Vacuum Enhanced Recovery Treatability Study Results Report
Nevada Environmental Response Trust Site
Henderson, Nevada

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

LIST OF ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
amsl	above mean sea level
AP	ammonium perchlorate
ASTM	American Society for Testing and Materials
bgs	below ground surface
BL	baseline
Cascade	Cascade Drilling, LP
cm/s	centimeters per second
COPC	chemical of potential concern
DAQ	Clark County Department of Air Quality
DO	dissolved oxygen
DVSR	Data Validation Summary Report
EC	electrical conductivity
ETI	Envirogen Technologies, Inc.
FBR	Fluidized Bed Reactor
ft btoc	feet below top of casing
ft w.c.	feet of water column
g/cc	grams per cubic centimeter
gpm	gallons per minute
GWETS	Groundwater Extraction and Treatment System
GWTP	Groundwater Treatment Plant
HASP	Health and Safety Plan
Hp	horsepower
hr	hour
in Hg	inches of mercury
In-Situ	In-Situ, Inc.
IWF	Interceptor Well Field
kW	kilowatt
L	liter
LRP	liquid-ring pump
$\mu g/m^3$	micrograms per cubic meter
mg/kg	milligram per kilogram
mg/L	milligrams per liter
mL	milliliter

Acronyms/Abbreviations	Definition
NDEP	Nevada Division of Environmental Protection
NDWR	Nevada Division of Water Resources
NERT or Trust	Nevada Environmental Response Trust
NOI	Notice of Intent
O&M	operation and maintenance
ORP	oxidation-reduction potential
PEST	Parameter ESTimation software
PID	photoionization detector
ppm	parts per million
PVC	polyvinyl chloride
Qal	Quaternary alluvium
ROI	radius of influence
scfm	standard cubic feet per minute
Site	Nevada Environmental Response Trust site
TDS	total dissolved solids
TestAmerica	TestAmerica Laboratories, Inc.
Tetra Tech	Tetra Tech, Inc.
TOC	total organic carbon
tpy	tons per year
Tronox	Tronox Limited
TSS	total suspended solids
UMCf	Upper Muddy Creek formation
USEPA	United States Environmental Protection Agency
VER	vacuum enhanced recovery
VOC	volatile organic compound

CERTIFICATION

Vacuum Enhanced Recovery Treatability Study Results Report

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

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

Office of the Nevada Environmental Response Trust

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

not individually, but solely as Pres. Jay

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: 7-11-18

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: Vacuum Enhanced Recovery Treatability Study Results Report, Nevada Environmental Response Trust Site, Henderson, Nevada

Kyle J. Hansen

July 12, 2018

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

Date

Nevada CEM Certificate Number: 2167
Nevada CEM Expiration Date: September 18, 2018

EXECUTIVE SUMMARY

This report summarizes the technical approach and findings for the vacuum enhanced recovery (VER) treatability study conducted at the Nevada Environmental Response Trust (NERT or Trust) site (Site) in Henderson, Nevada. The work was performed in accordance with the *Vacuum Enhanced Recovery Treatability Study Work Plan*, approved by the Nevada Division of Environmental Protection (NDEP) on September 18, 2017. The VER treatability study was performed between September 2017 and February 2018, in the vicinity of the Interceptor Well Field (IWF). Objectives of the VER treatability study included the following:

- Evaluate the extent to which vacuum enhancement will improve groundwater recovery in the Upper Muddy Creek formation (UMCf) compared to conventional pumping.
- Evaluate the extent to which operating deeper groundwater extraction wells (completed within the UMCf) in the vicinity of the IWF, may affect the operation of the IWF.
- Collect site-specific design data to support the Feasibility Study.

<u>Pre-Field Activities</u>

One intermediate VER extraction well, two intermediate monitoring wells, one deep VER extraction well, and two deep monitoring wells were installed to support the VER treatability study. The intermediate VER extraction well and intermediate monitoring wells were screened in the UMCf from 55 to 70 feet below ground surface (bgs). The deep VER extraction well and deep monitoring wells were screened in the UMCf from 90 to 110 feet bgs. Background monitoring was conducted to evaluate groundwater conditions prior to implementing the treatability study.

<u>Intermediate VER Treatability Study</u>

The intermediate VER treatability study consisted of a step-drawdown test (Phase A), a constant-rate pumping test (Phase B), and a VER test followed by a groundwater elevation monitoring period (Phase C) performed on the intermediate-depth VER extraction well, VER-01I. Groundwater drawdown and water level recovery were recorded at nearby monitoring wells during the tests using electronic pressure transducer/data logger units and electronic water level indicators. Based on the results of the step-drawdown test, a flow rate of 2.0 gallons per minute (gpm) was selected for the constant-rate pumping test (Phase B). The constant-rate pumping test was performed for approximately 37 hours. The Phase C VER test was conducted by extracting groundwater from VER-01I for approximately 8 hours using conventional pumping only, followed by 70 hours of pumping under an applied vacuum supplied by a trailer-mounted VER system. The main findings of the intermediate VER treatability study include the following:

- The highest concentrations of perchlorate (830 milligrams per kilogram [mg/kg]), chlorate (3,600 mg/kg), and hexavalent chromium (20 mg/kg) in soil were detected in samples collected from 50 feet bgs. The highest concentrations of perchlorate, chlorate, and hexavalent chromium in groundwater were encountered between 55 and 70 feet bgs (corresponding with the screened interval of VER-01I). Perchlorate, chlorate, and hexavalent chromium concentrations decreased in soil below 50 feet bgs and decreased in groundwater below 70 feet bgs.
- Concentrations of perchlorate, chlorate, hexavalent chromium, and chloroform detected in groundwater samples from VER-01I increased initially prior to stabilizing after 12 hours during the constant-rate test (Phase B). Perchlorate concentrations increased from 300 milligrams per liter (mg/L) to 1,200 mg/L, chlorate concentrations increased from 680 mg/L to 3,800 mg/L, hexavalent chromium concentrations increased from 2.2 mg/L to 13 mg/L, and chloroform concentrations increased from 0.110 mg/L to 0.730 mg/L.
- Chlorite was not detected at a concentration above the laboratory reporting limit in any of the groundwater samples collected as part of the intermediate VER treatability study.

- The average groundwater extraction rate using conventional pumping during the first eight hours of the intermediate VER test was 3.12 gpm. The average groundwater extraction rate using conventional pumping and applying a vacuum was 4.05 gpm, an approximate 30 percent increase in the groundwater extraction rate over the comparable time period. The average groundwater extraction rate using conventional pumping with vacuum was 3.83 gpm over the total 70-hour period when vacuum was applied.
- Based on pressure transducer data, up to 6.75 feet of drawdown (M-221) was observed in performance monitoring wells located 66 feet from pumping well VER-01I during the VER test.
- Based on the Groundwater Extraction and Treatment System (GWETS) metrics data provided by Envirogen Technologies, Inc. (ETI), drawdown was observed in IWF pumping wells I-F, I-G, I-Q, and I-X, ranging from 1.73 feet (I-X) to 7.09 feet (I-F) during the intermediate VER test. IWF pumping wells I-F, I-G, I-Q, and I-X are located 44 feet, 140 feet, 65 feet, and 72 feet from VER-01I, respectively. As such, additional evaluation is necessary to determine the maximum sustainable pumping rate that will not jeopardize the operation or the capture zone of the IWF.
- Groundwater flow modeling indicated that applying vacuum at VER-01I would result in increasing the simulated groundwater radius of influence (ROI) from approximately 95 to 120 feet.
- Groundwater flow modeling identified that applying vacuum at VER-01I resulted in an approximately 14 percent increase in the capture zone radius in comparison to conventional pumping alone (i.e., from 70 feet to 80 feet).
- The maximum vacuum ROI measured during the intermediate VER test was 28 feet.
- During the intermediate zone VER test, perchlorate concentrations in the extracted groundwater from VER-01I generally remained stable ranging from 1,100 to 1,300 mg/L, chlorate concentrations remained within a range of 2,900 to 3,400 mg/L, and hexavalent chromium concentrations increased from 7.7 to 13 mg/L.
- Perchlorate concentrations in groundwater at VER-01I exhibited an overall increasing trend with respect to baseline (pre-aquifer testing) concentrations prior to stabilizing during the constant rate test, increasing from 300 mg/L (baseline) to 1,200 mg/L (end of the constant rate test).
- Low amounts of VOCs were extracted from the subsurface, and the mass removal efficiency of the vapor phase carbon was greater than 98.5%.

Deep VER Treatability Study

The deep VER treatability study consisted of a step-drawdown test (Phase A), a constant-rate pumping test (Phase B), and a VER test followed by a groundwater elevation monitoring period (Phase C) performed on the deep-depth VER extraction well, VER-01D. Groundwater drawdown and water level recovery were recorded at nearby monitoring wells during the tests. Based on the results of the step-drawdown test, a flow rate of 0.5 gpm was selected for the constant-rate pumping test, which was performed for approximately 48 hours. The VER test was conducted by extracting groundwater from VER-01D for approximately 12 hours using conventional pumping only, followed by 84 hours of pumping under an applied vacuum supplied by a trailer-mounted VER system.

The main findings of the deep VER treatability study include the following:

- The highest concentrations of perchlorate (6.4 mg/kg) and chlorate (11 mg/kg) in soil corresponding to the screened interval of VER-01D (90 to 110 feet bgs) were detected in samples collected from 90 feet bgs. Hexavalent chromium was only detected in one soil sample collected between 90 and 110 feet bgs at an estimated concentration of 0.31 mg/kg at 110 feet bgs.
- The highest concentrations of perchlorate (53 mg/L), chlorate (140 mg/L), and hexavalent chromium (0.040 mg/L) detected in baseline groundwater samples from the deep UMCf well VER-01D. The

concentrations detected in groundwater samples from VER-01D were less than concentrations detected in baseline groundwater samples from VER-01I, VMW-01I, and VMW-02I.

- Concentrations of perchlorate, chlorate, hexavalent chromium, and chloroform detected in samples from VER-01D exhibited a decreasing trend from baseline concentrations as the constant-rate test progressed (Phase B). Perchlorate concentrations decreased from 53 mg/L to 0.89 mg/L, chlorate concentrations decreased from 140 mg/L to 3.2 mg/L, hexavalent chromium concentrations decreased from 0.17 mg/L to 0.027 mg/L, and chloroform concentrations decreased from 0.029 mg/L to 0.00041 mg/L.
- Chlorite was not detected at a concentration above the laboratory reporting limit in any of the groundwater samples collected as part of the deep VER treatability study.
- The average groundwater extraction rate using conventional pumping during the first 12 hours of the deep VER test was 0.53 gpm. The average groundwater extraction rate using conventional pumping and applying a vacuum was 0.64 gpm, an approximate 21 percent increase in the groundwater extraction rate.
- Based on pressure transducer data, drawdown greater than 10 feet was observed in performance monitoring wells located up to 55 feet from pumping well VER-01D during the VER test.
- Based on the GWETS metrics data provided by ETI, drawdown was not observed in the nearest IWF pumping wells (I-F, I-G, I-Q, and I-X) during the deep constant-rate or VER test. IWF pumping wells I-F, I-G, I-Q, and I-X are located approximately 30 feet, 130 feet, 50 feet, and 66 feet from VER-01D, respectively. As such, pumping of the deeper UMCf should not impact operation of the IWF.
- The VER technology slightly increased the simulated groundwater ROI from 125 feet for conventional pumping to 135 feet after applying vacuum at VER-01D, an 8 percent increase.
- Groundwater flow modeling indicated implementing VER technology at VER-01D resulted in an approximately 14 percent increase in the capture zone radius from 22 to 25 feet.
- Vacuum influence was only observed at M-172, located 13 feet from VER-01D.
- During the deep VER test, perchlorate concentrations in the extracted groundwater from well VER-01D decreased from 2.0 to 0.57 mg/L, chlorate concentrations decreased from 4.4 to 1.7 mg/L, and hexavalent chromium concentrations remained relatively stable between 0.018 and 0.025 mg/L.
- Perchlorate concentrations in groundwater at VER-01D exhibited an overall decreasing trend with respect to baseline (pre-aquifer testing) concentrations prior to stabilizing during the VER test, decreasing from 5.3 mg/L (baseline) to 0.890 mg/L (end of constant-rate pumping test).
- Low amounts of VOCs were extracted from the subsurface, and the mass removal efficiency of the vapor-phase carbon was up to approximately 97%.

Conclusions

VER increased groundwater extraction rates by approximately 30 percent over the first 8 hours of the intermediate VER test and increased the simulated extraction well groundwater ROI by approximately 26 percent within the intermediate screened depth of 55 to 70 feet bgs. However, the Feasibility Study will evaluate whether VER is a more cost-effective alternative to traditional groundwater extraction.

VER increased groundwater extraction rates by approximately 21 percent over the first 12 hours of the deep VER test, and increased the simulated extraction well groundwater ROI by approximately 8 percent within the deep screened depth of 90 to 110 feet bgs.

Groundwater extraction using conventional pumping and VER at VER-01I caused drawdown in several IWF wells, but groundwater extraction using conventional pumping and VER at VER-01D was not observed to cause appreciable drawdown on the IWF wells.

The results of this VER treatability study will be incorporated into the Feasibility Study to be prepared by NERT following completion of the Remedial Investigation. The evaluation of the applicable or relevant and appropriate remedial action alternatives in the Feasibility Study will consider the findings of this treatability study, as well as others conducted, to prepare NERT's recommendation for remedial action alternatives to address Henderson legacy conditions that satisfies the Remedial Action Objectives.

1.0 INTRODUCTION

On behalf of the Nevada Environmental Response Trust (NERT or Trust), Tetra Tech, Inc. (Tetra Tech) has prepared this *Vacuum Enhanced Recovery Treatability Study 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) as part of the Remedial Investigation consistent with the Interim Consent Agreement effective February 14, 2011. The report presents a summary of the technical approach and an evaluation of the results of a vacuum enhanced recovery (VER) treatability study performed in the vicinity of the Interceptor Well Field (IWF) (***Figure 1***). The VER treatability study was implemented in accordance with the *Vacuum Enhanced Recovery Treatability Study Work Plan* (Tetra Tech, Inc., 2017a), approved by the NDEP on September 18, 2017.

1.1 OBJECTIVE

Objectives of the VER treatability study included the following:

- Evaluate the extent to which vacuum enhancement will improve groundwater recovery in the Upper Muddy Creek formation (UMCf) compared to conventional pumping.
- Evaluate the extent to which operating deeper groundwater extraction wells (completed within the UMCf) in the vicinity of the IWF may affect the operation of the IWF.
- Collect site-specific design data to support the feasibility study.

1.2 SITE DESCRIPTION

The Site has been used for industrial purposes since 1942, when it was initially developed by the United States government as a magnesium plant to support World War II military operations. Since that time, the Site and the surrounding properties have been used for chemical manufacturing, including the production of various chlorate and perchlorate compounds. Entities that operated at the Site include Western Electrochemical Company, American Potash and Chemical Company, Kerr-McGee Chemical Corporation, and Tronox Incorporated. On February 14, 2011, NERT took title to the Site as part of the settlement of the Tronox Chapter 11 bankruptcy proceedings. As part of a long-term lease, Tronox Limited (Tronox) operates a manufacturing facility on 114 acres of the Site to produce manganese and boron products. Historical industrial production and related waste management activities conducted at the Site have resulted in the contamination of various environmental media, including soil, groundwater, and surface water. The most notable site-related contaminants of potential concern (COPCs) are perchlorate and hexavalent chromium (Ramboll Environ, 2017a).

Groundwater extraction has been implemented at the Site to address impacts to groundwater resulting from historical releases of perchlorate and hexavalent chromium. Collectively, the entire system of extraction wells, water conveyances, and treatment plants is referred to as the Groundwater Extraction and Treatment System (GWETS). The GWETS treats water from three groundwater extraction well fields: the IWF; the Athens Road Well Field; and the Seep Well Field. Pipelines and lift stations convey groundwater from the well fields to the Site to be treated by the on-site treatment plant. This treatment plant is comprised of the following components: the Groundwater Treatment Plant (GWTP) to reduce hexavalent chromium to trivalent chromium and then to precipitate trivalent chromium from groundwater extracted from the IWF; the Biological Treatment Plant that utilizes Fluidized Bed Reactors (FBRs) to treat perchlorate in groundwater from all of the well fields; the GW-11 Pond, which is used for water storage and equalization; the Equalization Area, which includes equalization tanks and a granular activated carbon pretreatment system; and the effluent pump station and pipeline, which convey treated effluent from the FBR treatment plant to an outfall at the Las Vegas Wash (Tetra Tech, Inc., 2015). The GWTP, has been treating groundwater extracted from the IWF since its construction in 1986 to 1987. Envirogen Technologies, Inc. has operated and maintained the GWTP and the rest of the GWETS since July 25, 2013.

The IWF was installed in 1986 in the shallow water-bearing zone to capture contaminated onsite groundwater, downgradient from the onsite source areas. The IWF consists of 30 extraction wells, 27 of which were active (as of February 2018). Well depths range from 35 feet to 51 ft bgs. From 2012 to 2017, the IWF operated at approximately 66.2 gallons per minute (gpm); the average extraction rate at individual IWF wells from July 2016 to June 2017 ranged from 0.1 gpm (I-G) to 7.3 gpm (I-Z) (Ramboll Environ, 2017a). To further enhance groundwater capture, a barrier wall was constructed in 2001 approximately 50 feet downgradient of the IWF across the higher concentration portion of the perchlorate plume (***Figure 2***). The barrier wall is approximately 1,600 feet in length, 60 feet deep, and constructed to tie into approximately 30 feet of the UMCf (Ramboll Environ, 2017a).

1.3 REPORT ORGANIZATION

This report is organized as follows:

- **Introduction (Section 1.0):** Provides the primary objectives of the VER treatability study, the site description, and the organization of this report.
- **Technology Description (Section 2.0):** Provides an overview of VER technology.
- **Field Treatability Study Activities (Section 3.0):** Provides a summary of activities performed for the VER treatability study including permitting, well installation, baseline soil and groundwater sample collection, VER system installation, step-drawdown tests, constant-rate pumping tests, and VER tests.
- **Analysis of Results (Section 4.0):** Summarizes results of baseline soil and groundwater analytical results, step-drawdown tests, constant-rate pumping tests, VER tests, and groundwater modeling.
- **Summary of Key Findings (Section 5.0):** Summarizes the overall findings of the VER treatability study and provides considerations for a conceptual design for the large-scale implementation of VER at the Site.
- **References (Section 6.0):** Lists the documents referenced in this report.

2.0 TECHNOLOGY DESCRIPTION

VER is a technique of applying high vacuum to a recovery well to enhance the liquid recovery of that well by increasing the net effective drawdown in a low-permeable formation. The application of vacuum to a recovery well increases the effective hydraulic gradient and thus increases the capture zone and the liquid recovery rate at the well. The increased liquid recovery rate enhances the rate of removal of dissolved contaminants. Through the application of high vacuum, capillary pressures can be overcome, forcing the release of trapped water held in soil pores. VER also increases the mass removal of the volatile and semi-volatile contaminants, by maximizing dewatering and facilitating volatilization from previously saturated sediments via the increased air movement (Ayyaswami, 1996). VER has successfully been applied at sites like the NERT Site to:

- Enhance the overall capture zone and liquid recovery rate of recovery wells, especially under low-permeability conditions as in the UMCf.
- Increase the mass removal rates of COPCs present in soil and groundwater.

Implementation of a VER system is most applicable in fine-grained formations with a hydraulic conductivity between 10^{-3} to 10^{-5} centimeters per second (cm/s), such as the upper portion of the UMCf. The implementation of a VER system in a low-permeability zone generally results in the development of rapid or significant drawdown with a narrow cone of depression and an associated steep hydraulic gradient (Blake & Gates, 1986). The geologic and hydrogeologic conditions within the VER treatability study area, specifically the UMCf, are similar to the recommended conditions for implementing VER. NERT's implementation of VER may provide multiple advantages over conventional recovery systems including increasing the size of the capture zone around an extraction well, capturing impacted groundwater migrating underneath the barrier wall, reducing the number of recovery wells required, and accelerating the rate of mass removal. VER has the potential to effectively recover the COPCs at the Site based on the physical properties of the contaminants and reduce operational cost.

3.0 FIELD TREATABILITY STUDY ACTIVITIES

This section summarizes the activities performed as part of the VER treatability study.

3.1 PERMITTING REQUIREMENTS

This subsection identifies the permitting and regulatory approvals required to implement the VER treatability study. A Notice of Intent (NOI) card and associated amendments were obtained from the State of Nevada, Department of Conservation and Natural Resources, Division of Water Resources (NDWR), issued on September 22, 2017) for the installation of the four monitoring wells (as two well clusters) and two VER extraction wells associated with the treatability study.

An application for a Permit to Appropriate Water for Environmental Purposes was submitted to the NDWR prior to installation of VER extraction wells VER-01I and VER-01D. NDWR issued the requested permit (Permit #87305E) for the VER treatability study on October 18, 2017.

Tetra Tech submitted a request for a case-by-case determination of insignificant activity exempt from permitting for the VER treatability study, under Clark County Rule 12.1.2(d), to the Clark County Department of Air Quality (DAQ) on September 13, 2017. The information provided in the request demonstrated that emissions associated with the VER treatability study were less than the threshold values of 2 tons per year (tpy) of any criteria pollutant or 5 tpy for any combination of criteria pollutants, which made the VER treatability study eligible for a finding of insignificant activity exempt from permitting under Clark County Rule 12.1.2(d). DAQ approved Tetra Tech's request to deem the trial associated with the VER treatability study as an insignificant activity on October 16, 2017.

The VER trailer-mounted system utilized for this treatability study was powered by a trailer-mounted 56-kilowatt (kW) generator that utilized an integrated 103-gallon diesel fuel tank. The size of the diesel fuel tank (greater than 60 gallons of a combustible liquid stored outdoors) triggered the requirement for a permit to store flammable/combustible liquids from the Clark County Department of Building and Fire Prevention. Prior to operating the generator, Tetra Tech prepared and submitted a Temporary Operational Fire Permit application on December 11, 2017. A representative of the Clark County Department of Building and Fire Prevention Department inspected the VER trailer-mounted system on December 22, 2017. A Temporary Operational Fire Permit (Permit #FP17-56790) was issued on December 22, 2017.

Dust Control Permit #47835 was issued by the Clark County DAQ on June 15, 2017, for proposed treatability study activities within the Ammonium Perchlorate (AP) Area, which includes the VER treatability study area.

3.2 HEALTH AND SAFETY

All field work was conducted in accordance with an Activity Hazard Analysis and other elements of the site-wide Health and Safety Plan (HASP), which addressed potential chemical and physical hazards associated with the VER treatability study and related tasks (Tetra Tech, Inc., 2017b). Modified Level D personal protective equipment was required for all field activities. Available chemical fact sheets and safety data sheets had been incorporated into the HASP, and were made available on-Site at all times during field activities. No health and safety incidents occurred during the implementation of the VER treatability study.

3.3 WELL INSTALLATION

This subsection describes the installation of four monitoring wells (as two well clusters) and two VER extraction wells used during the VER treatability study.

3.3.1 Utility Clearance

Tetra Tech retained the services of Cascade Drilling, LP of Las Vegas, Nevada, (Cascade) to clear each borehole for utilities to at least 5 feet bgs using an air knife rig. In addition, Cascade verified the diameter, location, and depth of the GWETS subsurface groundwater conveyance piping in the VER treatability study area, in accordance with the *Contingency Plan for the Vacuum Enhanced Recovery Treatability Study* (Tetra Tech, Inc., 2017c), approved by NDEP on October 5, 2017. Boring locations were adjusted in the field, as needed, to avoid utilities.

3.3.2 Baseline Soil and Groundwater Samples

Six soil borings were drilled in the VER treatability study area at each VER extraction and monitoring well location prior to the installation of wells to obtain lithologic information, physical parameters, and contaminant concentrations. These borings were completed as four monitoring wells (VMW-01I, VMW-01D, VMW-02I, VMW-02D), one intermediate VER extraction well (VER-01I), and one deep VER extraction well (VER-01D), which are depicted on ***Figure 3***. Tetra Tech retained the services of Cascade to advance the soil borings using hollow-stem auger drilling and complete the borings as monitoring wells. Drilling activities were conducted from September 28 through October 24, 2017. Soil samples were collected for lithological logging purposes from ground surface to the total depth of each borehole using a CME Continuous Sample Tube System consisting of a 3-inch by 5-foot sample tube with a cutting shoe that extends below the auger head. The soil borings were logged in general accordance with the American Society for Testing and Materials (ASTM) Standard D-2488-09 *Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)* (ASTM International, 2009). The soil boring logs are provided in ***Appendix A***.

To evaluate contaminant concentrations with depth, the soil borings installed during well installation were advanced through the alluvium and UMCf to a total depth of 115 feet bgs. Soil samples for chemical analysis were collected from soil borings VMW-01D, VMW-02D, VER-01I, and VER-01D at 5-foot intervals in the unsaturated zone to evaluate vadose zone impacts, at 10-foot intervals in the saturated zone, and at lithologic or color changes. No soil samples for chemical analysis were collected from soil borings VMW-01I and VMW-02I due to their proximity to the deeper well pair. Soil samples for particle-size distribution analysis were collected from boring location VMW-01I at 62 feet bgs and from boring location VMW-01D at 100 feet bgs; these data were used to support the selection of the well-screen slot size and filter pack material. Soil samples for additional physical parameter analysis were collected using a Shelby tube from boring locations VMW-01I, VMW-02I, and VER-01I at 62 feet bgs and from boring locations VMW-01D, VMW-02D, and VER-01D at 100 feet bgs. Before the drill rig mobilized to each soil boring location, down-hole drilling equipment was cleaned with a high-pressure, high-temperature water spray to avoid potential cross-contamination. Management of investigation-derived solid waste and decontamination fluids is discussed in Section 3.3.4.

Soil samples for laboratory analysis were collected in laboratory-supplied containers, labeled, placed in plastic bags, and stored in a cooler on ice for transport to TestAmerica Laboratories, Inc. of Irvine, California (TestAmerica) under chain-of-custody documentation. Soil samples for particle-size distribution analysis were shipped to Geotechnical & Environmental Services, Inc. of Las Vegas, Nevada. Soil samples for physical parameter analysis were shipped to PTS Laboratories, Inc. of Houston, Texas.

Depth-discrete groundwater samples were attempted to be collected within the alluvium above the Quaternary alluvial (Qal)-UMCf interface at boring locations VMW-01D, VMW-02D, VER-01I, and VER-01D; however, lack of sufficient groundwater prevented collection of these samples. Depth-discrete groundwater samples were collected from the interval at the top of the UMCf (below the Qal-UMCf interface) at boring locations VMW-01D, VMW-02D, VER-01I, and VER-01D. Groundwater samples were collected using a Simulprobe™ depth-discrete groundwater sampling tool, transferred to clean laboratory-supplied containers, and shipped to TestAmerica under chain-of-custody documentation. The baseline groundwater sample analyses are identified in ***Table 1***.

Table 1 Baseline Soil and Groundwater Sample Analyses

Parameter(s)	Method	Purpose
Soil Analyses		
Perchlorate	E314	Assess vertical extent of perchlorate in unsaturated and saturated soil
Chlorate	E300.1	Assess vertical extent of chlorate in unsaturated and saturated soil
Chlorite	E300.1	Assess vertical extent of chlorite in unsaturated and saturated soil
Hexavalent Chromium	SW7199	Assess vertical extent of hexavalent chromium in unsaturated and saturated soil
Total Chromium	SW-6010B	Assess vertical extent of chromium in unsaturated and saturated soil
Physical Parameters[1]	Various	Assess geophysical properties of soil
Groundwater Analyses		
Perchlorate	E314	Assess vertical extent of perchlorate impacts
Chlorate	E300.1	Assess vertical extent of chlorate impacts
Chlorite	E300.1	Assess vertical extent of chlorite impacts
Hexavalent Chromium	SW7199	Assess vertical extent of hexavalent chromium impacts
Total Chromium	SW-6010B or 6020	Assess vertical extent of chromium impacts
Volatile Organic Compounds (VOCs)	SW-846 8260B	Assess vertical extent of VOC impacts, including chloroform

Notes:

[1] Physical parameters include native-state permeability to water (hydraulic conductivity), grain density, grain size, dry bulk density, total porosity, air-filled porosity, moisture content and total pore fluid saturation (reported as water only).

3.3.3 Installation of VER Extraction and Groundwater Monitoring Wells

The six soil borings were completed as two clustered monitoring wells (VMW-01I/D and VMW-02I/D), one intermediate VER extraction well (VER-01I), and one deep VER extraction well (VER-01D) (***Figure 3***). The extraction wells, VER-01I and VER-01D, were constructed with 4-inch diameter, Schedule 80 polyvinyl chloride (PVC) and a 0.010-inch slot wire-wrapped stainless-steel well screen. The clustered monitoring wells were constructed with 2-inch diameter, Schedule 80 PVC and a Schedule 80 PVC well screen. A washed sand filter pack (#2/16) was installed in the annular space around the well screen and extended up to 2 feet above the top of screen interval. A minimum 5-foot hydrated bentonite seal was placed above the filter pack. The remainder of the annular space was backfilled with cement containing approximately 5 percent bentonite. The monitoring wells and VER extraction wells were installed with flush-mounted, traffic-rated well boxes at an elevation approximately 0.50 inch above grade. A summary of the well construction details is provided as ***Table 2*** and the well construction details are provided in ***Figures 4a and 4b.***

Table 2 Summary of VER Extraction Well and Monitoring Well Construction Information

Well ID	Riser Construction and Interval	Screen Construction and Interval
VER-01I[1]	4-Inch Schedule 80 PVC (0 – 55 feet bgs)	4-Inch wire-wrapped 0.010-inch slot size stainless-steel well screen (55 – 70 feet bgs)
VER-01D[2]	4-Inch Schedule 80 PVC (0 – 90 feet bgs)	4-Inch wire-wrapped 0.010-inch slot size stainless-steel well screen (90 – 110 feet bgs)
VMW-01I	2-Inch Schedule 80 PVC (0 – 55 feet bgs)	2-Inch Schedule 80 PVC 0.010-inch slot size well screen (55 – 70 feet bgs)
VMW-01D	2-Inch Schedule 80 PVC (0 – 90 feet bgs)	2-Inch Schedule 80 PVC 0.010-inch slot size well screen (90 – 110 feet bgs)
VMW-02I	2-Inch Schedule 80 PVC (0 – 55 feet bgs)	2-Inch Schedule 80 PVC 0.010-inch slot size well screen (55 – 70 feet bgs)
VMW-02D	2-Inch Schedule 80 PVC (0 – 90 feet bgs)	2-Inch Schedule 80 PVC 0.010-inch slot size well screen (90 – 110 feet bgs)

Notes:

[1] VER-01I was installed with a 5-foot blank casing sump from 70 to 75 feet bgs.
[2] VER-01D was installed with a 5-foot blank casing sump from 110 to 115 feet bgs.

Tetra Tech developed the newly installed wells a minimum of 24 hours after completion of well construction. Well development consisted of using a surge block and bailer to swab and surge the filter pack and remove sediment from the wells. This process was followed by using a submersible pump to purge the well of fine-grained sediment. Well development was considered complete for the performance monitoring wells when three to ten casing volumes of water were removed from the well, and index parameters consisting of pH, specific conductivity, turbidity, and temperature were stable (pH within 0.1 and other parameters within 10 percent) over three consecutive measurements. Well development for the extraction wells was conducted over an approximate 6- to 8-hour period for each extraction well, during which index parameters were collected. All index parameter readings were recorded by Tetra Tech on well development logs, which are included in ***Appendix A***.

Baseline groundwater sampling, conducted on November 7 and 8, 2017, consisted of collecting groundwater samples from each of the monitoring wells and VER extraction wells. Baseline groundwater sampling used the low-flow methodology with dedicated bladder-type sampling pumps. The depth to groundwater was measured in each well with an electronic water level indicator prior to purging the well. After one pump/discharge line volume of groundwater was removed from a well, water quality field parameters [temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), oxidation-reduction potential (ORP), and turbidity] were measured at 5-minute intervals during purging using a YSI multiparameter instrument mounted in an in-line flow cell. Purging was considered complete when three consecutive sets of field parameter measurements had stabilized to within the following values: temperature ±1 degrees Celsius, pH ±0.1 pH unit, EC ±3%, DO ±0.3 milligrams per liter (mg/L), ORP ±10 millivolts, and turbidity <10 Nephelometric Turbidity Units or ±10% if >10 Nephelometric Turbidity Units. After purging was complete, the flow cell was disconnected and samples were collected in laboratory-provided containers directly from the sample tubing. The sample containers were labeled, placed in resealable plastic bags, and stored in an ice chest cooled with water ice pending shipment to TestAmerica for analysis, as outlined in ***Table 1,*** under chain-of-custody protocols.

Tetra Tech retained the services of Atkins of Henderson, Nevada, to survey the horizontal coordinates of each well relative to North American Datum 83 with an accuracy of 0.1 foot, and the elevation of the ground surface and top of well casing measuring point relative to North American Vertical Datum 88 with accuracies of 0.1 foot and 0.01 foot, respectively. The well survey data are provided in ***Appendix B***.

3.3.4 Management of Investigation Derived Waste

Waste generated during the well installation and development activities was managed according to applicable state, federal, and local regulations and as described in *Field Sampling Plan, Revision 1* (ENVIRON, 2014). The waste generated included soil cuttings, personal protective equipment, equipment decontamination water, and groundwater generated during depth-discrete groundwater sampling and well development. Soil cuttings were stored in two plastic-lined 10 cubic yard roll-off bins (bin numbers 2627 and 2696) provided by Republic Services of Las Vegas, Nevada.

A total of 58 soil samples were collected during drilling activities. Based on their analyses, the waste was shipped to the Republic Services Apex Landfill for disposal on January 11 and 12, 2018, under an existing waste profile previously developed for nonhazardous soil from the NERT site (Profile #3825-17-9665), which expires on January 12, 2020.

Waste water produced during purging or decontamination activities was temporarily stored in 55-gallon drums or poly-totes and transferred into the GW-11 Pond. Containers used to store waste carried “pending analysis” labels, which addressed the date accumulation began, contents, source, and contact information, and were stored in a designated area.

3.4 VER SYSTEM INSTALLATION

Installation of the VER system and associated piping was completed from December 18 through 22, 2017. A depiction of the VER system layout is provided in Figure 3 and a process flow diagram is provided as Figure 5. The VER system consists of the following components:

- VER extraction wellheads including 1-inch diameter conveyance piping/hose, flow meters, valves, sample ports, gauges, and fittings;
- Two groundwater extraction pumps (Grundfos Redi-Flo3, Model #10SEQ07-180NE);
- One trailer-mounted unit with a 20-horsepower (Hp) liquid-ring pump (LRP) (Dekker Vacuum Technologies, Inc.), an air-liquid separator, a centrifugal transfer pump, and a 55-gallon drum filled with vapor-phase granular activated carbon;
- 21,000-gallon frac tank with secondary containment;
- 56-kW trailer-mounted diesel generator (MQ Power); and
- One-horsepower centrifugal transfer pump (Goulds Water Technology) and 1-inch diameter groundwater conveyance hose to transfer water from the 21,000-gallon frac tank to the influent tank of the chromium treatment plant.

In addition, a 1-inch Schedule 40 PVC drop pipe and wellhead fittings were installed within groundwater monitoring wells VMW-01I, VMW-01D, VMW-02I, VMW-02D, and M-172. The 1-inch drop pipes were extended to approximately one foot above the bottom of each well and the wellheads were sealed. Vacuum gauges installed in the monitoring wellheads were used to measure the induced vacuums in the surrounding soils.

3.5 BACKGROUND GROUNDWATER ELEVATION EVALUATION

Electronic pressure transducers/data logger units (In-Situ, Inc. [In-Situ] Level TROLL 400) with vented cables were installed in monitoring wells VMW-01I, VMW-01D, VMW-02I, VMW-02D, and in VER extraction well VER-01I on December 11, 2017, to evaluate variations in groundwater elevations prior to performing the VER testing and determine whether the steady state conditions identified in the *Vacuum Enhanced Recovery Treatability*

Study Work Plan (Tetra Tech, Inc., 2017a) could be achieved. The steady state conditions were defined to be when water levels, as measured at the newly installed monitoring wells VMW-01I/D and VMW-02I/D, changed less than 0.01 feet over a period of 30 minutes. The pressure transducers/data logger units recorded water pressure within the wells every 15 minutes from December 11, 2017 through January 4, 2018. Atmospheric pressure was recorded using an In-Situ BaroTROLL to correct the pressure transducer data for barometric pressure fluctuations. The background data were used to determine the typical variation in water level expected over the course of 30 minutes, which exceeded a fluctuation of 0.01 feet over 30 minutes. Based on the average change observed over a 15-minute interval, a request was provided to NDEP to modify the steady state conditions to be water level fluctuations of 0.02 feet or less over 15 minutes. NDEP verbally approved the revised steady state conditions on January 5, 2018. The background transducer groundwater elevation monitoring data are provided in graphical format in ***Appendix C***.

3.6 INTERMEDIATE VER TREATABILITY STUDY

The intermediate VER treatability study consisted of a step-drawdown test (Phase A), a constant-rate pumping test (Phase B), and a VER test followed by a groundwater elevation monitoring period (Phase C) performed on the intermediate VER extraction well, VER-01I. This section describes the field activities associated with each test. The comprehensive field data and analytical data tables, including all manually measured water levels, for each test are included in ***Appendix D***. A hydrograph based on groundwater elevation data collected from the performance monitoring wells is provided as ***Figure 6****.*

3.6.1 Intermediate Zone Step-Drawdown Test (Phase A)

The step-drawdown test, conducted on January 5, 2018, included pumping the extraction well at four rates (0.5 gpm, 1.0 gpm, 2.0 gpm, and 3.0 gpm) for approximately 2 hours each to determine the pumping rate for the constant-rate pumping test that would not dewater the extraction well. Groundwater extraction rates were monitored throughout the test, approximately every 15 minutes, with a totalizing flow meter. The groundwater extraction rates were adjusted to maintain the target rates throughout each step using a potentiometer to control the speed of the groundwater extraction pump impeller.

Transducer/data logger units recorded water pressure on 1-minute intervals in monitoring wells M-65D, M-221, VMW-01I, VMW-02I, and VMW-02D. The pressure transducers were set in the performance monitoring wells on January 4, 2018, to record barometric and diurnal effects on static water levels prior to the start of the step-drawdown test. Water levels were manually gauged at wells M-56, M-65, M-65D, M-78, M-164, M-172, M-221, I-F, VMW-01I/D, and VMW-02I/D throughout the test to enable an evaluation of drawdown in additional wells where pressure transducers were not installed, provide a fail-safe if the pressure transducers unexpectedly shutdown, and verify the accuracy of the transducer data.

Water level recovery data were collected until water levels in the pumped well, VMW-01I and VMW-02I had achieved at least 90 percent of initial static levels. Water levels in VER-01I recovered to 90 percent of initial static levels approximately 40 minutes after pumping stopped. The results of the VER-01I step-drawdown test was evaluated to determine the target extraction rate for the constant-rate pumping test.

3.6.2 Intermediate Zone Constant-Rate Pumping Test (Phase B)

The constant-rate pumping test was conducted for approximately 37 hours from January 11 through January 12, 2018. To identify the groundwater radius of influence (ROI) at the extraction well, pumping continued until water levels measured in the pumped well, VMW-01I, and VMW-02I had met the steady state conditions of less than a 0.02-foot change over a period of 15 minutes. The constant-rate pumping test was initiated after the water levels in the extraction and monitoring wells VMW-01I and VMW-02I had recovered to 90 percent of background following the step-drawdown test. The step-drawdown test indicated that an extraction rate over 2 gpm could not be sustained during the constant-rate pumping test. Therefore, a flow rate of 2.0 gpm was selected for the constant-rate pumping test to ensure that well VER-01I did not dewater during the test. The groundwater extraction rate was monitored throughout the test, generally every 15 minutes, with a totalizing flow meter. The groundwater extraction rate was adjusted to maintain the target rate throughout the test. The results of the intermediate zone step-drawdown test are discussed in Section 4.2.1, and the results of the intermediate zone constant-rate pumping test are discussed in Section 4.2.2.

Groundwater extraction rates, drawdown, and water level recovery data were monitored during the constant-rate pumping test. Transducer/data logger units recorded water pressure in wells M-65D, M-221, VMW-01I, VMW-02I, and VMW-02D. Water levels were periodically collected manually at monitoring wells I-F, M-65, and M-164. A groundwater sample was collected from the pumping well at the start of the test (0-Hour) and additional samples were collected every 12 hours (12-Hour, 24-Hour, and 36-Hour) until the performance criteria (steady state conditions) were achieved. The groundwater samples were analyzed for general water quality parameters, primary contaminants, and VOCs as presented in ***Table 3***. Groundwater samples were collected to enable an evaluation of the effects of pumping on contaminant concentrations in the intermediate UMCf.

Table 3 Groundwater Samples and Analysis for the Intermediate Constant-Rate Pumping Test

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of Constant-Rate Pumping Test)			
Parameter	**Analytical Method**	**0**	**12**	**24**	**36**
EC	Horiba U-52	X	X	X	X
pH	Horiba U-52	X	X	X	X
DO	Horiba U-52	X	X	X	X
ORP	Horiba U-52	X	X	X	X
Temperature	Horiba U-52	X	X	X	X
Turbidity	Horiba U-52	X	X	X	X
Laboratory Analyses					
Perchlorate	E314	X	X	X	X
Chlorate/Chlorite	E300.1	X	X	X	X
Hexavalent Chromium	SW7199	X	X	X	X
Total Chromium	SW-6010B or 6020	X	X	X	X
VOCs	SW-846 8260B	X	X	X	X

Notes:

DO: Dissolved oxygen
EC: Electrical conductivity
ORP: Oxidation-reduction potential
VOCs: Volatile organic compounds

3.6.3 Intermediate Zone VER Test (Phase C)

The Phase C VER test was conducted for approximately 78 hours from January 15 through January 18, 2018 as this was the duration necessary to achieve the test's objective of obtaining steady state conditions based on measured water levels in the pumped well, VMW-01D, and VMW-02D changing less than 0.02-feet over a period of 15 minutes. The VER test began after monitoring documented that water elevations had recovered to 90 percent of baseline conditions. The start of this test included pumping VER-01I at the maximum achievable extraction rate (i.e., continuously pumping the well dry) for 8 hours using only conventional pumping. An approximate vacuum of 23 to 27 feet of water column (ft w.c.; 20 to 24 inches of mercury [in Hg]) was applied to wellhead VER-01I using a LRP for the next 70 hours while pumping continued. The average groundwater extraction rate using conventional pumping during the first eight hours of the intermediate VER test was 3.12 gpm. The average groundwater extraction rate over the subsequent eight hours with conventional pumping and applying a vacuum was 4.05 gpm, an approximate 30 percent increase in the groundwater extraction rate over the comparable time period.

The groundwater extraction rate was monitored throughout the test, generally every 15 minutes, with a totalizing flow meter. Transducer/data logger units recorded water pressure on 1-minute intervals in monitoring wells M-65D, M-221, VMW-01I, VMW-02I, and VMW-02D throughout the test. Water levels were manually gauged at monitoring wells M-56, M-65, M-65D, M-78, M-164, M-172, M-221, I-F, VMW-01I/D, and VMW-02I/D throughout the test.

A groundwater sample was collected from VER-01I at the start of the test (0-Hour; start of conventional pumping without vacuum), additional groundwater samples were collected every 12 hours, and a final sample was collected at the termination of the VER test. Groundwater samples were collected using a groundwater sample port installed on the extraction well manifold (***Figure 5***). The groundwater samples were analyzed in the field and at an analytical laboratory, as identified in ***Table 4***. Groundwater samples were collected to enable an evaluation of the effects of pumping while applying vacuum on contaminant concentrations in the intermediate UMCf. Samples for additional parameters were collected once steady state conditions were achieved (78-hours) to support the design of a potential water treatment system and recovery well design for a full-scale application if warranted.

Table 4 Groundwater Sampling and Analysis for the Intermediate VER Test

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of VER Test)							
Parameter	**Analytical Method**	**0**	**12**	**24**	**36**	**48**	**60**	**72**	**78***
EC	Horiba U-52	X	X	X	X	X	X	X	X
pH	Horiba U-52	X	X	X	X	X	X	X	X
DO	Horiba U-52	X	X	X	X	X	X	X	X
ORP	Horiba U-52	X	X	X	X	X	X	X	X
Temperature	Horiba U-52	X	X	X	X	X	X	X	X
Turbidity	Horiba U-52	X	X	X	X	X	X	X	X
Perchlorate	E314	X	X	X	X	X	X	X	X
Chlorate/Chlorite	E300.1	X	X	X	X	X	X	X	X
VOCs	SW-846 8260B	X	X	X	X	X	X	X	X
Hexavalent Chromium	SW7199	X	X	X	X	X	X	X	X
Total Chromium	SW-6010B or 6020	X	X	X	X	X	X	X	X
Alkalinity	SM 2320B								X
Calcium	200.7								X
Dissolved Metals[1]	SW6010/6020								X
Ferrous and Ferric Iron	HACH Method 8008/8147								X
Hardness	SM 2340C								X
Magnesium	200.7								X
Manganese	SW6010B								X
Nitrate	E300/SW9056								X
Sulfate	E300/SW9056								X
Sulfite	HACH Method 8131								X
Total Nitrogen	E351.1								X

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of VER Test)							
Parameter	Analytical Method	0	12	24	36	48	60	72	78*
Total Phosphorus	E365.1								X
TDS	SM 2540C								X
TOC	SM 5310B								X
TSS	160.2								X

Notes:

DO: Dissolved oxygen
EC: Electrical conductivity
ORP: Oxidation-reduction potential
TDS: Total dissolved solids
TOC: Total organic carbon
TSS: Total suspended solids
VOCs: Volatile organic compounds
1. Dissolved metals include the following: aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, silver, thallium, uranium, vanadium, and zinc
* The final sampling event corresponded with the end of the intermediate VER Test.

Vapor extraction flow rates were calculated using differential pressure readings from a 1-inch Dwyer in-line flow sensor, vacuum measurements were obtained using a vacuum gauge, and temperature measurements were obtained using a thermometer installed on the air conveyance piping. Applied vacuum was recorded using a vacuum gauge affixed to the VER-01I wellhead. Vacuum measurements were collected from M-172, VMW-01I/D, VMW-02I/D, and VER-01I during the intermediate VER test.

Soil vapor samples were collected from VER-01I and from the effluent stack of the vapor treatment unit. The soil vapor sampling and analysis for the intermediate VER test are presented as ***Table 5***.

Table 5 Soil Vapor (Air) Sampling and Analysis for the Intermediate VER Test

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of VER Test)								
Parameter	Analytical Method	0	12	16	20	32	44	56	68	78*
Field Parameters										
PID Measurements	MiniRAE 3000	X	X	X	X	X	X	X	X	X
Laboratory Analyses										
VOCs	TO-15	X	X	X	X	X	X	X	X	X

Notes:

PID: Photoionization detector
*The final sampling event corresponded with the end of the intermediate VER test.
1. Soil vapor samples were collected from a sample port on the vapor conveyance line from VER-01I at a sampling frequency consistent with this table.
2. Soil vapor samples were collected from the effluent stack of the vapor treatment unit at four times during the intermediate VER test, at approximately 16, 32, 46, and 78 hours after the start of the intermediate VER test.

Samples were collected from the influent vapor treatment soil vapor sample port to evaluate the concentrations of chemicals in the extracted vapors and to identify whether the vapor concentrations changed over time. Influent vapor samples were collected with a 1-liter (L) Tedlar bag and a vacuum box for field screening. Influent and effluent vapor samples were collected using certified pre-cleaned 1-L Summa canisters provided by TestAmerica for laboratory analysis. The Summa canisters were shipped to TestAmerica under chain-of-custody documentation for VOC analysis by Method TO-15.

Recovery for the intermediate VER test began on January 18 and continued until January 22, 2018, when baseline conditions for groundwater elevations were reached. Transducer/data logger units recorded water pressure on 1-minute intervals in monitoring wells M-65D, M-221, VMW-01I, VMW-02I, and VMW-02D throughout the recovery monitoring period. Water levels were manually gauged at monitoring wells VMW-01I/D and VMW-02I/D throughout the recovery monitoring.

3.7 DEEP VER TREATABILITY STUDY

The deep VER treatability study consisted of a step-drawdown test, a constant-rate pumping test, and a VER test followed by a groundwater elevation monitoring period performed on the deep VER extraction well, VER-01D. This section describes the field activities associated with each phase of the deep VER treatability study. The comprehensive field data and analytical data tables for each phase (discussed in Sections 3.7.1 through 3.7.3) are included as part of ***Appendix E***. A hydrograph based on groundwater elevation data collected from the performance monitoring wells is provided as ***Figure 7***.

3.7.1 Deep Zone Step-Drawdown Test (Phase A)

The step-drawdown test, conducted on January 22, 2018, included pumping the extraction well at three rates (0.5 gpm, 0.75 gpm, and 1.0 gpm) for approximately 2 hours each to determine the pumping rate for the constant-rate pumping test that would not dewater the extraction well. An extraction rate greater than 1.0 gpm could not be maintained at VER-01D due to the slow recharge rate and significant drawdown. Groundwater extraction rates were monitored throughout the test, approximately every 15 minutes, with a totalizing flow meter. The groundwater extraction rates were adjusted to maintain the target rates throughout each step using a potentiometer to control the speed of the groundwater extraction pump impeller.

Transducer/data logger units recorded water pressure on 1-minute intervals in monitoring wells M-222, VMW-01I, VMW-01D, VMW-02I, and VMW-02D. The pressure transducers were set in the wells on January 22, 2018, to record barometric and diurnal effects on static water levels prior to the start of the step-drawdown test. Water levels were manually gauged at wells I-F, M-56, M-65, M-65D, M-78, M-162, M-163, M-164, M-172, M-221, M-222, VMW-01I/D, and VMW-02I/D throughout the test to enable an evaluation of drawdown in additional wells where pressure transducers were not installed, provide back-up data if the pressure transducers unexpectedly shutdown, and verify the accuracy of the pressure transducer data.

Water level recovery data were collected until water levels in the pumped well recovered to within 90 percent of initial static water level.

3.7.2 Deep Zone Constant-Rate Pumping Test (Phase B)

The constant-rate pumping test was conducted for 48 hours from January 23 through January 25, 2018. To identify the groundwater ROI at the extraction well, pumping continued until water levels measured in the pumped well, VMW-01D, and VMW-02D had met the steady state conditions of less than a 0.02-foot change over a period of 15 minutes. The constant-rate test began after the water levels in the extraction and monitoring wells had recovered following the step-drawdown test. The step-drawdown test indicated that an extraction rate over 0.5 gpm could not be sustained during the constant-rate pumping test. Therefore, a flow rate of 0.5 gpm was selected for the constant-rate pumping test to ensure that well VER-01D did not dewater during the test. The results of the deep zone step-drawdown test are discussed in Section 4.3.1, and the results of the deep zone constant-rate pumping test are discussed in Section 4.3.2.

Groundwater extraction rates, drawdown, and water level recovery data were monitored for the constant-rate pumping test. Transducer/data logger units recorded water pressure in wells M-222, VMW-01I, VMW-01D, VMW-02I, and VMW-02D. Water levels were manually gauged at wells I-F, M-56, M-65, M-65D, M-78, M-162, M-163, M-164, M-172, M-221, M-222, VMW-01I/D, and VMW-02I/D. Water level recovery data were collected until water levels at wells VER-01D, VMW-01D, and VMW-02D had recovered to within 90 percent of pre-test levels. A groundwater sample was collected from VER-01D at the start of the test (0-Hour) and additional groundwater samples were collected every 12 hours until the performance criteria (steady state conditions) were achieved (12-Hour, 24-Hour, 36-Hour, and 48-Hour). The groundwater samples were analyzed for general water quality parameters, primary contaminants, and VOCs consistent with ***Table 6***. Groundwater samples were collected to enable an evaluation of the effects of pumping on contaminant concentrations in the intermediate UMCf.

Table 6 Groundwater Sampling and Analysis for the Deep Constant-Rate Pumping Test

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of Constant-Rate Pumping Test)				
Parameter	**Analytical Method**	**0**	**12**	**24**	**36**	**48**
EC	Horiba U-52	X	X	X	X	X
pH	Horiba U-52	X	X	X	X	X
DO	Horiba U-52	X	X	X	X	X
ORP	Horiba U-52	X	X	X	X	X
Temperature	Horiba U-52	X	X	X	X	X
Turbidity	Horiba U-52	X	X	X	X	X
Laboratory Analyses						
Perchlorate	E314	X	X	X	X	X
Chlorate/Chlorite	E300.1	X	X	X	X	X
Hexavalent Chromium	SW7199	X	X	X	X	X
Total Chromium	SW-6010B or 6020	X	X	X	X	X
VOCs	SW-846 8260B	X	X	X	X	X

Notes:
DO: Dissolved oxygen
EC: Electrical conductivity
ORP: Oxidation-reduction potential
VOCs: Volatile organic compounds

3.7.3 Deep Zone VER Test (Phase C)

The VER test was conducted for approximately 96 hours from February 5 to February 9, 2018 as this was the duration necessary to achieve the test's objective of obtaining steady state conditions based on measured water levels in the pumped well, VMW-01D, and VMW-02D changing less than 0.02-feet over a period of 15 minutes. The VER test began after monitoring documented that water elevations in the aquifer had recovered to baseline conditions following the constant-rate test. The start of this test included pumping VER-01D at the maximum achievable extraction rate (i.e., continuously pumping the well dry) for 12 hours using only conventional pumping. An approximate vacuum of 16 to 25 feet of water column (14.5 to 22 in Hg) was applied to wellhead VER-01D using a LRP for the next 84 hours, while pumping continued. The average groundwater extraction rate using conventional pumping during the first 12 hours of the deep VER test was 0.53 gpm. The average groundwater extraction rate during conventional pumping and applying a vacuum was 0.64 gpm, an approximate 21 percent increase in the groundwater extraction rate.

The groundwater extraction rate was monitored throughout the test with a totalizing flow meter. Transducer/data logger units recorded water pressure in wells M-222, VMW-01I, VMW-01D, VMW-02I, and VMW-02D. Water levels were manually gauged at wells I-F, M-56, M-65, M-65D, M-78, M-162, M-163, M-164, M-172, M-221, M-222, VMW-01I/D, and VMW-02I/D. Vacuum measurements were collected from M-172, VMW-01I/D, VMW-02I/D, and VER-01D during the deep VER test.

A groundwater sample was collected from VER-01D at the start of the test (0-Hour; start of conventional pumping without vacuum); additional groundwater samples were collected every 12 hours, and a final sample was collected at the termination of the VER test. Groundwater samples were collected using a groundwater sample port installed on the extraction well manifold (***Figure 5***). The groundwater samples were analyzed in the field and at an analytical laboratory, as identified in ***Table 7***. Groundwater samples were collected to enable an evaluation of the effects of pumping while applying vacuum on contaminant concentrations in the UMCf. Samples for additional parameters were collected once steady state conditions were achieved (96-hours) to support the design of a potential water treatment system and recovery well design for a full-scale application.

Table 7 Groundwater Sampling and Analysis for the Deep VER Test

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of VER Test)								
Parameter	**Analytical Method**	**0**	**12**	**24**	**36**	**48**	**60**	**72**	**84**	**96***
EC	Horiba U-52	X	X	X	X	X	X	X	X	X
pH	Horiba U-52	X	X	X	X	X	X	X	X	X
DO	Horiba U-52	X	X	X	X	X	X	X	X	X
ORP	Horiba U-52	X	X	X	X	X	X	X	X	X
Temperature	Horiba U-52	X	X	X	X	X	X	X	X	X
Turbidity	Horiba U-52	X	X	X	X	X	X	X	X	X
Perchlorate	E314	X	X	X	X	X	X	X	X	X
Chlorate/Chlorite	E300.1	X	X	X	X	X	X	X	X	X
VOCs	SW-846 8260B	X	X	X	X	X	X	X	X	X
Hexavalent Chromium	SW7199	X	X	X	X	X	X	X	X	X
Total Chromium	SW-6010B or 6020	X	X	X	X	X	X	X	X	X
Alkalinity	SM 2320B									X
Calcium	200.7									X
Dissolved Metals[1]	SW6010/6020									X
Ferrous and Ferric Iron	HACH Method 8008/8147									X
Hardness	SM 2340C									X
Magnesium	200.7									X
Manganese	SW6010B									X
Nitrate	E300/SW9056									X
Sulfate	E300/SW9056									X
Sulfite	HACH Method 8131									X
Total Nitrogen	E351.1									X
Total Phosphorus	E365.1									X
TDS	SM 2540C									X
TOC	SM 5310B									X
TSS	160.2									X

Notes:

DO: Dissolved oxygen
EC: Electrical conductivity
ORP: Oxidation-reduction potential
TDS: Total dissolved solids
TOC: Total organic carbon
TSS: Total suspended solids
VOCs: Volatile organic compounds

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of VER Test)								
Parameter	Analytical Method	0	12	24	36	48	60	72	84	96*

Notes:

1. Dissolved metals include the following: aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, silver, thallium, uranium, vanadium, and zinc

* The final sampling event corresponded with the end of the deep VER Test.

Vapor extraction flow rates were calculated using differential pressure readings from a 1-inch Dwyer in-line flow sensor, vacuum measurements using a vacuum gauge, and temperature measurements using a thermometer installed on the air conveyance piping. Applied vacuum was recorded using a vacuum gauge affixed to the VER-01D wellhead. Vacuum measurements were collected from M-172, VMW-01I/D, VMW-02I/D, and VER-01D during the deep VER test.

Soil vapor samples were collected from VER-01D and from the effluent stack of the vapor treatment unit. The soil vapor sampling and analysis for the deep VER test are presented in ***Table 8***.

Table 8 Soil Vapor (Air) Sampling and Analysis for the Deep VER Test

Analytical Requirements		Sampling Frequency (Approximate Hours After Start of VER Test)									
Parameter	Analytical Method	0	16	20	24	36	48	60	72	84	96*
Field Parameters											
PID Measurements	MiniRAE 3000	X	X	X	X	X	X	X	X	X	X
Laboratory Analyses											
VOCs	TO-15	X	X	X	X	X	X	X	X	X	X

Notes:

PID: Photoionization detector

*The final sampling event corresponded with the end of the deep VER test.

1. Soil vapor samples were collected from a sample port on the vapor conveyance line from VER-01D at a sampling frequency consistent with this table.
2. Soil vapor samples were collected from the effluent stack of the vapor treatment unit at nine times during the deep VER test, at approximately 16, 20, 24, 36, 48, 60, 72, 84, and 96 hours after the start of the deep VER test.

Samples were collected from the influent vapor treatment soil vapor sample port to evaluate the concentrations of chemicals in the extracted vapors and to identify whether vapor concentrations changed over time. Influent vapor samples were collected with a 1-L Tedlar bag and a vacuum box for field screening. Influent and effluent vapor samples were collected using certified pre-cleaned 1-L Summa canisters provided by TestAmerica for laboratory analysis. The Summa canisters were shipped to TestAmerica under chain-of-custody documentation for VOC analysis by Method TO-15.

Recovery for the deep VER test began on February 9, 2018 and continued until February 22, 2018, when baseline conditions for groundwater elevations were achieved. Transducer/data logger recorded water pressure in monitoring wells M-222, VMW-01I, VMW-01D, VMW-02I, and VMW-02D throughout the recovery monitoring period. Water levels were manually gauged at monitoring wells VMW-01I/D and VMW-02I/ throughout the recovery monitoring period

3.8 MANAGEMENT OF EXTRACTED VAPOR AND GROUNDWATER

Soil vapor extracted during the intermediate and deep VER tests first had excess moisture removed by an air-liquid separator, then was treated by a vapor-phase carbon vessel, and finally was discharged to the atmosphere.

Potential carbon breakthrough was monitored by collecting samples on an approximate 10 to 16-hour basis (typically every 12 hours) from the effluent vapor treatment sample port and using a photoionization detector (PID) to assess relative VOC concentrations. The PID testing indicated a carbon changeout for the vapor-phase carbon vessel was not necessary. Effluent vapor samples were collected daily in Summa canisters and transported to TestAmerica under chain-of-custody documentation for VOC analysis by Method TO-15 to verify that carbon breakthrough did not occur. Used vapor-phase carbon was transported to California Carbon Company, Inc. in Wilmington, California for regeneration.

Groundwater extracted during the intermediate and deep VER tests was transferred to a 21,000-gallon frac tank for temporary storage and then transferred to the influent tank of the Chromium Treatment Plant. The discharge flow rate and total volume transferred were recorded using a totalizing flow meter. Extracted groundwater generated during the intermediate VER treatability study (approximately 21,882 gallons) was transferred to the Chromium Treatment Plant from January 16 through 18, 2018. Extracted groundwater generated during the deep VER treatability study (approximately 6,000 gallons) was transferred to the Chromium Treatment Plant on February 12, 2018. Section 4.2.4 presents the perchlorate and chromium mass removed as part of the intermediate treatability study, and Section 4.3.4 presents the perchlorate and chromium mass removed as part of the deep treatability study.

Clean Harbors of Las Vegas, Nevada, pressure washed the interior of the frac tank under a confined space entry permit on February 14, 2018. The wash water generated during the tank cleaning was recovered with a vacuum truck and discharged to the GW-11 Pond.

4.0 ANALYSIS OF RESULTS

4.1 BASELINE SOIL AND GROUNDWATER RESULTS

This section summarizes the results of the baseline soil, depth-discrete groundwater, and baseline groundwater analytical results.

4.1.1 Baseline Soil Analytical Results

Soil samples were collected for laboratory analysis from borings VMW-01D, VMW-02D, VER-01I, and VER-01D at 5-foot intervals in the unsaturated zone (0 to 35 feet bgs), at 10-foot intervals in the saturated zone (35 to 110 feet bgs), and at lithologic or color changes. Analytical results for the baseline soil samples are provided in Appendix B.3 of the Data Validation Summary Report (DVSR), which is included as ***Appendix B.***

The highest concentrations of perchlorate (830 milligrams per kilogram [mg/kg]), chlorate (3,600 mg/kg), and hexavalent chromium (20 mg/kg) were detected in boring location VMW-01D at 50 feet bgs. Perchlorate concentrations in soil samples collected from 100 to 110 feet bgs, the maximum depth investigated, ranged from 0.027 mg/kg (estimated) to 1.3 mg/kg. Chlorate concentrations in soil samples collected from 100 to 110 feet bgs ranged from 0.150 mg/kg (estimated) to 3.0 mg/kg. Hexavalent chromium was detected in only one sample collected from 70 to 110 feet bgs at a concentration of 0.31 mg/kg. Chlorite was not detected at a concentration above the laboratory reporting limit in the baseline soil samples.

Soil samples for physical parameter analysis were collected at depths corresponding to the mid-point of the proposed screen intervals for pumping wells and groundwater monitoring wells. Soil samples were collected from borings VMW-01I, VMW-02I, and VER-01I at 62 feet bgs and from borings VMW-01D, VMW-02D, and VER-01D at 100 feet bgs The average dry bulk density for samples from 62 feet bgs was 1.25 grams per cubic centimeter (g/cc) with an average total porosity of 52.9 percent. The average vertical conductivity for the soil samples from 62 feet bgs was 3.06 x 10-5 cm/s, which was within the range of hydraulic conductivities where VER is typically applied of 10^{-3} to 10^{-5} cm/s as previously stated in Section 2. The average dry bulk density for the samples from 100 feet bgs was 1.48 g/cc with an average total porosity of 45.1 percent. The average vertical conductivity for the samples from 100 feet bgs was 1.56 x 10^{-7} cm/s, which is outside of the range of hydraulic conductivities where VER is typically applied. Laboratory reports for physical property analyses are provided in ***Appendix F*****.**

Soil samples were collected from boring VMW-01I at 62 feet bgs and from boring VMW-01D at 100 feet bgs for sieve analysis. ***Table 9*** summarizes the results of the sieve analyses. The sieve analysis laboratory report is provided in ***Appendix F.***

Table 9 Sieve Analysis Results

Soil Boring ID	Sample ID	Sample Depth (feet below ground surface)	Results (Grain Size)
VMW-01I	VMW-01I-62.0-20170928	62	37% Fine Sand 63% Fines
VMW-01D	VMW-01D-100.0-20170928	100	4% Coarse Gravel 12% Fine Gravel 5% Coarse Sand 5% Medium Sand 9% Fine Sand 65% Fines

Based on the results of the sieve analysis, a well-screen slot size of 0.010-inch and washed sand filter pack (#2 well slot sand) were selected for the monitoring and extraction wells.

4.1.2 Depth-Discrete Groundwater Sample Analytical Results

Due to insufficient water present, depth-discrete groundwater samples were not able to be collected in the Qal above the Qal-UMCf interface. Depth-discrete groundwater samples were collected from the top of the UMCf (below the Qal-UMCf interface) at boring locations VMW-01D, VMW-02D, VER-01I, and VER-01D to evaluate contaminant impacts at the Qal-UMCf interface. A summary of the depth-discrete groundwater analytical results is provided in ***Table 10***. The laboratory results for these groundwater samples are provided in Appendix B.3 of the DVSR, which is included as ***Appendix B***.

Table 10 Analytical Results for Depth-Discrete Groundwater Samples During Boring Advancement

Parameter	Concentration (milligrams per Liter)			
Well ID (feet below ground surface)	VMW-01D (34 feet bgs)	VMW-02D (35 feet bgs)	VER-01I (35 feet bgs)	VER-01D (35 feet bgs)
Perchlorate	950	1,000	740	880
Chlorate	4,200	4,000	3,500	780
Hexavalent Chromium	19	20	16	18
Total Chromium	18	19	19	16
Chloroform	1.1	0.750	1.1	0.630 J

Notes:
J –The result is an estimated quantity, but the result may be biased low.
1. Chlorite was not detected at a concentration above the level of the reported sample quantitation limit in the depth-discrete groundwater samples.

The measured concentrations of perchlorate, hexavalent chromium, and chloroform were generally similar in soil samples collected from 34 to 35 feet bgs from VMW-01D, VMW-02D, VER-01I, and VER-01D. Chlorate concentrations in VER-01D, however, were about half an order of magnitude lower than in other sample locations, as summarized in ***Table 10***.

4.1.3 Baseline Groundwater Sample Analytical Results

Baseline groundwater samples were collected from the four monitoring wells and two VER extraction wells. Groundwater sampling field logs for the baseline sampling event are included in ***Appendix G***. The laboratory data packages for these baseline groundwater samples are provided in Appendix B.3 of the DVSR, which is included as ***Appendix B***. A summary of the baseline groundwater analytical results is provided in ***Table 11.***

Table 11 Baseline Groundwater Sample Analytical Results

Parameter	Concentration (milligrams per Liter)					
Well ID	VMW-01I	VMW-01D	VMW-02I	VMW-02D	VER-01I	VER-01D
Perchlorate	1,000	7.9	320	0.280	300	53
Chlorate	2,000	21	470	0.500	680	140
Hexavalent Chromium	6.9	0.021	1.0	0.022	2.2	0.040
Total Chromium	6.6	0.25	1.2	0.028	2.5	0.17

Parameter	Concentration (milligrams per Liter)					
Well ID	VMW-01I	VMW-01D	VMW-02I	VMW-02D	VER-01I	VER-01D
Chloroform	0.280	0.0021	0.069	0.00045	0.110	0.029

Notes:

1. Chlorite was not detected at a concentration above the level of the reported sample quantitation limit in the baseline groundwater samples.

The baseline perchlorate, chlorate, hexavalent chromium, and total chromium results indicated that samples from the deep wells (screened approximately 90 to 110 feet bgs) have concentrations one to two orders of magnitude lower than the concentrations detected in the intermediate wells (screened approximately 55 to 70 feet bgs). The concentrations of perchlorate, chlorate, hexavalent chromium, and chromium in VER-01I increased between the sampling event and the beginning of the intermediate VER treatability study, while the concentrations for the same parameters in VER-01D decreased between the baseline sampling event and the beginning of the deep VER treatability study. The analytical laboratory reports for the baseline sampling event are included in ***Appendix B***.

4.2 INTERMEDIATE VER TREATABILITY STUDY RESULTS

This section summarizes the results of the intermediate VER treatability study. The comprehensive field data and analytical data tables for the intermediate VER tests are included in ***Appendix D.*** The manual gauging measurements collected during the step-drawdown test, constant-rate pumping test, and intermediate VER test corroborated with the pressure transducer data. The analytical results for the intermediate VER groundwater and soil vapor samples are provided as part of the DVSR included as ***Appendix B***.

4.2.1 Step-Drawdown Test Results

The step-drawdown test was performed at four extraction rates, 0.5 gpm, 1.0 gpm, 2.0 gpm, and 3.0 gpm, for a total of approximately 8 hours to determine the pumping rate for the constant-rate pumping test that would not dewater the extraction well. The measured groundwater elevation at VER-01I experienced 29.16 feet of drawdown. Water levels in VER-01I recovered within 90 percent of initial static levels approximately 40 minutes after pumping stopped. ***Figure 6*** shows the drawdown calculated at each monitoring well during the step test. The groundwater elevation data for VER-01I based on manual gauging measurements collected during the step-drawdown test is summarized in ***Table D-1*** of ***Appendix D***. The groundwater elevation data for the performance monitoring wells based on manual gauging measurements collected during the step-drawdown test is summarized in ***Table D-2*** of ***Appendix D***.

4.2.2 Constant-Rate Pumping Test Results

The constant-rate pumping test was conducted for approximately 37 hours at an extraction rate of 2 gpm. ***Table 12*** summarizes the maximum drawdown observed at VER-01I and the performance monitoring wells during the constant-rate test. ***Figure 6*** provides a graph of the drawdown calculated at each monitoring well for both instrumented wells and manually gauged wells during the constant-rate test. The groundwater elevation data for VER-01I based on manual gauging measurements collected during the constant-rate pumping test is summarized in ***Table D-3*** of ***Appendix D***. The groundwater elevation data for the performance monitoring wells based on manual gauging measurements collected during the constant-rate pumping test is summarized in ***Table D-4*** of ***Appendix D***.

Table 12 Relative Groundwater Drawdown During the Intermediate Constant-Rate Pumping Test at VER-01I

Well ID (Screened Interval - feet below ground surface)[2]	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]
VER-01I (55-70)	0	34.11	54.79	20.68
VMW-02I (55-70)	26	32.37	37.14	4.77
VMW-02D (90-110)	26	26.07	26.15	0.08
M-172 (26.1-36.9)	28	33.37	33.56	0.19
VMW-01I (55-70)	42	31.38	35.51	4.13
VMW-01D (90-110)	42	23.86	23.90	0.04
I-F (11.8-41.8)[3]	44	32.94	34.51	1.57
M-65 (14.4-39.0)	62	32.77	32.95	0.18
M-65D (60-70)	66	33.56	35.58	2.02
M-221 (75-85)	66	32.71	35.10	2.39
M-56 (15.1-40.0)	92	30.98	31.20	0.22
M-78 (21.5-41.5)	129	32.72	32.76	0.04
M-164 (60-70)	145	34.99	35.36	0.37

Notes:

1. Depth to water at maximum relative drawdown did not consistently correspond to the end of the constant-rate pumping test.
2. Screen interval is presented in feet below ground surface (feet bgs).
3. I-F is an active IWF extraction well.
4. Based on GWETS metrics data provided by Envirogen Technologies, Inc. (ETI), drawdown attributed to the intermediate constant-rate pumping test was observed in IWF pumping wells I-F, I-G, I-Q, and I-X.

Monitoring wells VMW-01I and VMW-02I had the largest amount of drawdown (4.13 feet and 4.77 feet, respectively). These monitoring wells are screened in the same interval as VER-01I and are located 26 and 42 feet from VER-01I, respectively. Measurable drawdown was also observed in monitoring well, M-164, located 145 feet from the pumping well. Some wells screened in other deeper or shallower intervals, such as VMW-02D, VMW-01D, and M-78, experienced very small water level changes that were likely due to other factors rather than to the VER test.

A summary of the analytical results of samples collected during the intermediate constant-rate pumping test is provided in ***Table 13*** and ***Table D-5*** of ***Appendix D***.

Table 13 Groundwater Analytical Results for the Intermediate Constant-Rate Pumping Test at VER-01I

Parameter	Concentration (milligrams per Liter)			
Sampling Event	0 hr	12 hr	24 hr	36 hr
Perchlorate	930	1,200	1,200	1,200

Parameter	Concentration (milligrams per Liter)			
Sampling Event	0 hr	12 hr	24 hr	36 hr
Chlorate	2,400	3,200	3,100	3,800
Hexavalent Chromium	8.4	12	12	13
Total Chromium	8.8	15	15	14
Chloroform	0.460	0.710	0.680	0.730

Notes:
hr - hour
1. Sampling events correspond to approximately 12, 24, and 36 hours after the start of the constant-rate pumping test.
2. Samples were collected from a sampling port on the extracted groundwater pipeline.
3. Chlorite was not detected at a concentration above the level of the reported sample quantitation limit in the groundwater samples collected during the intermediate constant-rate pumping test.

Concentrations of perchlorate, chlorate, hexavalent chromium, total chromium, and chloroform in groundwater samples increased initially prior to stabilizing after 12 hours during the constant-rate pumping test. The analytical concentrations of the pumping test samples were slightly higher than the baseline groundwater sample concentrations.

The constant rate pumping test data were downloaded from the transducers in select intermediate wells (VER-01I, VMW-01I, VMW-02I, M-65D, and M-221) and the drawdown was calculated from the data. Constant rate test analysis was performed using the commercially-available AQTESOLV software (HydroSOLVE, Inc., 2007). The Theis method for analyzing aquifer tests was used to estimate hydraulic conductivity, transmissivity, and storage coefficients (Theis, 1935). The AQTESOLV interpretation plots are provided as ***Appendix H***. ***Table 14*** summarizes the results estimated from the constant rate test analysis. The average hydraulic conductivity and transmissivity for the intermediate wells were 1.09 ft/day and 40.14 ft^2/day, respectively. These data were used to guide the groundwater model calibration in Section 4.4.

Table 14 Estimated Hydraulic Conductivity and Transmissivity Based on the Results of the Intermediate Constant-Rate Pumping Test at VER-01I

Well	Well Type	Date	Hydraulic Conductivity		Transmissivity (ft^2/day)	Storage Coefficient[1]	Method
			(ft/day)	(cm/sec)			
VER-01I	Pumping	1/11/18	1.04E+00	3.67E-04	37.54	3.17E-03	Theis
VMW-01I	Observation	1/11/18	1.06E+00	3.73E-04	40.99	5.79E-04	Theis
VMW-02I	Observation	1/11/18	9.92E-01	3.50E-04	37.41	2.39E-03	Theis
M-65D	Observation	1/11/18	1.49E+00	5.27E-04	39.71	2.58E-03	Theis
M-221	Observation	1/11/18	8.62E-01	3.04E-04	45.03	2.02E-03	Theis

Notes:
cm/sec – centimeters per second
ft/day – feet per day
ft^2/day – square feet per day
1. Storage coefficient (storativity) is a dimensionless value.

4.2.3 Intermediate VER Test Results

The first eight hours of conventional pumping resulted in extraction rates that ranged from 2.66 gpm to 3.65 gpm, with an average of 3.12 gpm. The first eight hours of combined conventional pumping with applied vacuum resulted in extraction rates that ranged from 3.57 gpm to 4.42 gpm with an average of 4.05 gpm; this is a 30 percent increase in groundwater extraction rate over conventional pumping. The groundwater extraction rate slowly decreased over the remainder of the VER test; the average groundwater extraction rate with vacuum for the entire VER test was approximately 3.83 gpm. The air flow rate for the VER system ranged from approximately 0.27 standard cubic feet per minute (scfm) to 1.18 scfm. A graph depicting the groundwater extraction rates for the intermediate VER test is provided as ***Figure 8***. The groundwater elevation data for VER-01I based on manual gauging measurements collected during the first 8 hours of the intermediate VER test is summarized in ***Table D-6*** of ***Appendix D***. The groundwater elevation data for the performance monitoring wells based on manual gauging measurements collected during the intermediate VER test is summarized in ***Table D-7*** of ***Appendix D***.

Table 15 summarizes the maximum drawdown observed at VER-01I and the performance monitoring wells during conventional pumping techniques, prior to applying vacuum to VER-01I. ***Figure 6*** provides a graph of the drawdown calculated at each monitoring well for both instrumented wells and manually gauged wells during the VER test.

Table 15 Relative Groundwater Drawdown During the Intermediate VER Test (Prior to Vacuum)

Well ID (Screened Interval - feet below ground surface)	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]
VER-01I (55-70)	0	34.17	70	35.83
VMW-02I (55-70)	26	32.36	36.95	4.59
VMW-02D (90-110)	26	26.16	26.16	0.00
M-172 (26.1-36.9)	28	33.41	33.51	0.10
VMW-01I (55-70)	42	31.56	35.89	4.33
VMW-01D (90-110)	42	23.88	23.89	0.01
I-F (11.8-41.8)[2]	44	33.53	33.87	0.34
M-65 (14.4-39.0)	62	32.78	32.82	0.04
M-65D (60-70)	66	33.55	34.30	0.75
M-221 (75-85)	66	33.05	34.04	0.99
M-56 (15.1-40.0)	92	31.02	31.10	0.08
M-78 (21.5-41.5)	129	32.75	32.75	0.00
M-164 (60-70)	145	35.00	35.03	0.03

Notes:
1. To estimate the depth to water at maximum relative drawdown prior to applying vacuum to VER-01I, depth to water measurements collected between 03:30 and 10:30 on January 15, 2018, were compared to the depth to water at the start of the test.
2. I-F was an active IWF pumping well.
3. Based on GWETS metrics data provided by ETI, drawdown attributed to the intermediate VER test was observed in IWF pumping wells, I-F, I-G, I-Q, and I-X.

Table 16 summarizes the maximum drawdown observed at VER-01I and the performance monitoring wells during the intermediate VER test, after vacuum was applied to the pumping well.

Table 16 Relative Groundwater Drawdown During the Intermediate VER Test (After Vacuum)

Well ID (Screened Interval - feet below ground surface)	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]
VER-01I (55-70)	0	34.17	NM	NM
VMW-02I (55-70)	26	32.36	41.83	9.47
VMW-02D (90-110)	26	26.16	26.22	0.06
M-172 (26.1-36.9)	28	33.41	33.84	0.43
VMW-01I (55-70)	42	31.56	40.30	8.74
VMW-01D (90-110)	42	23.88	24.02	0.14
I-F (11.8-41.8)	44	33.53	40.96	7.43
M-65 (14.4-39.0)	62	32.78	33.05	0.27
M-65D (60-70)	66	33.55	37.21	3.66
M-221 (75-85)	66	33.05	39.80	6.75
M-56 (15.1-40.0)	92	31.02	31.64	0.62
M-78 (21.5-41.5)	129	32.75	32.99	0.24
M-164 (60-70)	145	35.00	35.82	0.82

Notes:

NM – Not measured

1. Relative drawdown was estimated from pressure transducer measurements of pressure in wells during the VER test or manual measurements of depth to water.
2. Based on GWETS metrics data provided by ETI, drawdown attributed to the intermediate VER test was observed in IWF pumping wells, I-F, I-G, I-Q, and I-X.

The application of vacuum at VER-01I increased the overall drawdown in the performance monitoring wells. During the constant-rate test, the well was not pumped at the maximum possible short-term rate but rather at a sustainable long-term rate of 2 gpm. The increased drawdown during the VER test due to maximum pumping at about 3-3.5 gpm followed by application of vacuum is clearly evident on ***Figure 6***.

Based on pressure transducer data, the most significant increases in the maximum drawdown were at M-65D and M-221 which are located within 66 feet of VER-01I. The maximum drawdown at M-65D increased from 0.75 feet during conventional pumping to 3.66 feet after applying vacuum. The maximum drawdown at M-221 increased from 0.99 feet to 6.75 feet after applying vacuum. The drawdown observed at M-65D and M-221 is likely the result of both wells being located within the simulated capture zone of VER-01I after vacuum was applied.

Based on manual gauging measurements (***Table D-7***; ***Appendix D***), the maximum drawdown at I-F increased from 0.34 feet to 7.09 feet after applying vacuum; however, since this well is an active groundwater extraction well, the increase in drawdown is also attributed to the pumping schedule of the well. The maximum drawdown at well M-164 increased from 0.03 feet to 0.82 feet after applying vacuum; well M-164 is located 145 feet from VER-01I.

Table 17 summarizes the maximum vacuum observed at the performance monitoring wells during the intermediate VER test.

Table 17 Intermediate VER Test Performance Monitoring Well Vacuum Readings

Well ID (Screened Interval – feet below ground surface)	Distance from Extraction Well (feet)	Maximum Measured Vacuum (inches of water column)	Average Measured Vacuum (inches of water column)
VMW-02I (55-70)	26	0.12	0.01
VMW-02D (90-110)	26	0.03	0.01
M-172 (26.1-36.9)	28	0.12	0.10
VMW-01I (55-70)	42	0.12	0.002
VMW-01D (90-110)	42	0.05	0.002

Vacuum measurements greater than 0.1 inches of water column (in w.c.) were considered evidence of vacuum influence at a monitoring point. A consistent vacuum response was measured at M-172 where readings ranged from 0.08 to 0.12 in w.c. during the intermediate VER test. A vacuum reading equal to or greater than 0.1 was only measured once in VMW-01I and VMW-02I (both measurements were collected at the start of the test). Vacuum readings equal to or greater than 0.1 in w.c. were not measured in VMW-01D, VMW-02D during the intermediate VER test.

The groundwater analytical results for samples collected during the intermediate VER test are summarized in ***Table 18*** and ***Table D-8*** of ***Appendix D.***

Table 18 Groundwater Sample Analytical Results for the Intermediate VER Test

Parameter	Concentration (milligrams per Liter)							
Sampling Event	**0 hr**	**12 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**78 hr**
Perchlorate	1,200	1,100	1,200	1,100	1,200	1,200	1,300	1,200
Chlorate	3,000	3,100	3,100	3,300 J	2,900	3,400	3,300	3,100
Hexavalent Chromium	7.7	12	11	13	12	13	12	12
Total Chromium	8.7	12	12	12	11	12	13 J	12
Chloroform	0.470	0.710	0.700	0.730	0.630	0.670	0.640	0.620

Notes:

hr - hour
J – The result is an estimated quantity. The associated numerical value is the approximate concentration of the analyte in the sample.
Samples were collected from a sampling port on the extracted groundwater pipeline.
1. Chlorite was not detected at a concentration above the level of the reported sample quantitation limit in the groundwater samples collected during the intermediate VER test.

Perchlorate concentrations in the extracted groundwater from VER-01I generally remained stable ranging from 1,100 to 1,300 mg/L, chlorate concentrations remained within a range of 2,900 to 3,400 mg/L, and hexavalent chromium concentrations increased from 7.7 to 13 mg/L. Groundwater concentrations of perchlorate, chlorate, and hexavalent chromium were similar to the concentrations detected in samples collected during the intermediate constant-rate pumping test.

The analytical results of soil vapor samples collected during the intermediate VER test are summarized in ***Table 19*** and ***Table D-9*** of ***Appendix D***. Influent soil vapor samples were collected from the influent soil vapor sample port (prior to treatment with vapor-phase carbon), and effluent soil vapor samples were collected after treatment with vapor-phase carbon.

Table 19 Soil Vapor Sample Analytical Results for the Intermediate VER Test

Parameter	**Influent Soil Vapor Concentrations (micrograms per cubic meter)**								
Sampling Event	**0 hr**	**12 hr**	**16 hr**	**20 hr**	**32 hr**	**44 hr**	**56 hr**	**68 hr**	**78 hr**
Chloroform	< 1.7	< 50	< 5.9	1.8 J	21	60	20	170	110
Total VOCs	5,095	160,933	15,063	5,216	2,751	1,099	1,682	1,481	2,495
PID as Hexane (parts per million)	3.5	NA	13.0	5.8	1.7	NA	0.7	NA	1.2
Parameter	**Effluent Soil Vapor Concentrations (micrograms per cubic meter)**								
Chloroform	NA	NA	< 1.2	NA	< 0.46	NA	< 0.46	NA	< 0.46
Total VOCs	NA	NA	518	NA	41	NA	19	NA	36

Notes:
hr - hour
J – The result is an estimated quantity. The associated numerical value is the approximate concentration of the analyte in the sample.
NA – not analyzed
PID - photoionization detector
VOCs – volatile organic compounds
1. Soil vapor samples were collected from the influent and effluent vapor treatment soil vapor sample ports.
2. Effluent soil vapor samples were collected after treatment with vapor-phase carbon. Samples were collected at a frequency of one sample per 24-hour period.

The influent soil vapor sample collected at the start of the 8-hour conventional pumping period of the intermediate VER test is defined as 0-Hour in ***Table 19***, and the lack of vapor-phase mass removal is reflective of the lower concentration of this sample compared to the 12-Hour influent soil vapor sample (collected after vacuum was applied). The total VOC concentration for the influent soil vapor samples ranged from 1,099 micrograms per cubic meter (µg/m^3) to 160,933 µg/m^3 (collected approximately 4 hours after the application of vacuum; approximately 12 hours after the start of the VER test). Total VOC concentrations were highest in the vapor samples collected approximately 4 and 8 hours after applying vacuum (approximately 12 to 16 hours after the start of the VER test), and total VOC concentrations decreased as the VER test continued. After 20 hours, total VOC concentrations decreased to levels at the start of the intermediate VER test. A total of 22 VOCs were detected in the influent soil vapor samples, but acetone, chloroform, ethylbenzene, 4-ethyltoluene, toluene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, m,p-xylene, and o-xylene were the VOCs detected at the highest concentrations in the influent soil vapor samples.

Influent chloroform detections ranged from 1.8 µg/m^3 to 170 µg/m^3; but after 20 hours, the chloroform concentrations in influent soil vapor exhibited an increasing trend, which was expected to occur while the surrounding formation was being dewatered and the chloroform was being stripped from the soil and groundwater. PID readings for the influent soil vapor samples ranged from non-detect to 13 parts per million (ppm). The total VOC concentration in the effluent soil vapor samples ranged from 19 µg/m^3 to 518 µg/m^3. The highest effluent total VOC concentration (518 µg/m^3) was detected in the sample collected approximately 8 hours after vacuum was applied (approximately 16 hours after the start of the VER test). Subsequent effluent VOC concentrations declined by an order of magnitude along with the influent total VOC concentrations. As anticipated, the effluent total VOC concentrations were successfully reduced by two to three orders of magnitude lower than the influent total VOC concentrations, indicating the vapor-phase carbon vessel effectively removed VOC constituents from the soil vapor stream.

The intermediate recovery monitoring period for the VER test was conducted from January 18 through January 22, 2018, when water elevations returned to baseline conditions.

4.2.4 Estimated Mass Removal Rates

Perchlorate and hexavalent chromium mass removal rates were calculated in manner consistent with the NDEP document entitled *Guidance for the Use of Significant Figures and Rounding Conventions in Water Quality Permitting* (NDEP, 2017). Mass removal rates from groundwater were calculated by multiplying perchlorate and hexavalent chromium concentrations in groundwater collected during the intermediate VER test by the flow rate measured at different points of the test. For example, the perchlorate and hexavalent chromium mass removal rates for the first 12 hours of test were calculated by multiplying the perchlorate and hexavalent chromium concentrations at the baseline (0-Hour) groundwater sample by the flow rate measured during the first 12 hours of the intermediate VER test. This procedure was repeated for samples collected at 12-hour intervals during the remainder of the intermediate VER test to capture concentration changes that may affect mass removal rates. During the first eight hours of the intermediate VER test, conventional pumping removed approximately 12.5 pounds of perchlorate and 0.08 pounds of hexavalent chromium from the extracted groundwater. During the last 70 hours of the intermediate VER test, conventional pumping under an applied vacuum removed approximately 156.5 pounds of perchlorate and 1.58 pounds of hexavalent chromium.

Total vapor-phase VOC and vapor-phase chloroform mass removal rates were calculated by multiplying total VOC and chloroform concentrations in influent soil vapor samples collected during the intermediate VER test by the flow rate measured at different points of the test. Approximately 0.0025 lbs (1.1 grams) of vapor-phase VOCs were extracted from the subsurface during the intermediate VER test after vacuum was applied. The vapor phase mass removed is below the Clark County DAQ exempt stationary source threshold values of 2 tpy for a criteria pollutant or 5 tpy for a combination of criteria pollutants, even without vapor treatment.

4.3 DEEP VER TREATABILITY STUDY RESULTS

This section summarizes the results of the deep VER treatability study. The comprehensive field data and analytical data tables for the deep VER tests are included in ***Appendix E.*** The manual gauging measurements collected during the step-drawdown test, constant-rate pumping test, and deep VER test corroborated with the pressure transducer data. The analytical results for the deep VER groundwater and soil vapor samples are provided in the DVSR included in ***Appendix B***.

4.3.1 Step-Drawdown Test Results

The step-drawdown test was performed at three rates, 0.5 gpm, 0.75 gpm, and 1.0 gpm, for a total of approximately 6 hours to determine the pumping rate for the constant-rate pumping test that would not dewater the extraction well. Well VER-01D could not be pumped at a rate greater than 1.0 gpm due to slow recharge and significant drawdown at VER-01D. The measured water elevation at VER-01D experienced 84.75 feet of drawdown during the step-drawdown test.

The greatest amount of drawdown measured in monitoring wells during the step-drawdown test was recorded at VMW-01D (12.25 feet). Drawdown measured in other monitoring wells did not exceed 0.35 feet, but drawdown was observed at wells located up to 128 feet from VER-01D. Water levels in VER-01D recovered within 90 percent of initial static levels by January 23, 2018 (within 24 hours after completion of the step-drawdown test). ***Figure 7*** shows the drawdown calculated at each monitoring well during the step test. The groundwater elevation data for VER-01D based on manual gauging measurements collected during the step-drawdown test is summarized in ***Table E-1*** of ***Appendix E***. The groundwater elevation data for the performance monitoring wells based on manual gauging measurements collected during the step-drawdown test is summarized in ***Table E-2*** of ***Appendix E***.

4.3.2 Constant-Rate Pumping Test Results

The constant-rate pumping test was conducted for approximately 48 hours at an extraction rate of 0.5 gpm. The groundwater elevation data for VER-01D based on manual gauging measurements collected during the constant-rate pumping test is summarized in ***Table E-3*** of ***Appendix E***. The groundwater elevation data for the performance monitoring wells based on manual gauging measurements collected during the constant-rate pumping test is summarized in ***Table E-4*** of ***Appendix E***.

Table 20 summarizes the maximum drawdown observed at VER-01D and the performance monitoring wells during the constant-rate pumping test. Drawdown directly attributable to the deep constant-rate pumping test was not observed in IWF pumping wells I-F, I-G, I-Q, and I-X. The groundwater elevation data for VER-01D based on manual gauging measurements collected during the constant-rate pumping test is summarized in ***Table E-3*** of ***Appendix E***. The groundwater elevation data for the performance monitoring wells based on manual gauging measurements collected during the constant-rate pumping test is summarized in ***Table E-4*** of ***Appendix E***.

Table 20 Relative Groundwater Drawdown During the Deep Constant-Rate Pumping Test at VER-01D

Well ID (Screened Interval – feet below ground surface)	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]
VER-01D (90-110)	0	29.69	86.02	56.33
M-172 (26.1-36.9)	13	33.25	33.15	-0.10
VMW-01I (55-70)	18	31.40	31.19	-0.21
VMW-01D (90-110)	20	26.17	39.42	13.25
I-F (11.8-41.8)[2]	28	33.12	32.80	-0.32
VMW-02I (55-70)	52	32.20	32.06	-0.14
VMW-02D (90-110)	55	27.85	32.10	4.25
M-56 (15.1-40.0)	78	30.98	30.81	-0.17
M-65 (14.4-39.0)	89	32.58	32.47	-0.11
M-65D (60-70)	92	32.34	33.35	1.01
M-221 (75-85)	92	32.98	32.73	-0.25
M-222 (100-110)	101	28.57	30.48	1.91
M-163 (80-90)	108	28.71	29.64	0.93
M-162 (100-110)	113	24.29	26.85	2.56
M-164 (60-70)	120	34.91	34.78	0.13
M-78 (21.5-41.5)	128	32.50	32.40	-0.10

Well ID (Screened Interval – feet below ground surface)	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]

Notes:

1. Depth to water at maximum relative drawdown did not consistently correspond to the end of the deep constant-rate pumping test.
2. I-F is an active IWF pumping well.

Monitoring wells VMW-01D (located 20 feet from VER-01D) and VMW-02D (located 55 feet from VER-01D) had the greatest amount of measured drawdown. These monitoring wells are screened in the same interval as VER-01D. Wells M-162 and M-222, screened at similar depths to VER-01D, had maximum drawdowns of 2.56 and 1.91 feet, respectively. Wells M-65D and M-163, both screened above 90 feet bgs, had 1.01 and 0.93 feet of drawdown, respectively. ***Figure 7*** provides a graph of the drawdown calculated at each monitoring well for both instrumented wells and manually gauged wells during the constant-rate test. Due to the lower hydraulic conductivity of the UMCf at this depth, a longer recovery period was allowed between the VER-01D tests than between VER-01I tests to ensure that monitoring wells VMW-01D and VMW-02D recovered to within 90 percent of pre-test static levels.

A summary of the analytical results of samples collected during the deep constant-rate pumping test is provided in ***Table 21*** and ***Table E-5*** of ***Appendix E***.

Table 21 Groundwater Sample Analytical Results for the Deep Constant-Rate Pumping Test at VER-01D

Parameter	Concentration (milligrams per Liter)				
Sampling Event	**0 hr**	**12 hr**	**24 hr**	**36 hr**	**48 hr**
Perchlorate	4.6	1.2	1.1	1.1	0.890
Chlorate	21	4.8	3.7	3.4	3.2
Hexavalent Chromium	0.024	0.027	0.026	0.026	0.027
Total Chromium	0.044	0.028	0.026	0.025	0.037
Chloroform	0.0047	0.00088	0.00055	0.00051	0.00041 J

Notes:

hr - hour

J – The result is an estimated quantity. The associated numerical value is the approximate concentration of the analyte in the sample.

1. Samples were collected from a sampling port on the extracted groundwater pipeline.
2. Chlorite was not detected at a concentration above the level of the reported sample quantitation limit in the groundwater samples collected during the intermediate constant-rate pumping test.

Perchlorate, chlorate, and chloroform concentrations decreased at VER-01D as the constant-rate pumping test progressed, and concentrations were approximately one order of magnitude lower than the baseline groundwater sample concentrations. One potential explanation for this observation is that the contaminant impacts may be present in more isolated areas in the deep zone. When the constant-rate pumping test started, groundwater may have been pulled from less-impacted areas. Hexavalent chromium concentrations increased slightly before stabilizing after 12 hours. Total chromium concentrations fluctuated slightly during the constant-rate pumping test.

The constant rate pumping test data were downloaded from the transducers in select deep wells (VER-01D, VMW-01D, VMW-02D, and M-222) and the drawdown was calculated from these data. Constant rate test analysis was performed using the commercially-available AQTESOLV software (HydroSOLVE, Inc., 2007). The Theis method for analyzing aquifer tests was used to estimate hydraulic conductivity, transmissivity, and storage coefficient (Theis, 1935). The AQTESOLV interpretation plots are provided as ***Appendix H***. ***Table 22*** summarizes the results estimated from the constant rate test analysis. The average hydraulic conductivity and transmissivity for the deep wells were 0.04 ft/day and 3.35 ft^2/day, respectively. These data were used to guide the groundwater model calibration in Section 4.4.

Table 22 Estimated Hydraulic Conductivity and Transmissivity Based on the Results of the Deep Constant-Rate Pumping Test at VER-01D

Well	Well Type	Date	Hydraulic Conductivity		Transmissivity (ft^2/day)	Storage Coefficient[1]	Method
			(ft/day)	(cm/sec)			
VER-01D	Pumping	1/23/18	3.20E-02	1.13E-05	2.67	1.11E-03	Theis
VMW-01D	Observation	1/23/18	4.15E-02	1.46E-05	3.56	5.29E-04	Theis
VMW-02D	Observation	1/23/18	4.08E-02	1.44E-05	3.42	6.93E-04	Theis
M-222	Observation	1/23/18	4.59E-02	1.62E-05	3.76	1.29E-03	Theis

Notes:
cm/sec – centimeters per second
ft/day – feet per day
ft^2/day – square feet per day
1. Storage coefficient (storativity) is a dimensionless value.

4.3.3 Deep VER Test Results

The first 12 hours of conventional pumping ranged from 0.48 gpm to 0.61 gpm with an average flow rate of 0.53 gpm. The first 12 hours of the combined conventional pumping with applied vacuum resulted in extraction rates that ranged from 0.59 gpm to 0.68 gpm with an average flow rate of 0.64 gpm, a 21 percent increase in the groundwater extraction rate over conventional pumping. The groundwater extraction rate slowly decreased over the remainder of the VER test; the overall average groundwater extraction rate with vacuum was approximately 0.59 gpm. The air flow rate for the VER system ranged from approximately 0.970 scfm to 10.4 scfm. A graph depicting the groundwater extraction rates for the deep VER test is provided as ***Figure 9***. The groundwater elevation data for VER-01D based on manual gauging measurements collected during the first 12 hours of the deep VER test is summarized in Table E-6 of ***Appendix E***. The groundwater elevation data for the performance monitoring wells based on manual gauging measurements collected during the deep VER test is summarized in ***Table E-7*** of ***Appendix E***.

Table 23 summarizes the maximum drawdown observed at VER-01D and the performance monitoring wells during the approximate 12-hour period using conventional pumping techniques, prior to applying vacuum to VER-01D. ***Figure 7*** provides a graph of the drawdown calculated at each monitoring well for both instrumented wells and manually gauged wells during the VER test.

Table 23 Relative Groundwater Drawdown During the Deep VER Test (Prior to Vacuum)

Well ID (Screened Interval – feet below ground surface)	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]
VER-01D (90-110)	0	26.80	NM	NM
M-172 (26.1-36.9)	13	32.61	32.57	-0.04
VMW-01I (55-70)	18	30.57	30.60	-0.03
VMW-01D (90-110)	20	24.18	39.25	15.07
I-F (11.8-41.8)[2]	28	31.95	31.82	-0.13
VMW-02I (55-70)	52	31.63	31.56	-0.07
VMW-02D (90-110)	55	26.39	28.05	1.66
M-56 (15.1-40.0)	78	30.38	30.36	-0.02
M-65 (14.4-39.0)	89	32.14	32.17	0.03
M-65D (60-70)	92	32.93	32.91	-0.02
M-221 (75-85)	92	32.46	32.41	-0.05
M-222 (100-110)	101	28.54	28.58	0.04
M-163 (80-90)	108	28.33	28.34	0.01
M-162 (100-110)	113	23.78	24.63	0.85
M-164 (60-70)	120	34.60	34.56	-0.04
M-78 (21.5-41.5)	128	31.82	31.77	-0.05

Notes:

NM – Not measured
1. To estimate the depth to water at maximum relative drawdown prior to applying vacuum to VER-01D, depth to water measurements collected between 03:30 and 15:30 on February 5, 2018, were compared to the depth to water at the start of the test.
2. I-F is an active IWF pumping well.

Table 24 summarizes the maximum drawdown observed at VER-01D and the performance monitoring wells during the deep VER test, after vacuum was applied to the pumping well.

Table 24 Relative Groundwater Drawdown During the Deep VER Test (After Vacuum)

Well ID (Screened Interval – feet below ground surface)	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]
VER-01D (90-110)	0	26.80	NM	NM
M-172 (26.1-36.9)	13	32.61	32.60	-0.01
VMW-01I (55-70)	18	30.57	29.83	-0.74

Well ID (Screened Interval – feet below ground surface)	Distance from Extraction Well (feet)	Depth to Water at Start of Test (feet below top of casing)	Depth to Water at Maximum Drawdown (feet below top of casing)	Maximum Relative Drawdown Observed (feet)[1]
VMW-01D (90-110)	20	24.18	51.00	26.82
I-F (11.8-41.8)	28	31.95	31.93	-0.02
VMW-02I (55-70)	52	31.63	30.98	-0.65
VMW-02D (90-110)	55	26.39	38.72	12.33
M-56 (15.1-40.0)	78	30.38	30.39	0.01
M-65 (14.4-39.0)	89	32.14	32.17	0.03
M-65D (60-70)	92	32.93	32.93	0.00
M-221 (75-85)	92	32.46	32.47	0.01
M-222 (100-110)	101	28.54	35.00	6.46
M-163 (80-90)	108	28.33	31.75	3.42
M-162 (100-110)	113	23.78	31.50	7.72
M-164 (60-70)	120	34.60	34.66	0.06
M-78 (21.5-41.5)	128	31.82	31.82	0.00

Notes:

NM – Not Measured

1. Relative drawdown was estimated from pressure transducer measurements of pressure in wells during the VER test or manual measurements of depth to water.

The application of vacuum at VER-01D increased the drawdown in the performance monitoring wells. Based on pressure transducer data, the most significant increases in drawdown in the performance monitoring wells were measured at VMW-01D, located 18 feet from VER-01D and VMW-02D, located 55 feet from VER-01D.

Based on manual gauging measurements, drawdown of 3.42 feet and 7.72 feet was observed at M-163 and M-162, located 108 and 113 feet from VER-01D. Based on GWETS metrics data provided by ETI, drawdown was not observed in IWF pumping wells I-G, I-Q, and I-X during the deep VER test.

Table 25 summarizes the maximum vacuum observed at the performance monitoring wells during the deep VER test.

Table 25 Deep VER Test Performance Monitoring Well Vacuum Readings

Well ID (Screened Interval – feet below ground surface)	Distance from Extraction Well (feet)	Maximum Measured Vacuum (inches of water column)	Average Measured Vacuum (inches of water column)
M-172 (26.1-36.9)	13	0.15	0.10
VMW-01I (55-70)	18	0.03	0.001
VMW-01D (90-110)	20	0.06	0.01
VMW-02I (55-70)	52	0.04	0.01
VMW-02D (90-110)	55	0.03	0.01

Vacuum measurements greater than 0.1 in w.c. were considered evidence of vacuum influence at a monitoring point. A consistent vacuum response was measured at M-172 (the closest vacuum monitoring well to VER-01D); vacuum readings ranged from 0.07 to 0.15 in w.c. No vacuum reading equal to or greater than 0.1 in w.c. was measured in at VMW-01I, VMW-01D, VMW-02I, and VMW-02D during the deep VER test, indicating that the lithology of the UMCf was limiting air flow across the formation. However, the limited air flow did not affect the increase in groundwater extraction rate.

The groundwater analytical results for samples collected during the deep VER test are summarized in ***Table 26*** and ***Table E-8*** of ***Appendix E***.

Table 26 Groundwater Sample Analytical Results for the Deep VER Test

Parameter	Concentration (milligrams per Liter)								
Sampling Event	0 hr	12 hr	24 hr	36 hr	48 hr	60 hr	72 hr	84 hr	96 hr
Perchlorate	2.0	0.980	1.1	0.830	0.800	0.720	0.660	0.670	0.570
Chlorate	4.4	3.7	2.9	2.4	2.2	2.0	1.8	1.8	1.7
Hexavalent Chromium	0.018	0.026	0.026	0.026	0.025	0.026	0.025	0.025	0.025
Total Chromium	0.028	0.028	0.028 J	0.028 J	0.028 J	0.027 J	0.030	0.028	0.028
Chloroform	0.0012	0.00066	0.00046 J	0.00044 J	0.00033 J	0.00030 J	0.00029 J	0.00027 J	0.00026 J

Notes:

hr - hour
J – The result is an estimated quantity. The associated numerical value is the approximate concentration of the analyte in the sample.
1. Samples were collected from a sampling port on the extracted groundwater pipeline.
2. Chlorite was not detected at a concentration above the level of the reported sample quantitation limit in the baseline groundwater samples.

Perchlorate, chlorate, and chloroform concentrations decreased as the deep VER test progressed. Hexavalent chromium concentrations increased slightly before stabilizing, and total chromium concentrations remained stable throughout the deep VER test.

Ten influent soil vapor samples (collected prior to carbon treatment) and four effluent soil vapor samples (collected after carbon treatment) were collected during the deep VER test. PID readings (calibrated to hexane gas) were collected in conjunction with the influent soil vapor samples. Analytical results of soil vapor samples collected during the deep VER test are summarized in ***Table 27*** and ***Table E-9*** of ***Appendix E***.

Table 27 Soil Vapor Sample Analytical Results for the Deep VER Test

Parameter	Influent Soil Vapor Sample Concentrations (micrograms per cubic meter)									
Sampling Event	**0 hr**	**16 hr**	**20 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**
Chloroform	780	< 0.46	440	320	< 0.46	0.52 J	170	130	180	7.6
Total VOCs	2,997	26	608	484	33	140	472	336	485	34
PID as Hexane (parts per million)	0.40	NA	0.10	NA	NA	0.0	0.0	0.10	0.0	0.20
Parameter	**Effluent Soil Vapor Sample Concentrations (micrograms per cubic meter)**									
Sampling Event	**0 hr**	**16 hr**	**20 hr**	**24 hr**	**36 hr**	**48 hr**	**60 hr**	**72 hr**	**84 hr**	**96 hr**
Chloroform	NA	< 0.46	NA	NA	< 0.46	NA	< 0.46	NA	< 0.46	NA
Total VOCs	NA	4.0	NA	NA	60	NA	17	NA	15	NA

Notes:
hr - hour
J – The result is an estimated quantity. The associated numerical value is the approximate concentration of the analyte in the sample.
NA – not analyzed
PID – photoionization detector
VOCs – volatile organic compounds

1. Soil vapor samples were collected from the influent and effluent vapor treatment soil vapor sample ports.
2. Effluent soil vapor samples were collected after treatment with vapor-phase carbon. Effluent soil vapor samples were collected at a frequency of one sample per 24-hour period.

The influent soil vapor sample collected at the start of the 12-hour conventional pumping period of the deep VER test is defined as 0-Hour in ***Table 27***, which had the highest concentrations of total VOCs and chloroform in any of the influent soil vapor samples collected during the deep VER test. The total VOC concentrations for the influent soil vapor samples ranged from 26 micrograms per cubic meter (µg/m^3) to 2,997 µg/m^3. While soil vapor concentrations fluctuated during the deep VER test, they were consistently one to two orders of magnitude lower than the baseline soil vapor concentrations. A total of 22 different VOCs were detected in the influent soil vapor samples; the VOCs with the highest detected concentrations include acetone, 2-butanone, chloroform, tetrachloroethylene, toluene, trichloroethylene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, m,p-xylene, and o-xylene. The highest chloroform concentration in the influent soil vapor samples (780 µg/m^3) was detected in the baseline soil vapor sample; chloroform concentrations fluctuated by two orders of magnitude during the remainder of the deep VER test, from non-detect to 440 µg/m^3, indicating fluctuating air flow in the tight formation. PID readings for the influent soil vapor samples ranged from non-detect to 0.40 ppm.

The total VOC concentrations detected in the effluent soil vapor samples ranged from 4.0 µg/m^3 to 60 µg/m^3. The highest effluent total VOC concentration (60 µg/m^3) was detected in the sample collected approximately 24 hours after the start of the deep VER test. As anticipated, the effluent total VOC concentrations were consistently lower than the influent soil vapor concentrations; total VOC concentrations in the effluent soil vapor samples were an order of magnitude less than the influent soil vapor samples in three of the four samples collected.

The recovery monitoring period for the deep VER test was conducted from February 9 through February 22, 2018, when water elevations returned to baseline conditions.

4.3.4 Estimated Mass Removal Rates

The estimated mass removal rates for groundwater and soil vapor for the deep VER test were calculated in a manner consistent with the procedures presented in Section 4.2.4 for the intermediate VER test. During the first 12 hours of the deep VER test, conventional pumping removed approximately 0.0072 pounds of perchlorate and 0.000066 pounds of hexavalent chromium from the extracted groundwater. During the last 84 hours of the deep VER test, conventional pumping under an applied vacuum removed approximately 0.023 pounds of perchlorate and 0.00063 pounds of hexavalent chromium. Approximately 0.0001 pounds (0.045 grams) of vapor-phase VOCs were extracted from the subsurface during performance of the deep VER test after vacuum was applied. The vapor-phase mass removed is below the Clark County DAQ exempt stationary source threshold values of 2 tpy for a criteria pollutant or 5 tpy for a combination of criteria pollutants, even without vapor treatment.

4.4 GROUNDWATER FLOW MODELING

This section describes the groundwater flow modeling performed based on the results obtained during the VER treatability study implementation. Groundwater flow modeling was performed to simulate the aquifer tests at the VER extraction wells VER-01I and VER-01D to simulate the extraction of groundwater with and without vacuum in the UMCf from the VER extraction wells and to estimate the expected drawdown, groundwater radius of influence, pumping rates, and the capture zone at the VER extraction wells. The simulated drawdown and capture zone results were used to predict if the IWF wells were influenced by the VER wells in the UMCf. The simulated capture zones will also be used to develop future conceptual designs of larger-scale VER systems.

4.4.1 Model Construction

The groundwater flow model for this treatability study (VER Model) is based on Ramboll Environ's *Phase 5 Transient Groundwater Flow Model* (Ramboll Environ, 2016). Differences in model construction between the Phase 5 model and the VER Model are briefly described below.

The VER Model was converted to MODFLOW-SURFACT to utilize the PCG5 (preconditioned conjugate gradient) solver and ATO (adaptive time-stepping and output control) package, which is more robust, faster, and able to achieve convergence for complex groundwater conditions, such as this study. The VER Model also uses the FWL (fracture-well) package for the IWF wells, which allows the user to specify well pump levels so extraction wells will not dry up, but will be drawdown-limited based on the water level and pump elevations.

Given the regional areal extent of the Phase 5 model, the model domain was decreased to a 295 feet by 330 feet area focused on the VER Study Area, which is located in the vicinity of the IWF, just to the east of the GWTP. This areal reduction also allowed the horizontal grid spacing to be refined to uniform 5 feet by 5 feet model cells to aid model calibration. Two additional model layers were added to simulate the correct location of the well screens in the VER pumping and monitoring wells. The model layer thicknesses were constant except for model layers 1 and 2; the elevation of the Qal/UMCf contact was used for the bottom of model layer 1 and the top of model layer 2, based on lithologic data from the recently installed VER extraction and monitoring wells and from existing borings/wells.

External model boundary conditions were set far enough away to not influence water level changes at the IWF or VER wells. They were also utilized to simulate the water level elevations and hydraulic gradient observed in the VER study area before step-drawdown testing began. Internal boundary conditions include the IWF barrier wall (model layers 1-3) and the IWF wells (model layers 1-3). No recharge was applied to the VER model. A combined steady-state and transient model was constructed to simulate background water level elevations and both VER constant-rate pumping tests (Phase B).

4.4.2 Model Modifications for VER Testing

Due to the low permeability of the UMCf and the application of vacuum to enhance groundwater recovery, a modification to extraction rates during VER testing was made to accurately simulate water level change and changes in capture zone and groundwater radius of influence. Conventional groundwater flow models, such as MODFLOW, cannot directly simulate VER. Therefore, a correction factor was applied to the extraction rate at the VER test wells (under vacuum) to simulate the effects of VER in low-permeability sediments, such as the UMCf. The correction factor is an exponential term that relates the groundwater radius of influence to the distance to the downgradient stagnation point (Suthersan & McDonough, 1996). If the ratio of these two terms is near one, then MODFLOW can be used without modification. In this case, the low permeability of the UMCf resulted in requiring the extraction rates in the intermediate and deep zones to be multiplied by 15 percent and 40 percent, respectively, using the method in Suthersan and McDonough (1996). Groundwater radius of influence and capture zone are discussed further in Section 4.4.4.

4.4.3 Model Calibration

Both a steady state and transient calibration were performed to match water level elevations before testing and drawdown targets during and after VER testing. Drawdown targets included constant-rate tests and VER tests for both the intermediate and deep extraction wells. Step-drawdown testing was not included in the calibration. Also, drawdown targets at the pumping wells during testing were weighted much less than the drawdown observed at the monitoring wells since there were measurable responses at the monitoring wells. However, recovery water levels from the pumping wells were weighted equally to monitoring well water levels. Model parameters that could be modified included horizontal and vertical hydraulic conductivity, storage coefficients, and the hydraulic characteristic of the IWF barrier wall. Initial model parameter values were used from the Phase 5 model and the constant-rate pumping tests from this study.

Calibration of the groundwater flow model was performed both manually and with the assistance of the Parameter ESTimation (PEST) PEST software (Watermark Numerical Computing, 2016). PEST was also used to conduct sensitivity analysis during calibration to evaluate which parameters had the most influence on the hydraulic head and drawdown observations. Results of the model calibration are described below.

Table 28 identifies the 14 steady-state calibration targets and the simulated water level elevations. There was a good match to water level elevations in the VER study area both spatially and vertically. Calibration statistics are within industry standards.

Table 28 Steady-State Calibration Targets for the Groundwater Flow Model

Well ID	Model Layer	Observed Water Level Elevation (feet above mean sea level)	Simulated Water Level Elevation (feet above mean sea level)	Residual[1] (feet)
M-65	2	1721.26	1721.86	-0.60
M-71	2	1711.45	1711.30	0.15
M-164	4	1712.67	1712.51	0.16
VER-01I	4	1717.43	1718.80	-1.37
VMW-01I	4	1717.64	1717.06	0.58
VMW-02I	4	1719.53	1719.76	-0.23
M-65D	4	1721.00	1721.45	-0.45
M-163	6	1719.41	1718.42	0.99

Well ID	Model Layer	Observed Water Level Elevation (feet above mean sea level)	Simulated Water Level Elevation (feet above mean sea level)	Residual[1] (feet)
M-221	6	1721.56	1721.70	-0.14
VMW-01D	7	1724.99	1723.61	1.38
VMW-02D	7	1725.62	1724.70	0.92
M-162	7	1724.28	1723.50	0.78
M-222	7	1726.78	1725.27	1.51
VER-01D	7	1723.47	1723.78	-0.31

Notes:
[1] Residual is defined as observed water level elevation minus simulated water level elevation.

Table 29 shows the calibration statistics for the hydraulic heads.

Table 29 Steady-State Calibration Statistics for the Groundwater Flow Model

Statistic	Value
Residual Mean	0.24
Residual Standard Deviation	0.79
Absolute Residual Mean	0.68
Residual Sum of Squares	9.61
Root Means Square Error	0.83
Minimum Residual	-1.37
Maximum Residual	1.51
Range of Observations	15.33
Standard Deviation/Range as a percentage	5.2%

The transient model calibration involved matching water level changes during the constant-rate testing, VER testing, and recovery periods. ***Figure 10*** shows observed and simulated drawdowns at wells VMW-02I and VMW-02D. The model typically matches the water level changes observed during constant-rate and VER testing. However, the model has a bias toward slightly underpredicting drawdown at most locations. Given the heterogeneity of the UMCf (such as sand stringers, which are smaller than the model cell dimensions), getting more exact water level matches is difficult. Also, the deep zone has a more elongated tail during recovery than the intermediate zone (***Figure 10***). This prolonged recovery could not be simulated by the VER model. This recovery is likely due to heterogeneity and dual porosity effects in the deep zone of the UMCf.

4.4.4 Groundwater Radius of Influence and Capture Zone Analysis

The extraction well groundwater ROI was estimated for each phase of testing during this treatability study by using the VER model. The groundwater ROI is defined for this study as the radial distance from the pumping well to the location where 1.0 foot of water level change was observed during each test. One foot was chosen for the following reasons: 1) to be conservative, 2) to account for model error, which is on the order of approximately 0.5 feet, and 3) to recognize that this value is observable in the field with instrumentation after correcting for barometric pressure changes. ***Table 30*** shows the estimated groundwater radii of influence for the constant-rate and VER tests.

Table 30 Estimated Groundwater Radii of Influence from Constant-Rate and VER Testing from the Groundwater Flow Model

Test	Duration (days)	Groundwater Radius of Influence (feet)
Intermediate Zone Constant-Rate Test	1.53	95
Intermediate Zone VER Test	2.96	120
Deep Zone Constant-Rate Test	2.01	125
Deep Zone VER Test	3.84	135

The simulated groundwater ROI for the constant-rate and VER tests ranges from approximately 95 to 135 feet. The reasons the groundwater ROIs were larger for the deep zone testing than for the intermediate zone testing are attributed to the following: 1) The deep zone test pumped for a longer duration than the intermediate zone test, even though the deep zone test was conducted at a lower flow rate and the deep zone has a lower permeability; and 2) The IWF barrier wall, installed to an approximate depth of 60 feet bgs, impacts the local groundwater flow direction. Well cluster M-162, M-163, and M-164 is located downgradient of the IWF barrier wall. The maximum water level change observed at M-162 (screened from 100 to 110 feet bgs), M-163 (screened from 80 to 90 feet bgs), and M-164 (screened from 60 to 70 feet bgs) from the constant-rate or VER testing were 7.72 feet, 3.42 feet, and 0.13 feet, respectively. These observed water level changes corroborate the groundwater ROI estimated by the VER model, since M-164 is approximately 145 feet away from VER-01I and M-162 is approximately 113 feet away from VER-01D. The intermediate zone VER wells are screened from 55 to 70 feet bgs. Therefore, approximately 5 feet of barrier wall impedes the drawdown cone from fully developing north of VER-01I and decreases the groundwater ROI, but does not affect pumping in the deep zone, which is approximately 50 feet below the bottom of the barrier wall.

Groundwater capture zones were also simulated using the VER model. Capture zones are defined as the three-dimensional region that contributes the groundwater extracted by one or more wells. Even though there is drawdown observed at a monitoring well, it will not necessarily be captured depending on the extraction well pumping rate, aquifer hydraulic conductivity, etc. Therefore, a capture zone radius is typically smaller than the groundwater ROI. Given the short duration of the constant-rate and VER testing, capture zones were not simulated using particle tracking with the calibrated model. Therefore, the VER model was modified to simulate pumping at VER-01I and VER-01D for 180 days each to estimate the capture zone from pumping at the same rate as the constant-rate test and the VER test. ***Figure 11*** shows the constant-rate capture zones after 180 days from pumping VER-01I (blue lines) and VER-01D (yellow lines). The VER-01I capture zone extends from upgradient of M-65 (approximately 70 feet from VER-01I) to VMW-01I (approximately 40 feet). The VER-01D 180-day capture zone extends to VMW-01D and has a radius of approximately 22 feet. When the vacuum is simulated from the pumping wells, the capture zone radius increases from 70 to 80 feet in the intermediate zone and from 22 to 25 feet in the deep zone.

Groundwater modeling results confirmed the aquifer parameters derived from the conventional constant-rate aquifer tests conducted in wells VER-01I and VER-01D (refer to Sections 4.2.2 and 4.3.2). Groundwater modeling results were used to calculate groundwater ROI and they also confirmed the drawdown observations measured at the monitoring wells during the intermediate and deep constant-rate and VER tests. Finally, groundwater modeling was used to predict 180-day capture zone extents to assess future design of a potential larger-scale VER system.

4.5 DATA VALIDATION

Field sampling was conducted in accordance with the existing *Site Management Plan, Revision 3* (Ramboll Environ, 2017b) and *Field Sampling Plan, Revision 1* (ENVIRON, 2014). Sampling and analytical methods were selected to meet the project data quality objectives and quality control criteria. The laboratory analytical data were verified and validated in accordance with procedures described in the NDEP *Data Verification and Validation Requirements - Supplement April 2009* established for the BMI Plant Sites and Common Areas Projects, Henderson, Nevada (NDEP, 2009) and with correspondence from NDEP personnel. The analytical data were evaluated for QA/QC based on the following documents: *Quality Assurance Project Plan, Revision 2* (Ramboll Environ, 2017c); NDEP *Revised Guidance on Qualifying Data due to Blank Contamination for the BMI Complex and Common Areas* (NDEP, 2012); *National Functional Guidelines for Inorganic Superfund Methods Data Review* (USEPA, 2017a); *National Functional Guidelines for Superfund Organic Methods Data Review* (USEPA, 2017b)*;* and the *SW-846 Third Edition, Test Methods for Evaluating Solid Waste,* including Updates I, II, IIA, IIB, III, and IV (USEPA, 1996) and laboratory methods. All samples were validated to Stage 2A. For the final round of sampling, 90 percent of the data were validated to Stage 2B and 10 percent to Stage 4. The VER treatability study DVSR is provided as ***Appendix B.***

5.0 SUMMARY OF KEY FINDINGS

The objectives for the VER treatability study were achieved with the successful implementation of intermediate and deep VER treatability studies. This section summarizes the key findings of the intermediate and deep VER treatability studies.

5.1 INTERMEDIATE VER TREATABILITY STUDY

Key findings of the intermediate VER treatability study include the following:

- The highest concentrations of perchlorate (830 mg/kg), chlorate (3,600 mg/kg), and hexavalent chromium (20 mg/kg) in soil were detected in samples collected from 50 feet bgs. The highest concentrations of perchlorate, chlorate, and hexavalent chromium in groundwater were encountered between 55 and 70 feet bgs. Perchlorate, chlorate, and hexavalent chromium concentrations in soil decreased below 70 feet bgs.
- Concentrations of perchlorate, chlorate, hexavalent chromium, and chloroform detected in groundwater samples from VER-01I increased initially prior to stabilizing after 12 hours during the constant-rate test (Phase B). Perchlorate concentrations increased from 300 mg/L to 1,200 mg/L, chlorate concentrations increased from 680 mg/L to 3,800 mg/L, hexavalent chromium concentrations increased from 2.2 mg/L to 13 mg/L, and chloroform concentrations increased from 0.110 mg/L to 0.730 mg/L.
- Chlorite was not detected at a concentration above the laboratory reporting limit in any of the groundwater samples collected as part of the intermediate VER treatability study.
- The average groundwater extraction rate using conventional pumping during the first eight hours of the intermediate VER test was 3.12 gpm. The average groundwater extraction rate using conventional pumping and applying a vacuum over the first eight hours was 4.05 gpm, an approximate 30 percent increase in the groundwater extraction rate over the comparable time period. The average groundwater extraction rate using conventional pumping and applying a vacuum was 3.83 gpm over the total 70-hour period when vacuum was applied. However, the final determination of whether VER is a more cost-effective alternative to traditional groundwater extraction will be determined in the Feasibility Study.
- Based on pressure transducer data, up to 6.75 feet of drawdown (M-221) was observed in performance monitoring wells located 66 feet from pumping well VER-01I during the VER test.
- Based on the GWETS metrics data provided by ETI, drawdown was observed in IWF pumping wells I-F, I-G, I-Q, and I-X, ranging from 1.73 feet (I-X) to 7.09 feet (I-F) during the intermediate VER test. IWF pumping wells I-F, I-G, I-Q, and I-X are located 44 feet, 140 feet, 65 feet, and 72 feet from VER-01I, respectively. As such, additional evaluation is necessary to determine the maximum sustainable pumping rate that will not jeopardize the operation or the capture zone of the IWF.
- Groundwater flow modeling indicated that applying vacuum at VER-01I would result in increasing the simulated groundwater ROI from approximately 95 to 120 feet.
- Groundwater flow modeling identified that applying vacuum at VER-01I resulted in an approximately 14 percent increase in the capture zone radius in comparison to conventional pumping alone (from 70 feet to 80 feet), and increased capture of groundwater migrating underneath the barrier wall.
- The maximum vacuum ROI measured during the intermediate VER test was 28 feet (M-172).
- During the intermediate zone VER test (Phase C), perchlorate concentrations in the extracted groundwater from VER-01I generally remained stable ranging from 1,100 to 1,300 mg/L, chlorate concentrations remained within a range of 2,900 to 3,400 mg/L, and hexavalent chromium concentrations increased from 7.7 to 13 mg/L.

- Perchlorate concentrations in groundwater at VER-01I exhibited an overall increasing trend with respect to baseline (pre-aquifer testing) concentrations prior to stabilizing during the constant rate test, increasing from 300 mg/L (baseline) to 1,200 mg/L (end of the constant rate test).
- The air flow rate for the VER system ranged from approximately 0.27 scfm to 1.18 scfm.
- Low amounts of VOCs were extracted from the subsurface, and the mass removal efficiency of the vapor phase carbon was greater than 98.5%.

A comparison of performance metrics for conventional pumping to VER technology for VER-01I is summarized in ***Table 31***.

Table 31 Performance Metrics for Conventional and VER Extraction at VER-01I

Intermediate Well Screening Criteria	Conventional Extraction	Vacuum Enhanced Recovery Extraction	Percent Change
Average Groundwater Extraction Rate (gallons per minute)[1]	3.12	4.05	+30%
Estimated Groundwater Radius of Influence (feet)[2]	95	120	+26%
Estimated Groundwater Capture Zone (feet)[3]	70	80	+14%

Notes:
NA – Not Applicable
1. Average groundwater extraction rate was based on an 8-hour period of conventional pumping prior to application of vacuum to VER-01I and the initial 8-hour period after application of vacuum to VER-01I during the intermediate VER test.
2. Determined from groundwater flow model based on the distance from the pumping well where a drawdown of greater than 1 foot was observed.
3. Determined based on particle tracking using the groundwater flow model to simulate pumping for a period of 180 days.

5.2 DEEP VER TREATABILITY STUDY

Key findings of the deep VER treatability study include the following:

- The highest concentrations of perchlorate (6.4 mg/kg) and chlorate (11 mg/kg) in soil corresponding to the screened interval of VER-01D (90 to 110 feet bgs) were detected in samples collected from 90 feet bgs. Hexavalent chromium was only detected in one sample collected between 90 and 110 feet bgs at an estimated concentration of 0.31 mg/kg at 110 feet bgs.
- The highest concentrations of perchlorate (53 mg/L), chlorate (140 mg/L), and hexavalent chromium (0.040 mg/L) detected in baseline groundwater samples from the deep UMCf were detected in VER-01D. The concentrations detected in groundwater samples from VER-01D were less than concentrations detected in baseline groundwater samples from VER-01I, VMW-01I, and VMW-02I.
- Concentrations of perchlorate, chlorate, hexavalent chromium, and chloroform detected in samples from VER-01D exhibited a decreasing trend from baseline concentrations as the constant-rate test progressed (Phase B). Perchlorate concentrations decreased from 53 mg/L to 0.89 mg/L, chlorate concentrations decreased from 140 mg/L to 3.2 mg/L, hexavalent chromium concentrations decreased from 0.17 mg/L to 0.027 mg/L, and chloroform concentrations decreased from 0.029 mg/L to 0.00041 mg/L.
- Chlorite was not detected at a concentration above the laboratory reporting limit in any of the groundwater samples collected as part of the deep VER treatability study.

- The average groundwater extraction rate using conventional pumping during the first 12 hours of the deep VER test was 0.53 gpm. The average groundwater extraction rate using conventional pumping and applying a vacuum was 0.64 gpm, an approximate 21 percent increase in the groundwater extraction rate. However, the final determination of whether VER is a more cost-effective alternative to traditional groundwater extraction will be determined in the Feasibility Study.
- Based on pressure transducer data, drawdown greater than 10 feet was observed in performance monitoring wells located up to 55 feet from pumping well VER-01D during the VER test.
- Based on the GWETS metrics data provided by ETI, drawdown was not observed in the nearest IWF pumping wells (I-F, I-G, I-Q, and I-X) during the deep constant-rate or VER test. IWF pumping wells I-F, I-G, I-Q, and I-X are located approximately 30 feet, 130 feet, 50 feet, and 66 feet from VER-01D, respectively. As such, pumping of the deeper UMCf should not impact operation of the IWF.
- The VER technology slightly increased the simulated groundwater ROI from 125 feet for conventional pumping to 135 feet after applying vacuum at VER-01D, an 8 percent increase.
- Groundwater flow modeling indicated implementing VER technology at VER-01D resulted in an approximately 14 percent increase in the capture zone radius from of 22 to 25 feet.
- Vacuum influence was only observed at M-172, located 13 feet from VER-01D.
- During the deep VER test, perchlorate concentrations in the extracted groundwater from well VER-01D decreased from 2.0 to 0.57 mg/L, chlorate concentrations decreased from 4.4 to 1.7 mg/L, and hexavalent chromium concentrations remained relatively stable between 0.018 and 0.025 mg/L.
- Perchlorate concentrations in groundwater at VER-01D exhibited an overall decreasing trend with respect to baseline (pre-aquifer testing) concentrations prior to stabilizing during the VER test, decreasing from 5.3 mg/L (baseline) to 0.890 mg/L (end of constant rate test).
- The air flow rate for the VER system ranged from approximately 0.970 scfm to 10.4 scfm.

A comparison of performance metrics for conventional pumping to VER technology for VER-01D is summarized in ***Table 32***.

Table 32 Performance Metrics for Conventional and VER Extraction at VER-01D

Deep Well Screening Criteria	Conventional Extraction	Vacuum Enhanced Recovery Extraction	Percent Change
Average Groundwater Extraction Rate (gallons per minute)[1]	0.53	0.64	+21%
Estimated Groundwater Radius of Influence (feet)[2]	125	135	+8%
Estimated Groundwater Capture Zone (feet)[3]	22	25	+14%

Notes:
NA – Not Applicable
1. Average groundwater extraction rate was based on a 12-hour period of conventional pumping prior to application of vacuum to VER-01D and the initial 12-hour period after application of vacuum to VER-01D during the deep VER test.
2. Determined from groundwater flow model based on the distance from the pumping well where a drawdown of greater than 1 foot was simulated.
3. Determined based on particle tracking using the groundwater flow model to simulate pumping for a period of 180 days.

5.3 COST CONSIDERATIONS FOR IMPLEMENTATION

The VER treatability study provided information useful for developing preliminary indications of the costs of future implementation. These preliminary indications are presented in the following subsections, but are subject to significant revision during the Feasibility Study. During the Feasibility Study, NERT will evaluate the applicability of a variety of remedial technologies and assemble applicable technologies into potential remediation alternatives designed to achieve the Remedial Action Objectives established for the Site. If VER is selected as a component of an alternative evaluated in the FS as the Final Remedy, then a detailed cost estimate and analysis will be prepared to evaluate the costs for implementation under a larger full-scale scenario.

5.3.1 Treatability Study Cost Summary

Table 33 provides a high-level cost summary for implementation of this VER Treatability Study. It should be noted that costs for treatability studies can vary tremendously and are directly related to the type of study, extent of monitoring, and length of the study. Data obtained and costs incurred during the treatability study will be used to inform the development of alternative costs in the Feasibility Study; however, due to the nature of treatability studies, costs are inherently higher than likely larger scale operations, and cannot be easily extrapolated to represent larger-scale system design, installation, and operational costs. These costs for implementing the treatability study should not be used for developing full-scale implementation costs on a per-well basis. For example, treatment footprints, durations, and associated operational costs will vary significantly depending on the specific risk-based remedial action goals established during the FS and other alternative implementation and operational variables that have not yet been defined.

Table 33 VER Treatability Study Cost Summary

Task	Approximate Cost
Work Plan Preparation	$70,000
Permitting and Final Design	$70,000
Monitoring and Extraction Well Installation	$220,000
VER System Installation	$110,000
Intermediate VER Tests	$150,000
Deep VER Tests	$150,000
Groundwater Modelling and Reporting	$160,000
Well Abandonment	$70,000
Total	**$1,000,000**

5.3.2 Preliminary Indications of Costs for Full-Scale Implementation of VER

The preliminary indications of costs provided in this section represent estimates for the full-scale implementation of VER and conventional pumping, for comparison purposes, and are considered to have an accuracy range of approximately -50% / +100%, typical of conceptual-level estimates. Detailed costs will vary significantly depending on the details and variables of the final remedy which have not yet been defined. These include, but are not limited to, the following:

- Extent of the areas selected for groundwater extraction;
- Depths at which groundwater extraction will be applied;
- Distance of the groundwater extraction wells from the treatment system and existing utilities;
- Extent of VOC impacts, which may require vapor phase treatment; and,
- Monitoring and maintenance requirements.

The capital cost to implement VER over 1,600 linear feet of transect is estimated to be $750,000 to $3,000,000. The capital cost to implement conventional groundwater extraction over 1,600 linear feet of transect is estimated to be $775,000 to $3,100,000. The increased estimated capital cost of a conventional groundwater extraction system is associated with more extraction wells due to smaller capture radii versus VER. The expected operations and maintenance (O&M) cost for a conventional groundwater extraction system is estimated to be $400,000 to $800,000 per year. The additional O&M costs associated with applying vacuum as part of a VER system is approximately $10,000 to $30,000 per year. The increased O&M costs for VER are associated with increased electrical power, maintenance, repairs, and vapor sampling. All estimates are in 2018 dollars.

These estimates are based on the following design concepts and assumptions, which will need to be refined as part of any final remedial design:

- Installation of 10 extraction wells for VER and 12 extraction wells for conventional pumping. The depth of all extraction wells was assumed to be 75 feet bgs. The number of extraction wells required was estimated using two times the estimated groundwater capture zone of 70 feet for conventional pumping and 80 feet for VER as indicated in Table 31. This assumes the extraction wells would be installed perpendicular to the groundwater flow direction.
- Each extraction well would be constructed of 4-inch diameter Schedule 80 PVC with a stainless-steel well screen and an affixed wellhead consisting of appropriate valves, gauges and sample ports for connection to the treatment system.
- Submersible pumps would be installed in each extraction well. The extracted groundwater would be conveyed to the GWETS for treatment. The costs for groundwater conveyance and treatment are not included in these estimates.
- The VER system would consist of two liquid ring pumps, temporary holding tank, manifold piping, and controls. No vapor phase treatment was included because the vapor-phase mass removed is expected to be below the Clark County DAQ exempt stationary source threshold values of 2 tpy for a criteria pollutant or 5 tpy for a combination of criteria pollutants.
- Additional monitoring wells would be installed to a depth of approximately 75 feet bgs. The monitoring wells would be constructed of 2-inch diameter Schedule 80 PVC and screened at the same interval as the VER extraction wells.

The O&M costs include estimates for daily system monitoring and inspections, routine maintenance, monthly performance groundwater monitoring events, extracted groundwater conveyance, and monthly reporting.

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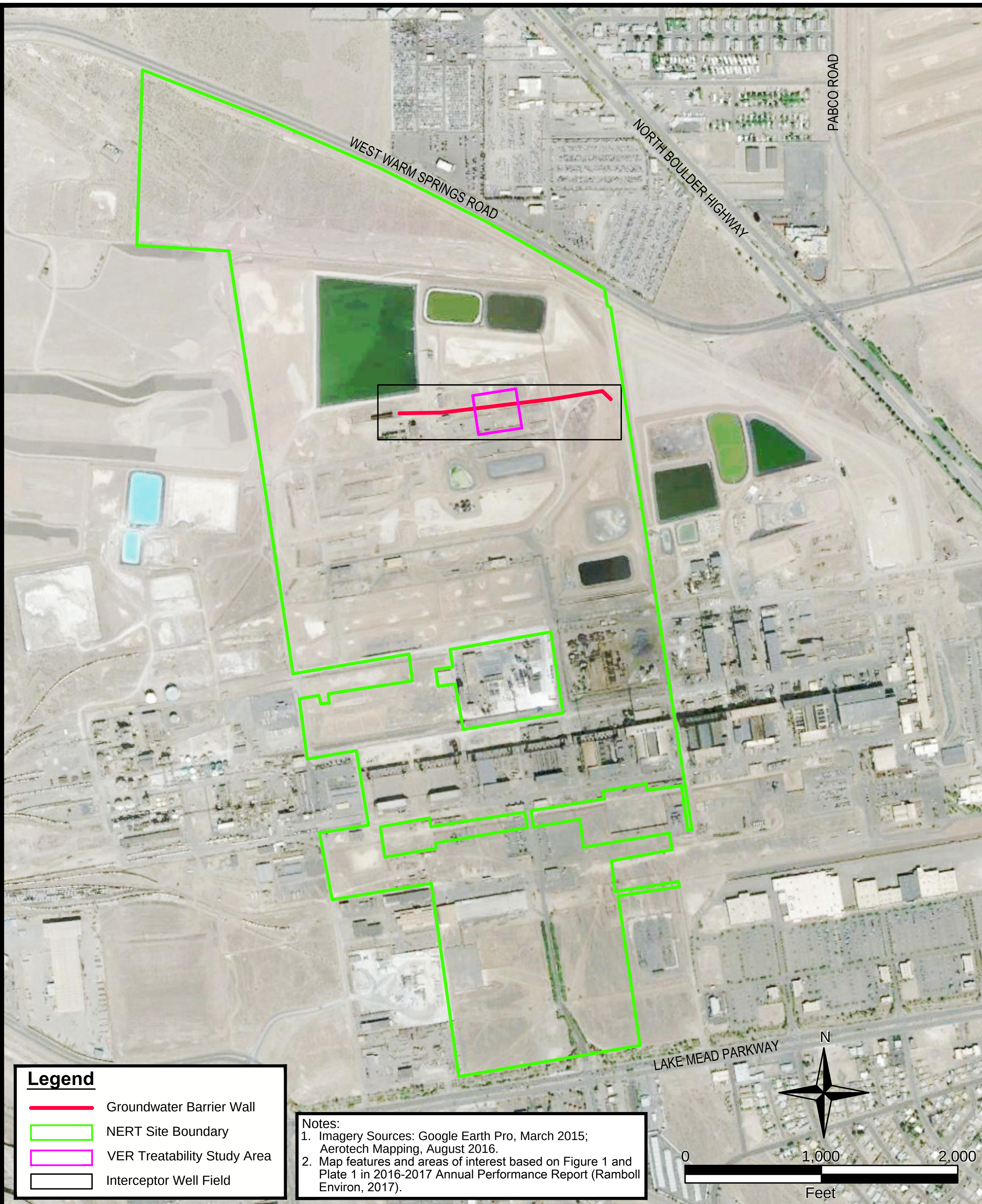
Figures



Notes:
1. Imagery Sources: Google Earth Pro, March 2015; Aerotech Mapping, August 2016.
2. Map features and areas of interest based on Figure 1 and Plate 1 in 2016-2017 Annual Performance Report (Ramboll Environ, 2017).

\\tts318fs1\tt.local\ces\ 87600015-NERT\ Figure 1 - Site Location Map 87600M16-18.dwg

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

VACUUM ENHANCED RECOVERY TREATABILTY STUDY RESULTS REPORT
HENDERSON, NEVADA

SITE LOCATION MAP

Project No:	117-7502018
Date:	MAY 9, 2018
Designed By:	DVK
Figure No.	1

Legend

M-55	Monitoring Well
I-M	Extraction Well
(magenta box)	VER Treatability Study Area
VER-01I	Intermediate VER Well Location
VER-01D	Deep VER Well Location
VMW-01I	Intermediate VER Monitoring Well
VMW-01D	Deep VER Monitoring Well

Notes:
1. Imagery Source: Aerotech Mapping, August 2016.
2. Monitoring well, extraction well, and groundwater barrier wall locations based on Figure 1 and Plate 1 in 2016-2017 Annual Performance Report (Ramboll Environ, 2017), Figure 7-1b in RI Data Evaluation Tech Memo (Ramboll Environ, 2016), and field observations.

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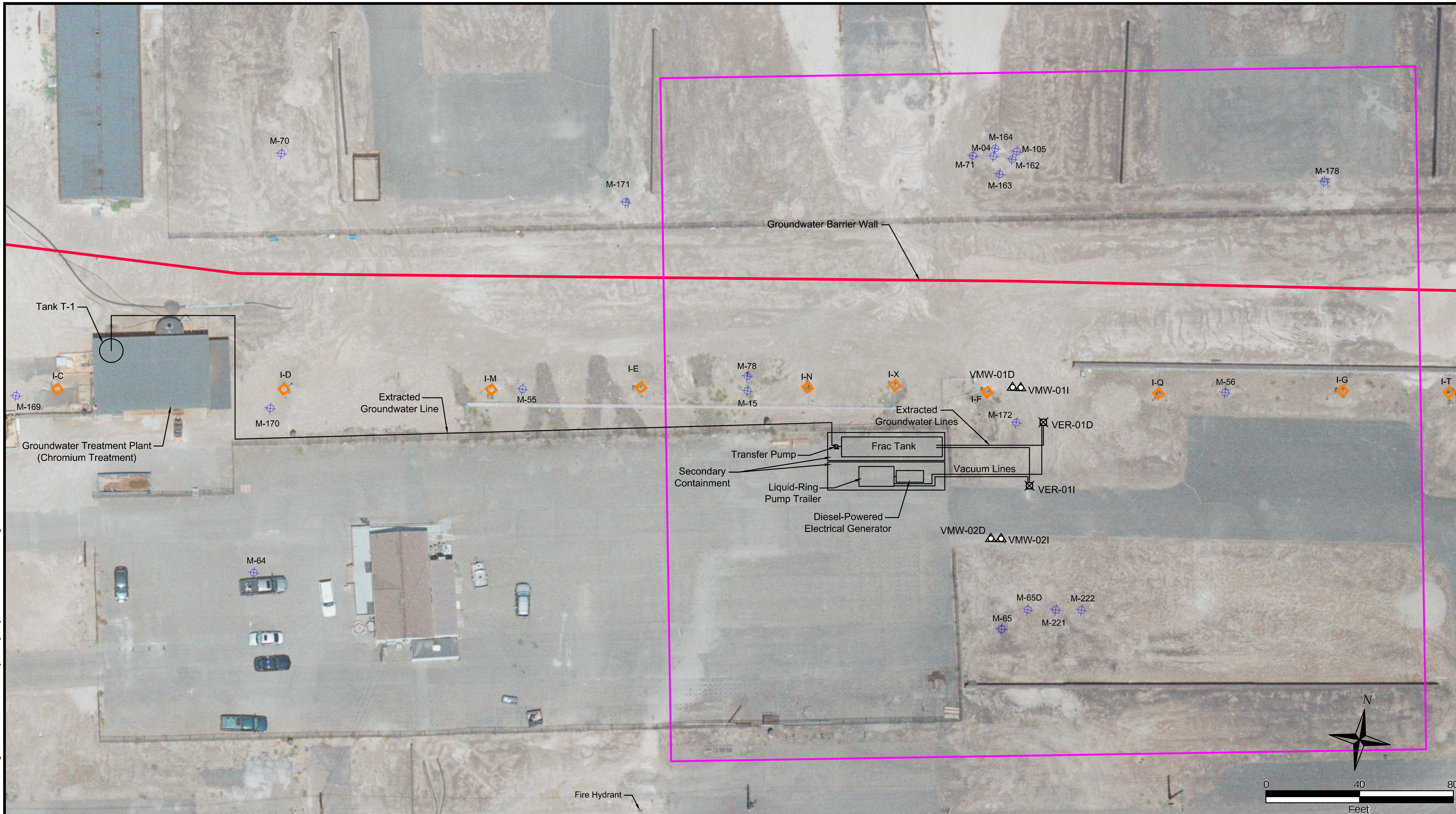
VER TREATABILITY STUDY LOCATION

Project No:	117-7502018
Date:	MAY 9, 2018
Designed By:	DVK
Figure No.	2

\\tts318fs1\tt.local\ces\ 87600015-NERT\ Figure 2 - VER Treatability Study Location 87600M16-18.dwg



\\tts318fs1\.tt.local\ces\ 87600015-NERT\ Figure 3 - VER Treatability Study Layout 87600M16-18.dwg

Legend

M-65	Monitoring Well	VER-01I	Intermediate VER Well Location
I-F	Extraction Well	VER-01D	Deep VER Well Location
	VER Treatability Study Area	VMW-01I	Intermediate VER Monitoring Well
		VMW-01D	Deep VER Monitoring Well

Notes:

1. Imagery Source: Aerotech Mapping, August 2016.
2. Monitoring well, extraction well, and groundwater barrier wall locations based on Figure 1 and Plate 1 in 2016-2017 Annual Performance Report (Ramboll Environ, 2017), Figure 7-1b in RI Data Evaluation Tech Memo (Ramboll Environ, 2016), and field observations.

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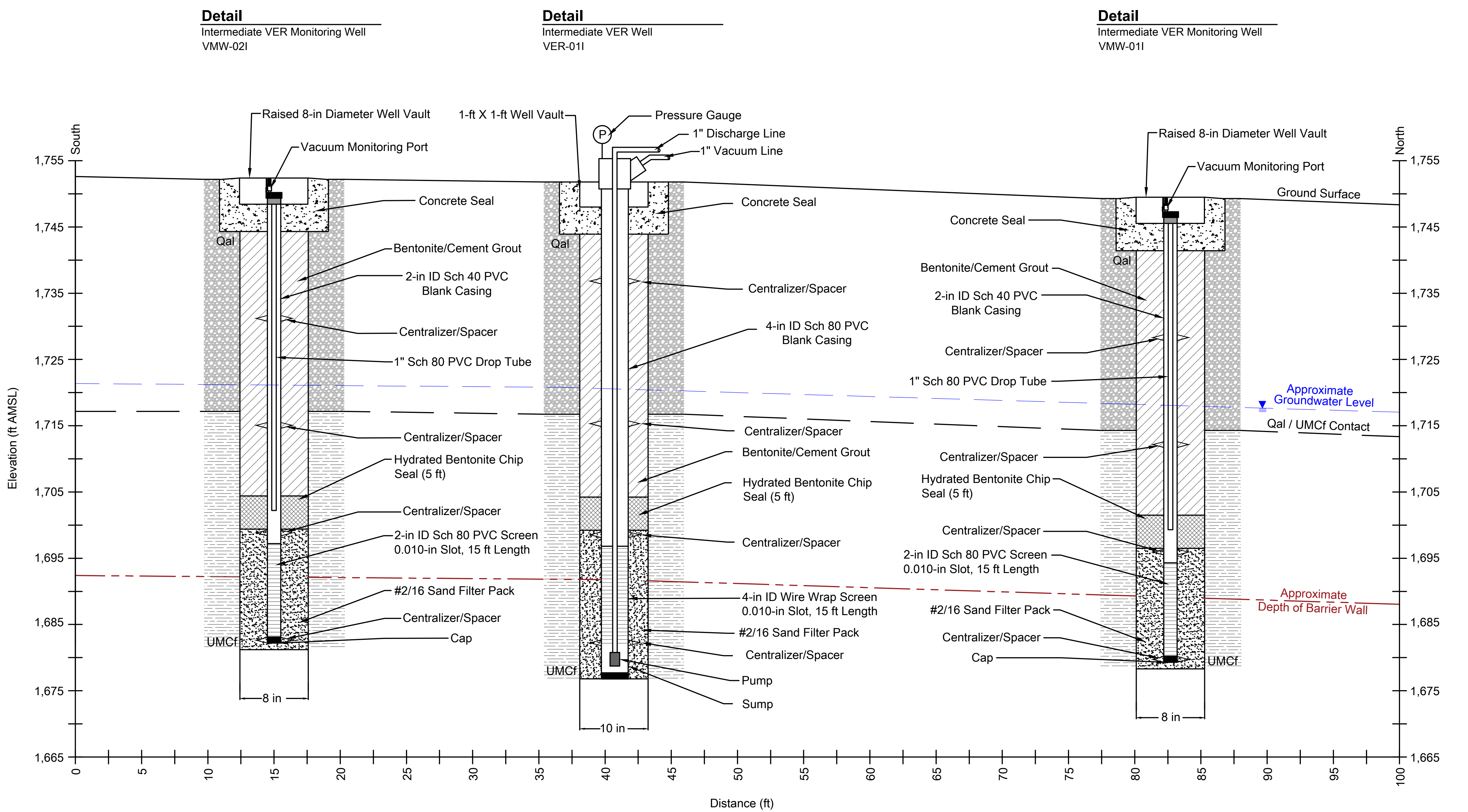
VER TREATABILITY STUDY LAYOUT

Project No:	117-7502018
Date:	MAY 9, 2018
Designed By:	DVK
Figure No.	3



Legend

▼	Groundwater Level	in = inch
Qal	Quaternary Alluvium	
UMCf	Upper Muddy Creek Formation	
ft	feet	
AMSL	Above Mean Sea Level	
Ⓟ	Pressure Gauge	

Note:
1. Scaled to approximate depth and relative horizontal distance.

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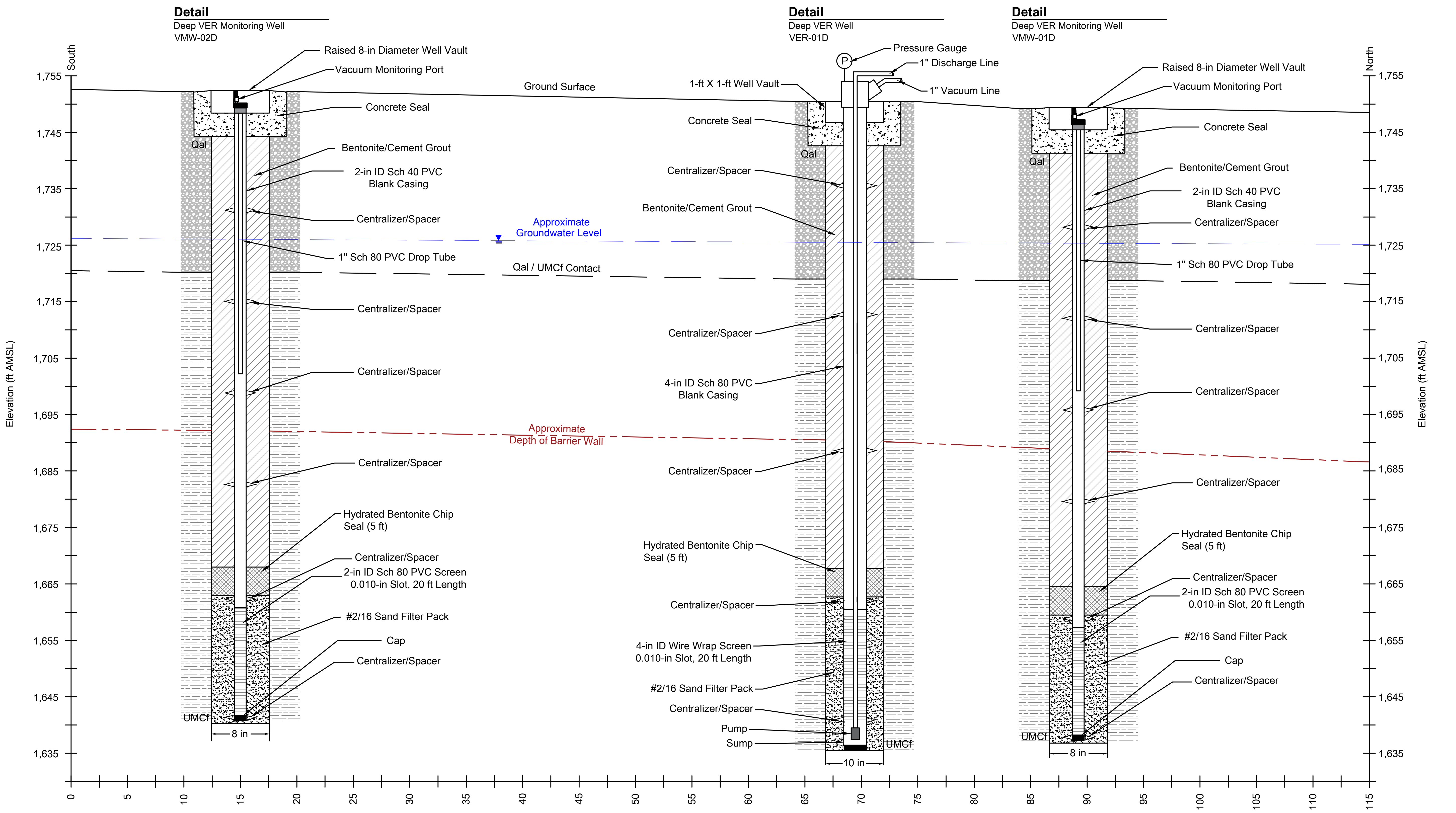
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

VACUUM ENHANCED RECOVERY TREATABILTY STUDY RESULTS REPORT
HENDERSON, NEVADA

WELL CONSTRUCTION DIAGRAMS - INTERMEDIATE

Project No:	117-7502018
Date:	MAY 9, 2018
Designed By:	DVK
Figure No.	**4a**

\\tts318fs1\tt.local\ces\ 87600015-NERT\ Figure 4a - Well Construction Diagrams - Intermediate 87600M16-18 r1.dwg



\\tts318fs1.tt.local\ces\ 87600015-NERT\ Figure 4b - Well Construction Diagrams - Deep 87600M16-18 r1.dwg

Legend

▼	Groundwater Level	in = inch
Qal	Quaternary Alluvium	
UMCf	Upper Muddy Creek Formation	
ft	feet	
AMSL	Above Mean Sea Level	
(P)	Pressure Gauge	

Note:
1. Scaled to approximate depth and relative horizontal distance.

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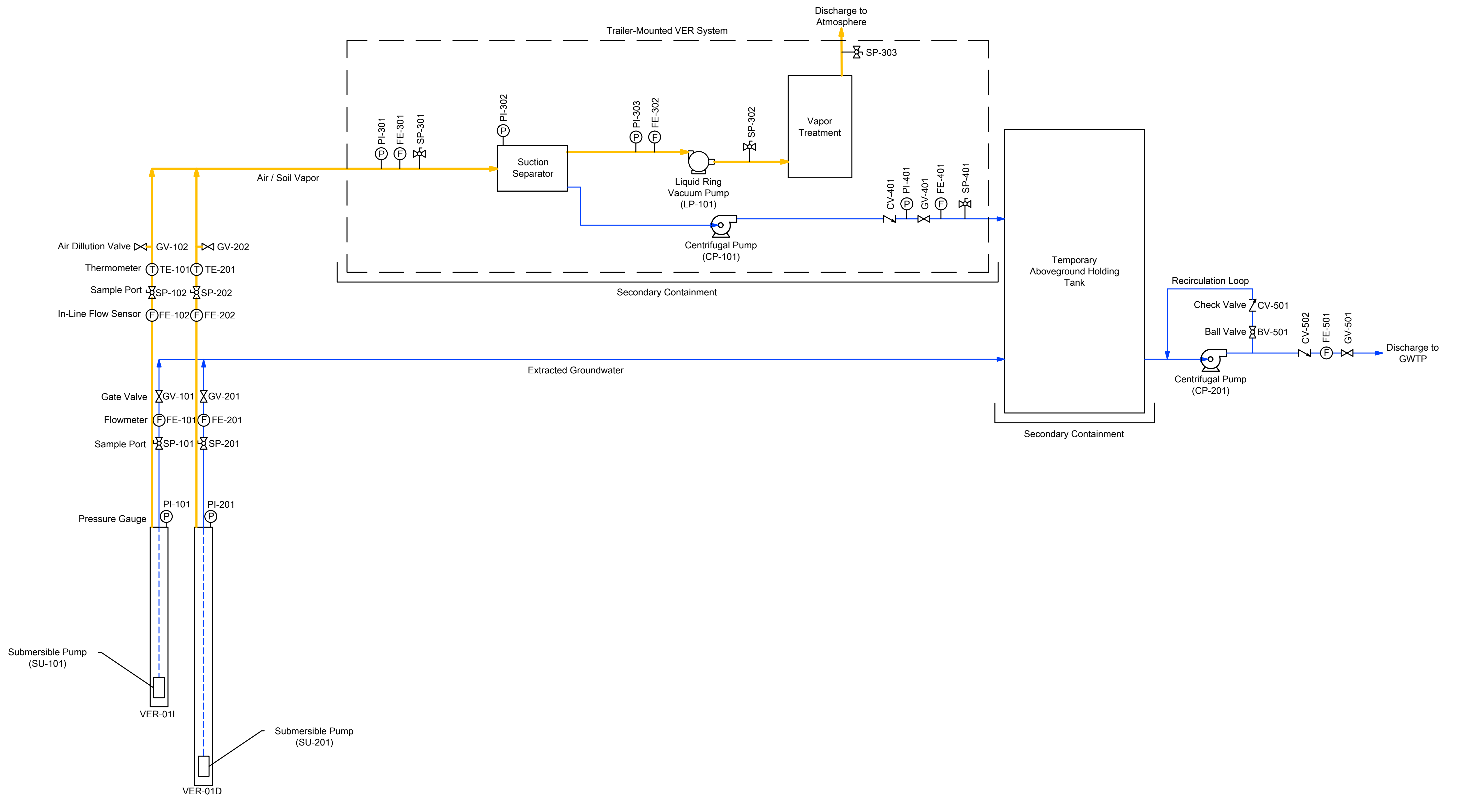
WELL CONSTRUCTION DIAGRAMS - DEEP

Project No: 117-7502018
Date: May 9, 2018
Designed By: DVK

Figure No.
4b



\\tts318fs1\tt.local\ces\ 87600015-NERT\ Figure 5 - Process Flow Diagram 87600M16-18.dwg

Legend

- Check Valve
- Pressure Gauge
- Gate Valve
- Flowmeter / Flow Sensor
- Sample Port
- Thermometer
- Ball Valve
- Extracted Groundwater Conveyance
- Air / Soil Vapor Conveyance

Notes:
1. Downhole pump extraction VER schematic depicted.
2. System controls not shown.
3. VER-01I and VER-01D were connected individually for testing.

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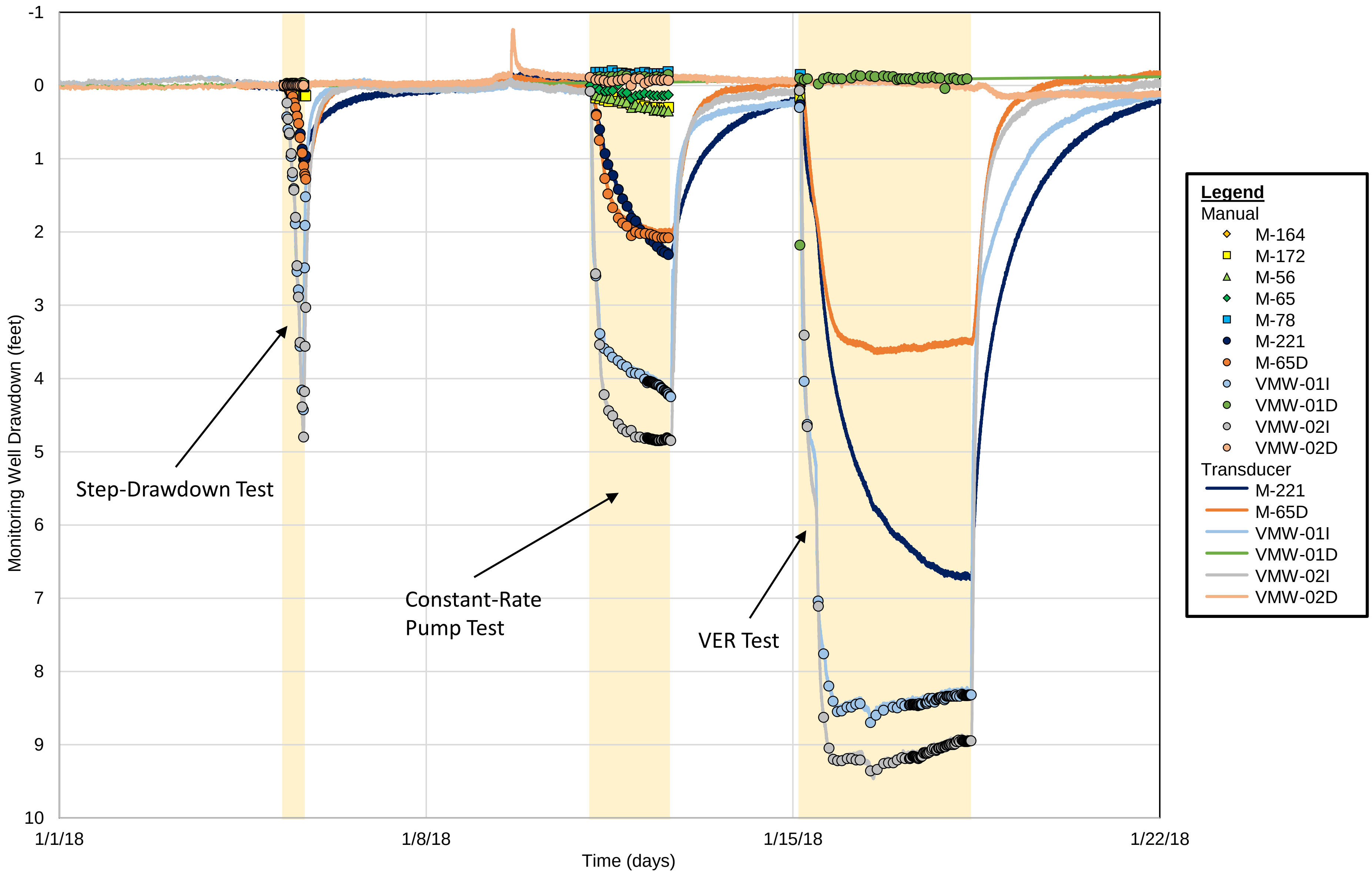
HENDERSON, NEVADA

PROCESS FLOW DIAGRAM

Project No:	117-7502018
Date:	MAY 9, 2018
Designed By:	DVK

Figure No.

5



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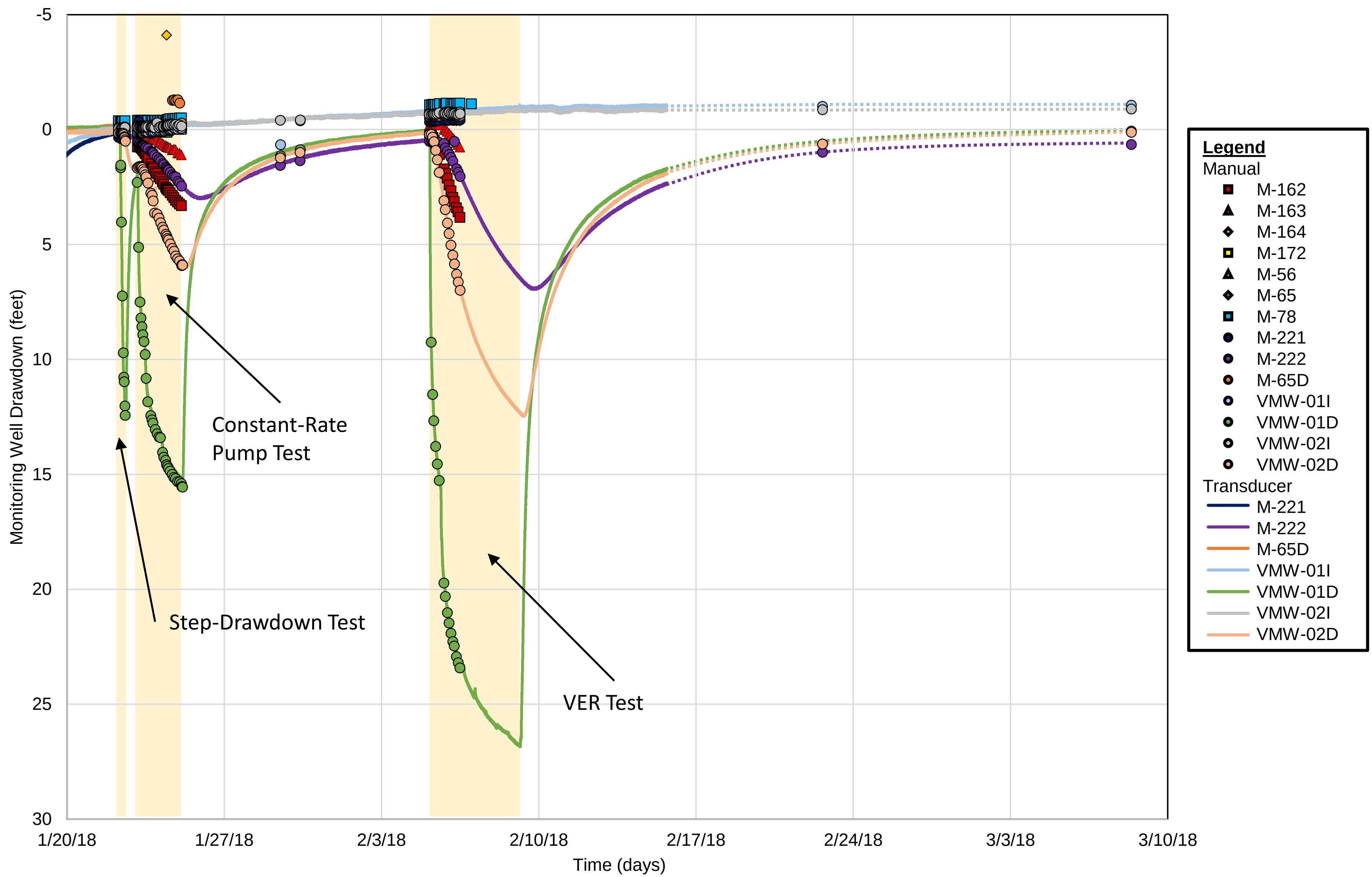
VACUUM ENHANCED RECOVERY TREATABILITY STUDY REPORT
HENDERSON, NEVADA

HYDROGRAPH FOR MONITORING WELLS DURING INTERMEDIATE VER TREATABILITY STUDY PUMPING TESTS

Project No.:	117-7502018
Date:	MAY 10, 2018
Designed By:	ACC

Figure No.
6



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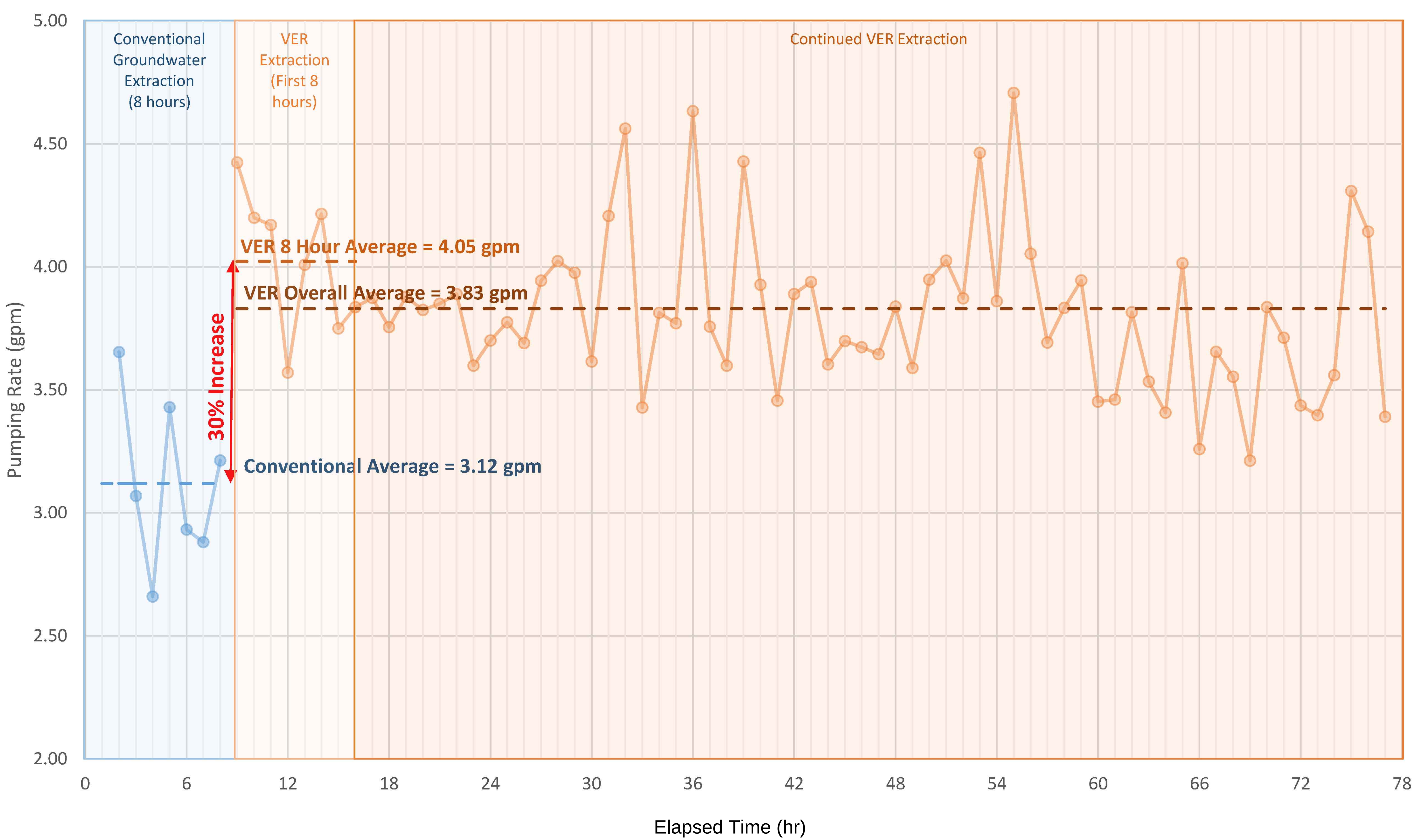
NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

VACUUM ENHANCED RECOVERY TREATABILITY STUDY REPORT
HENDERSON, NEVADA

HYDROGRAPH FOR MONITORING WELLS DURING DEEP VER TREATABILITY STUDY PUMPING TESTS

Project No.:	117-7502018
Date:	MAY 10, 2018
Designed By:	ACC
Figure No.	7

\\tts134fs1\GEOSUP\VOL1\PROJECTS\NERT\M16\TS Report\VER_Hydrographs.pptx



Legend

- Average Hourly Conventional Pumping Rate
- Overall Average Conventional Pumping Rate
- VER 8 Hour Average Pumping Rate
- Average Hourly VER Pumping Rate
- Overall Average VER Pumping Rate

gpm gallons per minute
hr hour

Note:
1. Pumping rate from first hour of test excluded from calculation as initial well volume was being pumped.

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HENDERSON, NEVADA

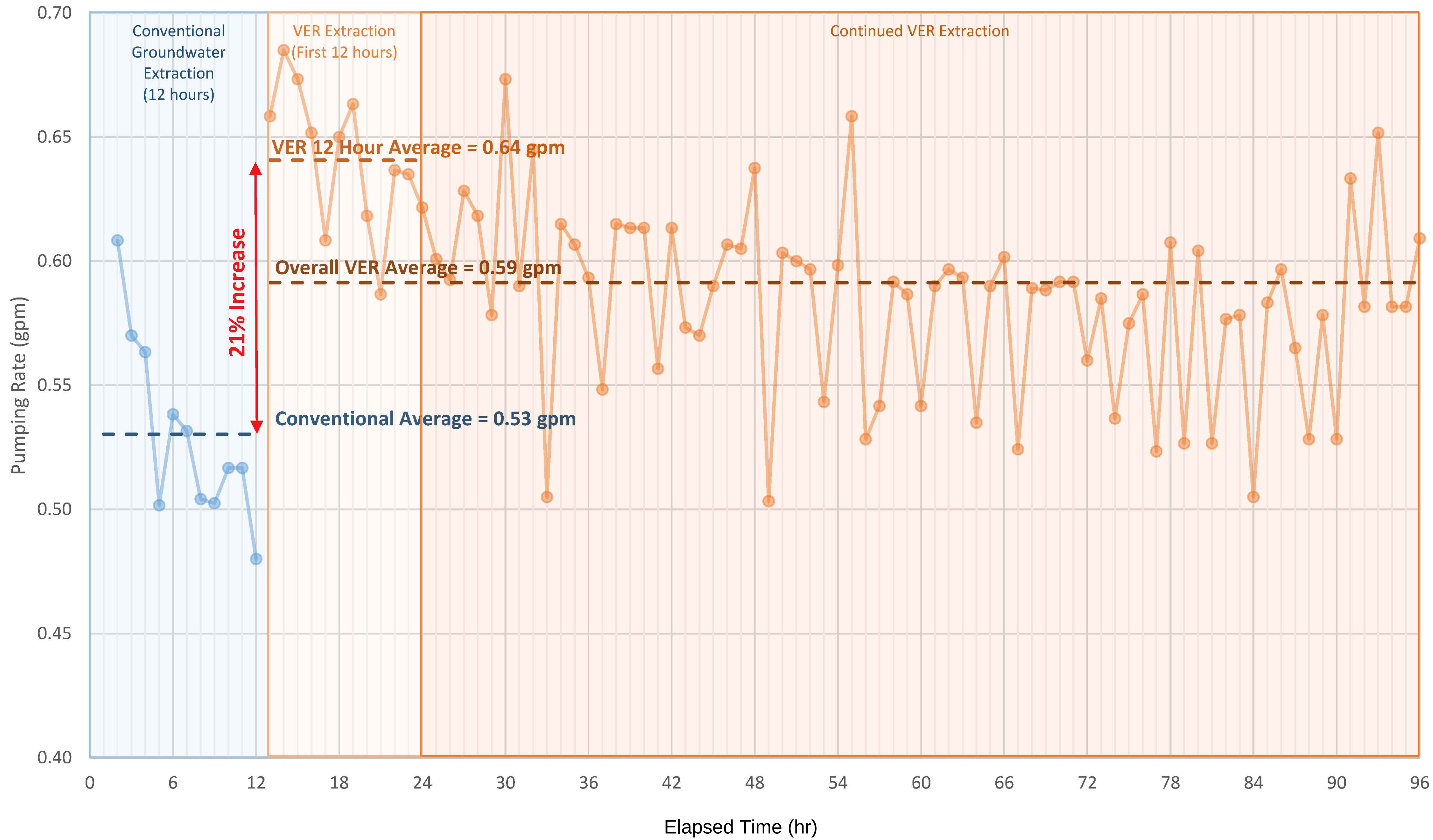
VER TEST GROUNDWATER EXTRACTION RATE GRAPH FOR VER-01I

Project No:	117-7502018
Date:	MAY 9, 2018
Designed By:	DVK

Figure No.

8

\\tts318fs1\t.tt\local\ces\ 87600015-NERT\ Figure 8 - VER Test Groundwater Extraction Rate Graph for VER-01I.dwg



\\tts318fs1\tt.local\ces\ 87600015-NERT\ Figure 9 - VER Test Groundwater Extraction Rate Graph for VER-01D.dwg

Legend

- Average Hourly Conventional Pumping Rate
- Overall Average Conventional Pumping Rate
- VER 12 Hour Average Pumping Rate
- Average Hourly VER Pumping Rate
- Overall Average VER Pumping Rate

gpm gallons per minute
hr hour

Note:
1. Pumping rate from first hour of test excluded from calculation as initial well volume was being pumped.

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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

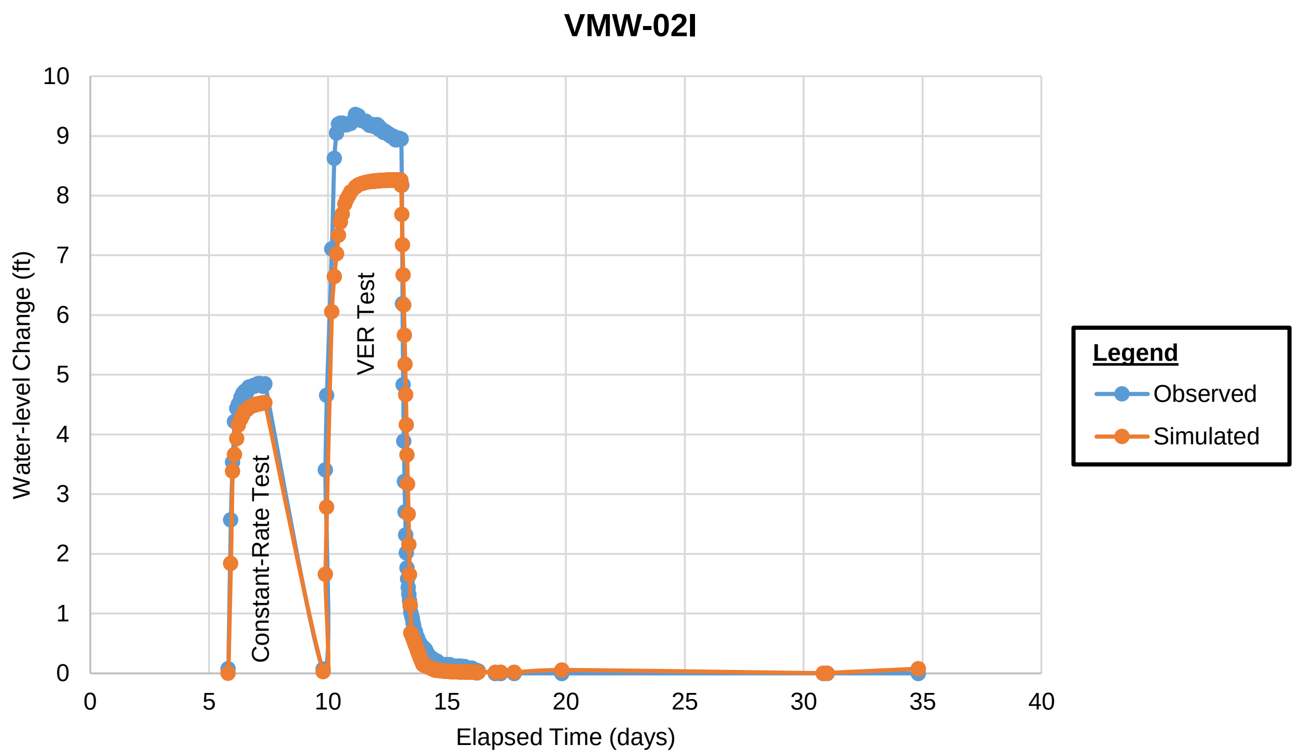
VACUUM ENHANCED RECOVERY TREATABILTY STUDY RESULTS REPORT
HENDERSON, NEVADA

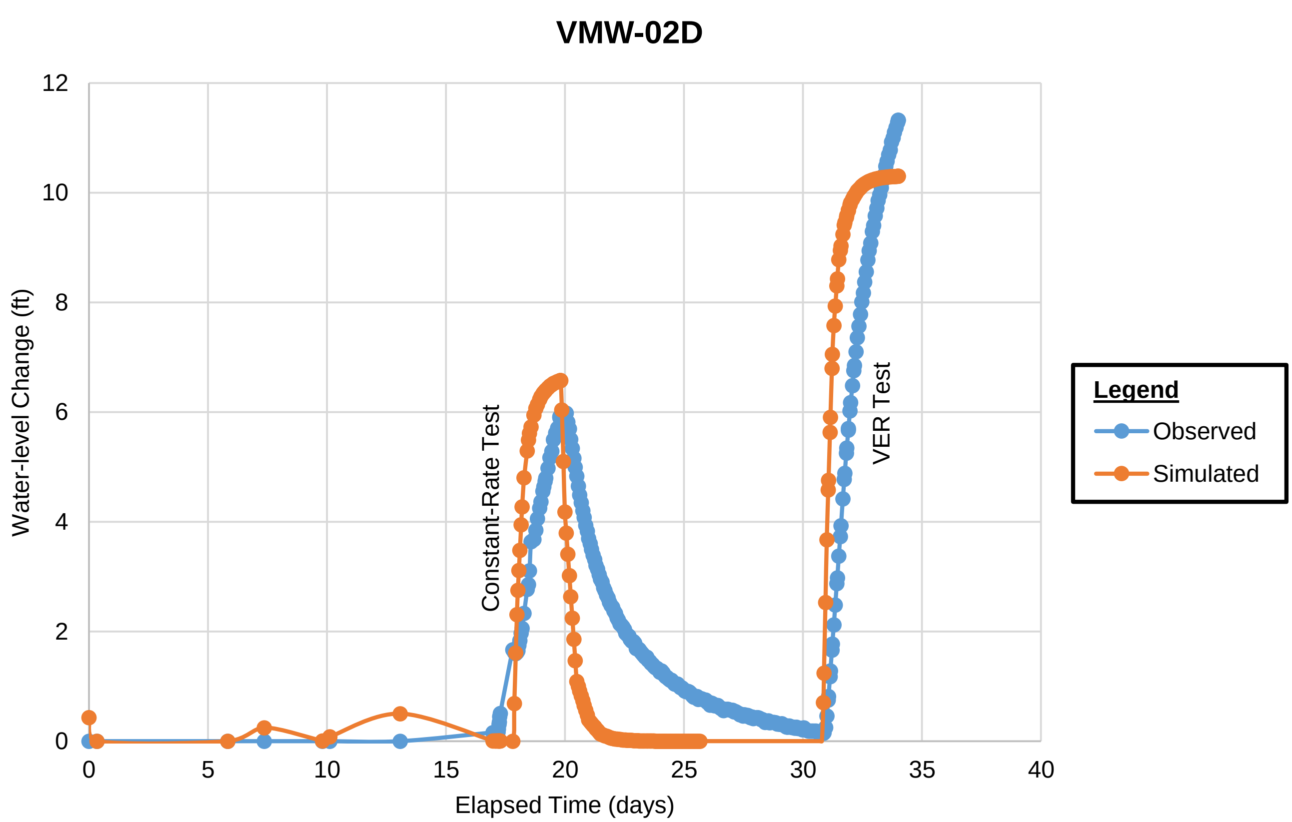
VER TEST GROUNDWATER EXTRACTION RATE GRAPH FOR VER-01D

Project No:	117-7502018
Date:	APRIL 19, 2018
Designed By:	DVK

Figure No.

9





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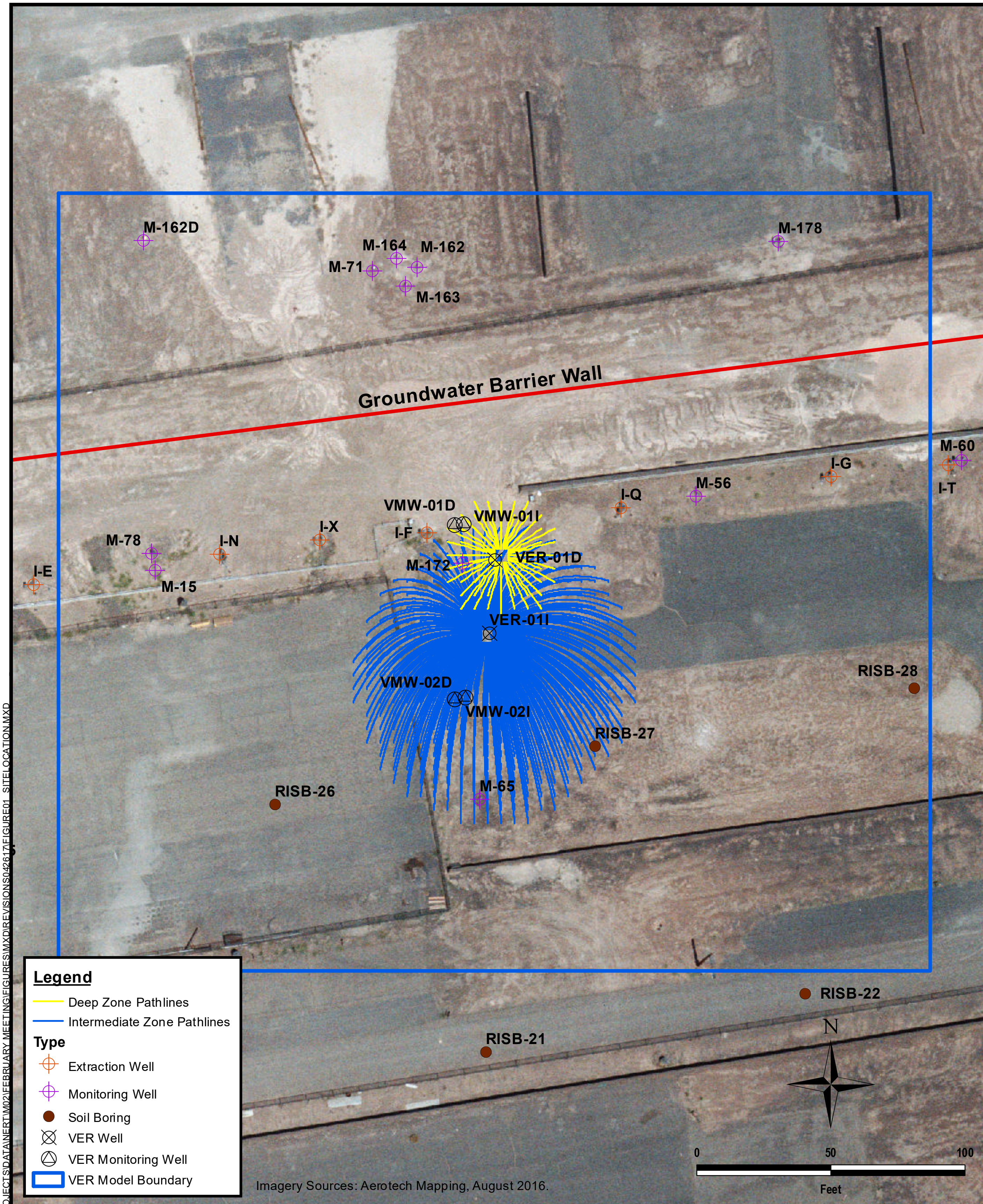
VACUUM ENHANCED RECOVERY TREATABILITY STUDY REPORT
HENDERSON, NEVADA

SIMULATED VERSUS OBSERVED WATER-LEVEL CHANGES DURING VER TESTING

Project No.:	117-7502018
Date:	MAY 10, 2018
Designed By:	GR

Figure No.
10



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NEVADA ENVIRONMENTAL RESPONSE TRUST SITE

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HENDERSON, NEVADA

180-DAY CAPTURE ZONES FROM INTERMEDIATE AND DEEP ZONES

Project No.:	117-7502018
Date:	MAY 10, 2018
Designed By:	GR

Figure No.

11

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