During well maintenance activities at SWFTS-IW19, it was also observed that once the upper portion of the well screen was cleaned of the calcium precipitates, the injection well became increasingly easier to clean with depth, likely due to the presence of more biomass at depth than calcium precipitates. In contrast, the material in the well screen at SWFTS-IW13B appeared to be comprised primarily of calcium precipitates. It should be noted that although SWFTS-IW13B did not accept injectate during injection event 5 following well maintenance, the post-maintenance specific capacity testing results did show a slight improvement when compared to the pre-maintenance results. Therefore, this injection well is expected to be amenable to injection well maintenance using slightly more aggressive cleaning and chemical addition processes[1].

Although all three techniques were effective at improving injectability, hydrojetting and hydrojetting with chemical addition appear to be slightly more effective that traditional surge and bail. Continued observations of sustained injection pressures and injection rates will be key in determining the most appropriate technique(s) for achieving more long-term improvement.

[1] Subsequent to this reporting period, injection well maintenance was performed in February 2020 on injection well SWFTS-IW13B using the combination of surge and bail, hydrojetting, and chemical addition. This injection well was successfully restored, with post-maintenance water injection testing indicating an injection rate of up to 9 gpm. The results of this maintenance event will be reported in the 2020 Annual Progress Report.

4.0 EFFECTIVENESS MONITORING

Effectiveness monitoring was performed throughout the reporting period to monitor both groundwater contaminant and geochemical changes following the injection events to evaluate continued ISB effectiveness. Because the original study objectives have been completed and the study extension is focused on long-term O&M, the sampling program was scaled back during this reporting period through a reduction in sampling frequency and associated analytes in accordance with Modification No. 6. This section summarizes the effectiveness monitoring program implemented during this reporting period and presents an analysis of the effectiveness monitoring results and hydrogeological evaluation in response to the ISB injections.

4.1 EFFECTIVENESS MONITORING ACTIVITIES

As part of the effectiveness monitoring program, groundwater samples were periodically collected from both upgradient and downgradient monitoring wells within the treatability study area (as shown in Figure 2). 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. Field low-flow purge logs for all groundwater sampling events are provided in Appendix E.

Per Modification No. 6, groundwater sampling and analysis for key parameters of perchlorate, chlorate, nitrate, total organic carbon (TOC), sulfate, and field parameters (dissolved oxygen [DO], oxidation-reduction potential [ORP], pH, turbidity, temperature, and conductivity) were performed once every six weeks during the reporting period, for a total of eight sampling events. Additional parameters of ferrous iron, sulfide, metals, methane, perchlorate reductase, and phospholipid fatty acids (PLFA) were also analyzed on a quarterly, semi-annual or annual basis in accordance with Modification No. 6.

4.1.1 Data Validation

A Data Validation Summary Report (DVSR) was prepared for the laboratory analytical data collected during the reporting period of November 2018 – December 2019. This report was prepared to assess the validity and usability of laboratory analytical data from 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 F to this results report. The laboratory analytical data were verified and validated in accordance with procedures described in the *Quality Assurance Project Plan, Revision 3* (Ramboll, 2019), “Data Validation Guidance” (NDEP, 2018), and the references contained therein. The samples were validated to Stage 2A. The review process also used professional judgment and guidance from the National Functional Guidelines to determine the final qualifiers, which were added to the database and presented in the DVSR tables.

4.2 EFFECTIVENESS MONITORING RESULTS

As explained in Section 4.1, groundwater samples were periodically collected and analyzed for a variety of constituents during the treatability study to evaluate the aquifer’s response to ISB injections and the effectiveness of ISB in remediating perchlorate and chlorate contamination in groundwater. This section provides an overview of the groundwater sampling results, including a discussion of the primary contaminants, additional chemical and geochemical parameters, and relationships among each of these parameters. Because remediation of perchlorate is the main focus of this treatability study, Section 4.2.1 presents a detailed discussion of the perchlorate degradation response, an estimate of perchlorate distribution, and an estimate of perchlorate mass destroyed during this reporting period. Other significant constituents, including chlorate, nitrate, and TOC, are also discussed in detail in Sections 4.2.2 through 4.2.4. Data for all parameters can be found in the comprehensive data tables provided in Appendix G, Tables G.1 through G.4. Data for perchlorate, chlorate, nitrate, and TOC are depicted graphically in individual well trend profiles provided in Appendix H. Additional parameters, including DO, ORP, pH, sulfate, sulfide, metals, and methane, have also been evaluated and are discussed in Section 4.2.5. Field logs from all groundwater sampling events are provided in Appendix E and the DVSR is provided in Appendix F.

4.2.1 Perchlorate

An evaluation of the perchlorate degradation response, perchlorate distribution throughout the study area, and estimates of perchlorate mass removal following the fourth and fifth injection events is presented in the subsequent sections.

4.2.1.1 Perchlorate Degradation Response

The overall average percentage decrease in groundwater perchlorate concentrations (compared to baseline concentrations) for the four monitoring wells located between the injection well transects ranged from 77 percent to 90 percent for sampling events performed during the reporting period of November 2018 through December 2019.

Of the four monitoring wells located between the injection well transects, groundwater perchlorate concentrations in samples collected from SWFTS-MW14 and SWFTS-MW16 were less than the federal PRG for perchlorate of 15 μg/L in six of the eight sampling events (Appendix H, Figures H.24 and H.26). Groundwater samples collected from SWFTS-MW02 had a perchlorate concentration of 740 μg/L soon after the fourth injection event (97 percent less than the baseline concentration of 25,000 μg/L; Appendix H, Figure H.8). Perchlorate concentrations in groundwater from this monitoring well continued to remain at concentrations significantly below baseline levels during this reporting period (ranging from 73 percent to 97 percent below baseline concentrations). Although still significantly below baseline concentrations, it should be noted that perchlorate concentrations have increased in groundwater samples collected from SWFTS-MW02 during the reporting period; this trend will continue to be evaluated with respect to the increasing upgradient concentrations and presence of the nearby paleochannel gravels in the alluvium. The fourth monitoring well located between the injection well transects, namely, SWFTS-MW15, has historically had a delayed and mediocre response to injections, despite its proximity to injection wells SWFTS-IW06A/B and SWFTS-IW07. Despite these fluctuations, groundwater perchlorate concentrations in three of the sampling events during this reporting period were among the lowest concentrations attained to date in this monitoring well at levels ranging from 5,300 μg/L to 6,400 μg/L, which is approximately 57 to 65 percent lower than its baseline concentration of 15,000 μg/L (Appendix H, Figure H.25). Following the fifth injection event, the perchlorate concentration increased slightly to 9,900 μg/L, mimicking past fluctuations that have been observed since injections began. It is possible that subsurface lithological and geochemical heterogeneity, potential back diffusion from the Upper Muddy Creek formation (UMCf), as well as fluctuations in injection rates and pressures from upgradient injection wells, could cause local variations and fluctuations in responses in monitoring wells such as SWFTS-MW02 and SWFTS-MW15. Perchlorate concentrations in groundwater from these two monitoring wells will continue to be evaluated for fluctuations in tandem with results from groundwater samples collected from monitoring wells located upgradient and downgradient of these two monitoring wells.

Monitoring wells located downgradient of the injection well transects exhibited an overall average percentage decrease in groundwater perchlorate concentrations (compared to baseline concentrations) ranging from 64 percent to 73 percent during the reporting period. Of the 16 monitoring wells located downgradient of the injection well transects, groundwater samples from nine monitoring wells exhibited perchlorate concentration reductions greater than 80 percent compared to their respective baseline concentrations during multiple sampling events. Groundwater samples collected from downgradient monitoring wells located closest to the injection well transects

(PC-91, PC-92, SWFTS-MW10A, and SWFTS-MW18 are within approximately 50 feet) indicated favorable responses to ISB injections. The largest decrease in groundwater perchlorate concentrations were observed in samples collected from PC-91, which included concentrations below the PRG of 15 μg/L (lowest to date) following the fifth injection event (Appendix H, Figure H.3). PC-92, which had thus far shown marginal decreases as well as several prior anomalous increases in groundwater perchlorate concentrations, finally showed signs of stabilization with groundwater concentration reductions generally between 30 and 40 percent during the reporting period (Appendix H, Figure H.4). As observed in Figure 2, the proximity of the paleochannel in this vicinity likely contributes to the varying effects on perchlorate concentrations in groundwater between PC-91 and PC-92. It is likely based on the groundwater flow patterns that both PC-91 and PC-92 are impacted by injections but PC-91 more so due to its proximity to SWFTS-IW11 and the paleochannel. Additionally, historical perchlorate concentration trends in groundwater samples collected from both wells were similar through 2015; however, after that (but prior to injections), concentrations in groundwater samples from PC-91 continued to be similar but samples collected from PC-92 began to indicate higher and less stable concentrations, which is similar to the observations at the nearby upgradient monitoring SWFTS-MW04. As a result, it is likely that the same upgradient influence is affecting both SWFTS-MW04 and PC-92, but not PC-91, likely due to the difference in screened interval.

Groundwater samples from well SWFTS-MW10A recorded the highest percentage decrease in groundwater perchlorate concentrations since the first injection event, with a decrease of 93 percent prior to the fifth injection event (Appendix H, Figure H.20). Following the fifth injection event, groundwater perchlorate concentrations at monitoring well SWFTS-MW10A increased respectively to 2,600 μg/L and 4,000 μg/L in the November and December 2019 sampling events, which still represents a 70 to 80 percent decrease in concentrations compared to baseline concentration. Results following the fifth injection event will continue to be evaluated with respect to preferential flows and the nearby paleochannel in the vicinity of SWFTS-MW10A. Lastly, groundwater perchlorate concentrations at monitoring well SWFTS-MW18 were consistently lower than in previous years, with concentrations ranging from 2,600 μg/L to 5,000 μg/L (compared to the baseline concentration of 13,000 μg/L) (Appendix H, Figure H.28).

Other noteworthy results include groundwater perchlorate concentrations at wells SWFTS-MW01, SWFTS-MW20, and SWFTS-MW21, which are located approximately 100 to 150 feet hydraulically downgradient of the injection well transects; all samples from these wells exhibited their lowest perchlorate concentrations observed to date. Groundwater samples from monitoring wells SWFTS-MW01 and SWFTS-MW20 had a decrease in perchlorate concentrations to 54 μg/L and 290 μg/L, respectively, during this reporting period, which represents a 99 percent decrease when compared to their respective baseline concentrations (Appendix H, Figures H.7 and H.30). Groundwater from monitoring well SWFTS-MW21, which is hydraulically downgradient of SWFTS-IW18, had a decrease in groundwater perchlorate concentrations to 690 μg/L, which represents an 88 percent decrease from the baseline concentration (Appendix H, Figure H.31). Groundwater in the monitoring well pair, SWFTS-MW05A/B, which is the easternmost well cluster downgradient of the injection well transects and also located approximately 100 feet hydraulically downgradient of the injection well transects, responded fairly well following the fourth and fifth injection events (Appendix H, Figures H.11 and H.12). SWFTS-MW05B, which is the deeper screened alluvium well and has considerably more gravel present compared to SWFTS-MW05A, had decreases in groundwater perchlorate concentrations that were generally greater than 80 percent compared to baseline concentrations. Groundwater samples from SWFTS-MW05A, which observed limited decreases following the first three injection events, attained a maximum 65 percent decrease compared to baseline concentrations following the fourth injection event, with the lowest concentration to date in this well of 2,600 μg/L observed in May 2019.

Groundwater in the farther downgradient monitoring wells (i.e., greater than 150 feet – PC-94, SWFTS-MW03, SWFTS-MW09A/B, SWFTS-MW22, SWFTS-MW24, and SWFTS-MW25; Appendix H, Figures H.5, H.9, H.18, H.19, H.32, H.34, and H.35) generally continued to exhibit perchlorate reductions ranging from 61 to 83 percent during the reporting period. Exceptions include the concentration trends observed at SWFTS-MW09B and SWFTS-MW22. Although decreases have been consistently observed, groundwater concentrations from samples collected from monitoring well SWFTS-MW09B have fluctuated since injections began (Appendix H, Figure H.19). Perchlorate concentration decreases have been consistently observed in groundwater samples collected from SWFTS-MW22, with December 2019 results indicating the lowest perchlorate concentration to date in this well at 1,600 μg/L (Appendix H, Figure H.32). The December 2019 results indicates a 68 percent decrease when compared to baseline concentrations.

In addition to the above results, one other noteworthy result was the decrease in concentrations in the groundwater samples collected from monitoring well SWFTS-MW12 during the November and December 2019 sampling events (Appendix H, Figure H.22). Specifically, the groundwater concentrations from samples collected from SWFTS-MW12 (located approximately 150 feet upgradient of the injection wells and the well from which most of the distribution water was extracted during injection event 5) showed dramatic decreases for the first time, with perchlorate concentrations reducing from 4,200 μg/L to less than the sample detection limit. A review of the long-term groundwater monitoring data and potentiometric surface indicate that groundwater elevations and flow patterns remain consistent with historical results for the area. Therefore, a combination of the extraction from SWFTS-MW12 and an increase in injection rates and pressures during the fifth injection event may have resulted in transport of the injectate to the vicinity of monitoring well SWFTS-MW12 (which would have reduced perchlorate concentrations in groundwater).

In conclusion, groundwater continues to respond favorably to injections following the fourth and fifth injection events. Some fluctuations continue in concentrations and/or more gradual responses at some downgradient locations. This is likely due to preferential flow pathways for carbon substrate migration, presence of paleochannels, and/or large lithological heterogeneity that was apparent during well drilling activities. In addition, perchlorate from the AMPAC plume is thought to be migrating in the vicinity of the Las Vegas Wash towards Pabco Road Weir downgradient of the treatability study area and may be impacting groundwater quality at the most distant downgradient monitoring wells.

4.2.1.2 Estimate of Perchlorate Distribution

Figures 4a and 4b present perchlorate plume isoconcentration contour interpretations during the reporting period compared to baseline concentrations. Specifically, the baseline event is intended to represent pre-injection perchlorate concentrations in groundwater within the vicinity of the treatability study, followed by depictions of subsequent sampling events post-injection. These comparisons show significant reduction in perchlorate concentrations during the reporting period. As illustrated in the isoconcentration maps on Figures 4a through 4b, a biologically active treatment zone was sustained following the fourth and fifth injection events, with perchlorate concentrations in groundwater reduced to less than 15 μg/L in the white contour intervals. As upgradient groundwater flowed through the treatment zone, perchlorate continued to reduce in concentration. In addition, perchlorate concentrations in groundwater downgradient of the treatment zone also reduced in concentration from baseline conditions.

Given the presence of the AMPAC's plume potentially migrating in the northern portions of the treatability study area, the downgradient extent of perchlorate concentrations below 15 μg/L is somewhat limited. Some areas within the treatment zone had slightly less reduction in perchlorate concentrations, which may be due to the heterogeneous nature of the subsurface and localized presence of low permeability within that particular portion of the injection well transect. If implemented full-scale, additional injection wells would be installed within these low permeability zones to achieve a more uniform biologically active treatment zone.

In addition to the two-dimensional visualizations provided in Figures 4a – 4b, three-dimensional visualizations are also presented in Figures 4c through 4f. These figures have been prepared to address previous NDEP requests to provide three-dimensional images of perchlorate concentrations over time, including the differences between the most recent and baseline concentrations as well as variations in concentration ranges (greater than 5,000 μg/L and all detected concentrations). Specifically, Figures 4c and 4d provide three-dimensional visualization of perchlorate distribution during baseline and select monitoring events following the fourth and fifth injection events with views using different concentration thresholds (i.e., greater than 5,000 μg/L and all detected concentrations). Figures 4e and 4f present the treated perchlorate from the baseline sampling event through December 2019, again with different concentration thresholds of greater than 5,000 μg/L and all detected concentrations.

4.2.1.3 Estimation of Perchlorate Mass Removal

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

- Groundwater sampling data from the March and July 2017 sampling events were assumed to represent baseline conditions.
- Saturated thickness was assumed to be constant throughout this study.
- The area of interest (AOI) was defined to include only the areas investigated during this study.

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

4.2.1.3.1 Data Sources

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

4.2.1.3.2 Procedures

As part of the mass removal calculations, a number of grid surfaces were first generated, as described in the prior *Seep Well Field Area Bioremediation Treatability Study Results Report* (Tetra Tech, 2019a). These surfaces represented Qal/UMCf contact, groundwater elevation, saturated thickness, hydraulic conductivity, and perchlorate concentrations during each groundwater monitoring event following a carbon substrate injection. The UMCf surface, groundwater elevation, saturated thickness, and hydraulic conductivity grids were not modified as part of the updated mass estimate calculations, since they did not change significantly over the course of the year. However, new perchlorate concentration grid surfaces were generated for each monitoring event conducted. Analytical results collected as part of effectiveness monitoring in the AOI were combined with analytical data obtained from the Ramboll database for wells outside the AOI to generate the perchlorate concentration grid surfaces.

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

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

The third step was to estimate the amount of mass present in the AOI during each monitoring event. The saturated thickness and concentration grids were used to estimate mathematically the mass of perchlorate present in the AOI. The average porosity of 25 percent obtained from NMR logging for the alluvial well screens within the treatability study area was used to estimate the mass present in pore spaces. Next, the net mass change in perchlorate mass between each monitoring event was estimated using the mass that entered the study area during the elapsed time in between events, minus the mass that left the study area during the elapsed time, plus the change in mass present in the study area. It should be noted that this analysis does not account for matrix diffusion of perchlorate from the UMCf. If the calculated net mass change between monitoring events was negative (i.e., the perchlorate increased in the area), then zero mass treatment was assumed for that time period. Finally, a time-weighted average was used to estimate the overall mass removal rate.

4.2.1.3.3 Results

During the reporting time frame of November 2018 through December 2019, an estimated total of 784 pounds of perchlorate was destroyed in the groundwater in the vicinity of the treatability study area (an average of 2 pounds per day). This is less than the daily average observed during the initial treatability study (August 2017 through October 2018) at 3 pounds per day, which is due in part to the upgradient groundwater perchlorate concentrations during the reporting period being lower than were present during the previous reporting period. Fluctuations in upgradient perchlorate concentrations are commonly observed within the study area.

4.2.2 Chlorate

Chlorate has been reported in groundwater within the treatability study area at concentrations that are often higher than those of perchlorate. Like perchlorate, chlorate is also amenable to anaerobic biodegradation. Chlorate concentrations are summarized in Appendix G, Table G.1, and are graphically depicted in Appendix H. Figures 5a through 5b present chlorate plume interpretations, which show significant reductions in chlorate concentrations similar to the perchlorate reductions observed in Figures 5a through 5b. In general, chlorate concentration trends followed a similar reducing pattern to the perchlorate concentration trends during this reporting period.

The overall average percentage decrease in chlorate concentrations in groundwater compared to baseline concentrations for the four monitoring wells between the injection well transects ranged from 69 percent to 82 percent during the reporting period. The majority of groundwater samples collected from three of the four monitoring wells, namely SWFTS-MW02, SWFTS-MW14, and SWFTS-MW16, were below the sample detection limit, representing greater than 99 percent decrease when compared to baseline concentrations (Appendix H, Figures H.8, H.24, and H.26). Although chlorate concentrations were the lowest to date in groundwater samples collected from SWFTS-MW02 during the majority of the reporting period, it should be noted that chlorate concentrations increased in December 2019 to a concentration of 2,700 μg/L, which is still 95 percent below the baseline concentration of 58,000 μg/L. Groundwater in the vicinity of the fourth monitoring well, namely SWFTS-MW15, did not respond as favorably to chlorate reduction, with several samples collected during the reporting period indicating chlorate concentrations slightly greater than baseline concentrations (Appendix H, Figure H.25). As was the case for perchlorate at this location, it is possible that local subsurface lithological and geochemical heterogeneity could be causing these fluctuations in responses in SWFTS-MW15. Additionally, it is possible that some of the chlorate could be transiently contributed from perchlorate biodegradation.

The overall average percentage decrease in groundwater chlorate concentrations compared to baseline concentrations for the monitoring wells downgradient of the two injection well transects ranged from 74 to 83 percent, which was approximately 10 percent greater than the equivalent decrease for perchlorate even though the baseline concentrations for chlorate were generally much higher than perchlorate. The average percentage decrease in chlorate concentrations in downgradient wells during this reporting period was also approximately 10 percent greater than that estimated during sampling events from the previous two years of operation. Groundwater samples collected from downgradient monitoring wells located closest (within 50 feet) to the injection well transects (namely PC-91, PC-92, SWFTS-MW10A, and SWFTS-MW18; Appendix H, Figures H.3, H.4, H.20, and H.28, respectively) all indicated favorable responses to ISB injections. Of these monitoring wells, groundwater samples collected from PC-91 and SWFTS-MW10A exhibited chlorate concentrations less than the sample detection limit in multiple events during the reporting period, while groundwater concentrations at SWFTS-MW18 were the lowest to date of 6,600 μg/L (representing an 87 percent decrease compared to baseline concentrations). Groundwater from monitoring well PC-92, which after the third injection event had shown several anomalously high increases in chlorate concentrations, finally showed groundwater concentration reductions as great as 65 percent during the reporting period.

Monitoring wells located approximately 100 to 150 feet hydraulically downgradient of the injection well transects (SWFTS-MW01, SWFTS-MW05A/B, SWFTS-MW20, and SWFTS-MW21; Appendix H, Figures H.7, H.11, H.12, H.30, and H.31) exhibited their lowest groundwater chlorate concentrations to date, which includes greater than 99 percent reduction compared to baseline in the majority of sampling events during this reporting period. With the exception of SWFTS-MW09B, groundwater in the farther downgradient monitoring wells (i.e., greater than 150 feet) generally continued to witness chlorate reductions ranging from 56 to 98 percent during the reporting period when compared to baseline concentrations. Although groundwater chlorate concentrations have decreased over time (averaging 40 percent during the reporting period) in SWFTS-MW09B (Appendix H, Figure H.19), chlorate concentrations have fluctuated since injections began and the groundwater within this zone continues to be slower to respond to injections. Chlorate concentration trends in groundwater from SWFTS-MW09B will continue to be evaluated during future sampling events.

Finally, similar to perchlorate, chlorate concentration in groundwater also decreased in groundwater samples collected from monitoring well SWFTS-MW12 during the November and December 2019 sampling events (Appendix H, Figure H.22). Specifically, the groundwater concentrations from monitoring well SWFTS-MW12 (located approximately 150 feet upgradient of the injection wells and the well from which most of the distribution water was extracted during injection event 5) showed dramatic decreases for the first time, with chlorate concentrations decreasing from 31,000 μg/L prior to injection event 5 to less than the sample detection limit.

4.2.3 Nitrate

Nitrate concentrations are continuing to be evaluated during the study extension since it is the most likely competing electron acceptor as well as a consumer of organic carbon substrate. Both perchlorate and chlorate biodegradation generally commences when nitrate biodegradation (denitrification) is substantially complete. However, perchlorate and chlorate biodegradation could also occur concurrently along with nitrate biodegradation. In the presence of a continuing carbon source, and once DO and nitrate have been reduced, both chlorate and perchlorate act as an electron acceptor for anaerobic respiration. Nitrate concentrations are summarized in Appendix G, Table G.1, and are graphically depicted in Appendix H. Figures 6a through 6b present nitrate plume interpretations, which show significant reductions in nitrate concentrations during the treatability study.

Similar to perchlorate and chlorate concentration trends, nitrate was not detected during the reporting period in groundwater samples from monitoring wells SWFTS-MW14 and SWFTS-MW16 (Appendix H, Figure H.24 and H.26), which are located between the injection well transects. Groundwater samples from a third monitoring well, SWFTS-MW02, which is also between the injection well transects, were also mostly free of nitrate except for the December 2019 sampling event (Appendix H, Figure H.8). The fourth monitoring well, SWFTS-MW15, is the sole monitoring well location between the injection well transects that continues to have high concentrations of nitrate in groundwater, similar to the persistent elevated perchlorate and chlorate concentrations (Appendix H, Figure H.25).

As presented in Figures 6a through 6b, nitrate concentrations were significantly reduced not only within the biologically active treatment zone but also in much of the downgradient portion of the study area. Nitrate concentrations in groundwater samples collected from the 16 monitoring wells located hydraulically downgradient of the injection well transects reduced by an average of 50 percent when compared to their baseline concentrations.

4.2.4 Total Organic Carbon

Total organic carbon can sometimes be a surrogate parameter to evaluate carbon substrate distribution in the subsurface. As a result, TOC has continued to be analyzed during the reporting period to monitor changes in concentrations after injections compared to baseline pre-injection concentrations. TOC concentrations are summarized in Appendix G, Table G.1, and are graphically depicted in Appendix H.

During the reporting period, there were only isolated events of noteworthy TOC concentrations. The highest groundwater TOC concentration measured between the injection well transects during this reporting period was in August 2019 at a concentration of 6.7 mg/L, while the highest concentration in groundwater samples collected for downgradient monitoring wells was 5.9 mg/L measured in November 2019. This phenomenon is realistic and to be expected over time as the injectate (measured as TOC) is consumed closer to be injection well transect(s) themselves and does not get transported in significant quantities to downgradient locations.

The one exception to the typical TOC concentration trends is the notable increase in the TOC concentrations in groundwater samples collected from upgradient monitoring well SWFTS-MW12, which indicated a very high increase in TOC concentrations (560 mg/L) following the fifth injection event. This phenomenon can be attributed to a transient transport of the injectate from injection wells in an upgradient direction due to extraction from SWFTS-MW12 (used as water source during injections) and greater than average flows established in injection wells targeting an injection zone that appears hydraulically connected with this upgradient monitoring well. The TOC in groundwater from this well decreased to 230 mg/L in December 2019 and is expected to continue to decrease in upcoming sampling events in 2020.

4.2.5 Additional Chemical and Geochemical Evaluation

This section provides a summary of the additional data collected during the treatability study (namely, field parameters [DO, ORP, and pH], methane, sulfate and sulfide) and their influence on perchlorate biodegradation. A discussion of metals, including arsenic, iron, and manganese, has also been included due to the potential for metals mobilization during implementation of ISB systems. Results for all parameters discussed herein are presented in the comprehensive data tables provided in Appendix G, Tables G.1 through G.3.

4.2.5.1 Field Parameters

The field parameters DO, ORP, pH, turbidity, temperature, and conductivity are recorded during groundwater sampling events. Of these parameters, DO, ORP, and pH are of interest as they relate to bioremediation processes. This section summarizes the results for DO, ORP, and pH and their significance in the on-going bioremediation processes.

4.2.5.1.1 Dissolved Oxygen and Oxidation-Reduction Potential

DO and ORP measurements are often useful parameters 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. ORP readings sometimes provide a valuable tool to identify the redox conditions in groundwater and ascertain reducing conditions. At some sites, ORP readings correlate well with DO values and, therefore, provide a means to verify the extent of reduction. However, in aquifers with several electron acceptors and redox pairs, such as iron pairs, nitrogen pairs, perchlorate/chlorate/chloride and sulfur pairs, redox measurements may not always be accurate and inferences from these data should be made cautiously. As part of the treatability study extension, both DO and ORP measurements were collected using field equipment as part of low-flow groundwater sampling during all effectiveness monitoring events.

Baseline conditions prior to injections occurring for this treatability study indicated that the aquifer was generally aerobic, with DO and ORP readings averaging 1.39 mg/L and 97.7 millivolts (mV), respectively. Following the injection of carbon substrate, the aquifer generally indicated anaerobic conditions, with DO and ORP readings less than 0.5 mg/L and -100 mV, respectively, in most monitoring wells. Based on the results following the first three injection events, it was concluded that DO and ORP can be useful indicators during the early stages of ISB when carbon substrate is first injected into the groundwater and reducing conditions are established. Monitoring wells that showed the most significant and consistent perchlorate and chlorate biodegradation also appeared to be consistently reducing throughout the treatability study, as inferred from DO and ORP readings.

During the November 2018 – December 2019 reporting period, groundwater from three of the four monitoring wells located between the injection well transects, namely SWFTS-MW02, SWFTS-MW14, and SWFTS-MW16, regularly had DO readings in groundwater that were less than 0.5 mg/L, despite stray anomalous readings that were greater than 1.0 mg/L. ORP readings in groundwater generally correlated with DO results in groundwater samples collected from SWFTS-MW14 and SWFTS-MW16, which generally had negative ORP readings throughout the reporting period, while ORP readings fluctuated at SWFTS-MW02. These concentrations are consistent with results from earlier sampling events, indicating a robust establishment of anaerobic conditions in this vicinity that bodes well for sustained perchlorate and chlorate treatment. Groundwater samples collected from the fourth monitoring well located between the injection well transects, SWFTS-MW15, which consistently has had less of a response to injections, generally had DO concentrations greater than 0.5 mg/L with two readings above 1.0 mg/L and fluctuating ORP values. These results indicate that the strongly anaerobic conditions are not as prevalent in this vicinity.

Groundwater DO measurements in downgradient monitoring wells generally indicated reducing conditions, while the ORP readings generally observed more fluctuation and did not always correlate with DO. For example, groundwater in PC-91 and PC-92 witnessed their lowest DO measurements of 0.05 mg/L and 0.09 mg/L following the fourth injection event, while ORP readings fluctuated and generally remained positive values. Groundwater from SWFTS-MW20, which consistently observed significant decreases in both perchlorate and chlorate, had low DO measurements averaging 0.55 mg/L during the reporting period, although the ORP readings did not correlate, with readings typically above 100 mV. Other notable results include DO concentrations greater than 1.0 mg/L and ORP measurements greater than 100 mV in groundwater samples collected from PC-94, despite maintaining consistent groundwater perchlorate and chlorate reductions generally around 70 percent.

While DO in groundwater in most upgradient monitoring wells did not change much from previous years and remained fairly aerobic, the one exception was groundwater in the vicinity of SWFTS-MW12, with groundwater samples indicating anaerobic conditions during the last two sampling events following the fifth injection event (i.e., DO measurements ranging from 0.29 to 0.84 mg/L and ORP readings less than -200 mV). This is likely attributed to the transport of carbon substrate into the vicinity of monitoring well SWFTS-MW12, as previously explained in Sections 4.2.1 through 4.2.4.

Overall, DO readings provide a general indication of the reducing conditions in groundwater following carbon substrate injections, with monitoring wells that showed the most significant and consistent perchlorate biodegradation also appearing to be consistently reducing throughout the treatability study. In many cases, ORP readings fluctuated and did not consistently correlate with DO measurements. As a result, ORP may not be a very reliable parameter for determining the establishment of reducing conditions.

4.2.5.1.2 pH

Most of the pH values in groundwater from monitoring wells within the SWF Area Bioremediation Treatability Study area ranged between 6.5 to 7.5 standard units, which is quite conducive to most microorganisms. Biological activity often results in a reduction in pH in groundwater. However, the presence of natural gypsum (calcium sulfate) in the aquifer likely serves as a pH buffer. The buffering capacity of the aquifer minimizes pH changes during biological activity, thereby making this groundwater a favorable candidate for long-term carbon substrate injections for ISB.

4.2.5.2 Sulfate and Sulfide

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

Sulfate reductions appear to have stabilized in groundwater at monitoring wells located between the injection well transects as well as monitoring wells farther downgradient. Overall, the average decrease in sulfate concentrations during the reporting period was 42 percent between the injection well transects and 24 percent for areas downgradient of the injection well transects. It should be noted that the average decrease in sulfate concentrations in groundwater in upgradient wells during this reporting period was 18 percent. The maximum transient decrease in groundwater sulfate concentrations during the reporting period was at well location SWFTS-MW14, which was as high as 70 percent in April 2019, but sulfate reduction was only 40 percent during the December 2019 sampling event when compared to baseline concentrations. These levels of sulfate reduction are lower than the previous maximum transient decrease of 95 percent observed following the third injection event. The highest transient decrease in groundwater sulfate concentrations at SWFTS-MW16 during the reporting period was 61 percent compared to the highest previous transient decrease of 77 percent following the second injection event. Therefore, the amount of sulfate reduction between the injection well transects seem to be decreasing and stabilizing. The only exception to this is observed in the groundwater samples collected from SWFTS-MW12 following the fifth injection event, which indicated a sulfate reduction of approximately 99 percent in December 2019. As previously discussed, this correlates with the high TOC concentrations observed in groundwater samples collected from this monitoring well following the fifth injection event. As TOC concentrations reduce, it is expected that sulfate concentrations will return to historical levels.

Sulfide detections were not observed in most of monitoring wells within the study area, with the exception of relatively insignificant measurements of less than 1 mg/L in groundwater from monitoring wells SWFTS-MW14 and SWFTS-MW16 (located between the injection well transects). None of the monitoring wells located in the downgradient portion of the study area had sulfide detections in groundwater during the reporting period. Upgradient monitoring well SWFTS-MW12 had a sulfide detection in groundwater of 1.4 mg/L following the fifth injection event, which was expected due to observed elevated TOC concentrations and sulfate reductions in groundwater samples from this well.

In conclusion, the limited sulfate reduction and sulfide production observed in this treatability study are consistent with the results of the previous ISB study performed at the City of Henderson facility and suggest the potential negative impacts of sulfate biodegradation in this high sulfate environment may be minimized and/or controlled during implementation of perchlorate bioremediation. Sulfate reduction is fairly well controlled with the exception of groundwater between the injection well transects (although the level of sulfate reduction observed between the injection well transects has also decreased during this reporting period). The employment of the slow-release carbon substrate, EVO, is likely to be one reason for the limited sulfate reduction, because EVO comprises long-chain fatty acids that adsorb to the soil grains and gradually hydrolyze to provide the type of organic carbon (such as triglycerides followed by acetate and hydrogen) that is then used by microorganisms in their growth and respiration process. This gradual hydrolytic process does not appear to produce strongly reducing conditions and therefore, limits sulfate degradation. Secondly, the groundwater flow rates in this setting are relatively high, a hydraulic phenomenon that may not provide sufficient residence time for sulfate biodegradation to prosper. Sulfate and sulfide will continue to be monitored through the study.

4.2.5.3 Metals

Under anaerobic conditions, metals such as arsenic, iron, and manganese can be reduced, mobilized and precipitated out into the aquifer, a phenomenon that can sometimes increase metals concentrations and/or decrease hydraulic permeability in the aquifer. Accordingly, dissolved metals and ferrous iron were analyzed during baseline and periodically during the treatability study to monitor metals mobilization. The bulleted summary below provides an overview of key observations related to dissolved metals and ferrous iron during this reporting period.

- Arsenic is sometimes released from minerals in the saturated subsurface when reducing conditions are created following the injection of a carbon substrate. However, in many cases, these transient increases of arsenic ultimately precipitate out as arsenic sulfide over time. Although some slight increases in dissolved arsenic concentrations were observed during earlier sampling events in the area between the injection well transects, these concentrations have since dramatically decreased. For example, groundwater samples collected from SWFTS-MW14 and SWFTS-MW16 (located between the injection well transects) had dissolved arsenic concentrations below the sample detection limit and at 2.6 μg/L, respectively, during the reporting period, which is significantly lower than the baseline concentrations that were up to 110 μg/L within the study area. Dissolved arsenic concentrations in groundwater samples collected from farther downgradient monitoring wells were below 100 mg/L during this reporting period, which is consistent with pre-injection concentrations.
- Dissolved iron concentrations in groundwater were periodically evaluated due to the potential for iron to undergo reduction and mobilization under anaerobic conditions and precipitate out in the subsurface, potentially decreasing the hydraulic permeability in the aquifer. Pre-injection dissolved iron concentrations were typically less than 1.5 mg/L. Monitoring well SWFTS-MW16 was the only location where an increase in groundwater dissolved iron concentrations occurred, but the concentration was only at 4.3 mg/L, indicating minimal iron mobilization. The lack of iron mobilization is further supported by field measurements of ferrous iron in groundwater, which indicated only relatively low, transient detections of up to 4.5 mg/L. Almost all groundwater samples collected from downgradient monitoring wells were devoid of measurable ferrous concentrations during the reporting period.
- Manganese can also undergo reduction and mobilization under anaerobic conditions and precipitate out in the subsurface, potentially decreasing the hydraulic permeability in the aquifer. During this reporting period, dissolved manganese concentrations in groundwater generally remained below 6 mg/L throughout the study area with the exception of samples collected from SWFTS-MW12, which exhibited concentrations of up to 44 mg/L. Because this location is upgradient of the actual treatment area, it is expected that as groundwater from this location flows downgradient, manganese concentrations will decrease over time (as observed with previous transient increases of dissolved manganese). Dissolved manganese will continue to be monitored at key locations in the SWF Area in 2020 to track changes with this parameter, particularly in downgradient locations to ensure that any manganese which has solubilized gradually gets precipitated out with distance.
- Dissolved phosphorus concentrations in groundwater were generally below the sample detection limit throughout the reporting period, which 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. Only groundwater samples collected from monitoring wells SWFTS-MW12

(upgradient) and SWFTS-MW14 (between the injection well transects) had marginal dissolved phosphorus concentrations, albeit at low concentrations of 1.9 mg/L and 0.2 mg/L, respectively.

4.2.5.4 Methane

Methanogenic conditions (signified by biological methane production) require highly reducing conditions that are generally not warranted for perchlorate biodegradation. Methane, however, often transiently increases in groundwater soon after a carbon substrate is injected, particularly at monitoring locations close to injection locations. Methane is currently being measured on an annual basis. Results from the November 2019 sampling event indicated that groundwater from two of the monitoring wells located between the injection well transects, namely, SWFTS-MW14 and SWFTS-MW16, have consistently observed methane concentrations at 9.3 mg/L and 11 mg/L, respectively. Methane concentrations in groundwater samples collected from downgradient wells were generally lower, ranging from less than the sample detection limit to 4.3 mg/L. Generally, methane concentrations in groundwater are expected to decrease over time in downgradient monitoring wells and are also very likely to be rapidly oxidized to carbon dioxide in the gravelly and sandy alluvium below the ground surface. Methane will continue to be monitored in groundwater during the treatability study.

4.2.6 Microbial Evaluation

Sampling was included in the effectiveness monitoring program to continue to examine the microbial response to carbon substrate additions at key locations. Specifically, in November 2018 and December 2019, Bio-Traps® were deployed at select injection and monitoring wells. The November 2018 event included deployment of Bio-Traps® in injection wells SWFTS-IW06A, SWFTS-IW11, and SWFTS-IW20. In December 2019, Bio-traps® were deployed at four locations, namely, SWFTS-MW07A (upgradient monitoring well), SWFTS-IW02A (injection well), SWFTS-MW14 (monitoring well between the injection well transects), and SWFTS-MW09B (downgradient monitoring well). During both events, 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. Complete analytical results for the microbial analyses performed during the treatability study can be found in Appendix G, Table G.4. Microbial laboratory data reports are provided in Appendix I.

The PLFA analysis, which is used to estimate the population of the variable biomass, indicated that groundwater from upgradient monitoring well SWFTS-MW07A had the lowest total biomass at 7.36×10^4 bacterial cells per bead, while the Bio-Trap® from the injection wells during both events had the highest total biomass ranging from 7.3×10^5 to 3.0×10^6 bacterial cells per bead. These results are indicative of heightened microbial response at the injection well locations due to the addition of carbon substrate. The total biomass numbers in groundwater were also elevated to 1.29×10^5 bacterial cells per bead in SWFTS-MW14, which is located between the injection well transects and observed a very good response with respect to groundwater perchlorate and chlorate degradation. Microbial cell numbers in groundwater from SWFTS-MW09B were 7.47×10^4 bacterial cells per bead, which is slightly greater than the upgradient monitoring well. It should be noted that SWFTS-MW09B is one of the locations that has historically been slower to respond to carbon substrate injections.

PLFA analysis on community structure in groundwater indicated that between approximately 38 percent and 65 percent of the bacterial population belonged to the Proteobacteria structural group in all Bio-Traps® analyzed during the reporting period. Proportions of Proteobacteria are of interest because they are one of the largest groups of bacteria and represent a wide variety of anaerobic and aerobic microorganisms. Proteobacteria are generally capable of adapting quickly to changes in the environment and grow opportunistically when food is available. The Bio-Trap® collected from downgradient well SWFTS-MW09B had the highest proportion of General (Nsats) at 62.22 percent during the reporting period, which is indicative of a less diverse population and possibly one reason why groundwater in this vicinity has been slower to respond to ISB injections with respect to perchlorate and chlorate degradation. Nsats are normal saturated fatty acids that are found in all organisms, and, therefore, the prevalence of these types of fatty acids and absence of other fatty acids that may indicate more diverse organisms indicates that the bacteria population may be less diverse in this area. Microbial results from this well with the aid of Bio-Trap® deployment will continue to be analyzed and evaluated at this location along with chemical and geochemical results in 2020.

Firmicutes were generally present only in the Bio-Traps® from the injection wells, which is expected because this group is representative of anaerobic fermenting bacteria that are responsible for generating hydrogen from complex long-chain substrates such as EVO via the process of fermentation. Bio-Traps® from the injection wells and monitoring well SWFTS-MW14 indicated the presence of sulfate-reducing bacteria (SRB)/Actinomycetes at only small fractions ranging from 0.73 to 6.79 percent of the total population. Eukaryotes (organisms such as fungi, protozoa, and diatoms) were present in measurable proportions in the Bio-Traps® from the injection wells and monitoring well SWFTS-MW14 (ranging from 1.48 to 14.83 percent of the total population). The emergence of low percentages of Eukaryotes is sometimes an indirect indication of efficient destruction of the prime contaminants. It may be noted that groundwater from SWFTS-MW14 has historically responded the most rapidly and favorably to the injection of the carbon substrate throughout the study period.

Slowed growth ratios are an indication or measure of the availability of carbon substrate and ratios for decreased permeability are an indication or measure of toxicity. Results for slowed growth ratios and decreased permeabilities were not very consistent with the overall microbial analyses for this event. The ratios for both of these indicators were slightly above 1.0 in the Bio-Trap® from monitoring well SWFTS-MW14. Although higher ratios (greater than 1.0) are sometimes reflective of a community that is stressed, the other results associated with this well (i.e., sustained perchlorate and chlorate decreases in groundwater) do not typically correlate with a stressed community. The ratios of slowed growth and decreased permeability in the Bio-Trap® from SWFTS-MW09B were 0.47 and 0, respectively, despite the observation that groundwater in the vicinity of this monitoring well has been slower to respond to ISB injections. These ratios will continue to be monitored during the treatability study to evaluate the overall microbial response to carbon substrate injections and contaminant decreases in the area.

Finally, the perchlorate reductase gene was detected at concentrations less than 250 cells per bead in all Bio-Traps® collected during the reporting period. In general, groundwater in the vicinity of monitoring wells that have indicated decreases to perchlorate and chlorate concentrations often have very low or negligible detects of perchlorate reductase over time because the gene is not as easily identifiable when the contamination is at very low concentrations. Additionally, the Bio-Traps® from the injection wells did not show the presence of the perchlorate reductase enzyme because perchlorate in this immediate vicinity is likely to degrade very rapidly. Under these conditions, likely due to perchlorate being virtually absent in groundwater in the vicinity of the injection wells (given the plentiful availability of organic carbon and rapid degradation slightly upgradient of the well itself due to radial distribution of the injection substrate), perchlorate reducing microorganisms as identified by the perchlorate reductase gene are generally present at numbers below Microbial Insight's method detection level. Another factor that needs to be considered is that the perchlorate reductase gene codes for a single enzyme that mediates the breakdown of perchlorate to chlorate and chlorite and is the common standard bearer and default analyses currently available as far as molecular biology tools (MBTs) are concerned. In reality, there could be several enzymes that could also perform the same microbial-mediated degradation of perchlorate that cannot be currently easily identified with MBTs.

4.3 HYDROGEOLOGICAL EVALUATION

Changes in hydrogeological conditions over time can affect treatability study results. Therefore, long-term water level monitoring transducers were installed in 2017 and have been recording data since then to monitor hydrogeological conditions over the course of the treatability study. A detailed description of the monitoring program and results is provided in Appendix J. Ten transducers were installed in wells within the treatability study area itself, while two transducers were installed upgradient of the study area near City of Henderson Pond 13 to monitor discharges of clean treated effluent to the pond. These periodic discharges of clean treated effluent are known to affect perchlorate concentrations migrating toward the study area.

Each of the two injection events (January 21 through February 10, 2019; September 30 through October 25, 2019) was visible in the transducer data as small rises of a few inches in groundwater elevation each day that injection occurred. Because the transducers are located in monitoring wells that are at least 20 feet away from the injection wells and the hydraulic conductivity in the area is high, the amount of water level rise observed was expected to be fairly small.

Other than the effects of the two injection events, in general only gradual changes to water level were observed in the transducer data. These changes, in which all the water levels slowly increased or decreased together, resulted in no significant changes to groundwater gradient. During each effectiveness monitoring event, water levels were also measured prior to sampling and used to construct potentiometric surfaces. These potentiometric surfaces confirmed that no significant changes to gradient or groundwater flow patterns occurred during this reporting period.

5.0 SUMMARY OF KEY FINDINGS AND FUTURE ACTIVITIES

This section presents the overall findings of the treatability study activities associated with Modification No. 6, results from the reporting period, and recommendations for modifications to the on-going treatability study extension.

5.1 SUMMARY OF KEY FINDINGS

Expanding on the information presented in Sections 2 through 4, this section presents a summary of the overall results and conclusions from the activities and data collected during the reporting period. Performance criteria tables were also generated to evaluate the operations, maintenance, and monitoring results and include a summary of the performance criteria, metrics, confirmation methods, and study demonstration. These tables can be found in Appendix K.

Overall, groundwater in this area continues to be amenable to biodegradation of perchlorate, chlorate, and nitrate. As demonstrated, the periodic injections of EVO and amendments continued to provide a sustained biologically active treatment zone with the reducing conditions required for effective and continual perchlorate and chlorate biodegradation in the groundwater. The main findings and conclusions below draw upon the various tasks performed during this reporting period as part of the extension to the SWF Area Bioremediation Treatability Study.

Operations

- The ability of the formation to accept substrate injections following five injection events indicates ISB is a feasible long-term option for groundwater in the alluvium at this site.
- Periodic injections of carbon substrate are lasting longer than earlier injection events, as demonstrated with the observed injection frequency of approximately once every 7 to 8 months during this reporting period.
- Specific gravity of the injectate was periodically analyzed during injection event 5, which confirmed that the blending of the carbon substrate, amendments, and water was very consistent through the batch mixing and injection process.

Maintenance

- Based on the limited analysis from SESI, video logging, and injection well maintenance, it appears that any accumulation of material within the injection wells is generally limited to microbial biomass and/or chemical precipitates, primarily consisting of calcium carbonate and/or calcium oleate.
- Common injection well maintenance techniques can be successfully implemented in injection wells to maintain injectability.
- Only two of the 25 injection wells have periodically not accepted injectate solution during an injection event. One of these wells was substantially improved using the common well maintenance technique of hydrojetting; this well received injectate at an average rate of 10 gpm during injection event 5. The remaining injection well did show improvement when comparing the results of the pre- and post-maintenance results, and therefore, it is expected that slightly more aggressive well maintenance will improve injectability into this well.[2]

[2] Subsequent to this reporting period, injection well maintenance was performed in February 2020 on injection well SWFTS-IW13B using the combination of surge and bail, hydrojetting, and chemical addition. This injection well was successfully restored, with post-maintenance water injection testing indicating an injection rate of up to 9 gpm. The results of this maintenance event will be reported in the 2020 Annual Progress Report.

- While pre- and post-maintenance specific capacity testing can be a useful measure of potential well injectability, the best test of injectability is to perform injection testing and compare injection rates and pressures to previous injection events.

Monitoring

- Nitrate, chlorate, and perchlorate continue to be substantially degraded throughout the reporting period.
- The study extension continued to demonstrate the ability of ISB using a slow-release carbon substrate to achieve the groundwater perchlorate PRG of 15 µg/L in groundwater within the alluvium at multiple locations.
- DO concentrations and ORP readings provide some indication of the sustained reducing conditions in groundwater, with monitoring wells that showed the most significant and consistent perchlorate biodegradation also appearing to be consistently reducing, as inferred from DO measurements and ORP readings (although ORP fluctuations have been observed in groundwater at many wells).
- Limited sulfate reduction continues to be observed in groundwater during the treatability study. The use of the slow release carbon substrate, EVO, helps to prevent wide-spread sulfate reduction because it comprises long-chain fatty acids that very gradually hydrolyze and limit the amount of usable carbon for native microorganisms to use for biological deoxygenation, denitrification, and perchlorate/chlorate biodegradation. Secondly, the groundwater flow rates in this setting are relatively high and may not provide sufficient residence time for sulfate biodegradation to occur. Limited sulfide production was also observed, indicating that microbial-based sulfate reduction was largely contained.
- Secondary groundwater geochemical impacts, including arsenic, iron, manganese, methane, and phosphorus mobilization, were either limited or transient and did not appear to create a significant downgradient footprint of concern in groundwater.
- During each effectiveness monitoring event, water levels were measured prior to sampling and used to construct potentiometric surface maps. These maps confirmed that no significant changes to gradient or groundwater flow patterns occurred during this reporting period, which are indicative that the hydraulic properties of the formation have generally remained the same since the study began in 2017.

5.2 COST EVALUATION

In addition to the implementability and effectiveness of a technology, the remedial alternatives evaluation to be conducted as part of the forthcoming FS will also include an evaluation of costs. This study extension provides information on key long-term operation and maintenance requirements of an ISB remedy that influence the costs, such as frequency of injections, quantities of injectate (carbon, nutrients, and distribution water), and injection well maintenance requirements to sustain injectability into the subsurface. As a result, this section provides a summary of lessons learned and adjustments that have been made to date as part of this study extension that have or could have an impact on the projected costs of an ISB remedy during the remedial alternatives evaluation in the FS.

- As previously explained, injection frequency and carbon substrate requirements for ISB systems can vary over the operational time frame, particularly with passive systems that involve the periodic injection of slow-release carbon substrates, such as EVO, which tend to persist for longer periods over time. In general, the adsorption, persistence, and capacity of EVO and its associated slow-release hydrolyzed products gradually increase with additional injection events. Therefore, timeframes between properly implemented injections of EVO tend to increase over time until a point of optimization is attained. This point of optimization is best determined over the course of a treatability or pilot study and would likely result in either reduced needs for carbon substrate injectate quantities or reduced injection frequencies over time. Therefore, the injection frequency and required carbon substrate quantities are key long-term operation and maintenance components that not only determine remedy effectiveness but also can significantly impact costs.

- Since the study began in 2017, the carbon substrate quantities were reduced during each of the third, fourth, and fifth injection events to approximately 85 percent of the amount that was initially injected during the first injection event. Depending on the size of full-scale ISB application, a reduction in substrate quantity over time can result in significant cost savings over the duration of the project. Additionally, continued negotiations with vendors to maximize discounts provided for bulk orders of substrate, locations of blending facilities, and transportation costs can also provide further cost savings. When comparing the first injection event to the most recent injection event, a cost savings of approximately $50,000 per injection event has been recognized from the reduced quantities ordered, negotiated vendor cost reduction, and improved efficiency of injection events. As part of this study extension, the quantities of substrate will continue to be evaluated to determine if, over time, additional refinements in substrate quantities can be performed while continuing to sustain a biologically active zone for perchlorate and chlorate biodegradation.
- As presented in Section 2.3, the injection frequency has decreased over time (i.e., more months in between injection events) while still sustaining the required biologically active zone. While initial injection events occurred once every four months, the injection event frequency is now generally once every seven to eight months. This reduction in injection frequency has resulted in the overall injection program being reduced by 50 percent compared to the first year of the study. This is obviously an important issue to understand to prepare an accurate remedial cost estimate in the FS.

- Maintaining injectability into the subsurface is key to the long-term success of ISB systems. During the first 24 months of operations associated with the SWF Area Bioremediation Treatability Study, maintenance was not required for any of the 25 injection wells. This was likely due to the judicious employment of a slow-release substrate, which releases carbon very gradually thereby preventing rapid biomass overgrowth, and the use of copious quantities of distribution water that flush the carbon substrate into the formation. As presented in Section 3.4, the first injection well maintenance event occurred at only nine of the 25 injection wells. Of these nine injection wells selected for maintenance during the reporting period, seven were still accepting injectate but were starting to indicate increases in injection pressures and decreases in injection flow rates. Therefore, for purposes of this treatability study extension and evaluation of maintenance techniques, they were selected for maintenance. The initial evaluation of injection well maintenance indicated that all three methods tested were effective at improving injectability. This provides the potential for selection of the most economical mechanism for well maintenance during ISB implementation. Additionally, all three maintenance methods tested are commonplace in the industry and were easy to implement within the treatability study area. Preliminary costs were approximately $4,000 per well. As noted, multiple techniques were implemented and evaluated as part of the first maintenance event, which also included pre- and post-aquifer testing. Similar to injection and monitoring costs, the well maintenance costs are expected to be reduced as data from early evaluations are incorporated into future activities.
- Because the original study objectives have been completed and the study extension is focused on long-term O&M, the sampling program was scaled back during this reporting period through a reduction in sampling frequency and associated analytes in accordance with Modification No. 6. As a result, the annual effectiveness monitoring program has decreased by approximately $180,000 per year.

5.3 FUTURE ACTIVITIES

As part of this study extension, periodic injections will continue to be performed through remedial design, or until otherwise as directed by the Trust, to develop a more thorough understanding of the key operation and maintenance components as they relate to long-term applications of ISB for use in the implementability and cost evaluations in the FS. Additionally, periodic injection well maintenance will be performed as needed to maintain long-term injectability to accept the carbon substrate and to assess long term O&M resources and cost implications of this technology. Through an evaluation of data obtained through this reporting period, in lieu of a technical memorandum, the following activities are proposed for 2020:

<u>Operations</u>

- Perform the sixth injection event in June 2020, with the incorporation of in-line mixing operations implemented in accordance with the NDEP-approved *In-Situ Bioremediation Injections – In-line Mixing and Injections Field Guidance Document* (Tetra Tech, 2020);
- Perform the seventh injection event in late 2020 or early 2021 (exact timing dependent on effectiveness monitoring results following the sixth injection event) and continue to evaluate injection frequencies and substrate quantities.
- Continue to evaluate operations efforts to optimize procedures and thus costs as appropriate.

<u>Maintenance</u>

- Perform injection well maintenance prior to the seventh injection event (to the extent required) to maintain long-term injectability.
- Evaluate the long-term effects of the 2019 well maintenance activities by continuing to collect and evaluate injection pressure and flow rate data during injections to determine the most effective well maintenance technique and approximate the frequency that well maintenance activities may be required for long-term ISB operations.
- Discontinue specific capacity testing as part of pre- and post-maintenance activities, as injection testing is the most applicable test for determination of maintenance effectiveness.
- Continue to evaluate maintenance efforts to optimize procedures and thus costs as appropriate.

<u>Monitoring</u>

- Continue the current effectiveness monitoring program to determine remediation effectiveness; timing of sampling events will be dependent on resulting injection frequencies and on-going effectiveness monitoring results.
- Perform annual microbial sampling via the deployment of Bio-Traps® in the same four injection/monitoring wells to develop a more thorough understanding of long-term microbial trends.
- Monitor the potentiometric surface within the study area to evaluate groundwater flow patterns and gradients, which are indicative of the hydraulic properties of the formation.

<u>Reporting</u>

- Continue to submit progress reports to NDEP on a quarterly basis.
- Prepare the 2020 Annual Progress Report, which will include updates to all information presented herein plus an evaluation of different substrate mixing techniques (batch mixing versus in-line mixing).

6.0 REFERENCES

ENVIRON (2014). *Field Sampling Plan, Revision 1, Nevada Environmental Response Trust Site, Henderson, Nevada.*

Nevada Division of Environmental Protection (NDEP). (2018). *"NDEP Data Verification and Validation Requirements*." July 13

Ramboll Environ. (2017). *Quality Assurance Project Plan, Revision 2, Nevada Environmental Response Trust Site, Henderson, Nevada.*

Ramboll. (2019). *Quality Assurance Project Plan, Revision 3, Nevada Environmental Response Trust Site, Henderson, Nevada.*

Tetra Tech. (2018). *Treatability/Pilot Study Modification No. 6 – Seep Well Field Area Bioremediation Treatability Study, Nevada Environmental Response Trust, Henderson, Nevada.* December 11.

Tetra Tech. (2019a). *Seep Well Field Area Bioremediation Treatability Study Results Report, Nevada Environmental Response Trust, Henderson, Nevada.* August 13.

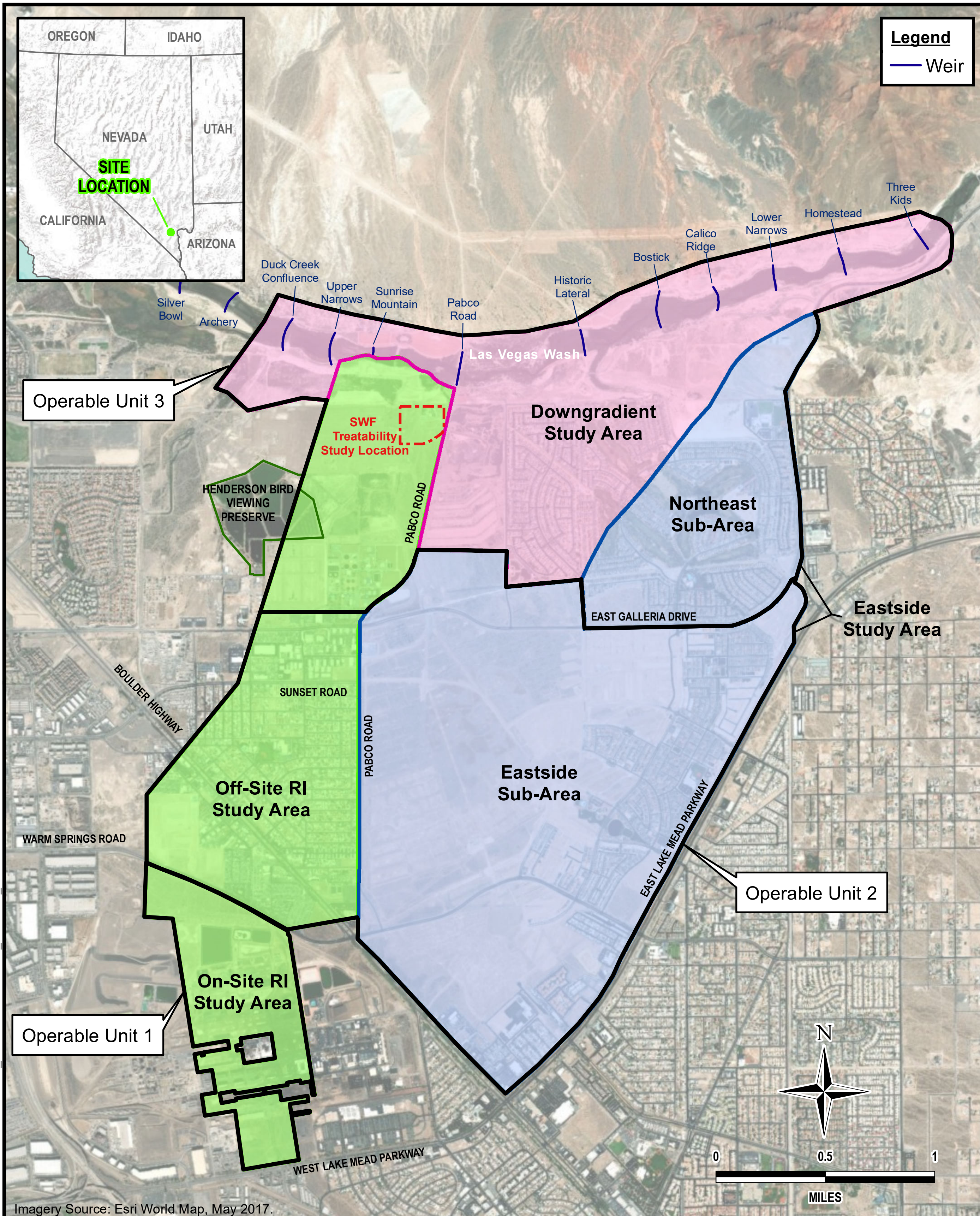
Tetra Tech. (2019b). *Proposed Injection Well Maintenance Activities – Seep Well Field Area Bioremediation Treatability Study, Nevada Environmental Response Trust, Henderson, Nevada.* September 18.

Tetra Tech. (2019c). *In-Situ Bioremediation Injections – Batch Mixing and Injections Field Guidance Document, Nevada Environmental Response Trust, Henderson, Nevada.* November 8.

Tetra Tech. (2020). *In-Situ Bioremediation Injections – In-Line Mixing and Injections Field Guidance Document, Nevada Environmental Response Trust, Henderson, Nevada.* March 23.

U.S. Environmental Protection Agency (USEPA). (2013). *Introduction to In Situ Bioremediation of Groundwater.* Office of Solid Waste and Emergency Response. EPA 542-R-13-018. December.

Figures



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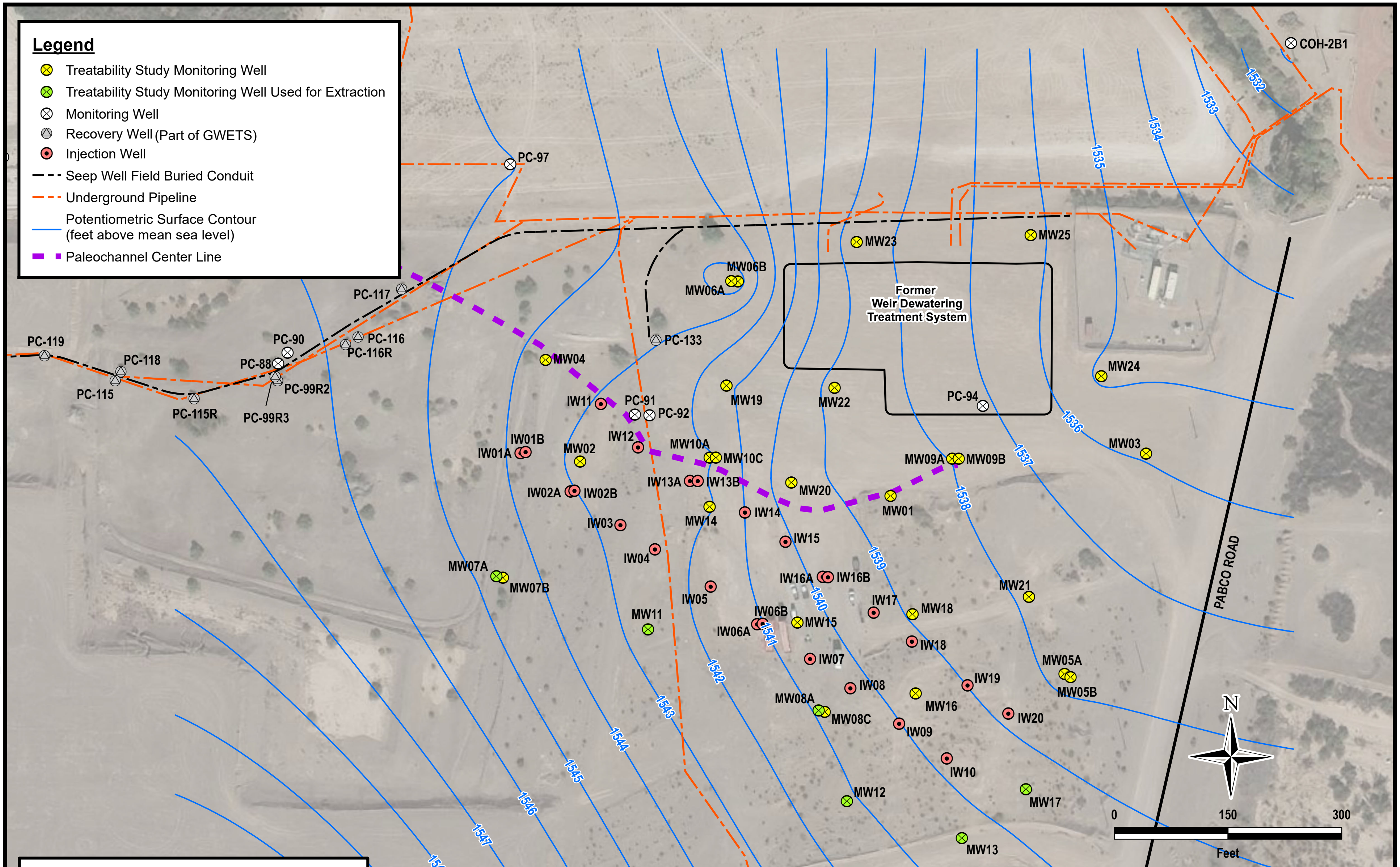
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY
2019 ANNUAL PROGRESS REPORT
HENDERSON, NEVADA

TREATABILITY STUDY LOCATION

PROJECT NO.:	117-7502018
DATE:	APRIL 01, 2020
DESIGNED BY:	ACC

Figure No.
1



\\TTS134FS1\GEOSUPVOL1\PROJECTS\NERT\GIS\M11_2019PROGRESSRPT_FIGURE2_TSLAYOUT.MXD

Notes:
1. Field Test Area located within Parcel 161-31-101-002.
2. The prefix 'SWTFS-' not shown for wells labeled as MW or IW. (MW03 = SWTFS-MW03)
3. Groundwater potentiometric contours presented are based on water levels collected during the groundwater sampling event in December 2019.
4. Imagery Source: Esri World Map, May 2017.

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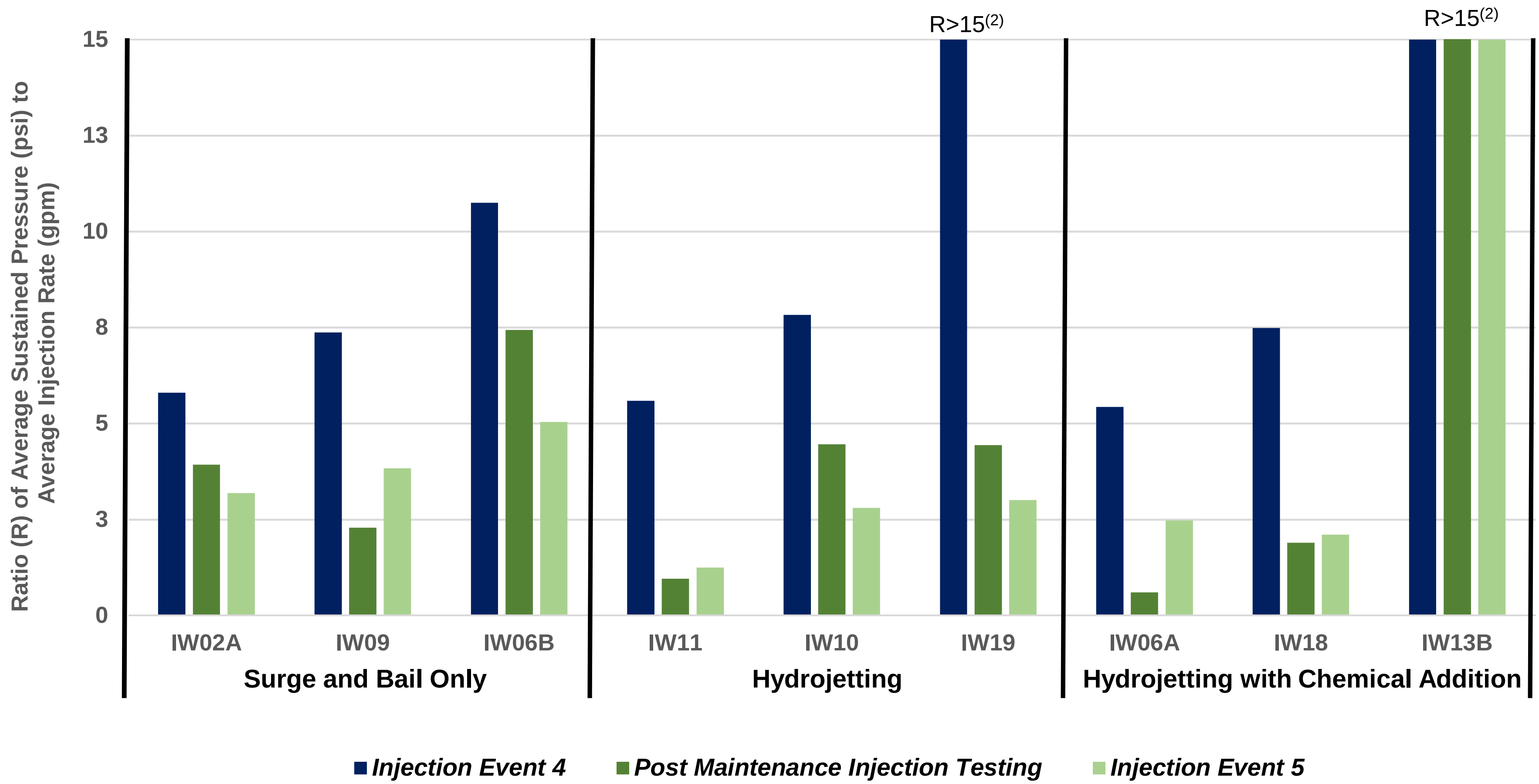
TREATABILITY STUDY LAYOUT

Project No.:	117-7502018
Date:	AUGUST 18, 2020
Designed By:	ACC
Figure No.	2



Notes:
R - ratio of average sustained pressure to average injection rate
psi - pounds per square inch
gpm - gallons per minute
(1) Well maintenance (surge and bail only, hydrojetting, or hydrojetting with chemical addition) performed between injection events 4 and 5.
(2) No injections possible at pressures less than permitted limit of 35 psi.
(3) Note that the prefix "SWFTS-" was removed from well name displayed. IW02A indicates injection well SWFTS-IW02A.

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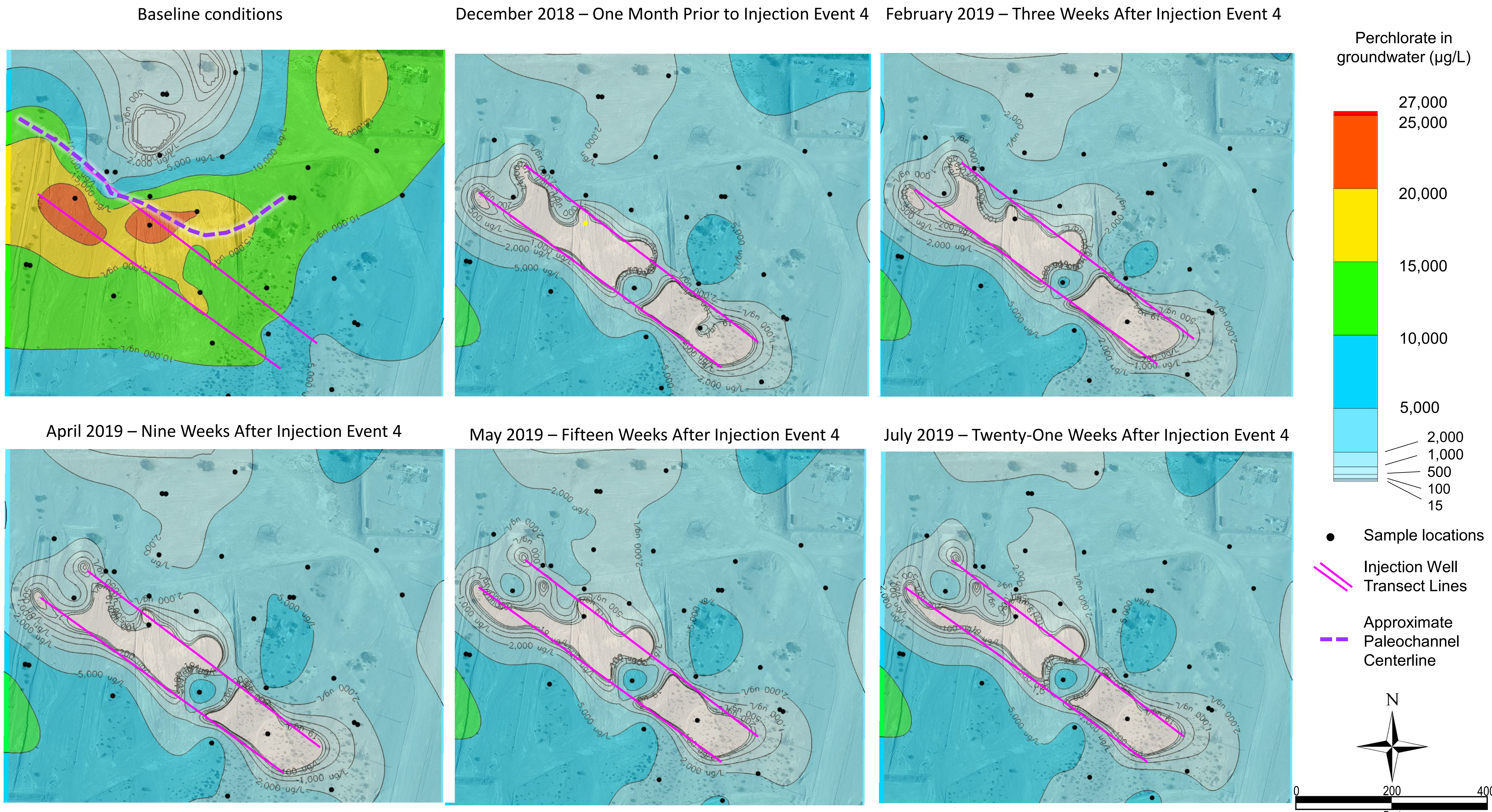
INJECTION WELL PERFORMANCE BY WELL MAINTENANCE METHOD(1)

Project No.:	117-7502019
Date:	APRIL 1, 2020
Designed By:	ES
Figure No.	3



Notes:

1. Each image represents a horizontal slice through the interpolated perchlorate concentration plume at 1522 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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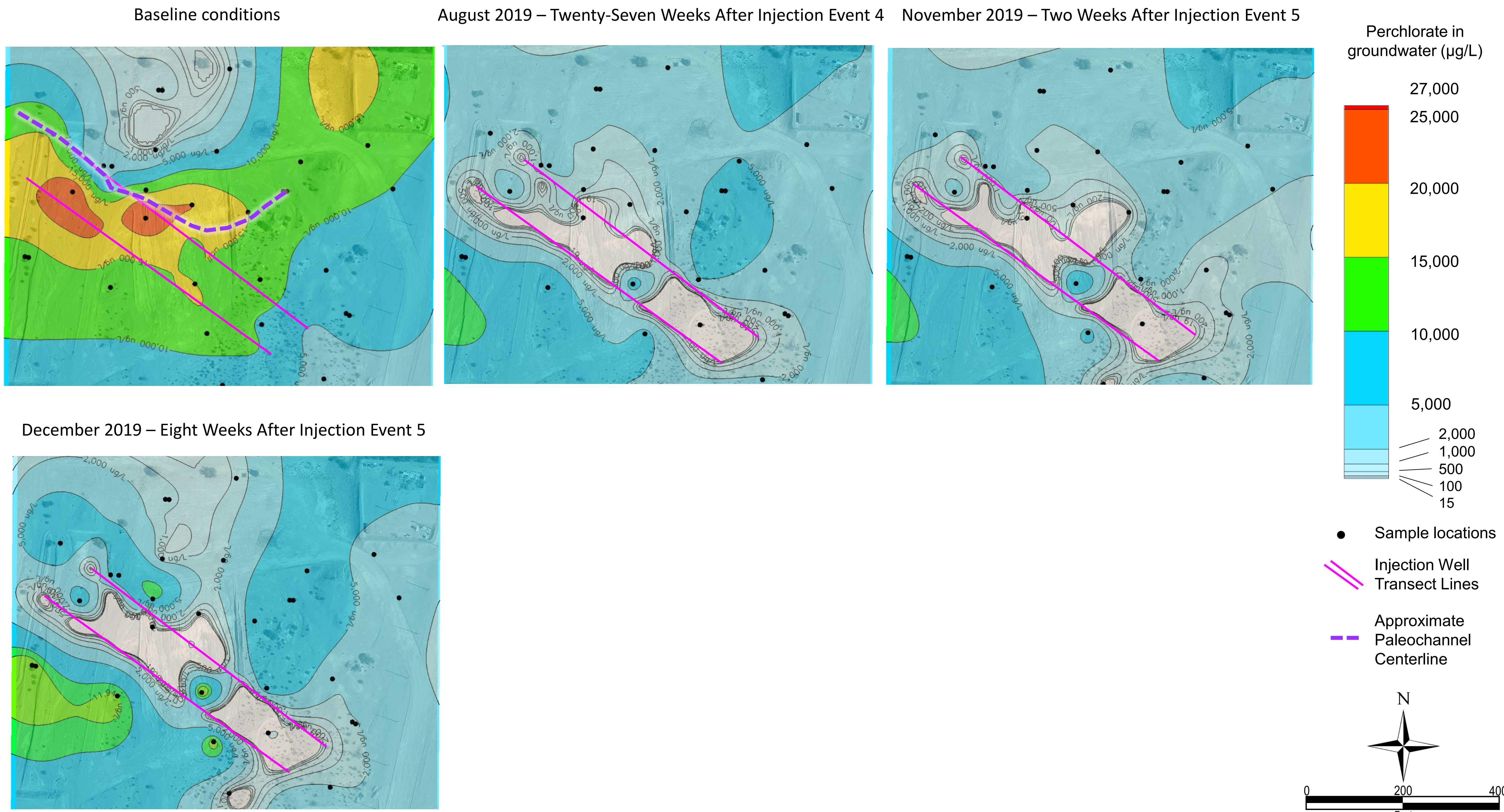
	PERCHLORATE DISTRIBUTION IN GROUNDWATER – DECEMBER 2018 TO JULY 2019

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	CKG
Figure No.	**4A**



Notes:

1. Each image represents a horizontal slice through the interpolated perchlorate concentration plume at 1522 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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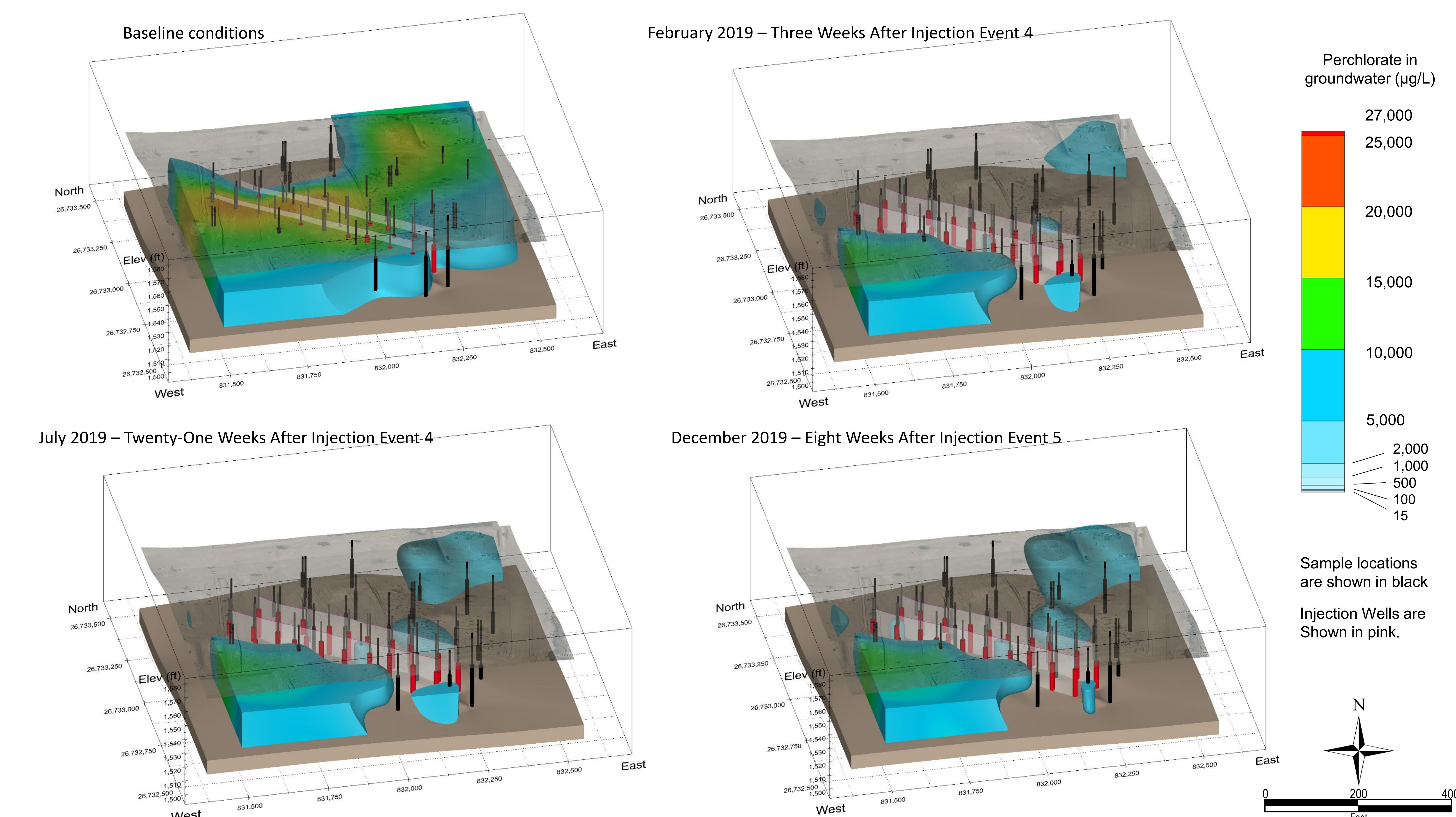
2019 ANNUAL PROGRESS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER – AUGUST 2019 TO DECEMBER 2019

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	CKG
Figure No.	**4B**



Notes:
1. Each image represents the interpolated perchlorate concentration plume where concentrations exceed 5,000 µg/L.
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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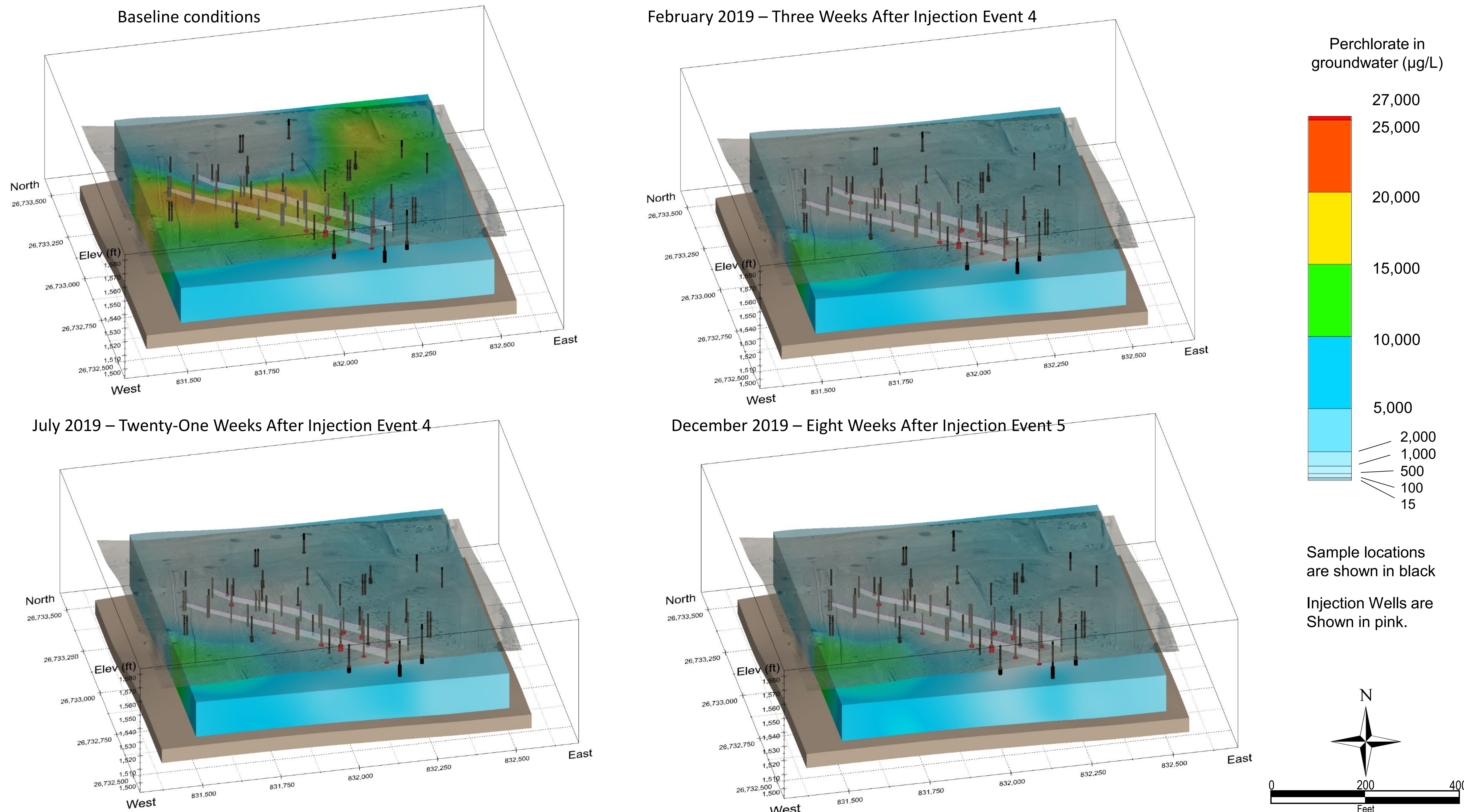
3D VISUALIZATION OF PERCHLORATE DISTRIBUTION IN GROUNDWATER FOR CONCENTRATIONS GREATER THAN 5,000 µg/L

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	CKG
Figure No.	**4C**



Notes:

1. Each image represents the interpolated perchlorate concentration plume for all concentrations.
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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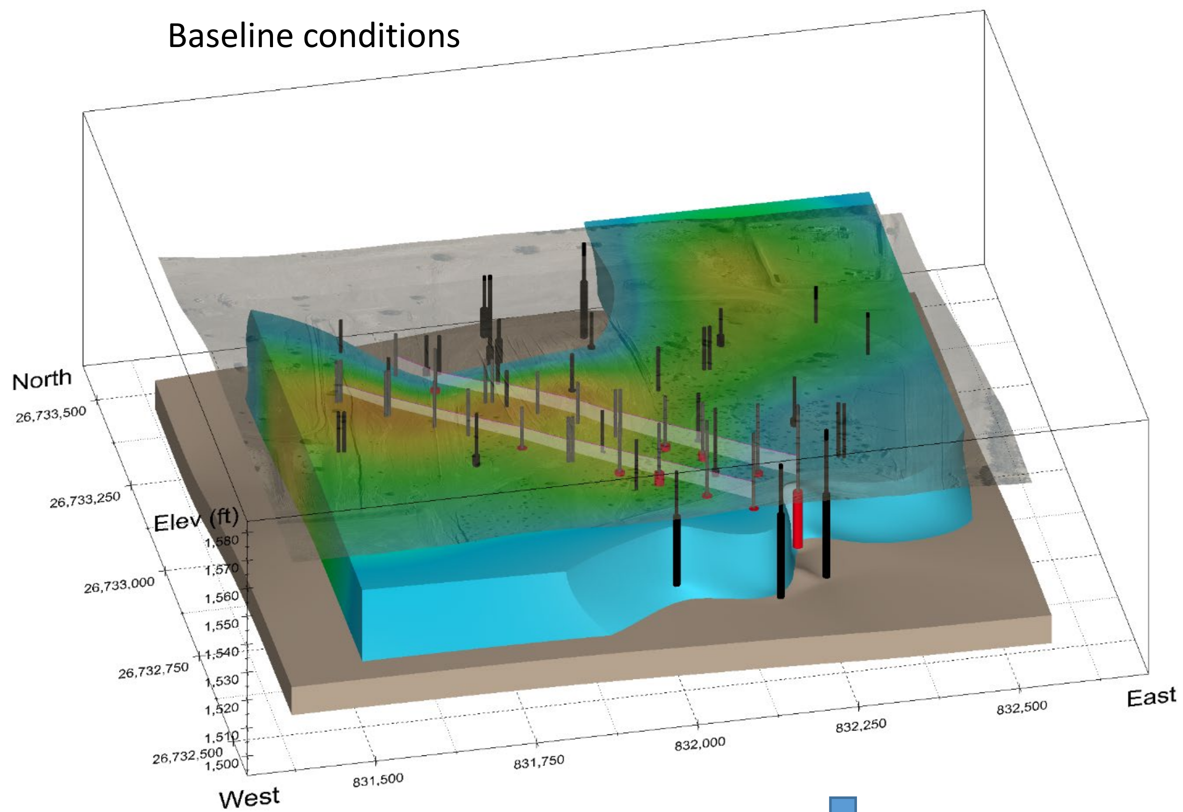
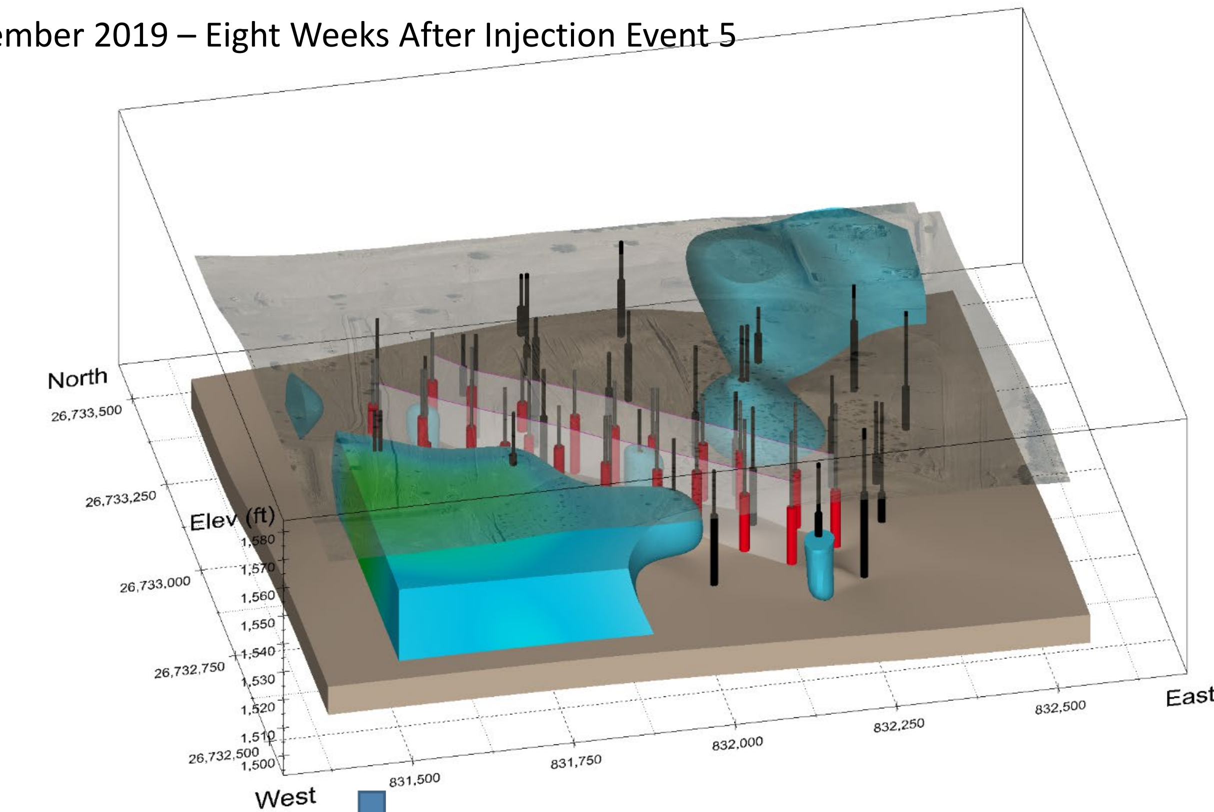
3D VISUALIZATION OF PERCHLORATE DISTRIBUTION IN GROUNDWATER FOR ALL DETECTED CONCENTRATIONS

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	CKG
Figure No.	**4D**

Baseline conditions



December 2019 – Eight Weeks After Injection Event 5

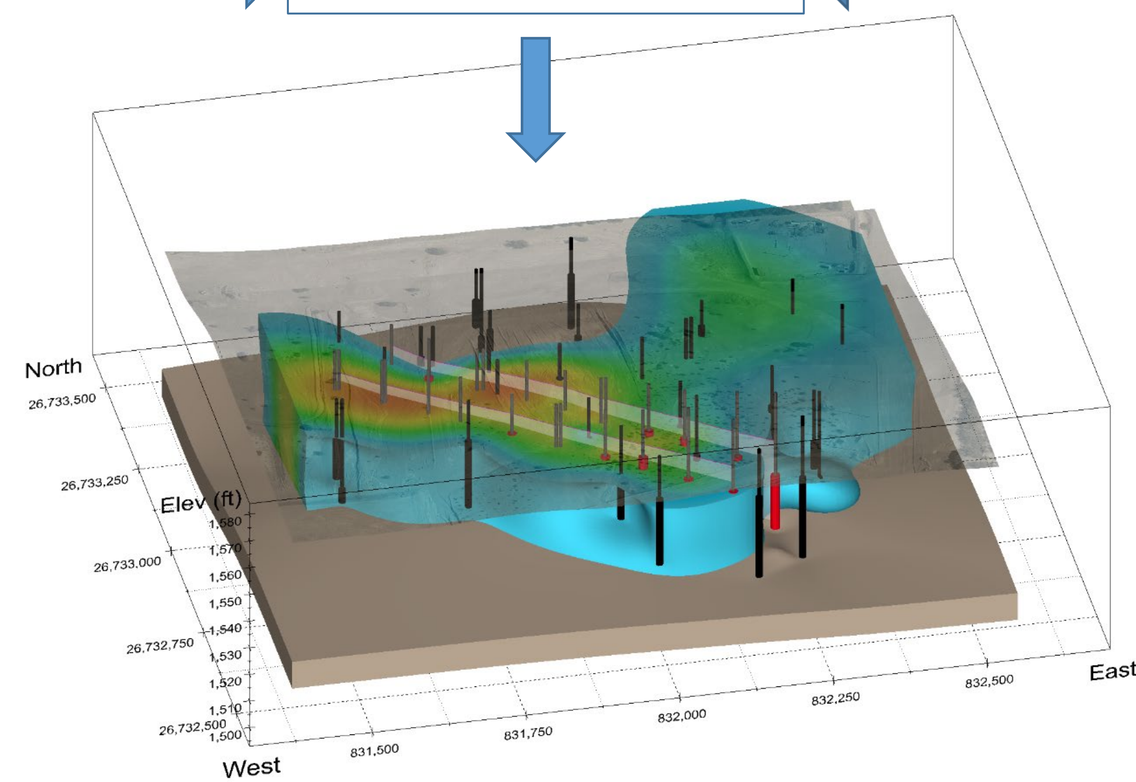


Perchlorate in groundwater (μg/L)

27,000
25,000
20,000
15,000
10,000
5,000
2,000
1,000
500
100
15

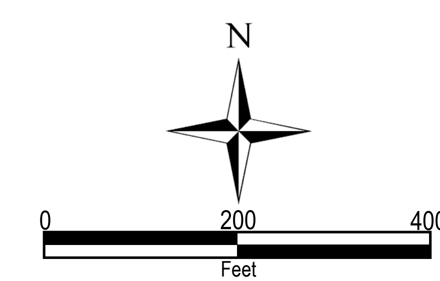
Baseline - December 2019

Visualization of Perchlorate Treated through December 2019



Sample locations are shown in black

Injection Wells are Shown in pink.



Notes:

1. Each image represents the interpolated perchlorate concentration plume where concentrations exceed 5,000 μg/L.
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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3D VISUALIZATION OF TREATED PERCHLORATE GREATER THAN 5,000 μg/L DURING TREATABILITY STUDY

Project No.:	117-7502019
Date:	April 30, 2020
Designed By:	CKG
Figure No.	4E

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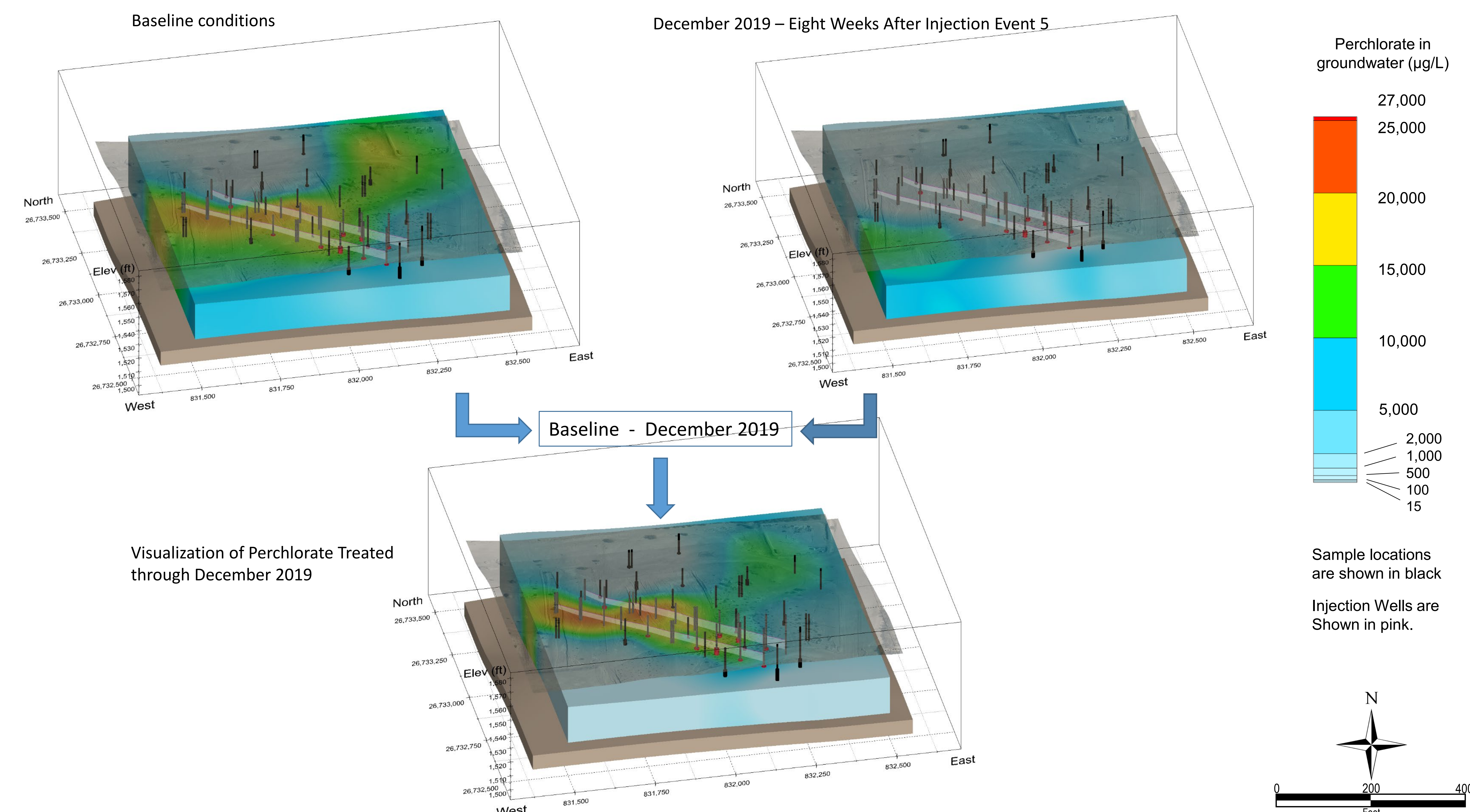

Notes:
1. Each image represents the interpolated perchlorate concentration plume for all concentrations.
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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3D VISUALIZATION OF TREATED PERCHLORATE DURING TREATABILITY STUDY

Project No.:	117-7502019
Date:	April 30, 2020
Designed By:	CKG
Figure No.	4F

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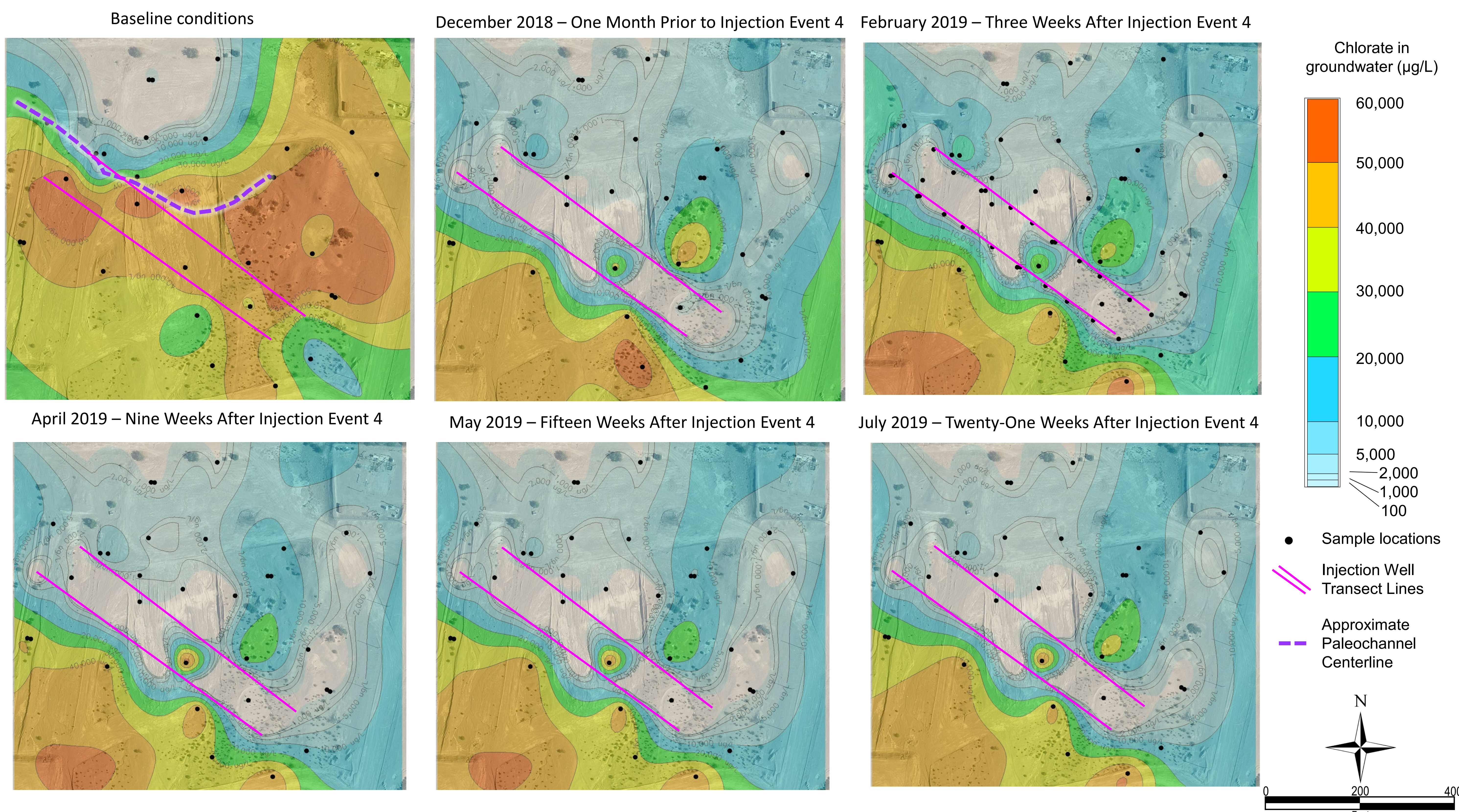

Notes:

1. Each image represents a horizontal slice through the interpolated chlorate concentration plume at 1522 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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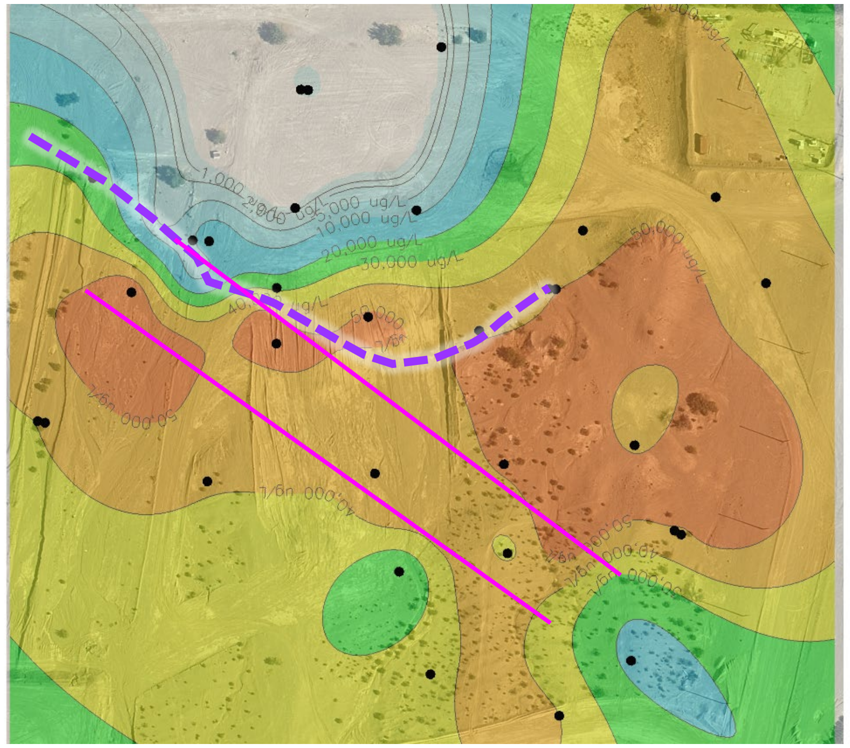
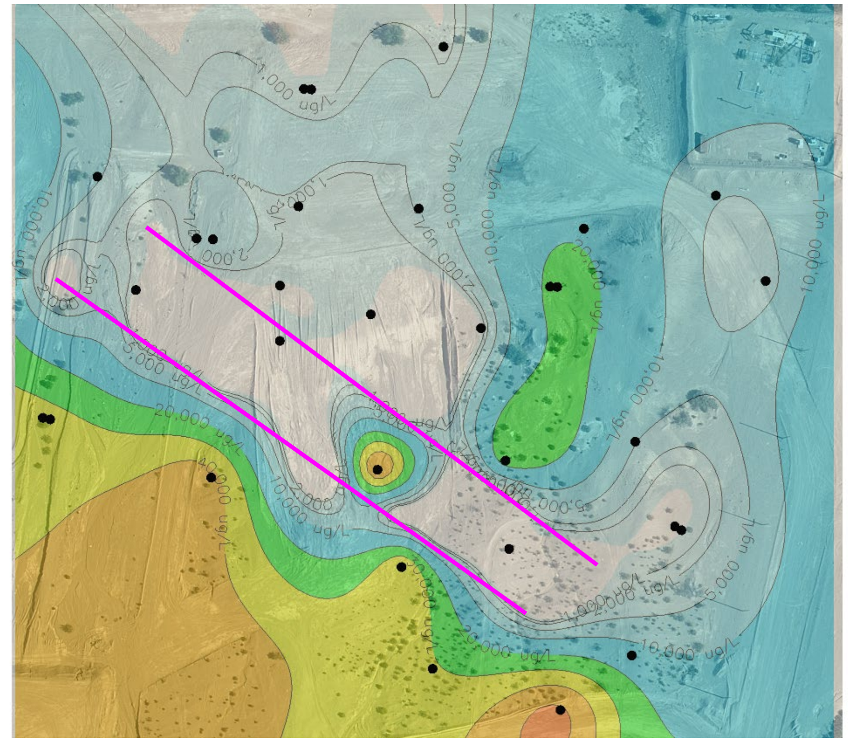
CHLORATE DISTRIBUTION IN GROUNDWATER – DECEMBER 2018 TO JULY 2019

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	BCS
Figure No.	**5A**

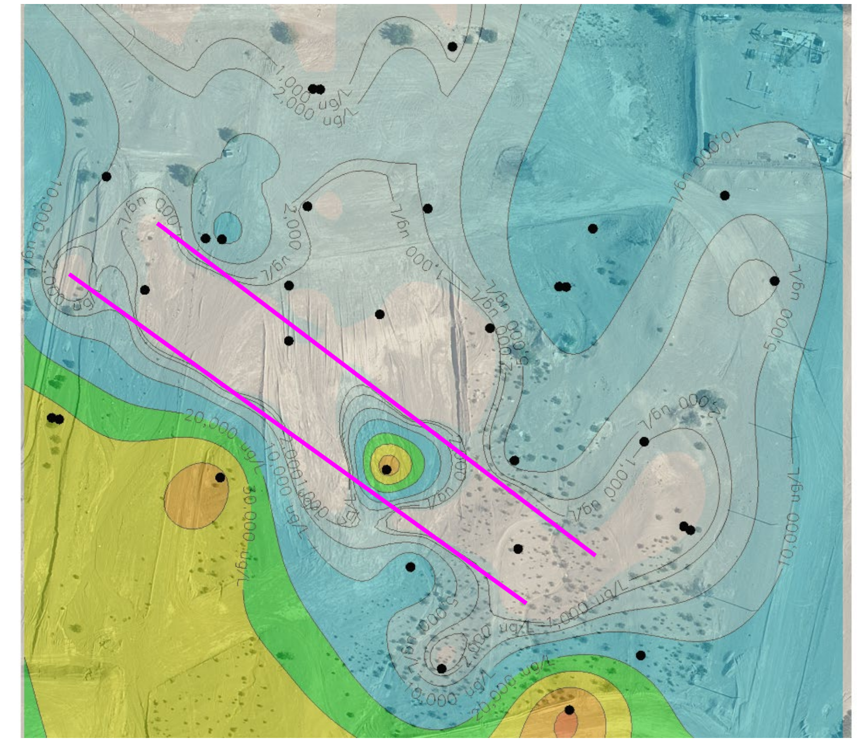
Baseline conditions



August 2019 – Twenty-Seven Weeks After Injection Event 4



November 2019 – Two Weeks After Injection Event 5



Chlorate in groundwater (µg/L)

60,000
50,000
40,000
30,000
20,000
10,000
5,000
2,000
1,000
100

● Sample locations

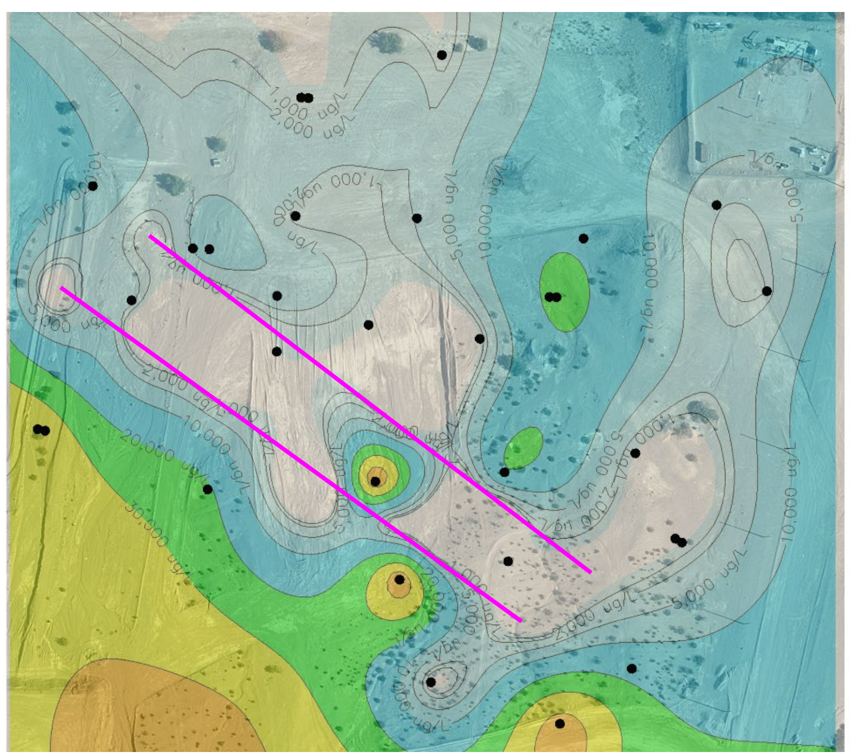
Injection Well Transect Lines

Approximate Paleochannel Centerline

N

0 200 400
Feet

December 2019 – Eight Weeks After Injection Event 5



Notes:

1. Each image represents a horizontal slice through the interpolated chlorate concentration plume at 1522 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth and fifth injection events (January/February 2019 and October 2019).

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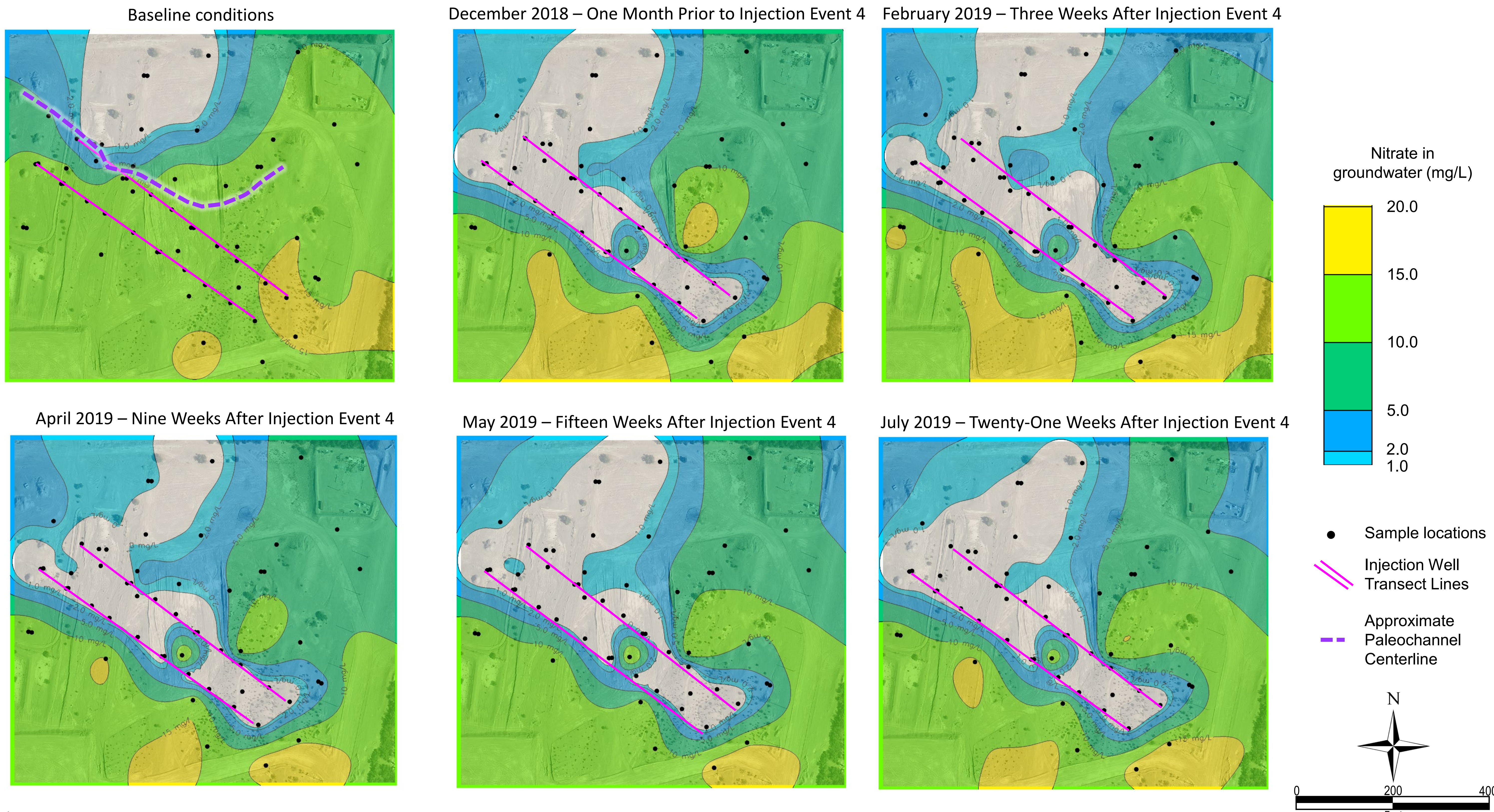
CHLORATE DISTRIBUTION IN GROUNDWATER – AUGUST 2019 TO DECEMBER 2019

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	BCS
Figure No.	**5B**

T:\NERT\M11\ppt_Figs\2020\Report Figure 10a-c. chlorate_GW_Baseline_2019.pptx



Notes:

1. Each image represents a horizontal slice through the interpolated nitrate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth injection event in January/February 2019.

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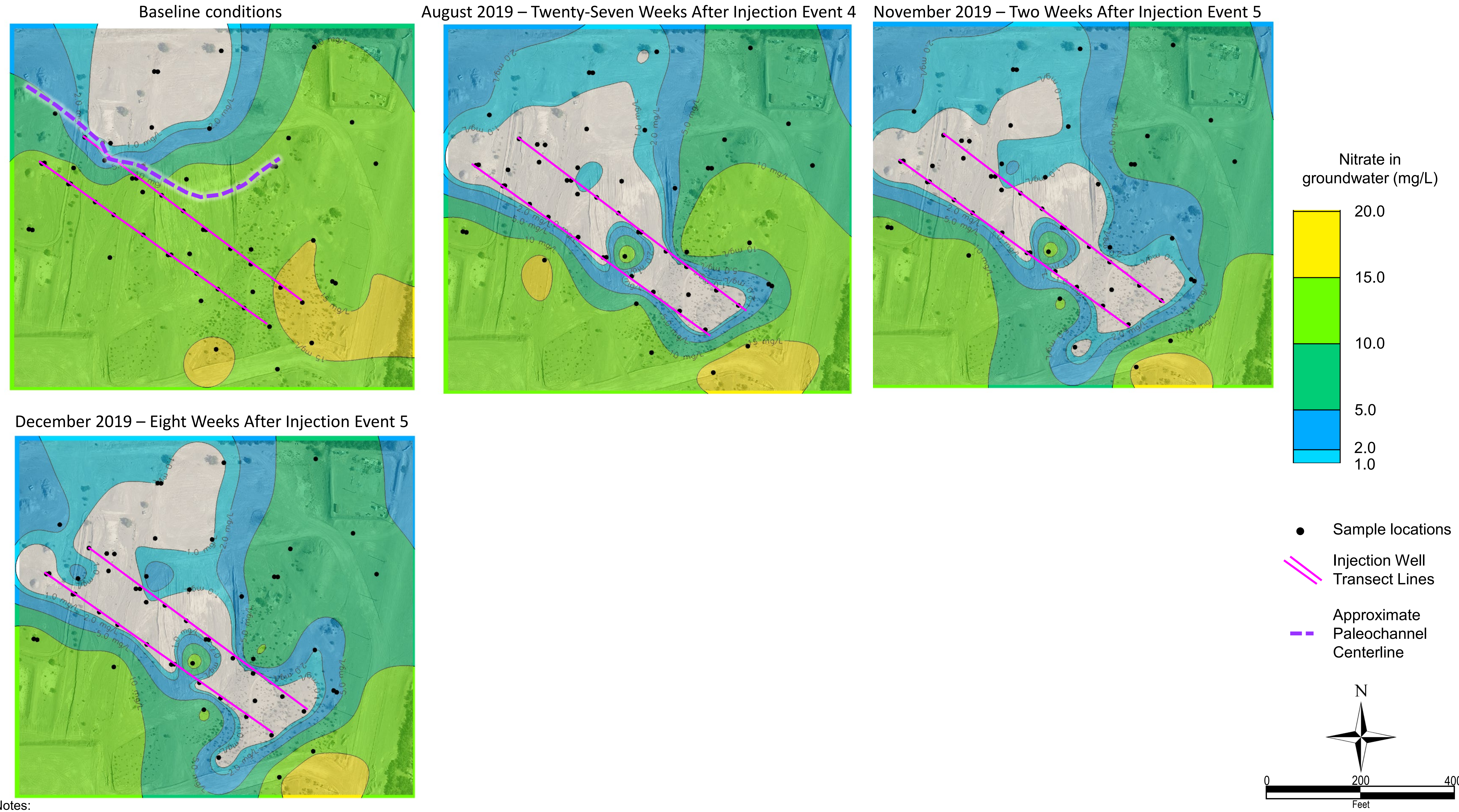
NITRATE DISTRIBUTION IN GROUNDWATER – DECEMBER 2018 TO JULY 2019

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	BCS
Figure No.	6A

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



Notes:

1. Each image represents a horizontal slice through the interpolated nitrate concentration plume at 1521 feet amsl (above mean sea level).
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
3. Injection events have occurred in August/September 2017, January/February 2018, June 2018, January/February 2019 and October 2019. Images presented in this figure represent groundwater sampling events that have occurred following the fourth injection event in January/February 2019.

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

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NITRATE DISTRIBUTION IN GROUNDWATER – AUGUST 2019 TO DECEMBER 2019

Project No.:	117-7502018
Date:	April 30, 2020
Designed By:	BCS
Figure No.	**6B**