Seep Well Field Area Bioremediation Treatability Study

2020 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
Cascade	Cascade Technical Services
DO	Dissolved Oxygen
DVSR	Data Validation Summary Report
EVO	Emulsified Vegetable Oil
FS	Feasibility Study
Gpm	Gallons per Minute
ISB	In-Situ Bioremediation
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
O&M	Operation and Maintenance
ORP	Oxidation-Reduction Potential
PLFA	Phospholipid Fatty Acids
PRG	Preliminary Remediation Goal
Psi	Pounds per Square Inch
QA/QC	Quality Assurance/Quality Control
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
USEPA	United States Environmental Protection Agency

CERTIFICATION

Seep Well Field Area Bioremediation Treatability Study 2020 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: 9/29/21

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 2020 Annual Progress Report

September 29, 2021

David S. Wilson, CEM
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Tetra Tech, Inc.

Date

Nevada CEM Certificate Number: 2385
Nevada CEM Expiration Date: September 19, 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 2020 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 January 2020 through December 2020 (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) and recommendations from the NDEP-approved *Seep Well Field Area Bioremediation Treatability Study – 2019 Annual Progress Report* (Tetra Tech, 2020b) (Referred to herein as 2019 Annual Progress Report).

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).

Since the SWF Area Bioremediation Treatability Study demonstrated that ISB can be effective at reducing perchlorate concentrations in groundwater based on multiple injection events performed within the area, NERT recommended that this treatability study be continued to evaluate long-term operation and maintenance requirements. Factors being evaluated for long term operation and maintenance include injection frequencies, injection well pressures and flow rates, and injection well maintenance requirements. 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 effective at achieving the remedial action objectives, but also equally important to evaluate key components of the alternative that will make it successful with regards to both implementation and long-term operation and maintenance. This study extension was detailed in Treatability/Pilot Study Modification No.6, which was approved by NDEP on December 14, 2018.

1.2 OBJECTIVES

Because the original SWF Area Bioremediation Treatability Study demonstrated the effectiveness of the ISB technology at reducing perchlorate and chlorate concentrations in groundwater, 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 within the NERT Remedial Investigation (RI) Study Area. Specifically, the objectives of the study extension are as follows:

- 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 within the NERT RI Study Area related to evaluation of the following:
    - 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; and
    - Costs associated with long-term operation and maintenance (O&M) 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 of 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. From 2017 through 2020, six injection events were performed as part of the SWF Area Bioremediation Treatability Study. All injection events have been performed by Cascade Technical Services (Cascade) under Tetra Tech oversight and direction. The first three injection events were performed under the original treatability study scope of work and were summarized in the Results Report (Tetra Tech, 2019a). The fourth and fifth injection events were performed as part of Modification No. 6 activities and were summarized in the 2019 Annual Progress Report (Tetra Tech, 2020b). One injection event (Injection Event 6) was performed during this reporting period (January 2020 through December 2020). This section provides a summary of this sixth injection event, which includes a discussion of injection event activities, quantities, procedures, and frequency.

2.1 INJECTION EVENT 6

The sixth injection event was performed from May 29 through June 18, 2020. 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. During this injection event, in-line mixing was evaluated as an alternative substrate mixing technique compared to batch mixing, which was the mixing technique used in previous injection events. The in-line mixing process is detailed in Section 2.1.2.

2.1.1 Designed Injection Quantities

As stated in the Results Report and the 2019 Annual Progress Report, the designed carbon substrate and distribution water requirements for the ISB system were determined based on several criteria including:

- 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 engineers/remedial designers; and
- Discussions with EOS Remediation (the manufacturer of the selected EVO product).

Ultimately, an oil retention ratio was employed as the governing criterion for the selection of EOS® PRO quantities during the first injection event, and injection quantities were varied during the first three injection events as part of the treatability study injection design process, as discussed in the Results Report (Tetra Tech, 2019a). 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 injected during the first injection event, resulted in robust perchlorate and chlorate treatment and the sustainment of reducing conditions. Therefore, the same general quantities were injected during subsequent activities performed to date under Modification No. 6, namely Injection Event 4, Injection Event 5, and Injection Event 6.

The quantities injected during Injection Event 6 included a total of 17,084 gallons of EOS® PRO, 367 gallons of glycerin, 120 gallons of phosphate solution, and 300 pounds of sodium sulfite. Glycerin serves as an immediate source of carbon to rapidly drive the groundwater anaerobic and reduce acclimation time. 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 acts 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, the same water source as for 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. Extracted groundwater was then batch mixed with amendments in the frac tanks before being blended with EOS® PRO via in-line mixing to achieve a dilution ratio of 1:4 parts of EOS® PRO:water. Following injections of carbon substrate and amendments, approximately 344,449 gallons of extracted groundwater were injected as distribution water. Appendix A presents tabulated summaries of the injection and extraction quantities.

2.1.2 Injection Procedures

The overall injection system and framework for the first five injection events followed the same general protocols and procedures for batch mixing of the injectate solution. As recommended in the 2019 Annual Progress Report, in-line mixing was evaluated as an alternative substrate mixing technique during the sixth injection event in accordance with the NDEP-approved *In-Situ Bioremediation Injections – In-line Mixing and Injections Field Guidance Document* (Tetra Tech, 2020a). As part of this in-line mixing process, extracted groundwater and amendments (non-EVO amendments of glycerin, phosphate solution, and sodium sulfite) were mixed in batches following the same general procedures of previous injection events. Extracted groundwater was collected in the two 16,400-gallon frac tanks until the targeted water quantity was achieved for each batch of amendments/groundwater. The required quantities of glycerin, phosphate solution, and sodium sulfite (based on the injectate solution recipe) were then added to the frac tank of extracted groundwater. The amendments/groundwater solution was recirculated within the frac tank using a submersible pump to ensure mixture consistency prior to in-line mixing with the EOS® PRO.

After the groundwater and amendments had been mixed, one of the centrifugal pumps was connected directly to the EOS® PRO delivery tank to be solely dedicated to pumping the EOS® PRO product. The second centrifugal pump was connected to the frac tank containing the amendments/groundwater solution. The amendments/ groundwater solution and EOS® PRO were each then pumped through a static in-line mixer (approximately 24-inches in length and 2.5” in diameter) to blend the injectate solution at the targeted ratio of 1 part EOS® PRO to 4 parts amendments/groundwater solution prior to subsurface injection. The dilution of the EOS® PRO was controlled using the variable speed function on the centrifugal pumps. Multiple flow meters were used to measure flow at different points within the injection and mixing system to track mixing accuracy.

The blended injectate solution flowed from the outlet of the static in-line mixer to the injection wells via an injection manifold system that was connected to up to 10 injection wells at a single time. Upon completion of carbon 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. 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.4 and A.5. Following completion of the injections, the frac tanks were cleaned and all equipment was dismantled and removed from the study area.

2.1.3 Injection Well Performance

During the sixth 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 18 pounds per square inch (psi). Twenty-one of the 25 injection wells received their targeted injectate solution and follow-up distribution water quantities. Four of the 25 injection wells (namely, SWFTS-IW12, SWFTS-IW13B, SWFTS-IW15, and SWFTS-IW19) only received a portion of their designed carbon substrate solution quantity before not accepting injectate additions at 35 psi, which is the maximum permissible pressure established in NERT's Underground Injection Control (UIC) injection permit. As a result, the additional carbon substrate quantities targeted for those wells were distributed into nearby injection wells. Despite only receiving a portion of their target carbon substrate quantities, all four injection wells successfully accepted the targeted follow-up distribution water at reasonable injection rates and pressures.

Performance of injection wells SWFTS-IW12 and SWFTS-IW15 has been acceptable in all five of the previous injection events, with injection pressure to injection rate ratios of less than 4. Although the overall injection rate and sustained pressure data indicate similar performance during Injection Event 6, injection pressure to injection rate ratios during the initial carbon substrate injections were elevated at SWFTS-IW12 and SWFTS-IW15, with ratios of 5.8 and 11.7, respectively. However, injection well performance improved significantly during the injection of follow-up distribution water, when injection pressure to injection rate ratios did not exceed 2 at either injection well. This variance is possibly due to the difference in the viscosity of the EOS® PRO blended with water versus the viscosity of distribution water only, with the EOS® PRO injectate solution likely requiring a higher pressure to enter the formation. Injection rates and pressures will be evaluated during future injection events and, if needed, these injection wells may be scheduled for routine well maintenance.[1]

Both SWFTS-IW13B and SWFTS-IW19 have exhibited gradual upward trends in injection pressure and decreasing injection rates during previous injection events. As a result, these injection wells were included in the first injection well maintenance effort performed in September 2019 as described in the *Proposed Injection Well Maintenance Activities Technical Memorandum* (referred to herein as Well Maintenance Technical Memorandum) (Tetra Tech, 2019b) and 2019 Annual Progress Report. This maintenance effort included evaluation of several different types of maintenance efforts, which resulted in hydrojetting with chemical addition performed on injection well SWFTS-IW13B and hydrojetting only (no chemical addition) on injection well SWFTS-IW19. Because injection well SWFTS-IW13B did not accept injectate during the fifth injection event (following the September 2019 well maintenance event), it was selected to receive a second round of maintenance in February 2020 (discussion of 2020 maintenance activities is presented in Section 3). The second well maintenance effort (also hydrojetting with chemical addition) made significant improvements to the performance of injection well SWFTS-IW13B, which during the sixth injection event accepted injectate (albeit in quantities slightly below the original target quantity) and follow-up distribution water. Injections into injection well SWFTS-IW19 were successful during the fifth injection event following well maintenance activities in September 2019. However, during the sixth injection event, injection well SWFTS-IW19 only accepted a portion of the targeted carbon substrate solution but successfully accepted the full targeted follow-up distribution water. Based on observations during the sixth injection event, injection well maintenance consisting of hydrojetting with chemical addition will be recommended for injection wells SWFTS-IW13B and SWFTS-IW19 prior to the seventh injection event.

[1] Subsequent to this reporting period, injection well maintenance was performed in February 2021 on injection well SWFTS-IW15 using surge and bail since this was the first maintenance activity performed on this injection well. Injectability was improved with an average injection rate of 11 gpm during the seventh injection event performed in February/March 2021 compared to the previous sixth injection event in May/June 2020 with an average injection rate of 6.9 gpm. The results of this maintenance event and seventh injection event will be reported in the 2021 Annual Progress Report.

2.2 EVALUATION OF MIXING OPERATIONS

Prior to injections, preparation of the designed carbon substrate solution (EOS® PRO, amendments, and dilution water) is a key operational component of ISB systems. Batch mixing has been the standard process used to prepare injectate solution for all five previous injection events performed as part of this treatability study. Batch mixing was primarily selected due to the large quantities of EVO involved, rapid timeframe of injections, advantages of having a system construction with fewer mechanical connections, and ease of mixing and blending the solution and amendments. As described in Section 2.1.2, in-line mixing was evaluated as an alternative substrate mixing technique during the sixth injection event to collect information for ISB remedy evaluation in the FS. As part of this in-line mixing process, extracted groundwater and amendments (non-EOS® PRO amendments of glycerin, phosphate solution, and sodium sulfite) were mixed in batches following the same general procedures of previous injection events. The amendments/groundwater solution and EOS® PRO were then each pumped via centrifugal pumps through a static in-line mixer to blend the injectate solution at the targeted ratio of 1 part EOS® PRO to 4 parts amendments/groundwater prior to subsurface injection. As previously explained, the dilution of the EOS® PRO was controlled using the variable speed function on the centrifugal pumps. Flow meters were installed at various points in the system including at the outlet of each centrifugal pump before entering the static mixer. In addition, specific gravity measurements of the mixed injectate solution were collected periodically during active injections to evaluate mixture consistency.

The following observations were noted during implementation of in-line mixing during the sixth injection event at the SWF Area Bioremediation Treatability Study:

- Based on field observations, flow from the EOS® PRO tanker and tank of groundwater/amendments must be continuously monitored to maintain proper dosage at the required injection rates and concentrations, with the pumps requiring continual manual adjustments as tank levels decrease during injections. As a result, the in-line mixing process was more labor intensive with regards to field labor, data collection, and troubleshooting compared to traditional batch mixing operations.
- Maintaining precise control over the ratio of EOS® PRO to the amended groundwater solution is required to ensure equitable distribution of carbon substrate and nutrients throughout the injection well transects. Although specific gravity measurements collected during the sixth injection event were within +/- 10 percent of the targeted specific gravity for the designed mixture, the measurements varied considerably within this range, which indicates an overall less consistent injection mixture throughout the duration of injections. Because the injections are not performed at all 25 injection wells simultaneously, a less consistent injection mixture over time could result in uneven distribution of carbon substrate among the injection well transects. Specific gravity measurements that are regularly collected during the batch mixing and injection process have indicated that batch mixing operations result in a reliable and controlled mixing and injection process with relatively consistent specific gravity measurements throughout the injection process.
- One of the distinct advantages of batch mixing when compared to in-line mixing is the ability to confirm the exact quantities of carbon substrate and amendments that are added to each batch through a series of verification checks. During the mixing process, tank level measurements and flow meter readings are collected before, during, and/or after addition of each injectate solution to confirm that required blending ratios are prepared according to the design. In addition, injection of the carbon substrate solution in batches allows for direct comparison of batch quantities with cumulative injection point totals at discrete intervals throughout the injection event.
- Lastly, the cumulative daily injection quantities during the first part of the in-line mixing injection event, which focused on the carbon substrate injections, were lower than injection events that use batch mixing. This lower daily injection quantity resulted from continuous field modifications and equipment adjustments required to produce a consistent injectate mixture. This aspect is likely to be of significance during large-

scale and prolonged applications of ISB from an overall implementability and cost perspective and therefore, is valuable knowledge garnered prior to remedy evaluation in the FS.

2.3 EVALUATION OF INJECTION FREQUENCY

As previously described in Section 1.2, the objectives of the treatability study extension include evaluating 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 the objective of evaluating 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 and distribution water quantities are key long-term O&M components that determine both remedy effectiveness and associated cost to maintain the remedial system.

Since the study began in 2017 through this reporting period, a total of six injection events have been performed as part of the original study and subsequent study extension. ***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
Event 5 to 6	8

As presented in ***Table 1***, the injection frequency has decreased over time (i.e., more months 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. Additional reductions in the sampling program based on the 2020 sampling results are recommended in Section 5. 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

ISB performed through periodic injections of a slow-release substrate is generally considered a passive remedy. As part of the ISB process, both perchlorate-degrading biomass and precipitated organic and inorganic solids are expected to develop over time, which can result in localized permeability reductions within the injection wells and surrounding filter pack. Injection wells that periodically encounter permeability reduction due to buildup of biomass and/or inorganic precipitates (as indicated by injection pressure fluctuations) generally require occasional physical and/or chemical well maintenance. Therefore, some degree of injection well maintenance will be necessary should ISB be selected as part of the final remedy (USEPA, 2013).

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. To address these concerns, this study extension continues to evaluate the maintenance requirements to sustain long-term injectability in an ISB remedy. The previous 2019 Annual Progress Report presented a thorough discussion of the biomass and precipitates typically observed in injection wells associated with ISB systems, as well as a summary and results of the injection well maintenance activities performed in 2019 (Tetra Tech, 2020b).

Based on the results of the 2019 well maintenance activities and injection well performance during the fifth injection event conducted in October 2019, additional limited injection well maintenance activities were performed in February 2020. This section provides a summary of the February 2020 injection well maintenance activities and a preliminary evaluation of the long-term effects of the well maintenance activities performed to date in terms of technique effectiveness and frequency of application.

3.1 INJECTION WELL SELECTION

As described in the Well Maintenance Technical Memorandum and 2019 Annual Progress Report, injection wells are selected for maintenance based on review of their respective injection pressures and injection rates collected during the most recent injection event (as well as trends throughout all injection events to date). Ratios of the injection pressure to injection rates observed during the injection events are calculated to highlight injection wells that exhibited an increase in injection pressures and a decrease in injection rates, thereby exhibiting higher ratios of pressure to flow. The empirical threshold or early signal for the need of well maintenance currently being considered is an injection pressure to injection rate ratio greater than 5.0. It should be noted that as this treatability study extension continues, this threshold may be adjusted based on collection of additional data.

As described in the 2019 Annual Progress Report, injection well maintenance was performed on nine injection wells in 2019 to evaluate a variety of maintenance techniques. Following the 2019 injection well maintenance activities, improvements in injectability were observed at eight of the nine injection wells. Although the 2019 post-maintenance specific capacity testing results did show a slight improvement when compared to the pre-maintenance results, injection well SWFTS-IW13B did not accept injectate during the fifth injection event. As discussed in the 2019 Annual Progress Report, the initial resistance of SWFTS-IW13B to improvements in injectability may in part be due to the shorter injection well screen and relatively high proportion of inorganic calcium precipitates observed at SWFTS-IW13B. As a result, injection well SWFTS-IW13B was selected for additional well maintenance activities in February 2020.

In addition, injection well SWFTS-IW01B was also selected for well maintenance in February 2020. This injection well was selected based on the injection pressure to injection rate ratio of 7.8 observed during Injection Event 5, which was the highest ratio at any injection well during the fifth injection event. In addition, the injection pressure to injection rate ratio of 7.8 is higher than ratios observed at SWFTS-IW01B during previous injection events. More detailed injection pressure and injection rate data are provided in Table A.6 of Appendix A.

3.2 INJECTION WELL MAINTENANCE ACTIVITIES

The second well maintenance effort was conducted on February 3 – 7, 2020. As part of this effort, hydrojetting was selected for injection well SWFTS-IW01B to address the elevated injection pressures and reduced injection rates observed during the fifth injection event. The presence of calcium precipitates at SWFTS-IW13B combined with the minimal improvement following the first maintenance event indicate that the most aggressive maintenance option using a combination of surge and bail with hydrojetting and the addition of chemicals (AQUA-CLEAR® MGA and AQUA-CLEAR® AE) was appropriate for injection well SWFTS-IW13B. Procedural details of these maintenance techniques are documented in the 2019 Annual Progress Report.

3.3 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.

3.3.1 Visual Inspection of Suspended Solids During Well Maintenance

During the initial surge/brush/bail activities conducted at each injection well, groundwater that was removed from the well 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 solids initially removed from the injection wells via brushing the well screen were soft with a malleable, soapy texture, and smeared easily with finger pressure, indicating the presence of calcium oleate (a breakdown product of EVO). Following the initial surge/brush/bail activities, one round of hydrojetting was conducted at injection well SWFTS-IW01B, while three successive rounds of hydrojetting/chemical addition were conducted at injection well SWFTS-IW13B. During hydrojetting/ chemical addition at SWFTS-IW13B, white relatively brittle inorganic precipitates were removed from the well during each successive round of hydrojetting, which may suggest that additional applications of these maintenance activities, even in the short time frame of a few days, can help remove additional solids from the surrounding filter pack to improve injectability even after injection well screen and casing are initially cleared. As the bulk of the accumulated solids were cleared from each injection well casing and screen, the groundwater that was removed from the well became relatively clear to light grey with only trace black organic fines, colloidal material, and/or inorganic precipitates.

3.3.2 Pre- and Post-Maintenance Aquifer Testing Results

Specific capacity testing was 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 on January 31, 2020, and during February 19 – 20, 2020, 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 0.1 gpm. The flow rate was then incrementally increased, provided that the injection well could support such pumping. During pre-maintenance testing, these low pumping rates resulted in excessive drawdown, a reduced number of steps completed, and relatively short pumping times for the step(s) completed. This was consistent with the findings of pre-maintenance specific capacity testing conducted during the first well maintenance event in 2019. Flow rates, drawdown, and water level recovery data were monitored throughout the test. During pre-maintenance testing of SWFTS-IW01B, which had not previously undergone well maintenance, the pump became clogged due to material present in the well. Therefore, the test was terminated, and water levels were monitored during recovery. Complete details on field procedures and data collection are provided in Appendix B.

Because drawdown in the wells did not stabilize during the relatively short steps completed, 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. As a measure of well efficiency, specific capacity, calculated by dividing the pumping rate by the 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 both SWFTS-IW01B and SWFTS-IW13B. During the post-maintenance testing, 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 B.

In conclusion, while specific capacity can be a useful measure of potential well injectability, the most appropriate approach in evaluating injectability is performance of injection testing. Therefore, as recommended in the 2019 Annual Progress Report, specific capacity testing will no longer be conducted as part of injection well maintenance activities for this study.

3.3.3 Evaluation of Post-Maintenance Injectability

Following completion of the well maintenance field activities, a short-term water injection test was performed from February 5 – 7, 2020. Injection testing was performed on the two wells included in the 2020 maintenance program (namely, SWFTS-IW01B and SWFTS-IW13B) and also on two additional wells (SWFTS-IW13A and SWFTS-IW20) to confirm that no maintenance was needed prior to the next injection event. The injection test consisted of injecting City of Henderson hydrant water into all four injection wells while monitoring both injection pressures and rates during injection. Injection testing data are provided in Table A.7 of Appendix A.

Injection wells SWFTS-IW01B and SWFTS-IW13B were selected for injection testing to evaluate post-maintenance injectability. Results were 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 injection wells that received well maintenance (SWFTS-IW01B and SWFTS-IW13B). As shown in Figure 3, improved injectability was demonstrated in both injection wells. Injection well SWFTS-IW01B, which exhibited an injection rate of 2.8 gpm during the fifth injection event, significantly improved and exhibited an injection rate of 20 gpm during the post-maintenance water injection test and an overall average of 7.1 gpm during the sixth injection event. Injection well SWFTS-IW13B, at which injectate was not accepted during the fourth or fifth injection events, also substantially improved and exhibited an injection rate of up to 9 gpm during post-maintenance water injection test. During the sixth injection event, SWFTS-IW13B accepted injections (less than the target for injectate solution but the full targeted quantity of distribution water) at an overall average of 3.8 gpm. Because well maintenance activities made significant improvements to the performance of this injection well, SWFTS-IW13B will undergo one more round of additional well maintenance before the seventh injection event, with the goal of the injection well accepting the full targeted injectate solution and distribution water.[2]

Injection wells SWFTS-IW13A and SWFTS-IW20 were included in the short-term water injection test to provide additional injection pressure and injection rate data between the fifth and sixth injection events. Specifically, injection well SWFTS-IW13A was selected since it is part of the paired injection well cluster with SWFTS-IW13B, which has had reduced injection capacity. SWFTS-IW20 was selected due to an increased injection pressure to

[2] Subsequent to this reporting period, injection well maintenance was performed in February 2021 on injection well SWFTS-IW13B using the combination of surge and bail, hydrojetting, and chemical addition. This injection well was successfully restored, with an injection rate of up to 13.6 gpm during the seventh injection event performed in February/March 2021. Additionally, all injection wells accepted the full targeted quantity of injectate and distribution water, with injection pressure to injectate flow rate ratios of less than 5.0, during the seventh injection event. The results of this maintenance event and seventh injection event will be reported in the 2021 Annual Progress Report.

injection rate ratio slightly above 5 during the fifth injection event. Test results indicate that both injection wells accepted water at reasonable injection rates (up to 22 gpm), which confirmed no maintenance was needed on either well prior to the sixth injection event.

3.4 PRELIMINARY EVALUATION OF LONG-TERM WELL MAINTENANCE

Evaluation of the O&M requirements to maintain long-term injectability of injection well networks associated with ISB systems at the NERT site is a key objective of this treatability study extension. Data collected regarding injection well maintenance frequency, optimal well maintenance techniques, and maintenance costs will be incorporated into the FS. Although a complete evaluation of long-term injection well maintenance will be performed at the conclusion of this study extension, a preliminary evaluation through this reporting period is included herein. ***Table 2*** presents a summary of well maintenance conducted at each injection well and the range of ratios of average sustained pressure to average flow rate observed during injection events before and after maintenance activities.

Table 2 Injection Well Maintenance Methods

Injection Well ID	Maintenance Event		Ratio of Average Sustained Pressure (psi) to Average Injection Rate (gpm)		
	September 2019	February 2020			
	After Injection Event 4	After Injection Event 5	Injection Event 4	Injection Event 5	Injection Event 6
SWFTS-IW01A	None	None	2.0	1.4	1.8
SWFTS-IW01B	None	**Hydrojetting**	2.4	7.8	2.2
SWFTS-IW02A	**Surge and Bail**	None	5.8	3.2	1.6
SWFTS-IW02B	None	None	4.3	2.0	2.4
SWFTS-IW03	None	None	2.2	2.8	1.6
SWFTS-IW04	None	None	2.7	1.8	1.9
SWFTS-IW05	None	None	0.6	3.2	1.7
SWFTS-IW06A	**Hydrojetting with Chemical Addition**	None	5.4	2.5	3.1
SWFTS-IW06B	**Surge and Bail**	None	10.7	5.0	9.8
SWFTS-IW07	None	None	1.5	3.4	1.3
SWFTS-IW08	None	None	2.0	2.0	2.0
SWFTS-IW09	**Surge and Bail**	None	7.4	3.8	3.2
SWFTS-IW10	**Hydrojetting**	None	7.8	2.8	2.4
SWFTS-IW11	**Hydrojetting**	None	5.6	1.2	1.9
SWFTS-IW12	None	None	2.2	1.2	2.7
SWFTS-IW13A	None	None	3.5	3.9	2.6
SWFTS-IW13B	**Hydrojetting with Chemical Addition**	**Hydrojetting with Chemical Addition**	– (1)	– (1)	8.4
SWFTS-IW14	None	None	1.5	2.4	2.9
SWFTS-IW15	None	None	3.6	3.3	2.9
SWFTS-IW16A	None	None	2.7	2.3	3.1
SWFTS-IW16B	None	None	2.9	2.5	3.1
SWFTS-IW17	None	None	3.9	1.4	3.3
SWFTS-IW18	**Hydrojetting with Chemical Addition**	None	7.5	2.1	3.0
SWFTS-IW19	**Hydrojetting**	None	– (1)	3.0	5.7
SWFTS-IW20	None	None	3.5	5.1	2.7

Injection Well ID	Maintenance Event		Ratio of Average Sustained Pressure (psi) to Average Injection Rate (gpm)		
	September 2019	February 2020			
	After Injection Event 4	After Injection Event 5	Injection Event 4	Injection Event 5	Injection Event 6
Total Wells Receiving Maintenance	**9**	**2**			

Notes:
1. No injections performed at this well due to zero flow at the maximum permissible pressure limit of 35 psi.
Bold font indicates wells that have had maintenance.

Six injection events have been performed over 4 years as part of this treatability study. Since inception of the treatability study, 15 of the 25 injection wells have required no injection well maintenance and continue to accept injectate solution at low injection pressure to injection flow rate ratios of less than 5.0. Of the 10 injection wells that have received well maintenance, all three well maintenance techniques (surge and bail, hydrojetting, and hydrojetting with chemical addition) have improved the injectability. Although initial efforts using hydrojetting with chemical addition were unsuccessful on injection well SWFTS-IW13B, the chemical quantities were slightly increased during a subsequent maintenance effort and, as a result, the injectability of SWFTS-IW13B was improved (see Table 2). During the sixth injection event, nine of the ten injection wells for which well maintenance has been performed exhibited improved injectability compared to pre-maintenance conditions, as indicated by lower injection pressure to injection rate ratios. The exception was SWFTS-IW06B, where surge and bail well maintenance was applied in September 2019. Approximately 8 months later during the sixth injection event, the ratio of injection pressure to flow rate had returned to near pre-maintenance conditions. However, this injection well continued to accept the targeted quantities of injectate solution and distribution water, despite the higher ratio of injection pressure to flow rate.

As previously stated, an objective of this study extension is to determine the most appropriate well maintenance technique and likely frequency that maintenance is required for long-term injectability. As these extension activities continue, more data will be collected on the injection pressures, injection rates, and preferred maintenance technique to arrive at the optimal criteria for when injection well maintenance should be performed and the associated frequency required for full-scale ISB applications. A complete evaluation of injection well maintenance will be provided at the conclusion of this study extension.

4.0 EFFECTIVENESS MONITORING

Effectiveness monitoring is on-going to observe both groundwater contaminant and geochemical changes following alterations to a variety of O&M components, such as modifications to the mixing/injection strategies (i.e., batch versus in-line mixing) and performance of different maintenance techniques on injection wells. Because ISB has already been demonstrated as effective, the sampling program was scaled back in 2019 through a reduction in sampling frequency and associated analytes in accordance with NDEP-approved 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.

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 C.

A total of seven groundwater sampling events were conducted during the 2020 reporting period. Per Modification No. 6, groundwater samples were analyzed 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). 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 January 2020 – December 2020. 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 D to this annual progress report. The laboratory analytical data were verified and validated in accordance with procedures described in the *Quality Assurance Project Plan, Revision 4* (Ramboll, 2020a), *Quality Assurance Project Plan, Revision 5* (Ramboll, 2020b), “Data Verification and Validation Requirements” (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 USEPA 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 varying O&M components related to ISB injections. This section provides an overview of the groundwater sampling results, including a discussion of the primary contaminants, additional chemical and geochemical parameters, and relationships among each of these parameters. Because perchlorate is the primary chemical of concern associated with 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 discussed in detail in Sections 4.2.2 through 4.2.4. Additional parameters, including DO, ORP, pH, sulfate, sulfide, metals, and methane, have also been evaluated and are discussed in Section 4.2.5. Data for all parameters can be found in the comprehensive data tables provided in Appendix E, Tables E.1 through E.4. Data for perchlorate, chlorate, nitrate, TOC, arsenic, phosphorus, DO, and ORP are depicted graphically in individual well trend profiles provided in Appendix F. Field logs from all groundwater sampling events are provided in Appendix C and the DVSR is provided in Appendix D.

4.2.1 Perchlorate

An evaluation of the perchlorate degradation response, perchlorate distribution throughout the study area, and estimates of perchlorate mass removal during the reporting period are presented in the subsequent sections.

4.2.1.1 Perchlorate Degradation Response

Groundwater perchlorate concentrations have continued to reduce following the fifth and sixth injection events when compared to baseline (pre-injection) concentrations. As previously described in Sections 2 and 3, several O&M components have varied since the study extension began, including implementation of additional mixing requirements during the fifth injection event, evaluation of in-line mixing during the sixth injection event, and variations in injection well maintenance techniques over multiple events. An evaluation of aquifer response to the ISB injections and varying O&M components is presented below based on the general location of the monitoring wells with respect to the study area.

Monitoring Wells Located Upgradient of the Injection Well Transects

During this reporting period, increased perchlorate concentrations were observed in groundwater samples collected at upgradient locations within the western portion of the study area from which groundwater migrates into the study area without passing through the treatment zone (such as monitoring wells PC-88 and SWFTS-MW04 [trends presented in Appendix F, Figures F.2 and F.10, respectively]). Groundwater samples collected from upgradient monitoring well SWFTS-MW04 indicate perchlorate concentrations increased to an average of 7,800 μg/L (and a maximum concentration of 12,000 μg/L), which is approximately 2.5 times higher than the average of 3,100 μg/L observed during the previous reporting period (Appendix F, Figure F.10). These increased perchlorate concentrations in the western portion of the study area migrate into the downgradient portions of the study area without passing directly through the treatment zone and is, therefore, not treated within the biologically active zone that is part of the treatability study.

As discussed in the 2019 Annual Progress Report, a decrease in perchlorate concentrations was observed in the groundwater samples collected from upgradient monitoring well SWFTS-MW12 during the November and December 2019 sampling events (Appendix F, Figure F.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 following the fifth injection event, with perchlorate concentrations reducing from 4,200 μg/L to less than the sample detection limit. During this reporting period, perchlorate concentrations in groundwater at SFWTS-MW12 ranged from <0.95 to 170 μg/L, indicating that perchlorate continues to be reduced in the vicinity of this upgradient monitoring well following the sixth injection event. A combination of the extraction from SWFTS-MW12 and an increase in injection rates and pressures during the fifth injection event likely resulted in transport of the injectate to the vicinity of monitoring well SWFTS-MW12 (which reduced perchlorate concentrations in groundwater). It should be noted that there was not a significant increase in TOC concentrations in groundwater samples collected from SWFTS-MW12 following the sixth injection event, suggesting that procedural changes that consisted of lower extraction rates from SWFTS-MW12 and slightly lower injection pressures and injection rates at nearby injections wells SWFTS-IW09 and SWFTS-IW10 were successful at mitigating transport of additional injectate solution upgradient towards the vicinity of SWFTS-MW12. Additional discussion of the TOC trends observed at SWFTS-MW12 is included in Section 4.2.4.

<u>Monitoring Wells Between Injection Well Transects</u>

There are four monitoring wells located between the injection well transects (SWFTS-MW02, SWFTS-MW14, SWFTS-MW15, and SWFTS-MW16) to monitor the creation of a biologically active zone. Perchlorate concentrations in groundwater samples collected from monitoring well SWFTS-MW16 were not detected above the sample detection limits, which were less than the federal PRG for perchlorate of 15 μg/L, in all seven sampling events during the reporting period (Appendix F, Figure F.26). The trend of non-detect concentrations in groundwater samples collected from this monitoring well has continued throughout most of the treatability study.

Perchlorate concentrations in groundwater samples collected from SWFTS-MW14 have similarly continued to not be detected above the detection limit until approximately 6 months following the fifth injection event, when perchlorate concentrations rebounded slightly to 97 μg/L. Following the sixth injection event, groundwater samples collected from SWFTS-MW14 indicated perchlorate concentrations reduced to below the detection limit in July 2020. However, during the three subsequent sampling events conducted between August and December 2020, perchlorate concentrations in groundwater slowly rebounded to 2,900 μg/L. Although these results still represent an 87 percent reduction compared to the baseline concentration of 23,000 μg/L (Appendix F, Figure F.24), perchlorate concentration fluctuations observed in groundwater samples collected from this monitoring well will continue to be evaluated to ascertain changes that could have occurred from varying O&M conditions in adjacent injection wells. Some fluctuations/increases in perchlorate concentrations in groundwater samples collected from this monitoring well may be due to its proximity to nearby injection well SWFTS-IW13B, at which (as described in Sections 2 and 3) injectate was not accepted during the previous fourth and fifth injection events and limited injectate was accepted during the sixth injection event. Future maintenance and injection events in this vicinity will continue to be evaluated with respect to fluctuating concentrations observed in groundwater samples collected from monitoring well SWFTS-MW14.

Groundwater samples collected from SWFTS-MW02, which is located along the western edge of the study area, had a perchlorate concentration of 2,700 μg/L soon after the fifth injection event (89 percent less than the baseline concentration of 25,000 μg/L; Appendix F, Figure F.8). Perchlorate concentrations in groundwater from this monitoring well continued to remain at concentrations significantly below baseline levels during this reporting period (ranging from 62 percent to 74 percent below baseline concentrations). Although a general upward trend has been observed in groundwater concentrations at SWFTS-MW02 during this reporting period, this trend is likely related to the increased concentrations observed upgradient of this monitoring well within the western portion of the study area from which groundwater migrates into the study area without passing directly through the treatment zone. This trend will continue to be evaluated with respect to the increasing upgradient concentrations.

Lastly, groundwater samples collected from monitoring well SWFTS-MW15 have historically indicated a delayed and modest response to injections, despite the monitoring well's proximity to injection wells SWFTS-IW06A/B and SWFTS-IW07. Prior to the sixth injection event, perchlorate concentrations in groundwater samples collected from SWFTS-MW15 had increased to 14,000 μg/L. However, following the sixth injection event, groundwater perchlorate concentrations in samples collected from SWFTS-MW15 were among the lowest to date at this location with concentrations ranging from 4,400 μg/L to 6,200 μg/L, which is approximately 59 to 71 percent lower than the baseline concentration of 15,000 μg/L (Appendix F, Figure F.25). 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 well SWFTS-MW15. Additionally, O&M components that may have resulted in the positive change in results during this reporting period include injection well maintenance performed in upgradient injection wells SWFTS-IW06A/B in late 2019.

Monitoring Wells Located Downgradient of the Injection Well Transects

Groundwater samples collected from seven of the 16 monitoring wells located downgradient of the injection well transects exhibited perchlorate concentration reductions greater than 70 percent compared to their respective baseline concentrations during multiple sampling events.

During the reporting period, groundwater samples were collected from downgradient monitoring wells located closest to the injection well transects (namely, PC-91, PC-92, SWFTS-MW10A, and SWFTS-MW18 are within approximately 50 feet). Results from these groundwater samples are described below.

- The largest decrease in groundwater perchlorate concentrations was observed in samples collected from PC-91, where concentrations reduced to levels below the sample detection limits (lowest to date and below the PRG of 15 μg/L) in all four sampling events following the sixth injection event (Appendix F, Figure F.3). However, groundwater samples collected from nearby monitoring well PC-92, which is screened deeper than PC-91 and has thus far shown marginal decreases as well as several anomalous increases in groundwater perchlorate concentrations, indicated that perchlorate concentrations fluctuated between 3,400 and 8,800 μg/L (twice the baseline concentration) before slowly trending downward after the sixth injection event (Appendix F, Figure F.4). Although the concentration observed during the December 2020 sampling event (5,100 μg/L) is elevated above the baseline concentration of 4,400 μg/L, it represents a 42 percent reduction compared to the most recent concentration high of 8,800 μg/L in March 2020. As noted in previous reports, 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. Based on the groundwater flow patterns, both PC-91 and PC-92 are likely impacted by injections but PC-91 more so due to its proximity to SWFTS-IW11. 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, the same upgradient influence is likely affecting both SWFTS-MW04 and PC-92, but not PC-91, likely due to the difference in the screened intervals of the wells.
- Groundwater samples from monitoring well SWFTS-MW10A recorded the highest groundwater perchlorate concentrations since before the first injection event, with concentrations ranging from 7,900 to 10,000 μg/L (Appendix F, Figure F.20). Following the fifth injection event, groundwater perchlorate concentrations at monitoring well SWFTS-MW10A increased from 2,600 μg/L in November 2019 to 10,000 μg/L in April 2020, and these elevated concentrations continued following the sixth injection event. This rise in perchlorate concentrations is accompanied by simultaneous increases in nitrate and chlorate concentrations to greater than baseline concentrations of 5.1 milligrams per liter (mg/L) and 27,000 μg/L, respectively (discussed further in Sections 4.2.2 and 4.2.3). These changes may be due to a number of factors, including both operational changes and lithological characteristics. Specifically, SWFTS-MW10A is located closest to injection well SWFTS-IW13B, which was the only injection well at which injectate was not accepted during the fourth and fifth injection events, but was accepted in a reduced amount during the sixth injection event, as described in Section 2. These increases could also be due to upflux of contaminated groundwater from the untreated UMCf where the paleochannel is incised into the UMCf surface in the vicinity of SWFTS-MW10A. Upflux of contaminated groundwater will be more thoroughly evaluated in the forthcoming RI Report for OU-3. In fact, groundwater perchlorate concentrations similar to those observed at SWFTS-MW10A were measured in groundwater collected in April 2020 from SWFTS-MW10C, which is screened in the UMCf at the same location. Finally, the elevated perchlorate concentrations in groundwater at SWFTS-MW10A observed during this reporting period may also be related to the increased upgradient concentrations in the western portion of the plume (discussed previously with regards to monitoring well SWFTS-MW02). Results for groundwater

samples collected from these monitoring wells will continue to be evaluated with respect to upgradient concentrations and the nearby paleochannel in the vicinity of SWFTS-MW10A and PC-92.

- Groundwater perchlorate concentrations in samples collected from monitoring well SWFTS-MW18 were consistently lower than in previous years, with concentrations trending from 4,400 μg/L to 3,100 μg/L (compared to the baseline concentration of 13,000 μg/L) following the sixth injection event (Appendix F, Figure F.28), which represents a 76 percent reduction compared to baseline in the final 2020 sampling event.

Other noteworthy results within farther downgradient portions of the treatability study area include groundwater perchlorate concentrations in samples collected from monitoring wells SWFTS-MW01, SWFTS-MW05A/05B, SWFTS-MW20, and SWFTS-MW21, which are located approximately 100 to 150 feet hydraulically downgradient of the injection well transects. It should be noted that farther downgradient areas within the treatability study are likely to be influenced by groundwater migrating into the study area from flow paths that originate outside of the study area and bypass the primary treatment zone.

- Groundwater samples from monitoring wells SWFTS-MW01 have shown fairly consistent results since injections began, with an overall average percent decrease for 2020 of approximately 63 percent (Appendix F, Figure F.7).
- Results from groundwater samples collected from the monitoring well pair SWFTS-MW05A/B indicate a generally favorable response following the sixth injection event (Appendix F, Figures F.11 and F.12). Although this monitoring well pair is generally downgradient of the injection well transect line, it is the easternmost well cluster located within the study area and therefore, not ideally situated downgradient of multiple injection wells. A review of the groundwater potentiometric surface (Figure 2 of this report and Plate 1 of the Annual Groundwater Monitoring and GWETS Performance Report [Ramboll US Consulting, Inc., 2021]) also indicates that contamination may be migrating into the vicinity of this monitoring well from directly south of the wells (i.e., east of the study area) that is not being treated by the upgradient injection well transect. SWFTS-MW05B, which is the deeper screened alluvium monitoring well and has considerably more gravel present at the screened interval compared to SWFTS-MW05A, had decreases in groundwater perchlorate concentrations that were greater than 80 percent compared to baseline concentrations in all events following the sixth injection event. Groundwater samples from SWFTS-MW05A, which observed limited decreases following the first three injection events, showed signs of stabilization with groundwater concentration reductions generally between 50 and 60 percent during the reporting period. Even though this monitoring location is less than ideal, perchlorate degradation has been consistently observed.
- Groundwater samples collected from monitoring well SWFTS-MW20 exhibited the lowest perchlorate concentrations observed to date in this well resulting in an approximate 98 to 99 percent reduction when compared to the baseline concentration of 20,000 μg/L during all seven sampling events in this reporting period (Appendix F, F.30).
- Groundwater samples collected from SWFTS-MW21 indicate an overall average percent decrease for 2020 of approximately 56 percent, which again is fairly consistent with past results (Appendix F, Figure F.31.

Groundwater samples collected from the farthest downgradient monitoring wells (i.e., greater than 150 feet downgradient of the injection well transects – PC-94, SWFTS-MW03, SWFTS-MW09A/B, SWFTS-MW22, SWFTS-MW24, and SWFTS-MW25; Appendix F, Figures F.5, F.9, F.18, F.19, F.32, F.34, and F.35) generally continued to exhibit perchlorate reductions ranging from 50 to 80 percent during the reporting period. Exceptions included the concentration trends observed at SWFTS-MW09B and SWFTS-MW22. Although decreases have been previously observed, groundwater perchlorate concentrations from samples collected from monitoring well SWFTS-MW09B have fluctuated since injections began (Appendix F, Figure F.19). It should be noted that the screened interval of monitoring well SWFTS-MW09B is only 5 feet and extends below the maximum depth treated within the upgradient injection well transect. Perchlorate concentration decreases have been consistently observed in groundwater samples collected from SWFTS-MW22 through December 2019 (Appendix F, Figure F.32). However, results during the 2020 reporting period indicate an increasing trend, which is likely associated with the simultaneously increasing concentrations hydraulically upgradient of SWFTS-MW22 in areas that are not being actively treated, as discussed above. These farther downgradient areas are likely to be influenced by groundwater migrating into the study area from the west that is not passing through the treatment zone.

Summary

In conclusion, groundwater continues to respond favorably to injections following the fifth and sixth injection events despite the alterations to a variety of O&M components, such as modifications to the mixing/injection strategies (i.e., batch versus in-line mixing) and performance of different maintenance techniques on injection wells. Some fluctuations continue in concentrations, which is likely due to a combination of factors including (1) increasing trends in groundwater perchlorate concentrations in the western portion of the study, where groundwater migrates into the study area without being influenced by the biologically active zone in the vicinity of the injection well transects, (2) tests of different mixing and injection procedures as well as experiments with different maintenance procedures on a variety of injection wells, (3) preferential flow pathways for carbon substrate migration, (4) presence of paleochannels and potential upflux from the UMCf, and/or (5) large lithological heterogeneity that was apparent during well drilling activities. In addition, perchlorate from the neighboring AMPAC plume (located west of the NERT Operable Unit 3 boundary) is migrating in the vicinity of the Las Vegas Wash towards the Pabco Road Weir downgradient of the treatability study area (Figure 1). Therefore, this plume is likely impacting groundwater quality at the most distant downgradient monitoring wells within the treatability study area. The delineation of the NERT and AMPAC perchlorate plumes will be defined in the forthcoming RI Report for OU-3.

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 and 4b, a biologically active treatment zone was sustained following the sixth injection event, 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 plume migrating in the northern portions of the treatability study area, the downgradient extent of perchlorate concentrations below 15 μg/L is somewhat limited. Some areas within the treatment zone had slightly less reduction in perchlorate concentrations, which may be due to the heterogeneous nature of the subsurface and localized presence of low permeability within that particular portion of the injection well transect. If ISB is selected as a component of the NERT final remedy, remedial design could account for situations like this by installing additional injection wells 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 and 4b, three-dimensional visualizations are presented in Figures 4c and 4d. These figures have been prepared to respond to previous NDEP requests for three-dimensional images of perchlorate concentrations over time, including the differences between the most recent and baseline concentrations. Specifically, Figure 4c provides three-dimensional visualization of perchlorate distribution during baseline and select monitoring events following the fifth and sixth injection events with views using a concentration threshold of greater than 5,000 μg/L. Figure 4d presents the treated perchlorate from the baseline sampling event through December 2020, again with a concentration threshold of greater than 5,000 μg/L.

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, the following assumptions were made:

- 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 this approximate 12-month treatability study reporting 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 the alluvium/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. To generate these grid surfaces, 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.

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 January through December 2020, an estimated total of 810 pounds of perchlorate was destroyed in the groundwater in the vicinity of the treatability study area (an average of 2.2 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. There are a couple factors that contribute to these lower values. First, the upgradient groundwater perchlorate concentrations coming from the south and southeast that flow through the treatment transect during this reporting period (i.e., vicinity of SWFTS-MW07, -MW08, -MW11, -MW13, and -MW17), were lower than were present during the previous reporting periods, thereby lowering the influx into the main portion of the biologically active zone. At the same time, upgradient concentrations in groundwater that migrates into the study area in and north of the paleochannel without passing directly through the treatment zone (i.e., SWFTS-MW04 and PC-88 areas) were also higher than previous reporting periods, resulting in higher concentrations on the northern side of the study area. Fluctuations in upgradient perchlorate concentrations are commonly observed within the study area and do not impact on achieving the goals of the treatability study extension.

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 amenable to anaerobic biodegradation. Chlorate concentrations are summarized in Appendix E, Table E.1, and are graphically depicted in Appendix F. Figures 5a and 5b present chlorate plume interpretations, which show significant reductions in chlorate concentrations similar to the perchlorate reductions observed in Figures 4a and 4b.

In general, chlorate concentration trends followed a similar reducing pattern to the perchlorate concentration trends during this reporting period. However, there are select wells (SWFTS-MW01 and SWFTS-MW05A/B) in which the chlorate reduction appears to be greater than the perchlorate reduction over time. Possible reasons for this phenomena could be that (a) the microbial kinetic degradation generally is higher for chlorate compared to perchlorate, and (b) literature studies have indicated that in some water systems, typical acclimated microorganisms (such as *Acinetobacter thermotoleranticus*, *Wolinella succinogenes*, and *Pseudomonas fluorescens*) may sometimes intermittently prefer chlorate as an electron acceptor compared to perchlorate and nitrate.

The majority of groundwater samples collected during the reporting period from two of the four monitoring wells located in between the injection well transects, namely SWFTS-MW14 and SWFTS-MW16, were below the sample detection limit, representing greater than 99 percent decrease when compared to baseline concentrations (Appendix F, Figures F.24 and F.26). Although chlorate concentrations in samples from SWFTS-MW02 increased compared to the previous reporting period, sample results indicate a 71 to 87 percent reduction from the baseline concentration of 58,000 μg/L. Groundwater in the vicinity of the fourth monitoring well, namely SWFTS-MW15, has previously not responded as favorably to chlorate reduction. However, groundwater samples from SWFTS-MW15 exhibited their lowest chlorate concentration to date of 14,000 μg/L during this reporting period, which represents a 67 percent decrease when compared to the baseline concentration of 43,000 μg/L (Appendix F, Figure F.25).

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 F, Figures F.3, F.4, F.20, and F.28, respectively) all indicated trends in chlorate concentrations similar to perchlorate. Of these monitoring wells, groundwater samples collected from PC-91 exhibited chlorate concentrations less than 100 μg/L in multiple events during the reporting period, while groundwater concentrations at SWFTS-MW18 indicated a decreasing trend after the sixth injection event to 8,100 μg/L (representing an 84 percent decrease compared to baseline concentrations). Groundwater samples collected from monitoring wells PC-92 and SWFTS-MW10A contained chlorate concentrations generally above baseline (PC-92) or near baseline concentrations (SWFTS-MW10A) during this reporting period. A similar rise in chlorate concentrations to above baseline concentrations was observed at PC-92 in 2018 associated with simultaneously increasing trends in concentrations upgradient of the western portion of the transect, as evidenced by trends at SWFTS-MW04, and SWFTS-MW07B (Appendix F, Figures F.10 and F. 16). Similar to perchlorate (as previously explained in Section 4.2.2), the elevated chlorate concentrations observed at PC-92 and SWFTS-MW10A are likely due in part to groundwater migrating into the study area from the west without passing directly through the treatment zone. Chlorate mass may also be migrating from the UMCf into the alluvium in the vicinity of these two monitoring wells due to their proximity to the paleochannel incised into the surface of the UMCf.

Groundwater results from samples collected from 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 F, Figures F.7, F.11, F.12, F.30, and F.31) exhibited chlorate concentrations below the sample detection limit in the majority of samples and a reduction of more than 99 percent from baseline in nearly all samples collected during this reporting period. The exception is groundwater samples collected from SWFTS-MW21, which indicated slight rebound in concentrations slightly prior to the sixth injection event. However, similar chlorate reductions of greater than 99 percent from baseline concentrations were achieved in groundwater at SWFTS-MW21 following the sixth injection event. One additional observation is that select wells (SWFTS-MW01 and SWFTS-MW05A/B) generally indicate a stronger chlorate degradation response compared to perchlorate. As noted above, possible reasons for this phenomena could be that (a) the microbial kinetic degradation rate generally is higher for chlorate compared to perchlorate, and (b) literature studies have indicated that in some water systems, typical acclimated microorganisms (such as *Acinetobacter thermotoleranticus*, *Wolinella succinogenes*, and *Pseudomonas fluorescens*) may sometimes intermittently prefer chlorate as an electron acceptor compared to perchlorate and nitrate.

Groundwater in the seven farther downgradient monitoring wells (i.e., greater than 150 feet downgradient of the injection well transects - PC-94, SWFTS-MW03, SWFTS-MW09A/B, SWFTS-MW22, SWFTS-MW24, and SWFTS-MW25; Appendix F, Figures F.5, F.9, F.18, F.19, F.32, F.34, and F.35) generally showed increasing trends prior to the sixth injection event. However, samples in six of these monitoring wells exhibited decreases in chlorate concentration following the sixth injection event. The one exception was SWFTS-MW22, where groundwater chlorate concentration increased to 9,600 μg/L, which is higher than the baseline concentration of 7,900 μg/L. As previously explained, these farther downgradient areas are likely to be influenced by groundwater migrating into the study area from the west that is not passing directly through the treatment zone.

Finally, similar to perchlorate, chlorate concentrations in groundwater decreased in groundwater samples collected from upgradient monitoring well SWFTS-MW12 during the reporting period (Appendix F, Figure F.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, with chlorate concentrations decreasing from 31,000 μg/L prior to injection event 5 to less than the sample detection limit. These non-detect results continued to be observed for six of the seven sampling events conducted during this reporting period. As previously explained, these concentration decreases are a result of a combination of the extraction activities from SWFTS-MW12 and an increase in injection rates and pressures during the fifth injection event that likely resulted in transport of the injectate to the vicinity of monitoring well SWFTS-MW12 (which reduced chlorate concentrations in groundwater).

4.2.3 Nitrate

Nitrate concentrations are continuing to be evaluated during the study extension because nitrate is the most likely competing electron acceptor as well as a consumer of organic carbon substrate. Both perchlorate and chlorate biodegradation generally commence when nitrate biodegradation (denitrification) is substantially complete. However, perchlorate and chlorate biodegradation could also occur concurrently 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 E, Table E.1, and are graphically depicted in Appendix F. Figures 6a through 6b present nitrate plume interpretations, which show continued significant reductions in nitrate concentrations during the treatability study.

Nitrate was generally not detected during the reporting period in groundwater samples from monitoring wells SWFTS-MW14 and SWFTS-MW16 (Appendix F, Figures F.24 and F.26), which are located between the injection well transects. Similar to perchlorate and chlorate concentration trends, groundwater samples from a third monitoring well SWFTS-MW02, which is also between the injection well transects, generally showed an increasing trend (Appendix F, Figure F.8), similar to the trend observed upgradient to the western portion of the transect at monitoring wells PC-88, SWFTS-MW04. Groundwater samples from the fourth monitoring well, SWFTS-MW15, exhibited the most significant decrease in nitrate concentrations since the study inception, decreasing to 3.8 mg/L, a reduction of 62 percent compared with baseline conditions (Appendix F, Figure F.25).

As presented in Figures 6a through 6b, nitrate concentrations were 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 10 monitoring wells located hydraulically downgradient of the injection well transects reduced by greater than 50 percent when compared to their baseline concentrations during several sampling events from this reporting period.

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 groundwater concentrations after injections compared to baseline pre-injection concentrations. TOC concentrations are summarized in Appendix E, Table E.1, and are graphically depicted in Appendix F.

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 34 mg/L in samples collected from SWFTS-MW15 in July 2020 following the sixth injection event. This is the first time during the treatability study that a significant TOC increase was observed in groundwater samples collected from SWFTS-MW15. This increase in TOC was associated with reductions in perchlorate, chlorate, and nitrate concentrations in groundwater at SWFTS-MW15, which had previously exhibited delayed/moderate responses in contaminant reductions.

The highest TOC concentration in groundwater samples collected from downgradient monitoring wells was 12 mg/L measured in July 2020 in samples collected from PC-91, which is within 50 feet of the injection well transect. No other significant increases in TOC concentration were observed in samples from downgradient monitoring wells during this reporting period. This observation is expected because over time the injectate (measured as TOC) is consumed closer to the 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 (up to 560 mg/L) in November 2019 following the fifth injection event. This occurred in the previous reporting period and was described previously in the 2019 Annual Progress Report. This TOC concentration increase can be attributed to a transient transport of the injectate from injection wells in an upgradient direction due to extraction operations 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. Results indicate TOC concentrations, which ranged from 4.8 mg/L to 14 mg/L during the 2020 reporting period, have decreased in groundwater at SWFTS-MW12 over time. In addition, a spike in TOC concentrations in groundwater samples collected from this well was not observed in sampling events following the sixth injection event, which indicates that the procedural changes implemented during the sixth injection that consisted of lower extraction rates from SWFTS-MW12 and slightly lower injection pressures and injection rates at nearby injections wells SWFTS-IW09 and SWFTS-IW10 were successful at mitigating transport of additional injectate solution upgradient. Therefore, the TOC concentrations in groundwater samples collected from this well are expected to continue to decrease in 2021 sampling events.

4.2.5 Additional Chemical and Geochemical Evaluation

This section provides a summary of the additional data collected during the reporting period (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 E, Tables E.1 through E.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 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 interpretations from this data should be made with a degree of caution. 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.

During baseline (pre-injection) activities, the aquifer was generally aerobic with DO concentrations greater than 1.0 mg/L and positive ORP averaging approximately 98 millivolts (mVs). Since injections began, average DO and ORP readings have generally been lower and indicative of sustained anaerobic conditions conducive to perchlorate biodegradation. In general, groundwater from 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 reporting period, groundwater samples collected from all four monitoring wells located between the injection well transects, namely SWFTS-MW02, SWFTS-MW14, SWFTS-MW15, and SWFTS-MW16, regularly had DO readings that were less than 1.0 mg/L, with numerous readings often less than 0.5 mg/L following the sixth injection event. ORP readings in groundwater samples collected from SWFTS-MW14, SWFTS-MW15, and SWFTS-MW16 were generally negative throughout the reporting period. While ORP readings fluctuated in groundwater samples collected from SWFTS-MW02, ORP values generally indicated a decreasing trend following the sixth injection event. These concentrations are generally consistent with results from earlier sampling events, indicating a robust establishment of anaerobic conditions 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. Although DO concentration increases were observed in the first half of the reporting period, DO concentrations decreased following the sixth injection event, with majority of groundwater samples collected from downgradient monitoring wells indicating DO concentrations less than 1.0 mg/L. During the end of the reporting period (December 2020), DO concentrations remained below 0.5 mg/L in groundwater samples collected from eight of the 16 downgradient monitoring wells. Groundwater samples collected from the remaining eight downgradient monitoring wells indicated an increase in DO concentrations to values slightly above 1.0 mg/L, which is generally expected since the last injection event was performed six months prior. These increasing trends in DO concentrations in groundwater samples collected from several downgradient monitoring wells are an early indication of the likely need for future injections in the coming months.

While DO concentrations in groundwater samples collected from the majority of upgradient monitoring wells were similar to previous years and generally indicative of aerobic conditions, the exception was groundwater in the vicinity of SWFTS-MW12, with DO results from groundwater samples continuing to indicate anaerobic conditions (DO concentrations less than 0.5 mg/L and ORP readings generally less than -200 mV). This result is likely attributed to persistence of sufficient carbon substrate in the vicinity of this monitoring well throughout the reporting period, 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 groundwater from monitoring wells that showed the most significant and consistent perchlorate biodegradation also appearing to be consistently reducing throughout the treatability study. ORP readings fluctuated and did not always correlate well with DO measurements. However, both DO and ORP will continue to be monitored as water quality parameters during future groundwater sampling events.

4.2.5.1.2 pH

Most of the pH values observed in groundwater samples collected from monitoring wells located between and downgradient of the injection well transects ranged from 6.41 to 7.96 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 and cause microbial toxicity under certain conditions; (iii) the formation of hydrogen sulfide; and (iv) loss of hydraulic permeability.

Sulfate reductions appear to have stabilized in groundwater samples collected from monitoring wells located between the injection well transects and farther downgradient. During this reporting period, sulfate concentrations in groundwater samples collected from the four monitoring wells located in between the injection well transects reduced by an average of 32 percent, which is considerably less than the overall average decrease of 42 percent in 2019 for groundwater samples collected from the same set of wells. Sulfate concentrations detected in groundwater samples collected from downgradient monitoring wells indicate an overall average decrease of approximately 21 percent when compared to baseline, which is fairly similar to the average decrease of 24 percent observed during the previous reporting period. It should be noted that the average decrease in sulfate concentrations in groundwater samples collected from upgradient monitoring wells during this reporting period was 13 percent. Lastly, as reported in the 2019 Annual Progress Report, the groundwater sample collected from upgradient monitoring well SWFTS-MW12 in December 2019 indicated a sulfate reduction of 99 percent (likely due to the transport of injectate to the vicinity as described previously). During this reporting period, the amount of sulfate reduction that is occurring in groundwater in the vicinity of this monitoring well has steadily improved, with the December 2020 sampling event indicating only 27 percent reduction when compared to baseline.

In general, sulfide was not detected in groundwater samples from the majority of monitoring wells within the treatability study area. Of the 36 monitoring wells located within the entire study area, sulfide was only detected at low concentrations (generally less than 1 mg/L) in groundwater samples collected from four monitoring wells, namely SWFTS-MW09A, SWFTS-MW12, SWFTS-MW14, and SWFTS-MW15. Sulfide was detected at 2 mg/L in groundwater samples collected from SWFTS-MW15 during the August 2020 sampling event, but sulfide concentrations decreased to only 0.3 mg/L during the October 2020 sampling event. During the previous reporting period, sulfide was detected at 1.4 mg/L in a groundwater sample collected from upgradient monitoring well SWFTS-MW12. However, groundwater samples collected during the 2020 reporting period from this well indicate that sulfide concentrations have reduced to below 1.0 mg/L.

In conclusion, the limited sulfate reduction and sulfide production observed in this treatability study are consistent with the results from previous years and suggest the potential negative impacts of sulfate biodegradation in this high sulfate environment can be minimized and/or controlled during implementation of perchlorate bioremediation. As stated in previous reports, 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 extension.

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. Because the study extension is focused on long-term O&M components to an ISB system, the frequency of metals analysis was reduced to a semi-annual; accordingly, two sampling events that included metals analysis were conducted during this reporting period. The bulleted summary below provides an overview of key observations related to dissolved metals and ferrous iron.

- 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. Groundwater samples collected from monitoring wells located between the injection well transects continue to indicate arsenic concentrations less than baseline (pre-injection) concentrations. Although concentrations have fluctuated in groundwater samples collected from both upgradient and downgradient monitoring wells, arsenic concentrations remain at or below the range of concentrations observed during baseline.

- 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, which could decrease the hydraulic permeability in the aquifer. Pre-injection dissolved iron concentrations were typically less than 1.5 mg/L. During this reporting period, dissolved iron concentrations in groundwater were generally less than 1.0 mg/L. Monitoring well SWFTS-MW16 is the only location with a notable increase in groundwater dissolved iron concentrations since injections began; however, groundwater concentrations were less than 5.0 mg/L in 2020, indicating minimal iron mobilization. The lack of iron mobilization is further supported by field measurements of ferrous iron in groundwater, which generally indicate non-detect or low concentrations of ferrous iron. Once again, only groundwater from monitoring well SWFTS-MW16 indicated a notable ferrous iron concentration of 4.5 mg/L.
- 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 remained below 6 mg/L throughout the study area. Groundwater concentrations observed in samples collected from upgradient monitoring well SWFTS-MW12, which exhibited concentrations of up to 44 mg/L in the previous reporting period, reduced significantly to less than 2.2 mg/L during this reporting period.
- 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 upgradient monitoring well SWFTS-MW12 had marginal dissolved phosphorus concentrations, although concentrations have now decreased from 1.9 mg/L in the previous reporting period to 0.37 mg/L during this reporting period.

4.2.5.4 Methane

Methanogenic conditions (signified by biological methane production) require highly reducing conditions that are generally not warranted for perchlorate biodegradation. However, methane concentrations often increase in groundwater following the injection of a carbon substrate, particularly in groundwater at monitoring locations close to injection locations. It should also be noted that any methane that is biologically generated would very likely be rapidly oxidized to carbon dioxide in the gravelly and sandy vadose zone overlying the saturated alluvium.

Results from the November 2020 sampling event indicated methane detections in groundwater samples collected from several of the monitoring wells located in between the injection well transects and downgradient of the study area. However, methane was generally detected in groundwater samples at concentrations less than 5 mg/L during the reporting period, except for the groundwater sample collected from SWFTS-MW14 that indicated a methane concentration of 6.7 mg/L. Although above 5 mg/L, this concentration has decreased considerably from previous sampling events that indicated concentrations up to 12 mg/L. Other notable observations during this reporting period include methane concentration decreases in groundwater samples collected from SWFTS-MW02 and SWFTS-MW10A. Although methanogenic conditions are generally not required for perchlorate biodegradation, the notable decrease in methane concentrations may be indicative of a less reducing environment in the vicinity of these wells when compared to previous reporting periods. This observation generally correlates with the increases in perchlorate concentrations observed in groundwater samples collected from these locations during this reporting period. Methane will continue to be monitored in groundwater samples collected on an annual basis during the treatability study.

4.3 MICROBIAL EVALUATION

Microbial sampling was included in the effectiveness monitoring program to continue examination of the microbial response to carbon substrate additions at key locations. In November 2020, 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). The Bio-traps® were left in-place for approximately 30 days and then 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 are presented in Appendix E, Table E.4. Microbial laboratory data reports are provided in Appendix G.

The PLFA analysis, which is used to estimate the population of the variable biomass, is generally consistent with 2019 results. The PLFA analysis indicated that the Bio-trap® from upgradient monitoring well SWFTS-MW07A had the lowest total biomass at 7.37×10^4 bacterial cells per bead, while the Bio-Trap® from the injection well had the highest total biomass at 3.95×10^6 bacterial cells per bead. These results are indicative of heightened microbial response in the vicinity of the injection wells due to the addition of carbon substrate. The total biomass numbers were also elevated in the Bio-trap® collected from SWFTS-MW14, which is located between the injection well transects, with a detection of 2.38×10^5 bacterial cells per bead. This was expected since the groundwater samples collected from this well throughout majority of the study have indicated substantial perchlorate and chlorate reductions when compared to baseline. Lastly, microbial cell numbers in the Bio-trap® from SWFTS-MW09B were 9.42×10^4 bacterial cells per bead, which is a similar order of magnitude compared to the Bio-trap® results from the upgradient monitoring well. As previously noted, groundwater samples collected from SWFTS-MW09B indicate a slower response to carbon substrate injections. Additionally, the screened interval for monitoring SWFTS-MW09B is only 5 feet and extends below the maximum depth treated within the upgradient injection well transect.

PLFA analysis on community structure indicated that over 60 percent of the bacterial population belonged to the Proteobacteria structural group in the three Bio-Traps® from SWFTS-MW07A, SWFTS-MW09B, and SWFTS-MW14. 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 (a carbon source) is available. The only exception was the Bio-trap® collected from SWFTS-IW02A, where results indicated a much lower percentage of Proteobacteria at approximately 26 percent. The reason for this lower percentage is due to the microbial shift to Firmicutes. Specifically, during this reporting period, the percentage of Firmicutes has increased substantially to 39 percent, which is indicative of microorganism populations that have the ability to ferment complex organic compounds such as EVO and its immediate by-products. This microbial shift in some vicinities between Proteobacteria and Firmicutes is not unexpected in active groundwater remedial situations and is indicative of the combined ability to ferment and make available simple carbon compounds that are then utilized by other communities for the direct respiration of perchlorate and other electron acceptors that reside in the system.

The percentage of General (Nsats) were below 30 percent in all four Bio-Traps® collected for analyses during the reporting period, which supports the above conclusion regarding the gradual increase in diversity of the microbial population since high proportions of Nsats generally indicate less diverse populations. In particular, the decrease in Nsats in groundwater from SWFTS-MW09B from 62 percent to 27 percent reflects a growing diversity in microbial population, which may indicate future decreases in perchlorate in this vicinity. Groundwater results (including chemical, geochemical, and microbial) will continue to be analyzed and evaluated in samples collected from this location in 2021.

Firmicutes were only present in significant quantities in the Bio-Trap® installed and collected from injection well SWFTS-IW02A, as previously noted to be at approximately 39 percent. Bio-Traps® from all wells indicated the presence of sulfate-reducing bacteria (SRB)/Actinomycetes at only low fractions (approximately 15 percent or less). Eukaryotes (organisms such as fungi, protozoa, and diatoms) and metal reducing microorganisms were present at very low proportions (less than 3 percent) in Bio-traps® from all four wells. In comparison, the Bio-trap® from monitoring well SWFTS-MW14 indicated Eukaryotes present at a marginally higher quantity (14 percent) during the 2019 reporting period. This marginal shift among bacterial communities is likely to continue to fluctuate slightly over time given the dynamic nature of the populations and minor changes in geochemical conditions.

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 are sometimes best studied in Bio-traps® installed in strategic wells over time as the results can be inconsistent. Except for the Bio-trap® from SWFTS-MW14, which had a low slowed growth ratio of 0.30, the ratio for the Bio-traps® collected from the other three wells ranged from 0.81 to 1.19. Comparatively, the ratio for the analyses performed during the 2019 reporting period indicated a slow growth ratio of 1.03 in the Bio-trap® collected from monitoring well SWFTS-MW14, which indicates that there is a decreased microbial stress in the system in this vicinity. On the other hand, the ratios for decreased permeability were all consistently low, ranging from 0 to 0.16, which indicates that there were no apparent toxic conditions present that could hinder the abundance of microorganisms. 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.

Lastly, the perchlorate reductase gene was not detected at a count greater than 250 cells per bead in three of the four 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 or rapidly reducing. However, the Bio-trap® collected from SWFTS-MW14 had a detection of 4,740 cells per bead, which is an order of magnitude greater compared to the count from the previous reporting period of less than 250 cells per bead. As a notable feature, perchlorate in groundwater samples collected from SWFTS-MW14 has increased slightly in 2020 compared to previous years as discussed in Section 4.2.1. Therefore, it may be tentatively concluded that actual perchlorate respiration and presence of the perchlorate reductase enzyme is measurable in the immediate vicinity of this well primarily due to the lingering presence of low levels of perchlorate at this location. Bio-trap® data will continue to be collected and analyzed in 2021 to make additional inferences and links between microbial characteristics and degradation of perchlorate in this vicinity.

4.4 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 H. 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.

The 2020 injection event (May 28 through June 18, 2020) 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 installed 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 2020 injection event, 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 (January 2020 through December 2020), 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 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 are presented in Appendix I.

As explained in Section 4.0, because the original study objectives showed that ISB was effective at remediating perchlorate- and chlorate-contaminated groundwater, the focus of this study extension is evaluation of long-term O&M of an ISB remedy. Despite the variety of O&M components, such as modifying the mixing/injection strategies (i.e., batch versus in-line mixing) and performing different maintenance techniques on injection wells, 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 operations, maintenance, and monitoring tasks performed during this reporting period as part of the study extension.

<u>Operations</u>

- The ability of the formation to continue to accept substrate injections following six injection events during the four-year operation period indicates ISB is a practical and feasible long-term option for groundwater remediation in the alluvium at this site.
- Injections of carbon substrate continue to have a more prolonged potency over time, as demonstrated through the current injection frequency of approximately once every 8 months during this reporting period compared to the approximate 4 months at the beginning of the study.
- Although in-line mixing was successfully implemented as the mixing technique during the sixth injection event, batch mixing generally provides a more controlled and reliable mixing process that results in less variation in mixture consistency, as well as higher daily injection rates.

<u>Maintenance</u>

- Common injection well maintenance techniques continue to be successfully implemented on injection wells to maintain injectability. Additionally, potentiometric surfaces developed using recent groundwater level data confirmed that no significant changes to gradient or groundwater flow patterns have occurred during this reporting period. Based on these results, biofouling of the aquifer has not been observed within the treatability study area and has not impacted the continued injection of carbon substrate.
- Completion of the limited well maintenance field activities during this reporting period resulted in increased injectability (in terms of reduced injection pressures and/or increased injection rates) for both wells at which maintenance was performed during this reporting period (i.e., SWFTS-IW01B and SWFTS-IW13B).
- Injection well SWFTS-IW13B, which did not accept injectate during the fourth or fifth injection events, substantially improved and exhibited an injection rate of up to 9 gpm during the post-maintenance water injection test and an overall average injection rate of 3.8 gpm during the sixth injection event. Although it did not accept the complete target for injectate solution, it did accept the full target of distribution water.

Because well maintenance activities made significant improvements to the performance of this injection well, SWFTS-IW13B will undergo one more round of additional well maintenance before the seventh injection event, with the goal of the injection well accepting the full target of injectate solution and distribution water.[3]

Monitoring

- Nitrate, chlorate, and perchlorate continue to be degraded in groundwater throughout the study area during this 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 sample locations.
- DO concentrations and ORP readings provide some indication of the sustained reducing conditions in groundwater. Groundwater that showed the most significant and consistent perchlorate biodegradation are located where reducing conditions exist, 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 widespread sulfate reduction because it consists of 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, as stated in previous reports, 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 minimal.
- Secondary groundwater geochemical impacts, including arsenic, iron, manganese, methane, and phosphorus mobilization, were either limited or transient and did not appear to create a noteworthy 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

A summary of a preliminary cost evaluation was presented in the 2019 Annual Progress Report, which included lessons learned that have already reduced operation, maintenance, and monitoring costs by up to $230,000 per year. During the 2020 reporting period, additional lessons learned and adjustments have been made as part of this study extension that have or could further reduce the projected costs of an ISB remedy as part of the remedial alternatives evaluation in the FS. Specifically, during the 2020 reporting period, in-line mixing was implemented as the mixing technique during the sixth injection event so that a comparison could be made to the previously used method of batch mixing. As noted in Section 2.2, in-line mixing resulted in a slightly lower daily injection rate compared to batch mixing, which resulted in one additional field day required for in-line mixing operations. As a result, the cost of batch mixing operations is approximately $8,000 less than in-line mixing for this treatability study. In addition to operations activities, the sampling frequency resulted in seven effectiveness

[3] Subsequent to this reporting period, injection well maintenance was performed in February 2021 on injection well SWFTS-IW13B using the combination of surge and bail, hydrojetting, and chemical addition. This injection well was successfully restored, with an injection rate of up to 13.6 gpm during the seventh injection event performed in February/March 2021. Additionally, all injection wells accepted the full targeted quantity of injectate and distribution water, with injection pressure to injectate flow rate ratios of less than 5.0, during the seventh injection event. The results of this maintenance event and seventh injection event will be reported in the 2021 Annual Progress Report.

monitoring events, which is one less event than previous years. This resulted in an annual cost reduction of approximately $15,000. Additional recommendations presented in Section 5.3 will further reduce costs of the continued implementation of the ongoing treatability study extension.

5.3 FUTURE ACTIVITIES

As part of this study extension, periodic injections will continue to be performed through until otherwise 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 forthcoming 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 the following activities are planned for the future treatability study operations performed from November 2021 through December 2022. :

<u>Operations</u>

- Perform the seventh injection event in February/March 2021 using batch mixing implemented in accordance with the NDEP-approved *In-Situ Bioremediation Injections – Batch Mixing and Injections Field Guidance Document* (Tetra Tech, 2019c)[4].
- Perform the eighth injection event in late 2021 (exact timing dependent on effectiveness monitoring results following the seventh injection event) and continue to evaluate injection frequencies and substrate quantities. During this injection event, the following operation changes are planned:
    - Reduce the quantity of distribution water to evaluate the distribution and subsequent effectiveness of ISB using less distribution water. The quantity of distribution water is a key operational component that, if reduced, could result in cost savings due to less field injection time required.
    - Remove phosphate from the injectate solution. Because phosphate has been added during all injection events to date, phosphorus should no longer be a limiting nutrient for microorganisms.
- Based on results previously presented in the 2019 Annual Progress Report, periodic quarterly progress reports, and recent results obtained as part of the on-going Las Vegas Wash Bioremediation Pilot Study, the specific gravity readings collected for the injectate solution were consistently within the designed specification throughout the injection activities. This confirms that the mixing process described in the *In-Situ Bioremediation Injections – Batch Mixing and Injections Field Guidance Document* (Tetra Tech, 2019c) results in a consistent, well-mixed injectate solution. As a result, it is recommended that specific gravity testing be discontinued during future injection events that are conducted in accordance with the *In-Situ Bioremediation Injections – Batch Mixing and Injections Field Guidance Document* (Tetra Tech, 2019c).
- Continue to evaluate operational efforts to optimize procedures and reduce costs as appropriate.

<u>Maintenance</u>

- Perform injection well maintenance prior to the seventh and eighth injection events (to the extent required) to maintain long-term injectability.
- Evaluate the long-term effects of the 2019 and 2020 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(s) and approximate frequency that well maintenance activities may be required for long-term ISB operations.
- Continue to evaluate maintenance efforts to optimize field procedures and streamline long-term operational costs for ISB as appropriate.

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[4] The seventh injection event was performed from February 24 through March 16, 2021.

Monitoring

- Because the original study demonstrated that ISB was effective at remediating perchlorate- and chlorate-contaminated groundwater and the focus of this study extension is evaluation of long-term O&M of an ISB remedy, the current effectiveness monitoring program can continue to be pared-down over time during the study extension. As a result, the following modifications are planned to the effectiveness monitoring program:
    - Groundwater sampling will be reduced to three monitoring events following each injection event. For example, if injections occur approximately once every eight months, then the sampling events should occur one, four, and seven months following injections. This will allow for observation of degradation both immediately before and after injections, while reducing the overall annual effectiveness monitoring program to approximately five sampling events per year.
    - Results to date indicate minimal increases in ferrous iron and sulfide concentrations in groundwater. Based on these results, the frequency of ferrous iron and sulfide field screening will be reduced from quarterly to semi-annual sampling.
    - Analytical data collected since study inception indicate that metals mobilization within the study area has been limited and is not problematic. Because metals mobilization is still an important component to evaluate with respect to secondary effects of ISB, metals analysis will continue to be included in the effectiveness monitoring program. However, the frequency of metals analysis be reduced from semi-annual to annual.
- Perform annual microbial sampling via the deployment of Bio-Traps® in the same four injection/monitoring wells to improve understanding of long-term microbial trends.
- Continue to 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.

Reporting

- Continue to submit progress reports to NDEP on a quarterly basis.
- Prepare the 2021 Annual Progress Report, which will include a summary of 2021 activities and an update to all information presented herein.

6.0 REFERENCES

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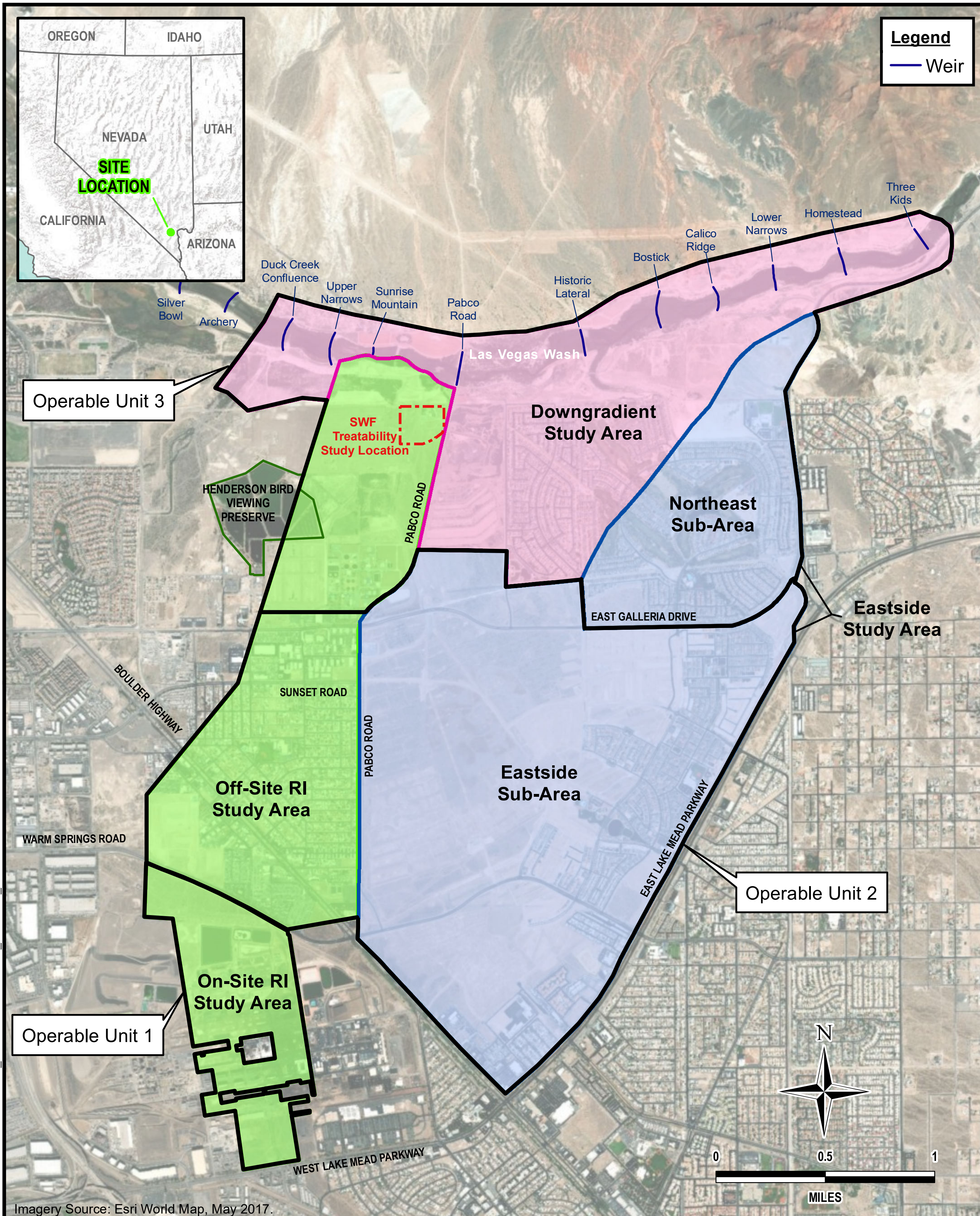
Figures



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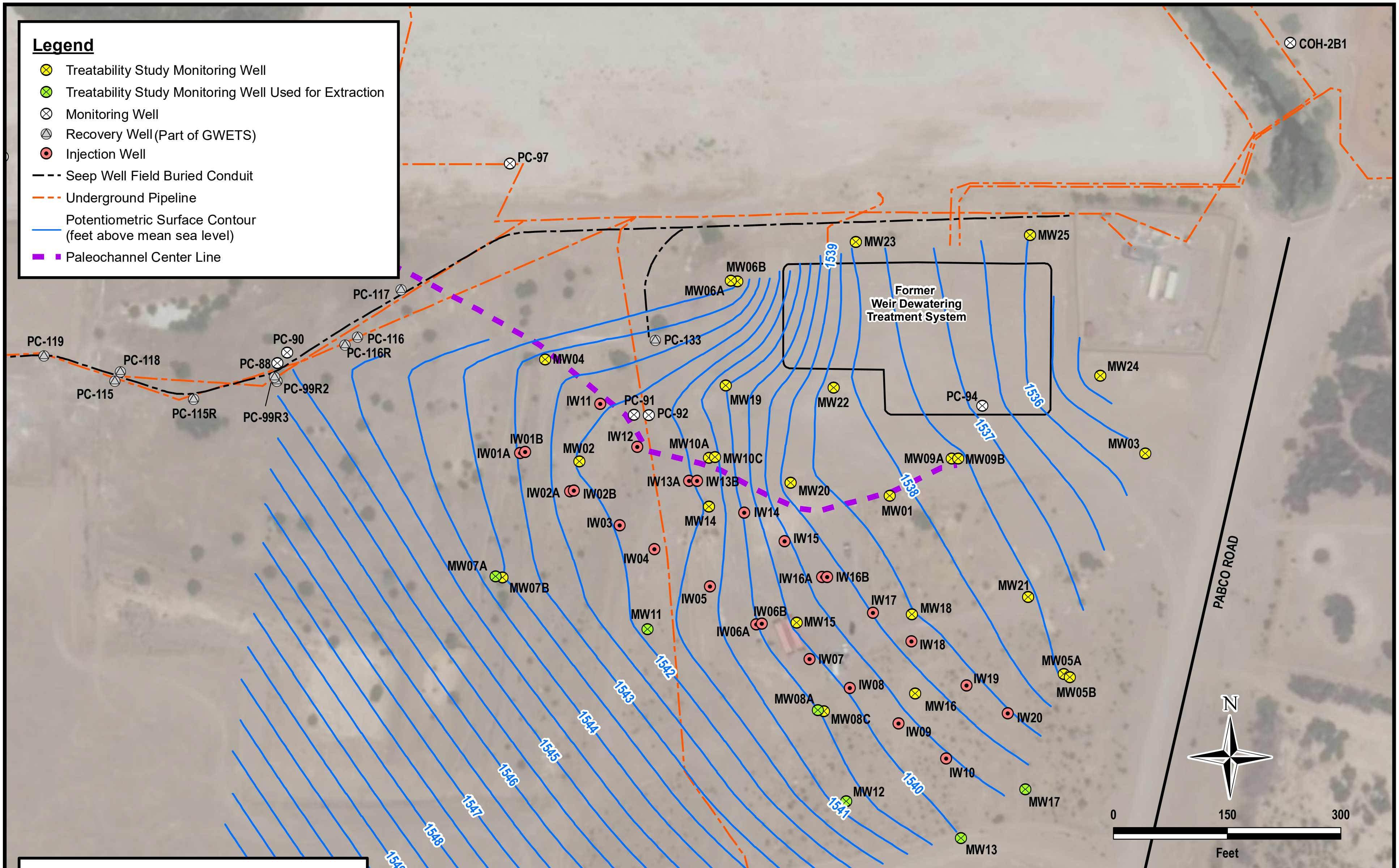
NEVADA ENVIRONMENTAL RESPONSE TRUST

SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY 2020 ANNUAL PROGRESS REPORT
HENDERSON, NEVADA

TREATABILITY STUDY LOCATION

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

Figure No.
1



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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 2020.
4. Imagery Source: Esri World Map, May 2017.

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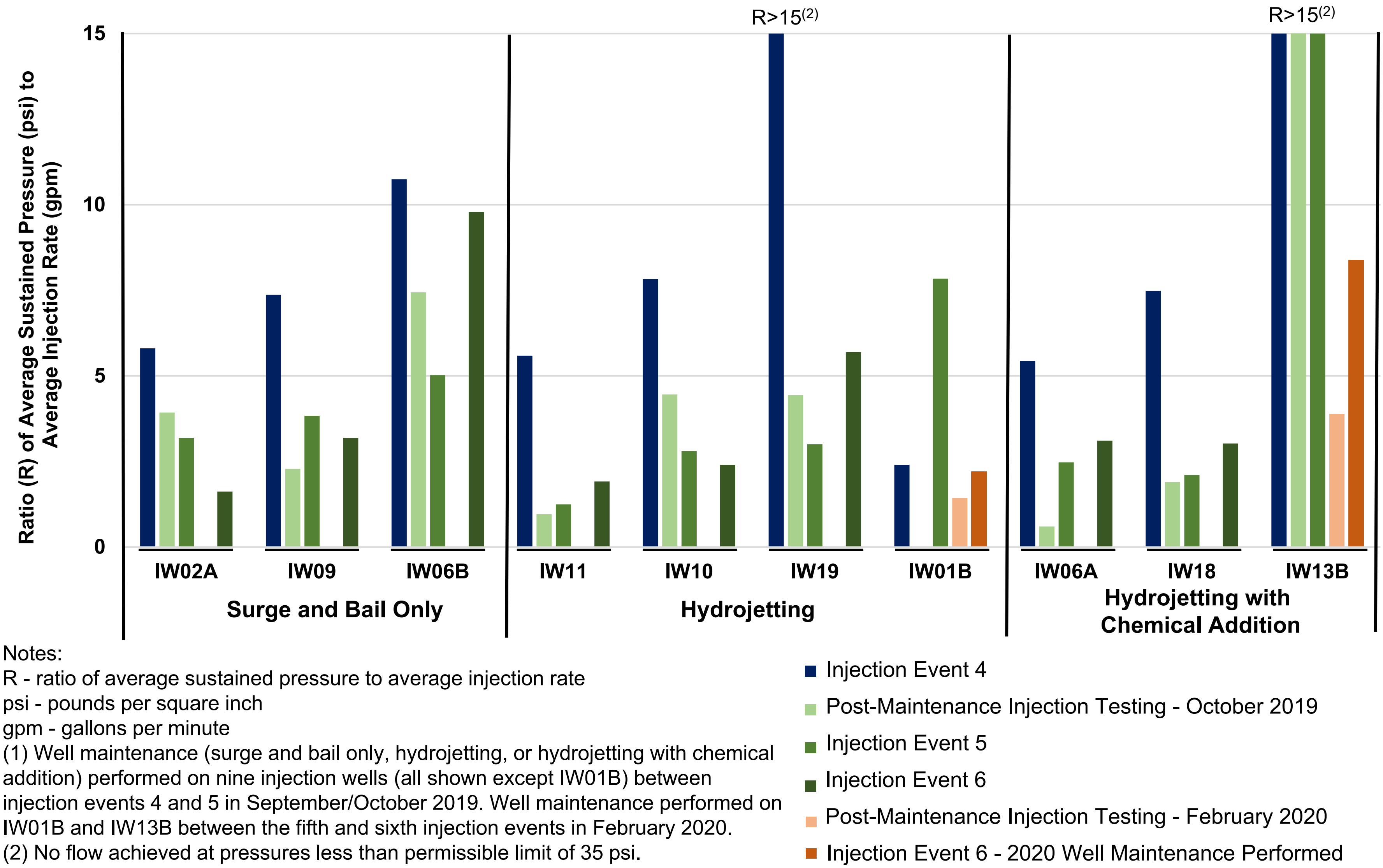
SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY
2020 ANNUAL PROGRESS REPORT
HENDERSON, NEVADA

TREATABILITY STUDY LAYOUT

Project No.:	117-7502018
Date:	MARCH 19, 2021
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 on nine injection wells (all shown except IW01B) between injection events 4 and 5 in September/October 2019. Well maintenance performed on IW01B and IW13B between the fifth and sixth injection events in February 2020.
(2) No flow achieved at pressures less than permissible 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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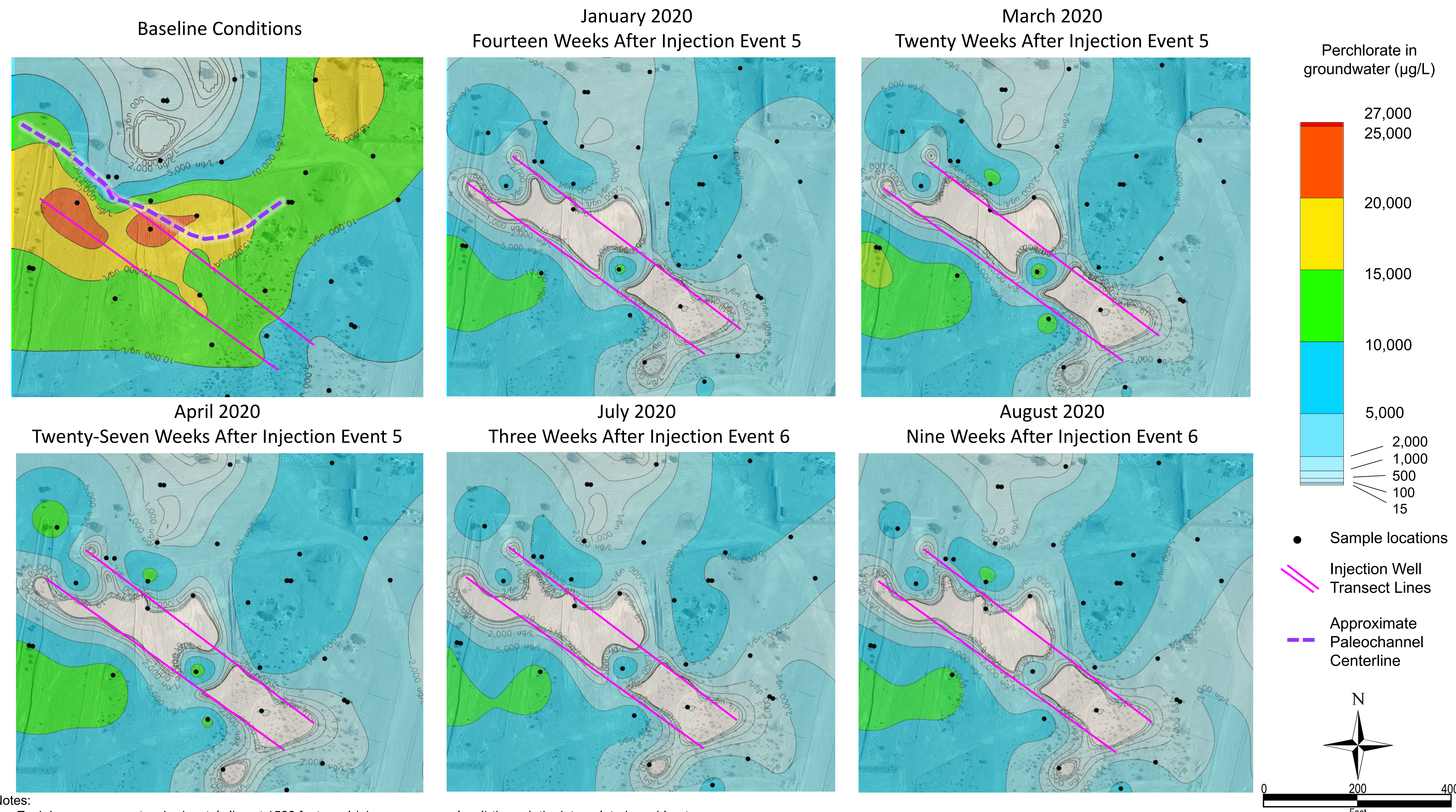
HENDERSON, NEVADA

INJECTION WELL PERFORMANCE BY WELL MAINTENANCE METHOD

Project No.:	117-7502018-M11
Date:	APRIL 22, 2021
Designed By:	JD
Figure No.	3



Notes:

1. Each image represents a horizontal slice at 1522 feet amsl (above mean sea level) through the interpolated perchlorate concentration plume. Concentrations represented at monitoring well clusters may vary from reported concentrations based on screen elevations.
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, October 2019 and May/June 2020. Images presented in this figure represent groundwater sampling events that have occurred during the 2020 reporting period following the fifth and sixth injection events performed in October 2019 and May/June 2020.

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2020 ANNUAL PROGRESS REPORT
HENDERSON, NEVADA

PERCHLORATE DISTRIBUTION IN GROUNDWATER – JANUARY 2020 TO AUGUST 2020

Project No.:	117-7502018-M11
Date:	September 16, 2021
Designed By:	CKG
Figure No.	**4A**

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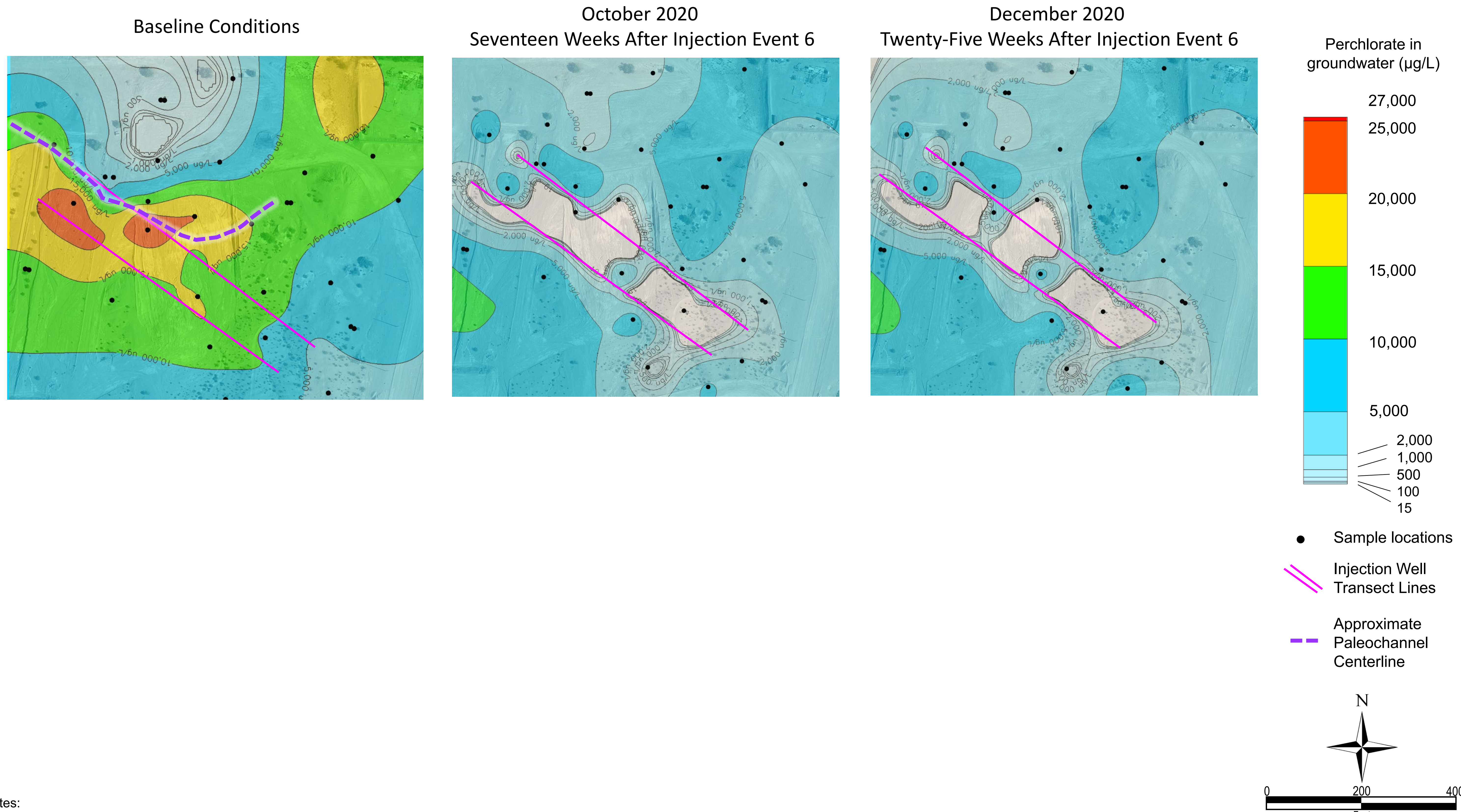

Notes:

1. Each image represents a horizontal slice at 1522 feet amsl (above mean sea level) through the interpolated perchlorate concentration plume. Concentrations represented at monitoring well clusters may vary from reported concentrations based on screen elevations.
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, October 2019 and May/June 2020. Images presented in this figure represent groundwater sampling events that have occurred during the 2020 reporting period following the fifth and sixth injection events performed in October 2019 and May/June 2020.

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PERCHLORATE DISTRIBUTION IN GROUNDWATER – OCTOBER 2020 TO DECEMBER 2020

Project No.:	117-7502018-M11
Date:	September 16, 2021
Designed By:	CKG
Figure No.	4B

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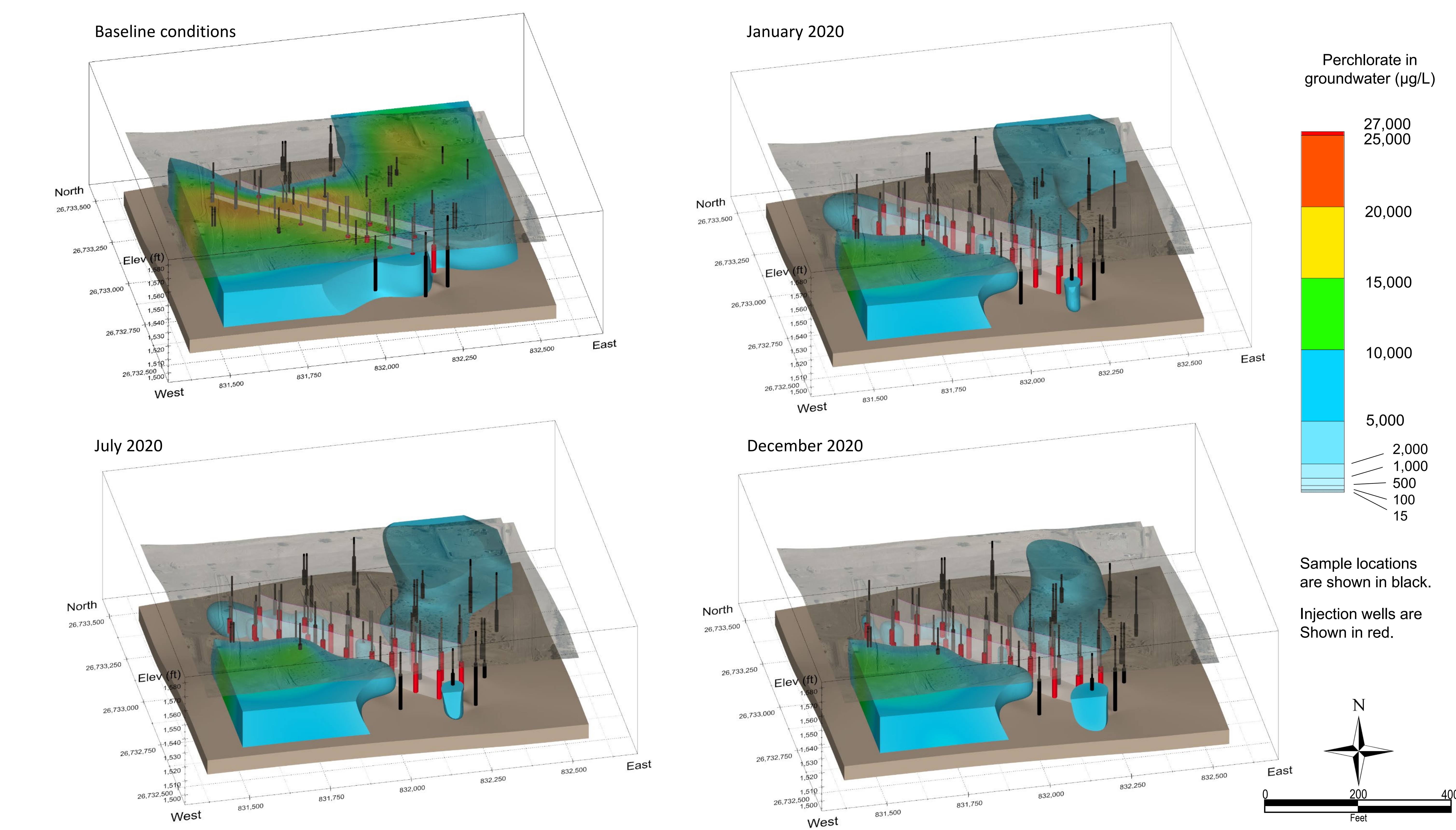

Notes:

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, October 2019 and May/June 2020. Images presented in this figure represent groundwater sampling events that have occurred during the 2020 reporting period following the fifth and sixth injection events performed in October 2019 and May/June 2020.

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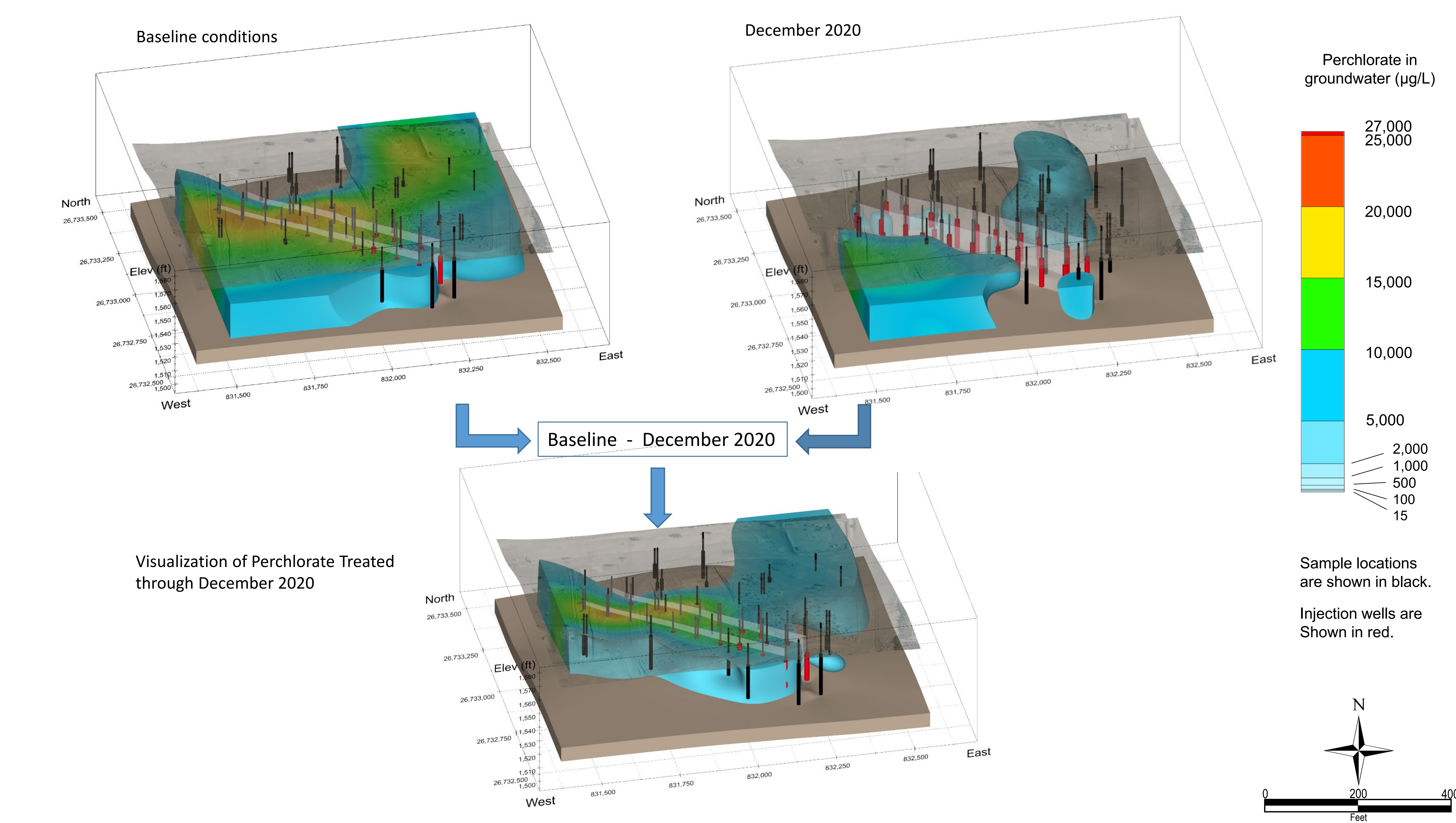
2020 ANNUAL PROGRESS REPORT
HENDERSON, NEVADA

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

Project No.:	117-7502018-M11
Date:	September 16, 2021
Designed By:	CKG
Figure No.	4C



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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, October 2019 and May/June 2020. Image presented in this figure represents the last groundwater sampling event that occurred during the 2020 reporting period in December 2020.

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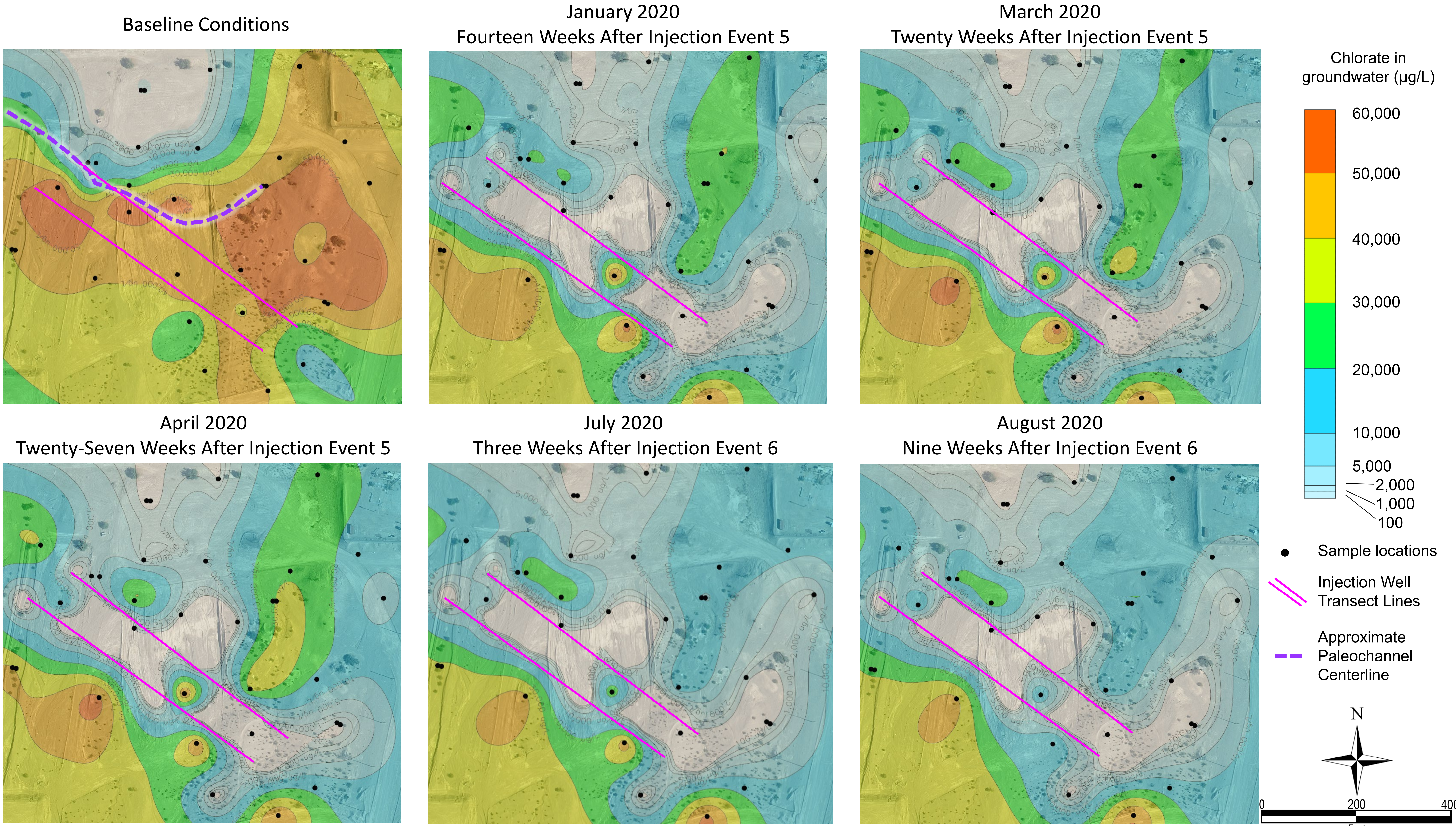
SEEP WELL FIELD AREA BIOREMEDIATION TREATABILITY STUDY
2020 ANNUAL PROGRESS REPORT
HENDERSON, NEVADA

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

Project No.:	117-7502018-M11
Date:	September 16, 2021
Designed By:	CKG
Figure No.	**4D**



Notes:

1. Each image represents a horizontal slice at 1522 feet amsl (above mean sea level) through the interpolated chlorate concentration plume. Concentrations represented at monitoring well clusters may vary from reported concentrations based on screen elevations.
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, October 2019 and May/June 2020. Images presented in this figure represent groundwater sampling events that have occurred during the 2020 reporting period following the fifth and sixth injection events performed in October 2019 and May/June 2020.

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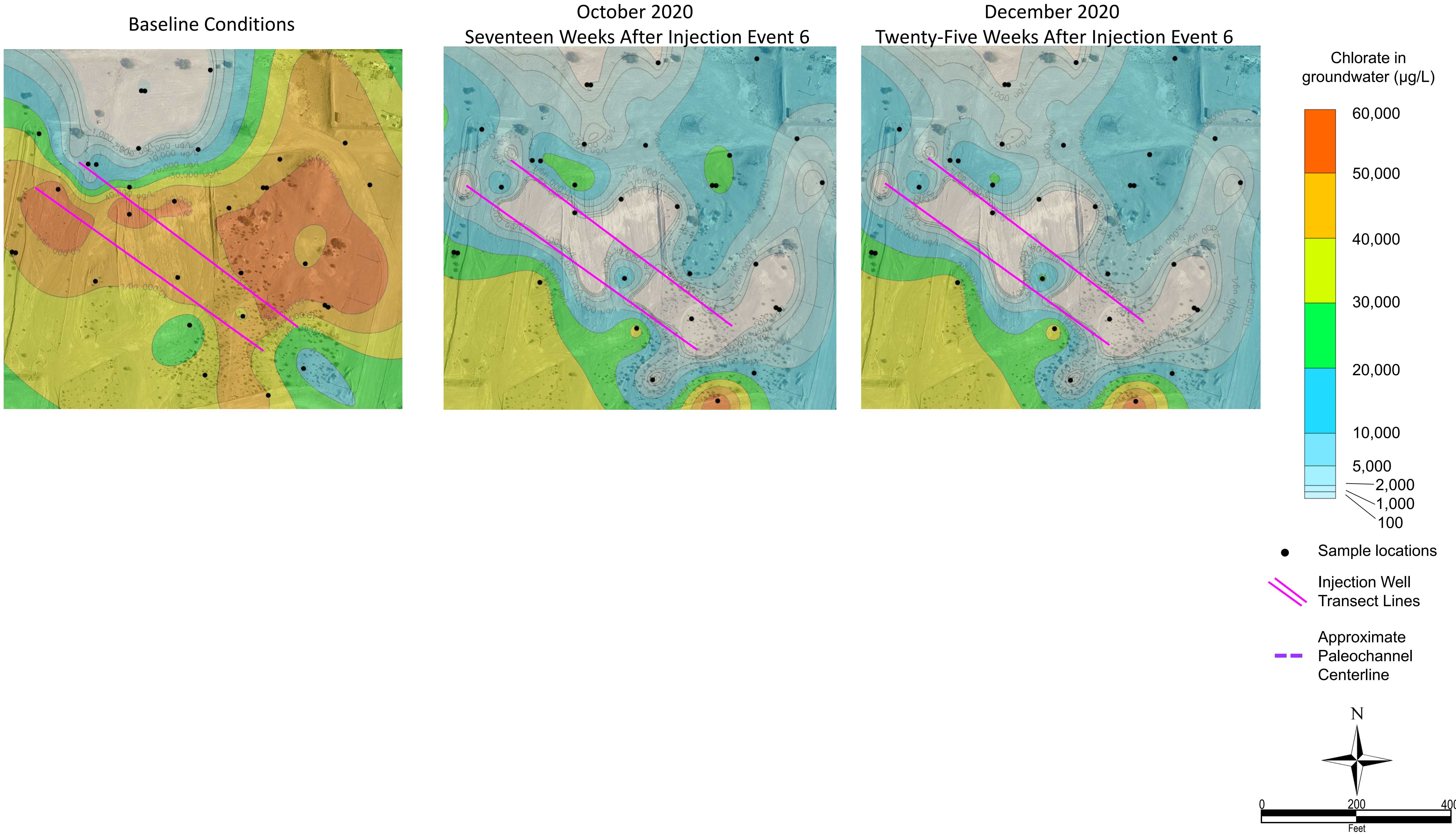
CHLORATE DISTRIBUTION IN GROUNDWATER – JANUARY 2020 TO AUGUST 2020

Project No.:	117-7502018-M11
Date:	September 16, 2021
Designed By:	CKG
Figure No.	**5A**



Notes:

1. Each image represents a horizontal slice at 1522 feet amsl (above mean sea level) through the interpolated chlorate concentration plume. Concentrations represented at monitoring well clusters may vary from reported concentrations based on screen elevations.
2. Baseline concentrations presented from July 2017 are representative of pre-injection conditions.
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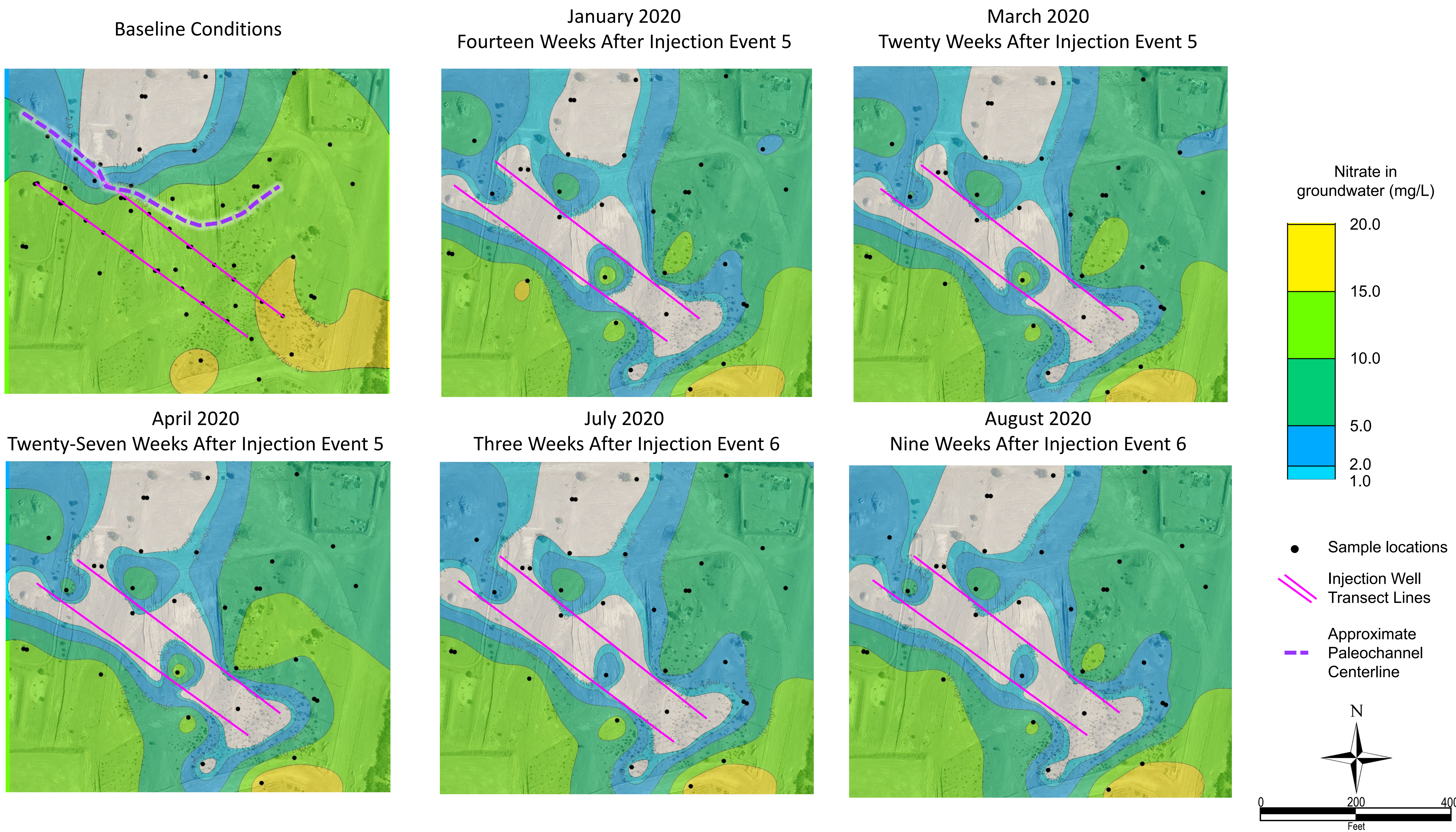
CHLORATE DISTRIBUTION IN GROUNDWATER – OCTOBER 2020 TO DECEMBER 2020

Project No.:	117-7502018-M11
Date:	September 16, 2021
Designed By:	CKG
Figure No.	5B



Notes:

1. Each image represents a horizontal slice at 1522 feet amsl (above mean sea level) through the interpolated nitrate concentration plume. Concentrations represented at monitoring well clusters may vary from reported concentrations based on screen elevations.
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, October 2019 and May/June 2020. Images presented in this figure represent groundwater sampling events that have occurred during the 2020 reporting period following the fifth and sixth injection events performed in October 2019 and May/June 2020.

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NITRATE DISTRIBUTION IN GROUNDWATER – JANUARY 2020 TO AUGUST 2020

Project No.:	117-7502018-M11
Date:	September 16, 2021
Designed By:	CKG
Figure No.	**6A**

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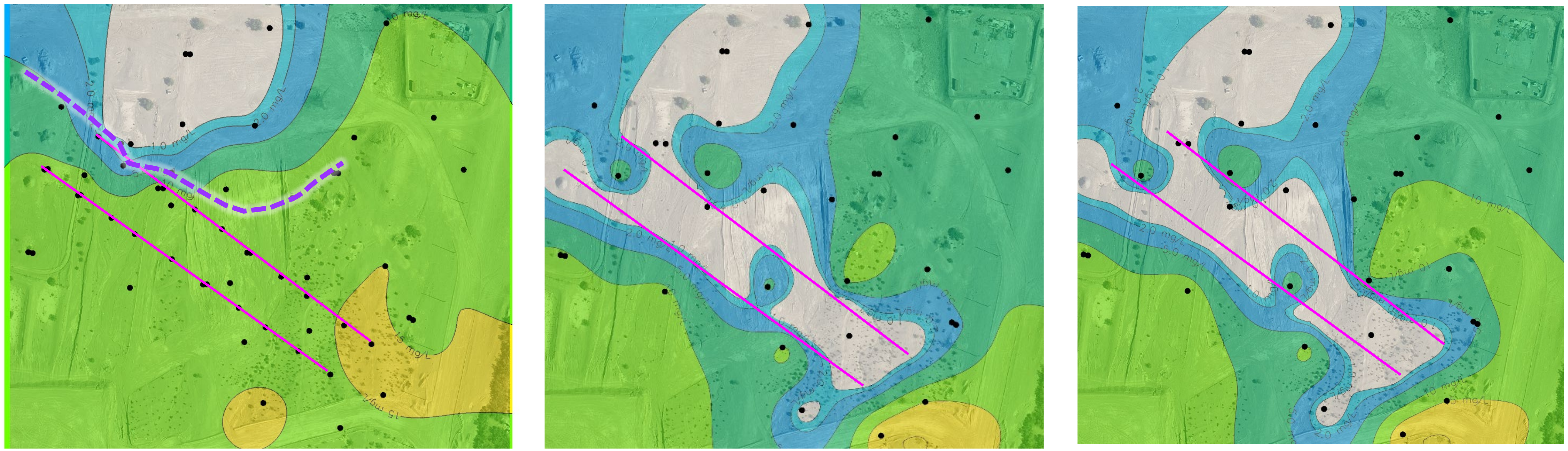
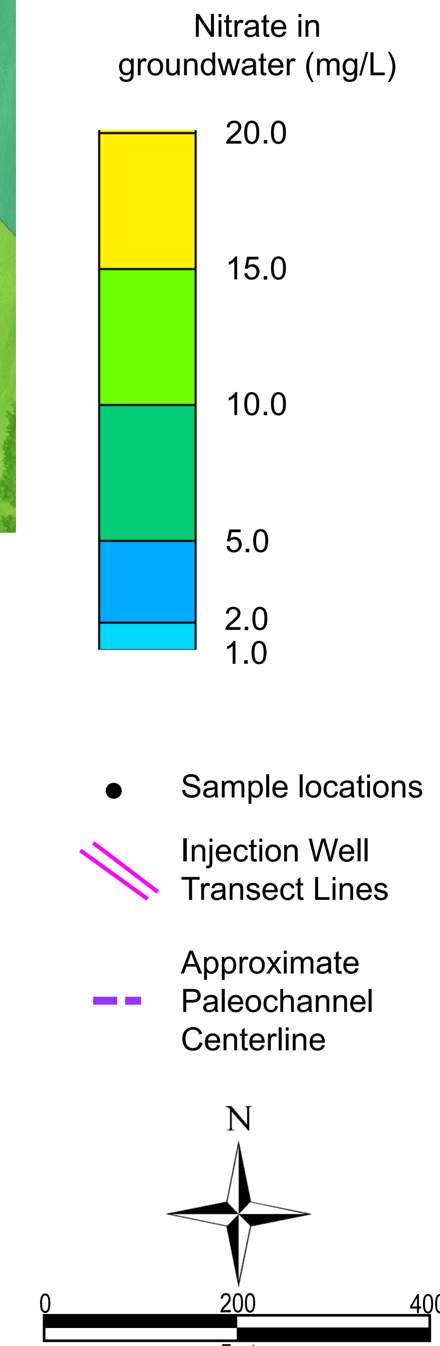
Baseline Conditions

October 2020
Seventeen Weeks After Injection Event 6

December 2020
Twenty-Five Weeks After Injection Event 6





Notes:

1. Each image represents a horizontal slice at 1522 feet amsl (above mean sea level) through the interpolated nitrate concentration plume. Concentrations represented at monitoring well clusters may vary from reported concentrations based on screen elevations.
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Project No.:	117-7502018-M11
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Figure No.	**6B**

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