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April 26, 2021

Mr. Adolph Everett, Chief
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US Environmental Protection Agency, Region 2
290 Broadway
New York, New York 10007-1866
Via: Electronic Copy

Re: St. Croix Alumina Site Administrative Order Docket No. RCRA-0202001-7301
Revised LNAPL CSM and Remedial Action Work Plan
EPA Facility ID No. VID090302084

Dear Mr. Everett:

The St. Croix Alumina (SCA) Project Operating Committee (POC) submitted a Light Non-aqueous Phase Liquid (LNAPL) Conceptual Site Model (CSM) and Remedial Action Work Plan on July 8, 2020. After receiving a series of comments and questions from EPA, the POC is submitting this Revised LNAPL CSM and Remedial Action Work Plan. This revised document addresses EPA's comments and questions. Please feel free to contact me if you have any questions or comments.

Sincerely,

Brian Epperson
Remediation Manager

Cc: Carol Stein (Electronic Copy)
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POC (Electronic Copy)

LNAPL CSM and Remedial Action Work Plan

St. Croix, U.S. Virgin Islands

Prepared for:

St. Croix Alumina Site

Prepared by:

EHS Support

April 2021

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Acronyms

µg/L	micrograms per liter
Al_2O_3	alumina
AOC	Administrative Order On Consent
API	American Petroleum Institute
B&R	Bouwer and Rice
BTEX	Benzene, Toluene, Ethylbenzene, Total Xylenes
CEM	Conceptual Exposure Model
CGM	Concentration Gradient Method
CSM	Conceptual Site Model
cSt	centistokes
DCC	Dynamic Closed Chamber
DO	dissolved oxygen
DPPHC	Dissolved Phase Petroleum Hydrocarbon Constituents
EC	electrical conductivity
Fe(III)	ferric iron
ft msl	feet above mean sea level
ft_2/day	square feet per day
gpd	gallon per day
LNAPL	light non-aqueous phase liquid
mg/L	milligrams per Liter
Mn(IV)	manganese
MNA	monitored natural attenuation
NAPL	non-aqueous phase liquid
NSZD	Natural Source Zone Depletion
ORP	oxidation reduction conductivity
PAH	Polycyclic aromatic hydrocarbons
PLM	Practical Limits of Mobility
POC	Project Operating Committee
PSH	phase separated hydrocarbon
PSPH	Phase Separated Petroleum Hydrocarbon
SGP	soil gas probe
SZNA	source zone natural attenuation
Tn	transmissivity
TPH-DRO	Total Petroleum Hydrocarbons Diesel Range Organics
USEPA	United States Environmental Protection Agency

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1 Introduction

St. Croix Alumina, L.L.C. ("SCA"), ALCOA World Alumina, L.L.C. (formerly known as ALCOA Alumina and Chemical, L.L.C.) ("ALCOA"), Virgin Islands Alumina Company ("VIALCO"), Century Aluminum Company, Inc., Lockheed Martin Corporation (Lockheed Martin), Hess Oil Virgin Islands Corp. ("HOVIC"), and HOVENSA L.L.C. ("HOVENSA") entered into an Administrative Order On Consent (AOC), with the United States Environmental Protection Agency, Region II, (USEPA), on May 14, 2001 with an effective date of May 24, 2001. Pursuant to the AOC, these companies have agreed to work together to address Phase Separated Petroleum Hydrocarbon (PSPH) and Dissolved Phase Petroleum Hydrocarbon Constituents (DPPHC) located beneath the St. Croix Alumina facility in St. Croix, U.S. Virgin Islands. As per the AOC, a Project Operating Committee (POC) was formed to design, install, and operate a monitoring and remediation system for the Site.

A final Draft PSPH Work Plan was submitted to the USEPA on July 23, 2001. USEPA approved the PSPH Work Plan on August 8, 2001. Implementation of the PSPH Work Plan has been initiated and both PSPH and DPPHC recovery is underway. The initial DPPHC Work Plan was submitted to the USEPA on September 21, 2001. The USEPA requested seven items to be incorporated into a revised draft. This revised Draft DPPHC Work Plan was submitted to the USEPA on December 21, 2001. In a January 15, 2002 letter, the USEPA conditionally approved the work plan with proposed changes to timeline items. An amended Draft was submitted to the USEPA on February 22, 2002 incorporating the requested USEPA timeline changes. The POC recommended that the quarterly status reports and the semiannual report be consolidated into one report submitted semiannually. The USEPA approved this recommendation in their March 3, 2005 letter.

The POC submitted a PSPH Pilot Study and DPPHC Sampling Plan Modification to USEPA on May 21, 2018. USEPA provided comments to the proposed plan, which were implemented by the POC, and a final PSPH Pilot Study and DPPHC Sampling Plan Modification was submitted on June 11, 2018. In the approved plan, the POC committed to expanding the remediation system by installing seven additional solar sippers and reinstalling one total fluid submersible pump in monitoring well VW13B. The original program included a one-year pilot study to assess the effectiveness of focused PSPH recovery in lieu of total fluids recovery was completed in August 2019. The light non-aqueous phase liquid (LNAPL) recovery operations as part of this program are currently ongoing.

This document provides an in-depth evaluation of historic data and assessment of the data collected from the PSPH Pilot Study and DPPHC Sampling Plan in order to develop an LNAPL Conceptual Site Model (CSM) and Remedial Action Work Plan. As part of this process the fundamentals of LNAPL mobility and recoverability (in both sedimentary rock and unconsolidated fine grained soils), summaries of relevant site geological and hydrogeological data, assessment of LNAPL chemistry, baildown tests and LNAPL recovery data has been completed to assess the recoverability of LNAPL and the benefits and practicability of further remediation of LNAPL.

Through the process of evaluation of data, uncertainties and data gaps are identified and supplemental programs of work have been proposed with the goal of developing an effective approach for LNAPL management and groundwater restoration with the goal of project completion.

1.1 Goals and Objectives

The specific objective of this Report is to develop an LNAPL CSM and to evaluate where and what active remediation of LNAPL is required before LNAPL has been recovered to the "extent practicable" at this site. This report leverages past assessments to develop an LNAPL CSM to evaluate the performance of past LNAPL recovery activities and define ongoing LNAPL recovery requirements by:

- Evaluating the potential hazards and risks posed by residual LNAPL impacts at the Site.
- Determining practical limits associated with remediation in the limestone materials that dominate the LNAPL impacted area at the Site.
- Assessing the past performance of LNAPL recovery wells and evaluating likely further performance.
- Assessing whether remedial actions and associated costs are proportionate to the benefits achieved in terms of LNAPL recovered, destroyed, or removed given the site constraints.

1.2 Scope of Work

Based on the objectives stated in **Section 1.1**, the scope of work for this LNAPL CSM and LNAPL Remedial Action Work Plan is as follows:

- Evaluate the fundamentals of LNAPL mobility in sedimentary rock and fine-grained unconsolidated deposits.
- Summarize the findings of relevant historical investigations and LNAPL recovery attempts undertaken at the Site.
- Provide a detailed assessment of the baildown testing and the LNAPL recovery performance at the Site.
- Based on LNAPL fundamentals provide a brief characterization of the site geological and hydrogeological controls on LNAPL mobility and recoverability.
- Using the LNAPL physical properties, baildown test and recovery data and LNAPL gauging data assess the stability and inherent immobility of LNAPL at the Site.
- Provide recommendations which can be incorporated into a modified program of assessments and LNAPL recovery efforts at the Site.
- Document the proposed future remedial actions for the Site and outline LNAPL shutdown criteria for the Site to support transition to NSZD and MNA.

1.3 Site Setting and Location

The St. Croix Alumina facility, currently owned by St. Croix Renaissance Group, LLLC (SCRG) is located along the coast in the south-central portion of St. Croix (**Figure 1-1**).

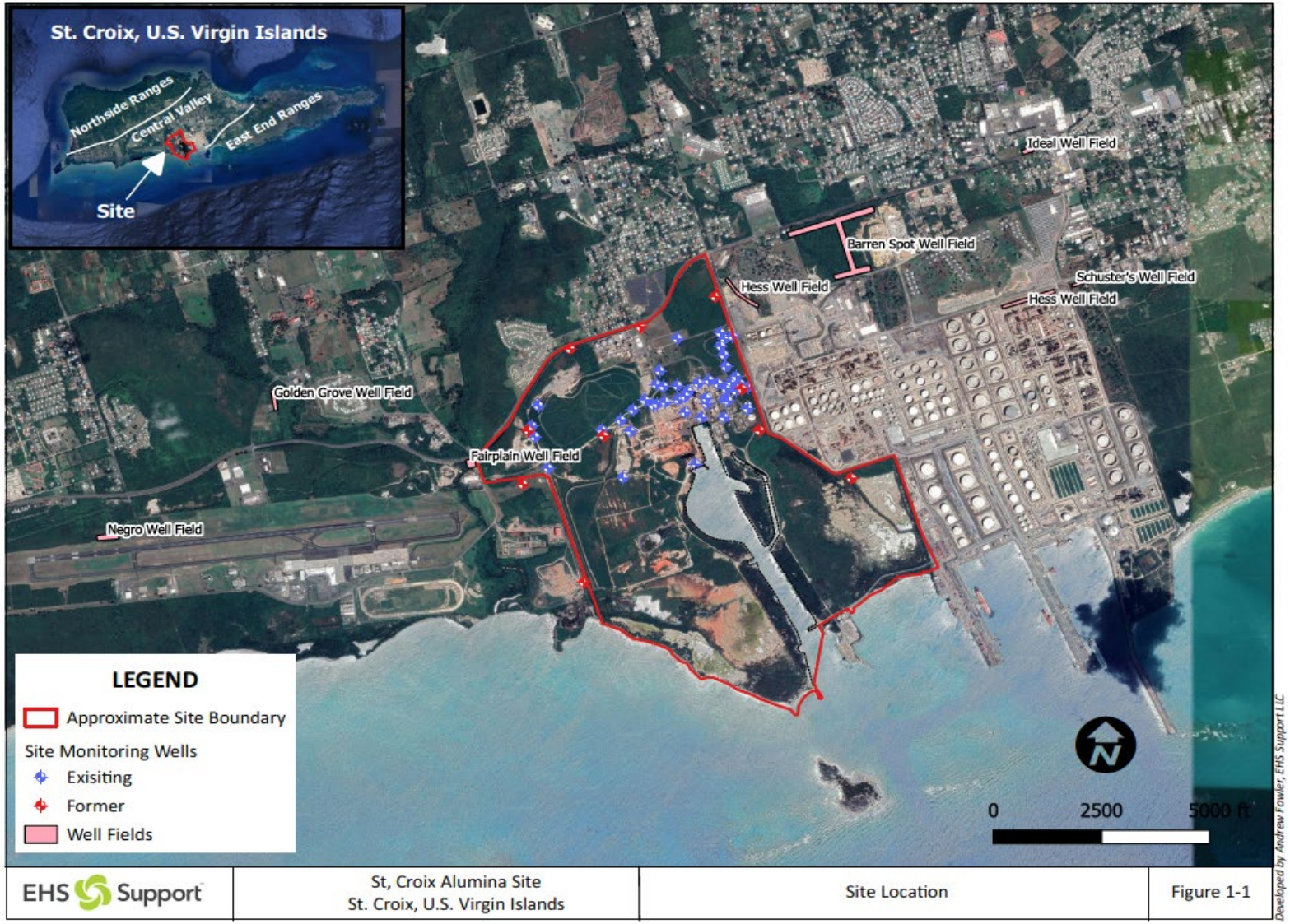


Figure 1-1 Site Location

Topographically, the facility is situated on a gently sloping alluvial plain with a mountain range located to the north. The elevation of the facility ranges from near sea level along the shoreline to 100 feet above mean sea level (ft MSL) in the northern portion of the site.

Historically, filling activities and dredging was conducted to support the development of the site and facilitate ship loading and unloading activities. This included development of a shipping channel, which extends south to north through the Site. A terminal and petroleum refinery are located immediately east of the site.

St. Croix has a semi-arid tropical climate typical of Caribbean islands. This means monthly temperature ranges from 76 to 82 degrees Fahrenheit. Annual rainfall averages 39 inches per year with a standard deviation of 13.5 inches per year. Most of the precipitation occurs during two seasonal periods, in May and June, and September through November.

1.4 Historical Site Operations

No active operations currently occur at the facility with bauxite processing terminating in 2000. The Site is a former refinery where bauxite ore was processed for alumina extraction and residues from the process were deposited on site. Alumina refining operations began in 1968. The former refinery consisted of administrative offices and other buildings (many of which have been decommissioned/demolished): material storage structures (silos, tanks, and shed); grinding operations; digestion, thickening, filtration, precipitation, and calcination operations; coal- and oil-fired boilers; water desalination units; warehouses; laboratories; maintenance facilities; storm water collection and cooling ponds; bauxite residue (i.e., red mud) disposal areas; recreational areas; and a dock that provides access to the ship channel. In addition, the Diageo rum distillery in the northern portion of the property was constructed in 2009-2010 and began operating in November 2010. Molasses tanks for the distillery are installed in the former location of refinery tanks.

The former refinery at the Site extracted alumina (Al_2O_3) from bauxite via the Bayer process, which involved crushing and grinding of the ore; dissolution of alumina with caustic soda at high temperatures and pressures; separation and on-site disposal of undigested solid residues (i.e., red mud) from the supernatant; precipitation as alumina hydrate; and washing and calcination of the hydrate to form crystalline alumina. The principal waste generated from the process was red mud which was neutralized and conveyed to two separate disposal areas.

LNAPL impacts occurred during facility operations as result of diesel fuel releases over time including potential LNAPL migration from the adjacent refinery site.

2 LNAPL Recovery and Groundwater Monitoring Activities

As described above, PSPH and DPPHC Plans were developed for the Site and implemented in 2002. These Plans have been implemented with changes made over time in terms of the recovery wells and technologies applied. Groundwater monitoring frequency, well locations and analytes have also varied since 2002.

A historical chronology of historical LNAPL recovery and monitoring is provided in **Table 2-1** below, with LNAPL recovery wells highlighted in red. This chronology has been developed based on review of all of the status reports developed for the site and other documentation. Further discussion of the key components of the program are described in the sections below.

Table 2-1 Historical Chronology of LNAPL Recovery and Monitoring Activities

Well Name	Description of Historical and Current Operational Status
VW1	Historically monitored and gauged. Proposed addition to the sampling program in 2nd Semi-annual 2017 Status report
VW2	Historically monitored and gauged. Proposed addition to the solar sipper program in 2nd Semi-annual 2017 Status Report. Operation as solar sipper since 2nd Half 2018 and as part of trial. Vacuum event conducted on well.
VW3	Monitoring - Gauging only
VW4	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018. Not part of solar sipper trial.
VW5	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 and as part of trial. Vacuum event conducted on well.
VW6	Solar Sipper installed August 2, 2012 and included as part of trial. Was historically a pneumatic total fluids recovery pump. Noted as recovery well on maps as early as 2002. Described as pneumatic as early as 2006 semi-annual report. Vacuum event conducted on well.
VW7	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018. Vacuum event conducted on well.
VW8	Monitoring - Gauging Only
VW9R	Monitoring - Gauging Only
VW10	Monitoring - Gauging Only
VW11	Monitoring - Gauging Only
VW12	Monitoring - Gauging Only
VW13	Solar Sipper installed August 2, 2012 and used as part of trial. Historically a pneumatic total fluids recovery pump. Noted as recovery well as early as 2002 and described as pneumatic total fluids recovery well as early as 2006 reports. Shown as recovery well on 2002 Map. Vacuum event conducted on well.
VW13B	Grundfos Total Fluids Electric Submersible Pump. Was Offline 2nd half of 2017

Well Name	Description of Historical and Current Operational Status
VW14	Solar Sipper installed August 2, 2012 and part of the trial. Historically was a pneumatic total fluids pump. Noted as pneumatic recovery pump as early as 2006 report and shown as recovery well on 2002 map. Vacuum event conducted on well.
VW15	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 and as part of trial. Vacuum event conducted on well.
VW16	Monitoring - Gauging and Sampling
VW17	Monitoring - Gauging Only
VW18	Solar Sipper installed August 2, 2012. Solar Sipper removed from well November 24, 2014 due to no LNAPL. Used as Solar Sipper well again starting 2nd Half 2018 and as part of trial
VW19	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 but not part of trial.
VW20	Solar Sipper installed August 2, 2012 but not part of trial. Electric total fluids pump up to May 2007 and then pneumatic total fluids pump until replaced by solar sipper. Noted as recovery well on 2002 Map. Vacuum event conducted on well.
VW20B	Grundfos Electric Submersible Pump used in this well. Was offline 2nd Half 2017 and became solar sipper well 2nd Half 2018 but not part of trial. Electric total fluids pump was moved to this well from VW20 in May 2007.
VW21	Solar sipper well August 2012 but not part of trial. Historically a pneumatic total fluids recovery well. Noted as recovery well on 2002 map. 2006 Reports describes as pneumatic total fluids pump.
VW21B	Grundfos Electric Submersible Pump used in this well installed August 15, 2013. Grudfos offline 2nd half of 2017 and solar sipper installed 2nd half 2018 but not part of trial.
VW22	Monitoring - Gauging Only. Well is historically dry.
VW23	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 and as part of trial.
VW24	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 and part of trial.
VW25	Monitoring - Gauging and Sampling
VW26	Solar Sipper installed August 2, 2012. February 18, 2013 solar sipper removed due to absence of LNAPL and recovery. Total loading pneumatic pump location 2009 to 2012. Map from 2002 shows well as recovery well but not described as recovery well in 2006 through 2008 reports
VW27	Monitoring - Gauging and Sampling
VW28	VW26 Solar sipper was considered a contingent replacement in this well but insufficient LNAPL in well to support recovery. Historically was electric total fluids which was converted to pneumatic total fluids in August 2009. Noted as operational in 2006 reports but not shown as recovery well on 2002 Map. Vacuum event conducted on well

Well Name	Description of Historical and Current Operational Status
VW29	Solar Sipper installed April 11, 2013 and part of trial.
VW30	Solar Sipper from VW18 moved to this well on November 24, 2014 but not part of trial.
VW31	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 and part of trial.
VW32	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 but not part of trial. Vacuum events conducted on this well
VW33	Monitoring - Gauging Only
VW34	Historically gauging well only. Added to sampling program for 1st semiannual 2018 event
VW35	Historically monitoring and gauging only. Used as a Solar Sipper well starting 2nd Half 2018 but not part of trial.
VW36	Monitoring - Gauging Only
VW37	Monitoring - Gauging and Sampling
VW38	Grundfos Pump installed in this well for recovery. Well off-line 2nd Semi-annual event 2017 and solar sipper installed 1st half of 2019 but not part of trial. Vacuum events conducted on this well.
GM22	Monitoring - Gauging Only
GM11	Monitoring - Gauging and Sampling
GM14	Monitoring - Gauging and Sampling
MM9	Monitoring - Gauging Only
MMX	Monitoring - Gauging and Sampling
GM7	Monitoring - Gauging Only. Well is historically dry.
50	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018
97	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018
98	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018
99	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018
172	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018
231	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018
386	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018

Well Name	Description of Historical and Current Operational Status
471	Offsite well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018
GM13D	Well historically in monitoring and gauging program. Not in monitoring program since 2nd half of 2018

2.1 LNAPL Recovery Activities

A range of LNAPL remedial activities have been conducted at the Site, including the use of skimming, total fluids, and dual pump LNAPL recovery wells and vacuum trucks to remove LNAPL. The current LNAPL recovery program consists of the following elements:

- Solar Sipper skimmers in 13 recovery wells.
- Groundwater depression and LNAPL recovery at one location (well VW13B) using an electric submersible pump for groundwater removal and a solar sipper for LNAPL removal in the same well.

As documented in the 1st Semiannual Status Report 2017, the recovery systems were shut down on March 2nd 2017 and the pumps were removed from the wells to allow a sitewide groundwater gauging event. All wells were gauged on a weekly basis to monitor the rebound in LNAPL Thicknesses and evaluation the potential for LNAPL plume migration. LNAPL Baildown tests were conducted in select wells and upon completion of all testing the Solar Sippers were reinstalled and LNAPL recovery recommenced on April 26, 2017. The electric submersible pumps were not reinstalled in the wells, with the exception of well VW13B in 2018.

The data from this assessment and modelling was submitted to USEPA on July 25, 2017 in a report titled, “Aquifer Testing and PSH Plume Recoverability/Stability at the Former St Croix Alumina Site”. The recommendations from this report were that the recovery strategy would shift to LNAPL-only recovery with an expansion of the number of solar sippers at the site (from 7 to 13) and the ongoing depression of groundwater at VW13B through use of an electric submerisble pump in combination with the solar sipper.

As outlined in the status report the configuration of recovery wells was designed with the following emphasis:

- Perimeter LNAPL wells – installation of Solar Sippers in wells VW2, VW13, VW18, VW23 and VW31.
- Central LNAPL wells – installation of Solar Sippers in well VW5, VW6 VW14 and VW15 and periodic extraction from well VW13B.
- Spot treatment of wells with greater than 0.5 feet of LNAPL: VW20, VW24, VW29 and VW30.

In the PSPH Pilot Study and DPPHC Sampling Plan Modification, the POC committed to expanding the remediation system by installing seven additional Solar Sippers and reinstalling a total fluids submersible pump in monitoring well VW13B. The PSPH Pilot Study was approved by USEPA and implementation of the study began on August 20, 2018 with the additional Solar Sippers taking the total to 13 skimming pumps. As part of the operation of these pumps sitewide monitoring wells were gauged on a monthly basis and based on this data the Solar Sippers were moved between wells to optimize recovery.

In general, all of the LNAPL recovery operations that have been in place since 2018 have continued. The fluids recovered by the Solar Sippers are pumped into drums adjacent to the wells with the drum contents periodically removed (typically monthly) via a vacuum truck and discharged to the Limetree Bay Terminals oily water sewer line where it flows to the facility API Separator. Recovered fluid from the total fluid's recovery pump in well VW13B is directly discharged to the oily water sewer line.

Recovery rates from each well are calculated by measuring the accumulated fluids in the drum prior to removal. Recovery rates from electric submersible pump at VW13B are measured by a totalized (which is manually read monthly) with the oil/water cuts in the extracted fluids determined by periodic three-gallon bucket tests on the total extracted fluids.

In addition, vacuum events have been conducted in select wells since May 2019. As part of this process, monitoring wells are gauged for thickness and then vacuum events conducted for a period of 45 minutes to 1 hour with on average 800 gallons of liquid recovered from each well. As noted in Status Reports VW2, VW5, VW6, VW7, VW14, VW15, VW20, VW28, VW31, VW32 and VW38 have undergone vacuum events. Following completion of the vacuum recovery events the wells are re-gauged with all wells showing no measurable LNAPL after the recovery activities. Per EPA's request four 330 gallon holding tanks were installed in 2020 to allow for quantification of LNAPL recovered.

2.2 Groundwater Monitoring Program

Groundwater monitoring is conducted at the Site on a semi-annual basis involving the gauging of all wells (including those containing LNAPL) and the collection of groundwater samples for chemical analysis. The current status of the monitoring program is summarized in Table 6 of the Status Report which is replicated below.

Groundwater samples are collected at the Site by low-flow groundwater sampling methods (purged and sampled at a rate of 300 milliliters/minute or less) with groundwater parameters monitored via a flow-through cell.

Groundwater samples collected at the site (based on the absence of measurable LNAPL in wells) are analyzed for benzene, toluene, ethylbenzene, total xylenes (BTEX) and naphthalene via USEPA Method 820B and total petroleum hydrocarbons diesel range organics (TPH-DRO) via USEPA Method 8015B. In addition, during 2018 and 2019 groundwater samples from four (4) wells (VW1, VW34, VW27 and GM11) were analyzed for the Skinner list of organic constituents.

Historical monitoring records indicate that the monitoring program has generally had a consistent set of wells that were monitored: VW-16, VW25, VW27, VW37 and GM11, GM14 and MMX. In 2002/2003 for a short period of time additional wells such as VW11, VW22 and VW36 were gauged and sampled. In addition since the 1st semi-annual event of 2018 wells VW1 and VW34 have been added to the monitoring program.

Table 2-2 Status of Groundwater Gauging and Monitoring (replicated from GeoMonitoring Services 2020)

WELL NAME	MAP X COORDINATE *(feet)*	MAP Y COORDINATE *(feet)*	WELL USE	COMMENTS
VW1	613975.88	1235603.18	Monitoring - Gauging and Sampling	Added to sampling program in 1st Half 2018
VW2	614593.77	1235421.13	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW3	615692.71	1235067.89	Monitoring - Gauging Only	
VW4	614508.40	1235599.53	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW5	614615.16	1235224.21	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW6	614416.88	1235332.08	Recovery Only	Used as solar sipper during 1st Half 2019
VW7	614761.98	1235334.12	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW8	615005.85	1235103.19	Monitoring - Gauging Only	
VW9R	615303.00	1235049.52	Monitoring - Gauging Only	
VW10	615518.78	1234978.12	Monitoring - Gauging Only	
VW11	615836.00	1234969.96	Monitoring - Gauging Only	
VW12	615755.82	1235254.21	Monitoring - Gauging Only	
VW13	614204.52	1235069.85	Recovery Only	Used as solar sipper during 1st Half 2019
VW13B	614206.04	1235076.29	Recovery Only	Electric Submersible Pump
VW14	614457.66	1235107.87	Recovery Only	Used as solar sipper during 1st Half 2019
VW15	614592.10	1234918.58	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW16	613763.79	1235053.78	Monitoring - Gauging and Sampling	
VW17	614098.57	1234658.22	Monitoring - Gauging Only	
VW18	614240.00	1234642.64	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW19	614678.01	1234706.63	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW20	614407.15	1234233.73	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW20B	614403.30	1234224.01	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW21	614200.02	1234003.00	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW21B	614202.34	1234007.95	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW22	614568.14	1233491.39	Monitoring - Gauging Only	Well Historically Dry
VW23	614180.33	1235146.81	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW24	614544.08	1233975.91	Recovery Only	Used as solar sipper during 1st Half 2019
VW25	613425.31	1232889.96	Monitoring - Gauging and Sampling	
VW26	614066.10	1233414.57	Monitoring - Gauging Only	Historically Used as Recovery
VW27	613887.36	1234155.93	Monitoring - Gauging and Sampling	
VW28	614093.46	1233506.66	Monitoring - Gauging Only	Historically Used as Recovery
VW29	614281.69	1234157.71	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW30	614600.11	1234459.76	Recovery Well	Used as solar sipper during 1st Half 2019
VW31	613950.69	1232955.27	Recovery Well	Used as solar sipper during 1st Half 2019
VW32	614187.37	1233224.77	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW33	614057.18	1230761.02	Monitoring - Gauging Only	
VW34	613694.28	1232669.86	Monitoring - Gauging and Sampling	Added to sampling program in 1st Half 2018
VW35	614524.89	1233654.30	Monitoring and Recovery	Used as solar sipper during 1st Half 2019
VW36	613552.94	1230613.71	Monitoring - Gauging Only	
VW37	613291.78	1230680.28	Monitoring - Gauging and Sampling	
VW38	5,790.95	10,044.09	Monitoring - Gauging Only	Used as solar sipper during 1st Half 2019
GM22	4,366.15	8,595.95	Monitoring - Gauging Only	
GM11	6,559.93	9,394.28	Monitoring - Gauging and Sampling	
GM14	6,065.27	8,358.76	Monitoring - Gauging and Sampling	
MM9	6,648.65	11,418.68	Monitoring - Gauging Only	
MMX	6,063.56	10,757.40	Monitoring - Gauging and Sampling	
GM7	2,794.42	9,353.96	Monitoring - Gauging Only	Well Historically Dry

3 LNAPL Fundamentals

The characteristics of the product types, the hydrogeologic conditions at the St. Croix Site and the manner in which the product may have been released are the primary factors that influence the historical and current movement and distribution of LNAPL in the subsurface. In general, the lateral LNAPL distribution reflects the geology, groundwater gradients and flow regime at the Site. The transition from limestone to alluvium in the south has facilitated primarily cross gradient migration of LNAPL as LNAPL migration to the south was constrained by the high pore entry pressures required for LNAPL to enter the alluvium. However, within the limestone itself, the low conductivity of the primary porosity and likely presence of conductive secondary porosity features likely was also a significant contributor to the observed lateral cross gradient migration of LNAPL. In the context of the low hydraulic conductivity of the primary porosity the historical the rate of downward vertical LNAPL movement from near surface releases had the potential to exceed the lateral migration rate and provide sufficient LNAPL heads for LNAPL to facilitate further lateral (cross hydraulic gradient) spreading.

There are no significant indications of LNAPL being trapped below the water table as would be evident by major increases in measured LNAPL thickness during periods of low groundwater elevation. While historical modeling has considered a multi-phase model (LNAPL and water competing for the same pore spaces), not a “pancake layer” model which assumes the LNAPL exists as a distinct layer with 100% saturation of pore spaces, this model is designed for porous media (soils) and has inherent limitations in assessing recoverable LNAPL volumes within the sedimentary rocks and has overestimated the mobility and recoverability at this site.

The volume of recoverable LNAPL in the formation is primarily a function of the properties of the media (soil or bedrock) and LNAPL. The principles of LNAPL migration in porous media are well understood reflecting the greater uniformity of conditions within this matrix. In sedimentary rocks, the combination of inter-granular porosity and secondary porosity (fracturing and dissolution features) play important roles in the mobility and recoverability of LNAPL. While, the principles of LNAPL mobility and recoverability in porous media are equally applicable to these types of rock. The differences in rock type/weathering impact on the size of pore spaces within the rock the presence and size of fractures or dissolution cavities and the percentage and amount these secondary porosity features that are in-filled. As a result, at a pore scale, portions of the rock can behave like sand while other portions can behave like clay but secondary porosity features are likely the dominant feature impacting on LNAPL mobility and recoverability at this site.

These porous media processes are discussed in further detail in the sections below, evaluated in the context of LNAPL distribution and flow within secondary porosity, and then explored using site specific data in later sections.

3.1 LNAPL Properties

Physical properties such as viscosity, density, and LNAPL saturation influence LNAPL mobility within the subsurface. Viscosity is an important limiting factor of LNAPL mobility because the higher the viscosity, the more internal resistance the LNAPL has to flow. Low viscosity LNAPLs such as gasoline will tend to flow readily given sufficient volumes and LNAPL gradients, while a high viscosity LNAPL such as crude oil, has very little migration potential despite the volume of the release, with migration only occurring during the initial release when LNAPL gradients are greatest.

As detailed by Higinbotham et al. (2003), viscosity has a major effect on LNAPL inherent mobility and recoverability. In general, Higinbotham et al. (2003) and other American Petroleum Institute (API) Research has demonstrated that only low viscosity products (diesel through gasoline) exhibit high inherent mobilities which support potential recovery. Medium to high viscosity compounds (viscosities greater than 20 centistokes (cSt)) are effectively immobile and unrecoverable in most geologic settings. Crude oils and lube oils will exhibit limited to no mobility or recoverability. As viscosity of LNAPL increases (due to higher proportions of heavier crude oils and/or weathering) the potential for mobility decreases.

Density is another important physical property when evaluating LNAPL mobility, especially when LNAPL-groundwater interaction is of interest. By definition, LNAPL is lighter than water, making density an important concept in understanding LNAPL buoyancy and associated interaction with groundwater in the saturated zone. LNAPLs with higher densities (approaching 0.94 for crude oils) also have a greater ability to displace water from pore spaces than low density products as they require lower heads to exert sufficient pressure to displace water from pore spaces.

Saturation is the third key property in understanding LNAPL mobility in the subsurface. As shown on **Figure 3-1** below, saturation and LNAPL type (and viscosity) directly impact LNAPL conductivity, or the ability for the LNAPL to move within the subsurface. Unlike groundwater, which is implicitly known to be at 100% saturation within the saturated zone, LNAPL saturation never reaches 100% saturation in the subsurface and therefore saturation becomes a major limiting factor on LNAPL mobility.

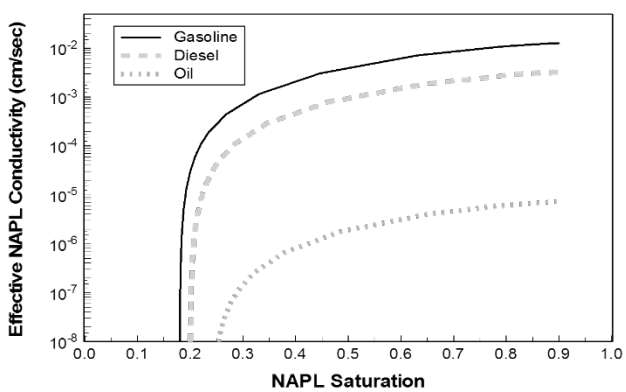


Figure 3-1 NAPL Saturation (Reproduced from RTDF, 2005)

The concept of LNAPL saturation and its relationship to the aquifer properties is discussed further in the sections below.

3.2 Vapor Phase Partitioning

Because LNAPL is often comprised of volatile constituents at relatively high concentrations compared to soil and groundwater, evaluating the maximum potential soil gas concentration of a particular constituent within LNAPL is important in evaluating natural degradation via mass loss.

The maximum potential soil gas concentration of a constituent is a function of the constituent's vapor pressure and mole fraction within the LNAPL mass as given by Raoult's Law for ideal gas mixtures:

$$C_{sg} = x_i \, vp_i \, MW_i / RT$$

Where:

C_{sg} = maximum potential soil gas concentration of the constituent "i";
x_i = mole fraction of constituent "i" in the LNAPL;
vp_i = vapor pressure of constituent "i" in the LNAPL;
MW_i = molecular weight of constituent "i";
R = Ideal Gas Constant
T = temperature

This relationship is important because it demonstrates that the mole fraction of the constituent within the LNAPL is a key control of the potential soil gas concentrations observed above a LNAPL source. For example, higher mole fractions of LNAPL constituents (e.g., ethylbenzene and xylenes) result in higher equilibrium concentrations in the vapor phase above the LNAPL. These relationships can be used to evaluate mass loss of various constituents within the LNAPL through volatilization and the potential risks associated with flux from LNAPL into a vapor phase.

3.3 Aqueous Phase Partitioning

In order for constituents within LNAPL to act as a potential source of impacts to groundwater, the constituents must be able to partition into the aqueous phase. Aqueous concentrations of constituents in the LNAPL are dependent upon the aqueous solubility of each constituent in the LNAPL and the relative mass of each constituent in the LNAPL. The relationship between aqueous solubility of a constituent and its concentration within the LNAPL is analogous to Raoult's law for ideal gas mixtures. For LNAPL in contact with water, the aqueous phase concentration of a LNAPL constituent is equal to the aqueous solubility of the constituent multiplied by the mole fraction of the constituent within the LNAPL mixture. This relationship can be written as:

$$C_w^i = x_i S_i$$

Where:

$C_w^i =$ effective aqueous solubility of the constituent "i";
$x_i =$ mole fraction of constituent "i" in the LNAPL; and
$S_i =$ aqueous solubility of pure constituent in water.

Similar to vapor phase partitioning, the mole fraction of a constituent in LNAPL (relative to the total composition of the LNAPL) becomes a major limiting factor on the maximum potential constituent concentration in pore water in contact with LNAPL. For example, a constituent with a pure phase aqueous solubility of 1,000 milligrams per Liter (mg/L) that has a mole fraction of 0.5 (close to 50% of the entire LNAPL composition) will have an effective solubility (maximum potential aqueous concentration) of 500 mg/L. This same constituent with a mole fraction of 0.05 of the LNAPL will only have an effective solubility of 50 mg/L. This concept illustrates the importance of understanding the composition of the LNAPL in order to evaluate its potential as a continuing source to groundwater.

The actual dissolved concentrations measured in groundwater monitoring wells will be lower than the effective solubility due to a combination of processes including:

- Not all groundwater has been in direct contact with LNAPL and as a result, groundwater concentrations are diluted by groundwater that has not been in contact with LNAPL.
- Natural mass loss mechanisms (biodegradation and sorption) which occur within the saturated zone.

Note that where groundwater constituent concentrations measured in the wells are close to or above the effective solubility of the LNAPL, the data is a strong indicator that LNAPL and or sheens were sampled and that LNAPL is present within the aquifer matrix in close proximity to the well.

3.4 Multiphase Interaction and LNAPL Saturation

LNAPL within the subsurface coexists as a multiphase system within the pore spaces in the formation, as shown below (**Figure 3-2**).

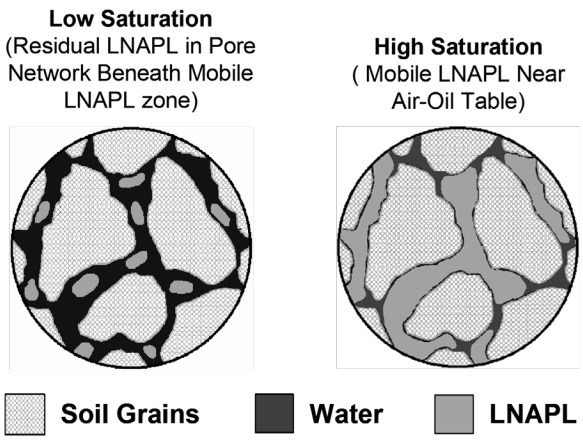


Figure 3-2 Multiphase System Within the Pore Spaces (Reproduced from API, 2004)

Within the vadose zone, the multiphase system consists of a mixture of LNAPL, air, and water. Beneath the water table, pore space is occupied by either LNAPL or water. LNAPL occurs as either residual or mobile LNAPL in this multiphase system. The term residual refers to LNAPL that is retained by soil/matrix capillary forces and/or is trapped within discontinuous pore spaces and thus is stuck within the formation. The residual saturation of LNAPL (the soil's/matrix's capacity to trap LNAPL) is dependent upon the pore throat size distribution, the nature of the LNAPL, the relationship between capillary forces and water content in the pore throats, and the movement of the LNAPL with respect to the water table.

Mobile LNAPL occurs when the LNAPL saturation is sufficient to create a continuous LNAPL phase between pores in the soil matrix by either occupying air-filled pore spaces within the vadose zone or displacing water-filled pores within the saturated zone. This mobile LNAPL volume has the potential to migrate vertically or laterally within the formation. Because sufficient LNAPL mass must be present to exceed internal and external controls on LNAPL mobility (e.g., LNAPL physical properties and aquifer properties) to overcome the residual saturation, LNAPL saturations are generally lower in the

unsaturated zone, where pore space is occupied by LNAPL, air, and water, than in the saturated zone where only LNAPL and water fill the pore spaces (**Figure 3-2**) (API, 2004).

It is important to note, that when LNAPL saturation exceeds residual levels, it only has the *potential* to move and redistribute through the pore network. However, this inherent mobility alone is not enough to cause movement of the LNAPL; a LNAPL gradient (or head) is required before migration can occur. In addition, there are a variety of resistant forces, such as capillary entry pressure (the pressures required to enter a pore space and displace air or water), that will further impede migration and stabilize LNAPL plumes. Typically, LNAPL plumes expand and migrate when LNAPL is first released into the subsurface and continue to migrate as long as additional LNAPL is added to the plume. Once the source is removed, LNAPL plumes tend to rapidly stabilize with redistribution of LNAPL occurring primarily within the plume with little to no continued LNAPL plume expansion.

However, current site data indicate that LNAPL within the subsurface coexists with water as a multiphase fluid within secondary porosity features. This has critical implications on both LNAPL mobility and recoverability.

In contrast to the multiphase concept described above, historically the vertical distribution of LNAPL at the water table was based on the idea that LNAPL occurs as a distinct lens in which the drainable pore space is completely saturated with LNAPL. This was often referred to as the "pancake layer" conceptualization where LNAPL was present at 100% pore volume saturation within specific intervals. This conceptualization predicted large free LNAPL volumes, high mobilities, and large recoverable volumes and did not consider soil or LNAPL properties which could inhibit mobility and recoverability (RTDF, 2005). This historic conceptualization of LNAPL has led to gross overestimates of LNAPL mobility and recoverability and has been proven to be highly inaccurate and unrepresentative of site conditions.

3.5 LNAPL Migration and Distribution

For the purpose of further discussion, we will consider a surface or near surface source as the LNAPL release mechanism, as shown below (**Figure 3-3**).

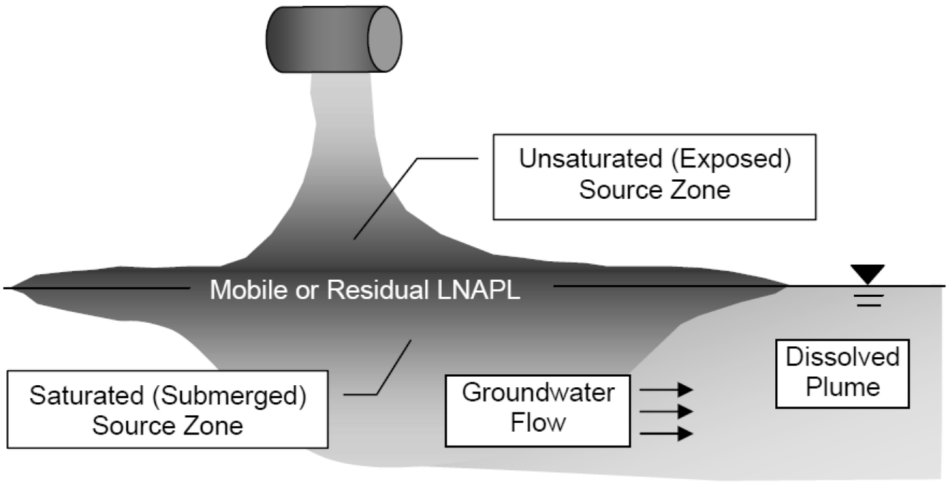


Figure 3-3 LNAPL Release Mechanism (Reproduced from ITRC, 2009a.)

When LNAPL is released at the surface, LNAPL migrates vertically downward under the force of gravity. The dynamic and heterogeneous character of the subsurface influences LNAPL conditions and allows for preferential flow and inhibition of LNAPL migration. As shown on the figure below, mobile LNAPL will tend to migrate in more permeable and porous soils or intervals within the rock structure (as a result of higher LNAPL conductivity). LNAPL migration is preferentially confined to the intervals of higher LNAPL intrinsic permeabilities where the LNAPL heads required to displace groundwater (pore entry pressures) are lowest. In these high-permeability zones, the migration of LNAPL is ultimately controlled by the continuity of these units, with low-permeability units which interrupt the coarse-grained units acting as "stratigraphic traps" or low-permeability dikes which limit or prevent further migration of the LNAPL.

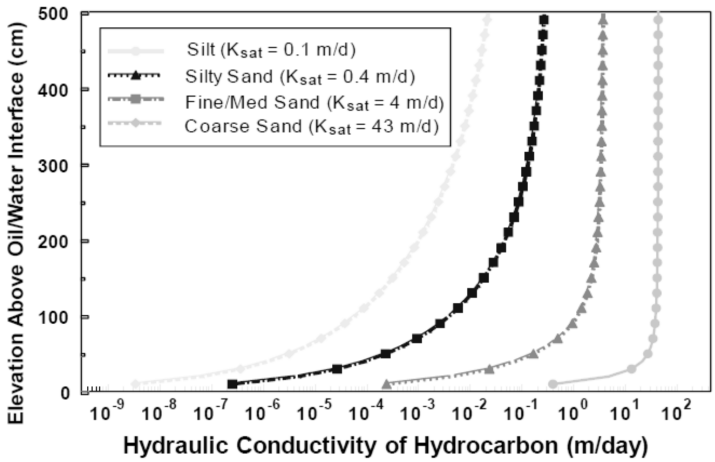


Figure 3-4 Hydraulic Conductivity of Hydrocarbon (Reproduced from RTDF, 2005.)

Due to capillary forces some LNAPL will always be retained in the pore spaces as residual LNAPL, as described above in **Figure 3-4**. As the LNAPL moves through the subsurface, portions of the LNAPL become trapped (residualized) within the soil pore structure, with LNAPL of a finite volume migrating until it is effectively all trapped as residual in the formation.

When the volume of the release is sufficient to overcome the controls on LNAPL mobility, the LNAPL migrates through the unsaturated zone to the capillary fringe and water table. Once at the capillary fringe, the increasing water content, and the effects of LNAPL buoyancy impede the vertical movement of the LNAPL near the water table. Because LNAPL is less dense than water, LNAPL begins to migrate laterally along the water table. In general, the lateral LNAPL migration reflects the groundwater gradients and flow regime at the Site. However, if the rate of downward vertical LNAPL movement from surface exceeds the lateral migration, LNAPL will mound, displacing water from the aquifer pore spaces below and flow can become somewhat radial. This radial flow concept is evident mostly in low permeability formations or in fractured rock where LNAPL flow is limited by the finite number and conductivity of fractures.

Because residual LNAPL saturation limits vary above and below the water table, LNAPL is significantly influenced by vertical fluctuations in the water table. Vertical water table fluctuations produce unique conditions where LNAPL becomes trapped or released from the pore network due to the location of the water table and, as a result, the vertical movement of the groundwater table affects the volume of mobile and residual LNAPL. The resulting vertical movement of the water table can produce a residual

smear zone within the saturated and unsaturated zone. In fractured rock this process can push LNAPL into low permeability or poorly connected portions of the formation where it becomes trapped and potentially disconnected from the main LNAPL plume.

In general, LNAPL thicknesses observed in monitoring wells situated within an unconfined aquifer will generally increase when water levels fall and will decrease or in some cases may totally disappear when water levels rise. This effect is generally more pronounced in coarser soils and sites with large water table fluctuations. These fluctuations result in vertical redistribution of LNAPL within the subsurface which affect the mobility and, ultimately, the residualization of LNAPL. This process is reflected in **Figure 3-5** below.

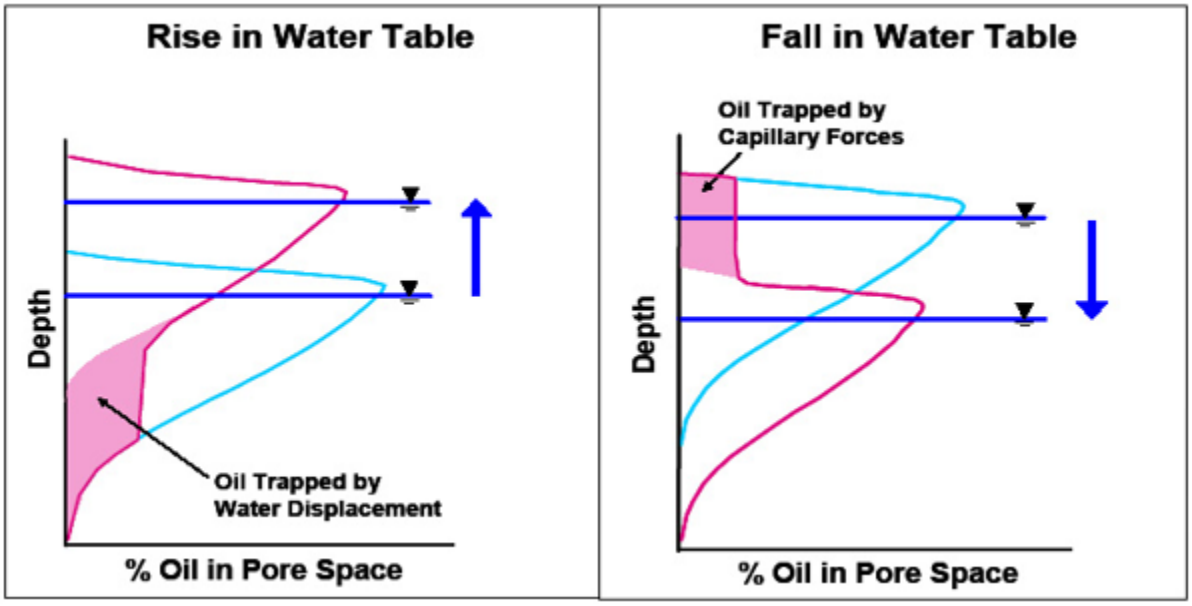


Figure 3-5 Effects of Water Level Fluctuations (API, 2007)

3.6 LNAPL Transmissivity

A fundamental nuance of multiphase flow is that the effective conductivity of LNAPL strongly diminishes as the LNAPL saturation decreases. Therefore, two key factors to LNAPL migration, LNAPL gradient and saturation, diminish through time (through residualization and mass loss processes) and result in exponential decreases in the ability for LNAPL to move through an aquifer. The ability for LNAPL to move through a cross sectional area of an aquifer is described as LNAPL transmissivity. Generally speaking, the higher the transmissivity value, the greater the LNAPL saturation and therefore the greater the potential for mobile LNAPL to be present within the formation. The equation to calculate LNAPL transmissivity is provided below:

$$T_n = K_n * b_n$$

Where:

T_n = LNAPL Transmissivity;
K_n = LNAPL conductivity; and
b_n = LNAPL thickness under vertical equilibrium.

However, as discussed earlier, the effective conductivity of LNAPL is a function of saturation and therefore varies throughout a LNAPL plume where saturations decrease with distance from the source of the release. In practice, LNAPL transmissivity values are often derived from baildown test results from wells within the center of the plume where sufficient LNAPL is present within a monitoring well. Although these results can reasonably estimate the LNAPL transmissivity values in the plume center, it is important to recall the transmissivity values are not uniform across a plume area and decrease rapidly with distance from the source.

Consistent with the multi-phase principles discussed above, the highest transmissivities are typically observed in coarse grained soils with the highest LNAPL saturations. Finer grained soils (silts and clays) typically need high LNAPL saturations before any measurable LNAPL mobility and recoverability is observed. High LNAPL saturations in fine grained soils are typically only observed in areas near the release area where LNAPL heads were sufficient to displace water from pore spaces and facilitate high LNAPL saturations.

3.7 LNAPL Recovery

Based on the principles discussed above, it follows that in homogeneous soils, the greatest LNAPL recoveries are possible in the center of the plumes where thickness, saturations, and pore scale mobility are highest. Towards the edges of the plumes, saturations decrease to below residual concentrations, pore entry pressures resist the penetration of more LNAPL, and hydraulic recovery becomes inefficient and ineffective. In more heterogeneous soils, the differences in soil properties (grain size and percent fines) in combination with saturations further reduce the mobility and recoverability of LNAPL.

An evaluation of recovery case studies conducted by Beckett and Huntley (2002) determined that total LNAPL recovery was typically less than 30% of the original volume in place consistent with the theory described above. In finer grained materials recovery of more than 15% of the LNAPL in place would be unusual. This is consistent with oil industry experience where extensive effort has been expended to recover oil from the ground in conditions more conducive to recovery (fractured rock and confined reservoirs). Studies of oil reservoir rocks have shown residual oil left behind at the conclusion of water flooding typically ranges from 25 to 50% of the pore volume (Chatzis et al, 1988; Melrose and Bradner 1974).

3.7.1 LNAPL Mobility and Recoverability Principles to Sedimentary Rocks

As noted in the introduction to this section, LNAPL can be contained within the inter-granular porosity or secondary porosity features of the sedimentary rock. Petroleum reservoirs are contained within sedimentary rock structures, with the sandstones typically forming the oil and gas reservoirs and the mudstones, siltstones and claystones forming the cap rock. The structural elements of petroleum reservoirs provide us with an understanding of the behavior of LNAPL in sedimentary rock.

Just like petroleum reservoirs, the LNAPL is likely to exhibit mobility and recoverability within the higher transmissivity rocks; for the St. Croix site this includes areas where limestone dissolution features dominate and the calcarenite where coarse shells and coral dominate. The highly weathered limestone and evaporite deposits are finer grained and significantly limit LNAPL mobility. These differences in mobility primarily reflect the diameter of pore throats within these differing rock types. In addition to pore throat diameters, other functional differences between the rock types are associated with their ductility and weathering. The depositional nature of the area will see infilling of secondary porosity features with more (sandy) or less transmissive (silty clayey) materials. The less transmissive materials in combination with calcification are likely to result in large areas of weathered limestone having low hydraulic conductivity and low LNAPL transmissivity. In other areas discrete features (for example, old reef features) will have very high hydraulic conductivity and LNAPL transmissivity.

Based on LNAPL mobility at this Site being primarily controlled by presence of these high transmissivity units (further discussion is provided in **Section 5**) LNAPL mobility and recoverability will ultimately be controlled by the elevation, orientation, and continuity of these features. The dynamic and heterogeneous character of the subsurface influences LNAPL behavior, with preferential flow occurring in some conditions and inhibition of LNAPL migration occurring in others. In particular, historically mobile LNAPL will tend to migrate in the more permeable and porous units within the limestone material and discrete more transmissive (shell-dominated areas) of the alluvium.

Away from the release area (where LNAPL heads are reduced) LNAPL migration was preferentially confined to the high transmissivity zones where intrinsic permeabilities are highest and the LNAPL heads required to displace groundwater (pore entry pressures) are lowest. In these high permeability zones, the migration of LNAPL is ultimately controlled by the continuity of these units, with infilling with fine grained materials (caused by weathering of the parent rock) and the transition to finer grained alluvium resulting in “stratigraphic traps” or low permeability dikes which limit or prevent further migration of the LNAPL.

On the basis of the fundamentals described above and likely rock properties (where the majority of LNAPL is encountered), the key controls on mobility and recoverability at the Site are summarized below:

1. The lateral continuity of higher permeability fractures within the limestone; ultimately the mobility and recoverability of LNAPL will be controlled by the continuity, orientation, and elevation of these higher conductivity features with which LNAPL has become trapped in the formation under natural conditions and during active remediation.
2. The infilling of the secondary porosity (including calcification) with fine grained materials resulting in low hydraulic conductivities and LNAPL transmissivities and high poor entry pressures that inhibit mobility and recoverability and large areas of the limestone and geochemical transition zones where gypsum may be forming.
3. The geologic transitions between limestone and alluvium which result in marked hydraulic conductivity and LNAPL transmissivity contrasts.
4. The high-water saturations within the formation and likely low LNAPL saturations which result in very low LNAPL intrinsic permeability in the plume fringe areas.
5. The limited storage of LNAPL in secondary porosity features which inherently will result in overestimates of LNAPL volumes (storage is low and highly variable) as well as low LNAPL pore fluid saturations in areas where infilling of secondary and primary porosity is evident at the site.

3.8 Natural Source Zone Depletion of LNAPL, Natural Mass Losses of LNAPL, and Dissolved Phase Constituents

As described in the previous sections, LNAPL mass at this site is primarily distributed at or below the water table and in cases of periods of low groundwater elevations, areas of higher saturation may be present above the water table. In this context, mass losses can occur through a range of mechanisms including volatilization into the vadose zone, dissolution, and biodegradation.

The term monitored natural attenuation (MNA) as a component of a protective groundwater remedy is well known. The parallel concept of natural attenuation of LNAPL bodies has emerged more recently. A popular term is Natural Source Zone Depletion (NSZD), but the term source zone natural attenuation (SZNA) is often used interchangeably.

Advances in measurement of natural LNAPL depletion rates in recent years has led to increased interest in understanding and quantifying natural attenuation of subsurface LNAPL bodies because LNAPL depletion due to gaseous transport in the subsurface has been greatly under-estimated (and under-appreciated) until recent years (Garg, et. al. 2017).

It is clear that a paradigm shift regarding natural depletion of LNAPL bodies has evolved towards appreciating the importance of natural loss of subsurface LNAPL through the soil gas pathway, where abundant LNAPL depletion rates on the order of several hundred to a few thousand gallons/acre/year are typical. Further it is recognized that most natural LNAPL depletion is due to gaseous efflux through the 'vadose' zone (on the order of greater than 90 percent) with the remaining LNAPL depletion being attributable to dissolution in groundwater (Johnson et al., 2006). A modern simplified conceptual model for natural LNAPL depletion is shown below in **Figure 3-6**.

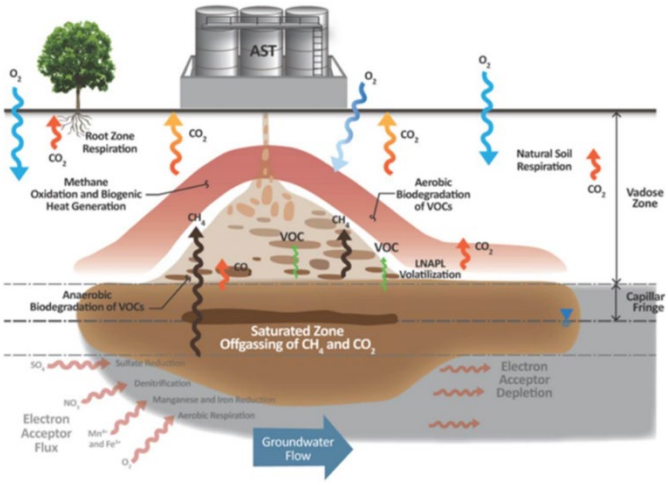


Figure 3-6 NSZD Simplified Conceptual Model

Figure Source: http://www.environmentalrestoration.wiki/index.php?title=Natural_Source_Zone_Depletion_(NSZD)

The ITRC, a state-led, national coalition of personnel from the environmental regulatory agencies of all 50 states and the District of Columbia, three federal agencies, tribes, and public and industry stakeholders, fostered renewed interest in measuring natural LNAPL depletion rates when it published its then-current state of science guidance document in 2009 entitled *Evaluating Natural Source Zone*

Depletion at Sites with LNAPL (ITRC, 2009a). ITRC recognized that LNAPL lost to soil gas might be chronically under-appreciated and under-estimated and gave the following conceptual model (**Figure 3-7**) for LNAPL loss through gas transport in the vadose zone.

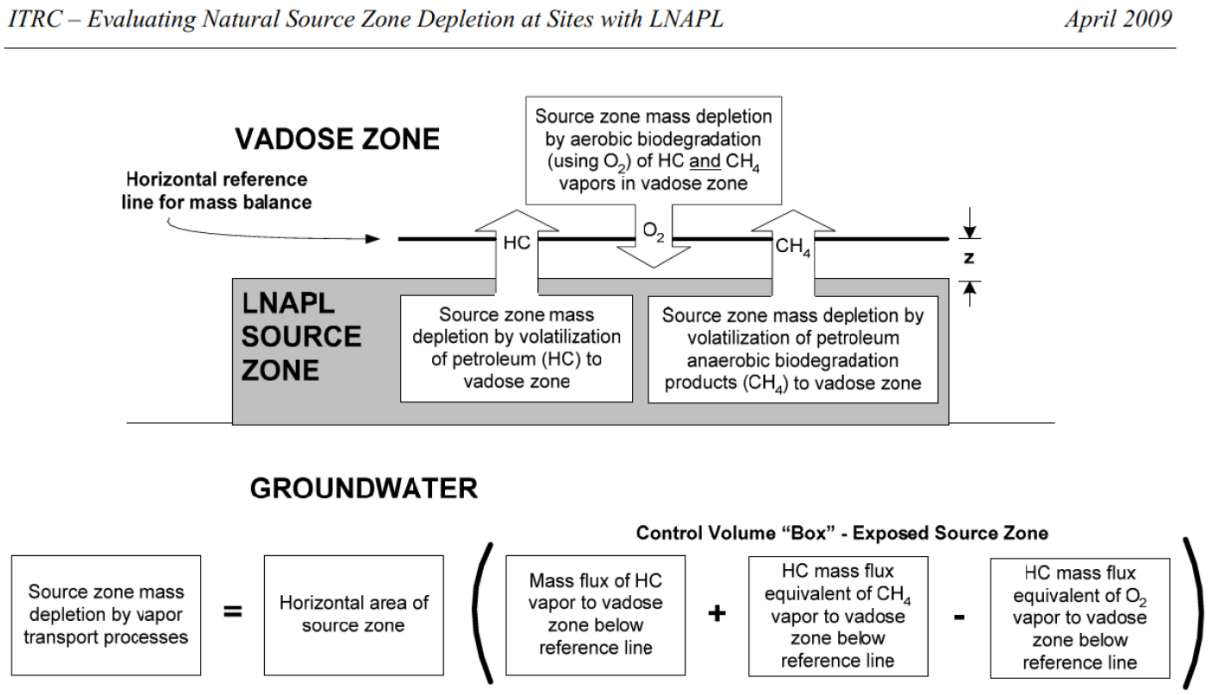


Figure 3-7 Simplified Conceptual NSZD Mass Balance Model

ITRC's adaptation of the work by Johnson et al. (2006) provided a means of assessing LNAPL loss by volatilization and gas-phase biodegradation by measuring hydrocarbons, methane, carbon dioxide, and oxygen content across a horizontal control plane near the LNAPL body. This approach is well-suited to the Site as a robust soil gas data set is available (as measured by USEPA in June 2016) (Weston, 2018). A detailed discussion of historical soil gas investigations (including sampling methodologies) and a compilation of data is contained in the FMP RIR (Weston, 2018).

Suthersan et al. (2015) and McCoy et al. (2015) have confidently concluded that past estimates of natural LNAPL depletion have been greatly under-estimated because of an under-appreciation of the relatively large amount of natural LNAPL depletion that occurs in the vadose zone and the role of methanogenesis. Further, the Naval Facilities Engineering Command issued new guidance on "New Developments in LNAPL Site Management (April 2017)" also referencing the following key studies.

Typical measured rates of natural LNAPL depletion rates due to losses to soil gas losses are:

- 134 to 1,340 gallons/acre/year -Lundegard and Johnson (2006)
- 1,600 gallons/acre/year - Sihota et al. (2011)
- 2,100 to 7,700 gallons/acre/year - McCoy et al. (2015)
- 1,100 to 1,700 gallons/acre/year - Los Angeles LNAPL Workgroup (2015)
- 300 to 3,100 gallons/acre/year - Piontek et al. (2014)
- 1,400 to 14,000 gallons/acre/year - McCoy et al. (2015)
- 300 to 7,700 gallons/acre/year - Palaia (2016)

These estimates on other projects have been compared to more active source remediation alternatives and served as a basis to determine if enhanced bioremediation (through additions of amendments) may hold merit. Palaia (2016) has given the following example of such a comparison (**Figure 3-8**):

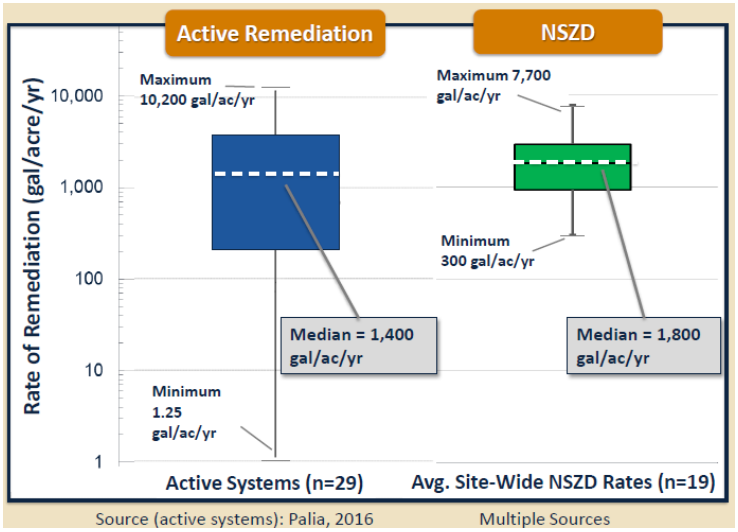


Figure 3-8 Comparison of Mass Losses Between Active and Natural Source Remediation (Newell et al., Presentation to FRTR 11/02/2016)

The science of assessing NSZD is evolving with recent additions to assessment methods including (**Figure 3-9**):

1. Measurement of biogenic gaseous methane and carbon dioxide flux with Flux Chamber methods like Dynamic Closed Chamber samplers or, for carbon dioxide only, with passive samplers such as CO_2 Traps, Map-Traps, and Fossil Fuel-Traps offered by E-Flux; http://soilgasflux.com.
2. Measurement of temperature rise near source zones attributable to biogenic (metabolic) heat resulting from robust biodegradation in vicinity of source material such as that offered by Thermal NSZD; https://www.thermalnszd.com.

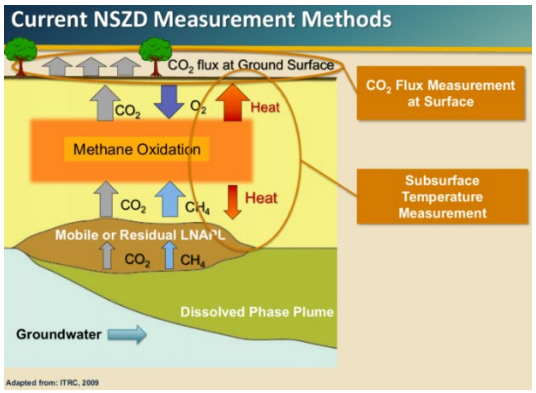


Figure 3-9 NSZD Measurement Methods

(Source: Newell, 2016)

The utility of using thermal gradient (temperature) measurements to accurately and inexpensively assess LNAPL depletion is gaining traction, as evidenced by recent abundant technical publications on the subject:

- Garg et al., 2017
- Newell et al, 2016
- Southersan, 2015
- Stockwell, 2015
- Warren and Bekins, 2015
- Sweeney and Ririe, 2014

The concept behind using thermal gradients is illustrated on **Figure 3-10**.

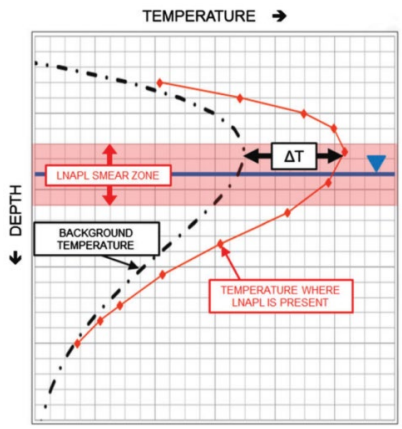


Figure 3-10 Thermal Gradient Conceptualization

Source: Southersan, 2015

Likewise, the utility of using passive soil gas efflux monitors continues to evolve (E-Flux; http://soilgasflux.com). However, the CO_2 -Trap version may suffer from underestimation of LNAPL depletion rates at sites where biogenic methane gas is incompletely oxidized to CO_2 gas by the time it reaches the near-surface planted passive samplers.

Eichert et al. (2017) compared variability of NSZD rates measured by three different soil gas measurement tools:

- Dynamic Closed Chamber (DCC)
- Concentration Gradient Method (CGM)
- CO_2 Traps (passive near-surface sampler)

In this study, they found the concentration gradient method applied to shallow probes showed relatively low variability compared to the other test methods. These findings support the use of USEPA's 2016 soil vapor dataset and specifically the "soil gas probe" (SGP) sample set (Weston, 2018) as a line of evidence in assessing the Site's natural LNAPL depletion potential. In addition, groundwater temperature records from the 2017 groundwater sampling event serve as another line of evidence to assess LNAPL depletion via evaluation of biogenic heat signatures.

3.8.1 Biodegradation Processes in the Saturated Zone

Petroleum hydrocarbons are biodegraded via biological oxidation when electron donors and acceptors are combined to produce energy for microbial growth (and metabolic by-products). Petroleum hydrocarbons typically serve as electron donors in the microbial metabolism process. A range of electron acceptors are utilized in the process, including oxygen, nitrate, manganese [Mn(IV)], Fe(III), sulfate, and carbon dioxide.

Carbon dioxide, water, nitrogen gas, Mn(II), Fe(II), hydrogen sulfide, and methane are typically by-products produced from the biodegradation of petroleum hydrocarbons. The biodegradation process is mainly limited by electron acceptor availability, and generally will proceed until all of the contaminants that are biochemically accessible to the microbes are oxidized. It is generally observed that an adequate supply of electron acceptors is present in most, if not all, hydrogeologic environments (Wiedemeier et al., 1995, 1996 and 1999).

The sequential use of electron acceptors and metabolic by-products produced are shown on **Figure 3-11** below. This process involves the initial degradation of hydrocarbons using aerobic bacteria followed by the processes of denitrification, iron (III) reduction, and sulfate reduction, and lastly methanogenesis (where methane is produced).

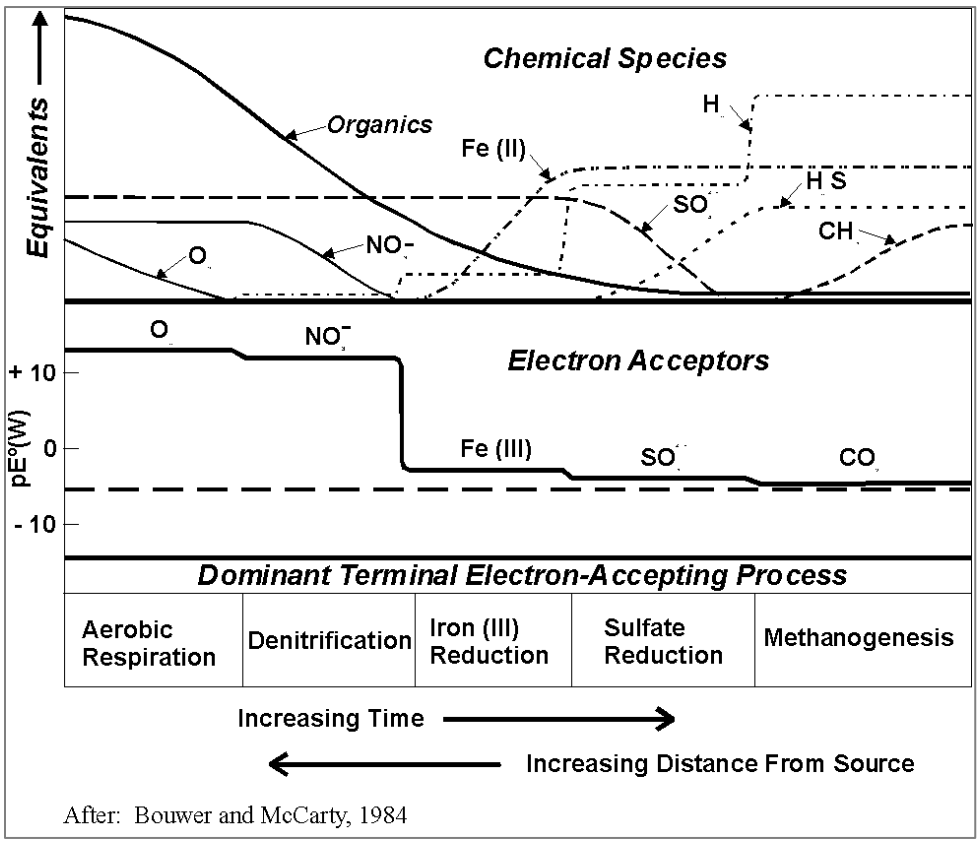


Figure 3-11 Use of Electron Acceptors and Metabolic By-Products Produced (Bouwer and McCarty, 1984)

The groundwater geochemistry for this site is not well-defined, but the presence of sulfur (potentially as sulfate or hydrogen sulfide) based on the minerology of soils provides opportunities for sulfate reduction to be an mechanism of natural attenuation of dissolved and LNAPL phase constituents. Degradation of long-chain LNAPL constituents (e.g., *n*-alkanes) has been demonstrated to occur via extra-cellular enzymatic activity (Bekins et al. 2005, Hostettler et al. 2007), as well as by anaerobes (e.g., Wilkes et al. 1995). Efroymson and Alexander (1991) noted that bacteria were capable of attaching to the solvent-water interface and suggest that the bacteria were capable of degrading the target constituent directly from the nonaqueous phase. Atlas (1981) also notes that hydrocarbon-degrading microbes have been observed growing on the surface of oil droplets. Microbial populations present at the LNAPL-water interface may contribute to the ultimate attenuation of LNAPL at environmental remediation sites especially where processes have residualised or smeared LNAPL in the formation and where LNAPL saturations are reduced such that the water/oil contact area is large.

The occurrence of enzymatic activity, the production of bio-surfactants and bioemulsions is considered a critical mechanism of degradation. Efroymson and Alexander (1994b) found bacteria may have excreted enzymes capable of increasing partitioning rates from non-aqueous phase liquid (NAPL) to water. This increased partitioning rate served to increase the bioavailability of the target constituent, resulting in an increase in aqueous-phase biodegradation. As noted above, alkane structures while relatively insoluble are observed to degrade and in many cases bacteria such as pseudomonas and sulfate reducing bacteria (which are known enzyme producers) have been attributed to this degradation. Sulfate reducing bacteria are commonly attributed to the degradation of diesel and the need to add biocides to address the 'diesel bug' which result in the formation of emulsions within diesel water mixtures. Similarly, in the rolling mill operations enzymatic activity and the production of bio-emulsions were commonly observed.

USEPA (1995) states that, while LNAPL constituents are available for biodegradation in the aqueous phase, it is unlikely that conditions exist within an LNAPL that are favorable for biodegradation. The more recent research does not necessarily imply that biodegradation is occurring within the LNAPL itself, but rather implies that bio-activity occurs at the LNAPL-water interface (e.g., enzyme secretion and microbial attachment at LNAPL-water interface). While the laboratory studies confirm that biodegradation of LNAPL does occur in some situations and environments, they also point to circumstances that would reduce or eliminate biodegradation of LNAPL. Consistent with the NSZD studies described above, in situ conditions in many cases (especially at sites where sulfate reduction is occurring) are sufficient to support direct biodegradation of LNAPL.

The following section evaluates the nature and extent of LNAPL and dissolution to groundwater through assessment of LNAPL physical properties and composition and LNAPL and groundwater data collected as part of LNAPL Investigation activities. As part of this assessment of stability of LNAPL and dissolved phase impacts are also assessed at the site.

4 Hydrogeological Setting

A detailed review of regional geologic and hydrogeologic assessment and site data has been conducted to refine the understanding of subsurface conditions and the key controls on LNAPL mobility and recoverability. Key findings from this assessment include:

- An interval variably composed of calcareous clay, silt, sand, and gravel is identified within the Kingshill Limestone that is broadly consistent with the location of the water table and screened intervals in many site wells.
- This interval likely represents lagoon deposits that accumulated during a global sea level low stand. The lagoon deposits are encapsulated by deeper marine limestone/marl rocks of the Kingshill Limestone that formed during sea level high stands.
- Abundant zones of no recovery encountered during drilling at the site may be attributed to loose sand/gravel wash-over deposits that were deposited in the Kingshill Limestone lagoon.
- Calcareous silt, sand and gravel with high hydraulic conductivity occur in the Kingshill Limestone lagoon deposits.
- Abundant clay deposits that likely formed in the Kingshill Limestone lagoon are associated with the evaporite minerals caliche (calcium carbonate), gypsum (calcium sulfate), and are associated with chert (organism frustules composed of silicon dioxide).
- A number of geologically recent alluvial channels that cut into the Kingshill Limestone are identified at the site on geologic maps that pre-date major site development. These alluvial channels do not appear to intersect the water table, except in the vicinity of VW-36.
- There is large lateral variability in hydraulic conductivity and LNAPL transport due to the heterogenous Kingshill Limestone lagoon deposits that are broadly coincident with well screen intervals.
- There is likely large variability in LNAPL transmissivity and storativity due to the heterogenous Kingshill Limestone lagoon deposits. As detailed in **Section 5** the presence of LNAPL within the limestone and its recoverability will likely be controlled by secondary porosity features and areas of higher long term recovery likely reflect areas dominated by more coarse grained materials.
- The fine grained limestone and Marl is likely to exhibit low groundwater and LNAPL transmissivities and the presence of these materials has likely facilitated lateral (cross gradient migration of LNAPL.
- The calcium rich nature of groundwater (which likely is super saturated with respect to calcium carbonate) will likely cause calcification of the intergranular porosity and lower LNAPL transmissivity and storativity.
- The presence of abundant gypsum deposits is important as this will be a key source of sulfate that can support sulfate reduction and potentially high rates of natural source zone depletion (as described in **Section 5**).

4.1 Regional Geology

Basement rocks of St. Croix consist of highly deformed Upper Cretaceous deep marine sedimentary rocks largely composed of volcanogenic turbidites, pelagic mudstone, and chert with intercalated with coarse-grained clastic and largely quartzo-feldspathic rocks that are intruded by mafic igneous bodies and dikes (Whetten, 1966; Speed, 1979). Basement rocks outcrop in the mountainous East End and Northside Ranges of the island, which are separated by a northeast-southwest trending sedimentary basin that forms the island's Central Valley (**Figure 1-1**).

In the Central Valley, gently folded Neogene marine rocks unconformably overlie Upper Cretaceous basement rocks and define an overall marine regressive sequence (McLaughlin et al., 1995). The Neogene marine rocks consist of Oligocene/Early Miocene marl of the Jealousy Formation that formed in an open marine (bathyl) setting; Miocene-age Kingshill Limestone[1] that includes interbedded limestone, marl, and intervals of coral/terrigenous sediments that represent shoaling to shallow marine conditions; and Pliocene and Pleistocene-age reef and lagoon deposits of the Blessing Formation that represent shoaling and near-shore conditions (Cedarstrom, 1950; Gerhardt, 1978; Lidz, 1982, Gill and Hubbard, 1985; Lidz, 1988, McLaughlin et al., 1995; Gill et al., 1999). A generalized stratigraphic section of the Neogene marine rocks is provided as **Figure 4-1**.

Whereas the Central Valley marine rocks reflect an overall sea level regressive sequence from deep to shallow water, layers within the Kingshill Limestone record shorter periods of relative sea level fluctuations. Specifically, distinctive beds of coral, shell fragments and terrigenous sediments within the Kingshill Limestone are thought to reflect a global sea level lowstand that occurred in the Middle to Upper Miocene (Gill et al., 1999). At this time, enhanced erosion of upland Cretaceous-age basement rocks provided a terrigenous component to this interval of shallower water deposits that occur within deeper marine marl and limestone of the Kingshill Formation (Gill et al., 1999). The Kingshill Limestone and overlying Blessing Formation sequence reach a maximum thickness of about 400 feet on the south shore of St. Croix, although are substantially thinner in places owing to erosion following more recent tectonic uplift and subaerial exposure that occurred in the late Pleistocene and Holocene (Cedarstrom, 1950; McLaughlin et al., 1995).

Localized and laterally discrete 8 to 51 feet-thick alluvial deposits overlie Neogene Marine rocks in south-central St. Croix, and consist of calcareous sand, gravel, and cobbles with localized lenses of silt and clay (Graves, 1995). These alluvial deposits are frequently overlain by between 5 and 8 feet of topsoil.

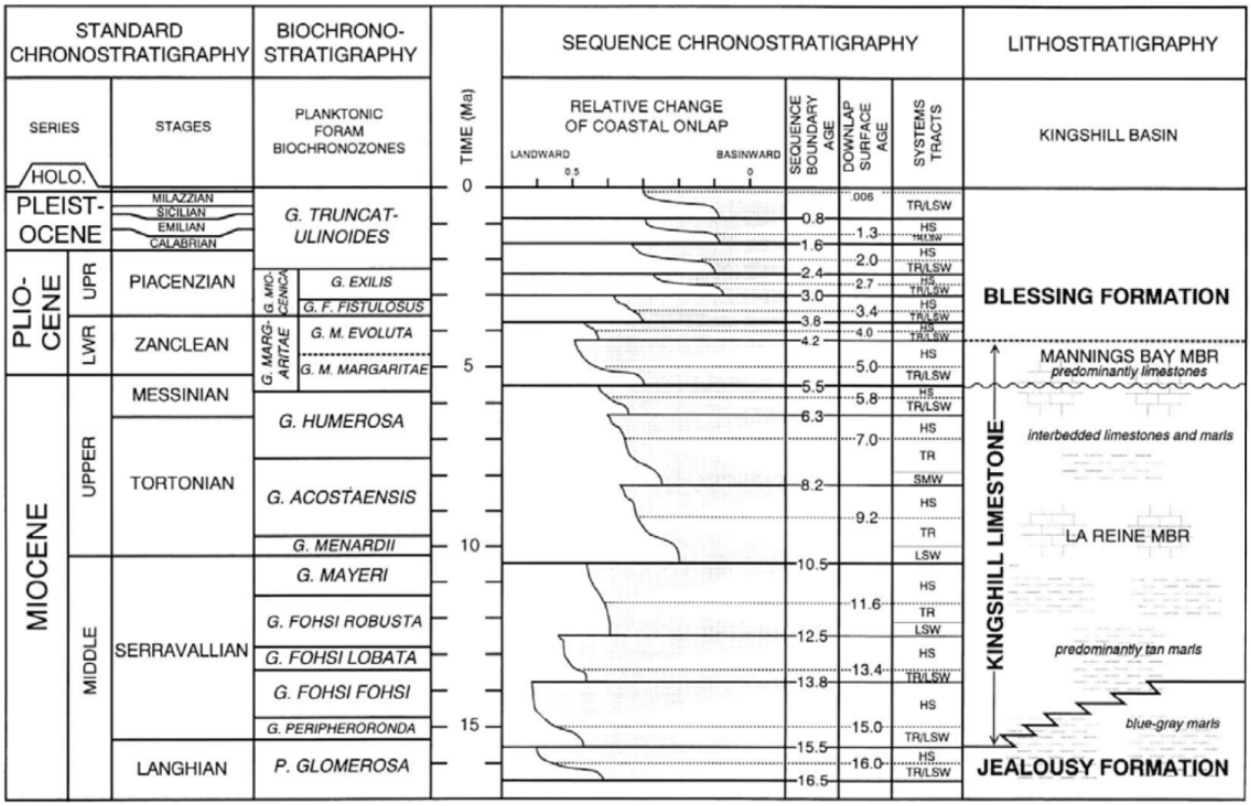


Figure 4-1 Generalized Stratigraphic Section of the Neogene Marine Rocks of St. Croix Central Valley, U.S. Virgin Islands (McLauglin et al., 1999).

4.2 Site Geology

The site is located on the south-central St. Croix coastline (**Figure 1-1**). The northern part of the site is situated on the Kingshill Limestone, and the southern portion overlies younger alluvial deposits that fill erosional channels in the Kingshill Limestone and grade into recent (pre- site development) reef and lagoon deposits principally of the former Krause Lagoon (Whetten, 1966) (**Figure 4-2**). During site development, areas of excavation and/or fill were established on the preexisting topography.

The Kingshill Limestone at the site and vicinity is described as buff- to white-colored soft marl (Graves, 1995). Deposits of the overlying Blessing Formation are absent at the site, and the nearest occurrence is reported from test holes drilled in Barren Spot well field approximately 1-mile northeast of the site (Graves, 1995) (**Figure 1-1**). Deposits of the Jealously Formation that underlie the Kingshill Limestone are typically encountered between 85 to over 120 feet bgs in the site vicinity in south-central St. Croix and are considered the base of the freshwater aquifer (Graves, 1995). The Jealously Formation is not likely encountered in site borings:

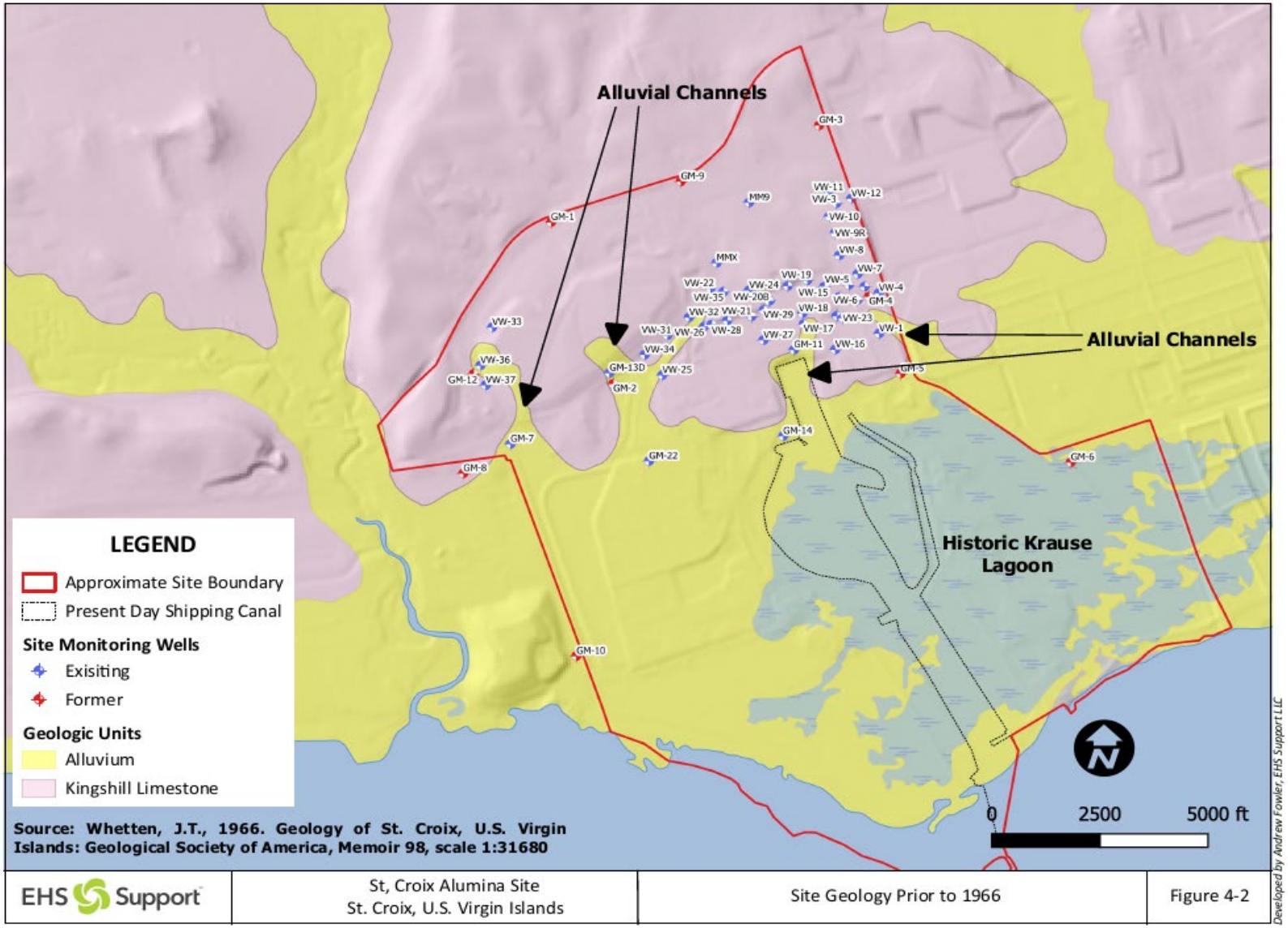


Figure 4-2 Site Geology Prior to 1966

As described on site boring logs (**Appendix A**), drilling at the site for monitoring well installation and geologic logging has utilized the following techniques:

- Hollow stem auger (HSA) with a split-spoon sampler (GM-1 through GM-12 and VW-33 through VW-37.
- Air rotary where cuttings were logged (VW-9R and VW-10).
- HSA with no sampler, solid stem augers (SSA), and unspecified rotary drilling where no *in-situ* samples were obtained and only cuttings were logged (VW-1 through VW-8, VW-11 through VW-32, and VW-38).
- No logs are presently available for wells GM-13D, GM-14, GM-22, MM9, or MMX for review.

Consequently, the distinction between limestone and silts/sands/gravels composed of limestone; or the distinction between voids and loose intervals of gravel/saturated sand; is not definitive and existing logs are of variable quality. The following discrepancies are identified in site drilling logs that support the contention information on several site drilling logs is questionable:

- VW-13 is logged entirely as “Hard Limestone” from 6 feet below ground surface (bgs) to the total depth of 40 feet bgs. VW-13B, which is located less than 10 feet away from VW-13, is logged as containing an interval of gypsum (hydrated $CaSO_4$) deposits below a ¼-inch chert lens from approximately 22 to 30 feet bgs, and containing a clay interval interbedded with limestone near the base of the well.
- VW-20 is logged as “Moderate Limestone” from 5 to 40 feet bgs and “Hard Limestone with clay, fine sand lenses” from 40 to 50 feet bgs, and “no returns” from 50 to 55 feet bgs. VW-20B, which is located 10 feet away from VW-20, is logged as containing an interval of “Interbedded clays and sands with limestone” from 30 to 33 feet bgs, and “No Cuttings” from 42 to 59 feet bgs following the observation of some clay material.
- Details are missing for the following wells, which are logged entirely as limestone; a contention that is inconsistent with the highly variable lithology logged in wells where 2-foot long split spoon samples were collected at 5-foot intervals and generally showed equal to greater proportions of limestone and calcareous sediments and/or clay:
    - VW-13 -“hard limestone” from 6 feet bgs to the total depth of 40 feet bgs.
    - VW-14 -“soft limestone” from 5 feet bgs to 35 feet bgs followed by a 10-foot zone of no recovery to the total depth.
    - VW-17 -“moderate limestone to the total depth 55 feet bgs).
    - VW-20 -“moderate limestone from 5 to the total depth of 40 feet bgs).
    - VW-21 and VW-22 -“soft limestone” from 5 to 50 feet bgs; some clay and sand lenses from 40 to 50 feet bgs.
    - VW-23 -“moderate limestone” from 5 feet bgs to the total depth of 45 feet bgs.
    - VW-26 -“soft limestone” from 0 to 35 feet bgs” and “no returns” from 35 feet bgs to the total depth of 45 feet bgs.
    - VW-27 -soft and moderate limestone from 0 feet bgs to the total depth of 40 feet bgs.

By focusing on well logs that include sufficient detail (particularly the highest resolution ones where split-spoon samples were obtained every 5 feet), an interval of gravels, sands, silt and clay within the Kingshill Limestone is identified that is broadly coincident with the location of the water table and intervals over which most site wells are screened. Cross sections showing the identified intervals of gravels, sands, silts, and clays within the Kingshill Limestone are provided as **Figure 4-3** and **Figure 4-4**. The identified deposits appear to be contemporaneous with an interval of reef deposits containing coral

and mollusk fossils within the Kingshill Limestone that is exposed in the quarry directly west of former well GM-12 and on the hillside north of GM-4 (Geraghty and Miller, 1982). The occurrence of reef and sediment deposits within the Kingshill Limestone likely coincide with the global sea level lowstand in the Middle to Late Miocene that is commonly observed within the Kingshill Limestone (Gill et al., 1999) (**Figure 4-1**).

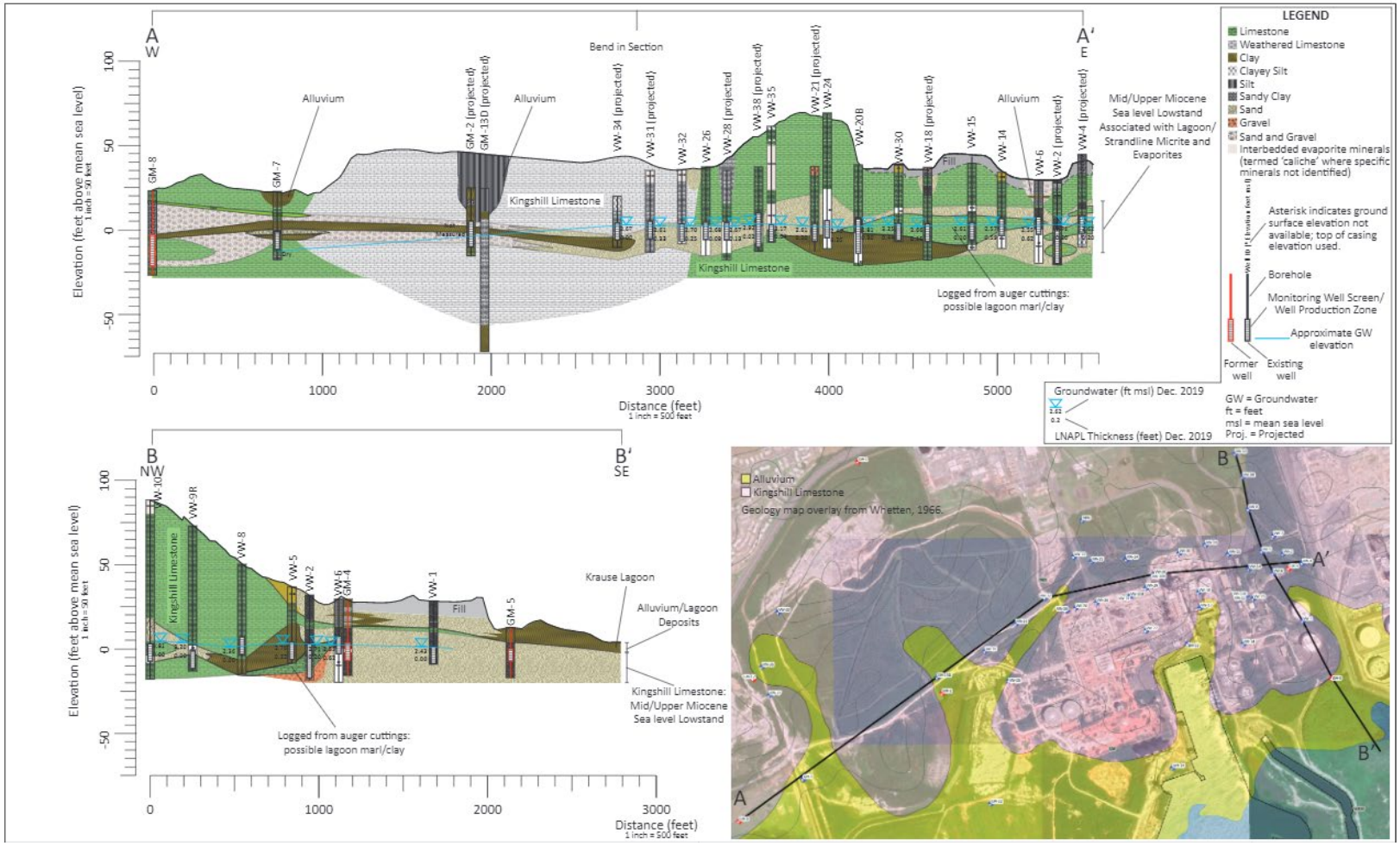


Figure 4-3 Cross Sections A-A' and B-B' (Small Scale)

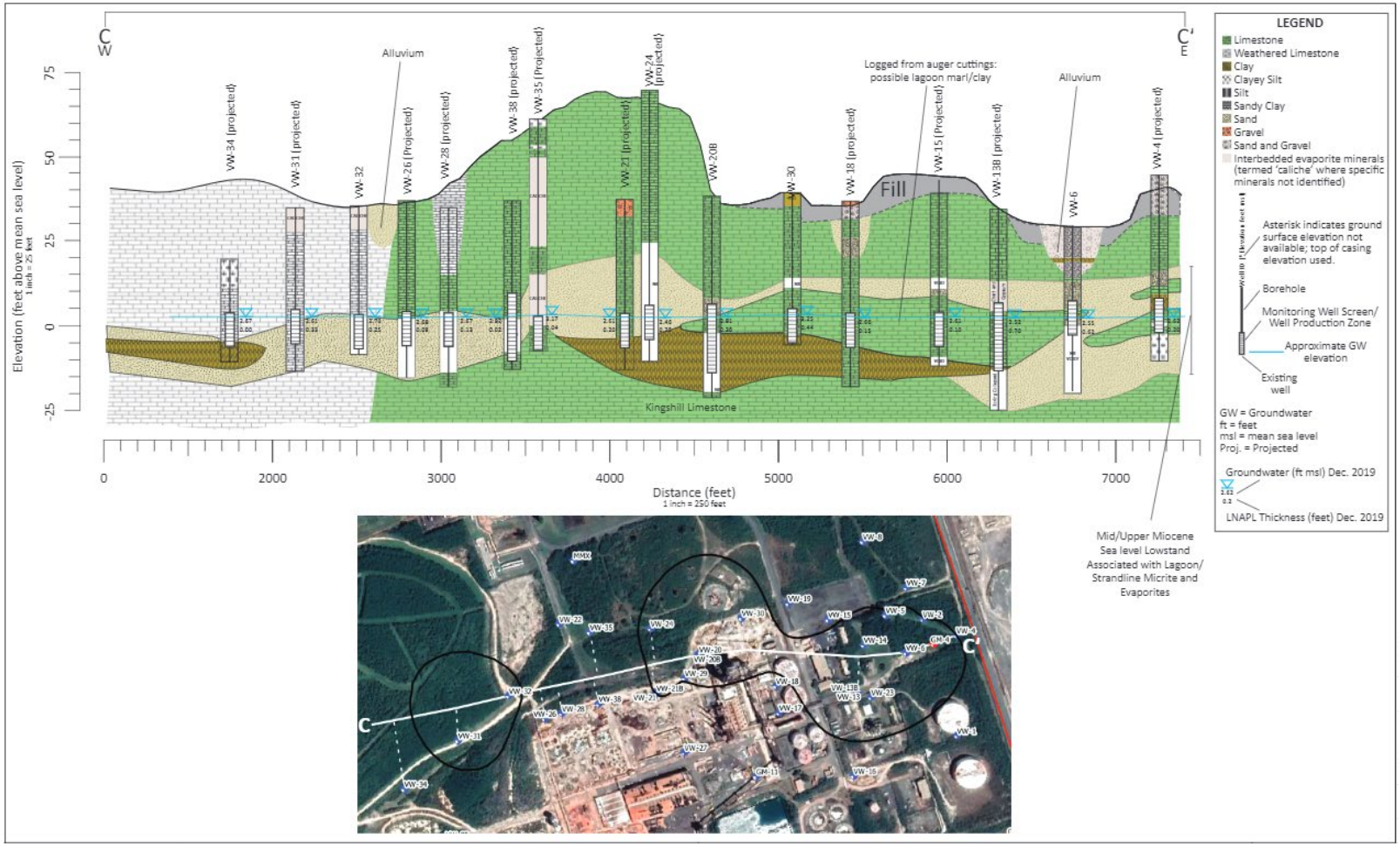


Figure 4-4 Cross Sections C-C' (Large Scale)

The identified deposits interbedded in the Kingshill Limestone are broadly consistent with facies models of carbonate lagoons, as shown in **Figure 4-5** below. At the site, sea level fall led to formation of a lagoon environment where lagoon muds (identified as clay in site borings) are interrupted laterally by deposits of calcareous sand and gravel "washover" deposits derived from barrier reef limestones during storm and/or extreme tidal events. Lagoons of this type that are somewhat isolated from seawater flux commonly contain assemblages of evaporite deposits that commonly precipitate from seawater in the sequence of calcium carbonate ($CaCO_3$) > gypsum ($CaSO_4$) > halite (NaCl) (Nichols, 2009). Lagoon evaporites also commonly contain a veneer of biogenic silicon dioxide (chert) that can form from diatom frustules that may accumulate in calm semi-isolated lagoons where evaporation is favored. Subsequent sea level rise led to a return to open marine conditions and deposition of the deep-water limestone and marl deposits more typical of the Kingshill Limestone.

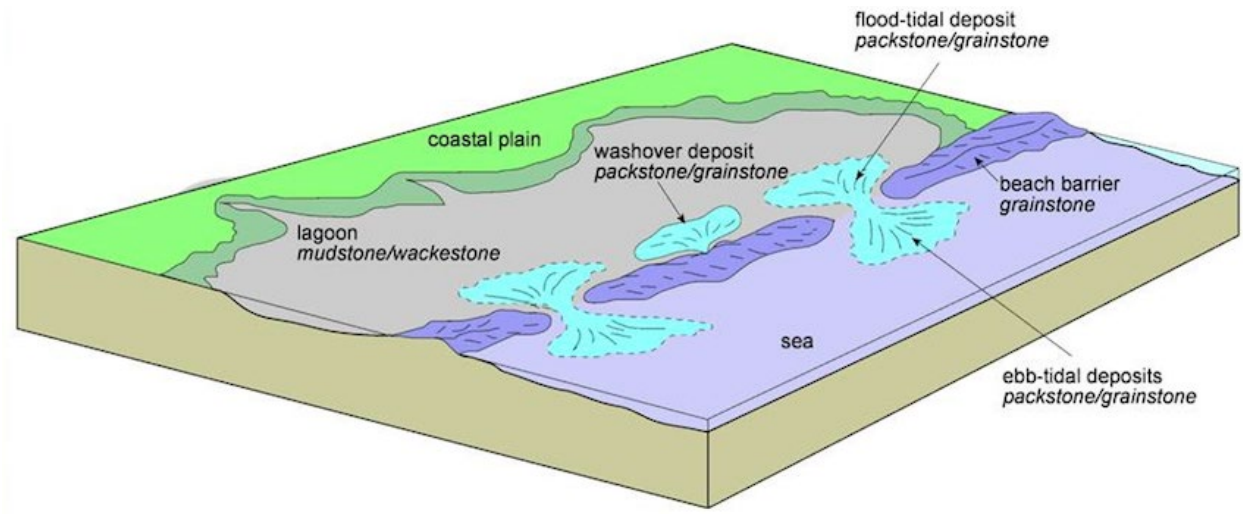


Figure 4-5 Generalized Facies Model of a Sheltered Lagoon in a Coastal Carbonate Depositional System (Nichols, 2009)

Chert, caliche (calcium carbonate), and/or gypsum deposits are identified within the Kingshill Limestone in site borings logs in wells VW-13B, VW-33, VW-37, VW-35, and VW-37, supporting the interpretation that deposits at the site within the Kingshill Limestone formed in a lagoon environment. Conceivably, these minerals are more widespread within the lagoon clay identified in several site borings but were not abundantly sampled due to the drilling techniques that were employed.

It important to clarify that evaporites are not the same as calcification of primary porosity and a reduction in permeability. Calcite that reprecipitated in pore spaces at the site identified and described by Geraghty and Miller, Inc., (1982) is (geologically speaking) a relatively recent process whereby groundwater supersaturated with respect to calcium carbonate precipitates calcite in cavities/porosity in the modern aquifer. Evaporite mineral sequences at the site (chert [amorphous SiO_2], calcite, and gypsum) are inferred to be depositional in origin. The log for well VW-13B (**Appendix A**) provides an excellent example of a marine evaporite sequence where a veneer of chert (biogenic silicon dioxide) overlies a sequence of interbedded gypsum. Primary permeability in these deposits is low for a different reason; lagoon evaporites are typically associated with low permeability and fine-grained siliciclastic (clay) and/or micrite (carbonate clay) associated with a relatively calm lagoonal/strandline depositional

environment. However, the occurrence of an evaporite lagoonal facies does not preclude the presence of secondary porosity or permeability features.

Following uplift and subaerial exposure of the Kingshill Limestone, several alluvial channels formed. The more recent alluvial channels are characterized by various proportions of soft or loosely consolidated sand, gravel, silt, and clay. The alluvial channels are now largely present in the subsurface beneath anthropogenic fill, although the channels are evident on a geologic map that was drafted prior to extensive site development (**Figure 4-2**). It is not clear how the channels are hydraulically connected to lagoon deposits within the Kingshill Limestone; however, available data suggests that the channels are largely above the water table on the northern half of the site (**Figure 4-3** and **Figure 4-4**).

South of the eroded edge of the Kingshill Limestone and on the southern portion of the site, soft to very stiff organic clays, silty clays, and clayey silt deposits are present that formed in the historic Krause Lagoon. Krause Lagoon and the surrounding mangrove swamps were drastically altered after about the 1960s following construction of industrial facilities and dredging of the shipping channel. The Krause lagoon deposits overlie a 4 to 10-foot-thick sand and gravel layer from about 10 to 30 feet below sea level that is derived from limestone and coral fragments weathered from the Kingshill Limestone. The hydraulic connection between the Krause lagoon and Kingshill Limestone deposits is uncertain (Geraghty and Miller, 1982; Gill and Hubbard, 1987).

4.3 Hydrogeology

The general direction of groundwater flow beneath the site is to the south-southwest and south towards the sea (GMS, 2020), consistent with groundwater equipotential in the broader region (Graves, 1995). The groundwater elevation at the site typically ranges from about 0.5 to 3.5 feet above mean sea level (msl) (**Figure 4-6**). Groundwater at the site is largely present within the Kingshill Limestone.

Site groundwater monitoring wells are designated as upgradient, source are, or downgradient. Source area wells were selected as those that most recently had LNAPL present, upgradient wells are located the north of the source area and downgradient wells are located south of the source area. Wells are listed on **Table 2-2**.

Carbonate lagoon deposits frequently include micrite interbedded with, sands, silts and reworked limestone clasts along the fringes that are sourced from periodic storm events (Harris, 1985). As a result, the hydraulic properties of carbonate lagoon deposits are highly variable. Original permeability of the Kingshill Limestone is in part related to the depositional environment; deeper water bathyal deposits and shallow lagoon deposits generally had low original porosity owing to a higher fraction of clay-sized carbonate particles (micrite), whereas shallower reef and washover deposits generally had a higher original porosity and permeability due to a larger grain size and the presence of coral and shell fragments (Geraghty and Miller, Inc., 1982). Therefore, the distribution of the lagoon deposits in relation to sand pack/well screen intervals at the site places a strong control on hydraulic properties of the groundwater saturated zone, specifically, large variations in hydraulic conductivity and storativity are expected. The location of the lagoon facies in relation to site well screens is provided as **Figure 4-7**, which illustrates the high variability of hydraulic properties in the monitored saturated zone at the site and associated controls on LNAPL mobility.

Geraghty and Miller, Inc., (1982) synthesized their own observations during monitoring well installations with information from geological and geotechnical studies carried out at the plant site and surrounding area by the USGS and researchers from various universities, to identify the following:

> *"Weathering and percolating subsurface waters have altered the original texture of the limestones in places. In many instances porosity has been destroyed by the alteration of sand grains to micrite (carbonate clay) and by infilling of the interstices between grains with crystalline calcite. In other places, percolating water has increased the porosity by dissolving cement between grains, and by creating cavities and caverns."*

Consequently, in addition to variations in the primary porosity of different lithologies at the site, percolation of precipitation and groundwater seepage at the site has re-precipitated sand-sized particles as micrite and filled pore spaces with secondary calcite (Geraghty and Miller, Inc., 1982). However, review of site borings logs has identified numerous poorly cemented and permeable layers within the Kingshill Limestone that consist of sand, gravel, sandstone, sandstone-marl mixtures. Indeed, the frequently encountered no recovery- zones during drilling at the site likely reflect zones of extremely loose sediment. Whereas these zones may have been attributed to void spaces, they are often associated with changes in drilling resistance which suggests not all of these intervals are indeed voids.

4.4 Hydraulic Conductivity

Slug testing was completed in five monitoring wells (VW-1, VW-17, VW-25, VW-27, and VW-34) by Groundwater and Environmental Services, Inc. (GES) (GES, 2017). Hydraulic conductivity (K) values spanned three orders of magnitude and are summarized in **Table 4-1**. The results are distinctive for wells screened across washover deposits, weathered/soft limestone, and moderate limestone.

The high K for VW-1 was previously attributed to the possible presence of an adjacent void or dissolution cavity in limestone (GES, 2017). The high K is equally attributable to the presence of saturated loose sand or washover gravels, despite the K value for VW-1 exceeding the upper end of representative K values for carbonate reef deposits (5,670 ft/day) and gravel deposits (8,500 ft/day) (Domenico and Schwartz, 1990). On the first hand, the lithology across the VW-1 screen/sand pack includes sands, sandy gravel, and gravel. The absolute value given for the VW-1 hydraulic conductivity is likely inaccurate given the anisotropic lithology across the screen/sand pack and limitations of curve fitting to rapid-response slug test data. However, the high value is qualitatively representative of a very permeable interval.

The material across which the VW-17, VW-25, VW-27, and VW-30 sand pack and well screens extend has K values that fall between 3.97 and 31 feet/day (**Table 4-1**). These values are within the range of K values typical of, but at the lower end of, karst/reef limestone deposits of 0.3 to 5,670 ft/day but are higher than the maximum range expected for limestone or dolomite formations of 1.7 feet/day (Domenico and Schwartz, 1990). This result suggests that limestone at the site contains conductive fractures, or, that lithological heterogeneity important for groundwater and LNAPL mobility was overlooked due to limitations in the drilling technique that was employed. Overall, the available hydraulic conductivity attest to the high variation in hydraulic properties of deposits at the site.

Table 4-1 Slug Testing Results (GES, 2017)

Well	Date	Bouwer and Rice Hydraulic Conductivity (ft/day)	Kansas Geological Survey (KGS) Hydraulic Conductivity (ft/day)	Screen/Sand Pack Geology
VW-1	3/29/2017	14,900	17,900	Fine to coarse sand, sandy gravel, and gravel
VW-17	3/28/2017	3.97	4.65	Moderate limestone
VW-25	3/28/2017	31	23.9	Soft limestone/No recovery
VW-27	3/29/2017	5.95	6.18	Moderate limestone
VW-34	3/30/2017	29.9	17.87	Weathered to hard limestone/marl

4.5 Groundwater Elevations

As shown on **Figure 4-3** and **Figure 4-4**, groundwater is typically encountered in the subsurface interval interpreted as lagoon facies, and it is across this interval that most site monitoring wells are screened. The exceptions are GM11, GM14, GM7, and GM13D, which monitor deeper groundwater intervals. The following details regarding water level elevations relative to well screen elevations are provided and are based on the data provided in Appendix B2.

Wells where LNAPL has historically been detected:

- Several wells have had screens submerged at some point in the past (VW2, VW6, VW15, VW18, VW29, and VW30).
- Of these wells, only VW2 and VW30 screens have consistently been submerged below the LNAPL.
- Of these wells, only VW-2 had a filter pack submerged below the LNAPL. This occurred on one occasion at which time the LNAPL elevation was equal to the filter pack elevation.
- Of these wells, only VW2 and VW30 had screens submerged below the LNAPL during the last three quarters.

Wells where LNAPL has *not* historically been detected:

- Three wells (VW3, VW11, and VW12) screens are submerged by groundwater during most monitoring events. These three wells are co-located at the upgradient site boundary where LNAPL is not expected. Additionally, wells VW7, VW8, VW9R, and VW10 are located between the LNAPL source area and the location of these wells. These wells delineate the extent of LNAPL impacts upgradient of the LNAPL plume.
- The screen for VW37 is consistently submerged. This well is up/side-gradient from the LNAPL source area and near VW-36, which has only had a submerged screen three times.
- GM11, GM14, GM7, and GM13D consistently have groundwater submerged screens. These wells monitor the dissolved-phase plume in deeper groundwater intervals beyond the network of shallower monitoring wells that do not have submerged screens.

As shown on **Figure 4-6**, the groundwater elevation at GM-22 is anomalous and represent a 'mound' when evaluated in the context of other site groundwater elevations. We note the following:

- GM-22 is within the footprint of the former red mud pond.
- Nearby and former well GM-10 historically had anomalously high groundwater elevations, which was attributed to artificial recharge from a former cooling pond that was 10 feet above sea level and filled with seawater for cooling a power plant and residual brine from a desalinization plant (Geraghty and Miller, 1982).
- Well GM-7 is frequently gauged as dry. The top of casing at GM-7 is 26.04 feet above sea level, and the well is 35 feet deep. Therefore, the groundwater mound is not present in this location.
- A complex wastewater treatment system recharges the groundwater system with reclaimed water west of wells GM-10 and GM-22. The system contains a network of subsurface pipes that may also potentially leak.

Consequently, groundwater at GM-22 (and GM-10) is likely perched due the buried historical features and/or abundant clay in these locations from the historic Krause Lagoon that was present where these wells are sited. The source of the water is conceivably from the groundwater recharge system or leaking infrastructure, which has been in place for decades. Groundwater geochemical fingerprinting is required to verify if the origin of the groundwater at GM-22 is injectate/leakage from the groundwater reclamation system (with the potential to locally affect site groundwater flow directions) or is precipitation/groundwater perched on buried historic infrastructure.

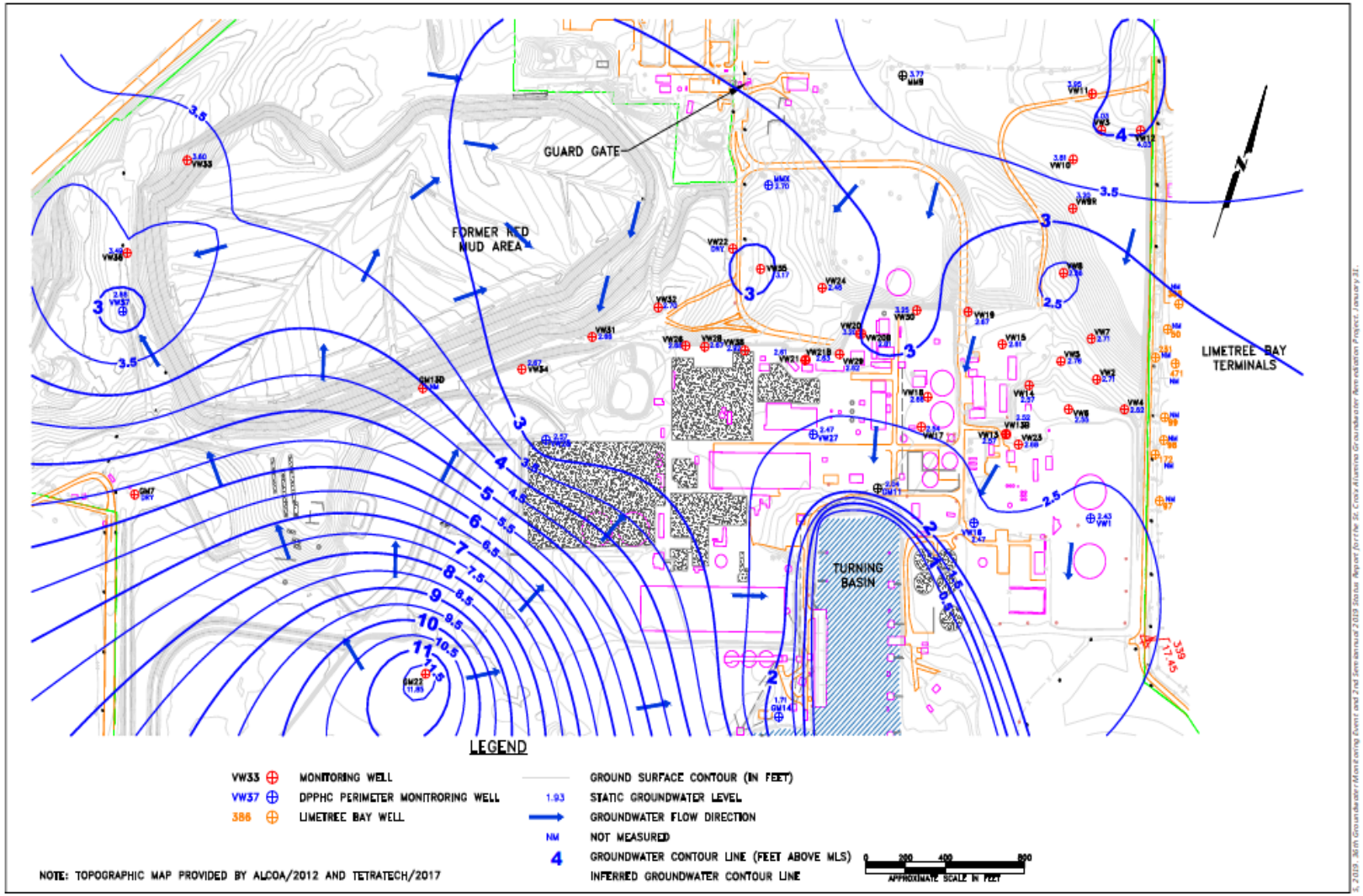


Figure 4-6 Groundwater Elevations (Corrected for LNAPL Density) December 2019

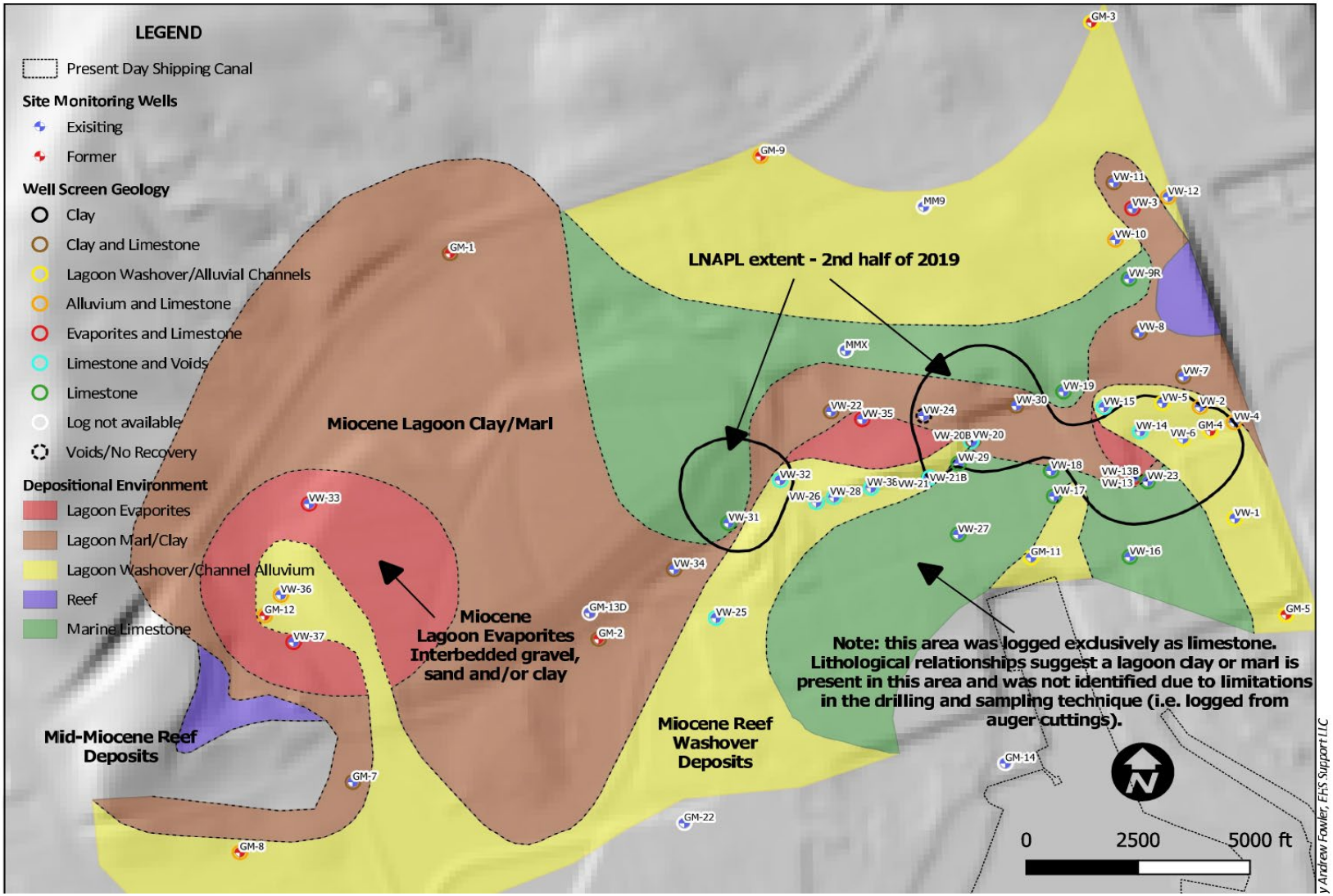


Figure 4-7 Well Screen Geology

4.6 Tidal Influence

GES evaluated water levels in twelve monitoring wells at various distances from the shoreline to determine the magnitude of tidal influence on groundwater levels at the site (GES, 2017). Overall, the magnitude of tidal influence was small (<0.2 feet) (**Table 4-2**), consistent with the low mean tidal range (0.69 feet) as measured at the nearby Lime Tree Bay National Ocean and Atmospheric Administration (NOAA) tide gauge (NOAA, 2020).

The general trend showed a decrease in tidal influence from 0.201 feet in GM-14 (100 feet from the shore) to 0.026 - 0.027 in MW-9R and MW-10 (1693 to 1914 feet from the shore, respectively) (see **Figure 4-8** below). The exception to the trend of decreasing tidal influence with increasing distance from shoreline is for VW-36 located 3739 feet from the shoreline with a tidal influence of 0.164 feet, which was the second highest value measured. VW-36 is located in the center of an historic alluvial channel that connects to the shoreline (**Figure 4-2**) and is screened across reef washover deposits. The tidal response in VW-36 suggests a hydraulic connection between alluvial deposits and washover deposits in this location.

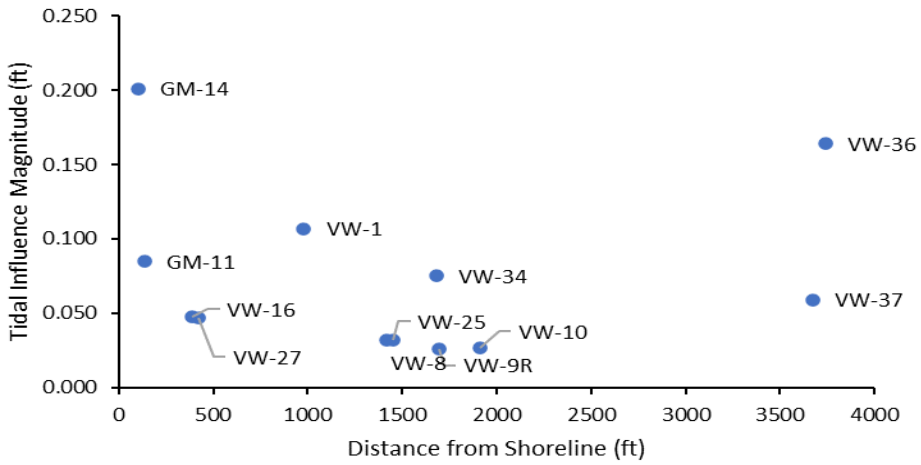


Figure 4-8 Tidal Influence in Twelve Site Monitoring Wells Based on Data from GES (2017)

Table 4-2 Tidal Influence in Twelve Site Monitoring Wells Based on Data from GES (2017)

Well	Tidal Influence Range		Well Location	Geology Over Screen/Sand Pack
	Time Period (days)	Water Level Change (feet)	Distance to Harbor Shoreline (feet)	
GM-11	0.525	0.085	135	Loose and permeable carbonate sand and gravel; carbonate sand gravel silt and clay.
GM-14	0.546	0.201	100	No log available
VW-1	1.135	0.107	979	Fine to coarse sand, sandy gravel, and gravel
VW-8	0.458	0.032	1,420	Hard limestone, clay interbeds
VW-9R	0.348	0.026	1,693	Moderate limestone
VW-10	0.944	0.027	1,914	Moderate limestone; void
VW-16	0.477	0.048	385	Soft, moderate, and hard limestone
VW-25	0.356	0.032	1,453	Soft limestone
VW-27	0.872	0.047	418	Moderate limestone
VW-34	0.629	0.075	1,681	Weathered to hard limestone
VW-36	0.269	0.164	3,739	Silt and clay; coarse calcareous sand
VW-37	0.654	0.059	3,673	Hard limestone; caliche ±shell fragments; clay

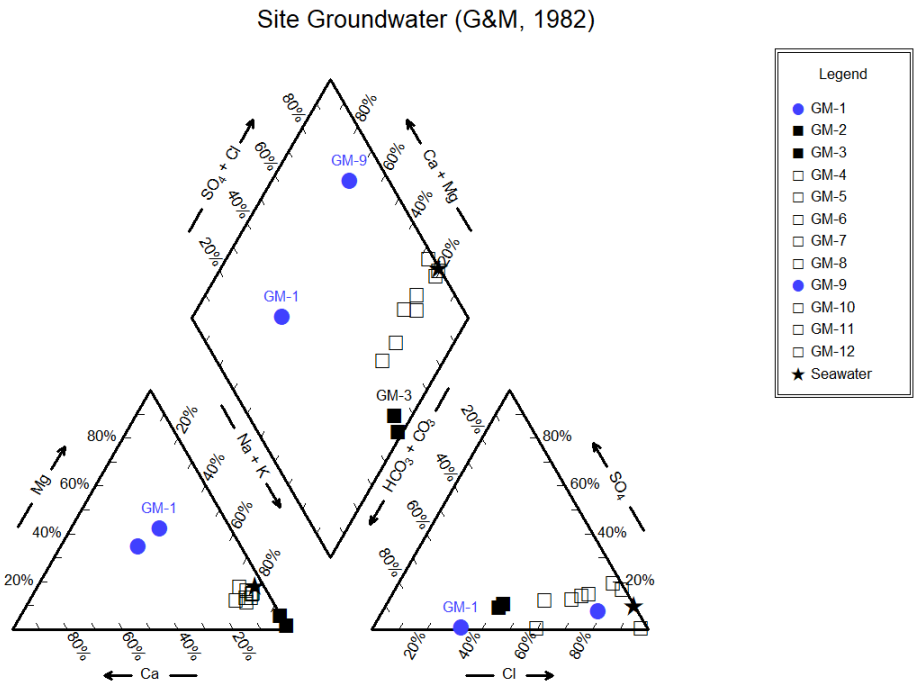
4.7 Groundwater Geochemistry

Groundwater inorganic geochemistry data for fingerprinting water types at the site is limited to the Geraghty and Miller, Inc., (1982) study. Groundwater in Kingshill Limestone is relatively fresh, although salinity increase sharply near the shoreline and in the vicinity of former wells GM-5, GM-6, and GM-10, which have chloride comparable to seawater.

In more detail, a Piper plot of the 1982 water samples (**Figure 4-9**) shows three main water types:

- Ca/Mg-HCO_3 and Ca/MgMg-SO_4 waters with relatively low TDS, low Na, and Ca=Mg represented by wells GM-1 and GM-9 along the upgradient site boundary. GM-1 has elevated phosphate and GM-9 has high nitrate, suggesting these samples were impacted by an off-site source of sewage effluent.
- Na-HCO_3 water with low Ca and Mg>>Ca. This water type is represented by wells GM-2 and GM-3 along the upgradient property boundary. This water type likely reflects regional groundwater sourced from precipitation that has reacted with limestone aquifer rocks.

- NaCl water compositions fall on a mixing line between the Na-HCO_3 water type and mean seawater. This water type accounts for most groundwater at the site and reflects the mild groundwater/seawater mixing across the site that occurs in response to the mild tidal influence.



Blue dots indicate samples likely influenced by sewage effluent (GM-1 and GM-9), Black squares indicate regional groundwater (GM-2 and GM-3), and open squares reflect mixing between groundwater and mean seawater.

Figure 4-9 Piper Plot of Groundwater Samples from GM (1982).

5 LNAPL Conceptual Site Model

5.1 LNAPL Extent

The extent of LNAPL impacts is currently limited to the interior portions of the site as shown on **Figure 5-1** and **Figure 5-2** below**;** a chronology of LNAPL extent is shown in **Appendix B1** and a table of well screens relative to historic water and LNAPL levels (October 2002 through December 2019) is provided in **Appendix B2**.

A simple comparison of historical maps for 2006 versus 2019 shows that the inferred LNAPL extent has reduced over time with notable reductions in LNAPL thicknesses in response to both LNAPL recovery activities and natural mass losses.

In interpretation of the data, it is important to note that five wells where LNAPL is present have had submerged screens in the past (VW2, VW6, VW15, VW18, VW29, and VW30), which may impact on the interpretation of temporal trends in LNAPL thickness. Of these wells only wells VW2 and VW30 had consistently screens submerged below the LNAPL, with well VW2 also having a filter pack submerged below the LNAPL. Assessment of LNAPL thicknesses during periods of low groundwater is important in these wells.

In addition, there are a number of other wells where submerged screens are present but LNAPL is not likely to be present. These include upgradient wells VW3, VW11 and VW12, side gradient well VW-36 and downgradient deep groundwater monitoring wells GM7, GM11, GM-13D and GM14. Other groundwater monitoring wells closer to the LNAPL, which do not have submerged screens, define the lateral limits of LNAPL impacts. The geometry of the LNAPL does not reflect groundwater gradients at the site and historical maps show an east to west extension of the LNAPL and limited migration to the south (except in the eastern most portion of the site. As described in **Section 4**, the geology of the site is complex and large contrasts in hydraulic conductivity are evident. The presence of marl and other low permeability lagoon deposits closer to the turning basin, which exhibit low to no LNAPL permeability, supported the observed dissipation of LNAPL in an east-west direction and prevent migration to the south.

The chronology of LNAPL extent shows that despite seasonal variability in groundwater elevations the LNAPL extent is stable to declining and consistent decreasing trends in recovery well LNAPL thickness measurements are observed over time. The major declines in LNAPL thickness over time are evident in the temporal plots of LNAPL thickness which are provided in **Appendix B** and discussed in further detail below.

This assessment is somewhat constrained by the limited LNAPL thickness monitoring data for some of the monitoring wells which have only been recently added to the gauging program. Major declines in LNAPL thickness over time are evident in monitoring wells VW4, VW7, VW19, VW32, 99, 231 and in the majority of recovery wells (VW5, VW15, VW18, VW23, VW24, VW26, VW28, VW29, VW29, VW31). The magnitude of these decreases in LNAPL thickness are significant and in combination with the consistent decreasing trends of LNAPL recovery over time demonstrate the success of past LNAPL removal actions and the decreasing benefits of ongoing recovery efforts. It should be noted that LNAPL thickness measurements at recovery well VW2 have been relative stable and this may be related to its proximity

to the groundwater depression associated with VW13B and its proximity to the source area on the eastern side of the property.

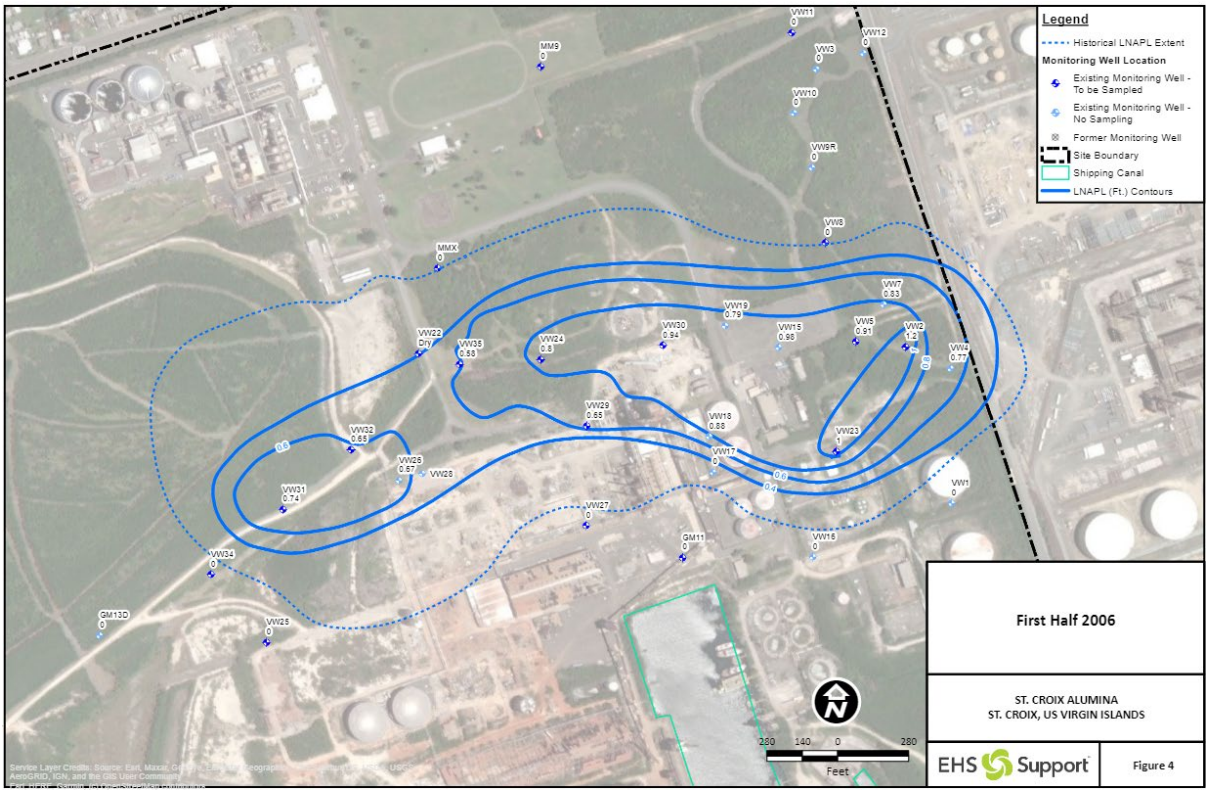


Figure 5-1 LNAPL Extent and Thickness 2006

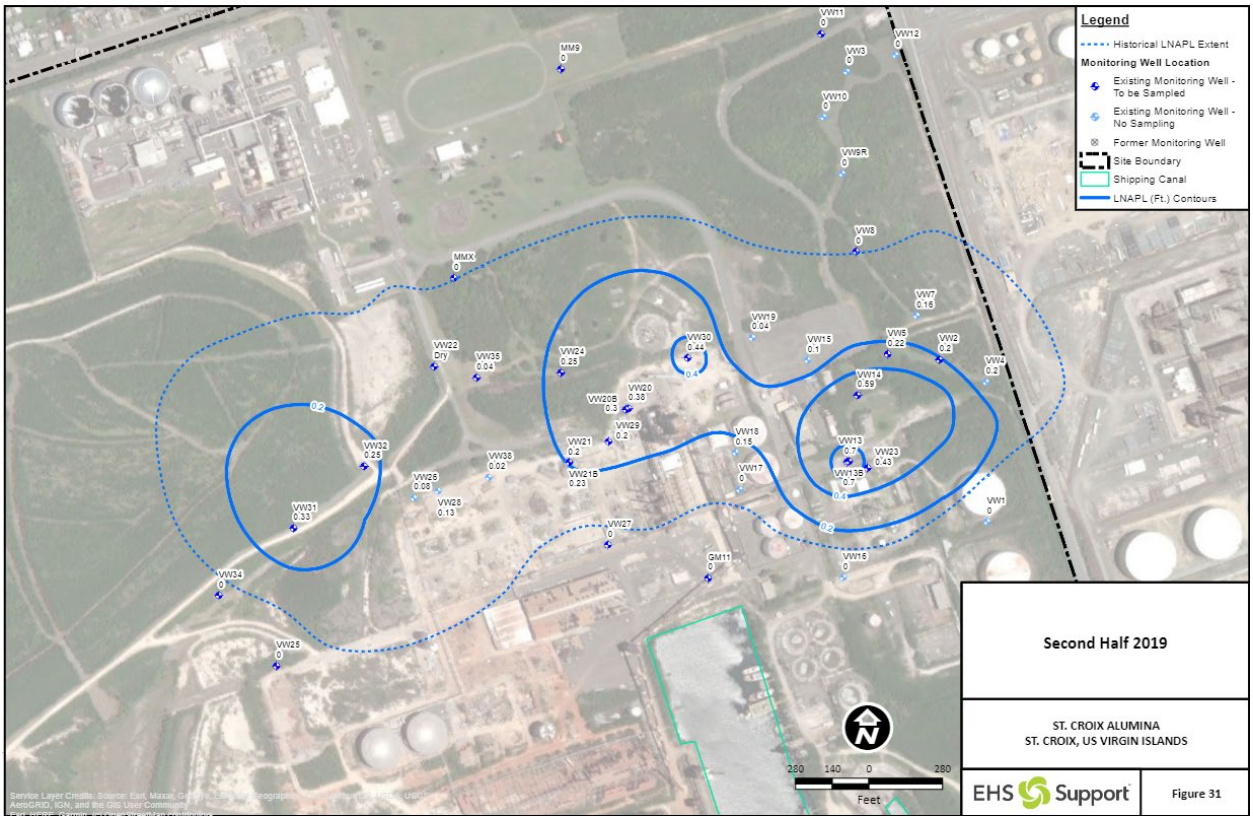


Figure 5-2 LNAPL Extent and Thickness 2019

5.2 LNAPL Chemistry

Assessment of the LNAPL chemistry at the site indicates that it is a middle distillate consistent with diesel or No.2 Fuel Oil. Fingerprinting conducted in 1997 (Hess Oil 1997) to assess possible sources has identified the LNAPL on the site to have a different chemical signature to that on the adjacent refinery/terminal site.

As part of the risk assessment completed for the site ES&T concluded,

"Chromotographic analysis have indicated that the PSPH at the site is a mixture of diesel and fuel oil and is highly weathered. Hence much of the volatile COCs from the PSPH have been degraded and the potential risk due to tap water consumption is low" (pp 11)

As part of the assessment completed by ES&T samples of LNAPL were collected from five wells and analyzed for BTEX and Polycyclic aromatic hydrocarbons (PAH) constituents and effective solubilities calculated. The calculated effectives solubilities from ES&T's report is summarized in **Table 5-1** below.

Table 5-1 Historically Calculated Effective Solubilities

Constituent	ES&G Calculated Action Level (µg/L)	Well Number and Associated Calculated Effective Solubility (µg/L)				
		VW4	VW15	VW18	VW23	VW28
Benzene	5	ND	3.31	ND	ND	0
Ethylbenzene	700	7.32	13.35	19.73	57.39	22.41
Toluene	1,000	4.83	12.97	1.73	13.46	1.41
Xylene	10,000	1.15×10^{-5}	2.35×10^{-5}	6.54×10^{-6}	2.34×10^{-5}	2.34×10^{-5}
Anthracene	256	1.4×10^{-2}	9.8×10^{-3}	2.0×10^{-2}	1.32×10^{-2}	1.3×10^{-2}
Benzo(a)anthracene	0.196	2.0×10^{-4}	5.0×10^{-4}	ND	2×10^{-4}	2.0×10^{-4}
Benzo(b)fluoroanthene	0.196	1.1×10^{-5}	6.92×10^{-6}	6.72×10^{-6}	9.33×10^{-6}	ND
Benzo(k)fluoroanthene	1.96	6.0×10^{-4}	6.0×10^{-4}	8.0×10^{-4}	6.0×10^{-4}	7.0×10^{-4}
Chrysene	19.6	ND	6.97×10^{-5}	6.21×10^{-5}	ND	2.3×10^{-5}
Fluoranthene	2044	5.9×10^{-2}	4×10^{-2}	7.0×10^{-2}	2.5 x 10-2	4.8×10^{-2}
Naphthalene	0.9	27.51	26.29	24.38	33.56	34.12
Phenanthrene	NA	1.62	1.48	0.76	1.42	1.52
Pyrene	25.5	7.4×10^{-2}	0.11	0.03	7.0×10^{-2}	8.0×10^{-2}

µg/L – micrograms per Liter
ND – non-detect

The historically calculated effective solubilities align well with literature values for the relative constituent ratios in diesel fuel and the calculated effective solubility. The literature values for constituent concentrations in diesel fuel are provided in **Table 5-2** and the calculated effective solubility is provided in **Table 5-3**. It should be noted that in the context of the Site the diesel would have been highly refined diesel from refineries conforming to US Standards (low aromatic diesel) and as such light and aromatic fractions would be at the low end of the values provided in **Table 5-2** below.

In general, there is good alignment between the ES&T values and literature values. The diesel and fuel oil LNAPL at the site appears to be more aromatic rich than the low end values provided in the table below. Despite this the LNAPL exhibits low solubility and consistent with the assessment conducted by ES&T does not contribute dissolved phase constituents above action levels.

Table 5-2 Range of Key Constituents in Diesel or No.2 Fuel Oil

Constituent	Weight %
Benzene	0.003 to 0.1
Ethylbenzene	0.007 to 0.2
Toluene	0.007 to 0.7

Constituent	Weight %
Xylene	0.02 to 0.5
Naphthalene	0.01 to 0.8
C5 – C8 Aliphatics	< 1%
C9-C18 Aliphatics	35%
C19+ Aliphatics	43%
C9 – C12 Aromatics	22%

Source: Polter and Simmons (1998) – Composition of Petroleum Mixtures Vol 2 – Total Petroleum Hydrocarbon Criteria Working Group Series. Amherst MA: Amherst Scientific.

Table 5-3 Effective Solubility Calculations Based on Literature Weight Percent for Diesel

Chemical	Solubility (mg/L)	Weight%	Molecular Weight (assumed compound for mixtures provided in brackets)	Effective Solubility
Benzene	1,790	<0.003	78.11	<0.14 mg/L
Ethylbenzene	169	<0.007	106.17	<0.02 mg/L
Toluene	526	<0.007	92.14	< 0.08 mg/L
Xylene	161	<0.2	106.16	< 0.06 mg/L
Naphthalene	31	0.01	128.17	$<5 \times 10^{-6}$ mg/L
C5 – C8 Aliphatic	0.07	< 1%	86.18 (hexane)	$<1.6 \times 10^{-3}$ mg/L
C13 – C18 Aliphatic	3.5×10^{-4}	35%	212.41(petadecane)	$<1.76 \times 10^{-4}$
C19 - C36 Aliphatic	1.5×10^{-6}	43%	338.62 (tetracosane)	$<6.6 \times 10^{-7}$
C6 – C10 Aromatic	51	5%	92.14 (toluene)	<5.5 mg/L
C11 – C28 Aromatic	5.8	17%	142.1 (1 methyl Naphthalene)	<1.7 mg/L

mg/L – milligrams per Liter

In the context of the site data to date, dissolution of hydrocarbons into groundwater and downgradient migration of constituents is not considered significant.

5.3 Dissolved Phase Conditions

In general, the historical data demonstrates that very limited dissolved phase hydrocarbon impacts are observed proximal and downgradient of the LNAPL effected areas, with limited to non-detectable concentrations of naphthalene and BTEX constituents. The dissolved phase impacts are consistent with the chemistry of the LNAPL, which comprises heavily weathered diesel/fuel oil range constituents.

Based on the second semiannual groundwater sampling event for 2019 (conducted on December 16-17, 2019) the key findings comprised:

BTEX were not detected in the groundwater samples collected from any of the groundwater monitoring wells at the site.

Only low concentrations of Naphthalene were detected in groundwater samples (results J flagged) with a maximum concentration of 0.0786J micrograms per liter (µg/L) detected in GM11.

Only low concentrations of TPH-DRO were detected in monitoring wells VW27, GM11, GM14, VW1, with the highest TPH-DRO concentration of 0.30 mg/L detected in GM11.

Evaluation of skinner list compounds identified no additional volatile constituents and low concentrations (J flagged) concentrations of PAHs and phthalates (Di n-butyl phthalate and Bis (2-ethylhexyl phthalate). The detections of low levels of PAHs is consistent with the chemistry of LNAPL and the very low solubility of these compounds.

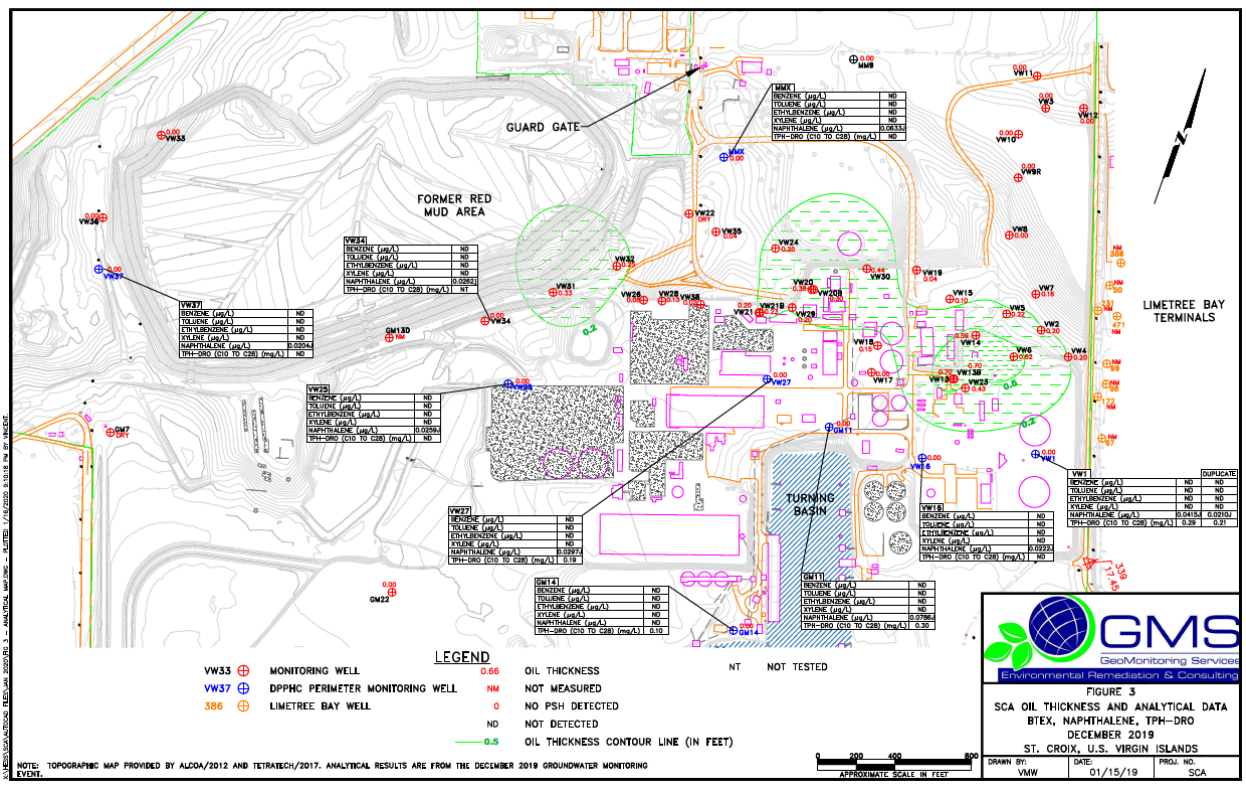


Figure 5-3 SCA Oil Thickness and Analytical Data

Source: GeoMonitoring Services, 2019

Review of the historical groundwater monitoring data (from 2002 to current) indicates conditions consistent with the data from the 2nd semi-annual 2019 groundwater sampling event. In general, BTEX and Naphthalene constituents are not detected in groundwater (trace hits of BTEX initially occurred in VW16 but resampling of the well yielded no BTEX detections). Low level concentrations of DRO constituents have been detected in groundwater and concentrations can be considered to be generally

stable with all concentrations detected below 1.0 mg/L. The DRO concentrations detected are not indicative of LNAPL and field observations have not noted the presence of LNAPL or sheens during sampling at those locations.

Extensive assessment of natural attenuation processes has not been conducted at the site. However, natural attenuation can be inferred via the results of low flow groundwater sampling techniques since stabilized groundwater parameter data are collected (pH, electrical conductivity [EC], dissolved oxygen [DO], and oxidation reduction conductivity [ORP]). This data clearly shows reducing conditions in wells potentially supportive of nitrate and sulfate reduction and methanogenesis in key downgradient locations relative to background (side- and upgradient) locations. Key wells where reducing conditions were observed are summarized in **Table 5-4** below from the 1st Semi-annual Status Report 2020 (GeoMonitoring Services, 2020).

Table 5-4 Groundwater Parameters

Well	ORP (mv)	Dissolved Oxygen (mg/L)	Well Location Relative to LNAPL Extent
VW16	-64	0.31	Downgradient
GM11	-299.9	0.12	Downgradient
VW27	-138.1	0.27	Downgradient
VW1	-165.2	0.16	Downgradient
VW-34	-159.2	0.18	Side- to downgradient
VW-25	61.2	0.64	Side- to downgradient
VW-37	96.4	5.7	Sidegradient
GM-14	72.7	0.65	Seawater affected, downgradient
MMX	98.8	1.64	Upgradient

mv – millivolt
mg/L – milligrams per Liter

In the discussion of that report, some of the LNAPL mass losses are attributed to natural attenuation (natural source zone depletion) processes. GeoMonitoring Services stated,

Based on field readings and calculated recovery rates, GMS estimates 11,858 barrels of oil have been recovered by the recovery system from January 1, 2002 through December 31, 2019. The GES/ES&T modeling estimate for remaining hydrocarbons in place for December 2019 was 3,379 barrels, which is a 34,418-barrel decrease from the baseline estimate from June 2004 data. **This 91.1% decrease in estimated hydrocarbons in place is indicative of the effectiveness of the recovery system and natural attenuation** (pp iii, emphasis added).

The estimates of mass removed via both recovery efforts and natural mass loss processes are compelling and requires further evaluation and assessment.

5.4 Risk Assessment on LNAPL and Dissolved Phase Impacts

In the context of the LNAPL and dissolved phase impacts at the Site the risks are limited to on-Site receptors. Groundwater monitoring data indicates that the plumes are stable and confined to the Site. In this context potential exposures are limited to on-Site receptors. Based on the depth to groundwater direct contact exposures are considered incomplete and the only potentially complete pathways comprise ingestion of groundwater (which is not currently a complete pathway) and vapor intrusion.

A detailed discussion of the Conceptual Exposure Model (CEM) is provided in Tier 1 Risk Assessment (ES&T 2002) and as described below a Tier 1 and Tier 2 risk assessment was completed for the site. Based on the Tier 1 risk assessment, it was determined that the dissolved phase constituents in all wells (with the exception of Naphthalene at GM11) were below the site wide action limits. However, the Tier 1 assessment identified the potential for naphthalene (based on its calculated effective solubility) to exceed Tier 1 action levels. In addition, numerous analyses had detection levels exceeding the Tier 1 action levels.

A Tier 2 risk assessment was conducted by ES&T (2003) to evaluate whether the observed concentrations and detection limits above action levels posed any unacceptable risks. This Tier 2 analysis involve an evaluation of site-specific risks through assessment of exposure pathways and utilizing site wide and local scale conditions to calculate Tier 2 RBSL values.

The results of the Tier 1 and Tier 2 risk assessments indicated that there is no potential for unacceptable risk from the facility with all observed dissolved phase concentrations below risk-based concentrations. Further, assessment of LNAPL chemistry indicates vapor intrusion and dissolution to groundwater does not result in concentrations exceeding risk based criteria. The key conclusions provided in the Tier 2 report were as follows:

- *All results for the DPHHC Tier 2 evaluation of measurements exceeding the Tier 1 Action levels are below Tier 2 risk threshold values. This includes the over 100 results for individual constituents where the detection limit exceeds the Action Level for the DPHHC Tier 1 Evaluation*
- *The Tier 2 evaluation of the soil concentrations computer from the PSPH composition indicates that there is not risk that exceeds an HQ of 1.0 and a target risk of 1E-4 for any of the PSPH samples.*

In terms of the potential for vapor intrusion within the area of the LNAPL (PSPH) plume ES&T conservatively calculated the cumulative cancer risk and Hazard Indices to range between 2×10^{-6} and 3×10^{-12} and 3.4×10^{-1} to 1.4×10^{-1}, respectively. This risk assessment is highly conservative as no sensitive receptors are located over the LNAPL plume. Further the use of effective solubilities is highly conservative as this is the theoretical concentration when water and oil are in contact and in equilibrium with one another at a pore scale. Dilution, dispersion, and mass losses (which result in disequilibrium) result in measured concentrations in groundwater an order of magnitude or two below the calculated effective solubilities.

Based on discussions with USEPA, it is understood that the risk assessment will need to be updated to reflect current conditions. Given that the plume extent has retracted and further weathering of the LNAPL has occurred over time, we do not consider major changes to the findings and conclusions of the risk assessment.

As described in **Section 2**, a range of LNAPL recovery approaches are being utilized at the Site to facilitate removal of LNAPL to the extent practical. The cleanup criteria for LNAPL was described in the USEPA-approved Phase Separated Petroleum Hydrocarbon Plume Remediation Work Plan (Hess, 2001).

> *"The clean-up criteria for PSPH are based on two independent factors: risk and mobility. Corrective measures for PSPH will be complete when it is determined that PSPH:*
>
> 1. *Poses no unacceptable risk to human health and the environment, or*
> 2. *Is below the Practical Limits of Mobility (PLM) and is not likely to impact a receptor in the future."*

5.5 LNAPL Mobility and Recoverability

A mobility analysis (using models) was conducted by ES&T (1996) and determined that a LNAPL thickness of less than 0.2 feet did not present a mobility risk at the site. Subsequent to this and consistent with the work conducted by GES an LNAPL seepage velocity of 0.1 foot/day was determined to indicate an immobile LNAPL plume and more recent modelling efforts (as described below) have demonstrated that the plume is functionally immobile.

As a primary line of evidence, the groundwater monitoring data for the Site is the clearest indicator of plume stability and for the last 15 years there has been no indications of plume expansion (refer to **Appendix B**). Considering the groundwater monitoring data and risk assessments completed at the site, it can be easily stated that the LNAPL plume is stable and poses no unacceptable risks to human health and the environment. As a consequence, the historic remedial goals have been achieved and in this context the remedial goals for the site can likely be reframed as follows:

1. Recovery of LNAPL to the extent practicable; and
2. Facilitate aquifer restoration through a combination of natural and engineered processes.

The framework for enhancement and understanding of the Site Conceptual Model in support of these goals is described below.

5.5.1 Bail Down Tests Assessments of Transmissivity and Mobility

LNAPL transmissivity measurements vary across the LNAPL plume and over time with fluctuations in water level (and associated local scale drainage of LNAPL into the well) providing for significant temporal variability. To further improve upon the prior understanding of LNAPL transmissivity, a detailed analysis was performed of the many LNAPL recoverability tests conducted across the plume.

To evaluate the transmissivity of LNAPL and facilitate modelling of LNAPL volume and recoverability bail-down tests were conducted between March 29th and April 3rd 2017 on recovery wells VW2, VW30 and VW31 (GES 2017). The data collected from the LNAPL baildown tests were analyzed using the API (2004, 2012) software and guidance and the equivalent ASTM (2013) guidance. In accordance with this guidance LNAPL conductivity and transmissivity were determined using a modified Bouwer and Rice (B&R) solution and methods contained in the API (2012) guidance.

As described by GES, they considered the rates of LNAPL recovery to be moderate with differences in LNAPL transmissivity values observed for the various methods applied with a number of the more recent methods which yielded higher values (and required assumed storage values) not applicable to secondary porosity features within the limestone geology of the Site. In this context the higher values (and the associated averages) need to be considered carefully with the values from API (2004) likely more aligned with LNAPL transmissivity values and the recovery rates observed at the Site.

Table 5-5 LNAPL Transmissivity Values from Baildown Testing (GES, 2017)

Table 3.

Summary of LNAPL Transmissivity Values from Baildown Test Analyses
Saint Croix Alumina Site, St. Croix, Virgin Islands

			API(2004)*		API (2012) and ASTM (2013) Methods**			Mean Values for All Methods	
Test Well ID	Test Date	Pre-Test Thickness, feet	Bouwer & Rice - Direct, ft^2/day	Bouwer & Rice - Parametric, ft^2/day	Bouwer & Rice, ft^2/day	Cooper & Jacob, ft^2/day	Cooper, Bredehoeft, & Papadopolous, ft^2/day	Arithmetic Mean, ft^2/day	Geometric Mean, ft^2/day
VW-2	4/3/2017	0.97	0.237	0.355	3.61	5.57	3.39	2.63	1.42
VW-30	3/31/2017	0.66	0.326	0.49	0.328	1.44	0.05	0.53	0.33
VW-31	3/30/2017	0.5	0.489	0.734	3.36	0.51	14.99	4.02	1.56
Mean		0.71	0.351	0.526	2.432	2.507	6.142	2.39	1.47
Geomean		0.68	0.336	0.504	1.584	1.599	1.364	1.08	0.90

* Lundy-Zimmerman (1996) modified Bouwer & Rice method, and Lundy (2006) B&R with parametric analysis to estimate matrix properties.
** Kirkman (2013) Modified Bouwer & Rice method for unconfined LNAPL, and Kirkman et al. (2013) for confined and perched LNAPL.

Using the data from the above baildown tests, GES (2017) updated the ARMOS model for the Site which has been used to evaluate LNAPL mobility and LNAPL volumes. It should be noted that the methods for the ARMOS model and baildown test analysis have been developed for porous media and as such have a core assumption around storage which may not properly align with the presence of LNAPL in secondary porosity as occurs at the Site. In this context the ARMOS model results very likely overestimate the total and recoverable volumes of LNAPL in the formation.

As described by GES (2017), historical modelling as documented in ES&T (2000) demonstrated that when LNAPL velocities were less than 0.1 feet/day the LNAPL plume was considered stable/immobile with the ES&T (2000) report identifying limited numbers of wells that exceeded this threshold. A limitation of the GES modelling was the use of LNAPL transmissivity data from VW2 and VW30 which had potentially submerged screens. As noted in ASTM E2856-13 “Standard Guide for Estimation of LNAPL Transmissivity” bail-down tests for LNAPL transmissivity should not be conducted on wells where screens are submerged at the time of testing. Historical data indicates that VW2 and VW30 has a submerged screen the majority of the time. However, the inflow of NAPL into the well during the test does indicates that the well screen may not have been submerged and/or that the LNAPL was potentially confined in this area.

Updated modelling simulations were conducted by GES (2017) using the 2017 baildown test data. No combination of revised parameters, using the arithmetic and geometric mean LNAPL transmissivity values, yielded LNAPL velocities greater than 0.1 feet per day. The maximum PSPH velocity calculated was 0.05 feet per day and this low value in combination with the other Site data that show the stable to decreasing extent of LNAPL impacts provides confidence in the conclusion that the plume is and will continue to be stable. Estimates of LNAPL volume were also provided by GES as part of the model

update however as noted above, those values are likely to be a significant overestimate in the context of the complexities of storage in secondary porosity.

GES (2017) noted that there are areas where thicknesses may be sufficient for ongoing recovery but did not comment on whether the LNAPL transmissivities measured were reaching practical recovery endpoints as recommended by ITRC. Review of the arithmetic and geometric mean LNAPL transmissivity values indicates that well VW30 falls within the range in which further LNAPL recovery is not considered practical. In addition, given the inherent calculation biases with the API (2012 methods) review of the API (2004) results also indicates that the other wells VW2 and VW31 also fall within the range. However, in the context of defining whether the practical limits of recovery have been achieved in wells at the Site, it is recognized that as part of the 2020 work program additional bail down testing, both spatially and temporally (to reflect changes in groundwater elevation) is required.

As described in the ITRC guidance, "where LNAPL mass recovery is ongoing, LNAPL transmissivity can provide a metric to understand remedy progress and define the point at which hydraulic LNAPL recovery is no longer beneficial or practical. LNAPL transmissivity directly varies with LNAPL saturation and thus offers a direct measure of the effect of LNAPL recovery on mobile LNAPL." The ITRC has defined an LNAPL transmissivity range of 0.1 to 0.8 square feet per day (ft^2/day) as the point at which LNAPL recovery is not practical.

Using the Theim Equation an approximation of LNAPL recovery rate to LNAPL transmissivity can be estimated as summarized in **Figure 5-4** below. In this context a recovery rate of around 1 gallon per day (gpd) is associated with the upper bound of the ITRC LNAPL transmissivity practicality end point of < 0.8 ft^2 /day.

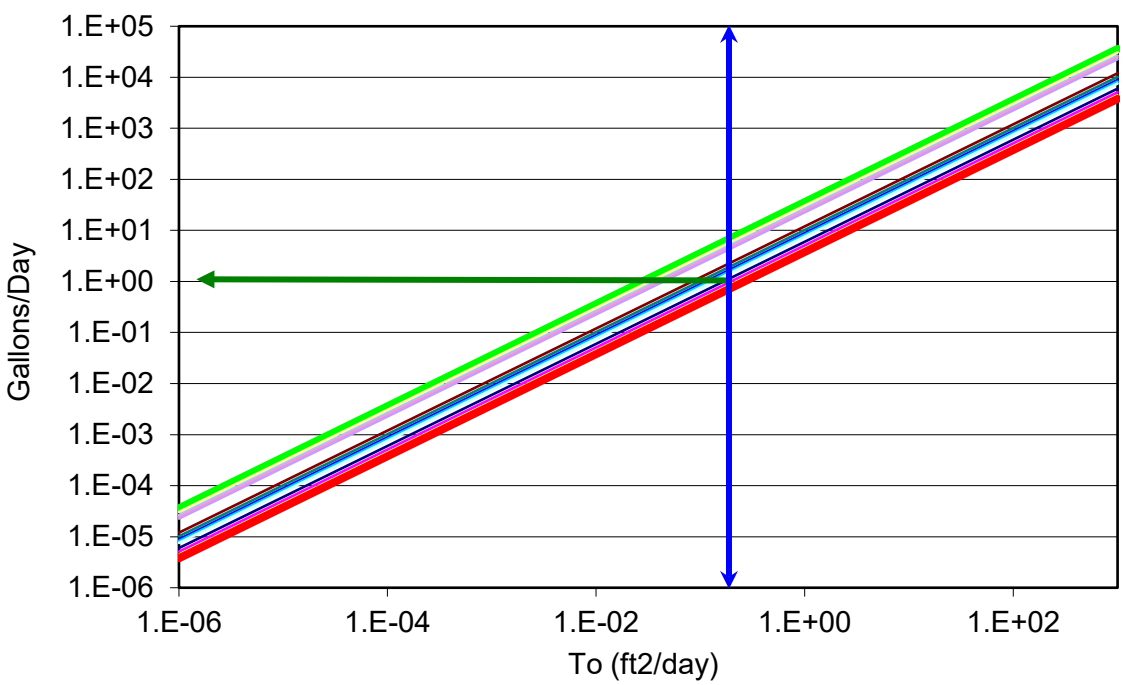


Figure 5-4 LNAPL Transmissivity and Potential Yield

This is further represented in the figure below for different LNAPL drawdown associated with either skimming or total fluids recovery. Note the drawdown is the net reduction in LNAPL head in the well relative to the formation which is the reduction in LNAPL thickness between non-pumping and pumping conditions.

As observed and consistent with the Theim equation the greater the drawdown the lower the LNAPL transmissivity to provide the yield observed. For example, based on an LNAPL drawdown of 0.3 feet (consistent with operation of the solar sippers at the site) and an LNAPL recovery rate of 1 gpd equates to a transmissivity of 0.8 ft^2/day. While a drawdown of only 0.1 feet requires an LNAPL transmissivity of 1.5 ft^2/day to yield 1 gpd.

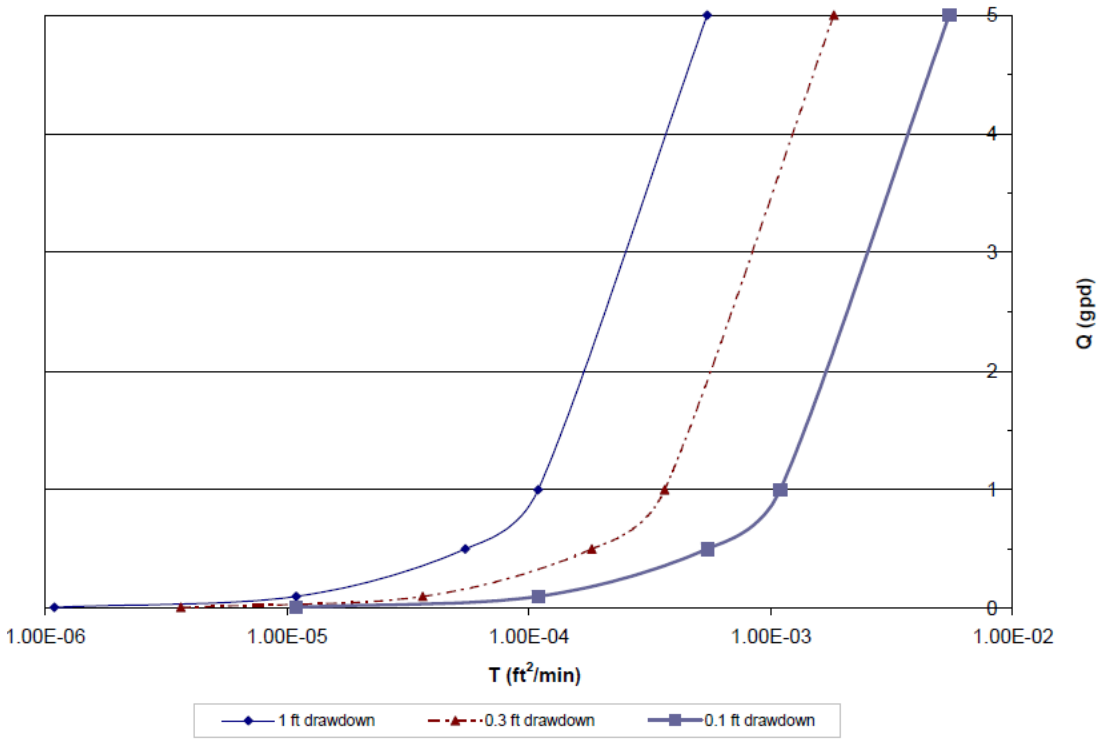


Figure 5-5 LNAPL Transmissivity Estimated Using Theim Equation for Different Drawdown

Bail-down Tests and Modelling Demonstrate the Plume is Functionally Immobile but some wells may have sufficient LNAPL Transmissivities to warrant ongoing LNAPL recovery over the short term.

5.5.2 Total Fluids and Solar Sipper LNAPL Recovery

LNAPL recovery activities have been conducted at the site since 2002 and a summary of the LNAPL recovery well and monitoring well history has been provided in **Section 2**. As described above early operations involved the use of total fluids recovery wells (combined pumping of LNAPL and groundwater) with more recent (2012) conversion of wells to skimming (solar sippers) which was expanded to additional wells in 2018.

In general, the majority of recovery wells have exhibited declining LNAPL recovery volume trends over time as summarized in **Table 5-6** below and the reservoir decline curves (which show decreases over time and were used to define the recovery trends) as provided in **Appendix C**.

Table 5-6 Assessment of Recovery Trends

Well	Slope	Intercept	R^2	P-value	Peak Recovery (gpd)	Latest date > 1 gpd
VW2	-0.0120069	-3.759	0.008	0.757	0.203	PSPH Recovery Rate Never > 1
VW5	0.0133841	-2.846	0.134	0.180	0.440	PSPH Recovery Rate Never > 1
VW6	-0.0000663	5.581	0.549	0.000	114.012	2019-07-01
VW13	-0.0000487	3.917	0.414	0.000	98.933	2019-10-01
VW13B	-0.0002469	2.964	0.184	0.009	21.914	2019-10-01
VW14	-0.0000383	5.025	0.598	0.000	87.374	2020-02-17
VW15	-0.1303936	-3.926	0.368	0.017	0.014	PSPH Recovery Rate Never > 1
VW18	0.0257979	-4.634	0.025	0.530	0.065	PSPH Recovery Rate Never > 1
VW20	-0.0000338	0.418	0.059	0.075	44.658	2013-06-01
VW20B	-0.0000658	2.872	0.167	0.013	61.165	2016-06-01
VW21	-0.0002464	3.888	0.522	0.000	46.713	2012-12-01
VW21B	0.0002511	-3.942	0.069	0.123	11.934	2016-12-01
VW23	0.0183060	-3.933	0.016	0.656	0.141	PSPH Recovery Rate Never > 1
VW24	-0.0065974	-1.467	0.042	0.463	0.577	PSPH Recovery Rate Never > 1
VW26	-0.0003966	4.022	0.424	0.000	54.769	2004-06-01
VW28	-0.0001279	2.092	0.026	0.583	19.951	2012-06-01
VW29	-0.0035094	0.294	0.264	0.007	0.803	PSPH Recovery Rate Never > 1
VW30	-0.0032995	-2.511	0.022	0.470	0.185	PSPH Recovery Rate Never > 1
VW31	-0.0020519	-0.688	0.061	0.376	1.087	2019-10-01
VW38	-0.0011012	2.918	0.394	0.000	12.704	2014-06-01

gpd – gallons per day
PSPH -Phase Separated Petroleum Hydrocarbon

Declining trends are observed in all wells with the exception of VW5, VW21B and VW23 as noted in **Table 5-6** above. For those three recovery wells, the increasing trends are considered statistical anomalies based on the following observations (refer **Appendix C**):

- VW5 is a new recovery well and has recovered limited LNAPL (just over 100 gallons) with low recovery rates (maximum less than 0.5 gpd)
- VW21B – Had a period of high recovery in 2015 and after this LNAPL recovery rates have declined significantly
- VW23 is a new recovery well and has recovered limited LNAPL (just under 25 gallons) with low recovery rate (maximum less than 0.15 gpd)

In terms of recovery many of the wells exhibit low LNAPL transmissivities indicating that ongoing recovery is not practical. These include wells VW2, VW5, VW15, VW18, VW23, VW24, VW29, VW30 which have consistently had recovery rates less than 1 gpd and VW26 which has a prolonged period of recovery less than 1 gpd (since 2004). Other wells have more recent records of recovery less than 1 gpd but additional data is required to determine if these low LNAPL recovery rates persist.

Reservoir Decline Curve Analysis is a common method used to determine recoverable LNAPL volumes and in combination with this linear regression projects can be used to determine the total volume of recoverable LNAPL. Simply put, the process involves plotting cumulative recovery versus recovery rate to determine the total volume of recoverable LNAPL (the point at which LNAPL recovery rate is projected to approach zero).

The recovery curves (refer **Appendix C**) provide a clear demonstration of success, with order of magnitude declines in LNAPL recovery rates observed in the majority of wells. These seven wells in particular (total volumes removed are also listed) are representative of successful remedial operations: VW14 (> 125,000 gallons), VW6 and VW13 (> 80,000 gallons), VW20B (> 60,000 gallons), VW20 (> 50,000 gallons), VW21 (> 25,000 gallons), and VW26 (> 18,000 gallons).

Both later time records with total fluids recovery and more recent operational data for the solar sippers demonstrates that LNAPL recovery rates and transmissivities have declined in all wells. However, the more recent data using solar sippers has a high degree of data variability (large variance) in recovery rates over time (refer **Appendix C**), especially when plotting the data on a log scale to support linear regression analysis. As a consequence of this variability, the regression coefficients are low and low confidence exists in projection of time frames for achiev ement of the 1 gpd threshold and estimation of the total volume of LNAPL potentially recoverable from the well. The cause of this variability is likely a function of numerous factors including:

1. The short recovery history for a number of the wells
2. The recent changes in recovery methods (from total fluids recovery to solar sippers)
3. Water table elevation changes in LNAPL transmissivity and recovery rates
4. LNAPL presence in secondary porosity and potential low storage coefficients which can result in steep declines in the recovery rates observed over time.

Despite these limitations it is evident from the linear plots that a number of the main recovery wells have experienced significant production declines over time and have recovered greater than 90% of potentially recoverable LNAPL. This includes recovery wells VW6, VW14, VW21, VW28, VW29 which have consistent declining recovery rates over time and recovery wells VW13, VW20, VW20B and VW38

that with assessment of modified temporal periods (excluding potential anomalous points) also show the majority of LNAPL has already been recovered. It is very likely that future recovery rates in these wells will be less than 1 gpd. However, due to the constrained LNAPL storage in the limestone, rapid declines in LNAPL recovery rates are likely to be experienced as we approach the maximum recoverable LNAPL volumes for each well. This inherently may result in steps in the decline curve or steep declines in recovery rate as have been observed in many of the late time responses in the reservoir decline curves.

5.5.3 Solar Sipper Pilot Test Program

Review of the pilot test data indicates that the solar sippers were effective at maintaining or decreasing LNAPL thicknesses and provided more efficient LNAPL removal as supported by higher oil percentages in the recovered oil. Note: **Table 5-7** reflects data extending beyond the initial 12-month pilot test period (a total of 21 month assessment periods extending from August 24th 2018 to May 31st 2020).

Review of the Solar Sipper pilot test data indicates that the majority of wells in 2018 and 2019 were recovering less than 1 gpd indicating that the majority of wells are below the ITRC upper bound LNAPL transmissivity threshold at which LNAPL recovery is not practical. As shown in **Table 5-7** the only wells where LNAPL recovery rates exceeded 1 gpd comprised:

- VW6 (10/6/2018 to 10/31/2018, 1/01/2019 to 1/31/2019, 3/01/2019 through 6/30/2019 and 12/01/2020 to 5/30/2020)
- VW13 (5/01/2019 to 5/31/2019 and 9/31/2019 to 9/30/2019)
- VW13B (10/6/2018 through 12/28/2019, 4/01/2019 to 7/31/2019, 9/31/2019 through 10/31/2019 and 1/02/2020 through 5/30/2020)
- VW14 (1/01/2019 to 1/31/2019, 4/01/2019 through 7/31/2019, 9/01/2019 to 9/30/2019 and 11/01/2019 through 5/31/2020)
- VW20B (10/6/2018 to 10/31/2018
- VW31 (1/01/2019 to 1/31/2019 and 10/01/2020 to 4/30/2020).

Further in the majority of cases the wells recovered less than 0.5 gpd of LNAPL with the only wells additional to those listed above comprising wells VW20 (1 of 21 monthly events) occasion and VW24 (2 of 21 monthly events), VW29 (1 of 21 monthly eventsVW32 (2 of 21 monthly events).

A summary of the LNAPL recovery volumes by well, the % recovery of the total and the well rankings are provided in **Table 5-7** and on **Figure 5-6** below for the period August 2018 through May 2020. Greater than 70% of the LNAPL is recovered in the eastern portion of the site (VW5, VW6, VW13, VW13B, VW14, VW23) in and around the VW13B pumping center. While VW13B (where an electric groundwater pump operates to provide groundwater depression) has the highest LNAPL recovery rate over the period, solar sipper recovery well VW14 has an equivalent recovery rate and considerably higher efficiency. Further recovery well VW13 (adjacent to VW13B) also exhibits high recovery rates with high efficiencies (high oil %) indicating that groundwater drawdown is not a critical factor in LNAPL recovery and use of the solar sippers alone can be as effective as total fluids recovery.

As discussed in **Section 4**, there are major contrast in hydraulic conductivity across the site with an area of higher hydraulic conductivity observed in the eastern portion of the site in and around VW6. The higher LNAPL transmissivities in this area are likely a function of the presence of LNAPL within coarser grained (less cemented) deposits but consistent with the interpreted site-specific geology this area is highly localized.

Table 5-7 Summary of Recovery August 2018 through to May 2020

Well	Total PSPH Recovered (gal)	LNAPL Recovery Rank	% of Total LNAPL	oil/water cut (%)
VW2	18.72	15	0.41%	38.37%
VW4	0.81	22	0.02%	5.41%
VW5	168.83	6	3.70%	58.58%
VW6	643.12	3	14.08%	97.98%
VW7	1.60	20	0.04%	44.44%
VW13	449.69	4	9.85%	84.12%
VW13B**	1,197.10	1	26.22%	0.14%
VW14	923.69	2	20.23%	99.78%
VW15	6.12	17	0.13%	20.72%
VW18	16.06	16	0.35%	11.79%
VW19	5.00	19	0.11%	16.62%
VW20	99.69	11	2.18%	86.71%
VW20B	157.79	7	3.46%	59.84%
VW21	5.94	18	0.13%	21.71%
VW21B	48.66	12	1.07%	36.34%
VW23	47.49	13	1.04%	25.96%
VW24	127.26	8	2.79%	39.88%
VW29	113.62	10	2.49%	41.86%
VW30	34.67	14	0.76%	17.81%
VW31	374.29	5	8.20%	85.53%
VW32	124.60	9	2.73%	78.81%
VW35	0.61	23	0.01%	2.44%
VW38	1.00	21	0.02%	16.39%
Total	4,566.37			0.53%

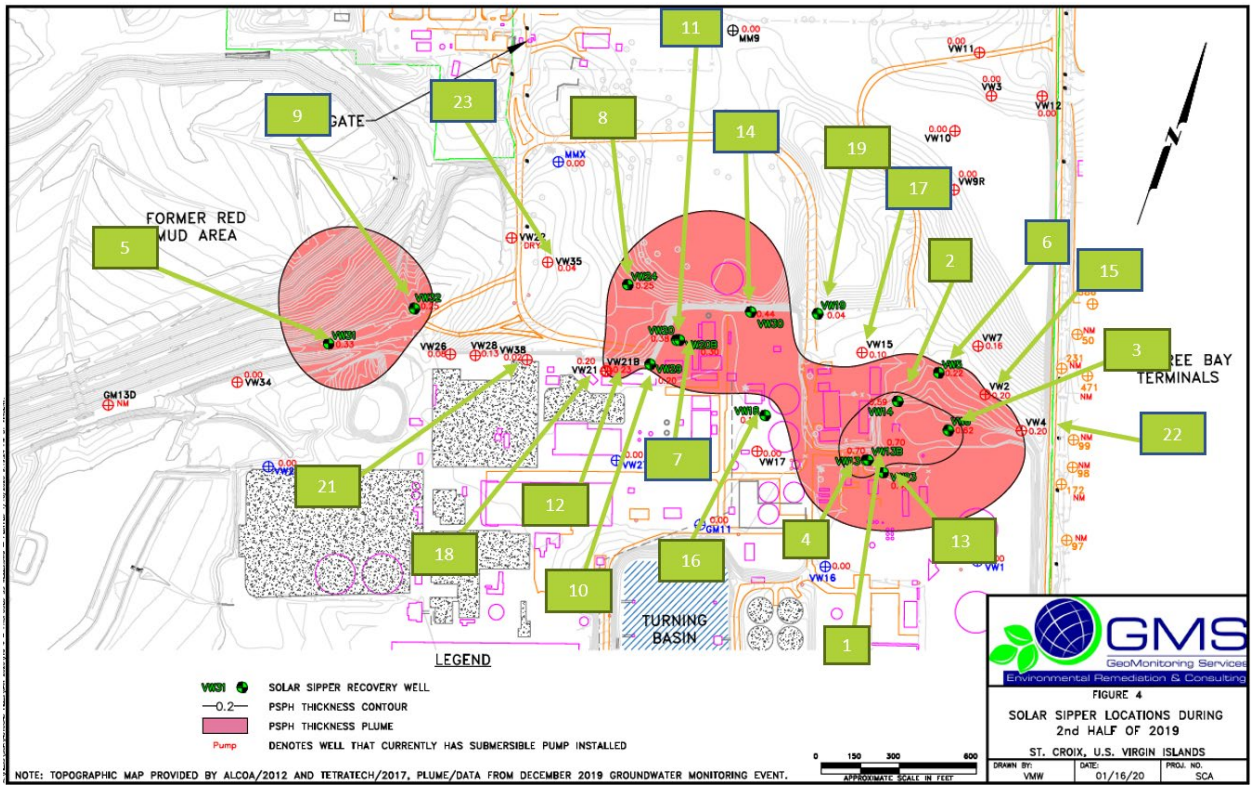


Figure 5-6 Distribution of Recovery Rankings

In review of the LNAPL thicknesses measured in operational recovery wells (refer **Appendix D**) there are a number of locations where LNAPL thicknesses at times are approaching 0.5 feet. This is a function of natural variability in LNAPL thickness in the wells (anticipated with water table fluctuations) and where the skimmer pump requires removal to support gauging or maintenance. Based on the gauging data, the operational cycles (time for on and off cycles) will be reviewed and modifications made as necessary in recovery wells VW2, VW6, VW13, VW21B (and other wells where LNAPL thickness over time approach 0.5 feet) to further optimize recovery.

5.5.4 Overview of Performance and Transmissivity

In the context of the narrative analysis provided above and the graphs provided in the Appendices key observations on recovery efficiency and transmissivity and ongoing operations are provided in **Table 5-8** below by recovery well. These includes both wells that are part of the historical and current recovery program.

Table 5-8 Recovery Efficiency and Transmissivity

Recovery Well	Recovery Efficiency	Transmissivity and Ongoing Operations
VW2	High oil percentages from well. Low recovery rates but LNAPL thicknesses are not effectively being removed from well	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds

Recovery Well	Recovery Efficiency	Transmissivity and Ongoing Operations
VW5	Recovery has been resulted in declines in LNAPL thickness over time but large volumes of LNAPL have not been recovered indicating low transmissivity and storage. Recovery rates and % oil recovery is declining indicating declines in removal efficiency associated with reductions in LNAPL transmissivity over time	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds
VW6	This was one of the major wells that has recovered LNAPL at the site. LNAPL thicknesses have declined in response to recovery efforts and historical total fluids recovery had low recovery efficiencies (low oil percentage). Solar sipper has seen improvement in efficiency (higher oil water cuts).	LNAPL thicknesses in the recovery well demonstrate some variability in response to water table fluctuations. Solar sipper trial recovery rates during the trial were greater than 1 gpd indicating transmissivity is above ITRC threshold.
VW13	Was total fluids recovery from 2002 to 2012. In the total fluids operations good oil recovery rates were achieved but the efficiency was low (oil percentages near 1%). Based on the low efficiencies of total fluids recovery, solar sippers were installed which have achieved removal rates greater than 1 gpd and oil percentages for the majority of the period approaching 100%.	LNAPL thicknesses in the recovery well demonstrate some variability in response to water table fluctuations. Solar sipper is maintaining LNAPL thicknesses in this well. Solar sipper trial recovery rates during the trial were generally below 1 gpd with 1 month of the 12 month trial above the threshold
VW13B	Total fluids recovery in VW13B was increased overtime from 2007 through to 2017 and in response to the intense pumping at this location oil recovery rates and oil percentages declined to zero. Reconfiguration of the pumping including a reduction in the total volume of liquids pumped (by approximately 75%) resulted in an increase in oil percent (0.1 to 0.8%) and improved recovery rates.	Recovery rates from the well continue to be greater than 1 gpd. Reduced groundwater pumping and improved LNAPL recovery indicates LNAPL transmissivity and LNAPL recovery rates are not sensitive to drawdown. The LNAPL thicknesses in this well have been maintained around 0.8 feet during recovery efforts and some minor changes in LNAPL thickness are observed with groundwater level fluctuations.
VW14	VW14 – Total fluids recovery was conducted in this well through 2012 when a solar sipper was installed in the well. High recovery rates were initially achieved in this well but rates declined and the efficiency became low (oil percentage near 1%). After installation of the solar sippers recovery rates improved to greater than 50 gpd with oil percentages near 100% but recovery rates have continued to decline over time.	Recovery rates in the pilot test are still greater than 1 gpd and recovery will continue. LNAPL thickness in the well is generally around 0.5 feet facilitating ongoing recovery.
VW15	Was implemented as a solar sipper well the 2nd half of 2018 but recovery volumes have been limited indicating that this well has a low LNAPL transmissivity. LNAPL thicknesses are up to 0.5 feet in this well but the transmissivity is low. No relationship between groundwater level and	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds. LNAPL thicknesses during the trial period generally maintained below 0.2 feet.

Recovery Well	Recovery Efficiency	Transmissivity and Ongoing Operations
	thickness is observed in the later records but historically thicker LNAPL was observed during lower groundwater elevations.	
VW18	LNAPL thicknesses have consistently declined over time and with the installation of a solar sipper LNAPL thicknesses have continued to decline. The well has never been a major producer of LNAPL.	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds. LNAPL thicknesses during the trial period generally maintained below 0.2 feet. Fluctuations in thickness observed with water table elevation changes (thicker during periods of low groundwater elevation)
VW20	Historically well was a total fluids recovery well and significant volumes of LNAPL were recovered. The installation of a solar sipper in this well resulted in improved efficiency (higher oil percentages) but recovery rates have been low indicating that this well is not in an area of High LNAPL Transmissivity.	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds. LNAPL thicknesses during the trial period have been variable and below 0.5 feet and exhibit fluctuations in response to water table elevation changes (thicker during periods of low groundwater elevation).
VW20B	Historically well was a total fluids recovery well and significant volumes of LNAPL were recovered but recovery efficiency declined over time. The conversion of the well to a solar sipper recovery resulted in improved efficiency and recovery rates and LNAPL thicknesses are less than 0.4 feet.	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds. LNAPL thicknesses during the trial period have been variable and generally below 0.4 feet and exhibit fluctuations which do not appear to be associated with increases induced by lower groundwater levels.
VW21	Historically well was a total fluids recovery well and significant volumes of LNAPL were recovered but recovery efficiency declined over time. The conversion of the well to a solar sipper recovery in 2012 resulted in improved efficiency but recovery rates have remained low.	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds. LNAPL thicknesses during the trial period have been variable and generally below 0.3 feet and exhibit fluctuations which do not appear to be associated with increases induced by lower groundwater levels.
VW21B	This well exhibited high initial LNAPL recovery rates with the installation of a electric total fluids recovery pump but LNAPL recovery rates rapidly declined before the electric pump was decommissioned. Recovery efficiencies with the electric total fluids recovery pump were very low and the commissioning of the solar sipper in 2018 resulted in higher LNAPL recovery efficiencies.	Recoveries since 2017 have consistently been below 1 gpd indicating transmissivities are below ITRC thresholds. LNAPL thicknesses during the trial period generally maintained below 0.2 feet. Fluctuations in thickness observed with water table elevation changes (thicker during periods of low groundwater elevation)
VW23	VW23 has shown significant declines in LNAPL thickness over time from greater than 1.4 feet in 2002 to less than 0.2 feet currently. A solar sipper was installed in the well in 2018 and LNAPL is being recovered but recovery efficiency has declined to below 30% oil in response to the declining LNAPL thicknesses.	Recoveries since 2018 have consistently been below 1 gpd indicating transmissivities are below ITRC thresholds. LNAPL thicknesses during the trial period were generally around 0.3 feet. Increases in LNAPL thickness do not appear to be associated with lower groundwater levels.

Recovery Well	Recovery Efficiency	Transmissivity and Ongoing Operations
VW24	Similar to VW23, LNAPL thicknesses have declined over time and currently are around 0.3 feet. A solar sipper was installed in 2018 with the LNAPL recovery rates in this well higher than those observed in VW23 indicating higher LNAPL transmissivities at this location with corresponding higher recovery efficiencies (higher average oil percentages).	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds and LNAPL thicknesses have been maintained around 0.2 feet.
VW26	Historically total fluids recovery was conducted in this recovery wells. However due to limited LNAPL thickness (currently less than 0.1 feet thickness) no recovery has occurred in this well since 2012.	Based on historical data LNAPL recoveries this well has limited recovery and it is anticipated that LNAPL Transmissivity is below the thresholds.
VW28	Historical total fluids recovery was conducted in this recovery wells. Major reductions in LNAPL thickness occurred in this well between 2002 and 2005 and total fluids recovery was terminated in 2012 due to the limited thickness in this well (less than 0.2 feet).	Based on historical data LNAPL recoveries this well has limited recovery and it is anticipated that LNAPL Transmissivity is below the thresholds.
VW29	LNAPL recovery commenced in this well with the installation of a solar sipper in 2013. In response to the commissioning of the solar sipper major reductions in LNAPL thickness were observed.	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds with LNAPL thicknesses in late 2019 and 2020 below 0.2 feet.
VW30	Reductions in LNAPL thickness have been observed in this well and a solar sipper was installed in 2014 supporting further reductions in LNAPL thickness. LNAPL recovery rates from this well have been generally low for much of the early period recovery rates being less than 1 gpd and an improvement in recovery rates through operational changes in 2018.	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds with LNAPL thicknesses ranging between approximately 0.5 and 0.2 feet. This variability likely reflects the operation of the skimmer.
VW31	Major reductions in LNAPL thickness have been observed in this well and a solar sipper was installed in 2018 which supported further reductions in LNAPL thickness. LNAPL recovery rates from this well have been generally low for much of the early period recovery rates being less than 1 gpd and an improvement in recovery rates through operational changes in 2018.	Recoveries are consistently below 1 gpd indicating transmissivities are below ITRC thresholds with LNAPL thicknesses in late 2019 and 2020 are generally below 0.4 feet. The variability in thickness likely reflects fluctuations associated with groundwater water level variability (thicker during low groundwater elevations).
VW38	Total fluids recovery was historically conducted in this well but recover rates have declined over time as recovery efficiencies also declined. A solar sipper was installed in the well in 2019 and operations did achieve reductions in LNAPL thickness. However, the LNAPL prior to pump	Recoveries since 2015 are consistently below 1 gpd indicating transmissivities are below ITRC thresholds with LNAPL thicknesses approaching 0.1 feet in the recovery well.

Recovery Well	Recovery Efficiency	Transmissivity and Ongoing Operations
	installation was not thick (0.3 feet) and recovery rates have been slow.	

Table 5-9 below provides a key snapshot of the performance of recovery at the site showing the concentration of LNAPL recovery volumes in a limited number of wells and the major declines in LNAPL recovery rates over time (~5 year periods). Rapid volume declines are consistent with the limited storativity of LNAPL in the limestone which corresponds to rapid declines in LNAPL recovery rates. Comparing early recovery (the first period) to late time recovery (the last period) 1 to 2 order of magnitude declines in recovered LNAPL volume have been observed.

In addition to the declines in LNAPL recovery rates the patterns evident in the solar sipper data are also apparent in the long term recovery data with recovery wells in the eastern part of the site (VW6, VW13, VW13B, VW14) accounting for 60% of the total recovered volume and wells VW20 and VW20B accounting for another 20%. The remainder of recovery wells have made only small contributions to the total recoverable volume.

Table 5-9 Summary of LNAPL Recovery by Well Over Time

Well	Total LNAPL Recovery	% of Total Recovery	Pump Start Date	Pump End Date (if applicable)	Gallons Recovered in Period			
					2002 through 2005	2006 through 2010	2011 through 2015	2016 to May 30, 2020
VW2	29.7	0.01%	9/1/2018	7/1/2019	0.0	0.0	0.0	29.7
VW4	0.8	0.00%	11/1/2018	12/1/2018	0.0	0.0	0.0	0.8
VW5	99.3	0.02%	9/1/2018		0.0	0.0	0.0	99.3
VW6	86,672.8	17.23%	2/1/2002		53,005.7	23,126.9	9,582.3	958.0
VW7	1.6	0.00%	12/1/2018	1/1/2019	0.0	0.0	0.0	1.6
VW13	83,750.0	16.65%	2/1/2002		49,692.7	25,409.6	8,001.4	646.3
VW13B	19,237.4	3.82%	6/1/2007		0.0	8,634.4	9,609.6	993.4
VW14	126,367.0	25.12%	2/1/2002		58,734.1	49,060.6	17,543.0	1,029.3
VS15	1.0	0.00%	9/1/2018	10/1/2018	0.0	0.0	0.0	1.0
VW18	23.0	0.00%	12/1/2013		0.0	0.0	10.9	12.1
VW19	5.0	0.00%	12/1/2018	9/1/2019	0.0	0.0	0.0	5.0
VW20	52,098.9	10.36%	2/1/2002		6,304.2	30,678.5	14,795.3	320.9
VW20B	61,070.8	12.14%	12/1/2007		0.0	28,259.3	32,365.6	445.9
VW21	26,880.1	5.34%	2/1/2002		10,122.4	13,788.6	2,963.1	5.9
VW21B	6,331.9	1.26%	12/1/2007	8/1/2019	0.0	236.9	5,657.4	437.6
VW23	21.8	0.00%	9/1/2018		0.0	0.0	0.0	21.8
VW24	124.1	0.02%	9/1/2018		0.0	0.0	0.0	124.1
VW26	19,452.3	3.87%	2/1/2002		19,325.0	127.3	0.0	0.0
VW28	13,259.4	2.64%	6/1/2005	7/1/2012	3,939.2	7,951.9	1,368.4	0.0
VW29	774.7	0.15%	6/1/2013		0.0	0.0	496.9	277.8

Well	Total LNAPL Recovery	% of Total Recovery	Pump Start Date	Pump End Date (if applicable)	Gallons Recovered in Period			
					2002 through 2005	2006 through 2010	2011 through 2015	2016 to May 30, 2020
VW30	210.6	0.04%	6/1/2013		0.0	0.0	106.7	103.9
VW31	249.7	0.05%	9/1/2018		0.0	0.0	0.0	249.7
VW32	50.7	0.01%	9/1/2018		0.0	0.0	0.0	50.7
VW35	0.6	0.00%	11/1/2018	12/1/2018	0.0	0.0	0.0	0.6
VW38	6,282.5	1.25%	12/1/2007	5/1/2019	0.0	4,133.6	1,943.3	205.5
TOTAL	**502,995.5**				**201,123.3**	**191,407.4**	**104,443.9**	**6,020.8**

5.6 Vacuum Events

The vacuum events which commenced in May 2019 with initial recovery activities (as reported in the 1st Semi-Annual 2019 Status Report (GeoMonitoring Services 2019) focused on monitoring wells VW5, VW6, VW7, VW14, VW20, VW31, VW32 and VW38. Subsequent extraction events (as reported in the 2nd Semi-Annual 2019 Status report) also included wells VW2 and VW28 during a September 2019 extraction event.

As noted in the Status reports, approximately 800 gallons of fluid is recovered from each well during the 45 minute to 1 hour vacuum extraction event. The relative proportion of LNAPL and water in the extracted fluids was not been quantified in 2019 but with the installation of four 330 gallon tanks in 2020 LNAPL recovery rates could be quantified.

LNAPL thickness is monitored prior to and after the vacuum recovery event with data showing that no LNAPL is present in the wells after completion of the vacuum events with wells in the interior of LNAPL plume slowly recharging LNAPL into the well over a 24 to 48 hour period and wells on the exterior plumes providing more slow recovery responses and not recovering to the original (pre-vacuum event thickness). In the 2nd Semi-Annual 2019 Status report it was noted that LNAPL Thicknesses in wells VW2, VW5 and VW28 have decreased in response to these recovery events. In the 1st Quarter 2020 Update report it was noted that the LNAPL recovery volumes in the 3 monthly events (February, March, and April) ranged from:

- VW2 – 63.6 to 109.1 gallons per event
- VW6 - 9.7 to 10.5 gallons per event
- VW14 – 10.5 to 13.5 gallons per event
- VW15 – 3 to 12 gallons per event
- VW31 – 6 to 9 gallons per event

As reported in the 2nd Semi-Annual 2019 Status Report dated January 2020 and 1st Quarter 2020 Recovery System Update dated April 2020 vacuum recovery events have been conducted in the following wells over time. These are summarized in **Table 5-10** below.

Table 5-10 Vacuum Recovery Events Over Time

Well	Recovery Events
VW2 (solar sipper well)	09/19, 2/20, 3/20, 4/20
VW5	05/19, 7/19, 8/19
VW6	05/19, 06/19, 07/19, 08/19, 2/20, 3/20, 4/20
VW7	06/19
VW14	05/19, 06/19, 2/20, 3/20, 4/20
VW15	2/20, 3/20, 4/20
VW20	06/19
VW28	09/19
VW31	05/19, 06/19, 07/19, 08/19, 09/19, 2/20, 3/20, 4/20

Well	Recovery Events
VW32	7/19, 8/19, 9/19
VW38	6/19

Based on the 2020 data, thee only well with appreciable recovery during the vacuum events is well VW2 which has also operated as a solar sipper well. All other wells recovered around 10 gallons of LNAPL per event which on a monthly perspective is considerably lower than 1 gpd and the performance of the current solar sipper wells. The results are consistent with historical data that has demonstrated the low transmissivity of LNAPL at these locations which is further supported by the slow recovery of LNAPL into the well. In many cases it took 24 to 48 hours for measurable LNAPL to return to the well, which clearly demonstrates that LNAPL transmissivity and recoverability at these locations is low.

6 Updated Remedial Action Work Plan

On the basis that the assessment completed at the Site has demonstrated that the LNAPL plume is stable and unlikely to exhibit mobility and that the LNAPL is not a major contributor to dissolved phase impacts, the historic remedial goals have been achieved. Neither the LNAPL or dissolved phase plumes poses any unacceptable risks to human health and the environment and an updated risk assessment will be prepared based on the current conditions at the site. The focus of the revised Remedial Action Plan is on:

- Removal of LNAPL through the current solar sipper system to the point that LNAPL recovery is no longer feasible in recoverable quantities.
- Optimization of LNAPL recovery efforts to align with the observed reductions in transmissivity over time.
- Continued monitoring to demonstrate that the lateral extent of LNAPL and dissolved phase impacts is stable and poses no risks to off-site receptors.
- Complete a systematic evaluation of natural masses losses (natural source zone depletion) to determine the key processes, magnitude of mass losses and the role these processes will have in restoration of the aquifer.
- Develop a detailed LNAPL Remedial Action Plan integrating LNAPL recovery and natural mass losses with monitoring to support ultimate restoration of groundwater quality.

In the context of the practical limits of LNAPL remediation it is considered that natural processes (natural attenuation and natural source zone depletion) will be integral to achieving the long-term goal of aquifer restoration at this site. To support the ongoing evolution of the LNAPL recovery activities, the monitoring and management of the Site and to validate the LNAPL CSM described above, a number of supplemental assessments will be conducted. These comprise:

1. Additional bail-down testing to determine LNAPL transmissivity in select recovery wells.
2. Continued operation of the recovery wells to evaluate the further decline in recovery rates and LNAPL transmissivities. In addition, it is proposed that updates to the reservoir decline curve analysis contained within this report.
3. Assessment of geochemical conditions within the aquifer system to understand the processes of natural mass losses that will support long term restoration of groundwater quality.
4. Evaluation of E-Flux consistent with the NSZD Fundamentals described above in order to quantify natural mass losses, enable comparison to engineered mass losses and ultimately support the transition of the site to an MNA/NSZD remedy.

Details on the various components of the remedial action work plan are provided in the sections below.

6.1 LNAPL Recovery Activities

As documented above, LNAPL recovery in the majority of LNAPL recovery wells has reached or is approaching a practicality endpoint. However, a number of uncertainties and data gaps have been identified during this assessment which indicate that Site remedial operations should continue without interruption (except for general maintenance and semi-annual groundwater monitoring events) through June 2021. At this time, it is anticipated that sufficient data will be available to support systematic shutdown of recovery wells and a transition to MNA/NSZD processes in accordance with the framework described below. It should be noted that this assessment will be done on a well by well basis and the

number of recovery wells that are shutdown after the evaluation period will be informed by the data collected during this period and the process described below.

On the basis of the historic and more recent pilot test data, the LNAPL recovery operations will be modified to the following though the period up to June 2021:

1. Continuous solar sipper operation at high LNAPL recovery rate wells VW6, VW13, VW13B, VW14 and VW31.
2. Continued operation of the electric submersible groundwater pump in recovery well VW13B for another 6 months at which time pumping will be terminated to assess recovery rates without groundwater depression.
3. Continuous solar sipper operation in low to moderate LNAPL recovery rate wells that have recovery rates that were less than 1 gpd but achieved around 100 gallons of recovery over the extended 21 month solar sipper trial period (wells VW5, VW20, VW20B, VW24, VW29 and VW32). The continuous operation will only be a period of approximately six months (but could be longer) to support the data collection to enable finalization of the reservoir decline analysis. After this recovery activities will be periodic until ultimately recovery activities are terminated in accordance with the shutdown framework provided below.
4. Periodic solar sipper operation in low recovery rate wells that had the highest recovery of the remaining wells. The initial focus will be on wells VW21B, VW23 and VW34 but if recovery rates are persistently low (for 3 months in succession during the assessment period and below the criteria outlined in the shutdown framework below, recovery will be terminated.. Solar sippers will then be relocoated to other low recovery rate wells or monitoring wells which baildown tests indicate LNAPL recovery may be warranted (see baildown discussion below)
5. No vacuum recovery events are proposed for the period. The recovery efficiency from vacuum recovery events is considered marginal and less effective than the solar sipper operations. Solar sipper recovery is better aligned with the low LNAPL transmissivity at this Site.

In addition to the revised LNAPL recovery program described above modifications to system operations, maintenance and inspection is proposed this will include:

1. Transition of LNAPL recovery well monitoring and inspection activities to a monthly regime. This will comprise a transition to weekly monitoring and inspections for a 2 month period and then conversion to monthly program with equipment upgrades as described below. The solar sippers will be in continuous operation and monthly inspection and maintenance is aligned with the typical requirements of the Site.
2. Installation of 300 gallon IBC Totes at the recovery wells (to replace the drums) to facilitate longer operational times and implementation of the monthly inspection and maintenance program for the solar sippers. The solar sippers have proven to be reliable and low maintenance and the use of 300 gallon totes (based on highest recovery rate from a well being 5 gallons per day) will facilitate less on-site maintenance, allow for adequate storage for uninterrupted operations, and provide increased operational times to further reduce the LNAPL thickness.

6.1.1 Rationale and Methodology for Reservoir Decline Curve Analysis

As discussed below, the long-term performance of the recovery systems will be evaluated in terms of percent recovery of the mobile/recoverable LNAPL fractions. A goal has been established whereby

90 percent of the maximum theoretical recoverable LNAPL fraction has to be recovered before advancement through the rest of the decision process.

To quantify the percent of recoverable LNAPL remaining in the formation, decline curve analyses will be conducted using the LNAPL recovery data for each of the recovery wells. These decline curve analyses will be conducted at periodic intervals as LNAPL recovery operations continue and as operational conditions change due to process optimization. The decline curve methodology discussed below is consistent with environmental (USEPA 2005) and petroleum engineering guidance (Falcone, Harrison, and Teodoriu 2007; Kewen and Horne 2003; Brillard and Mukheejee 1999).

Decline curve analyses will be conducted by normalizing the LNAPL recovery data as a rate per day for the period of interest and plotting this data on an x-y scatter plot. The daily recovery will be plotted on the y-axis against the cumulative recovery on the x-axis. A linear regression will then be statistically fit to the decreasing portion of the data. Each data set is visually checked for goodness of fit and overall accuracy. The correlation coefficient (R^2) value will be used as a statistical indicator of goodness of fit for the linear regression of the data set. In general, as the R^2 value increases (gets closer to 1), the accuracy of the linear regression and the prediction of total recoverability will increase.

As discussed above some of the historical decline curve analyses provided low R^2 values. This result was because of the variability in operating conditions over the long operational history of these wells, particularly the groundwater pumping rates and periods of shutdown. Despite the low R^2 values, the overall decreasing recovery rates are still evident in the data. Given the variability that is inherent within geostatistical data sets, it is considered desirable that an R^2 value of greater than 0.1 be obtained before interpreting the data and evaluating trends. Statistical outliers can be removed from the data using non-biased and systematic statistical methods such as Cook's D statistics to improve the data fit and correlation coefficients. However, this is typically not recommended due to the potentially negative perception associated with adjusting and modifying the raw data set.

A lot of variability has been observed in the 21-month solar sipper trial period and the collection of additional data through June 2021 will aid in reductions in data variability. Once the linear regressions are visually checked, the estimated total recoverable LNAPL is determined by the x-value, where the trendline intersects the x-axis. The recovered LNAPL volumes can then be compared to the theoretical total recoverable LNAPL volume to determine achievement of the 90 percent recovery goal.

6.1.2 LNAPL in Monitoring and Former Extraction Wells

To facilitate long term assessment of the mobility and recoverability in monitoring wells or former extraction wells LNAPL baildown tests will be conducted to determine whether LNAPL transmissivity is sufficient to support LNAPL recovery. It is proposed that LNAPL baildown tests will be conducted in all former LNAPL extraction wells not included in the recovery program above and in any wells where the LNAPL thickness increases outside the range observed for 2018 through 2020 (prior to and during the solar sipper trial period).

Repeated baildown tests (at least 3 in a row) will be completed to address the likely limited storage of LNAPL in the secondary porosity of the Marl or Limestone, and where persistent values greater than 0.8 ft^2/day (consistent with anticipated recovery rates of 1 gpd) are identified, wells will be included in the recovery program. If the wells consistently yield LNAPL transmissivities < 0.8 ft^2/day then the LNAPL

Transmissivities will be documented and the wells will be determined to have already reached a practical endpoint for LNAPL recovery (no further recovery actions warranted).

LNAPL Transmissivity (Tn) will be calculated for bail-down test on each well using the API bail-down test calculators (both 2004 and 2012 workbooks). Using the aquifer responses (LNAPL thickness changes over time) and Site geology the appropriate analytical solution (confined/unconfined etc.) will be identified. These values will then be compared to the Tn threshold values at which a LNAPL recovery well of greater than 1 gpd is potentially achievable, (ITRC threshold of 0.8 ft^2/day or approximately 1×10^{-4} $feet^2$/minute equates to a recovery rate of 1 gpd).

6.1.3 Groundwater Gauging and Sampling

Groundwater gauging and sampling activities will continue to be conducted at the Site to ensure that the various components of the LNAPL Remedial Action Work Plan are implemented efficiently, and to demonstrate the stability of LNAPL and dissolved phase impacts.

These activities will consist of semi-annual groundwater monitoring events (gauging and sampling) which will be combined with O&M LNAPL gauging activities comprised of monthly gauging in all active LNAPL extraction wells and gauging every 2 months in historic LNAPL extraction wells (refer **Table 6-1** below.

In the context of a remedial approach which ultimately will result in a transition from active recovery to NSZD/MNA it is anticipated that groundwater monitoring will extend into the future with the explicit goal of demonstrating the long term stability of the plume after termination of recovery activities and to monitor the performance of these natural processes. Reductions in the frequency of monitoring is anticipated (initially to annual) but this will not occur until after all LNAPL recovery activities has ceased at the site and sufficient time has elapsed since termination of recovery (anticipated to be 4 semi-annual events) that plume stability (post recovery termination) has been demonstrated. Ultimately all groundwater monitoring will cease when the Tier II SSTLs are achieved in all perimeter wells.

The routine groundwater gauging and sampling activities will comprise the gauging of all Site wells and the sampling of groundwater monitoring wells downgradient of the LNAPL affected area. The wells proposed for sampling are identical to the wells sampling in the 2019/2020 sampling events. In accordance with the historical groundwater sampling and analysis groundwater samples will be analyzed for BTEX and Naphthalene via USEPA Method 820B and Total Petroleum Hydrocarbons Diesel Range Organics (TPH-DRO) via USEPA Method 8015B.

Based on the absence of significant detections for other organic constituents routine testing will not be conducted for the Skinner List of Organic Constituents. However to support future site closure, when LNAPL recovery actions have terminated and the plume has been demonstrated too be stable, testing for the Skinner List of Organic Constituents will be conducted in perimeter wells.

Table 6-1 Monitoring and Gauging Requirements

Well Number	Status	Required Monitoring
VW1	Monitoring - Gauging only	Included in semi-annual groundwater sampling event.

Well Number	Status	Required Monitoring
VW2	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Included in semi-annual groundwater sampling events.
VW3	Monitoring - Gauging only	Included in semi-annual groundwater sampling event.
VW4	Monitoring - Gauging only	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW5	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW6	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW7	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW8	Monitoring - Gauging Only	Included in semi-annual groundwater sampling event.
VW9R	Monitoring - Gauging Only	Included in semi-annual groundwater sampling event.
VW10	Monitoring - Gauging Only	Included in semi-annual groundwater sampling event.
VW11	Monitoring - Gauging Only	Included in semi-annual groundwater sampling event.
VW12	Monitoring - Gauging Only	Included in semi-annual groundwater sampling event.
VW13	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW13B	Continued operation of Solar Sipper LNAPL recovery pump to June 2021 and Grundfos pump for approximately six months of the assessment period.	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW14	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.

Well Number	Status	Required Monitoring
VW15	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW16	Monitoring - Gauging and Sampling	Included in semi-annual groundwater sampling comprehensive gauging event. Groundwater sampling to be conducted.
VW17	Monitoring - Gauging Only	Included in semi-annual groundwater sampling event.
VW18	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW19	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW20	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW20B	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW21	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW21B	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW22	Monitoring - Gauging Only. Well is historically dry.	Included in semi-annual groundwater sampling comprehensive gauging event.
VW23	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW24	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW25	Monitoring - Gauging and Sampling	Included in semi-annual groundwater sampling events.

Well Number	Status	Required Monitoring
VW26	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW27	Monitoring - Gauging and Sampling	Included in semi-annual groundwater sampling events.
VW28	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW29	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW30	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW31	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW32	Continued operation of solar sipper	Gauging to be conducted monthly as part of recovery activities. Included in semi-annual groundwater sampling comprehensive gauging event.
VW33	Monitoring - Gauging Only	Included in semi-annual groundwater sampling events.
VW34	Monitoring - Gauging and Sampling	Included in semi-annual groundwater sampling events.
VW35	Monitoring - Gauging only (if mobility from future baildown tests exceeds threshold will be included future recovery efforts)	Minimum gauging frequency every 2 months. Included in semi-annual groundwater sampling comprehensive gauging event.
VW36	Monitoring - Gauging Only	Included in semi-annual groundwater sampling events.
VW37	Monitoring - Gauging and Sampling	Included in semi-annual groundwater sampling events.

6.2 Proposed Framework for LNAPL Recovery Well Shutdown

As described in the sections above, shutdown criteria for active recovery wells have been developed based on a robust assessment of site-specific conditions and recovery data. This includes transmissivity values as well as recovery rates of 1 gpd (which are equivalent to ITRC's transmissivity threshold) and the potential to use reservoir decline curve analysis to define recovered volume relative to the volume of LNAPL recoverable at a location.

The historical use of model estimates of LNAPL recoverable mass in the formation is not considered appropriate as the ARMOS model is not designed for use with media where LNAPL is likely preferentially contained within the secondary porosity (dissolution features, cavities, or bedding planes) and likely provides gross overestimates of LNAPL mass in the subsurface materials. Rather, it is proposed to leverage the methodologies and approaches outlined in the Interstate Technology Regulatory Council 2018 LNAPL guidance (ITRC-3). Preliminary discussion of metrics with supporting decision logic diagrams are provided below and it is our understanding that the Group and USEPA will work collaboratively to refine these decision processes based on data collected from the planned program of works.

For purposes of advancing the discussion, metrics of success and decision logic diagrams from Appendix B of the ITRC-3 guidance are discussed below and preliminary draft decision logic diagrams have been included. A number of data gaps and uncertainties have been identified with supplemental assessments and monitoring proposed to address temporal variability of solar sipper recovery rates and obtain additional LNAPL transmissivity data.

Given the maturity of this site (i.e., where large volumes of LNAPL have been recovered, LNAPL plume extent and thicknesses have declined over time, and the limited risk [either based on the chemistry of the LNAPL or incomplete exposure pathways]), and the remedial goals described above (demonstrating recovery to the extent practical and achieving the long- term goal of groundwater restoration), decision logic flowcharts (**Figure 6-3** are considered relevant to the assessment of site conditions. It is understood that based on the findings from the supplemental LNAPL mobility/recoverability evaluations and NSZD evaluation, modifications to this process will be required.

In accordance with feedback provided by USEPA, the rules of thumb provided in Appendix C of ITRC-3 (2018) guidance have been referenced as key decision points/metrics to be considered in the process. In review of these rules of thumb there is alignment between the group and USEPA on the use of the LNAPL transmissivity thresholds (upper bound of 0.8 ft^2/day). Some of the other rules of thumb are more challenging to apply or are a key qualitative/semi-quantitative consideration.

Commonly, practitioners have relied on the ITRC transmissivity value referenced above, LNAPL recovery rates from wells (as noted above 1 gallon per day [gpd] has been used at numerous refineries), reservoir decline curve analysis (recovery relative to total theoretical recoverable volume) and recovery efficiency (oil/water cuts and using this ratio to estimate LNAPL transmissivity from groundwater transmissivity).

In addition to these rules of thumb, USEPA also lists a number of methods that can be used individually or in combination to demonstrate that free product has been removed to the maximum extent possible (Section 1.2 of the LNAPL-3 document). Commentary on the application of these criteria to the site is provided after each item

- *Comparing mobile LNAPL mass to the mass of LNAPL in the smear zone*. This assessment method usually involves coring and petrophysical testing. Pore fluid saturations (oil and water phase) and water displacing oil imbibition tests (for LNAPL in saturated zone) are conducted to define the potentially mobile and immobile fractions. The methods are typically applied to porous media but can be modified to consolidated materials (if LNAPL is in secondary porosity of limestone).
- *Analyzing the LNAPL recovery data and determining that future recovery will not be meaningful*. This was proposed in our approach with the use of reservoir/recovery decline curve analysis. Typical application of this criteria has included percent recovery relative to the maximum

theoretical recovery, a recovery rate metric aligned with LNAPL Transmissivity and oil/water percentages for total fluid recovery systems. As described further in **Table 2 of the NSZD Work Plan (Revision submitted to USEPA in April 2021)**, 80 percent and 90 percent of the maximum theoretical recovery has been used as a metric aligned with industry experience in upstream oil and gas. The proposed 1 gpd metric included in our report has been calculated based on the ITRC transmissivity threshold, and oil/water percentages are not applicable metrics for skimming.

- *Showing that LNAPL thicknesses are small and/or intermittently observed.* Routine gauging and groundwater sampling activities are conducted at the site. This data has demonstrated reductions in LNAPL thicknesses over time and a number of wells were LNAPL is only intermittently observed. As discussed extensively in the ITRC guidance, LNAPL thickness is not the primary determinant of LNAPL recoverability. LNAPL saturation and site geology are the critical controls on LNAPL transmissivity and in homogeneous geology LNAPL thickness is correlated with LNAPL transmissivity. Based on the complexity of the site geology (as described in the LNAPL CSM) LNAPL transmissivity at this site is more controlled by geology than thickness. Use of an LNAPL thickness metric is not recommended for this site and LNAPL baildown testing is considered a more reliable tool for assessing LNAPL transmissivity and recoverability.
- *Modeling future potential LNAPL recovery using a multi-phase model.* The American Petroleum Institute's (API) LNAPL Distribution and Recovery Model (LDRM) can be used to model the recoverability of LNAPL and provide future predictions. The model relies on the physical properties of soil, literature input values (potentially sourced from the API database), LNAPL saturation inputs or estimates, and estimates of LNAPL transmissivity. The models should be calibrated to current LNAPL recovery rates.
- *Demonstrating that the LNAPL body is stable and that stability will not change in the future.* Routine groundwater gauging and sampling is being conducted at the site and demonstrates that the plume is stable. Based on the hydraulic gradients at the site and that recovery efforts are focused on skimming, significant changes in groundwater conditions are not anticipated to occur. Long-term monitoring will be implemented when recovery activities are terminated at the site.
- *Presenting information that shows an unreasonable cost per gallon or pound of LNAPL recovered.* The cost of recovery at the site has significantly increased over time in response to the reduction in LNAPL recovery volumes. Early recovery efforts removed large volumes of LNAPL providing a low cost of removal. A graph of expenditures over time in dollars/gallon is provided **(Appendix F**). *More recent optimization of LNAPL recovery operation (installation of the solar sippers) has reduced costs but costs per gallon are still considerably higher than historical costs on a $/gallon basis.*

6.2.1 Preliminary Decision Flowcharts

Detail decision *logic diagrams* using a hierarchy of decisions for both monitoring wells and recovery wells are provided (**Figures 6-2 through 6-4**). The general decision process for a combined LNAPL and NSZD remedial approach is provided as **Figure 6-2** and is based on *ITRC LNAPL 3 Guidance Figure NSZD-14*. Specific decision logic diagrams for LNAPL recovery wells (which are incorporated into the process shown on **Figure 6-2**) are provided as **Figure 6-3** and the decision logic diagram for monitoring wells is provided as **Figure 6-4**. These preliminary decision logic diagrams have been developed based on feedback from USEPA on both the LNAPL CSM and RAWP and the NSZD Work Plan (refer to USEPA comments and POC comment responses provided in **Appendix E**). It is our understanding that the POC

and USEPA will collaboratively refine this process as data from both ongoing LNAPL recovery activities and the NSZD study is obtained.

For the decision logic diagram provided for monitoring wells (**Figure 6-4**), note that this flowchart is not applicable to recovery wells which are part of the permanent or temporary recovery program (see **Figure 6-3**). Once recovery and bail down tests have been completed and it has been determined that LNAPL has been recovered to the extent practical, recovery wells will be converted to long-term monitoring wells. The focus of the long-term monitoring program will be on demonstrating a *stable* LNAPL plume and that NSZD processes are continuing. As part of the process, changes in LNAPL thickness and extent will be evaluated to determine if recovery activities need to be reinstated in select wells.

In accordance with the process shown on **Figure 6-2** the following performance metrics, endpoints and transition criteria have been proposed in accordance with the guidance provided in ITRC LNAPL-3 (2018). These are preliminary criteria which will undergo revision upon USEPA review of data collected from the ongoing LNAPL recovery activities and NSZD Assessment. The cleanup criteria for LNAPL were described in the USEPA-approved Phase Separated Petroleum Hydrocarbon Plume Remediation Work Plan.

> *The clean-up criteria for PSPH are based on two independent factors: risk and mobility. Corrective measures for PSPH will be complete when it is determined that PSPH:*
>
> - *Poses no unacceptable risk to human health and the environment, or*
> - *Is below the Practical Limits of Mobility (PLM) and is not likely to impact a receptor in the future."*

A range of metrics have been tracked over the years, but no formal endpoints and transition criteria have been contextualized in documents. Proposed Criteria include:

- ***End Point – Restoration of Groundwater Quality.*** *As we understand the desired outcome is "restoration of groundwater" which will require no mobile/observable LNAPL in wells and achievement of water quality standards suitable for the future beneficial use of groundwater.*
- ***Performance Metrics –*** *A range of performance metrics are inherent with USEPA comments and EHS Supports LNAPL CSM these include:*
  - ***Ensure that the LNAPL plume is stable and not migrating****. Associated metrics would include:*
    - No measurement of LNAPL in *new* wells (wells that have not historically had LNAPL)
    - *LNAPL thicknesses measured in wells consistent with historic observations (and considering the potential effects of groundwater elevation fluctuations)*
  - ***Are the skimming pumps being effectively operated:***
    - *Are the intakes of the pumps within the LNAPL layer?*
    - *Are routine operational and maintenance activities being conducted to ensure high operational uptimes?*
    - *Do oil/water cuts (> 25%) support effective operation of the skimmer pump.*
    - *Are the LNAPL thicknesses in wells maintained below 0.33 feet (4 inches) – effective operational thickness.*
  - ***Recovery to the Maximum Extent Practicable (Practical Limits of Mobility) in individual wells (recovery will be terminated on a well by well basis) as defined by (in order of priority):***

        - *Baildown test LNAPL Thresholds in individual wells below the upper bound of ITRC Thresholds and not inconsistent with the observed LNAPL thickness in the well and geology/hydrogeology at that location. USEPA has requested a justification for use of the ITRC transmissivity value but has also asked us to use the ITRC guideline. The use of this guideline value is predicated on these values being the only defined quantitative guideline included in the guidance and its extensive use on other sites to define a point at which LNAPL recovery may be impractical.*
        - *LNAPL recovery rates less than 1 gpd (to be validated by baildown tests immediately conducted on suspension of recovery). This value as demonstrated in the LNAPL CSM equates to the LNAPL transmissivity threshold provided above. The use of an LNAPL recovery rate (as a surrogate for LNAPL Transmissivity) provides for ease of application but is metric which guides actions such as completing a baildown test or reservoir decline curve analysis (see decision logic diagram)*
        - *Reservoir decline curve analysis demonstrating that a minimum of 90% of the maximum theoretical LNAPL recovery volume has been achieved. It should be noted in the application of this criteria even if > 90% of the theoretical recoverable volume has been removed termination of recovery will be determined based on the measured transmissivity.*
        - *In the event that the reservoir decline curve analysis does not yield a strong regression coefficient after application of common data filtering methods (spline functions, time weighted averages to standardize the temporal records over time or other smoothing algorithms) then other methods such as comparison on mobile and residual mass (using petrophysical testing) may be required.*
    - ***Further recovery of LNAPL is uneconomic.*** *If USEPA wants to utilize the ITRC recommendations, we can also include a metric around cost effectiveness and leverage a metric of $/gallon (e.g.* ***Appendix F****). Typically costs that have been utilized at other sites have included (a) costs in excess of the value of the product (b) costs a factor of 10-fold more than the value of the product. These metrics in many cases are arbitrary and we consider that they should be a consideration, not a formal metric.*
- ***Transition Criteria – In addition to achievement of recovery to the extent practicable. Transition criteria will be linked to the key concepts:***
    - ***Natural Mass Losses are greater than engineered mass losses.*** *This is focused on the concept that the natural processes must be sufficiently robust that the incremental gains of continued recovery (once the maximum extent practicable metrics are achieved) are limited*
    - ***Natural source zone depletion can facilitate restoration of the aquifer within a "reasonable" period of time.*** *This would require quantification of NSZD mass loss rates and quantification of mass in place to support calculation.*

The approach proposed is also aligned with other guidance contained within ITRC Figure NSZD-15 (**Figure 6-5**) which includes the considerations discussed in the context of the site in Table 6-2 **of the NSZD Work Plan**. The group does understand that the metrics and goals provided above will have to be refined and if reservoir/recovery decline curve analysis is constrained in its application then alternative methods may have to be incorporated into the approach.

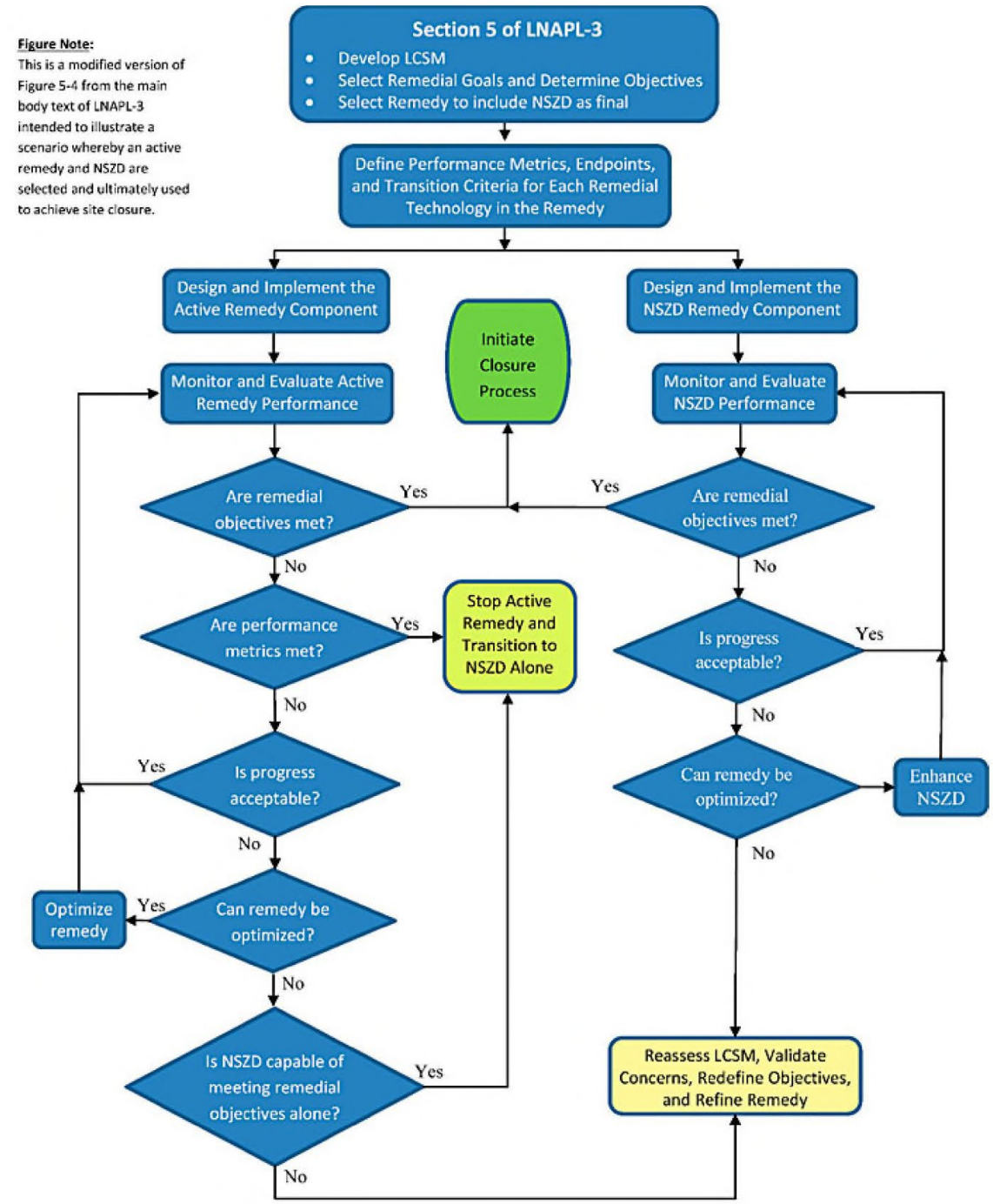


Figure 6-1. Combined Active-NSZD remedy management flowchart.
NSZD Appendix to 2017 ITRC LNAPL TechReg Guidance

Figure NSZD-14. Combined active-NSZD remedy management flowchart.

Figure 6-1 ITRC LNAPL-3 Figure 5-4

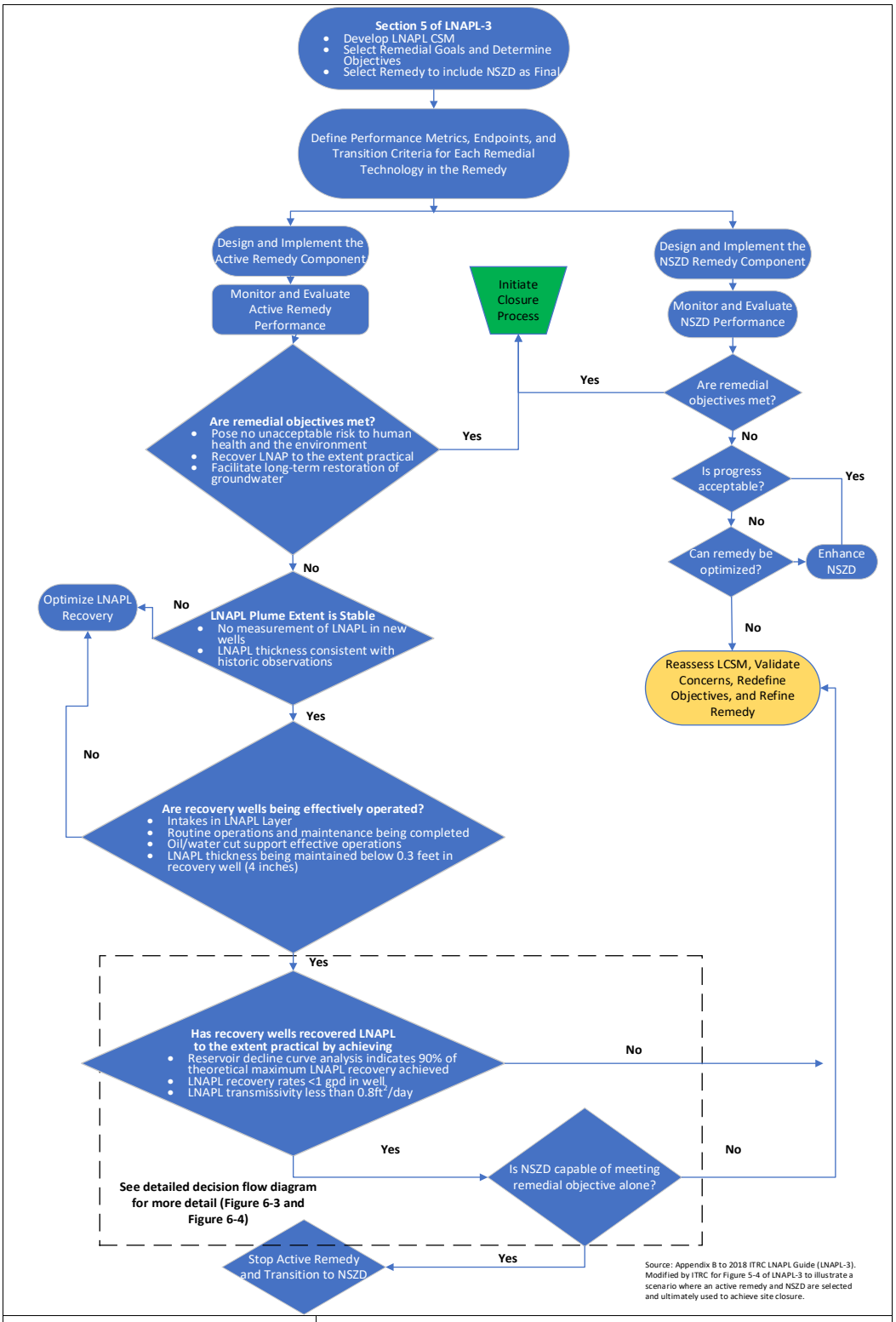


Figure 6-2 Decision Logic Diagram for Combined LNAPL Recovery and NSZD Remedy

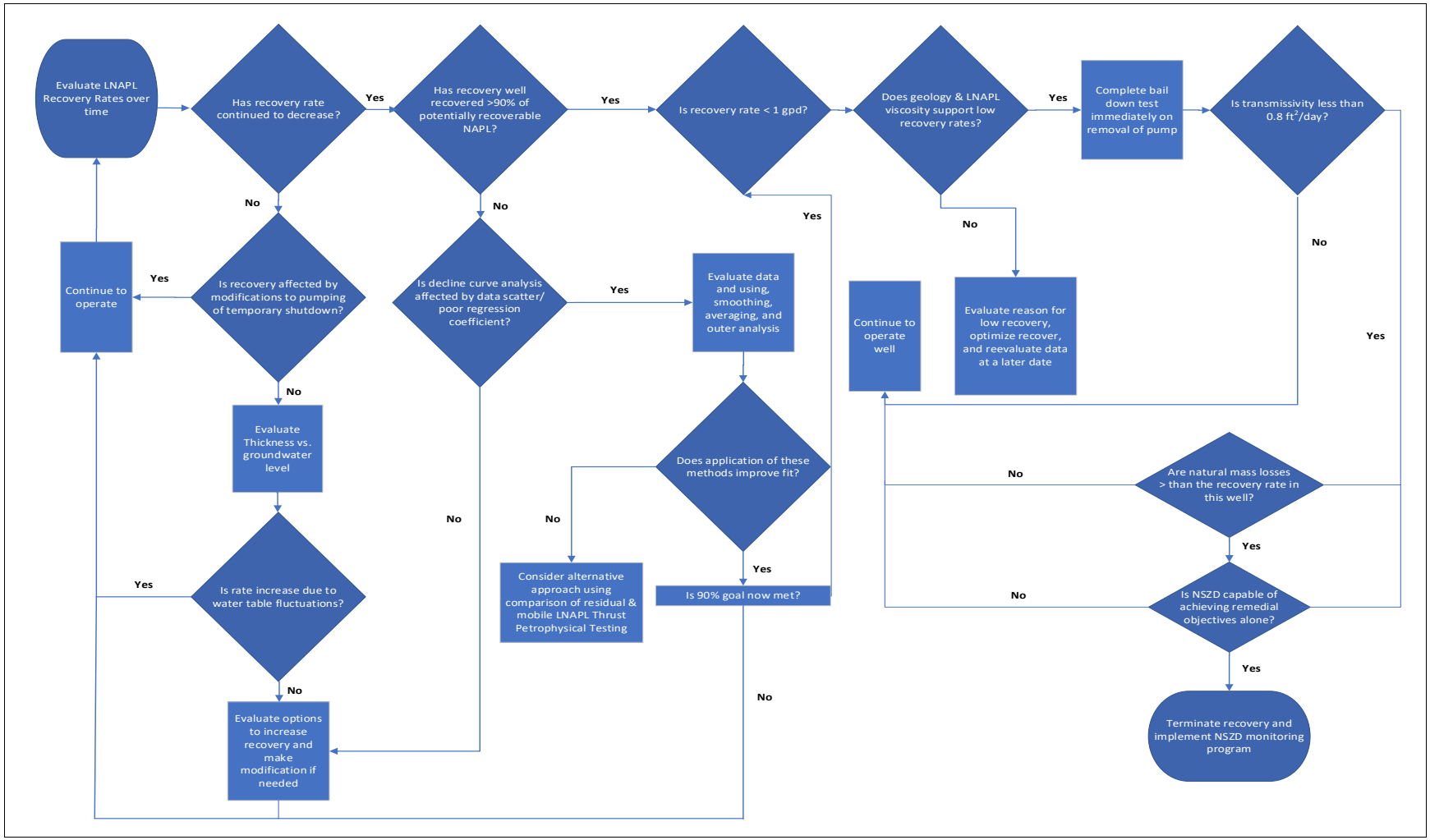
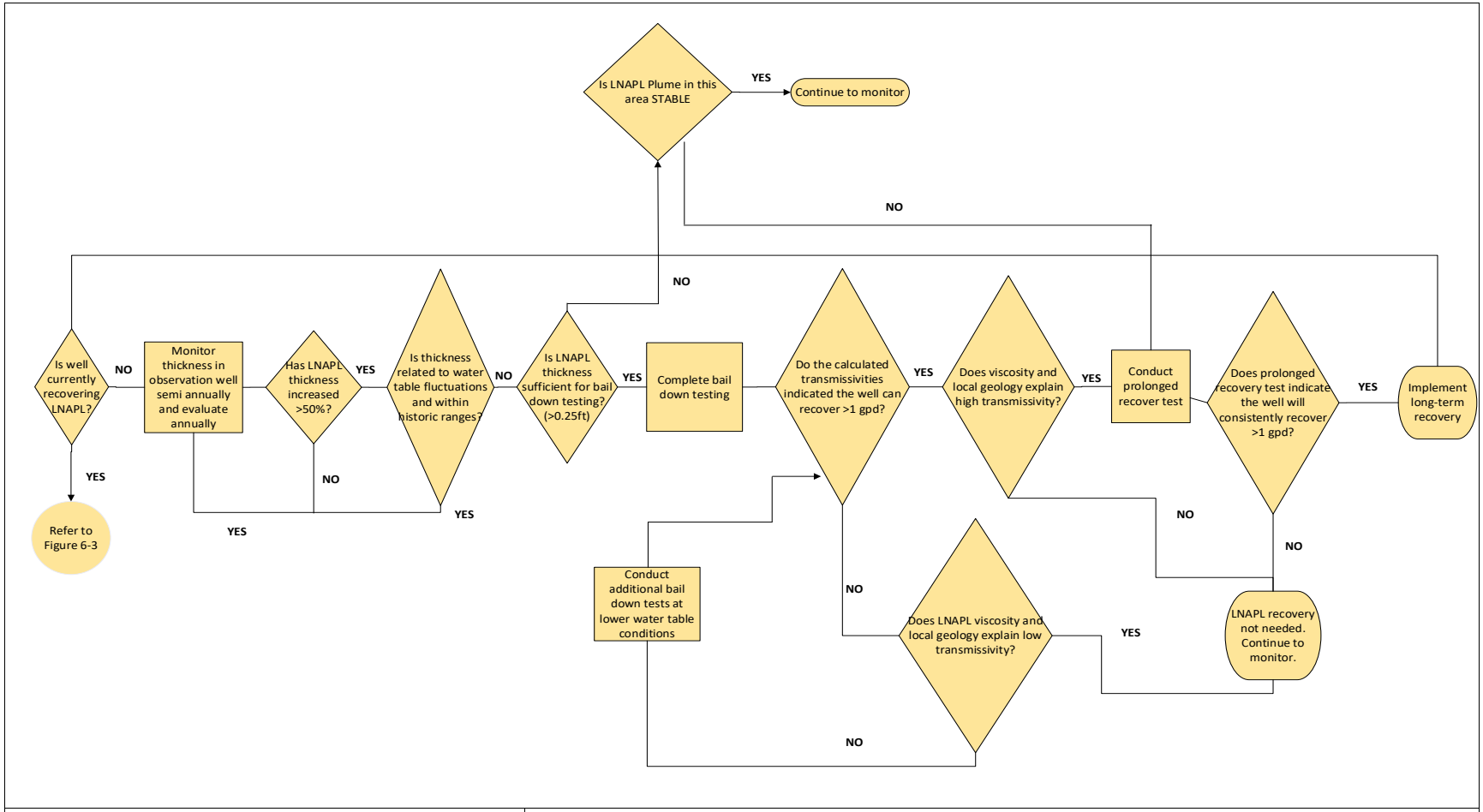


Figure 6-3 Decision Logic Diagram for LNAPL Recovery Wells



EHS Support

FIGURE 6-4 – LNAPL Decision Logic Diagram for Monitoring Wells with LNAPL (Wells Where Active Recovery is not Occurring)

Figure 6-4 LNAPL Decision Logic Diagram for Monitoring Wells with LNAPL

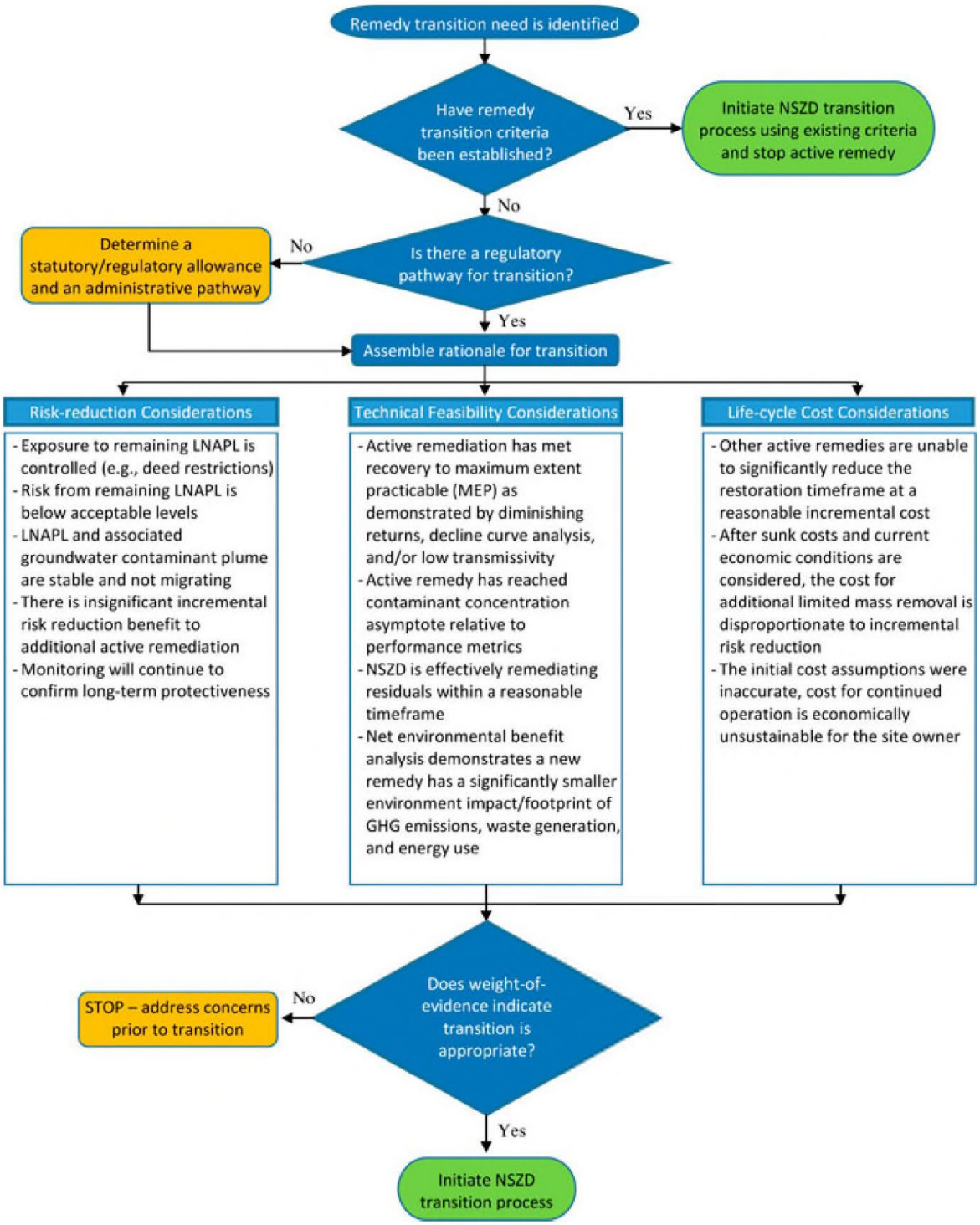


Figure NSZD-15. New transition need flow chart.

Figure 6-5 ITRC LNAPL-3 NSZD Figure 15.

6.3 Natural Source Zone Depletion Assessment and Quantification of Natural Mass Losses

As outlined in the decision flow chart above the quantification of natural mass losses is an important input into the decision logic process described above and will inform when a transition from active recovery to NSZD/MNA is implemented in select areas of the sites. As documented in the NSZD Work Plan a comprehensive assessment program has been developed for the site to define the nature of these processes and to facilitate quantification of mass losses. The concept of a transition from active recovery to an approach based on natural mass losses is captured conceptually in **Figure 6-6** below.

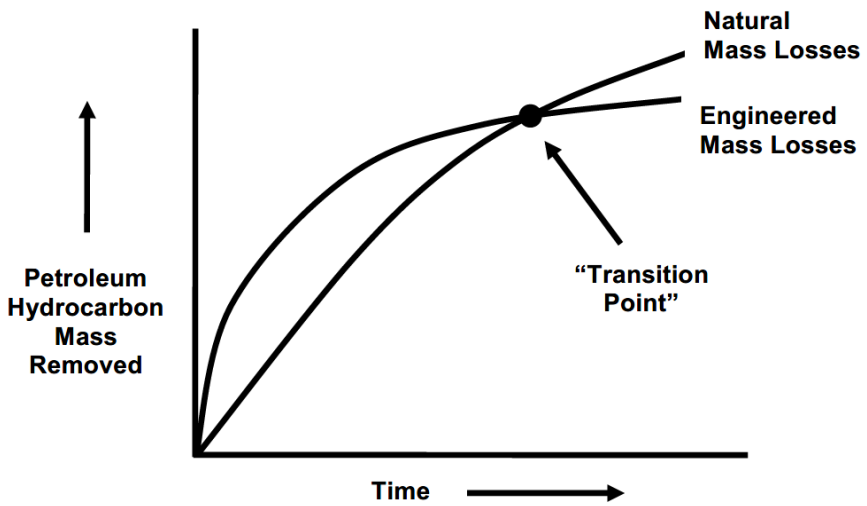


Figure 6-6 Natural Versus Engineering Mass Losses

Based on the Site geohydrology and limited geochemical data, a combination of sulfate reduction and methanogenesis processes appear to be active but requires confirmation via two discrete phases of work:

- Phase 1 - Collection of groundwater geochemistry data as part of the routine groundwater sampling activities to further understand current attenuation processes:
  - Dissolved Iron
  - Dissolved Manganese
  - Sulfate
  - Nitrate
  - Dissolved methane and carbon dioxide
  - Dissolved Oxygen and Redox (stabilized groundwater parameters)
  - General Water Chemistry which includes general cations and anions (to assess the geohydrology content and minerology of soils/bedrock in the area)
  - Head space of monitoring wells (near surface and down well) will be assessed to determine the distribution of biogenic gases at the LNAPL recovery wells
- Phase 2 – If determined to be beneficial, an assessment of subsurface biogenic gases and quantification of gaseous E-Flux to support determination of NSZD rates will be performed following work plan submittal to USEPA. The E-Flux Fossil Fuel trap, or equivalent CO2 efflux trap to quantify the natural source zone depletion can be used. This method leverages a grid-

based approach and the direct measurement of the efflux of carbon dioxide from the subsurface (via diffusion and natural advective processes) to quantify natural mass losses in the subsurface.

Further details on the proposed program of works are described in the NSZD Work Plan (EHS Support 2021) which has been reviewed by EPA (see comments and comment responses in **Appendix E**) with the final work plan and supporting Quality Assurance Project Plan (QAPP) submitted to EPA. Wells that will be targeted for the Phase 1 geochemical investigation include 17 wells located beneath the LNAPL-impacted area (VW2, VW5, VW6, VW13, VW13B, VW14, VW20, VW21B, VW20B, VW22, VW23, VW24, VW29, VW30, VW31, VW32 and VW35), 4 upgradient wells (MMX, VW8, MM9 and VW11), and 7 downgradient wells (VW25, VW27, VW34, VW37, GM11, GM14 and GM-22). This sampling will be conducted in conjunction with a semi-annual groundwater sampling event (wells VW25, VW27, VW34, VW37, GM11, GM14, and MMX are already part of groundwater sampling). Note: VW22 has been dry for several sampling events but will be checked and sampled if possible.

In terms of future implementation of the process (and after completion of the NSZD Studies) it is anticipated that engineered mass losses (gallons per day) for site wells will be tabulated from site recovery operation data as described above. NSZD rates will be calculated at locations where PSPH is present using several approaches to account for potential variability is site conditions (as outlined in the NSZD Workplan):

- Aqueous NSZD rates (gallons PSPH per day) will be estimated by comparing maximum, mean, and minimum differences of terminal electron acceptor (TEA) concentrations in groundwater and background wells to source zone (beneath PSPH) and downgradient wells, as outlined in CRC CARE (2018) and ITRC (2009). NSZD assimilative capacity (AC) values will be computed from the maximum, mean, and minimum differences to provide a range of NSZD rates at each location for comparison to engineered mass losses.
- Vapor phase and aqueous phase NSZD rates will be estimated using the differential temperature method, by measuring the temperature at specific points within the vadose zone and beneath water table. Heat flux will then be estimated using Fourier's first law of conduction, and divided by the enthalpy of formation for a middle distillate fuel oil to yield an NSZD rate (corrected by the heat capacity of water for the aqueous portion of the rate calculation and converted to units of gallons per day).
- Based on the outcome of the above assessments, an additional line of evidence will be selected to determine NSZD rates, that may include one or a combination of passive CO_2 traps, use of a dynamic closed chamber, and/or the vadose gas gradient method.

Given variability of conditions at the site, variability in NSZD rates are anticipated at different locations, and will be integrated across the maximum extent of LNAPL using a Thiessen Polygon approach for direct comparison to the total engineered PSPH mass loss.

7 Conclusions

Using a combination of historical and recently collected data, the nature, extent and mobility and recoverability of LNAPL at the Site has been assessed and are well understood. The complexity/heterogeneity of the Site geology has impacted the lateral extent and transmissivity/recoverability of LNAPL at the Site. The LNAPL is primarily present within the limestone and other cemented or partially cemented deposits. The lateral extent of these more transmissive components of this system were the key geologic controls on the historical migration of LNAPL and the resulting distribution. Migration of the LNAPL impacts was primarily orientated east to west (across hydraulic gradient) with limited migration to the south. This is likely a function of the transition from more transmissive materials to finer grained Marls or heavily cemented or weathered limestone with low LNAPL transmissivity.

LNAPL recovery efforts have been successful at decreasing LNAPL thickness (**Table 5-10**) but the majority of historical recovery has been focused in the eastern portion of the Site reflecting more transmissive areas of the formation. The geometry of the LNAPL areas over time indicates a stable to declining plume area. While LNAPL in select wells continues to be recovered, the LNAPL recovery rates have decreased orders of magnitude over time with the majority of wells recovering less than 1 gpd. Mobility testing conducted in select wells and assessment of recovery rates/recovery performance by well indicates that the LNAPL transmissivities are generally low and LNAPL storage is limited. Assessment of these LNAPL transmissivities indicates that the majority of values are below ITRC recommended practicality endpoints for LNAPL recovery.

Compositionally, the LNAPL is comprised of very small proportions of soluble fractions limiting the potential for partitioning into soil gas and groundwater. Partitioning calculations using LNAPL chemistry data indicated that maximum theoretical concentrations of key LNAPL constituents would not lead to exceedances of groundwater criteria and this is supported by groundwater monitoring data which show limited detections in groundwater. Further historical risk assessments have demonstrated that groundwater conditions (including partitioning into soil gas) do not pose unacceptable risks.

While the limited dissolved phase impacts are reflective of the low effective solubility of the LNAPL natural attenuation processes are also likely a contributor to the observed groundwater conditions. In addition to the mechanical processes residualizing LNAPL (e.g., groundwater fluctuations trapping LNAPL within small soil pores), natural degradation processes are important to LNAPL stability and long-term mass reduction of LNAPL. Natural degradation processes include direct degradation of LNAPL through cleavage of aliphatic compounds and subsequent degradation in groundwater of more soluble, lower carbon chain by-products, dissolution of soluble LNAPL constituents into groundwater and subsequent biodegradation, and direct volatilization of LNAPL constituents into the vadose zone. Geochemistry data and mineralogical observations demonstrate that sulfate reduction is likely a significant mechanism of biodegradation at the Site. The presence of abundant gypsum provides a plentiful supply of sulfate and redox conditions indicate that sulfate reduction and methanogenesis are likely important mass loss processes. Further assessment of NSZD processes have been proposed to understand the nature and magnitude of these processes.

A summary of key findings and recommendations is presented below:

Geologic and Hydrogeologic Controls Affecting Historical LNAPL Migration and Current/Future LNAPL Mobility

- Assessment of the regional and site specific geologic and hydrogeologic information indicates that the Site geology is complex and heterogeneous. The material at the water table where wells are screening comprises calcareous clay, silt, sand, and gravel which has been identified as within the Kingshill limestone. Large hydraulic conductivity and LNAPL transmissivity contrasts are observed in the saturated zone with:
  - Calcareous silt, sand and gravel with high hydraulic conductivity occur in the Kingshill Limestone lagoon deposits.
  - Abundant clay deposits that likely formed in the Kingshill Limestone lagoon are associated with the evaporite minerals caliche (calcium carbonate), gypsum (calcium sulfate), and are associated with chert (organism frustules composed of silicon dioxide).
- Review of the boring logs indicates that the materials are mildly to heavily cemented and as such LNAPL mobility and recoverability is likely controlled by secondary porosity features and intervals of more granular materials. The heavily weathered limestone and Marls which dominate in the southern portions of the Site are likely impermeable to LNAPL and therefore explain the geometry of the plume.
- In the context of LNAPL recovery this complexity and the rapid declines in LNAPL recovery rates are explained by the heterogeneity and complexity of subsurface and LNAPL storage that are primarily constrained to secondary porosity and intervals of less/poorly cemented granular materials.

Vertical and Lateral Extent of LNAPL

- The lateral extent of the LNAPL is well defined and the plume has been shown to be stable and receding over time.
- Based on the limited water table fluctuations observed at the Site (except for large scale monsoonal rain events) the vertical distribution of LNAPL is likely to be limited. In some recovery wells the gauging data does indicate some relationship between groundwater elevation and LNAPL thickness with greater thicknesses observed during low water stands. However, the magnitude of LNAPL thickness increases are small. Further in a large number of recovery wells no linkage between groundwater elevation and LNAPL thickness is observed.

Current/Future LNAPL Mobility and Recoverability

- LNAPL Transmissivity (Tn) has been evaluated in select wells via baildown testing. This data indicates that the LNAPL transmissivity is moderate to low. However, in situations where storage is limited (such as this site) baildown tests are likely to provide high estimates of LNAPL Transmissivity. Testing which comprises longer stress periods and more continuous removal will rapidly deplete storage and see order of magnitude declines in LNAPL transmissivity.
- Assessment of the LNAPL recovery data for both the total fluid recovery and solar sipper wells has shown orders of magnitude decreases in recovery rates overtime. LNAPL recovery rates in the majority of wells have declined to below 1 gpd. This recovery rate equates to a lower transmissivity than the bail-down tests and is below practical recoverability thresholds (ITRC, 2009b).

LNAPL Physical and Chemical Properties and Potential Source of Contamination to Groundwater

- Diesel and Fuel oils were historically utilized at the Site and forensic assessments have demonstrated that LNAPL is heavily weathered diesel and fuel oil.
- Consistent with the chemical properties of diesel, the aliphatic compounds dominate and BTEX is unlikely to be present (trace only) and only low concentrations of naphthalene are present.
- Calculated maximum groundwater concentrations using LNAPL chemistry data and groundwater monitoring data demonstrate that the LNAPL is not a major source of dissolved phase constituents. Dissolved phase impacts (trace levels) present in wells include wells where LNAPL was formerly observed and wells immediately adjacent to areas of LNAPL.

Natural Degradation of LNAPL

- Natural source zone depletion processes can result in significant mass losses over time.
- Assessment of limited groundwater geochemical data and mineralogical data indicates that sulfate reduction is likely to be a significant mechanism of mass loss with naturally occurring gypsum providing an abundant supply of sulfate.
- Assessment of groundwater monitoring data for the Site indicates that reducing conditions are present in numerous wells at the Site indicating that biodegradation of hydrocarbons is occurring at the Site.
- The redox conditions are moderate to highly reducing and indicate that both sulfate reduction and methanogenesis is likely occurring.
- Additional studies are recommended to better understand the nature and magnitude of the natural source zone depletion processes occurring at the Site.

Recommendations

- In the context of the evolving LNAPL Conceptual Site model a framework of ongoing LNAPL recovery and groundwater monitoring has been proposed for the Site. Based on the low LNAPL transmissivity observed at the Site it is likely that many wells have reached practicality endpoints for LNAPL recovery. It is proposed that additional operations of the solar sippers through June 2021 will be conducted to facilitate further assessment of LNAPL transmissivity and recoverable volumes.
- On the basis of more recent recovery efforts wells have been selected for ongoing recovery with total fluids recovery in well VW13B to continue for the short-term (noting that performance is not that much better than the adjacent solar sipper wells)
- Based on the low LNAPL transmissivity and limited storage of LNAPL in formation continued vacuum recovery events are not considered warranted. The yield of LNAPL by the formation and former recovery well operational data indicates that the volumes of recoverable LNAPL at these locations is limited.
- To better understand the processes that will support restoration of the aquifer a comprehensive assessment of natural source zone depletion processes is planned.

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Tables

Table 1
Data Use Objectives
NSZD Work Plan
St. Croix Alumina
St. Croix, U.S. Virgin Islands

Task	Data Use Objective	Scope	Anticipated Advantages	Potential Challenges
Phase 1				
Well headspace readings	Verify CH_4, CO_2, and H_2S gases are present/absent and indicative of active microbial mass depletion, and where NSZD is occurring spatially.	A single data collection event. In monitoring wells 2 feet below ground surface (with well annulus covered) and 1 foot above groundwater.	• Provides a rapid, cost effective screening method to confirm if NSZD is occurring. • Data may support decision on the location, duration, and deployment density of *in situ* soil gas flux measurement devices deployed in Phase 2. • Provides a baseline to assess effectiveness of soil gas traps deployed in Phase 2. • Determine if well headspace measurements will be effective in conjunction with shallow soil gas probes to calculate NSZD rates using the gradient method in Phase 2.	• Headspace gases may be affected by the carbonate lithology, which conceivably contribute to the background CO_2 soil gas flux. • Gas concentrations may be affected by municipal effluent or natural degradation of organic matter. • Instantaneous measurement that does not integrate variations of soil gas flux, therefore, of limited use for calculating temporal LNAPL mass depletion rates.
General geochemistry, cations, anions, nitrogen, ammonia, methane, sulfate, sulfide, carbon dioxide, total and dissolved iron and manganese	Verify and validate current LNAPL CSM by assessing the spatial distribution of different groundwater types (e.g. perched) in the context of site geology. Identify potential groundwater recharge areas that may affect temperature profile results.	A single data collection event. Upgradient, source area, and downgradient monitoring wells described in work plan.	• Piper, concentration and ion ratio plots are a robust means to identify hydrological variability due to the presence of different water types (e.g. background groundwater, municipal effluent, sea water), or variations in groundwater hydrogeochemistry due to different recharge loci. • Provides a robust, additional line of evidence to constrain in situ redox conditions.	• Results may be affected by timing of sampling relative to the tidal cycle, or a rapid recharge during a major precipitation event that is not representative of typical site conditions.
Key field parameters (e.g. ORP, DO)	Identify locations with favorable aqueous NSZD redox conditions, specifically using dissolved oxygen (DO) and oxidation reduction potential (ORP) measurements	A single data collection event. Upgradient, source area, and downgradient monitoring wells described in work plan.	•Field parameters are already measured at several locations during routine groundwater sampling events. •Cost effective and readily available technique.	•Hydrogeologic variability and complexity, such as tidal flushing, may lead to unrepresentative readings. •Potential interferences from dissolved gases (particularly CH_4, H_2S) •Potential redox disequilibrium may yield DO values that are not representative of *in situ* conditions
Temperature profiles	Verify NSZD is occurring based on the presence/absence of a thermal response from active microbial LNAPL mass depletion. Calculate vapor phase LNAPL NSZD mass depletion rates.	A single data collection event. Downhole vertical temperature readings collected from upgradient, source area, and downgradient monitoring wells described in work plan.	•Relatively small diurnal, seasonal, and background temperature fluctuations due to the tropical climate will minimize climate-related uncertainties. •Temperature difference accounts for vapor phase mass depletion, which is the dominant fraction of NSZD.	•Hydrogeologic variability and complexity may obscure temperature anomalies in locations with high hydraulic conductivity, tidal flux, or groundwater mixing. •Affected by groundwater recharge zones, which may be identified using general geochemistry and field parameter measurement assessment. •May be variable in areas of geologic complexity, and require assessment of thermal gradients in each unique geologic environment.
Electron acceptors	Assess changes in electron acceptors in up- and down-gradient wells to calculate aqueous phase LNAPL NSZD mass depletion rates.	A single data collection event. Collected from beneath the LNAPL/sheen in all wells where present, and several background and downgradient wells as described in the work plan.	•Existing monitoring well network provides access, and sampling can be readily piggy-backed with existing field monitoring/sampling events.	• Variability of electron acceptor concentrations may be affected by the presence/absence of evaporites (e.g. gypsum). • Results may be affected by sheen or LNAPL globules entrained in samples. • Impacts from effluent or tidal flushing with sea water may obscure electron acceptor concentrations. • Accounts for aqueous mass depletion only, which is a fraction of the overall mass depletion.

Table 1
Data Use Objectives
NSZD Work Plan
St. Croix Alumina
St. Croix, U.S. Virgin Islands

Task	Data Use Objective	Scope	Anticipated Advantages	Potential Challenges
Well GM-22 Survey	Identify reason for groundwater elevation in the well vicinity.	A single elevation measurement.	•Identification of well casing survey error will definitively resolve the reason for groundwater elevation discrepancies in this area.	•If the well survey data is not in error, additional desktop study (at minimum) will be required to identify if this is an area of groundwater recharge or if there is an alternative geologic reason/explanation for groundwater elevation discrepancies here. The results of a desktop study may result in proposal of additional field study. •Requires cation/anion sampling at minimum to identify recharge source if survey shows casing elevation is correct.
Phase 2				
Soil gas flux measurements using passive CO_2 traps	Provide soil gas flux measurements used to calculate vapor phase LNAPL mass depletion rates.	A single deployment. Grid extent and spacing to be informed by results of Phase 1 work.	•Deployed for a period of time, therefore, integrate effects of all processes that contribute to temporal flux variability.	•Affected by gas contributions from soil organic matter degradation. •Site conditions (e.g. gravel, concrete) may affect gas (e.g. O_2) readings requiring additional stoichiometric conversions. •Carbonate lithology presents an alternate fossil CO_2 source that must be resolved from the LNAPL contribution using non-standard techniques. •May be prohibitively expensive if Phase 1 results indicate substantial geological/hydrochemical variability and a tight grid spacing is needed. •Expensive analysis, and calculations typically performed by labs that may not be familiar with corrections for carbonate lithology sites.
Soil gas flux measurements using lycor meter	Provide soil gas flux measurements used to calculate vapor phase LNAPL mass depletion rates.	A single deployment if passive traps not used. Grid extent and spacing to be informed by results of Phase 1 work.	•Portable meter useful for multiple deployments or dense sampling grid network. •Established and robust method utilized in numerous NSZD evaluations elsewhere. •Rapid analysis with real-time data read out.	•Expensive up-front investment for equipment. •Does not directly distinguish contributions from different carbon sources (i.e. limestone, modern organic matter degradation in soil) and requires study of a large number of background locations. •Provides a snap-shot measurement that does not account for diurnal and temporal variations in gas flux. •Requires 3 sequential readings within an acceptable % threshold, which may prove challenging in complex settings.
Radiogenic carbon isotope (^{14}C) measurement of CO_2 in gas traps	Background correction to identify CO_2 from hydrocarbon degradation and modern soil organic matter degradation.	A select number of the gas trap samples, informed by results of Phase 1 work. A travel blank sample, a control sample, at minimum 3 background samples.	•Is the gold standard in correcting for CO_2 from modern sources and LNAPL NSZD. •Is a robust correction if there are no unimpacted areas for trap deployment to quantify background CO_2, if background locations have highly variable CO_2 flux, and if background locations have different natural processes (i.e. vegetation microbial activity) than impacted locations (McCoy et al. 2015). •May be used in conjunction with Lycor meter CO_2 measurement, should phase 1 results indicate passive trap method is prohibitively expensive due to the need for a tight grid spacing.	• A site with low ambient pH (> ~4.8) and considerable limestone ($CaCO_3$) may be a poor candidate for applying this technique as ancient carbonate deposits might dissolve at low pH and bias the analysis (Boyd et al., 2016). • Limestone lithology requires non-radiogenic ($\delta^{13}C$) data in addition, which may or may not identify limestone carbon contribution.

Table 1
Data Use Objectives
NSZD Work Plan
St. Croix Alumina
St. Croix, U.S. Virgin Islands

Task	Data Use Objective	Scope	Anticipated Advantages	Potential Challenges
Stable carbon isotope ($\delta^{13}C$) measurement of CO_2 in gas traps	Background correction to determine additional potential sources of CO_2, including Kingshill Limestone.	Gas trap samples analyzed for ^{14}C	• Marine carbonates typically yield soil CO_2 $\delta^{13}C$ values more than -15 ‰ (VPDB) with small fractionation on conversion to CO_2 at ambient temperatures. In contrast, CO_2 from NAPL and modern soil organic matter degradation typically have $\delta^{13}C$ values less than -25 ‰ (VPDB). The difference may be sufficiently large that the three potential reservoirs can be resolved when assessed in conjunction with ^{14}C.	• Identification of abiotic carbonate weathering requires unimpacted background locations with similar hydrogeochemistry to impacted areas. • Identification of abiotic carbonate weathering from microbial LNAPL mass depletion requires that both processes result in distinctive stable carbon isotope signatures that can be demonstrated with site-specific samples (Coffin et al. 2008).
CO_2 Gradient method calculated using Fick's first law of diffusion.	Provide soil gas gradient measurements used to calculate vapor phase LNAPL mass depletion rates.	A single data collection event. Well headspace readings 1 foot above water table in upgradient, source area, and downgradient monitoring wells described in work plan. 1 foot bgs soil headspace readings adjacent to measured monitoring wells. Readings made with a hand-held gas meter.	• Inexpensive technique to confirm vapor-phase NSZD rates. • Does not require expensive equipment or infrastructure installation.	•Does not directly distinguish contributions from different carbon sources (i.e. limestone, modern organic matter degradation in soil) and requires study of a large number of background locations. •Provides a snap-shot measurement that does not account for diurnal and temporal variations in gas flux.

Notes
CSM = Conceptual site model
DO = Dissolved oxygen
LNAPL = Light non-aqueous phase liquid
NSZD = Natural source zone depletion
ORP = Oxidation reduction potential
VPDB = Vienna PeeDee Belemnite

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Table 2
Key Literature References
NSZD Work Plan
St. Croix Alumina
St. Croix, U.S. Virgin Islands

Task	Data Use Objective	Key References
Phase 1		
Well headspace readings	Qualitatively assess active vapor-phase NSZD by verifying that CH_4, CO_2, and H_2S gases are present/absent, and identifying where NSZD is occurring spatially.	Sweeney and Ririe, 2017;
General geochemistry, cations, anions, nitrogen, ammonia, methane, sulfate, sulfide, carbon dioxide, total and dissolved iron and maganesese	Qualitatively assess active aqueous NSZD based on electron acceptor depletions relative to background locations.	Wiedemeier et al., 1995; Beck and Mann, 2010
Key field parameters (e.g. ORP, DO, etc.)	Identify locations with favorable aqueous NSZD redox conditions, specifically using dissolved oxygen (DO) and oxidation reduction potential (ORP) measurements	McMahon and Chapelle, 2008; Nordstrom and Wilde, 2005; Jurgens et al., 2009; Wiedemeier et al, 1998
Temperature profiles	Verify NSZD is occurring based on the presence/absence of a thermal response from active microbial LNAPL mass depletion. Calculate vapor phase LNAPL NSZD mass depletion rates.	Sweeney and Ririe, 2014; Warren and Bekins, 2015; Suthersan, 2015; Newell et al., 2016; Garg et al., 2017;
Electron acceptors	Quantitatively assess changes in electron acceptors in up- and down-gradient wells to calculate aqueous phase LNAPL NSZD mass depletion rates.	Wiedemeier et al., 1995; Beck and Mann, 2010
Phase 2		
Soil gas flux measurements using passive CO_2 traps	Provide soil gas flux measurements used to calculate vapor phase LNAPL mass depletion rates.	McCoy et al., 2014
Soil gas flux measurements using lycor meter	Provide soil gas flux measurements used to calculate vapor phase LNAPL mass depletion rates.	Sihota et al., 2011
Radiogenic carbon isotope (^{14}C) measurement of CO_2 in gas traps	Background correction to identify CO_2 from hydrocarbon degradation and modern soil organic matter degradation.	Landmeyerand Stone, 1995; Coffin et al, 2008; McCoy et al., 2014; Schindlbacher et al., 2015; Boyd et al., 2016
Stable carbon isotope ($\delta^{13}C$) measurement of CO_2 in gas traps	Background correction to determine additional potential sources of CO_2, including Kingshill Limestone.	Meckenstock et al., 2004; Nowak et al., 2016
CO_2 Gradient method calculated using Fick's first law of diffusion.	Provide soil gas gradient measurements used to calculate vapor phase LNAPL mass depletion rates.	Sweeney and Ririe, 2014

Notes
DO = dissolved oxygen
LNAPL = light non-aqueous phase liquid
NSZD = Natural source zone depletion
ORP = oxidation reduction potential

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Wiedemeier, T.H., Swanson, M.A., Moutoux, D.E., Gordon, E.K., Wilson, J.T., Wilson, B.H., Kampbell, D.H., Haas, P.E., Miller, R.N., Hansen, J.E. and Chapelle, F.H., 1998. Technical protocol for evaluating natural attenuation of chlorinated solvents in groundwater. Cincinnati, Ohio, USA: USEPA

Table 3
Groundwater Sampling and Analysis Plan
LNAPL Natural Source Zone Depletion Work Plan
St. Croix Alumina Site
St. Croix, U.S. Virgin Islands

Field Sample ID	Laboratory Provided Sample IDs	TPH-DRO (SW8015)	BTEX (SW8260)	Naphthalene Only (SW8270)	Field Parameters	Alkalinity (SM2320B)	Cations (6020A)	Total Fe & Mn (6020A)	Anions (300.0)	Dissolved Fe and Mn (6020A)	Sulfide (SM4500)	Ammonia and Nitrogen (SM4500)	Dissolved gases	DOC (415.1)
Upgradient Ground Water Samples														
MMX	MMX-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW8	VW8-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
MM9	MM9-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW11	VW11-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
Source Area Ground Water Samples														
VW2	VW2-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW5	VW5-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW6	VW6-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW13	VW13-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW13B	VW13B-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW14	VW14-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW20	VW20-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW20B	VW20B-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW21B	VW21B-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW22	VW22-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW23	VW23-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW24	VW24-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW29	VW29-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW30	VW30-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW31	VW31-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW32	VW32-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW35	VW35-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
Downgradient Ground Water Samples														
VW25	VW25-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW27	VW27-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW34	VW34-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
VW37	VW37-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
GM11	GM11-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
GM14	GM14-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		
GM22	GM22-yyyymmdd	A	B/I	N	C	D	C	F	G	H	E	J		

Table 3
Groundwater Sampling and Analysis Plan
LNAPL Natural Source Zone Depletion Work Plan
St. Croix Alumina Site
St. Croix, U.S. Virgin Islands

Field Sample ID	Laboratory Provided Sample IDs	TPH-DRO (SW8015)	BTEX (SW8260)	Naphthalene Only (SW8270)	Field Parameters	Alkalinity (SM2320B)	Cations (6020A)	Total Fe & Mn (6020A)	Anions (300.0)	Dissolved Fe and Mn (6020A)	Sulfide (SM4500)	Ammonia and Nitrogen (SM4500)	Dissolved gases	DOC (415.1)
Quality Control Samples														
EB-01	EB-01-yyyymmdd	A	B/I		C	D		C	F	G	H	E	J	
FB-01	FB-01-yyyymmdd	A	B/I		C	D		C	F	G	H	E	J	
TB-01	TB-01-yyyymmdd	A	B/I		C	D		C	F	G	H	E	J	
DUP-01	DUP-01-yyyymmdd	A	B/I	N	C	D		C	F	G	H	E	J	

FB = Field Blank (1 per event; pouring clean water directly into lab sample containers)
EB = Equipment Blank (1 per event; non-dedicated and reusable equipment only)
DUP = field duplicate (1 per event)
TB = Trip blank (1 per container of volatile organic compounds which will be consolidated in final shipment)

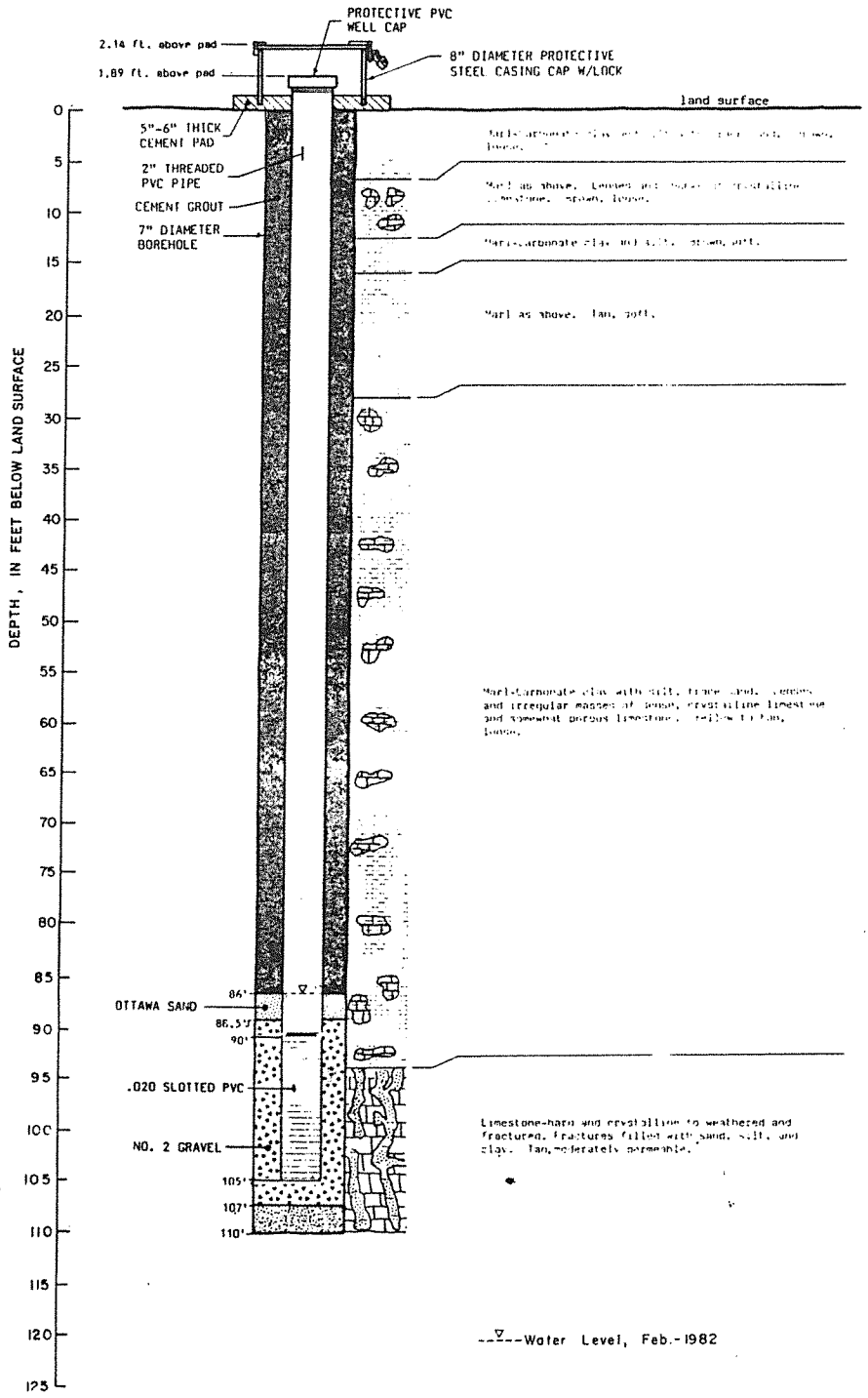
Field Parameters = temperature, pH, conductivity, dissolved oxygen, oxidation reduction potential, turbidity

DOC = dissolved organic carbon
HCl = Hydrochloric acid
HNO_3 = Nitric acid
H_2SO_4 = Sulfuric acid
mL = milliliter
MS = Matrix spike
MSD = Matrix spike duplicate
NA = Not applicable
BTEX = Benzene, toluene, ethylbenzene, xylenes,
TPH-DRO = Total petroleum hydrocarbons - diesel range organics
ZnAc = zinc acetate

Cations = Na, K, Ca, Mg
Anions = Cl, SO_4, NO_3, NO_2
Dissolved gases = methane and carbon dioxide

Recommended bottleware
(number of containers) container type - preservative; holding time
A: (3×) 40 ml Vials - unpreserved; 7 days
B: (3x) 40 mL Vials - HCl; 14 days
C: (1x) 250 mL plastic - unpreserved; NO2/NO3 48 hours & Cl/So4 28 days, Alk 14 days
D: (1x) 120 mL plastic - HNO_3; 6 months
E: (3x) 40 ml HCL vials (Methane) & (3x) 40ml unpreserved vials (CO2); 14 days
F: (1x) 120 mL plastic - filtered, HNO3; 6 months
G: (1x) 500 mL plastic - ZnAc; 7 days
H: (1x) 250 mL plastic - H_2SO_4; 28 days
I: (3x) 40 ml vials- unpreserved; 7 days
J: (2X) 40 ml vials- filtered, H2SO4; 28 days
N: None - field parameter

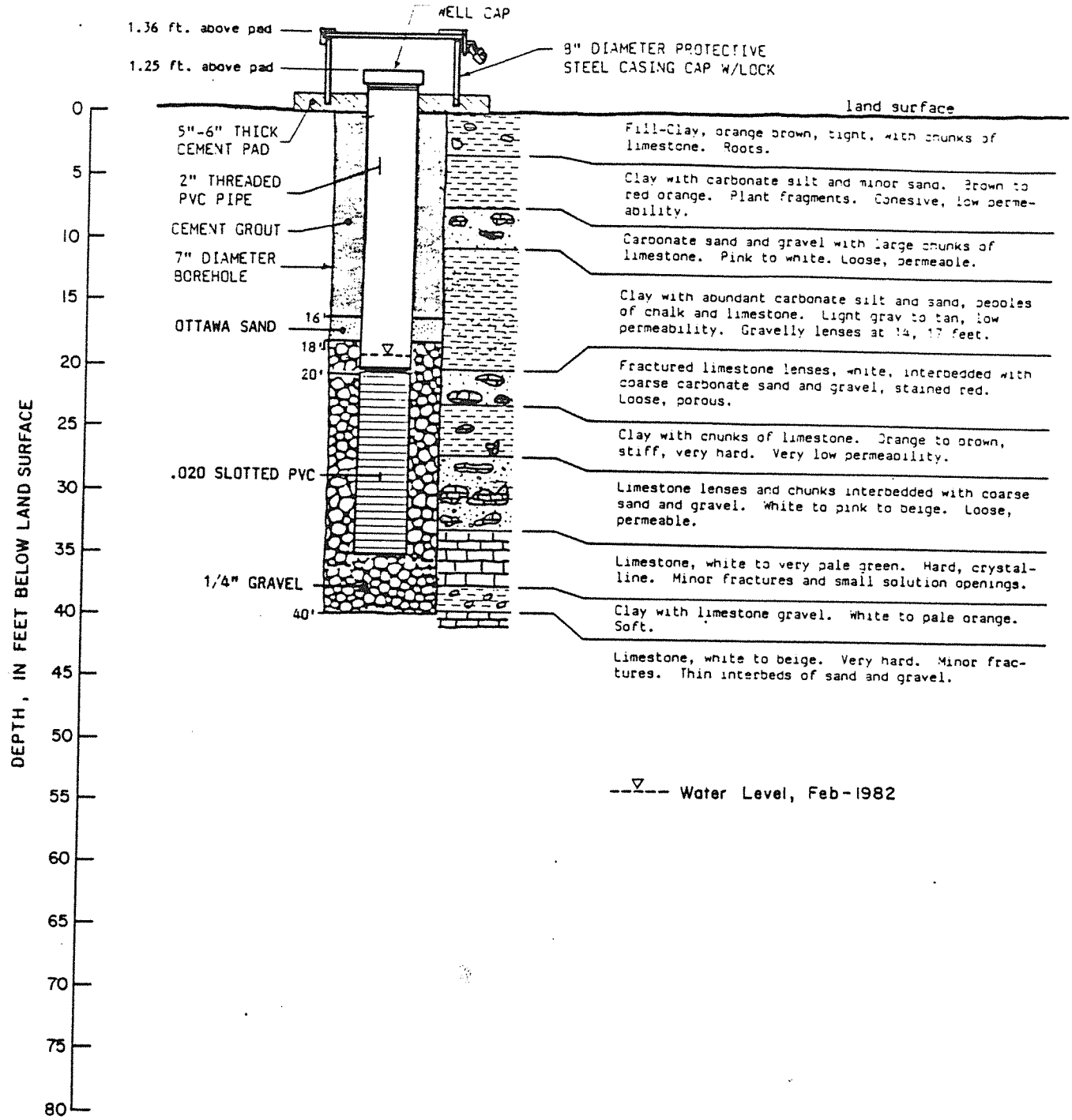
Appendix A Boring Logs



CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-1

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	D. NACHMAN R. PADULA W. BOIS	SHOWN 4-1982	A-1



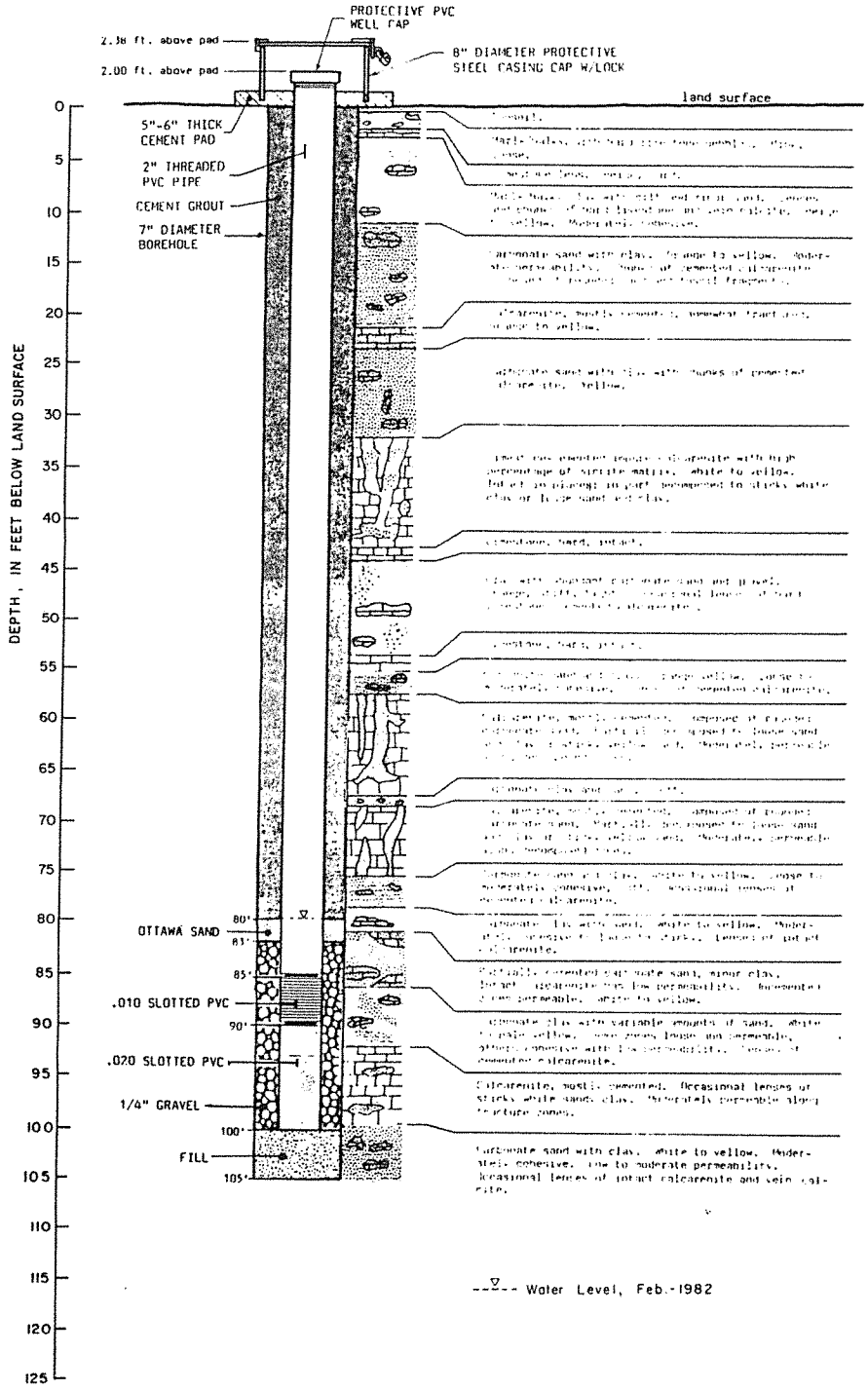
SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-2

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

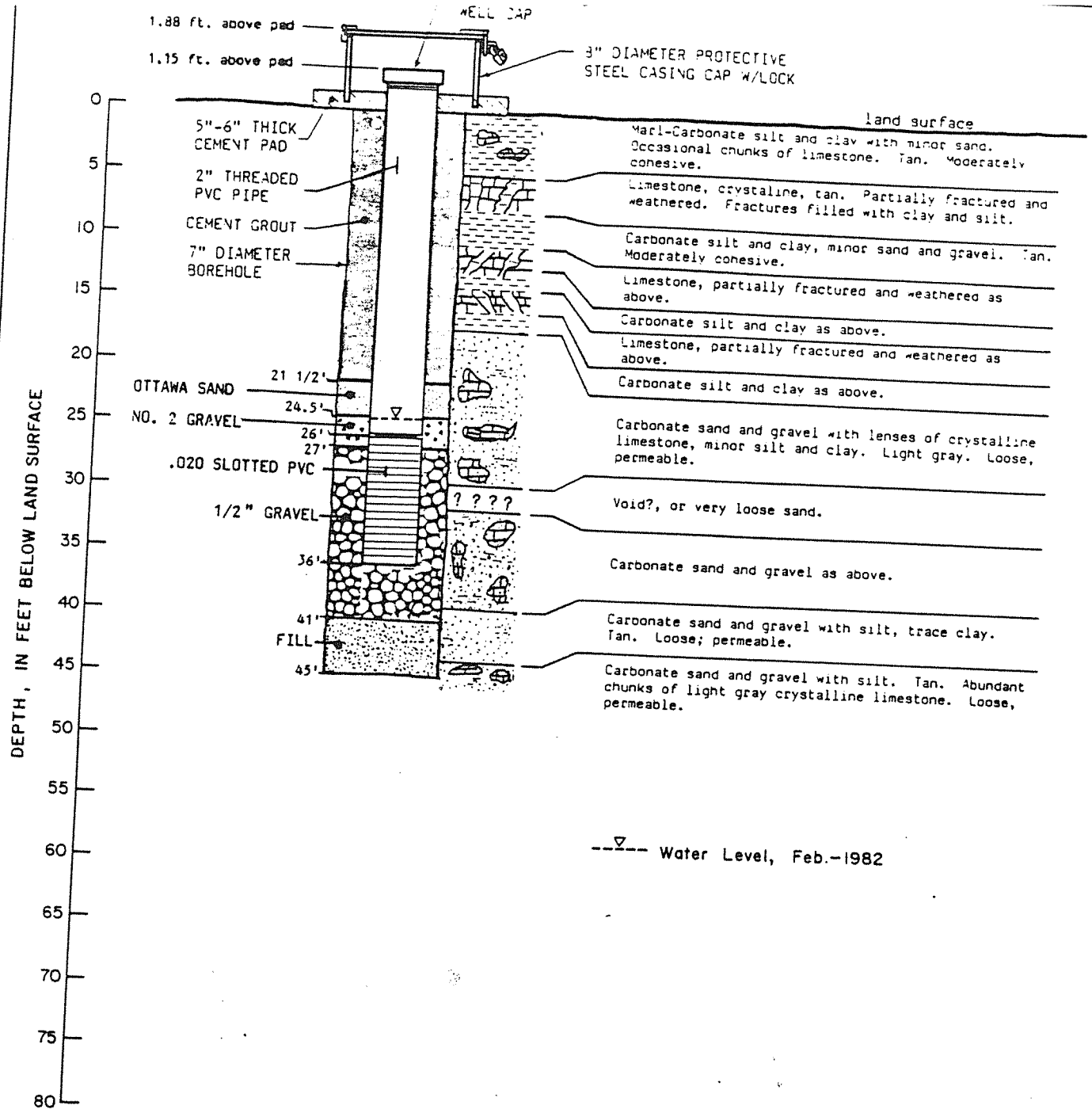
Geraghty & Miller, Inc.	COMPILED BY	D. NACHMAN	SCALE SHOWN	FIGURE A-2
	PREPARED BY	R. PADULA	DATE 4-1982	
	PROJECT MGR	W. BOIS		



CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-3

MARTIN MARIETTA ALUMINA
St Croix, U.S. Virgin Islands

Geraghty & Miller Inc	D. NACHMAN R. PADULA W. BOIS	SHOWN 4-1982	A-3



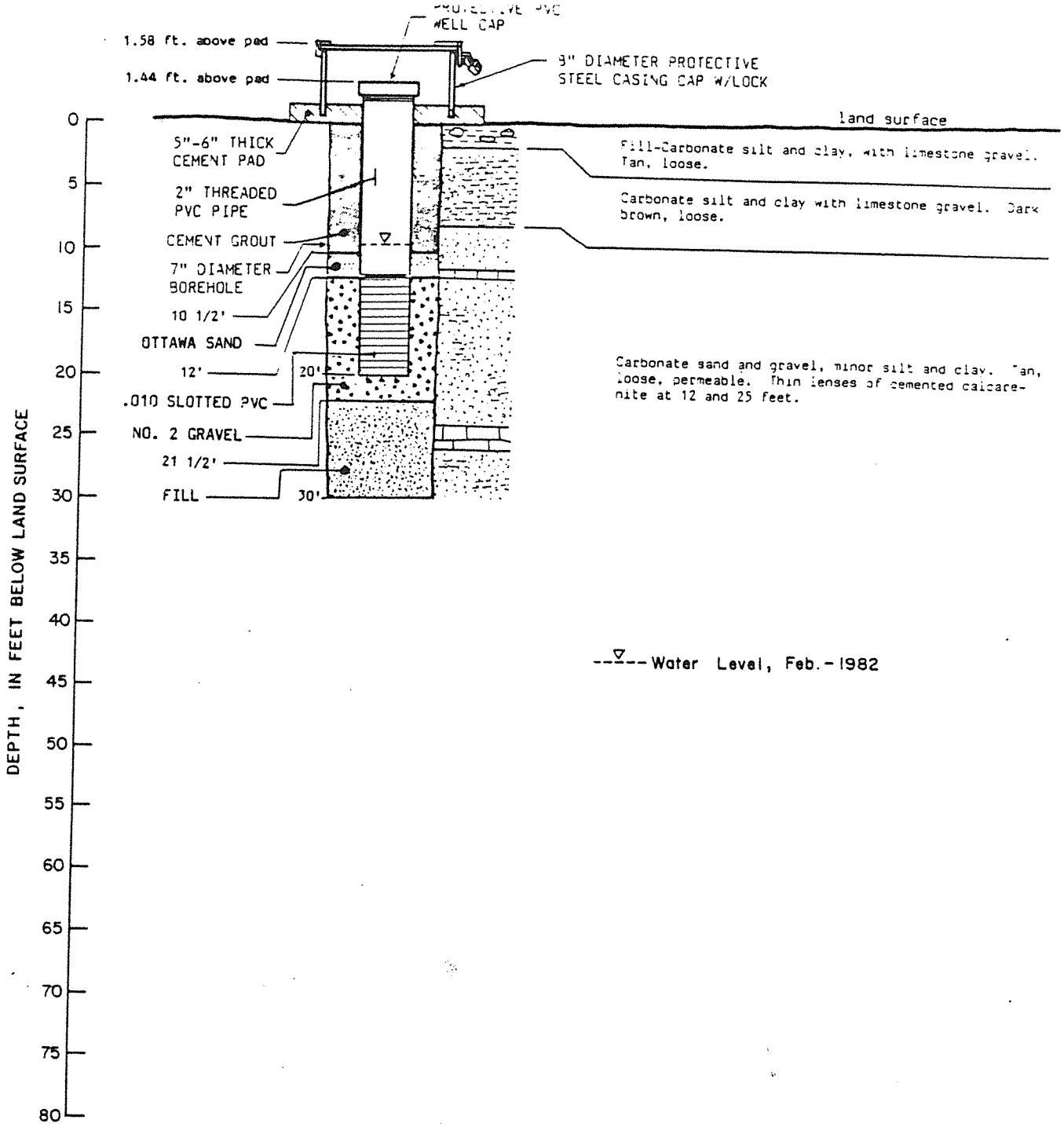
SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-4

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY D. NACHMAN	SCALE SHOWN	FIGURE A-4
	PREPARED BY R. PADULA		
	PROJECT MGR W. BOIS	DATE 4-1982	



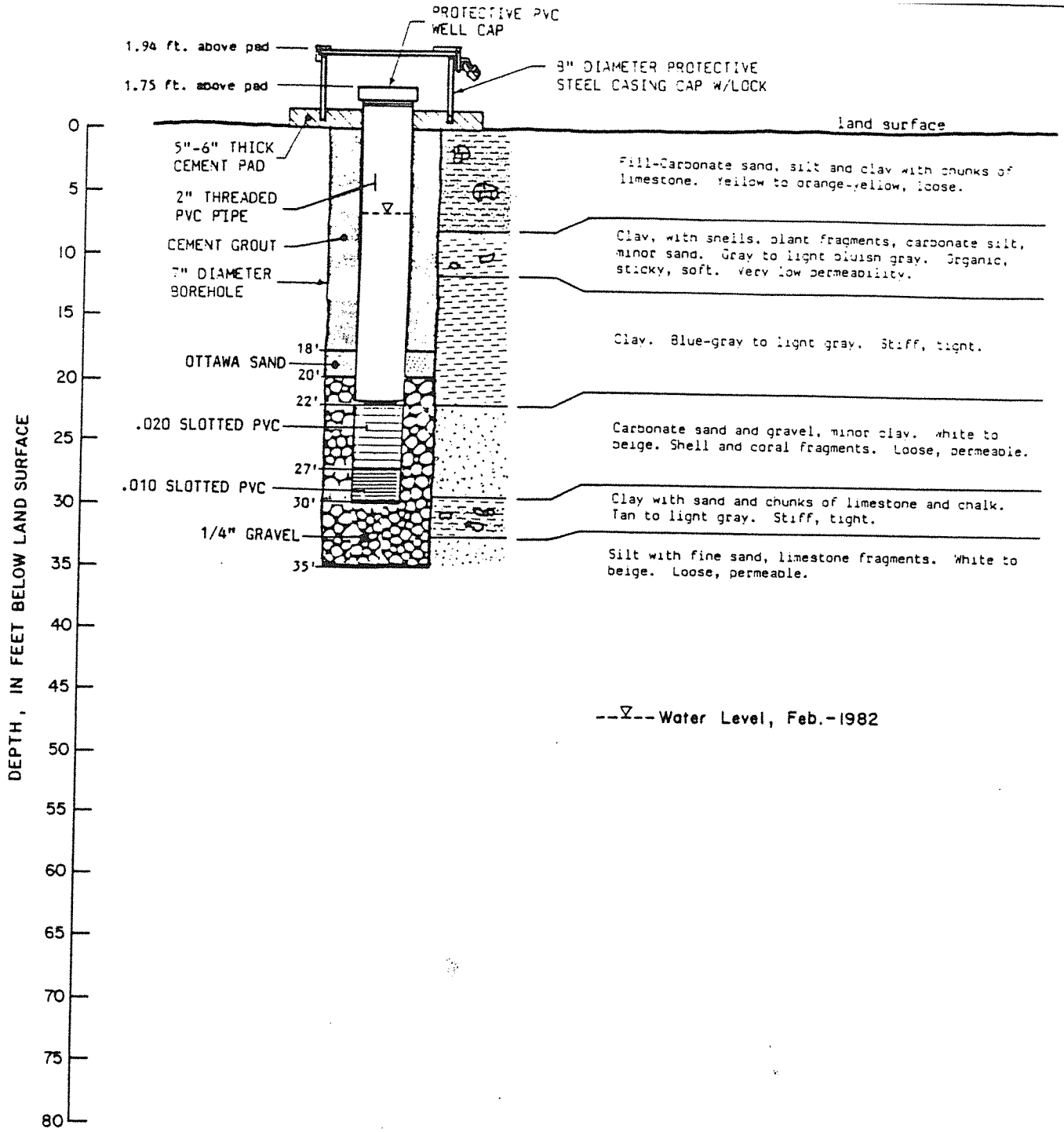
SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-5

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY	D. NACHMAN	SCALE SHOWN	FIGURE A-5
	PREPARED BY	R. PADULA	DATE 4-1982	
	PROJECT MGR	W. BOIS		



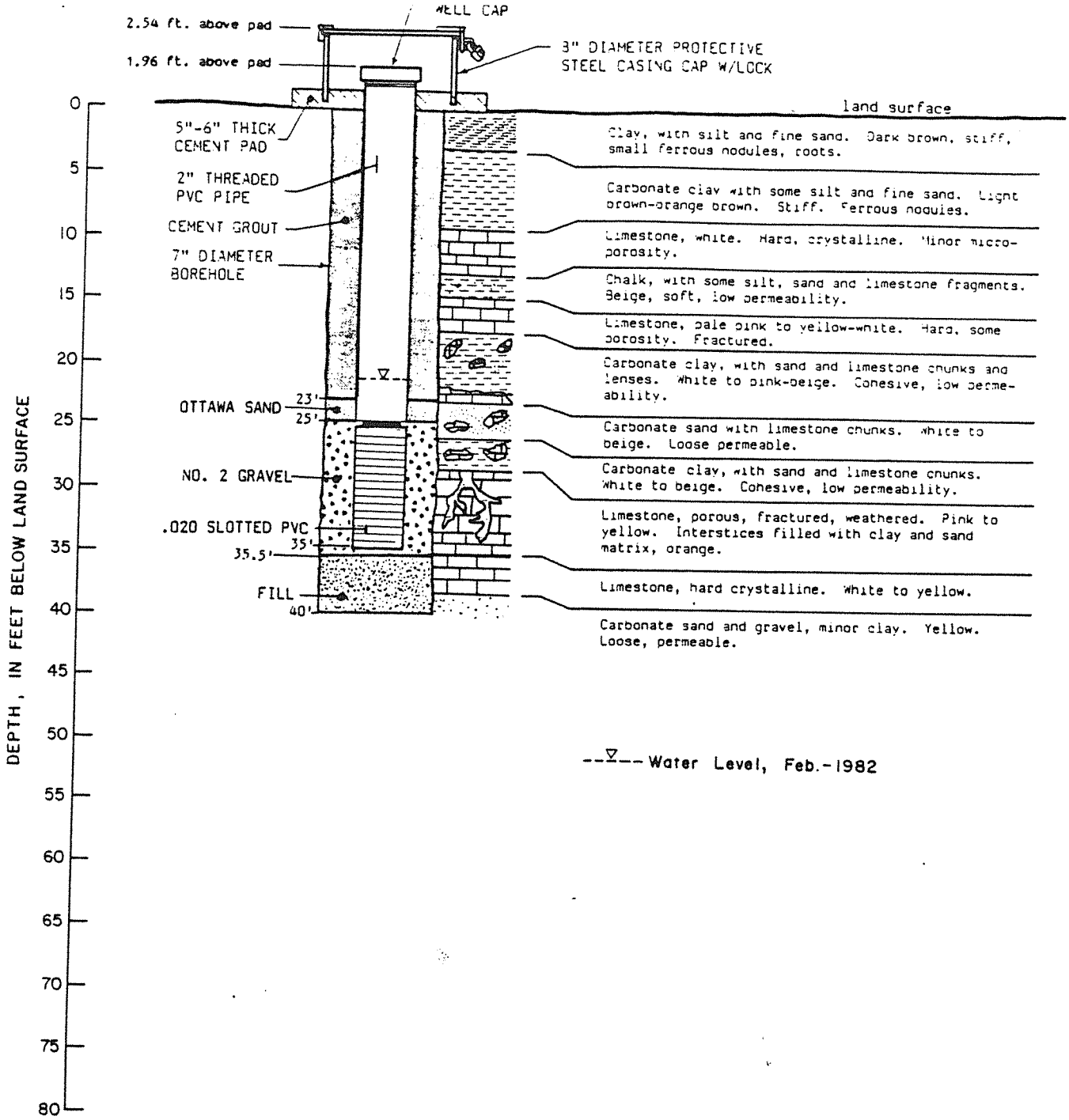
SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-6

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY D. NACHMAN	SCALE SHOWN	FIGURE A-6
	PREPARED BY R. PADULA	DATE 4-1982	
	PROJECT MGR W. BOIS		



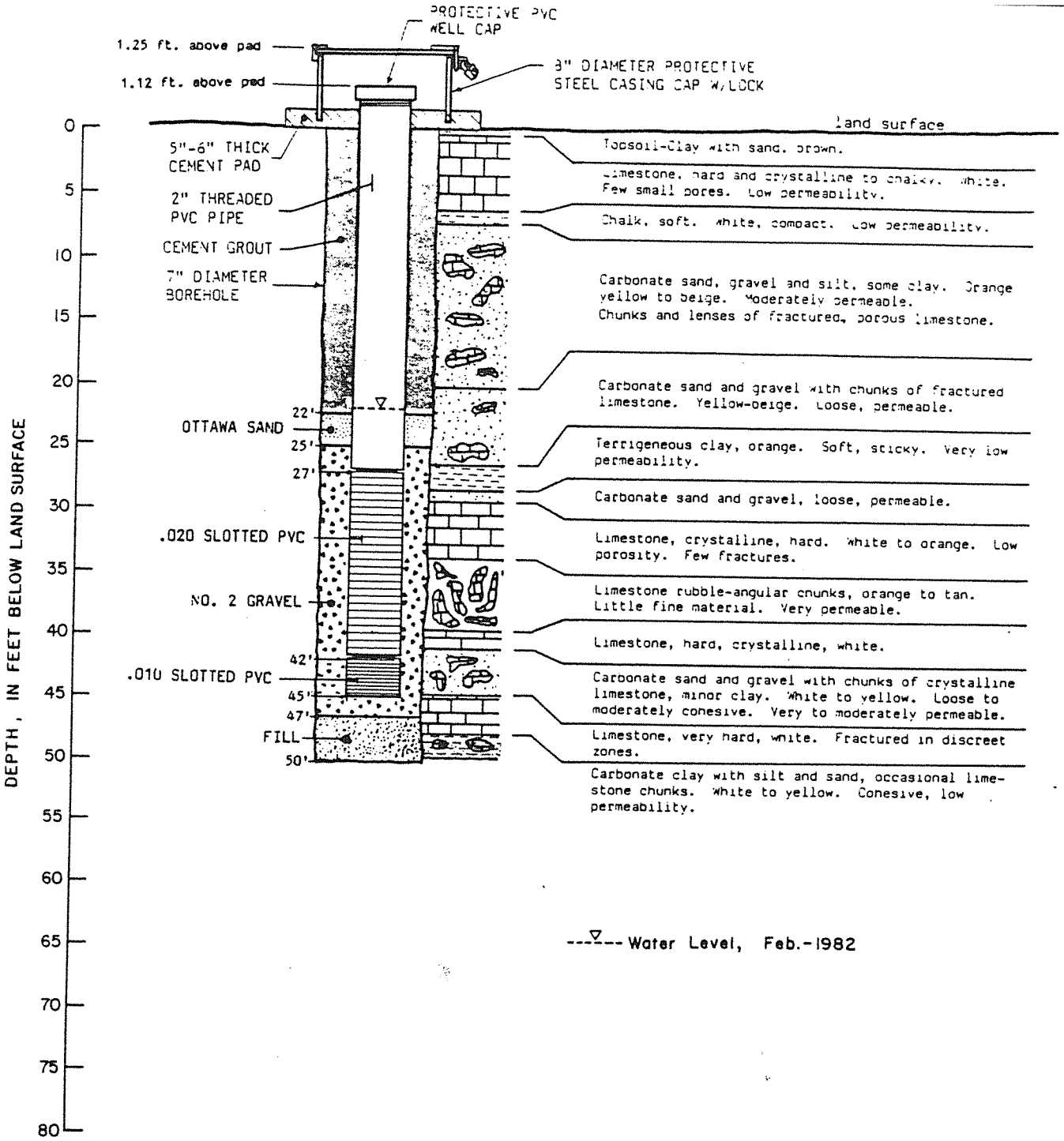
SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-7

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY D. NACHMAN	SCALE SHOWN	FIGURE A-7
	PREPARED BY R. PADULA	DATE 4-1982	
	PROJECT MGR W. BOIS		



SUBJECT

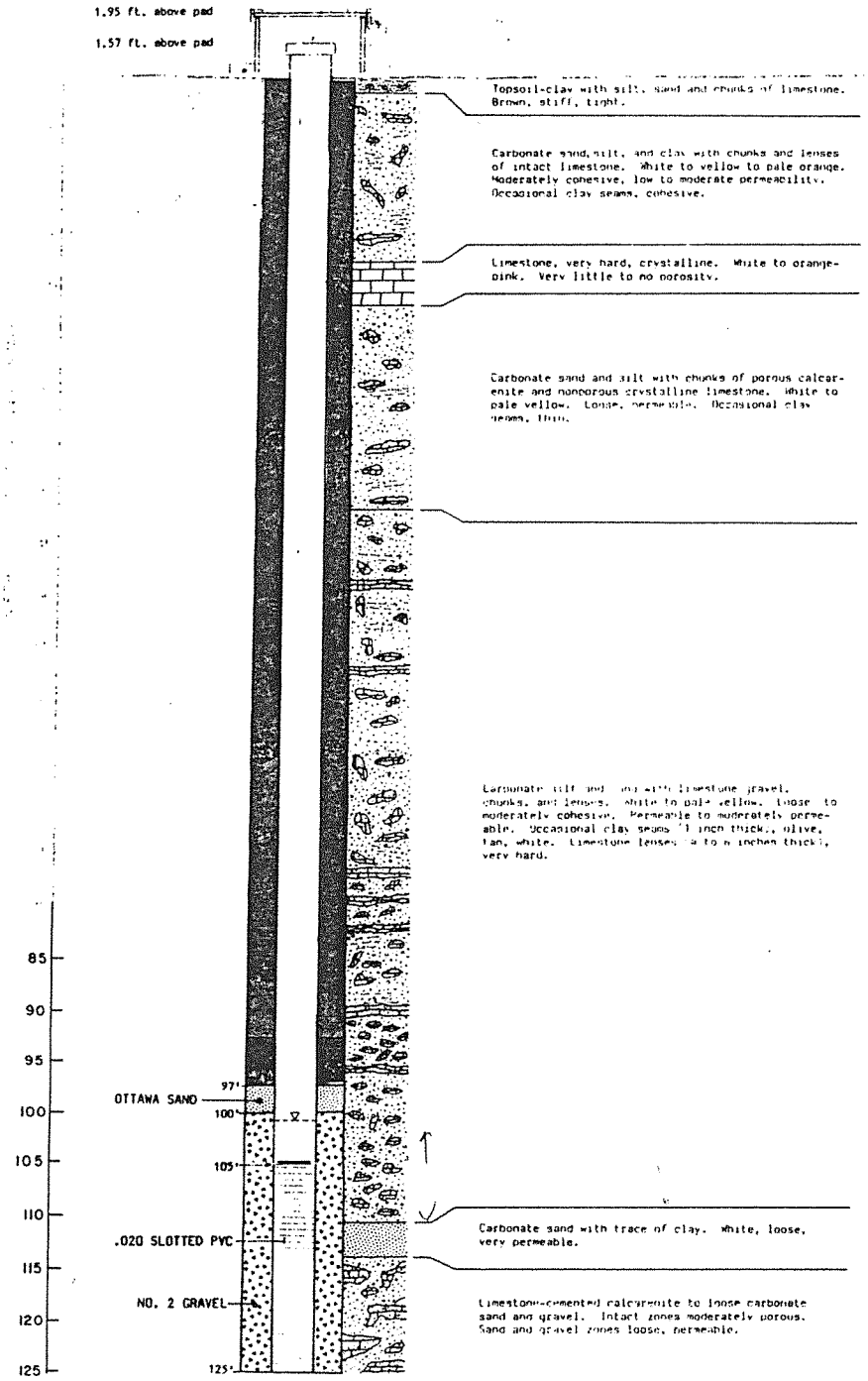
CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-8

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY	D. NACHMAN	SCALE SHOWN	FIGURE A-8
	PREPARED BY	R. PADULA	DATE 4-1982	
	PROJECT MGR	W. BOIS		

596-



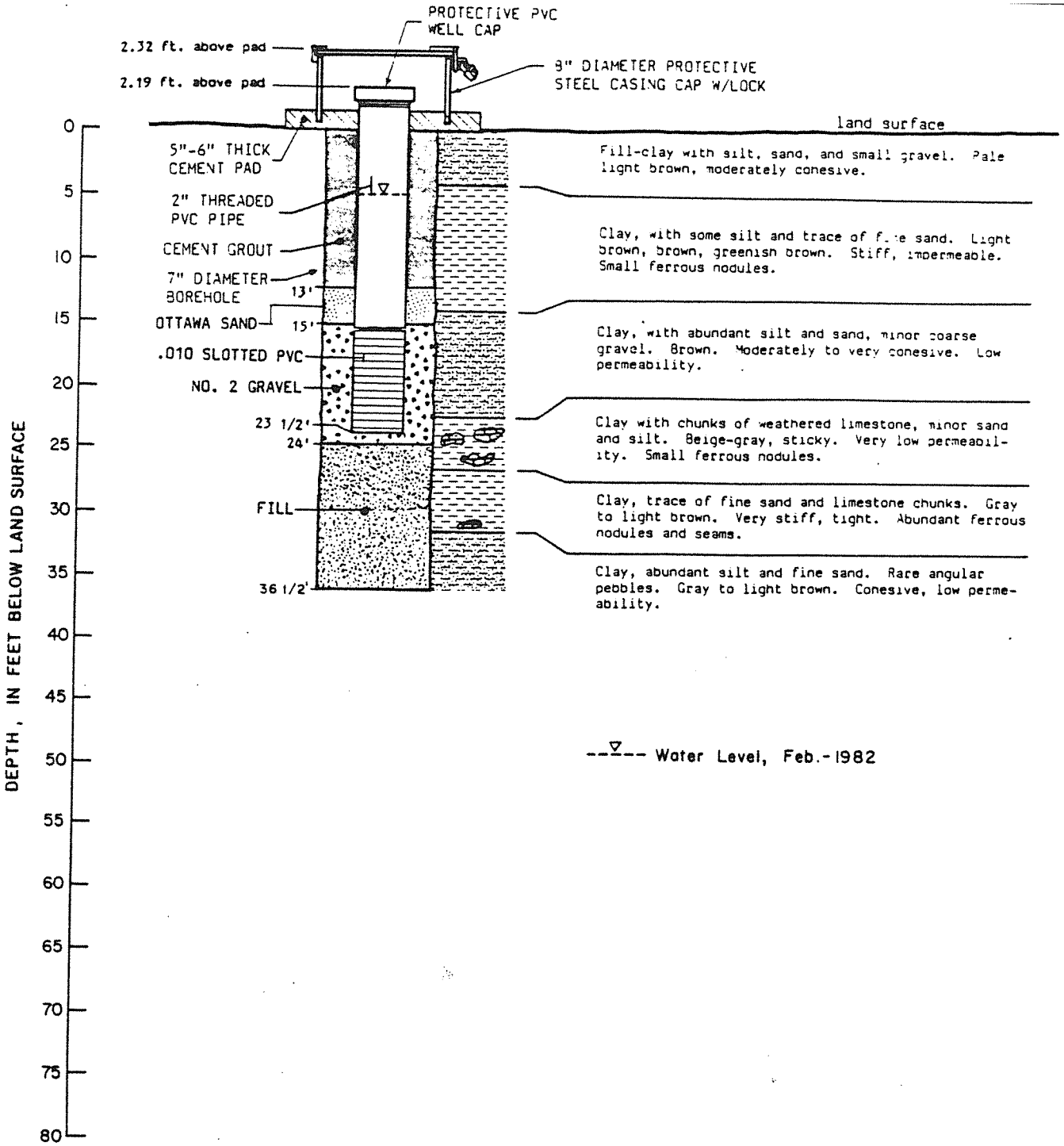
CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-9

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.

COMPILED BY	D. NACHMAN	SCALE SHOWN
PREPARED BY	R. PADULA	DATE 4-1982
PROJECT MGR	W. BOIS	A-9

596-



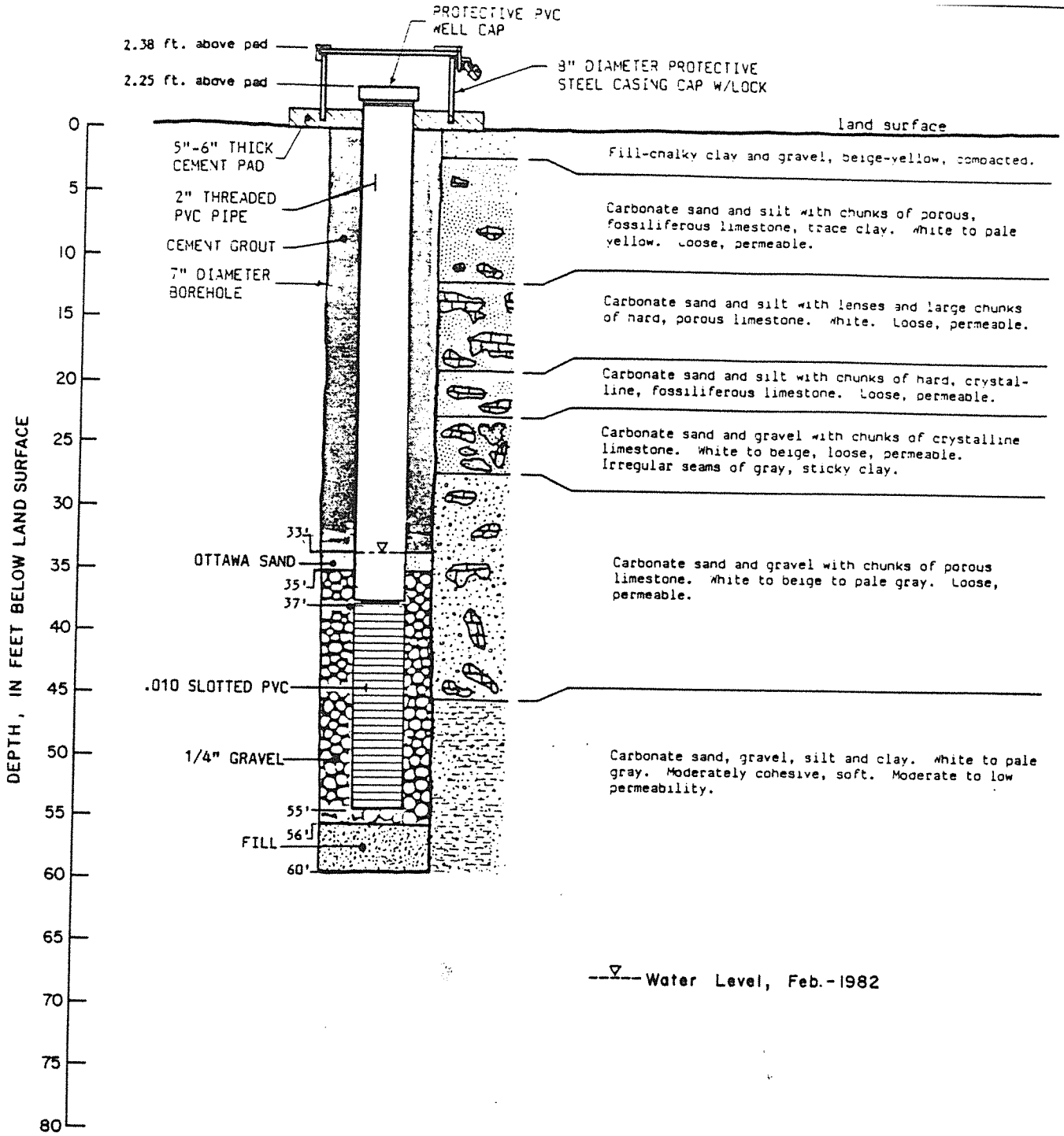
SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-10

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY	D. NACHMAN	SCALE SHOWN	FIGURE A-10
	PREPARED BY	R. PADULA	DATE 4-1982	
	PROJECT MGR	W. BOIS		



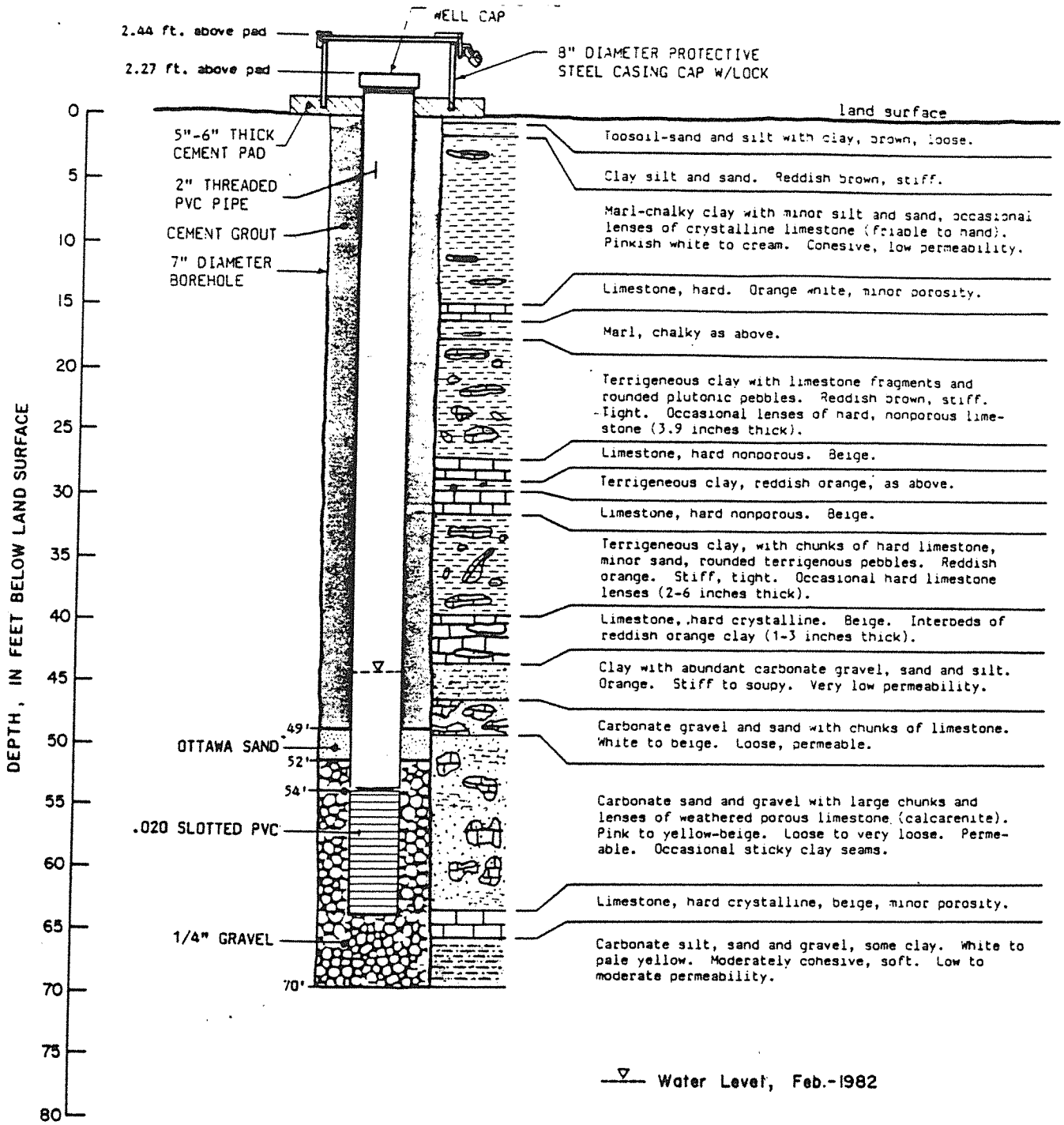
SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-11

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY D. NACHMAN	SCALE SHOWN	FIGURE A-11
	PREPARED BY R. PADULA	DATE 4-1982	
	PROJECT MGR W. BOIS		



SUBJECT

CONSTRUCTION DIAGRAM AND GEOLOGIC LOG OF MONITORING WELL G-12

PREPARED FOR

MARTIN MARIETTA ALUMINA
St. Croix, U.S. Virgin Islands

Geraghty & Miller, Inc.	COMPILED BY D. NACHMAN	SCALE SHOWN	FIGURE A-12
	PREPARED BY R. PADULA	DATE 4-1982	
	PROJECT MGR W. BOIS		

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING LOG

Well No.: VW-01 Permit No.: N/A Date Started: 7/20/94 Date Completed: 7/20/94

Owner: HESS OIL VIRGINS CORP. Well Location: VIALCO PROPERTY Use: OBSERVATION

Drilling Company: CARIBBEAN DRILLING SERV Drilling Method: HOLLOW STEM AUGER Sampling Method SPLIT SPOON

Borehole Diameter: 6" Total Depth of Borehole: 37'

Casing Type: PVC Casing Diameter: 2.0" Casing Length: 26'

Screen Type: PVC Screen Slots: 0.010 Screen Diameter: 2.0" Screen Length 10'

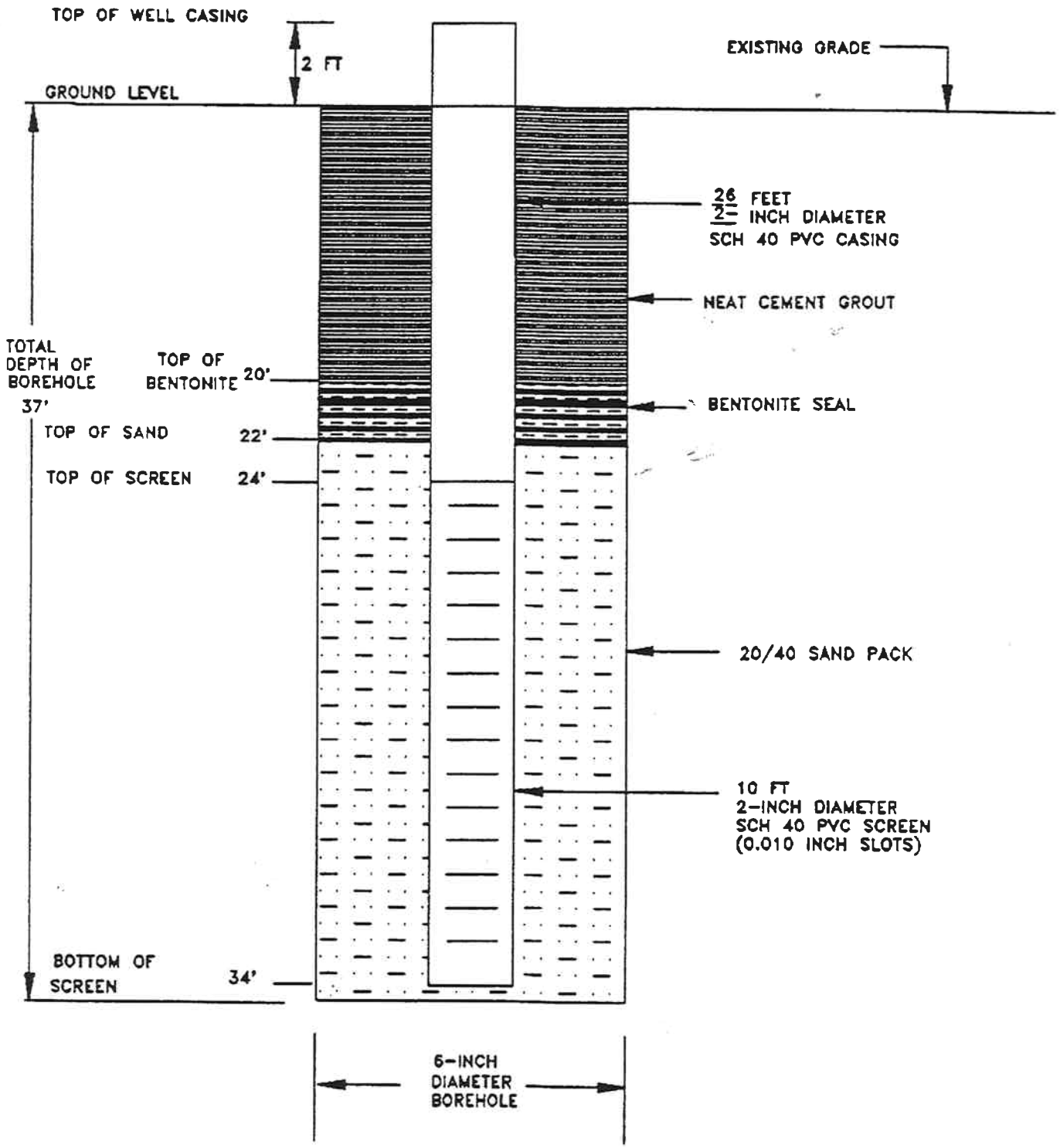
Gravel Pack Size: 20/40 Casing Seal BENTONITE Static Water Level 27.5'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (IN)	PID (ppm)	Lithologic Descriptions/Remarks
				BROWN LIMESTONE/CALICHE GRAVEL FINE TO COARSE BROWN SAND
				LIGHT BROWN FINE TO COARSE SAND. TRACE OF GRAVEL
5	17 15 17 20	12	0.0	SAME AS ABOVE
				SAME AS ABOVE W/ TRACE OF ANGULAR TO SUBROUNDED GRAVEL <10%
10	11 14 14 16	15	0.0	
				GRAY TO DARK GRAY GRAVELLY SAND. TRACE OF CLAY/MUD & SILT. GRAY WEATHERED LIMESTONE
15	60 REFUSAL	NONE	N/A	LIMESTONE (FRACTURED). ANGULAR TO SUBROUNDED LIMESTONE GRAVEL. TRACE OF SAND (FINE TO COARSE).
				SOFT/POROUS LIMESTOME
				ORANGE/BROWN FINE TO COARSE SAND W/ >25% LIMESTONE GRAVEL-CAVITY FILL MATERIAL.
20	20 31 35 15	15	0.0	CALCAREOUS WHITE/LIGHTH BROWN FINE TO MEDIUM SAND. TRACE OF CLAY/MUD AND SILT
				SAME AS ABOVE. WET AT APPROX. 26.5 - 27.0 FEET
25	21 24 30 15	18	0.0	
				BROWN FINE TO COARSE SAND W/ <20% GRAVEL. LIMESTONE GRAVEL-MEDIUM AND SUBROUNDED.
30	5 5 10 15	20	0.0	WHITE WEATHERED LIMESTONE (CHALKY) W/ TRACE OF SILT AND GRAVEL LEACHED REPLACEMENT

WELL No: VW-01

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (IN)	PID (ppm)	Lithologic Descriptions/Remarks
				BROWN FINE TO COARSE SAND AND GRAVEL
35	8 20 49 32	20		BROWN/TAN , FINE TO MEDIUM SAND. TRACE OF SILT AND CLAY/MUD
				END OF BORING

WELL # VW-01



EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLAND CORPORATION HOVIC FACILITY ST. CROIX, VI
	Drawn By: IA	Date: JULY 1994	Scale: NONE	

FILE NAME: GWWELL /IA/94

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING LOG

Well No.: VW-02 Permit No.: N/A Date Started: 7/21/94 Date Completed: 7/21/94

Owner: HESS OIL VIRGIN ISLANDS CORP. Well Location: VIALCO PROPERTY Use: OBSERVATION

Drilling Company: CARIBBEAN DRILLING SERV Drilling Method: HOLLOW STEM AUGER Sampling Method SPLIT SPOON

Borehole Diameter: 6" Total Depth of Borehole: 50'

Casing Type: PVC Casing Diameter: 2.0" Casing Length: 31'

Screen Type: PVC Screen Slots: 0.010 Screen Diameter: 2.0" Screen Length 20'

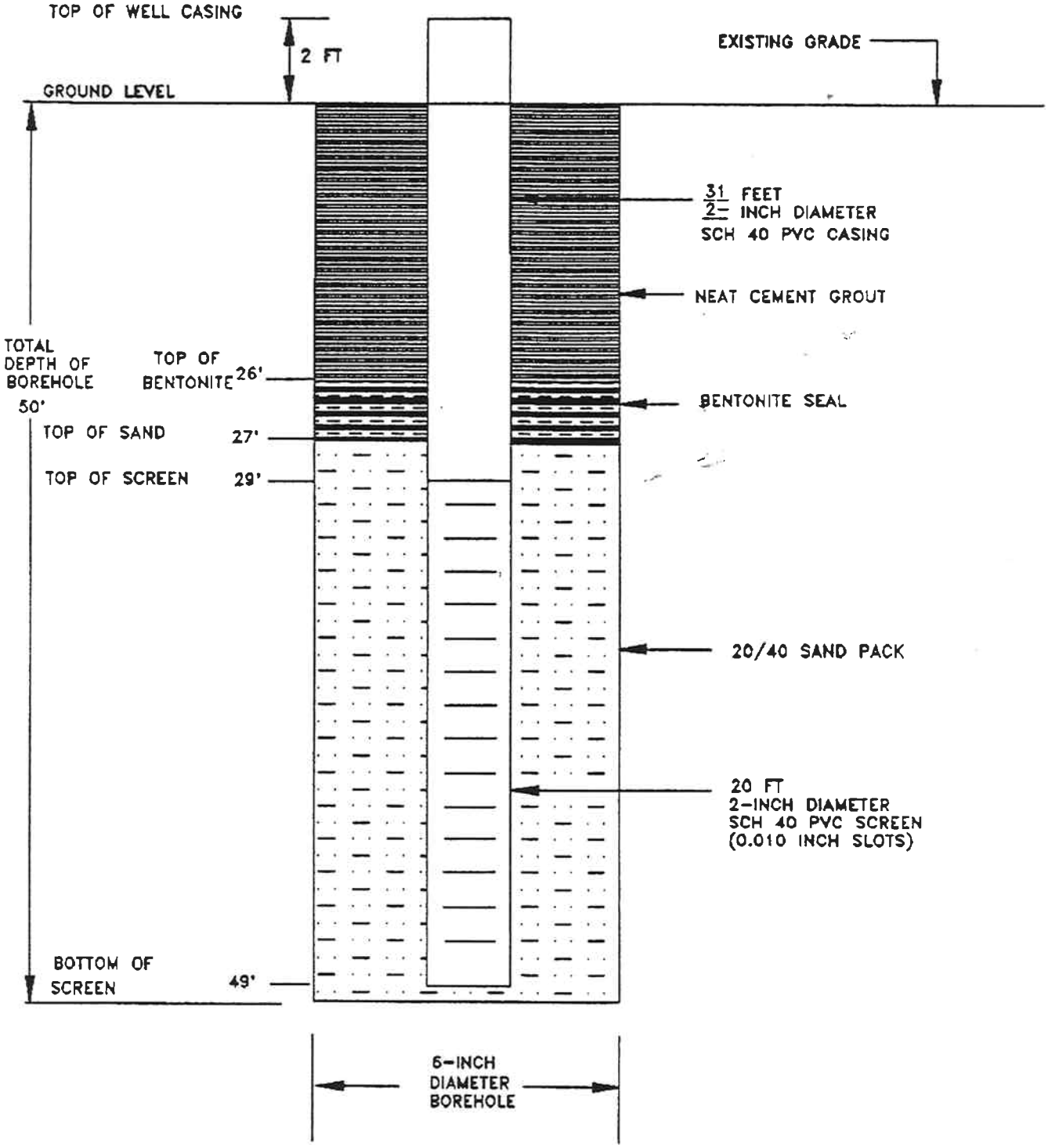
Gravel Pack Size: 20/40 Casing Seal BENTONITE Static Water Level 43'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (IN)	PID (ppm)	Lithologic Descriptions/Remarks
	5 7 7 7	10	0.0	REDDISH FINE TO COARSE SAND. TERRA ROSA SOIL, HARD W/CALCAREOUS GRAVEL AND ORGANIC DEBRIS.
				BUFF TO GRAY WAETHERED LIMESTONE/CALICHE W/ANGULAR LIMESTONE GRAVELS
5	4 5 7 10	<6	2.0	CHALKY, FRIABLE TO INDURATED LIMESTONE (BUFF/GRAY)
				BUFF LIMESTONE (MODERATELY INDURATED) W/LITHIC BROWN MATRIX
				BROWN CALCAREOUS FINE TO COARSE SAND
10	27 50 30 35	15	13.0	WHITE TO BUFF INDURATED, CHALKY LIMESTONE W/ MOTTLED BROWN FINE TO MEDIUN SAND
				SAME; GRADING TO FINE/MEDIUM W/ TRACE OF LIMESTONE GRAVEL- < 2%. SAND- LEACHED /REPLACEMENT, CORAL RUBBLES AND SILT.
15	30 34 40 34	18	2.0	BUFF TO TAN LIMESTONE, HARD TO MODERATE
				SAME AS ABOVE, MODERATE TO INDURATED
20	18 17 18 19	15	8.2	SAME AS ABOVE, EXCEPT WHITE TO TAN
				BROWN TO TAN , FINE TO MEDIUM CALCAREOUS SAND W/ < 5% FINE GRAVEL
25	22 28 30 50	10	4.0	CALCAREOUS, WHITE TO TAN SILTY SAND W/<10% GRAVEL (SUBROUNDED)
				BROWN SILTY SAND (FINE TO COARSE), APPROX. 20% SUBANGULAR GRAVEL
30	31 28 21 50	12	0.0	TAN LIMESTONE (MODERATE TO INDURATED) ATBASE OF SPOON W/ CALCAREOUS SILTY SAND

WELL NO: VW-02

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (IN)	PID (ppm)	Lithologic Descriptions/Remarks
				WHITE TO BUFF LIMESTONE, HARD
35	12 18 13 16	8	0.7	BROWN CALCAREOUS SILTY SAND (FINE TO COARSE); TRACE OF CLAY/MUD DAMP TO VERY MOIST
				TAN TO WHITE LIMESTONE; VUGGY @ 37 TO 39', SOFT/POROUS TO 40'
40	6 12 24 36			BROWN SILTY CLAY (40-41'); ENCOUNTERED WATER W/FREE PRODUCT @ 41 TO 42'; BUFF TO GRAY MODERATELY INDURATED LIMESTONE AT BASE OF SPOON
				BUFF TO GRAY LIMESTONE (HARD TO MODERATELY INDURATED)
45	15 10 10 8	8	48	MOTTLED GRAY TO TAN, FINE TO COARSE GRAVELLY SAND; CALCAREOUS, WET
				SAME AS ABOVE
50				END OF BORING

WELL # VW-02



EMS	MONITORING WELL CONSTRUCTION DIAGRAM		HESS OIL VIRGIN ISLAND CORPORATION HOVIC FACILITY ST. CROIX, VI
	Drawn By: IA	Date: JULY 1994	Scale: NONE

FILE NAME: GWWELL/IA/94

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING LOG

Well No.: VW-03 Permit No.: N/A Date Started: JULY 21,1994 Date Completed: JULY 22, 1994

Owner: HESS OIL VIRGIN ISLAND CORP. Well Location: VIALCO PROPERTY (NORTHEAST CORNER) Use: OBSERVATION

Drilling Company: CARRIBEAN DRILLING SERV Drilling Method: HOLLOW STEM AUGER Sampling Method S/S

Borehole Diameter: 8.0" Total Depth of Borehole: 85'

Casing Type: PVC Casing Diameter: 2.0" Casing Length: 75.0'

Screen Type: PVC Screen Slots: 0.010 Screen Diameter: 2.0" Screen Length 10.0'

Gravel Pack Size: 20/40 Casing Seal BENTONITE Static Water Level

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (IN)	PID (ppm)	Lithologic Descriptions/Remarks
	4 6 9 15	10.0"		ORGANIC HUMUS, TOP SOIL/RED BROWN SAND W/LIMESTONE FRAGMENTS
				LIGHT BROWN CALCAREOUS SAND FINE TO COARSE. LIMESTONE GRAVEL-ANGULAR TO SUBANGULAR-SMALL TO COARSE GRAIN.
5.0'	REFUSAL			DENSE/HARD LIMSTONE (GREY) WITH ANGULAR LITHIC FRAGMENTS AND GRAVEL MATRIX.
				LIGHT GREY TO BUFF LIMSTONE-FRIABLE. ANGULAR TO ROUNDED CARBONATE GRAVEL.
10.0'	49 50 REFUSAL			WHITE TO TAN WITH ORANGE TINT LIMSTONE-HARD
				SAME AS ABOVE (SAA)-BUT MODERATELY INDURATED
15.0'	22 24 28 33	12.0"	8.0	SAA
				BUFF LIMESTONE, POROUS AND VUGGY.
20.0'	4-REFUSAL.	0.0"		ORANGE/BROWN LIMSTONE <1.0'-ENCOUNTERED AT 20.5' (HARD) OVERLAIN BY LEACHED CAVITY FILLED WITH BROWN SILTY CLAY LIMESTONE-BROWN ANGULAR CARBONATE AGGREGATES.
25.0'	7 5 34 50	6.0"	0.0	WHITE/LIMESTONE (VUGGY) MOTTLED BROWN SILTY CLAY AS CAVITY FILLS
				CALCAREOUS FINE TO COARSE SANDY GRAVEL
30.0'	65 34 50	5.0		CALCAREOUS MOTTLED BROWN FINE TO COARSE SAND AND GRAVEL TO 31.5' BECOMING INDURATED
	REFUSAL			POROUS LIMESTONE-BROWN FINE SAND AND GRAVEL IN SILT MATRIX

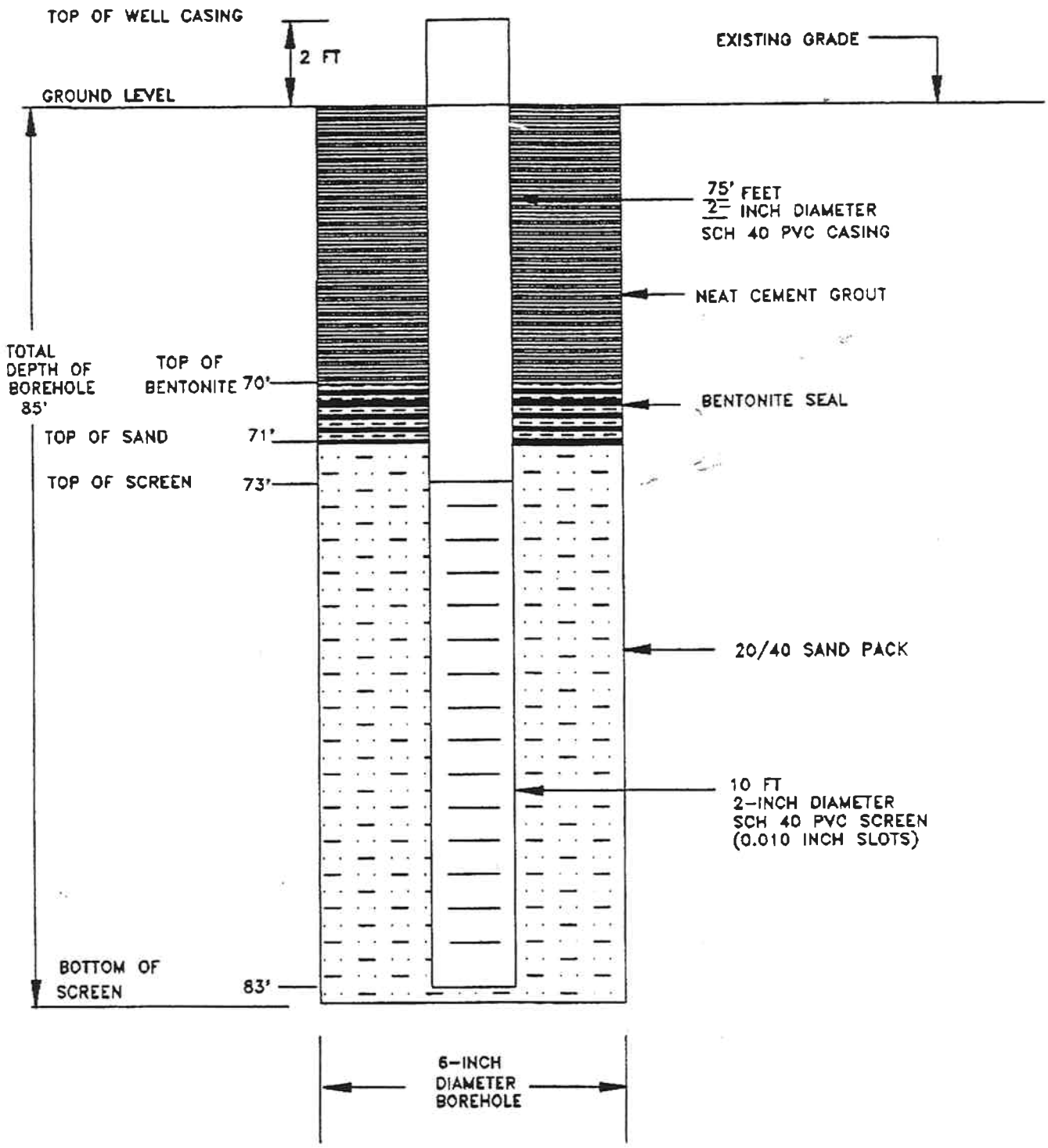
WELL NO. VW-03

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (IN)	PID ppm	Lithologic Descriptions/Remarks
35	23-REFU.	4.0"		FINE TO COARSE SAND WITH MOTTLED CLAY
				WHITE/TAN TO ORANGE LIMESTONE (HARD) CALCAREOUS MIXED SKELETAL DEBRIS-LIMSTONE BOULDER AT 37.0'.
40.0'	NO SPOON			BUFF TO GREY LIMESTONE HARD-BOULDER
				SAA
				POROUS LIMESTONE
45.0'	1-1-1-1	18	0.0	REDDISH-BROWN CLAY. TRACE OF FINE TO COARSE SAND AND GRAVEL <5% WET TO DAMP.
				ORANGE/REDDISH BROWN SANDY CLAY. TACE OF GRAVEL. BECOMING CLAYEY WITH DEPTH. CLAY PLASTIC AND SOFT. DAMP TO VERY MOIST.
50.0'	19-15-50	4.0"	0.0	SAA WITH CALICHE AT 54.0'(WEATHERED LIMESTONE)
55.0'	50-REFUSAL	0.0"	0.0	WHITE TO BUFF LIMESTONE (HARD)
				ALTERNATING BANDS OF POROUS LIMESTONE <1.5' THICK AND HARD LIMESTONE
60.0'	50-REFUSAL	0.0"	0.0	SAA
65.0'	50-REFUSAL	2.0		BROWN SILTY SANDY CLAY <1' LENSE
				ALTERNATING BANDS OF POROUS AND INDURATED LIMESTONE < 1' THICK
70	59-REFUSAL	4.0		LIGTH BROWN GRAVELLY SAND. TRACE OF SILTY CLAY, LIMESTONE GRAVEL-ANGULAR TO SUBANGULAR AGGREGATES AND CRYSTALLINE RUDDLE
				ALTERNATING LAYERS OF CEMENTED AND FRIABLE LIMESTONE LIGTH BROWN SANDY CLAY @ 74.5'; WET
75	42 24 12 18	10	3400	WHITE LIMESTONE. LIGTH BROWN SANDY SILTY CLAY AND GRAVEL. WATER IN SPOON. STRONG XYLENE-LIKE ODOR. NO PRODUCT OBSERVED.
				ALTERNATING LAYERS OF HARD LIMESTONE AND REPLACEMENT FILLS-REDDISH BROWN SILTY SAND, GRAVEL AND MUD.
80				SAA EXCEPT FOR MORE REDDISH BROWN, MOTTLED SILTY SANDY CLAY/MUD

WELL NO. VW-03

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (IN)	PID (ppm)	Lithologic Descriptions/Remarks
				SAA EXCEPT FOR MORE REDDISH BROWN MOTTLED SILTY SANDY CLAY/MUD GRAB SAMPLE AT 85' PID: 300 PPM
85				END OF BORING

WELL # VW-03



EMS	MONITORING WELL CONSTRUCTION DIAGRAM		HESS OIL VIRGIN ISLAND CORPORATION HOVIC FACILITY ST. CROIX, VI
	Drawn By: IA	Date: JULY 1994	Scale: NONE

FILE NAME: GWWELL/IA/94

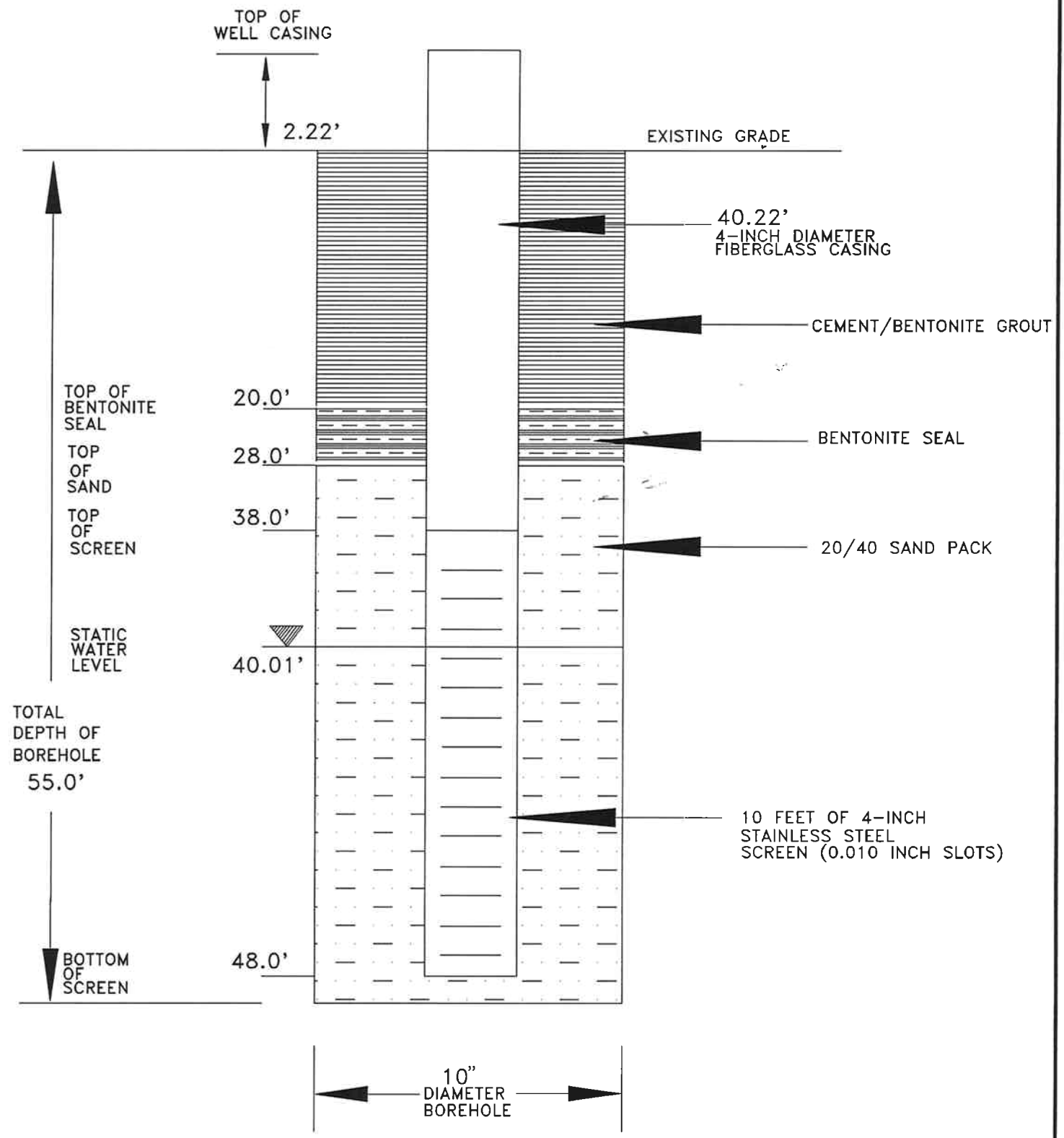
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-04 Date Started: 3/14/95 Date Finished: 3/15/95
Owner: HOVIC Well/Boring Location: VIALCO Use: MONITORING
Drilling Company: CARRIBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 55'
Casing Type: FIBERGLASS Casing Diameter: 4" I.D. Casing Interval: 38' TO GRADE+2
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4"I.D. Screen Interval: 48'-38'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 55'-28'
Casing Seal Interval: 28'-20' Casing Seal Type: BENTONITE Static Water Level: 40.01'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Backfill - coarse to fine SAND, medium to fine Gravel, loam, concrete, dry
5							
10							
							Soft Limestone; dry
15							
20							
25							Hard Limestone; dry
30							Soft formation - cuttings = Fine SAND, Limestone clasts; dry

Boring/Well Number: VW-04

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							(continued from 28.0 feet) Same
							Hard Limestone; dry
35							Soft formation – cuttings = Gray CLAY, w/traces of Silt and Sand; dry
40			1,400			▽	Hard Limestone; wet
							Soft formation – cuttings = clayey SILT; wet
45							Hard Limestone; wet
50							Soft formation – cuttings = clayey SILT; wet
55							Boring terminated at 55.0 feet.
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-04

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/14/95	Scale: None	

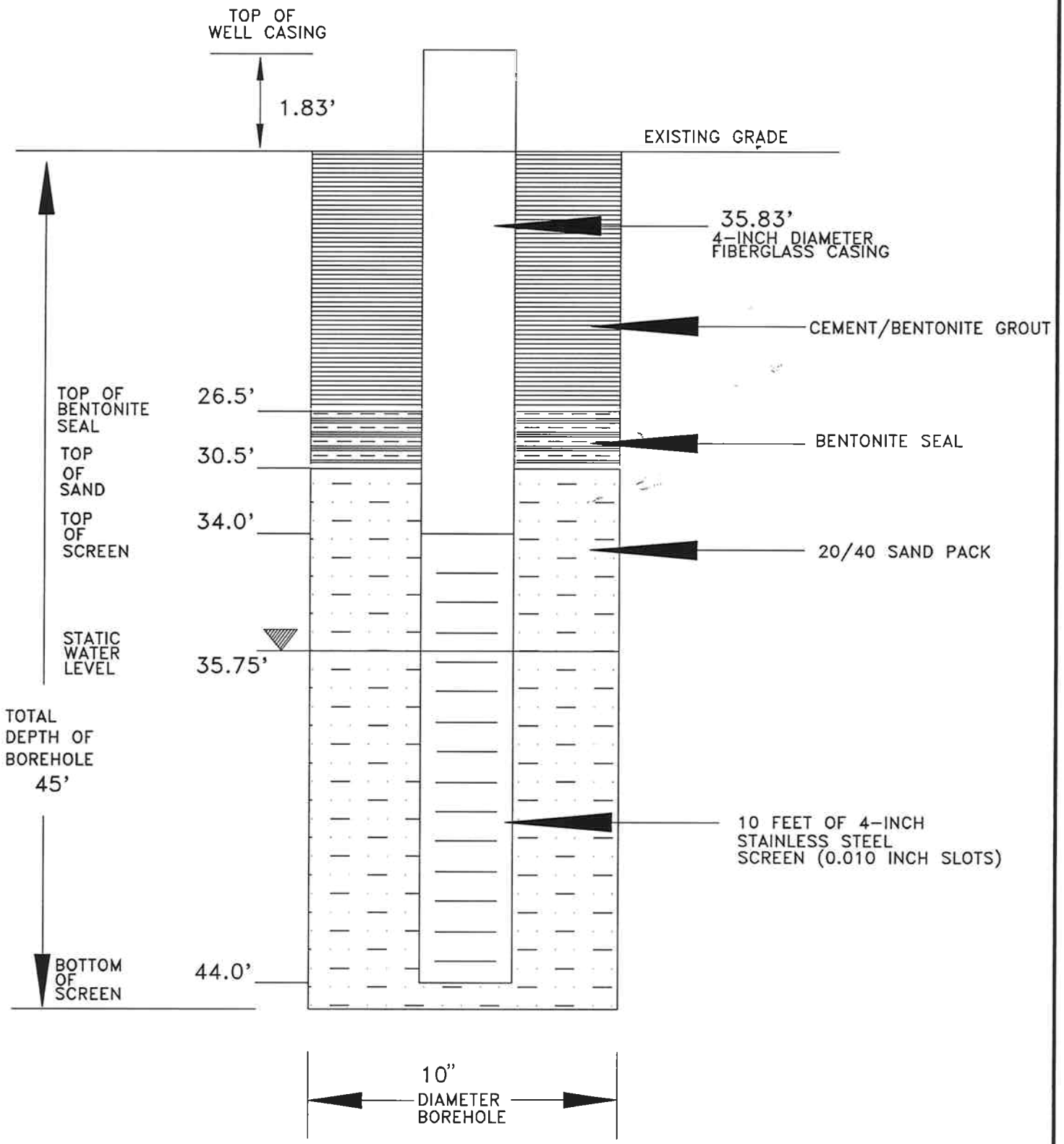
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-05 Date Started: 3/15/95 Date Finished: 3/15/95
Owner: HOVIC Well/Boring Location: VIALCO Use: MONITORING
Drilling Company: CARRIBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 45'
Casing Type: FIBERGLASS Casing Diameter: 4" I.D. Casing Interval: 34' TO GRADE+2'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" I.D. Screen Interval: 44'-34'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 45' - 30.5'
Casing Seal Interval: 30.5'-26.5' Casing Seal Type: BENTONITE Static Water Level: 35.75'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
5							Backfill loam, some Limestone clasts; dry
10							Moderate to hard Limestone; dry
							Soft formation - cuttings = CLAY, some coarse to fine SAND; dry
15							Hard Limestone; dry
							Moderate Limestone; dry
20							Hard to Very Hard Limestone; dry
25							Soft formation - cuttings = CLAY, some coarse to fine SAND; dry
30							

Boring/Well Number: VW-05

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							(continued from 21.0 feet)
							Same
35						▽	
			450				
40							
45							
							Boring terminated at 45.0 feet.
50							
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-05

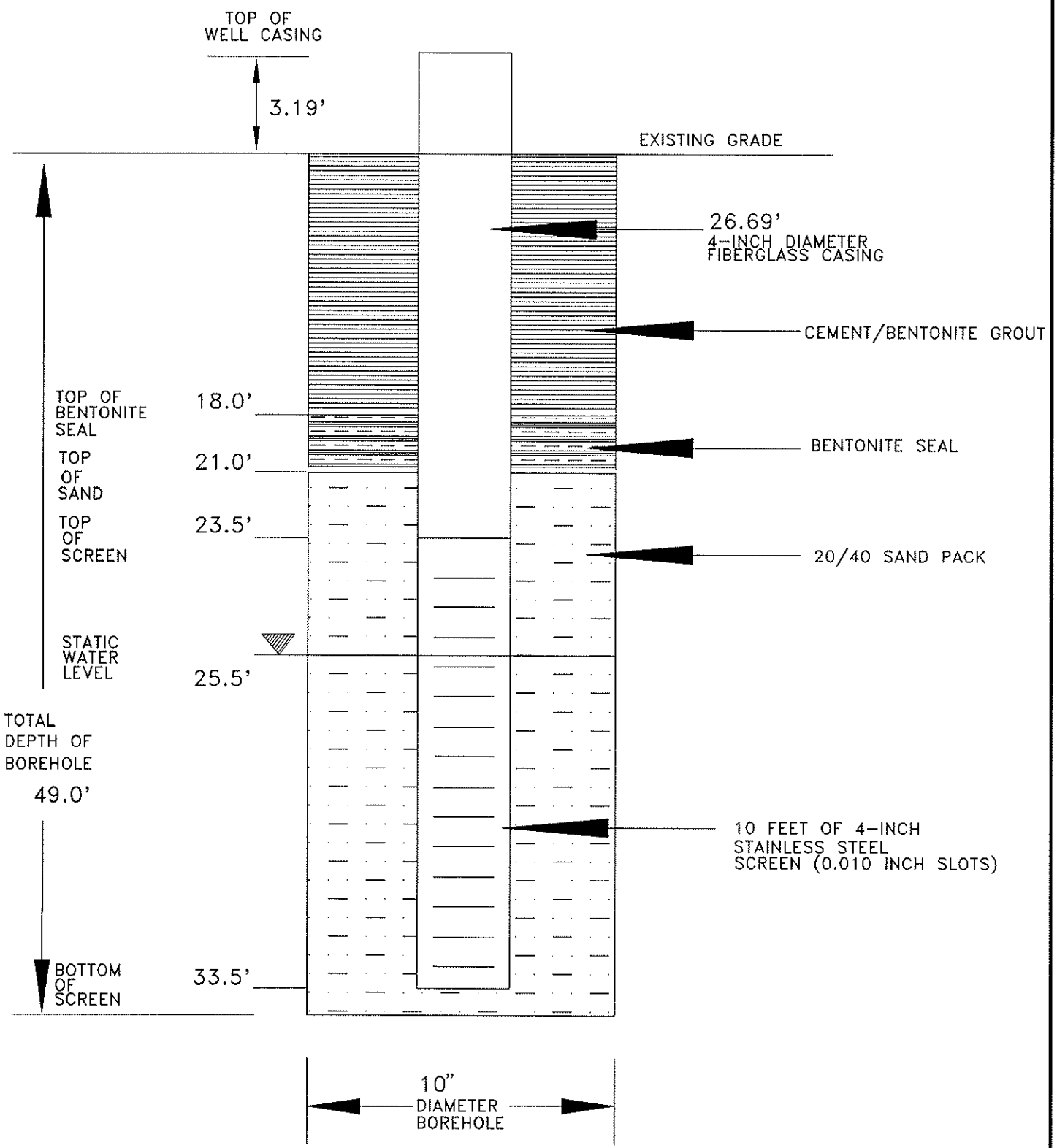
EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/15/95	Scale: None	

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-06 Date Started: 3/15/95 Date Finished: 3/15/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBERVATION
Drilling Company: CARRIBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 49.0'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 23.5' TO GRADE + 3.19'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 33.5'-23.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 49'-21'
Casing Seal Interval: 21'-18' Casing Seal Type: BENTONITE Static Water Level: 25.5'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
5							Coarse to fine Limestone GRAVEL, coarse to fine Sand, trace Silt; dry
10							Brown CLAY; dry
15							Coarse to fine Limestone GRAVEL, coarse to fine Sand, trace Silt; dry
							Moderate Limestone; dry
20							Terra Rosa fine SAND, and Limestone clasts; dry
25						▽	Moderate Limestone; dry
			150				Terra Rosa fine SAND, and Limestone clasts; wet
30							No recovery

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-06 Page 2 LITHOLOGY / REMARKS
							No recovery
35							
40							
45							
50							Boring terminated at 49.0 feet.
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-06

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/15/95	Scale: None	

GeoMonitoring Services
4123 Fifth Street
Brookshire, Texas 77423

Completion Date: 5/18/07

WELL: VW-13B

Location: Renaissance -SCA

Client: Hess
Location: **St Croix**
Elevation (toc) :
Lat/Long

Project Name:
Project Number:

Sampler Type: No Sampling
Inside Diameter:
Hammer Weight (LB): NA
Hammer Fall (IN): NA

Rig Type: Hollow Stem & Auger
Bit Type: Toothed Bit
Total Depth: 59.5'

Drilling Co.: Caribbean Drilling
Driller: Ken Eastman/Ray Tutein
Geologist: Rex Meyer

Hole Diameter: 9'

Screen Type: Stainless Steel - 20'
Joints: Screw-Coupled
Diameter: 4"
Screen: 0.01"
Sand Type: Silica Sand 00N 20/40

Riser Type: National Well -30'
Joints: Screw-Coupled
Diameter: 4"
Type: Fiberglass
Stickup: 3.5'

Drilling Notations:

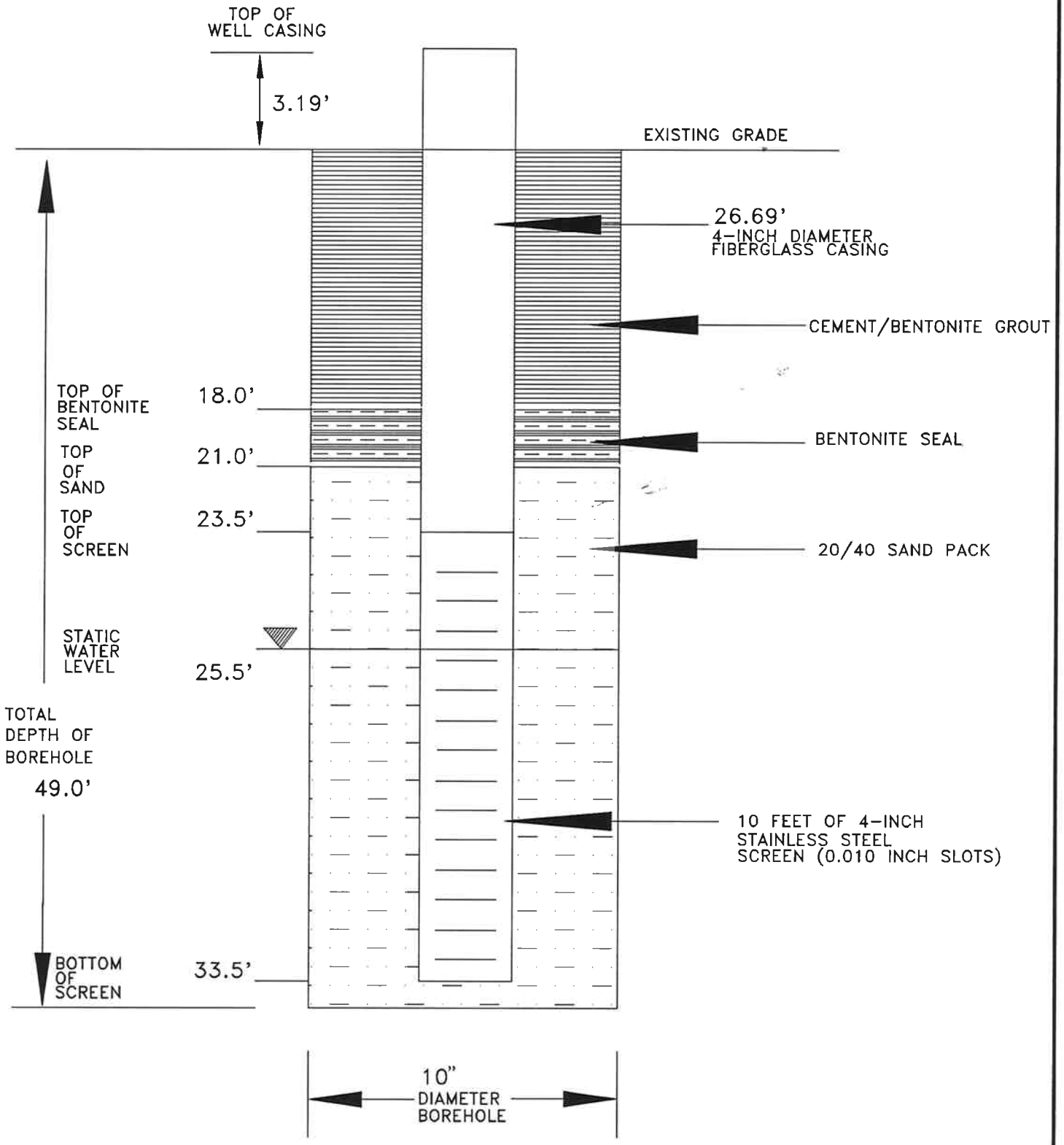
DEPTH FROM GRADE (FT)	SAMPLE DESIGNATION	Sample Core Composite	OVM Reading (ppm)	WELL CONSTRUCTION	**Matrix** Munsell Color	**Description**
+3						
+2						
+1						
0						
1					*10YR8/2*	**Soft Limestone**
2					White	**Moderate to Hard Dry Limestone**
3						
4	(Cement/Bentonite Grout) ---------					
5						
6						**Same**
7						
8						
9						
10						
11						**Same**
12						
13	(Cement/Bentonite Grout) ---------					
14						
15						
16						**Same**
17						
18						
19						
20						Thin (1/4") Chert Layer @ 22'
21		Bentonite Chips				
22	Top of Sand Pack @ 22'					*Gypsum Deposits to 30'*
23						
24						
25						
26						
27						
28						*Static - Oil @ 28' & Water @ 28.2'*
29						
30						
31						
32						
33						
34						
35						
36		(Sand Pack)				
37						
38						
39						
40						
41						
42						
43						
44						
45						
46						
47						Well TD @ 46.5' Below Grade
48						
49						
50						4" of Interbedded Clay
51						
52				*Boring Collapsed*		
53						
54						
55						
56						
57						
58						
59						Boring TD @ 59.5' Below Grade
60						Extremely Hard Limestone

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-06 Date Started: 3/15/95 Date Finished: 3/15/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBERVATION
Drilling Company: CARRIBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 49.0'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 23.5' TO GRADE + 3.19'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 33.5'-23.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 49'-21'
Casing Seal Interval: 21'-18' Casing Seal Type: BENTONITE Static Water Level: 25.5'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
5							Coarse to fine Limestone GRAVEL, coarse to fine Sand, trace Silt; dry
10							Brown CLAY; dry
							Coarse to fine Limestone GRAVEL, coarse to fine Sand, trace Silt; dry
15							Moderate Limestone; dry
20							Terra Rosa fine SAND, and Limestone clasts; dry
25						▽	Moderate Limestone; dry
			150				Terra Rosa fine SAND, and Limestone clasts; wet
30							No recovery

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-06 Page 2 LITHOLOGY / REMARKS
							No recovery
35							
40							
45							
50							Boring terminated at 49.0 feet.
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-06

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/15/95	Scale: None	

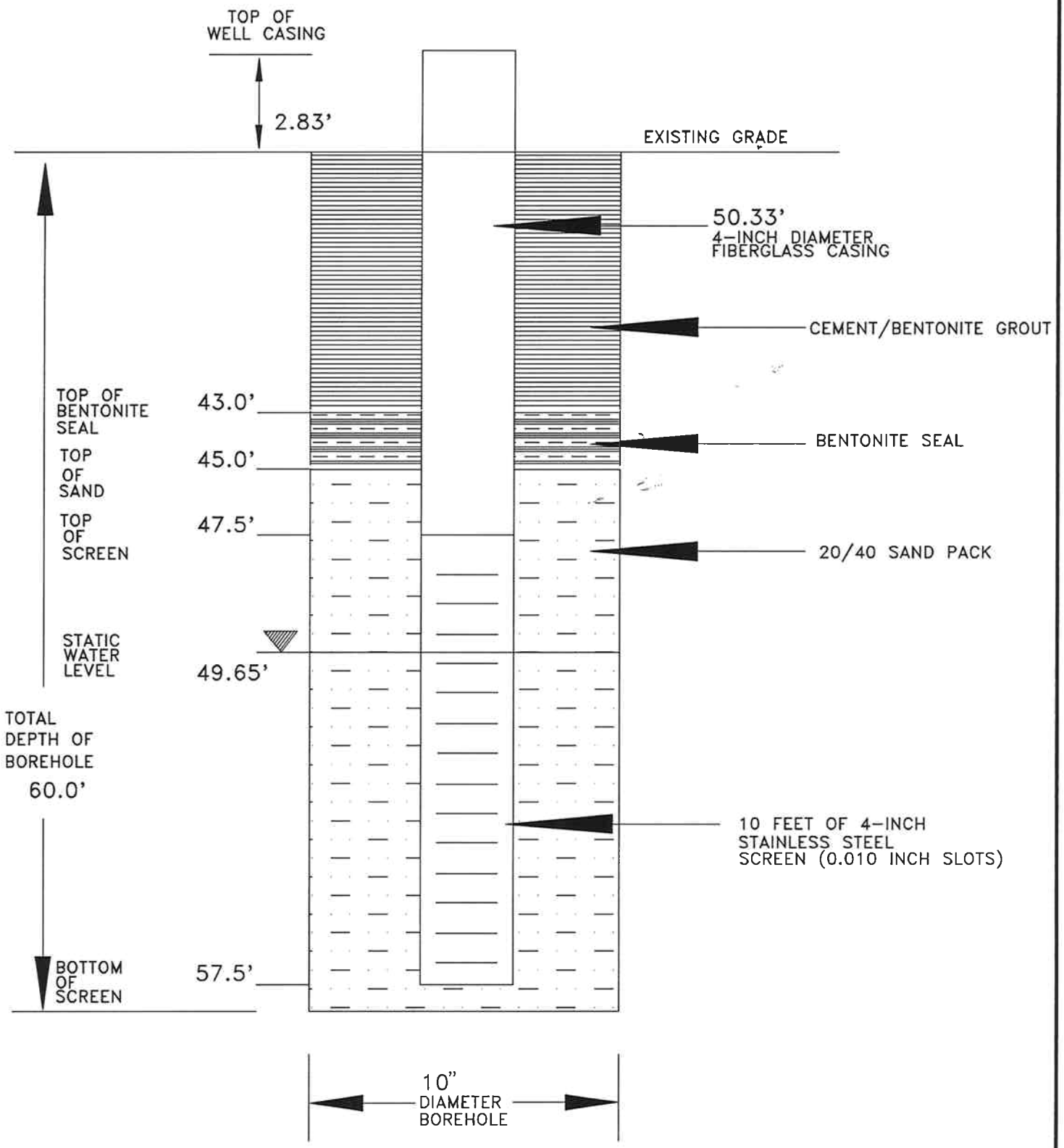
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-07 Date Started: 3/16/95 Date Finished: 3/16/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 60.0'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 47.5' TO GRADE +2.83'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 57.5'-47.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 60'-45'
Casing Seal Interval: 45'-43' Casing Seal Type: BENTONITE Static Water Level: 49.65'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Loamy soil; dry
							Soft weathered Limestone; dry
5							Soft Limestone; dry
10							
15							
							Hard Limestone; dry
							Soft Limestone; dry
20							Moderate Limestone; dry
25							Soft Limestone; dry
							Hard Limestone, with coral clasts; dry
30							Moderate Limestone; dry

Boring/Well Number: VW-07

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Moderate Limestone; dry
35							Soft Limestone; dry
40							Moderate Limestone; dry
45							
							Hard Limestone; dry
50			465			▽	Soft formation, sporadic cuttings of CLAY; wet
55			1,194				
60							Boring terminated at 60.0 feet.
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-07

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/16/95	Scale: None	

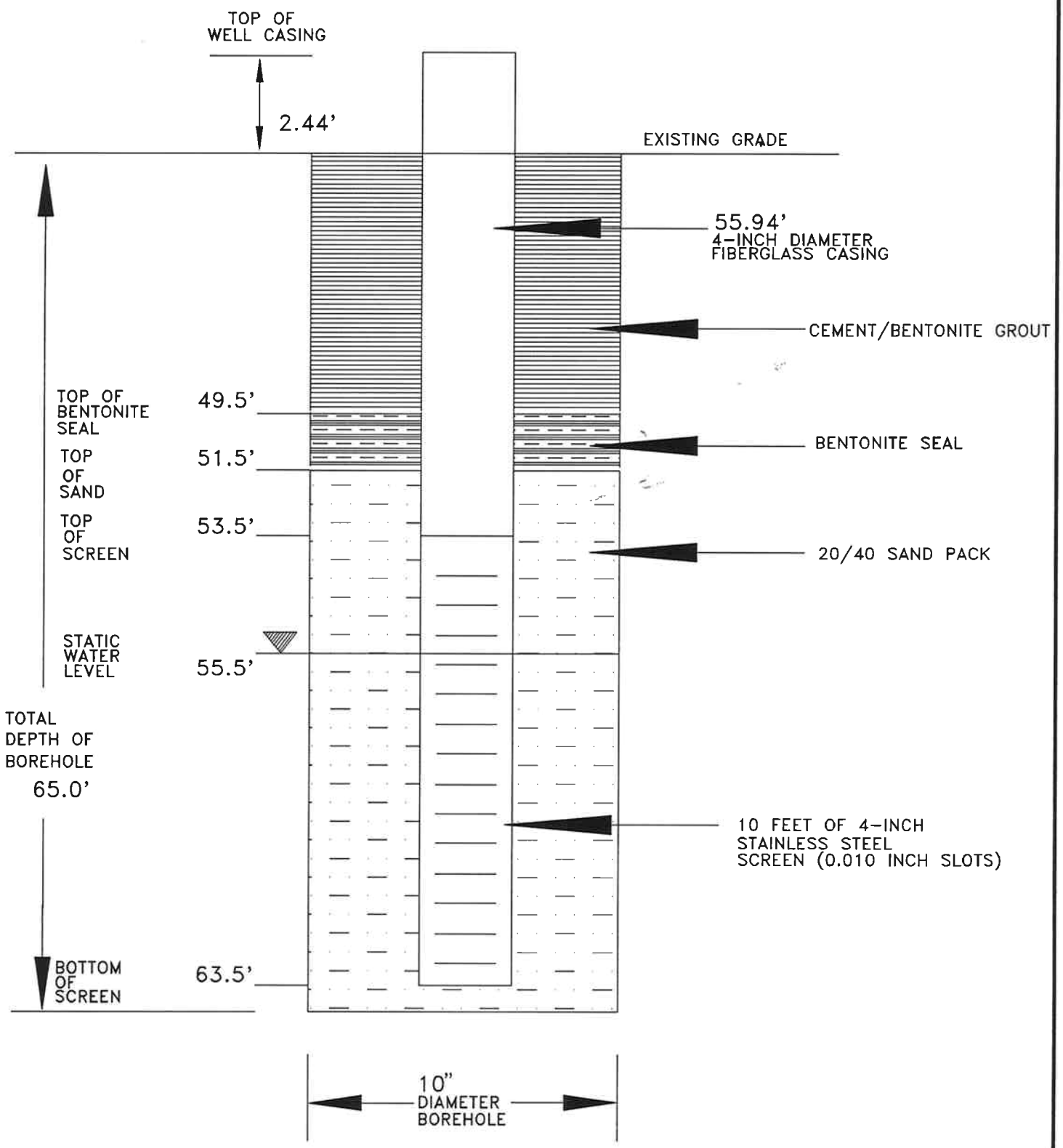
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-08 Date Started: 3/16/95 Date Finished: 3/17/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 65'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 53.5' TO GRADE +2.44'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 63.5' TO 53.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 65'-51.5'
Casing Seal Interval: 51.5'-49.5' Casing Seal Type: BENTONITE Static Water Level: 55.5'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Soft Limestone; dry
5							
10							
15							
							Moderate Limestone; dry
20							Soft Limestone; dry
							Moderate Limestone; dry
25							Soft Limestone; dry
							Moderate Limestone; dry
							Hard Limestone; dry
							Soft Limestone; dry
30							Moderate Limestone; dry

Boring/Well Number: VW-08

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Hard to moderate limestone; dry
35							Hard to soft Limestone; dry
40							Moderate Limestone; dry
45							Soft Limestone; dry
50							
			0.0				Very hard Limestone; dry – water encountered at 55.5'
55						▽	
			0.0				Soft formation, sporadic cuttings of CLAY; wet
60							
65							Boring terminated at 65.0 feet.
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-08

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/17/95	Scale: None	

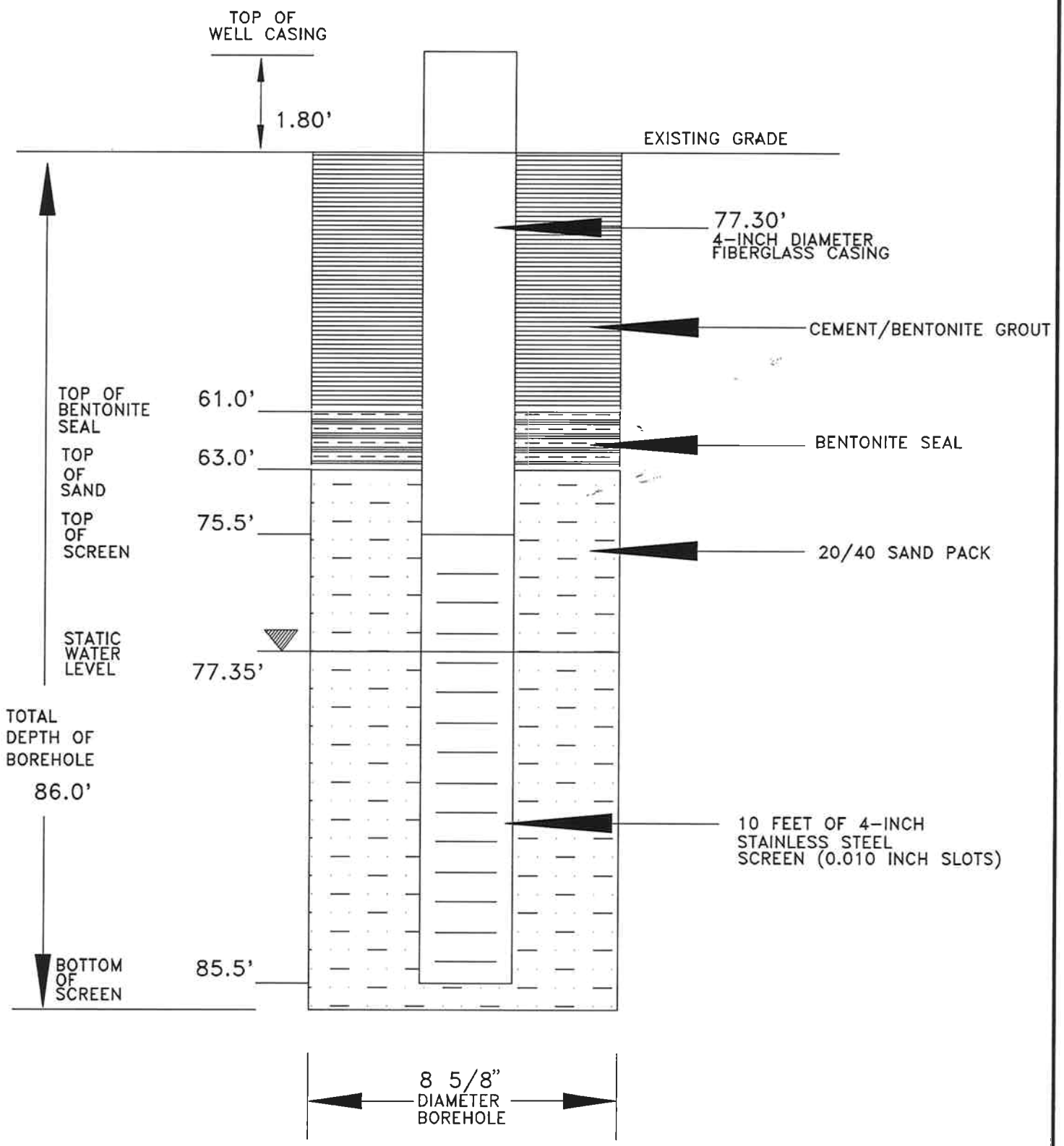
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-09R Date Started: 3/27/95 Date Finished: 3/28/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: AIR ROTARY Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CHICAGO PNEUMATIC Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 8 5/8" Total Depth of Borehole: 86.0'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 75.5' TO GRADE +1.8'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 85.5'-75.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 86.0' - 63.0'
Casing Seal Interval: 63'-61' Casing Seal Type: BENTONITE Static Water Level: 77.35'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Soft Limestone; dry
5							
10							
15							
							Moderate Limestone; dry
20							
25							
							Soft Limestone; dry
30							

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-09R — Page 2 LITHOLOGY / REMARKS
							Soft Limestone; dry
35							Moderate Limestone; dry
40							
45							Hard Limestone; dry
50							
55							
60							
65							Soft Limestone; dry
70							Soft Formation, no recovery
75						▽	Moderate Limestone; wet at 77.35'

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-09R — Page 3 LITHOLOGY / REMARKS
							Moderate Limestone; wet
			0.0				
80							
85							
							Boring terminated at 86.0 feet.
90							
95							
100							
105							
110							
115							
120							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-09R

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/28/95	Scale: None	

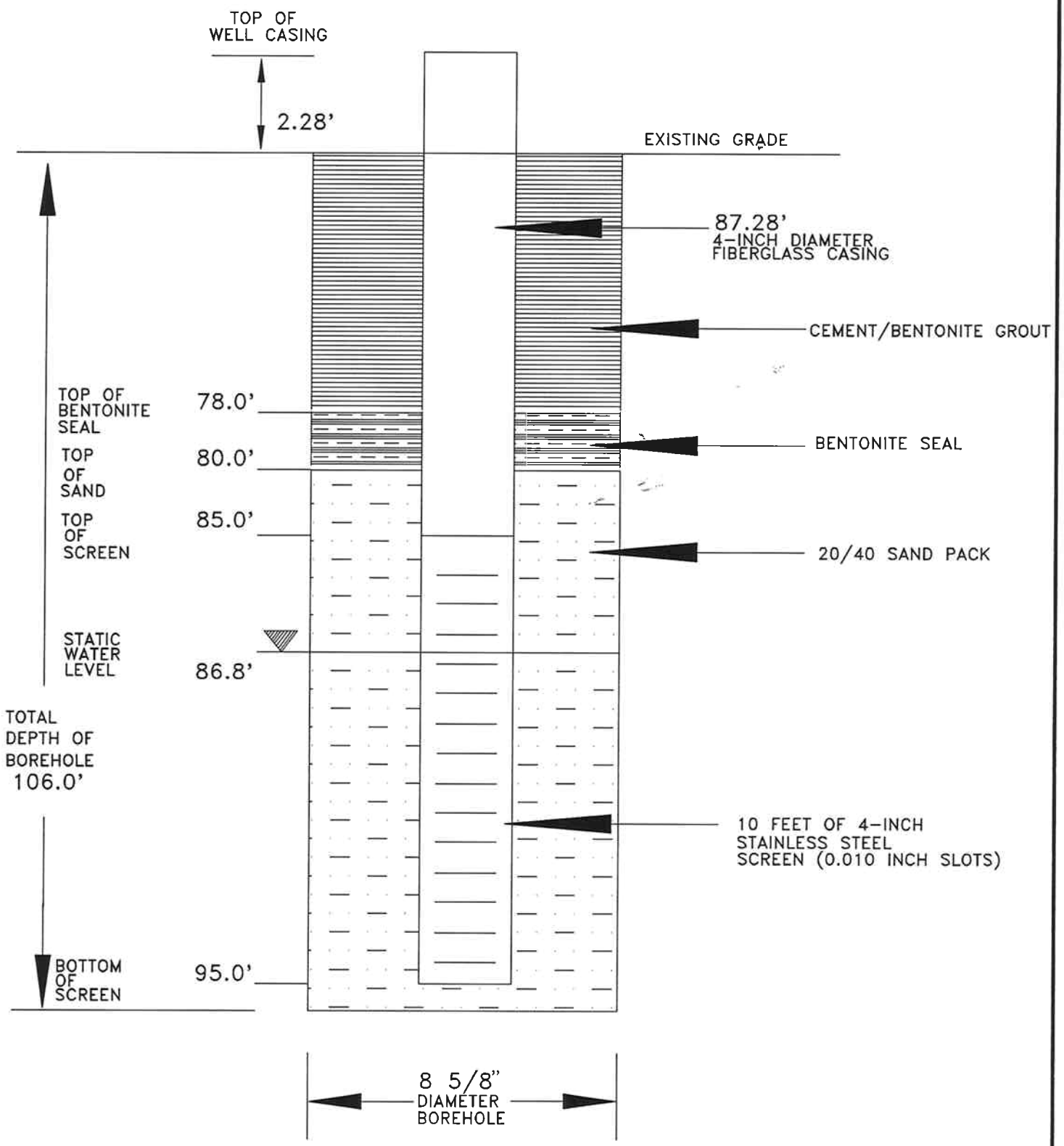
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-10 Date Started: 3/18/95 Date Finished: 3/21/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: AIR ROTARY Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CHICAGO PNEUMATIC Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 8 5/8" Total Depth of Borehole: 106.0'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 85' TO GRADE +2.28'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 95'-85'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 107'-80'
Casing Seal Interval: 80'-78' Casing Seal Type: BENTONITE Static Water Level: 86.8'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
5							Caliche; dry
10, 15							Moderate Limestone; dry
20, 25, 30							Hard to moderate Limestone; dry

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-10 Page 2 LITHOLOGY / REMARKS
							Hard to moderate Limestone; dry
35							
40							
45							
50							Very Hard Limestone; dry
55							
60							
65							
							Moderate Limestone; dry
70							Soft formation - cuttings = coarse to fine SAND, some Clay, trace Silt; dry
75							

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-10 Page 3 LITHOLOGY / REMARKS
80							Soft formation – cuttings = coarse to fine SAND, some Clay, trace Silt; dry
85							Hard Limestone; dry
90							Moderate Limestone; wet
95							Void
100 105							Moderate Limestone; wet
110 115 120							Boring terminated at 106 feet.



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-10

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/21/95	Scale: None	

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

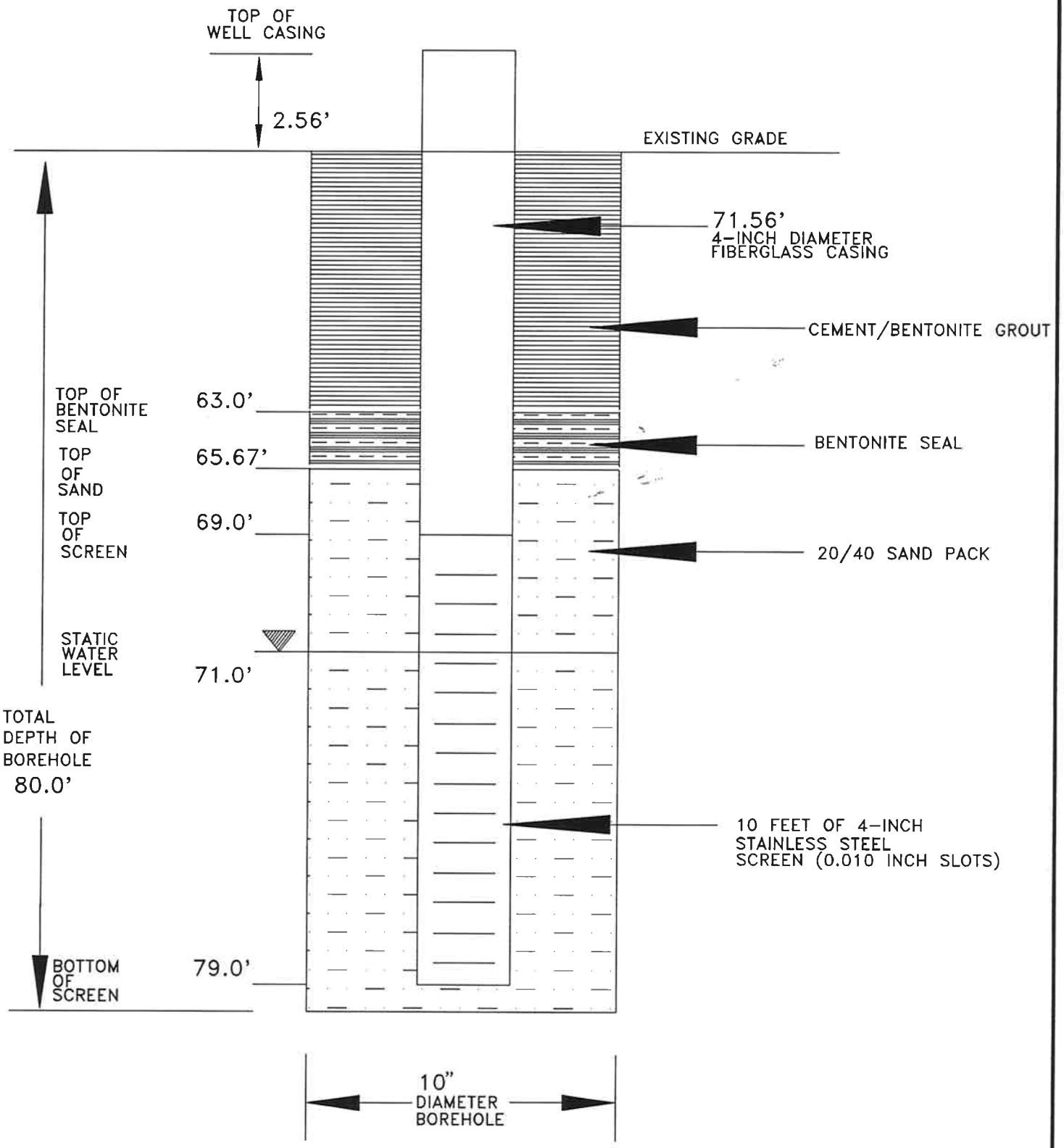
Well/Boring No.: VW-11 Date Started: 3/18/95 Date Finished: 3/20/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 80'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 69' TO GRADE +2.56'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 79'-69'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 80'-65.67'
Casing Seal Interval: 65.67'-63' Casing Seal Type: BENTONITE Static Water Level: 71'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
5							Caliche; dry
10, 15, 20							Moderate Limestone; dry
25							Hard Limestone; dry
30							Soft formation - cuttings = brown clay; dry

Boring/Well Number: VW-11

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Soft formation – cuttings = brown CLAY; dry
35							
							Soft formation – cuttings = brown CLAY, some Limestone clasts; wet at 71'
40							
45							
50							
55							
60							
65							
70			0.0			▽	
75							Hard Limestone; wet

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-11 Page 3 LITHOLOGY / REMARKS
							Hard Limestone; wet
80							Boring terminated at 80 feet.
85							
90							
95							
100							
105							
110							
115							
120							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-11

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/20/95	Scale: None	

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

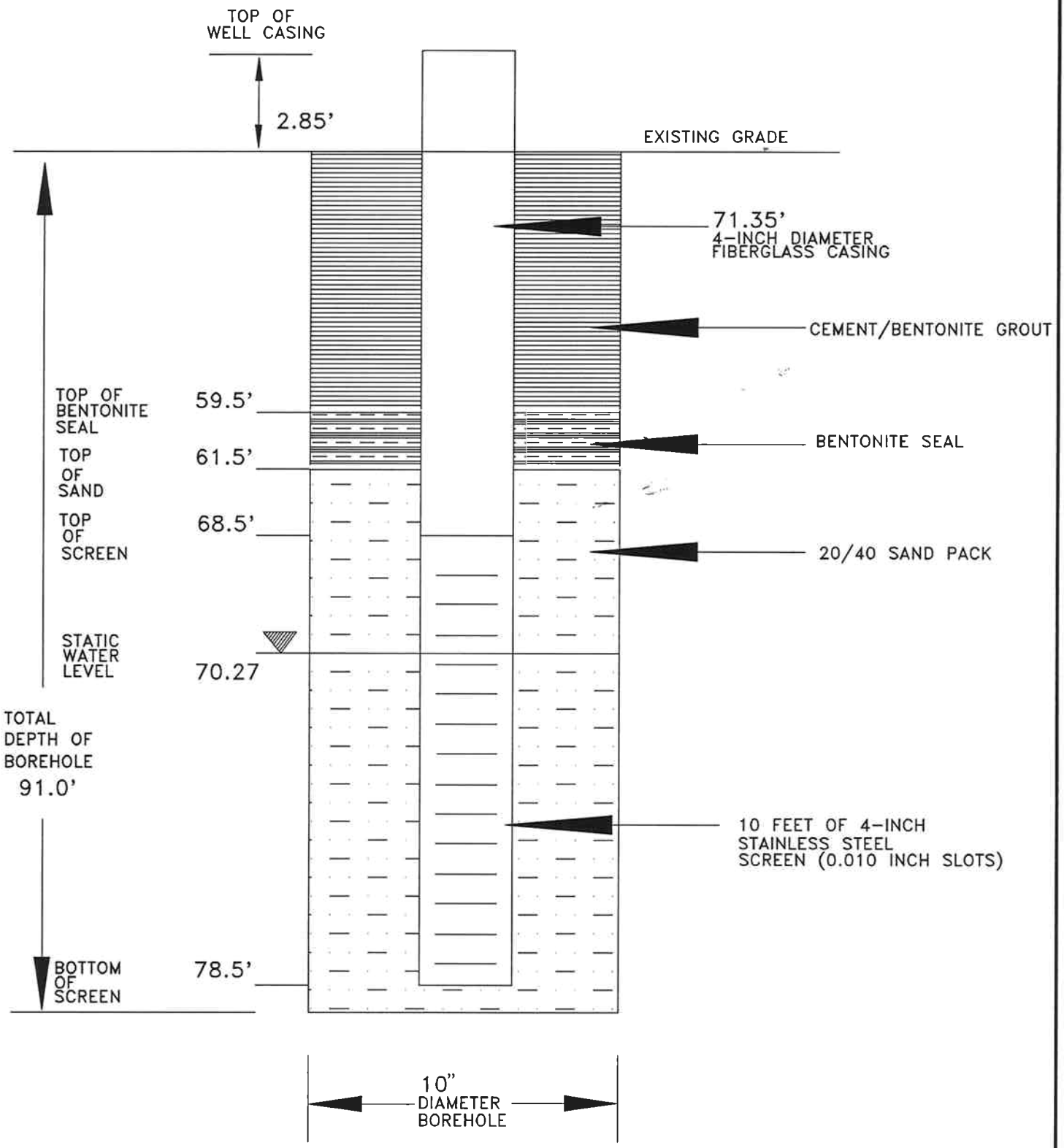
Well/Boring No.: VW-12 Date Started: 3/18/95 Date Finished: 3/21/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 91'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 68.5' TO GRADE +2.85'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 78.5'-68.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 91.0'-61.5'
Casing Seal Interval: 61.5'-59.5' Casing Seal Type: BENTONITE Static Water Level: 70.27'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Brown Soil; dry
5							Terra Rosa fine SAND; dry
10							Moderate Limestone; dry
15							
20							
25							Hard Limestone; dry
30							Very Hard Limestone; dry

Boring/Well Number: VW-12

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
35							Very Hard Limestone; dry
40							Soft formation – cuttings = coarse to fine SAND, some Clay, trace Silt; dry
45							Hard Limestone; dry
50, 55							Soft formation – cuttings = coarse to fine SAND, some Clay, trace Silt; dry
60, 65, 70, 75			0.0			▽	Soft formation – cuttings = coarse to fine SAND, some Clay; wet at 70' Note: chemical odor present, but no PID response.
							Hard Limestone; wet

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-12 Page 3 LITHOLOGY / REMARKS
80							Hard Limestone; wet
85							Soft formation - no return
90							
95							Boring terminated at 91 feet.
100							
105							
110							
115							
120							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-12

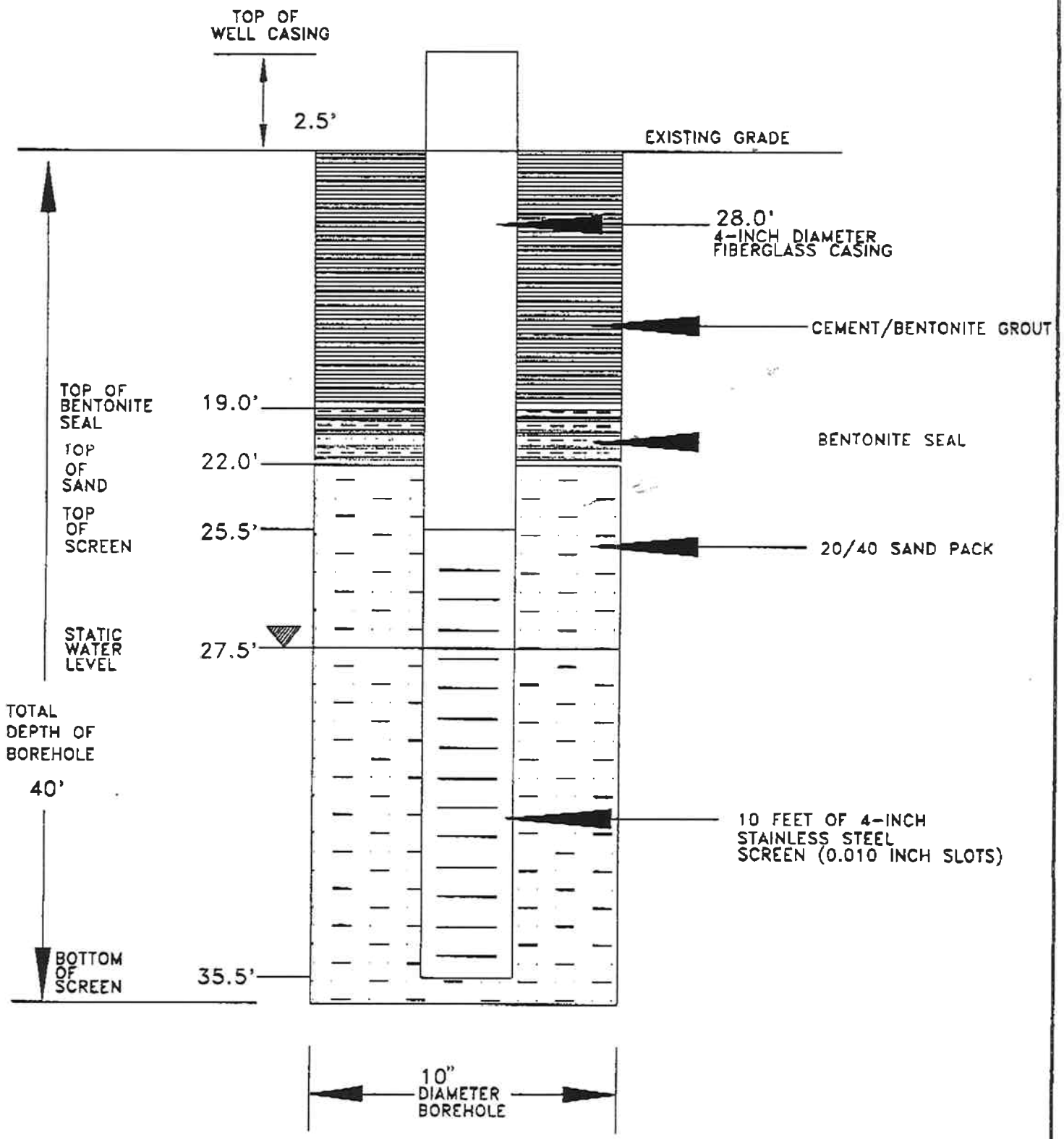
EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/21/95	Scale: None	

ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-13 Date Started: 11/1/95 Date Finished: SAME
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 40'
Casing Type: FIBERGLASS Casing Diameter: 4.0" Casing Interval: 25.5'TO GRADE+2.5'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4.0" Screen Interval: 25.5'-35.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 40' - 22'
Casing Seal Interval: 22' - 19' Casing Seal Type: BENTONITE Static Water Level: 27.5'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Moderate LIMESTONE; dry
5							
			118				Hard LIMESTONE; wet at 27.5'
10							
15							
20			0.0				
25			0.0				
						▽	
30			435				

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-13 Page 2 LITHOLOGY / REMARKS
							Hard LIMESTONE; wet
35							
40							Boring terminated at 40.0 feet.
45							
50							
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-13

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 11/1/95	Scale: None	

GeoMonitoring Services
4123 Fifth Street
Brookshire, Texas 77423

Completion Date: 5/18/07

WELL: VW-13B

Location: Renaissance -SCA

Client: Hess
Location: **St Croix**
Elevation (toc) :
Lat/Long

Project Name:
Project Number:

Sampler Type: No Sampling
Inside Diameter:
Hammer Weight (LB): NA
Hammer Fall (IN): NA

Rig Type: Hollow Stem & Auger
Bit Type: Toothed Bit
Total Depth: 59.5'

Drilling Co.: Caribbean Drilling
Driller: Ken Eastman/Ray Tutein
Geologist: Rex Meyer

Hole Diameter: 9'

Screen Type: Stainless Steel - 20'
Joints: Screw-Coupled
Diameter: 4"
Screen: 0.01"
Sand Type: Silica Sand 00N 20/40

Riser Type: National Well -30'
Joints: Screw-Coupled
Diameter: 4"
Type: Fiberglass
Stickup: 3.5'

Drilling Notations:

DEPTH FROM GRADE (FT)	SAMPLE DESIGNATION	Sample Core Composite	OVM Reading (ppm)	WELL CONSTRUCTION	**Matrix** Munsell Color	**Description**
+3						
+2						
+1						
0						
1					*10YR8/2*	**Soft Limestone**
2					White	**Moderate to Hard Dry Limestone**
3						
4	(Cement/Bentonite Grout) ---------					
5						
6						**Same**
7						
8						
9						
10						
11						**Same**
12						
13	(Cement/Bentonite Grout) ---------					
14						
15						
16						**Same**
17						
18						
19						
20						Thin (1/4") Chert Layer @ 22'
21		Bentonite Chips				
22	Top of Sand Pack @ 22'					*Gypsum Deposits to 30'*
23						
24						
25						
26						
27						
28						*Static - Oil @ 28' & Water @ 28.2'*
29						
30						
31						
32						
33						
34						
35						
36		(Sand Pack)				
37						
38						
39						
40						
41						
42						
43						
44						
45						
46						
47						Well TD @ 46.5' Below Grade
48						
49						
50						4" of Interbedded Clay
51						
52				*Boring Collapsed*		
53						
54						
55						
56						
57						
58						
59						Boring TD @ 59.5' Below Grade
60						Extremely Hard Limestone

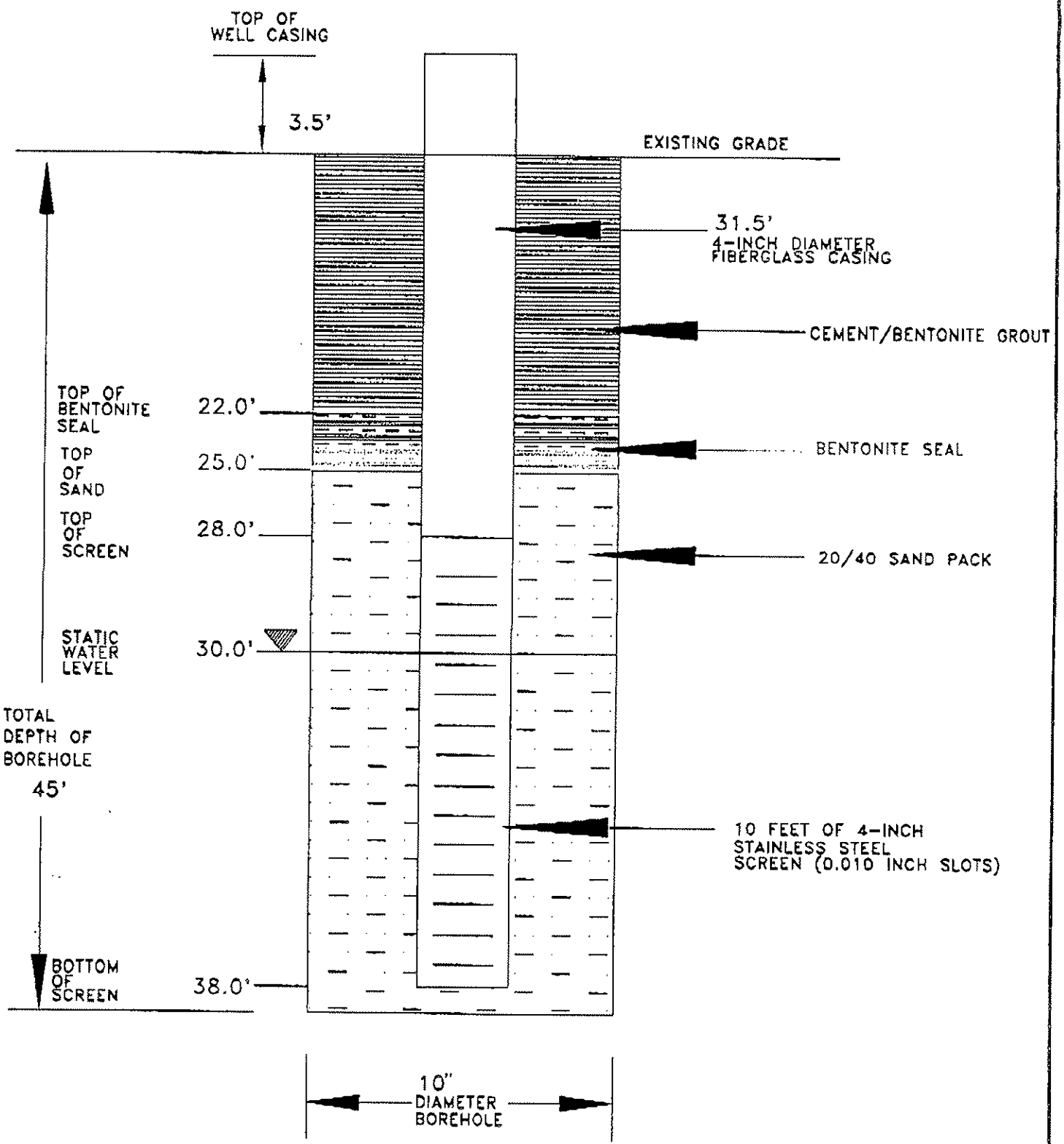
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-14 Date Started: 11/1/95 Date Finished: SAME
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 45'
Casing Type: FIBERGLASS Casing Diameter: 4.0" Casing Interval: 28'TO GRADE+3.5'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4.0" Screen Interval: 38-28'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 45' - 25'
Casing Seal Interval: 25' - 22' Casing Seal Type: BENTONITE Static Water Level: 30'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Brown LOAM, some Limestone chunks, vegetation;dry
5			0.0				Soft/moderate LIMESTONE; wet at 30'
10			0.0				
15			0.0				
20			0.0				
25			0.0				
30			168			▽	

Boring/Well Number: VW-14 Page 2

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Moderate LIMESTONE; wet
			12				
36							No recovery (void)
40							
45							Boring terminated at 45.0 feet.
50							
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-14

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 11/1/95	Scale: None	

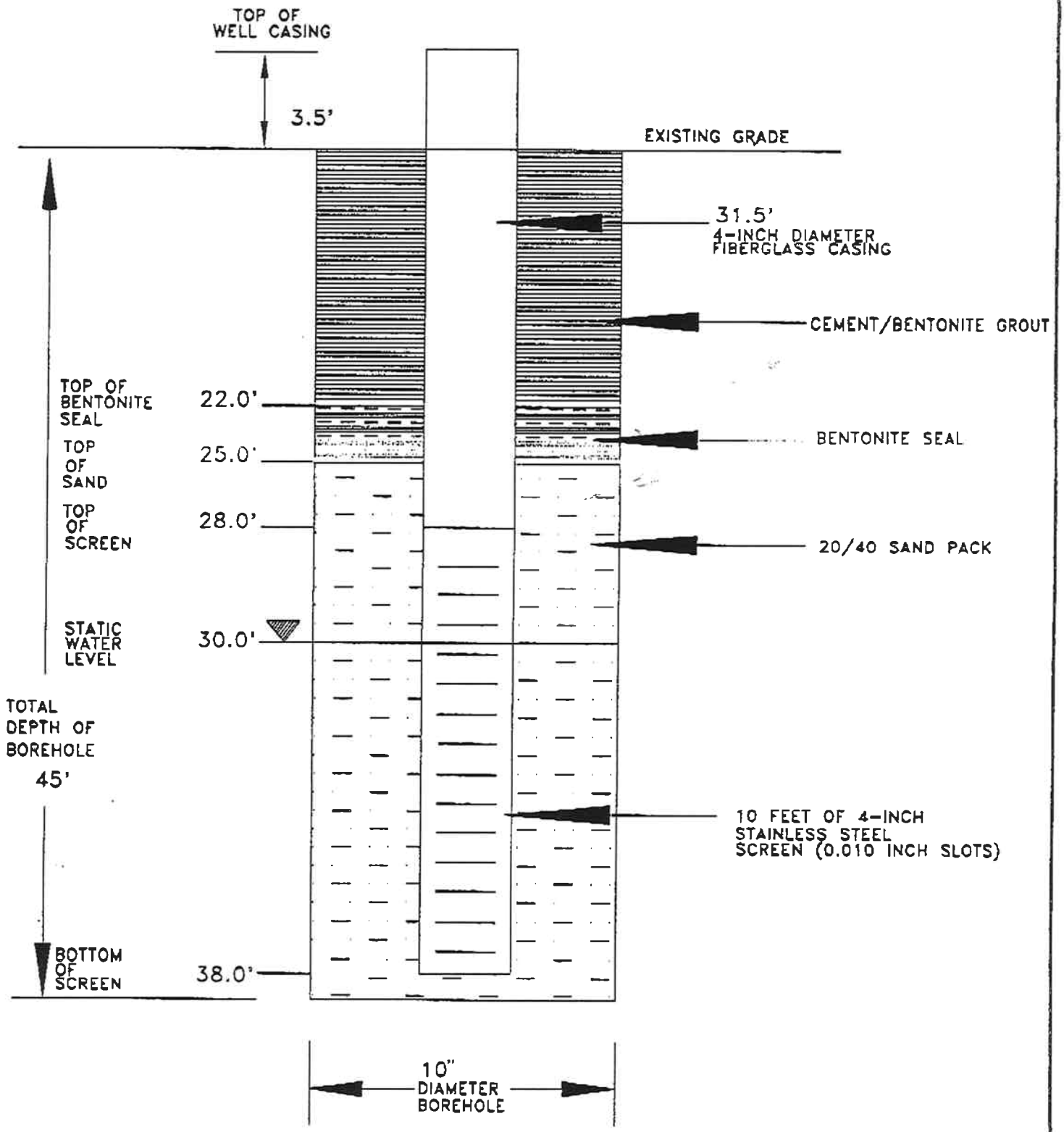
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-14 Date Started: 11/1/95 Date Finished: SAME
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 45'
Casing Type: FIBERGLASS Casing Diameter: 4.0" Casing Interval: 28'TO GRADE+3.5'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4.0" Screen Interval: 38-28'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 45' - 25'
Casing Seal Interval: 25' - 22' Casing Seal Type: BENTONITE Static Water Level: 30'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Brown LOAM, some Limestone chunks, vegetation;dry
5			0.0				Soft/moderate LIMESTONE; wet at 30'
10			0.0				
15			0.0				
20			0.0				
25			0.0				
30			168			▽	

Boring/Well Number: VW-14 Page 2

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Moderate LIMESTONE; wet
36			12				
							No recovery (void)
40							
45							
							Boring terminated at 45.0 feet.
50							
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-14

EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 11/1/95	Scale: None	

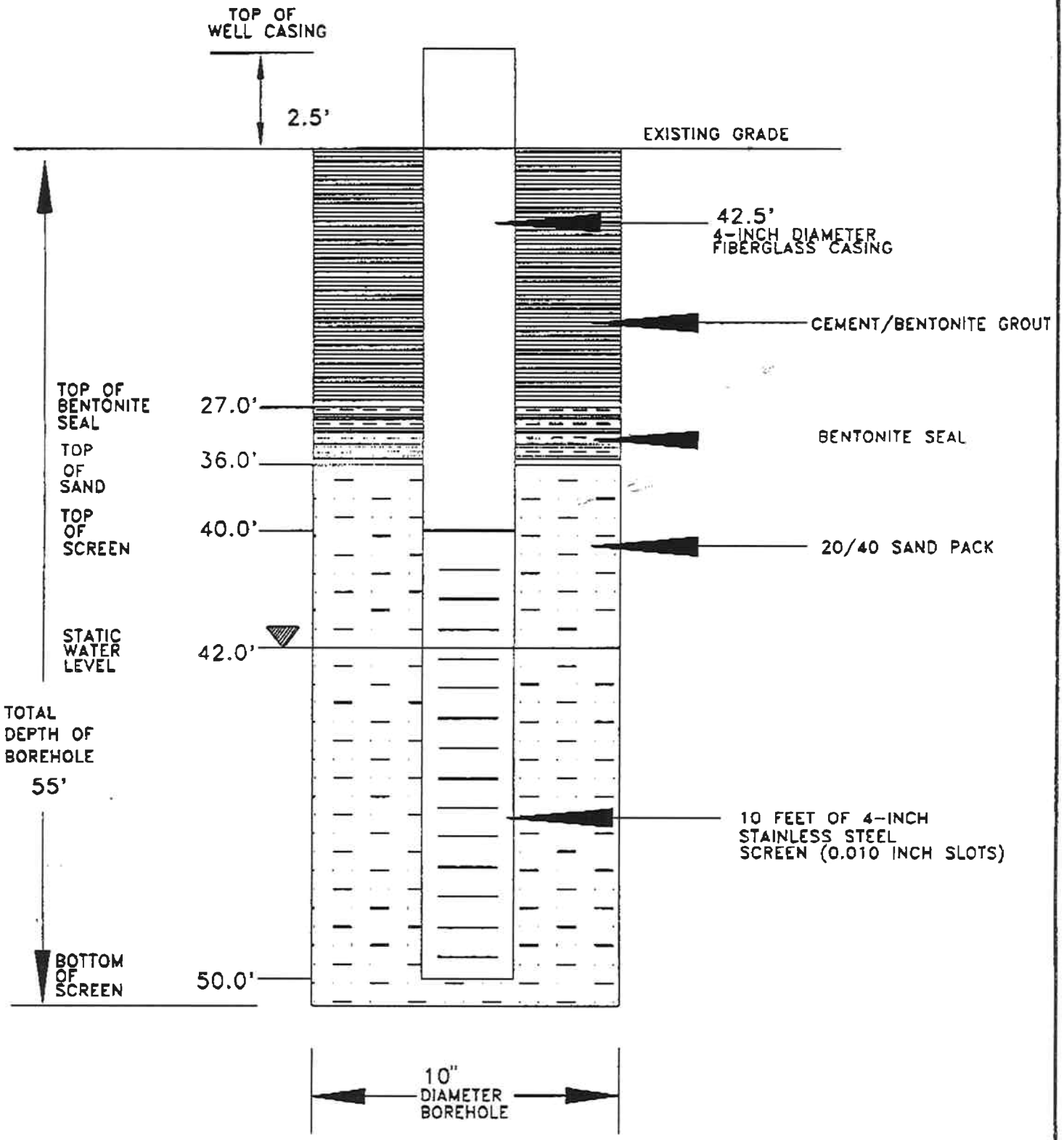
ENVIRONMENTAL MANAGEMENT SERVICES, INC.
BORING/WELL LOG

Well/Boring No.: VW-15 Date Started: 11/1/95 Date Finished: 11/2/95
Owner: HOVIC Well/Boring Location: VIALCO Use: OBSERVATION
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: CARPENTIER/ANTOINE Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 55'
Casing Type: FIBERGLASS Casing Diameter: 4.0" Casing Interval: 40'TO GRADE+2.5'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4.0" Screen Interval: 50-40'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 50' - 38'
Casing Seal Interval: 38' - 27' Casing Seal Type: BENTONITE Static Water Level: 42'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
			0.0				Soft LIMESTONE; dry
5							
10							
15							
20							
25							
30							No recovery (void)

Boring/Well Number: VW-15

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							No recovery (void)
							Coarse to fine SAND, little Clay; dry
35							
							Moderate LIMESTONE; wet at 42'
40							
						▽	
45							
50							
							No recovery (void)
55							Boring terminated at 55.0 feet.
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-15

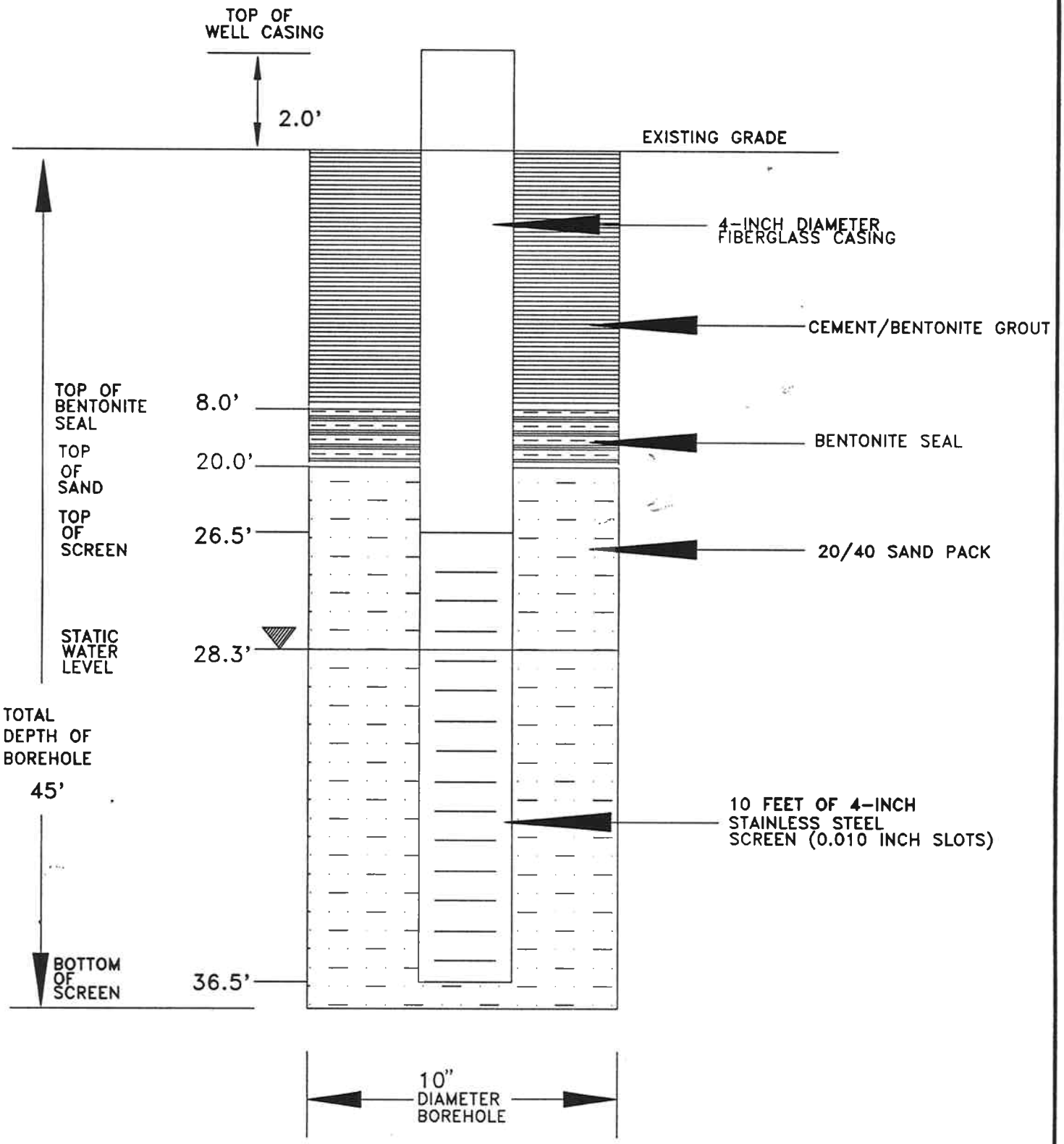
EMS	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 11/2/95	Scale: None	

FOSTER WHEELER ENVIRONMENTAL CORPORATION
BORING/WELL LOG

Well/Boring No.: VW-16 Date Started: 3/26/96 Date Finished: 3/27/96
Owner: HOVIC Well/Boring Location: ST. CROIX ALUMINA PLANT Use: MONITORING
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: J. CARPENTIER Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 45'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 26.5-GRADE+2'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 26.5-36.5'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 45 - 20'
Casing Seal Interval: 20 - 8' Casing Seal Type: BENTONITE Static Water Level: 28.3'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Tan coarse to fine SAND, medium to fine Gravel, trace Silt and Clay; dry
							Moderate LIMESTONE; dry
5							Hard LIMESTONE; wet at 28.3'
10							
15							
20							
25						▽	
30							

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-16 Page 2 LITHOLOGY / REMARKS
							Hard LIMESTONE; wet
35							Moderate LIMESTONE; wet
40							Soft LIMESTONE; wet
45							Boring terminated at 45.0 feet.
50							
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-16

FOSTER WHEELER ENVIRONMENTAL CORPORATION	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/27/96	Scale: None	

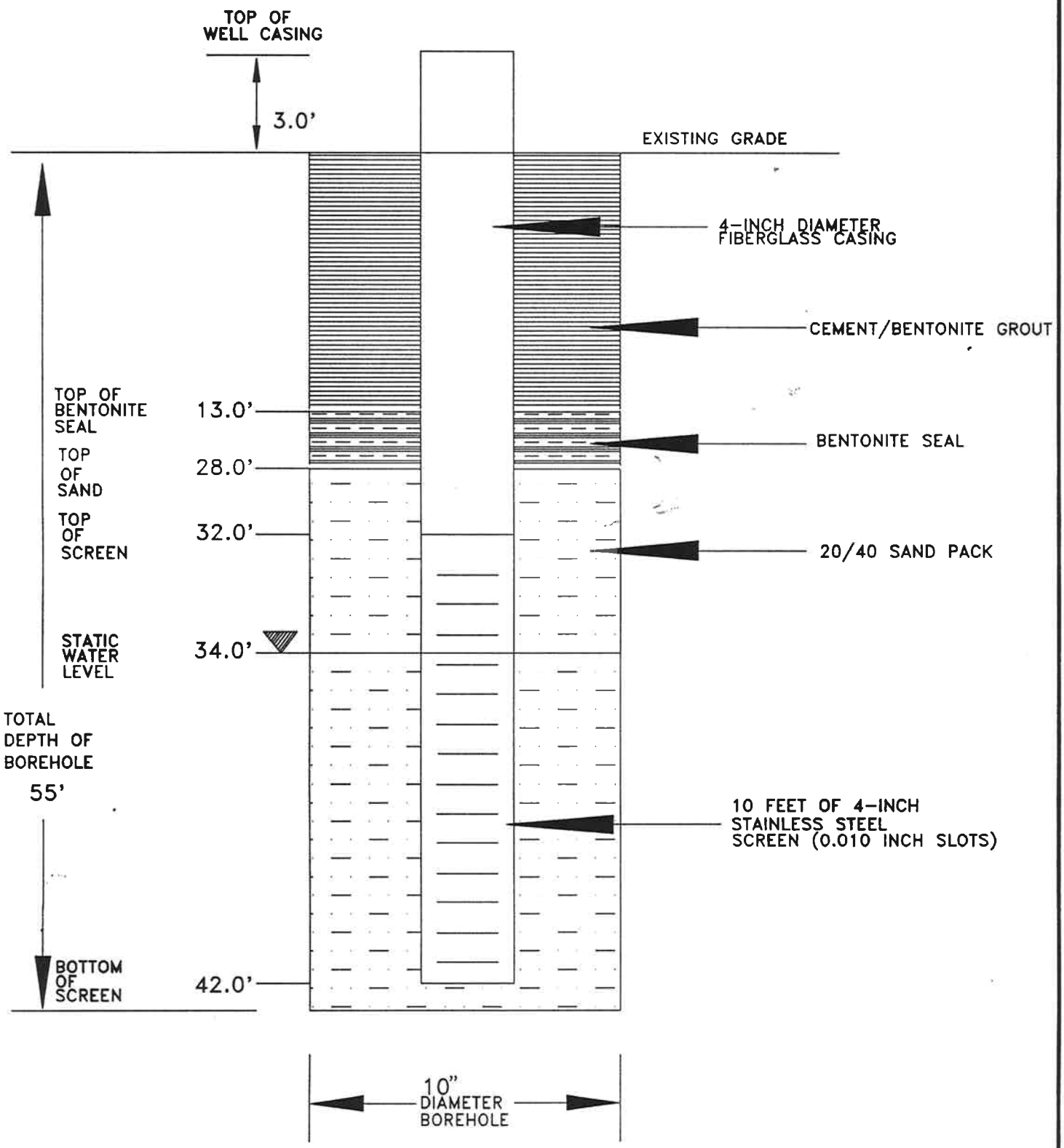
Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-17 Page 2 LITHOLOGY / REMARKS
							Moderate LIMESTONE; wet at 33.2'
						▽	
35							
40							
45							
50							
55							Boring terminated at 55.0 feet.
60							
65							
70							
75							

FOSTER WHEELER ENVIRONMENTAL CORPORATION
BORING/WELL LOG

Well/Boring No.: VW-18 Date Started: 3/25/96 Date Finished: 3/26/96
Owner: HOVIC Well/Boring Location: ST. CROIX ALUMINA PLANT Use: MONITORING
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: J. CARPENTIER Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 55'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 32-GRADE+3'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 42-32'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 55 - 28'
Casing Seal Interval: 28 - 13' Casing Seal Type: BENTONITE Static Water Level: 34.0'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Coarse GRAVEL, Topsoil; dry
			6.5				Red CLAY, coarse to fine Sand, fine Gravel; dry
5			32.4				Hard LIMESTONE (or concrete); dry
10			8.5				Tan coarse to fine SAND, medium to fine Gravel, trace Silt and Clay; dry
15							Moderate LIMESTONE; dry
20			4.8				
25			5.5				
							Soft LIMESTONE; dry
30							

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-18 Page 2 LITHOLOGY / REMARKS
							Soft LIMESTONE; wet at 34'
35						▽	
40							
45							
50							
55							Boring terminated at 55.0 feet.
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-18

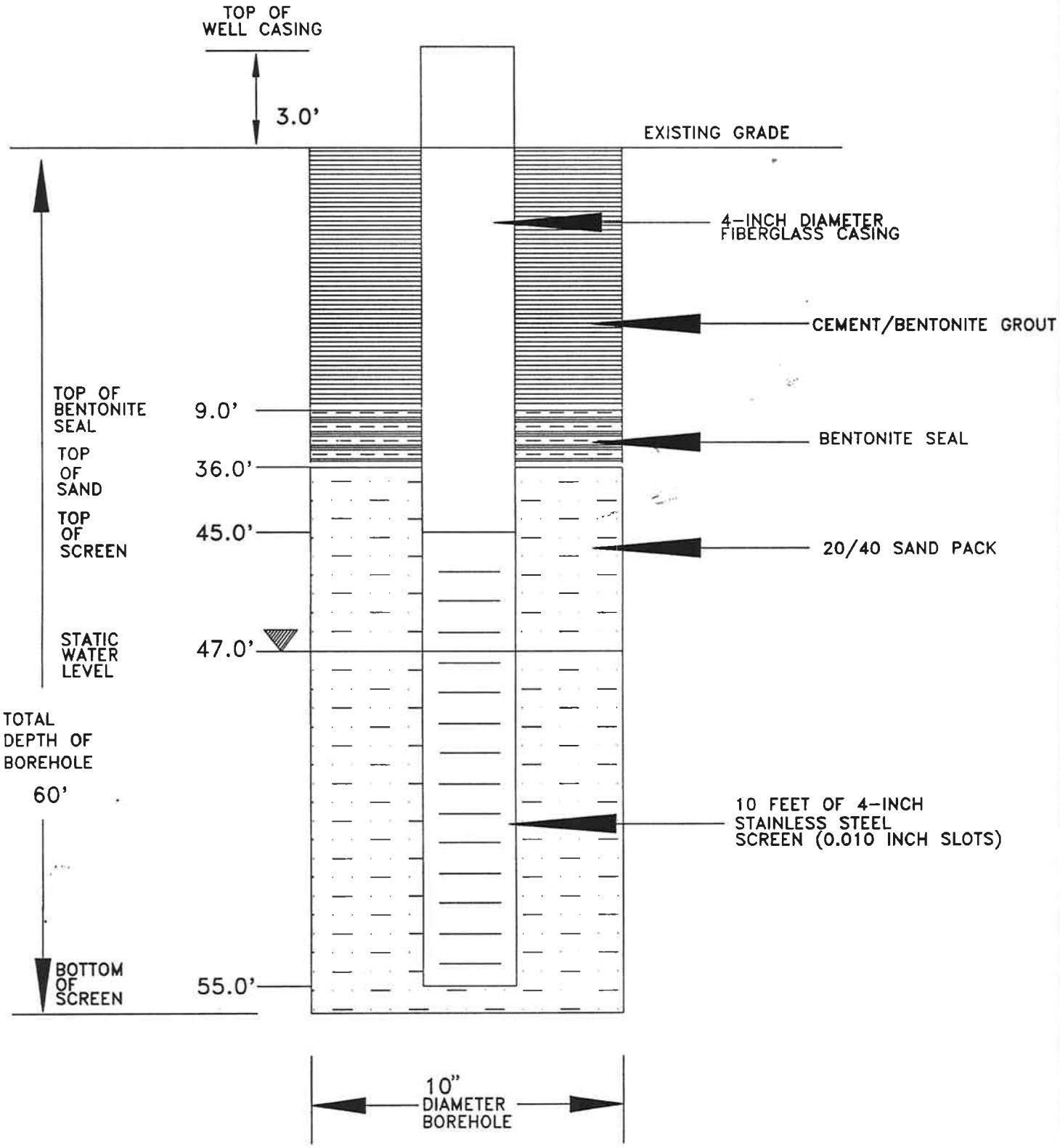
FOSTER WHEELER ENVIRONMENTAL CORPORATION	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/26/96	Scale: None	

FOSTER WHEELER ENVIRONMENTAL CORPORATION
BORING/WELL LOG

Well/Boring No.: VW-19 Date Started: 3/25/96 Date Finished: SAME
Owner: HOVIC Well/Boring Location: ST. CROIX ALUMINA PLANT Use: MONITORING
Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB
Geologist: J. CARPENTIER Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER
Borehole Diameter: 10" Total Depth of Borehole: 60'
Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 45-GRADE+3'
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 55-45'
Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 60 - 36'
Casing Seal Interval: 36 - 9' Casing Seal Type: BENTONITE Static Water Level: 47.0'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Asphalt
							Tan coarse to fine SAND, medium to fine Gravel, trace Silt and Clay; dry
5							Moderate LIMESTONE; dry
10			3.9				Soft LIMESTONE; dry
15							Moderate LIMESTONE; dry
20			9.1				Hard LIMESTONE; dry
25			8.4				Moderate LIMESTONE; dry
30			21.9				Hard LIMESTONE; dry

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-19 Page 2 LITHOLOGY / REMARKS
							Hard LIMESTONE; wet at 47'
35							
40							
45						▽	
50							
55							
60							Boring terminated at 60.0 feet.
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-19

FOSTER WHEELER ENVIRONMENTAL CORPORATION	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/25/96	Scale: None	

HESS

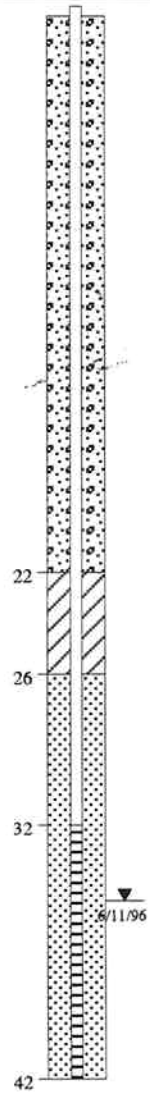
LOG OF BORING VW-20

Hess Oil Virgin Islands Corp.
St. Croix Refinery
St. Croix, U.S. Virgin Islands

Date Completed	: 6/11/96	Geologist	: K. Antoine
Drilling Method	: Rotary Auger	Owner	: HOVIC
Driller	: Caribbean Drilling	Location	: St. Croix Alumina
Sampling Method	: Grab	Surface Elevation	: 37.37 MSL

Depth in feet	DESCRIPTION	GRAPHIC	USCS	PID (ppm)
0	Soft LIMESTONE; dry			
5	Moderate LIMESTONE; wet at 36 ft.			15.0
10				12.3
15				8.3
20				
25				3.4
30				0.0
35				
40	Hard LIMESTONE with gray Clay, fine Sand thin lenses; wet			8.0
45				
50	no returns			55.5
55	Boring terminated at 55 ft.			

VW-20
ELEV: 40.27



Well Construction Information

WELL CONSTRUCTION

Date Compl.	: 6/11/96
Hole Diameter	: 10 in.
Drill. Method	: SSA
Company Rep.	: K. Antoine

WELL CASING

Material	: fiberglass
Diameter	: 4 in.
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 in.
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
SAND PACK	: 20/40
ANNULUS SEAL	: cement/grout

SURFACE CASING

Material	: Fiberglass
Diameter	: 4 in
Cap	: locking compression

NOTES

Offsite Investigation Well on St. Croix Alumina L.L.C. property (formerly VIALCO)

Map Coordinates:
(HOVIC datum)
10107.890 North
6475.306 East

Surface Elevation:
(HOVIC Datum) 37.37 ft. MSL

Pre-development Fluid Levels:
(from grade on 6/11/96)
35.00 ft. to Top of Product
35.50 ft. to Top of Water

GeoMonitoring Services

4123 Fifth Street
Brookshire, Texas 77423

Completion Date: 5/18/07

WELL: VW-20B

Location: Renaissance/SCA

Client: Hess
Location: **St Croix**
Elevation (toc) :
Lat/Long

Project Name:
Project Number:

Sampler Type: No Sampling
Inside Diameter:
Hammer Weight (LB): NA
Hammer Fall (IN): NA

Rig Type: **Hollow Stem & Auger**
Bit Type: Toothed Bit
Total Depth: **57.5'**

Drilling Co.: Caribbean Drilling
Driller: Ken Eastman/Ray Tutein
Geologist: Rex Meyer

Hole Diameter: 9.5"

Screen Type: Stainless Steel - 20'
Joints: Screw-Coupled
Diameter: 6"
Screen: 0.01"
Sand Type: Silica Sand 00N 20/40

Riser Type: Star Fiberglass -55'
Joints: Screw-Coupled
Diameter: 6"
Type: Fiberglass
Stickup:

Drilling Notations:

DEPTH FROM GRADE (FT)	SAMPLE DESIGNATION	Sample Core Composite	OVM Reading (ppm)	WELL CONSTRUCTION	**Matrix** Munsell Color	
+3						
+2				3.5' stick up		
+1						***Description***
0						
1					*10 YR 8/2*	**Soft Dry Limestone**
2					*White*	*White and Weathered Gray*
3						
4		(Cement/Bentonite Grout)				
5						
6						
7						
8						
9						
10						
11						
12						**Moderate to Soft no Voids**
13						
14						
15						
16						Bentonite from 15.5 to 18.5' Below Grade
17		Bentonite Chips				
18						
19						Sand Pack from 18.5 to 51.5' Below Grade
20						
21						
22						
23						
24						
25						
26						
27						
28						
29						
30						**Interbedded Clays & Sands with Limestone**
31						
32						
33						
34						**Moderate to Soft Limestone**
35						Static Oil @ 34.35' & Water @ 35'
36		(Sand Pack)				
37						**Wet**
38						
39						
40						
41						No Cuttings
42						**Moderate Limestone with Gray Clay**
43						
44						No Cuttings Potential Void
45						
46						
47						
48						
49						
50						No Returns
51						Well TD 51.5'
52						
53						Boring Rimed 4 times after caving
54				*Boring Collapsed*		
55						
56						
57						**Hard Limestone**
58						
59						
60						Boring TD 60'

GeoMonitoring Services

HESS

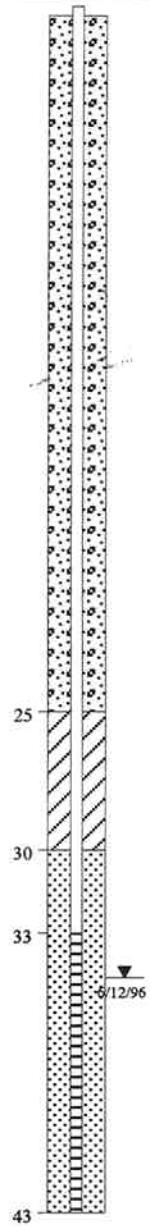
LOG OF BORING VW-21

Hess Oil Virgin Islands Corp.
St. Croix Refinery
St. Croix, U.S. Virgin Islands

Date Completed	: 6/12/96	Geologist	: K. Antoine
Drilling Method	: Rotary Auger	Owner	: HOVIC
Driller	: Caribbean Drilling	Location	: St. Croix Alumina
Sampling Method	: Grab	Surface Elevation	: 37.13 MSL

Depth in feet	DESCRIPTION	GRAPHIC	USCS	PID (ppm)
0	light brown coarse to fine SAND, trace Gravel; dry		SP	19.5
5	Soft LIMESTONE; wet at 35 ft.			
10				10.0
15				
20				10.8
25				
30				0.0
35				
40	Hard LIMESTONE with gray Clay, fine Sand thin lenses; wet			
45				136
50	Boring terminated at 50 ft.			

VW-21
ELEV: 39.74



Well Construction Information

WELL CONSTRUCTION
Date Compl. : 6/12/96
Hole Diameter : 10 in.
Drill Method : SSA
Company Rep. : K. Antoine
WELL CASING :
Material : Fiberglass
Diameter : 4 in.
Joints : threaded
WELL SCREEN :
Material : Stainless Steel
Diameter : 4 in.
Joints : threaded
Opening : 0.01 slot
Length : 10 ft.
SAND PACK : 20/40
ANNULUS SEAL : cement/grout
SURFACE CASING
Material : Fiberglass
Diameter : 4 in.
Cap : locking compression

NOTES

Offsite Investigation Well on St. Croix Alumina L.L.C. property (formerly VIALCO)

Map Coordinates:
(HOVIC datum)
9985.422 North
6190.497 East

Surface Elevation:
(HOVIC datum) 37.13 ft. MSL

Pre-development Fluid Levels:
(from TOC on 6/13/96)
37.19 ft. to Top of Product
37.41 ft. to Top of Water

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GeoMonitoring Services

4123 Fifth Street
Brookshire, Texas 77423

WELL: VW-21B

Completion Date: 5/17/07

Location: Renaissance/SCA

Client: Hess
Location: **St Croix**
Elevation (toc) :
Lat/Long

Project Name:
Project Number:

Sampler Type: No Sampling
Inside Diameter:
Hammer Weight (LB): NA
Hammer Fall (IN): NA

Rig Type: **Hollow Stem Auger**
Bit Type: Toothed Bit
Total Depth: 64'

Drilling Co.: Caribbean Drilling
Driller: Ken Eastman/Ray Tutein
Geologist: Rex Meyer

Hole Diameter: 9.5"

Screen Type: Stainless Steel - 20'
Joints: Screw-Coupled
Diameter: 6"
Screen: 0.01"
Sand Type: Silica Sand 00N 20/40

Riser Type: Star Fiberglass - 31.5'
Joints: Screw-Coupled
Diameter: 6"
Type: Fiberglass
Stickup: 3.5'

Drilling Notations:

DEPTH FROM GRADE (FT)	SAMPLE DESIGNATION	Sample Core Composite	OVM Reading (ppm)	WELL CONSTRUCTION	**Matrix** Munsell Color	**Description**
+3						
+2						
+1						
0						
1					*10 YR 8/2 White*	**Soft Limestone**
2						
3						
4		(Cement/Bentonite Grout) ---------				
5						**Very Soft Limestone**
6						**Same**
7						
8						
9						
10						
11						**Same**
12						
13						
14						
15						
16						**Same**
17						
18						
19						
20						
21		**Bentonite Chips**			*10 YR 8/1 White*	**White Harder Limestone**
22						
23						
24						
25						
26						
27						
28						
29						
30						
31						*Static Oil @ 33.7 & Water @ 34.2'*
32						**Saturated**
33						*No Cuttings from 33' to 35' & 37' to 41'*
34						Suggest Voids
35						
36		(Sand Pack)				**Harder Limestone**
37						
38						
39						**Moderate Limestone No Cuttings**
40						
41						
42						
43						
44						
45						**Limestone**
46						
47						
48						
49						**BOW 48.5'**
50						
51				*Boring Collapsed*		
52						
60						
64						*64' Total Drill depth 59-64' Very Hard*

GeoMonitoring Services

HESS

LOG OF BORING VW-22

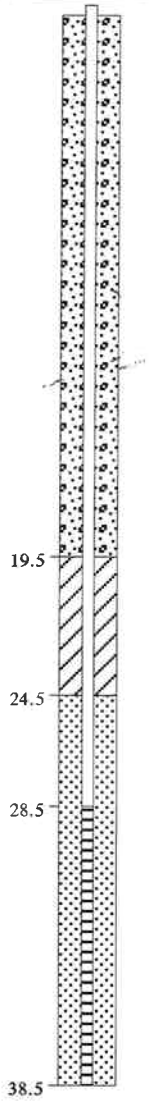
Hess Oil Virgin Islands Corp.
St. Croix Refinery
St. Croix, U.S. Virgin Islands

Date Completed	: 6/13/96	Geologist	: K. Antoine
Drilling Method	: 10 in.	Owner	: HOVIC
Driller	: Caribbean Drilling	Location	: St. Croix Alumina
Sampling Method	: Grab	Surface Elevation	: 54.39 ft.

Depth in ft.	DESCRIPTION	USCS	PID (ppm)
0	topsoil		
	light brown fine to coarse SAND, trace Gravel; dry	SP	
5	orange/red CLAY, fine Sand; dry	CL	
	light brown fine to coarse SAND; dry	SP	45.2
10	tan CLAY, fine to coarse Sand; dry	CL	4.9
15	moderate LIMESTONE; dry		1.0
20			
25			
30	orange/brown CLAY, coarse Sand; wet	CL	0.0
35	orange CLAY, coarse Sand, trace Gravel; wet	CL	0.0
40	orange CLAY; wet	CH	
45			
50	Boring terminated at 50 ft.		

GRAPHIC

VW-22
ELEV: 57.39



Well Construction Information

WELL CONSTRUCTION
Date Compl. : 6/13/96
Hole Diameter : 10 in.
Drill Method : SSA
Company Rep. : K. Antoine
WELL CASING :
Material : Fiberglass
Diameter : 4 in.
Joints : threaded
WELL SCREEN :
Material : Stainless Steel
Diameter : 4 in.
Joints : threaded
Opening : 0.01 slot
Length : 10 ft.
SAND PACK : 20/40
ANNULUS SEAL : cement/grout
SURFACE CASING
Material : Fiberglass
Diameter : 4 in.
Cap : locking compression

NOTES

Offsite Investigation Well on St. Croix Alumina L.L.C. property (formerly VIALCO)

Map Coordinates:
(HOVIC datum)
10498.369 North
5824.062 East

Surface Elevation:
(HOVIC datum) 54.39 ft. MSL

No fluid level measured in well. Saturated clay encountered at 30 ft.
Open hole water level:
46.15 ft. on 6/13/96.

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FOSTER WHEELER ENVIRONMENTAL CORPORATION
BORING/WELL LOG

Well/Boring No.: VW-23 Date Started: 3/27/96 Date Finished: SAME

Owner: HOVIC Well/Boring Location: ST. CROIX ALUMINA PLANT Use: MONITORING

Drilling Company: CARIBBEAN DRILLING Drilling Method: SSA Sampling Method: GRAB

Geologist: J. CARPENTIER Rig Type: CME-55 Soil Classification Method: MODIFIED BURMISTER

Borehole Diameter: 10" Total Depth of Borehole: 45'

Casing Type: FIBERGLASS Casing Diameter: 4" Casing Interval: 26.5-GRADE+2'

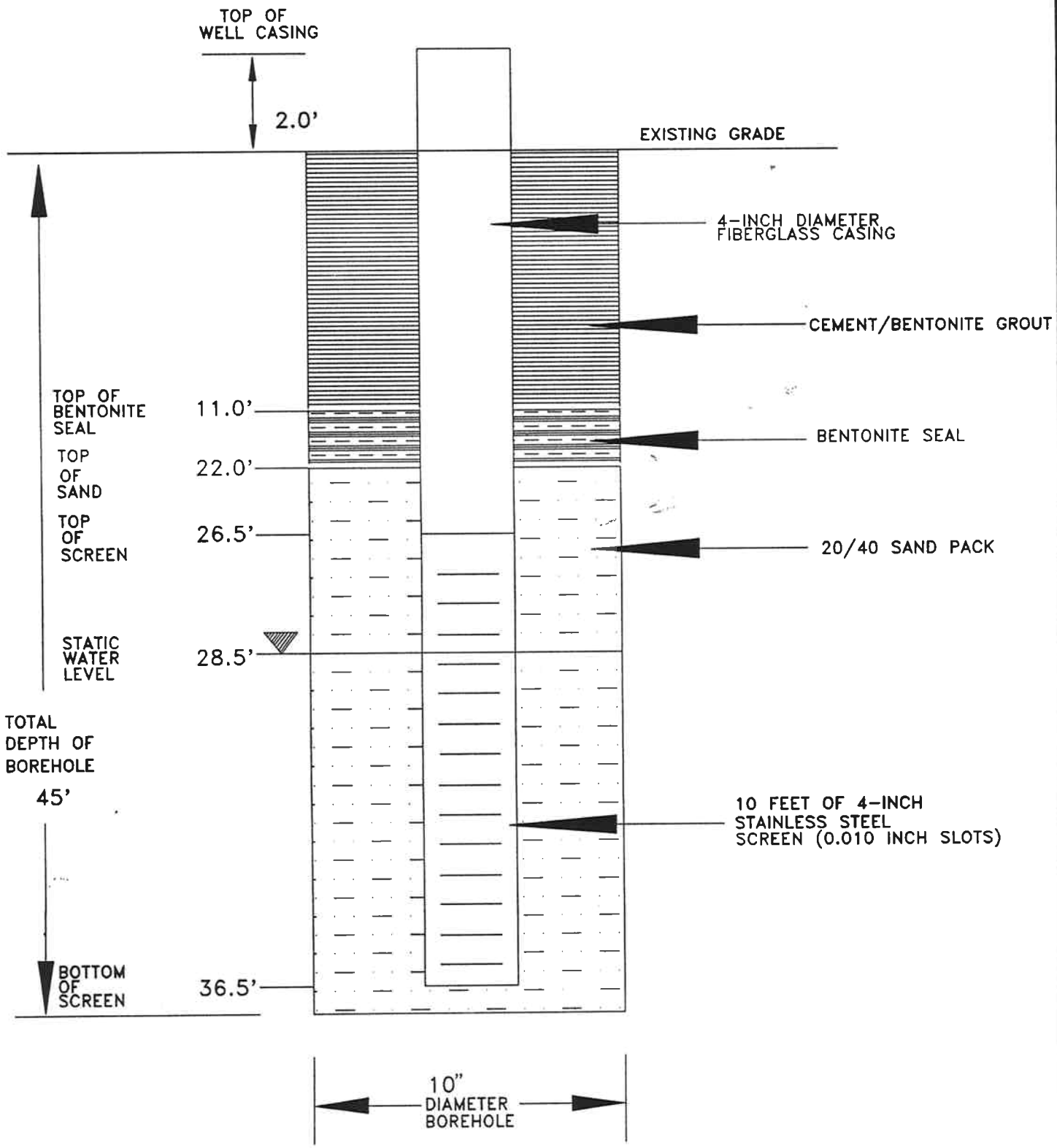
Screen Type: STAINLESS Screen Slots: 0.010" Screen Diameter: 4" Screen Interval: 26.5-36.5'

Gravel Pack Size: 20/40 RESEIVE Gravel Pack Interval: 45 - 22'

Casing Seal Interval: 22 - 11' Casing Seal Type: BENTONITE Static Water Level: 28.5'

Depth Below Surface (FT)	Blows per 6" Sampler	Recovery (%)	PID (PPM)	Sample Number	Sample Depth (Feet)	Saturation Depth	LITHOLOGY / REMARKS
							Tan coarse to fine SAND, medium to fine Gravel, trace Silt and Clay; dry
5							Moderate LIMESTONE; wet at 28.5'
10							
15							
20							
25							
						▽	
30							

Depth Below Surface (FT)	Blows Per 6" Sampler	Recovery (%)	PID (ppm)	Sample Number	Sample Depth (Feet)	Saturation Depth	Boring/Well Number: VW-23 Page 2 LITHOLOGY / REMARKS
							Moderate LIMESTONE; wet
35							
40							
45							Boring terminated at 45.0 feet.
50							
55							
60							
65							
70							
75							



* ALL VERTICAL MEASUREMENTS ARE FROM GRADE

WELL # VW-23

FOSTER WHEELER ENVIRONMENTAL CORPORATION	MONITORING WELL CONSTRUCTION DIAGRAM			HESS OIL VIRGIN ISLANDS CORP. KINGSHILL/ LIMETREE ROAD ST. CROIX, USVI
	Drawn By: JPC	Date: 3/27/96	Scale: None	

HESS

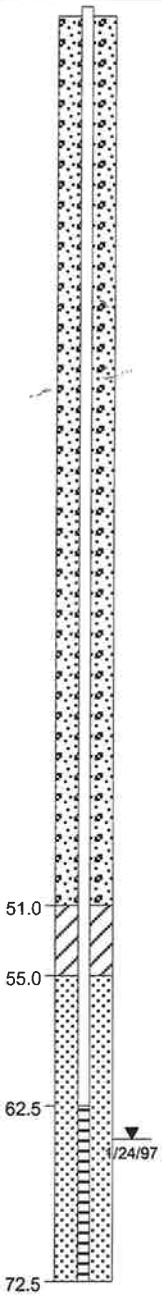
LOG OF BORING VW-24

Hess Oil Virgin Islands Corp.
St. Croix Refinery
St. Croix, U.S. Virgin Islands

Date Completed	: 1/24/97	Geologist	: K. Antoine
Drilling Method	: Rotary Method	Owner	: HOVIC
Driller	: Caribbean Drilling	Location	: St. Croix Alumina
Sampling Method	: Grab	Surface Elevation	: 65.88 MSL

Depth in ft	DESCRIPTION	GRAPHIC	USCS	PID (ppm)
0	Light tan soft LIMESTONE; dry			
5				
10				
15				0.0
20				0.0
25				0.0
30	Light tan moderate LIMESTONE; dry			0.0
35				0.0
40	Light tan soft LIMESTONE; dry			0.0
45	Moderate LIMESTONE; no cuttings			0.0
50				
55	Hard LIMESTONE; no cuttings			
60	Moderate LIMESTONE; no cuttings			0.0
65				
70				0.0
75				
80				

VW-24
ELEV: 68.83



Well Construction Information

WELL CONSTRUCTION

Date Compl.	: 1/24/97
Hole Diameter	: 10 in.
Drill Method	: SSA
Company Rep.	: K. Antoine

WELL CASING

Material	: Fiberglass
Diameter	: 4 in.
Joints	: Threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 in.
Joints	: Threaded
Opening	: 0.01 slot
Length	: 10 ft.
SAND PACK	: 20/40
ANNULUS SEAL	: cement/grout

SURFACE CASING

Material	: Fiberglass
Diameter	: 4 in.
Cap	: locking compression

NOTES

Offsite Investigation Well on St. Croix Alumina L.L.C. property (formerly VIALCO)

Ground Elevation : 65.88 MSL
Top of cement apron: 66.52 MSL
(HOVIC datum)

Map Coordinates:
10320.085 North
6274.402 East
(HOVIC datum)

Visible hydrocarbon on augers.

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HESS

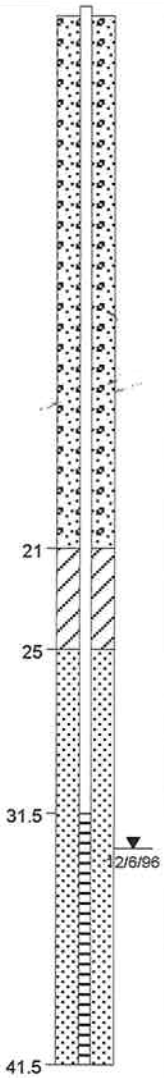
LOG OF BORING VW-25

Hess Oil Virgin Islands Corp.
St. Croix Refinery
St. Croix, U.S. Virgin Islands

Date Completed	: 12/6/96	Geologist	: K. Antoine
Drilling Method	: Rotary Auger	Owner	: HOVIC
Driller	: Caribbean Drilling	Location	: St. Croix Alumina
Sampling Method	: Grab	Surface Elevation	: 35.09 MSL

Depth in Feet	DESCRIPTION	GRAPHIC	USCS	PID (ppm)
0	Light tan soft LIMESTONE; dry			0.0
10	moderate LIMESTONE; dry			
	Tan soft LIMESTONE			0.0
15	Tan CLAY, fine to coarse Sand; dry		CL	
20	Tan soft LIMESTONE			
25				0.0
30				0.0
35				0.0
40	No returns; easy drilling - Soft material			
45				0.0
50				
55				

VW-25
ELEV: 38.20



Well Construction Information

WELL CONSTRUCTION

Date Compl.	: 12/6/96
Hole Diameter	: 10 in.
Drill. Method	: SSA
Company Rep.	: K. Antoine

WELL CASING

Material	: Fiberglass
Diameter	: 4 in.
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 in.
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
SAND PACK	: 20/40
ANNULUS SEAL	: cement/grout

SURFACE CASING

Material	: Fiberglass
Diameter	: 4 in.
Cap	: locking compression

NOTES

Offsite Investigation Well on St. Croix Alumina L.L.C. property (formerly VIALCO)

Ground Elevation: 35.09 MSL
Top of cement apron: 35.89 MSL (HOVIC datum)

Map Coordinates:
9608.077 North
4887.844 East
(HOVIC datum)

12-18-1996 c:\mtech3\vialco\vw-25.ge3

HESS

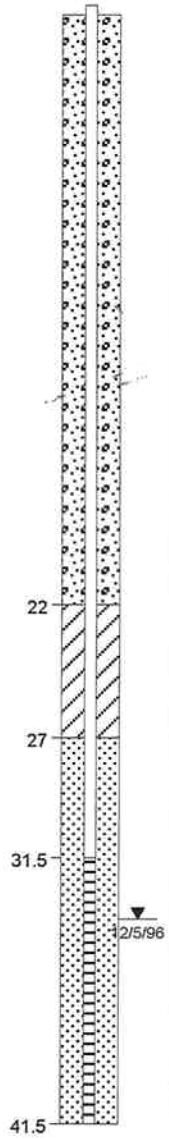
LOG OF BORING VW-26

Hess Oil Virgin Islands Corp.
St. Croix Refinery
St. Croix, U.S. Virgin Islands

Date Completed	: 12/5/96	Geologist	: K. Antoine
Drilling Method	: Rotary Auger	Owner	: HOVIC
Driller	: Caribbean Drilling	Location	: St. Croix Alumina
Sampling Method	: Grab	Surface Elevation	: 36.12 MSL

Depth in Feet	DESCRIPTION	GRAPHIC	USCS	PID (ppm)
0	Light tan soft LIMESTONE; dry			
5				0.0
10				
15				0.0
20				
25				0.0
30				
35	No returns			0.0
40				0.0
45	No returns but drilling is noticeably slower - in harder material.			
50				

VW-26
ELEV: 39.67



Well Construction Information

WELL CONSTRUCTION

Date Compl.	: 12/5/96
Hole Diameter	: 10 in.
Drill. Method	: SSA
Company Rep.	: K. Antoine

WELL CASING

Material	: Fiberglass
Diameter	: 4 in.
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 in.
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
SAND PACK	: 20/40
ANNULUS SEAL	: cement/grout

SURFACE CASING

Material	: Fiberglass
Diameter	: 4 in.
Cap	: locking compression

NOTES

Offsite Investigation Well on St. Croix Alumina L.L.C. property (formerly VIALCO)

Ground Elevation: 36.12 MSL
Top of cement apron: 36.83 MSL
(HOVIC datum)

Map Coordinates:
10047.193 North
5590.059 East
(HOVIC datum)

Pre-development Fluid Levels:
(from grade on 12/6/96)
33.70 ft. to Top of Product
33.75 ft. to Top of Water

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HESS

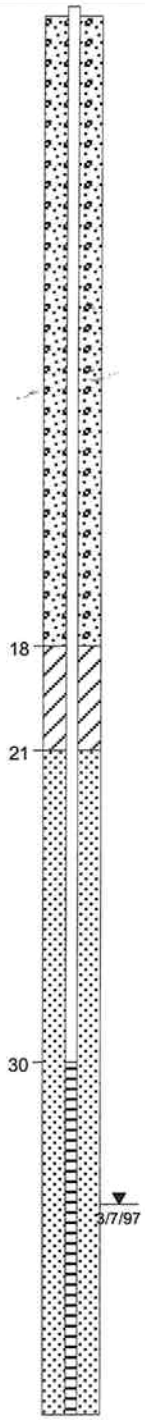
LOG OF BORING VW-27

Hess Oil Virgin Islands Corp.
St. Croix Refinery
St. Croix, U.S. Virgin Islands

Date Completed	: 3/6/97	Geologist	: K. Antoine
Drilling Method	: Rotary Method	Owner	: HOVIC
Driller	: Caribbean Drilling	Location	: St. Croix Alumina
Sampling Method	: Grab	Surface Elevation	: 36.08 MSL

Depth in ft	DESCRIPTION	GRAPHIC	USCS	PID (ppm)
0	Light tan soft LIMESTONE; dry			0.0
5				0.0
10	Light tan moderate LIMESTONE			
15				0.0
20				
25				0.0
30				0.0
35				0.0
40				

VW-27
ELEV: 38.17



Well Construction Information

WELL CONSTRUCTION

Date Compl.	: 3/6/97
Hole Diameter	: 12 in.
Drill Method	: HSA
Company Rep.	: K. Antoine

WELL CASING

Material	: Fiberglass
Diameter	: 4 in.
Joints	: Threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 in.
Joints	: Threaded
Opening	: 0.01 slot
Length	: 10 ft.
SAND PACK	: 20/40
ANNULUS SEAL	: cement/grout

SURFACE CASING

Material	: Fiberglass
Diameter	: 4 in.
Cap	: locking compression

NOTES

Offsite Investigation Well on St. Croix Alumina L.L.C. property (formerly VIALCO)

Ground Elevation: 36.08 MSL
Top of cement apron: 36.76 MSL
(HOVIC datum)

Map Coordinates:
9640.289 North
6235.286 East
(HOVIC datum)

3-14-1997 c:\mtech3\vialco\vw-27.ge3

LOG OF BORING LOG OF BORING VW-28

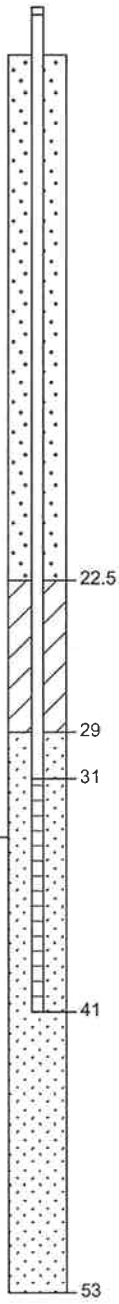
HOVENSA

#1 ESTATE HOPE
CHRISTIANSTED, VI 00820

Date Completed	: 1/18/02	Owner	: HOVENSA
Drilling Method	: Solid Stem Auger	Location	: St. Croix Alumina
Driller	: Caribbean Drilling	Surface Elevation	: 35.96
Geologist	: D. Watterson		

Well: VW-28
Elev.: 38.16

Depth in feet	Surf. Elev.	DESCRIPTION	GRAPHIC	USCS
0	0	Concrete		
		Buff/Tan LIMESTONE, highly weathered.		LS
5	-5			
		Weathered LIMESTONE, cuttings subangular.		LS
10	-10			
15	-15			
20	-20	Moderate LIMESTONE, small subangular cuttings < 1/4".		LS
		Soft LIMESTONE.		LS
25	-25			
30	-30			
		Moderate LIMESTONE, few cuttings.		LS
35	-35			
40	-40			
45	-45			
50	-50	Moderate LIMESTONE, not bringing up water at 48' - advance boring to 53'.		LS
55				



Well Construction Information

WELL CONSTRUCTION

Hole Diameter	: 8 inch
Type of Augers	: Solid Stem Auger

WELL CASING

Material	: Fiberglass
Diameter	: 4 inch
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 inch
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
Sand Pack	: 20/30
Sand Pack Seal	: Bentonite Pellets
ANNULUS SEAL	: Cement Grout

NOTES

St. Croix Alumina
Observation Well

Survey Coordinates
to HOVIC Datum:
10044.13 North
5686.12 East

09-06-2002 D:\HOVENSA\BORINGS\vw-28.bor

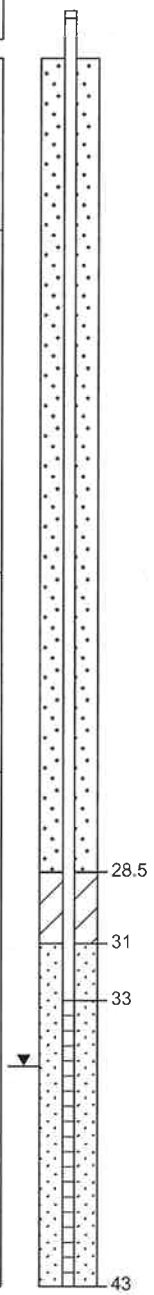
LOG OF BORING LOG OF BORING VW-29

#1 ESTATE HOPE
CHRISTIANSTED, VI 00820

Date Completed	: 1/22/02	Owner	: HOVENSA
Drilling Method	: Solid Stem Auger	Location	: St. Croix Alumina
Driller	: Caribbean Drilling	Surface Elevation	: 37.45
Geologist	: D. Watterson		

Depth in feet	Surf. Elev.	DESCRIPTION	GRAPHIC	USCS
0	0	Buff LIMESTONE, highly weathered, subangular cuttings.		LS
5	-5			
		Buff hard LIMESTONE, weathered cuttings.		LS
10	-10			
15	-15			
		Grey buff LIMESTONE, weathered cuttings.		LS
20	-20			
25	-25	LIMESTONE, hard at 25' and 37' bgs.		LS
30	-30			
35	-35			
40	-40			
45				

Well: VW-29
Elev.: 39.95



Well Construction Information

WELL CONSTRUCTION

Hole Diameter	: 8 inch
Type of Augers	: Solid Stem Auger

WELL CASING

Material	: Fiberglass
Diameter	: 4 inch
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 inch
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
Sand Pack	: 20/30
Sand Pack Seal	: Bentonite Pellets
ANNULUS SEAL	: Cement Grout

NOTES

St. Croix Alumina
Observation Well

Survey Coordinates
to HOVIC Datum:
10013.57 North
6363.24 East

09-06-2002 D:\HOVENSA\BORINGS\vw-29.bor

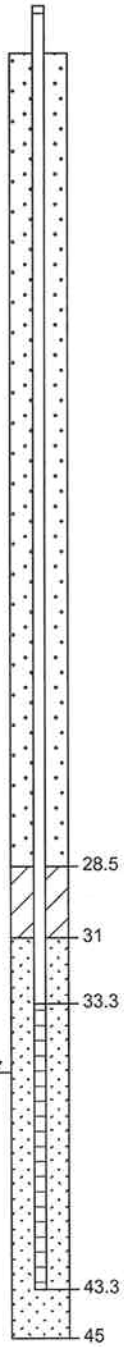
LOG OF BORING LOG OF BORING VW-30

#1 ESTATE HOPE
CHRISTIANSTED, VI 00820

Date Completed	: 1/22/02	Owner	: HOVENSA
Drilling Method	: Solid Stem Auger	Location	: St. Croix Alumina
Driller	: Caribbean Drilling	Surface Elevation	: 38.26
Geologist	: D. Watterson		

Well: VW-30
Elev.: 40.76

Depth in feet	DESCRIPTION	GRAPHIC	USCS
0	Crushed limestone FILL, buff colored.		FL
5	Buff soft LIMESTONE, subangular cuttings.		LS
10	Grey buff hard LIMESTONE, angular cuttings.		LS
20	Moderate LIMESTONE.		LS
	Hard, porous LIMESTONE.		LS
25	Hard LIMESTONE, no cuttings.		LS
	Tan-grey LIMESTONE.		LS
40	Moist, finer cuttings with less fragments.		LS
	Moist clayey material with limestone powder and blue limestone fragments.		CL
45			



Well Construction Information

WELL CONSTRUCTION

Hole Diameter	: 8 inch
Type of Augers	: Solid Stem Auger

WELL CASING

Material	: Fiberglass
Diameter	: 4 inch
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 inch
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
Sand Pack	: 20/30
Sand Pack Seal	: Bentonite Pellets
ANNULUS SEAL	: Cement Grout

NOTES

St. Croix Alumina
Observation Well

Survey Coordinates
to HOVIC Datum:
10218.31 North
6751.41 East

09-06-2002 D:\HOVENSA\BORINGS\vw-30.bor

LOG OF BORING LOG OF BORING VW-31

HOVENSA

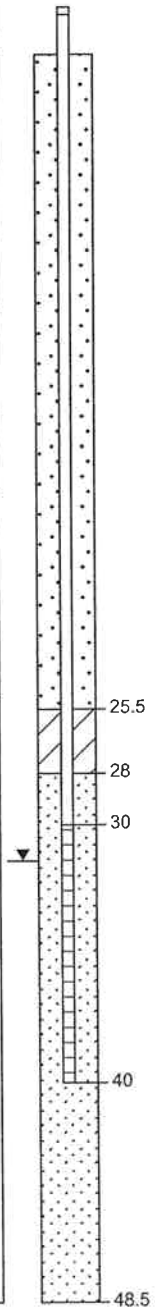
#1 ESTATE HOPE
CHRISTIANSTED, VI 00820

Date Completed	: 8/8/02	Owner	: HOVENSA
Drilling Method	: Solid Stem Auger	Location	: St. Croix Alumina
Driller	: Caribbean Drilling	Surface Elevation	: 35.33
Geologist	: D. Watterson		

Depth in feet	DESCRIPTION	GRAPHIC	USCS
0	Dark brown/grey CALICHE with 1-2" subangular fragments.		LS
5			
	Buff colored soft CALICHE/highly weathered LIMESTONE.		LS
10	Buff weathered LIMESTONE, subangular cuttings.		LS
15	Buff soft CALICHE/highly weathered LIMESTONE.		LS
	Buff moderate weathered LIMESTONE		LS
20			
25	Hard weathered LIMESTONE.		LS
30			
35			
40			
45			
50			

Well: VW-31

Elev.: 38.03



Well Construction Information

WELL CONSTRUCTION

Hole Diameter	: 8 inch
Type of Augers	: Solid Stem Auger

WELL CASING

Material	: Fiberglass
Diameter	: 4 inch
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 inch
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
Sand Pack	: 20/30
Sand Pack Seal	: Bentonite Pellets
ANNULUS SEAL	: Cement Grout

NOTES

St. Croix Alumina
Observation Well

Measurable PSH encountered.

Survey Coordinates
to HOVIC Datum:
10084.37 North
5118.10 East

LOG OF BORING LOG OF BORING VW-32

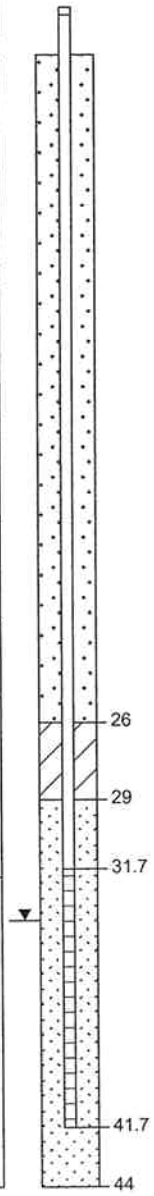
HOVENSA

#1 ESTATE HOPE
CHRISTIANSTED, VI 00820

Date Completed	: 8/7/02	Owner	: HOVENSA
Drilling Method	: Solid Stem Auger	Location	: St. Croix Alumina
Driller	: Caribbean Drilling	Surface Elevation	: 35.05
Geologist	: D. Watterson		

Depth in feet	DESCRIPTION	GRAPHIC	USCS
0	Brown to red clayey FILL.		FL
	Red highly weathered LIMESTONE/CALICHE.		LS
5	Tan moderate weathered LIMESTONE.		LS
	Light tan/buff moderate LIMESTONE.		LS
10	Light tan/buff moderate weathered LIMESTONE, minor voids.		LS
15	Soft weathered LIMESTONE.		LS
20	Moderate weathered LIMESTONE, minor voids, trace shell fragments.		LS
	Hard weathered LIMESTONE.		LS
25	Blue/grey moderate weathered LIMESTONE.		LS
30			
	Hard drilling, no cuttings.		LS
35			
40			
45			
50			

Well: VW-32
Elev.: 38.05



Well Construction Information

WELL CONSTRUCTION

Hole Diameter	: 8 inch
Type of Augers	: Solid Stem Auger

WELL CASING

Material	: Fiberglass
Diameter	: 4 inch
Joints	: threaded

WELL SCREEN

Material	: Stainless Steel
Diameter	: 4 inch
Joints	: threaded
Opening	: 0.01 slot
Length	: 10 ft.
Sand Pack	: 20/30
Sand Pack Seal	: Bentonite Pellets
ANNULUS SEAL	: Cement Grout

NOTES

St. Croix Alumina
Observation Well

Measurable PSH encountered.

Survey Coordinates
to HOVIC Datum:
10222.70 North
5449.09 East

SU 2'10" | TD 86.55
2.83'

Slow producer

Lithologic Log

Client: SCK
Project Name: DPPHC & PSPH Extend Study
Project Number:
Project Manager: Rex Meyer
Drilling Co.: Caribbean Drilling
Ken Eastman Ray & Marvin

Boring #: VW 33
Method/Dia.: Hollow Stem
Date Started: 2-10-03
Date Completed: 2-11-03
Total Depth:

Depth in Feet	Description	Sample #	Type	~~OVA~~ OVM Value	Stain	Odor
4	RM Caliche + Clay @ 3½' Chunk	15/12/11	/15	95% 0.2	No	No
8		29/50 41/49		95% 0.1	No	N
12	weathered white limestone weak	28/32 52 — NFA		95% 0.1 Lost 6"	No	No
16	weak weathered limestone					
20	Yellowish Tint	17/18 12/10		0.1 90%	N	No
24	weathered Limestone Not weak	16/6 NFA @ 32		70% 1" 50+ 0.1 ppm		
28	Highly weathered Limestone	50+ NA		N.R.		
32		50+ NA		NR		
36	Caliche 2½' – 0/3 pale yellow Tan of Clay 5'7	34/47 41/34		85% 0.1 ppm		
44		15/13/	14/14	95% 0.1 ppm		

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon

Lithologic Log

Client
Project Name
Project Number
Project Manager
Drilling Co.

Boring # VW33
Method/Dia.
Date Started
Date Completed
Total Depth 89

Depth in Feet	Description	Sample #	Type	OVA Value	Stain	Odor
46	Caliche, pale Yellow Clay <5%			100%		
50		60/4"	NHA	0.3 ppm	NO	NO
54	Increasing Pale Yellow Clay up to 25% Clay	30/30	30	126		
58		12/30	19	12		
62		15/14	21	40 = 4"		
66	Weathered Limestone (last 8")					
70	caliche	12/19	27	0.0 ppm	100%	
74	last 4" Pale Clay caliche wet @ 75' Limestone	14/13	9	50+ = 4"	NHA	
78	Saturated 79. caliche & Clay			0.0 ppm		
80		VW33@79 @602		12/31	14/20	14 inches
82	= Limestone			0.0 ppm		
86	caliche & Clay Clay @ 48%					

TD 89

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

GeoMonitoring Services
4123 Fifth Street
Brookshire, Texas 77423

Completion Date: February 5, 2003

Boring Number: **VW34**
Location: 450' West of VW31
900' East of GM13

Project Name St. Croix Alumina - DPPHC and PSPH Monitoring System
Project Number: SCARE

Client: Amerada Hess Corporation
Location: **St. Croix Alumina**

Sampler Type: **2 Ft Split Spoon Sampler**
Inside Diameter: 2 **Inches**
Hammer Weight (LB): 100
Hammer Fall (IN): 24

Rig Type: **Hollow Stem Auger**
Bit Type: Barrel Two Prong
Total Depth: **30 Feet**

Drilling Co.: Caribbean Drilling Company
Driller: Ken Eastman
Geologist: Rex Meyer

Hole Diameter: **10 inches** Hole Overdrilled with 10" Auger

Screen Type: 0.01 Slot - 10'
Joints: Screw-Coupled
Diameter: 4"
Type: Fiberglass
Sand Type: Silica 20/30

Riser Type: Fiberglass
Joints: Screw-Coupled
Diameter: 4"
Type: Fiberglass
Stickup: 2.26 Feet

Location:
9,933.17 N 4,765.90 E
Ground Elevation 19.98'

DEPTH FROM GRADE (FT)	SAMPLE INTERVALS & RECOVERY RATES	OVM Levels (ppm)	Hammer Blows (To Go 6")	Pocket Penetrometer (Tons/Ft²)	WELL CONSTRUCTION	Matrix Munsell Color	LITHOLOGIC DESCRIPTION (Feet Below Surface Grade)
+3, +2, +1, 0					Elevation of Top of Casing (TOC): 22.24 ' msl		
1, 2, 3, 4, 5	90% Recovery	(Cement/Bentonite Grout) 0	6/14/8/10	2.25		Silty Clay	**Silty Clay** - 7.5 YR 6/6 *with some Limestone Fragments* *Clay is Plastic*
6, 7, 8, 9, 10	100% Recovery for 5.5"	0	78 for 5.5"	NA			**Weathered Limestone**
11, 12, 13, 14, 15	80% Recovery	(Bentonite Pellets) 4.8	36/30/32/22	N/A			*Damp at 14'*
16, 17, 18, 19, 20	85% Recovery	(20/30 Silica Sand) 6.2	36/70 for 5"	N/A			*Static @ 17.76* *Core Sample Saturated @ 20'*
21, 22, 23, 24, 25							
26, 27, 28, 29, 30							**Very hard Limestone with Marl**
31, 32							

2' stickup 20.9' TD Well

150 yards west south west of VW 31

Lithologic Log

Client
Project Name
Project Number
Project Manager
Drilling Co.

Boring # VW-34
Method/Dia.
Date Started 2/5/03 WEDNESDAY
Date Completed 2/5/03
Total Depth 20 → TD well 26'

Depth in Feet	Description	Sample #	Type	OVA Value	Stain	Odor
4	7½ YR (6/6) Reddish Yellow 7½ YR (5/8) Strong Brn Silty Clay - Plastic PP - 2¼ T/Ft²	6/4/8/10		0	N	N
8	Caliche @ 8'					
10	Weathered Limestone - wash 2½" Size	78/6" NFA		—	N	N
12						
15	Dry - Not Sat.	36/30/32/22		4.8		
16						
20	STATIC 18.4' SATURATED @ 20'	36/70+	NFA	6.2		
24	VW 34 @ 20' @ 9:51					
28	Very HARD - Limestone Rock in Hole					
30	Boring T.D					
32	Re-Ream @ 1¹⁵ ↑					
36	SAND 20/30 6½ Bags					
40						
44						

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

330' → (X) ← 86' → (X) VW 22 Water 14 Stickup 2' Ray & Ken

VW 35

30 gallon heavy film on Water in Drum

Lithologic Log

Overcast + Drizzle in morning ⇒ 70+ ⇒ windy wind

Started @ 9:30

Client: SCA
Project Name: PBH Dol
Project Number:
Project Manager: Rex Meyer
Drilling Co.: Caribbean Drilling
Ken Eastman

Boring #: VW 35
Method/Dia.:
Date Started: 2/3/03 Monday
Date Completed: 2/4/03 Tuesday
Total Depth: 68 1/2'

1ST 6 1/2" Hollow Stem Auger

Depth in Feet	Description	Sample # (Blow Count)	Type	OVA Value	Stain	Odor
	Clayey Silt LT. Reddish Brn 2 1/2 YR 6/3	5/9/12	13	B/6" 70%	No	None
4	White (Whiter than Munsell) Highly Weathered Chalky White Limestone No Consolidation					
5 SS						
8						
10	White SAs A with Limestone Rock Chert	15/15/37	/24	-%		
	Some Iron Deposits @ 9 1/2' 2" LT RLB Silty Clay					
12						
15	Damp (PP @ 2T/Ft²) Reddish Yellow (Clay) 7 1/2 YR 7/6 (25%) (75 ⇒ Calcite)	7/14/10/11		80%		
16	B = Plastic Most 1/2" with Int. Drip Clay → Calcite - white to gray calc on chert					
20	30% More Clay (PP @ 2T/Ft²) 5YR 6/6 70% Calcite >2" Rock	6/11/11/11		85%		10 52
24	(PP @ 2T/Ft²) 40% Clay More Clay Same as above Same Calcite (60%)	9/9/9/10		95%		11 01
28	C LS 40/60% Same	5/6/9/10		65%		@ 11 22
32	@ 35' Void 2" — Drop @ Void					
33'	1st - 12" Same as above Inst 12" More Limestone	4/6/4/11		60%		@ 11 39
36	Weathered Limestone @ 35' 95% Limestone 5% Clay					
40	= 1" RB Clay @ 39 1/2	14/18/8/18		55%		@ 11 50
44	Back to Same as 30' except clay 5YR 6/4	5/4/11/7		65%		@ 12 05

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

From 13° to 4[17] Back to Depth

Pulled Casing

Rock Locked.

12' of Pipe Still Down Hole

Pulled remainder

So going back with Screw Auger

@ 2[42] pm

Pulled 12' of Pipe.

Hole ok

Outside @ 5[24] pm

T.D. 68 1/2'

Pulled Back to 63 1/2'

Thup ▶ 69'2 - 7' =

Btm Screen @ 62'2"

@ 63 BSG

10' SS Screen

60' Fiberglass Riser

2-30' Joint

Cut ___ ' off

Stickup from Grade

Sand in Standard Sand & Silica Co

6 By 20/30

Lithologic Log

Client
Project Name
Project Number
Project Manager
Drilling Co.

Boring # VW 35 Continued
Method/Dia.
Date Started
Date Completed
Total Depth 68½ – Well @ 62'2"

@ 12:10

Depth in Feet	Description	Sample #	Type	OVA Value	Stain	Odor
46	OVM @ 44 = 0.0				No	No
	Weathered Limestone					
50	OVM = 0.0 42/26/24/22			85%		
	6' Clay & Limestone Mix / The last 6' – Limestone Chert					
51	← Limestone + Clay in Pour spoon → 18/14/16/16			80%		
53						
54	OVM 54 6/8/13/16			Continuous	@ 43	
55	SS Clay & Chalk with Stain	VAPOR Sample	Zone	49 55'	@ 55' HC Odor	
Limit 57						
58	10/6/14/10 SATURATED @ 55¼ Film on water			90%		
60	HARD Limestone					
62	2/4/03					
	Drill to 64' – 10" Augers					
65						
66	@ 9:05 Broke overdrill Bit @ 45' → 6'-6" HS recovered					
	Recovered – New Bit added					
	Going Back @ 9:25 am					
70						
	2/6/03 – 61.7' PSH Film					
74	TD – 69.5' No Clinc Sand					
75						
78						
80						
82						
85						
86						

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

99-10

Tuesday

2^{30} to 4^{30}

Augur Decon
@ Tankwash Pad

TD: 59.4'
STickup 2.8'

Lithologic Log

West side of Red Mud Pit Northern most TWO

Client
Project Name
Project Number
Project Manager
Drilling Co.

Boring # VW 36
Method/Dia.
Date Started 2/7/03 Friday @900 am
Date Completed
Total Depth

Depth in Feet	Description	Sample #	Type	OVM ~~OVA~~ Value	Stain	Odor
4	Fill Limestone / Caliche weathered limestone & Caliche Dry	12/12/64 - 4"		0.2	25% No	No
8		10/16/18/16		0.2	90% No	No
12		22/54 - NFA 4"		0.4	90	
16	Caliche with increasing Clay 10R 3/6 10% clay 40% clay	22/34/40/44		0.3	100	
24		70/4 inches		0.2	100	
28	26½ – 29½ = 3' weathered Limestone Hard Caliche 30% Clay	52/50 - 4 NFA		0.4 ppm	100	
32	Color change to 7½ YR reddish yellow Note Red is still Present 6/6 SAME	25/22/16/25		0.0 ppm	100	
36	Increasing Increasing Clay Do green	55/4 inches		0.0 ppm	100%	
40	@ 40 – 75%					
44	silt Tan Caliche Clay	16/15/51/16		0.0 ppm	100%	

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

Lithologic Log

Client
Project Name
Project Number
Project Manager
Drilling Co.

Boring # VW 36 Continued
Method/Dia.
Date Started 2/7/03 @
Date Completed
Total Depth 60

0.9 ppm

Depth in Feet	Description	Sample #	Type	~~OVA~~ PID Value	Stain	Odor
46	saturated @ 47' } Coarse Limestones sand up Limestone hard 1"	to 1/2	Limestone chips			
48		50/14/44/50	NEA 1"		↑	
50					cleed	
54	screen 55'45"					
55						
56½	SD 56½'					
58	cut 1' off stick up 3½' 6½'	69				
60						
62						
65						
66	60					
70						
74	Bentonite Seal 44½'					
75	51.3					
78						
80	56½					
82						
85	Purged 42 gallons 2/8/03					
86	We then started Cleaning @ 25 gallons all sediments out.					

VW 36 @ 46½ to 47'
@ 1:35 pm 2/7/03

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

89-10

Stick up 2.02' ID - 60.25'

Develop 40 gall
No sediment
in well - Change 40 gal

WELL East of Red Bluff
Southern well

Lithologic Log

Client
Project Name
Project Number
Project Manager
Drilling Co.

Boring # VW 37
Method/Dia.
Date Started 2/5/03
Date Completed
Total Depth

Depth in Feet	Description	Sample #	Type	OVM ~~OVA~~ Value	Stain	Odor
	Red Brown Clay & Caliche - Fill 1½					
4	Caliche ↓ grading to White Weathered Limestone Dry	50 Blow	4"	0.0	No	No
8	Dry	60 B/4"		0.0	No	No
12	Dry	27/56		0.0		
16	Dry	16/14/39/26		0.0		
20						
24	Dry	70/1½"		0.1		
28	RIG Hydraulic Pipe Rebuilt @ 845 am 7/6/03 very Hard Limestone Damp	59/21/10/67		0.0 NA @ Lab	4"	Rig Break
32	Caliche 10YR 8/4 very Pale Brown to Yellow	7/10/13/50		0.0	No	No
36	10YR 8/5 Caliche 85% 15% Clay 10YR 7/4 Damp	2/8/2/16		0.0		
40	Dry					
44	Easy Drilling ↓ Decrease Clay Changing to White Weathered Limestone Caliche	27/15/41/50		0 + Lab	4"	
	Shell Frags @ 45' Dense Limestone weathered					

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

Lithologic Log

Client
Project Name
Project Number
Project Manager
Drilling Co.

Boring # VW-37 (Continued)
Method/Dia. Hollow Stem - Auger 10"
Date Started 2-5-03
Date Completed 2-6-03 @ 4:00 pm
Total Depth 59 - Btm Screen @ 57 1/2 - 2 Ft Stickup
PVC - 10 Screen 0.01

Depth in Feet	Description	Sample #	Type	OVA Value	Stain	Odor
46	weak clay / 47.6' / 10R - 3/6 - Dark Red to red 4/6	@ 46' softer - Caliche				
48	Red Brn Clay @ 48' - PP - 2 1/2 T/ft 4/6 3/6	clay @ 48'				
50	Caliche Saturated May Be Confined Dry on Top of Clay Wet under Clay					
54		VW-37 @ 49' - 50' @ 11:35				
55	Caliche with increase Clay Contents					
58	Bos					
60	Read to					
62	10' Screen PVC - PVC End Cap 6 Bags Sand 20/30 1 - 5 gal Bucket Bent Pellets.					
65						
66	STATIC 2/7/03 (Friday) 50.4	0		GW		
70		20				
74				50.4'		
75						
78						
80						
82						
85						
86						

GMS & ASSOCIATES

Type Sampler
SS = Split Spoon
ST = Shelby Tube

99-10

GeoMonitoring Services

4123 Fifth Street
Brookshire, Texas 77423

Completion Date: 5/21/07

WELL: VW-38

Location: Renaissance/SCA

Client: Hess
Location: **St Croix**
Elevation (toc) :
Lat/Long

Project Name:
Project Number:

Sampler Type: No Sampling
Inside Diameter:
Hammer Weight (LB): NA
Hammer Fall (IN): NA

Rig Type: Hollow Stem & Auger
Bit Type: Toothed Bit
Total Depth: 50'

Drilling Co.: Caribbean Drilling
Driller: Ken Eastman/Ray Tutein
Geologist: Rex Meyer

Hole Diameter: 9.5"

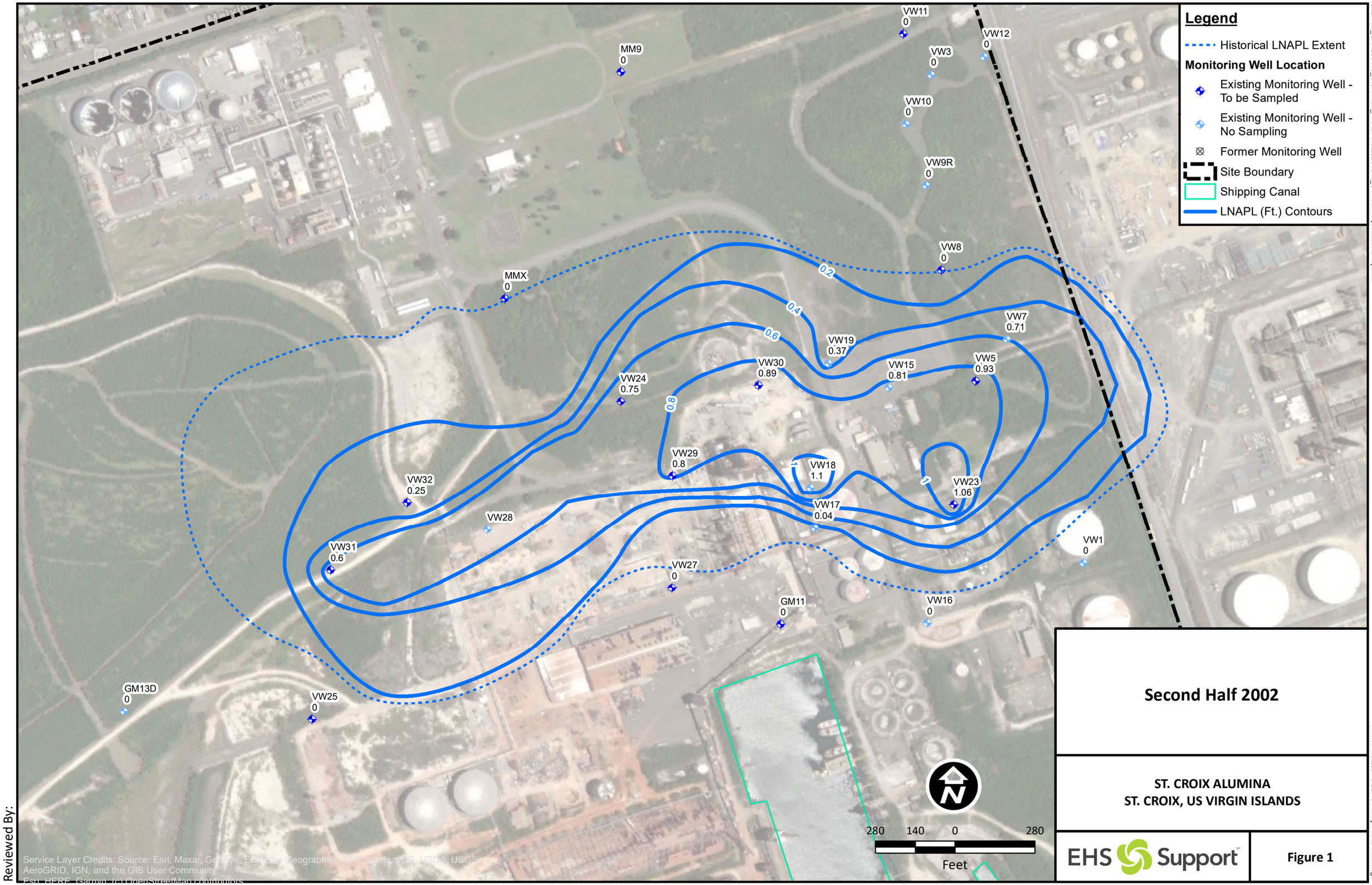
Screen Type: Stainless Steel - 20'
Joints: Screw-Coupled
Diameter: 6"
Screen: 0.01"
Sand Type: Silica Sand 00N 20/40

Riser Type: Star Fiberglass -28.5'
Joints: Screw-Coupled
Diameter: 6"
Type: Fiberglass
Stickup: 3' 1.5' Cut Off

Drilling Notations:

DEPTH FROM GRADE (FT)	SAMPLE DESIGNATION	Sample Core Composite	OVM Reading (ppm)	WELL CONSTRUCTION	**Matrix** Munsell Color	**Decription**
+3						
+2						
+1						
0						
1						**4 to 6 inches of Concrete**
2					*10 YR 8/2*	**Iron Rich Soft Limestone**
3					*White*	
4		(Cement/Bentonite Grout) ---------				
5						
6						**Same**
7						
8						
9						
10						
11						**Same**
12						
13						
14						
15		Bentonite Chips				
16						**Same**
17						
18						
19						
20						
21						**More White & Harder Limestone**
22						
23						
24						
25						
26						
27						
28						
29						
30						
31						
32						Saturated
33		(Sand Pack)				
34						*Static - Oil @ 34.61' & Water @ 35.04'*
35						Less cutting return
36						*No Cuttings - suggest void*
37						
38						
39						
40						
41						
42						
43						
44						
45						**Soft Limestone**
46						45.5' BOW
47						
48				*Boring Collapsed*		
49						
50						**Hard Limestone**
51						TD 50' - No Cutting Returns
52						
53						

Appendix B1 LNAPL Thickness Maps



Second Half 2002

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 1

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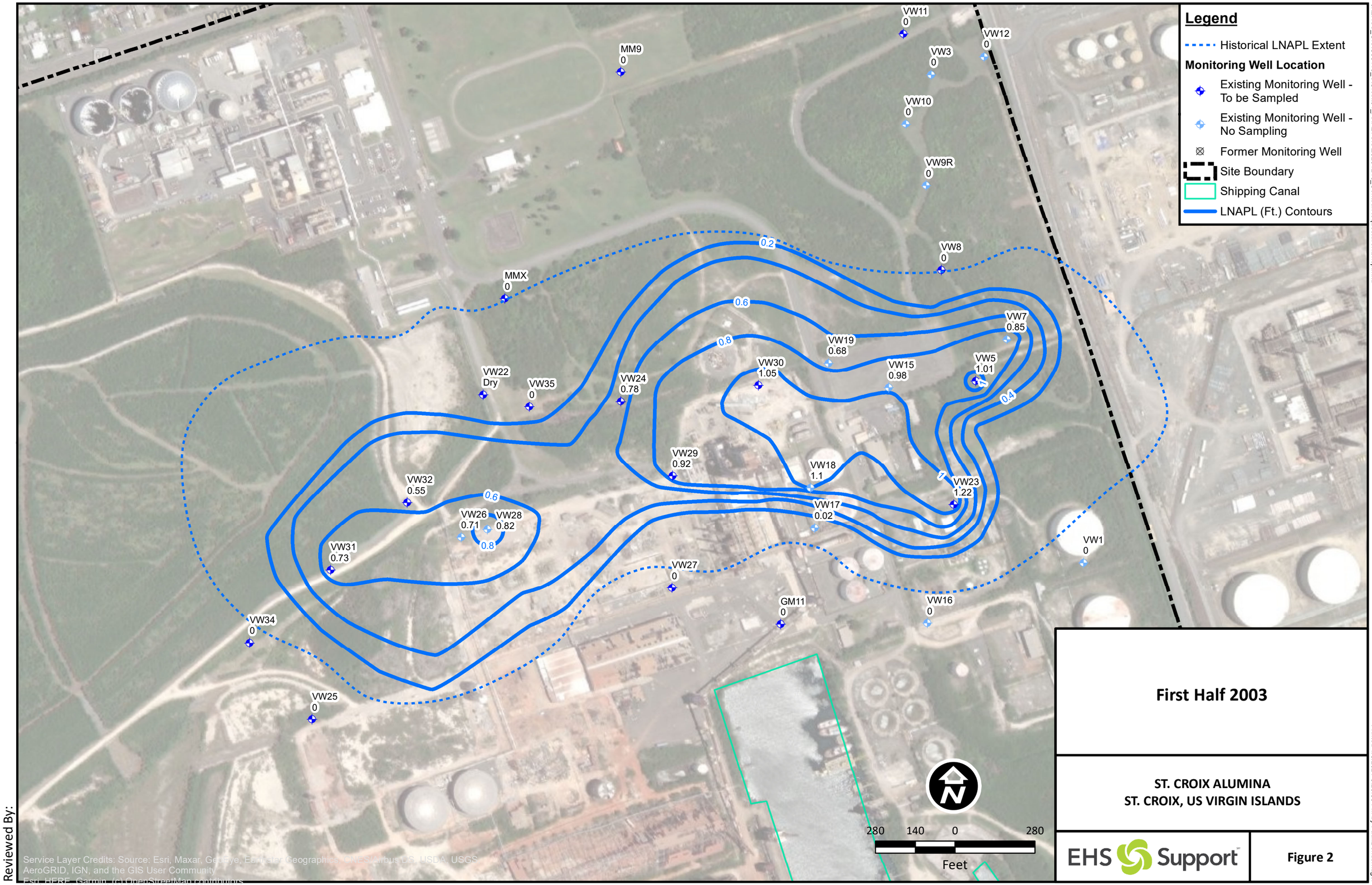

First Half 2003

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

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Figure 2

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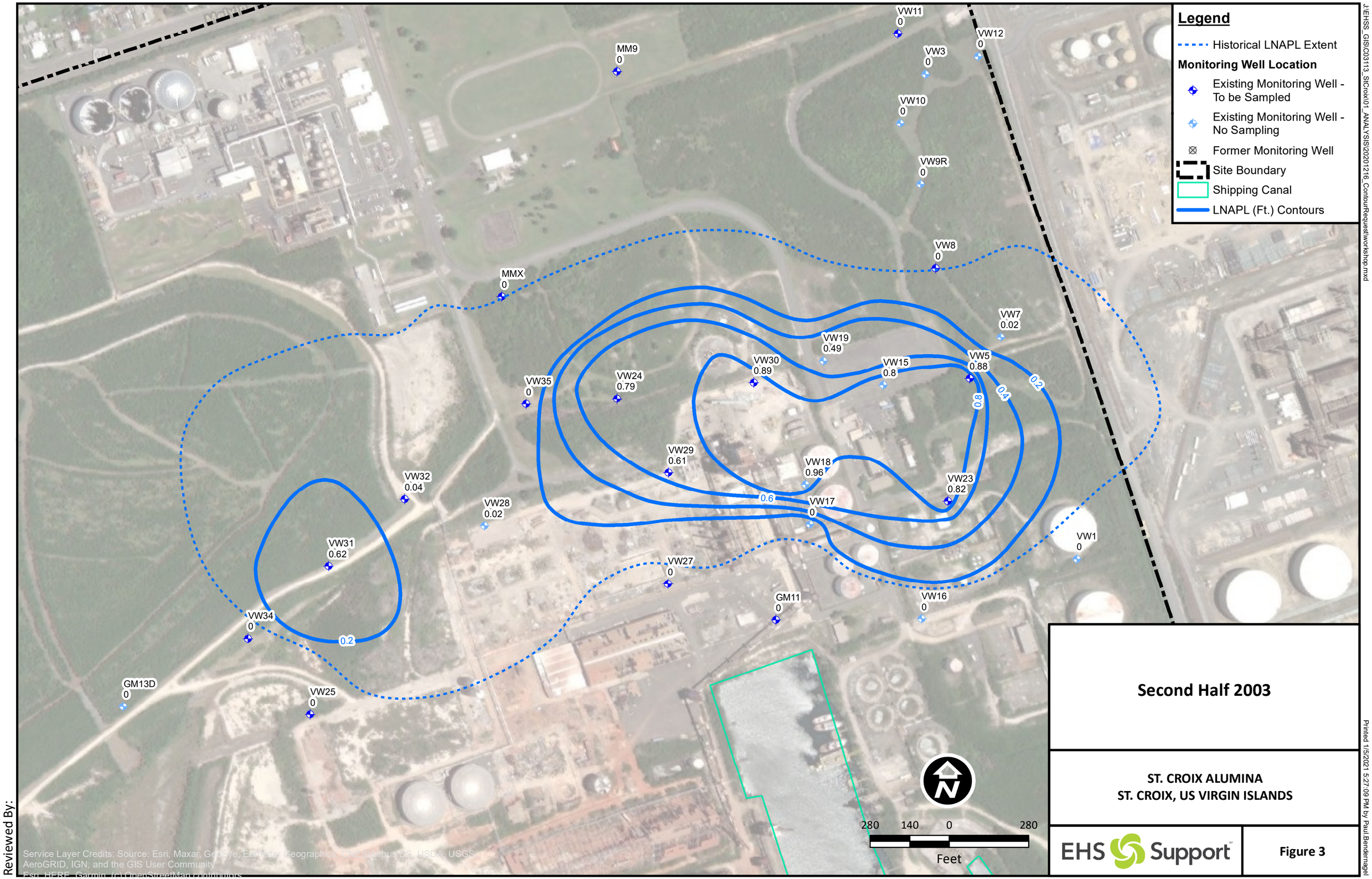

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Second Half 2003

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 3

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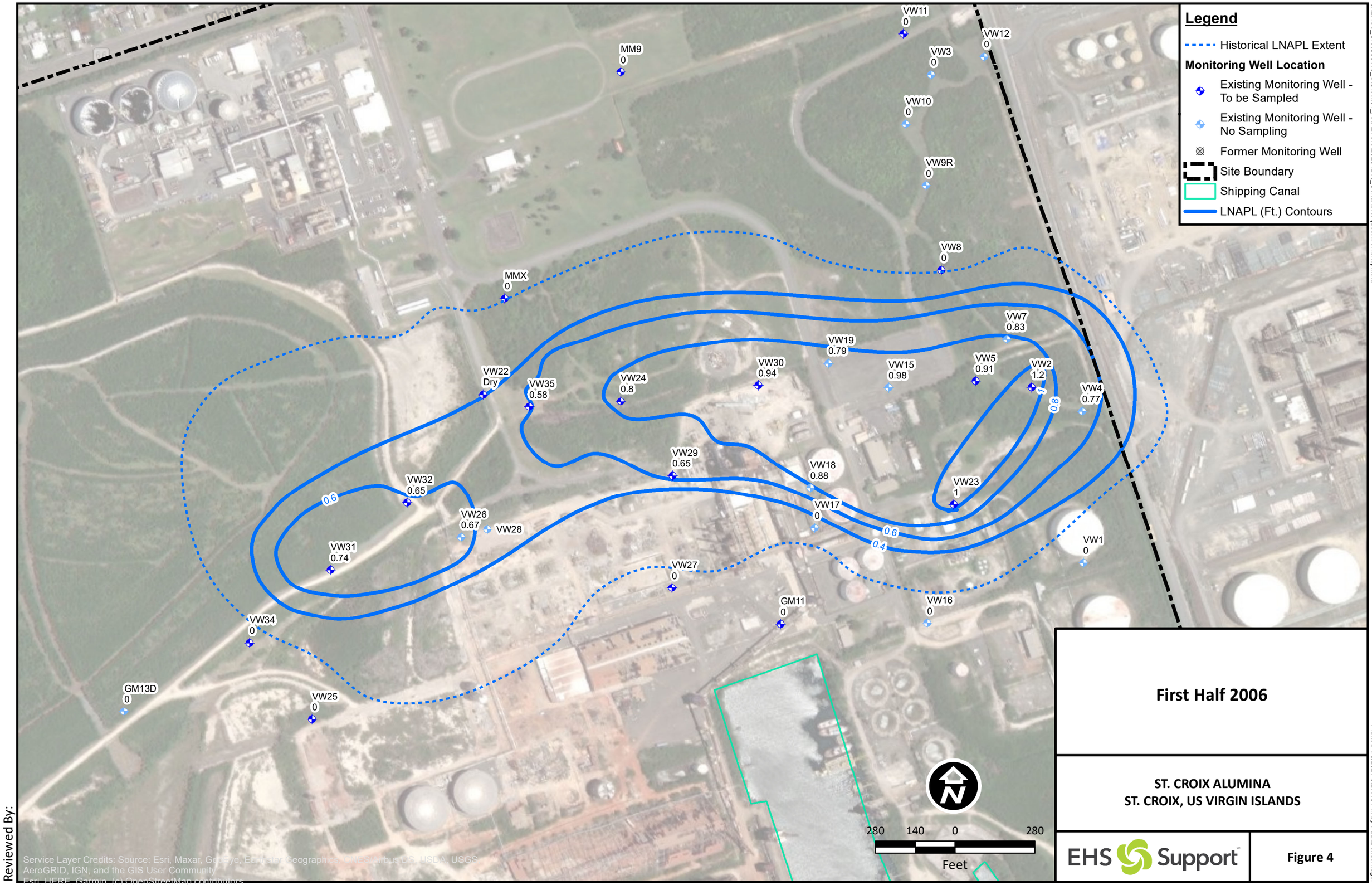

First Half 2006

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

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Figure 4

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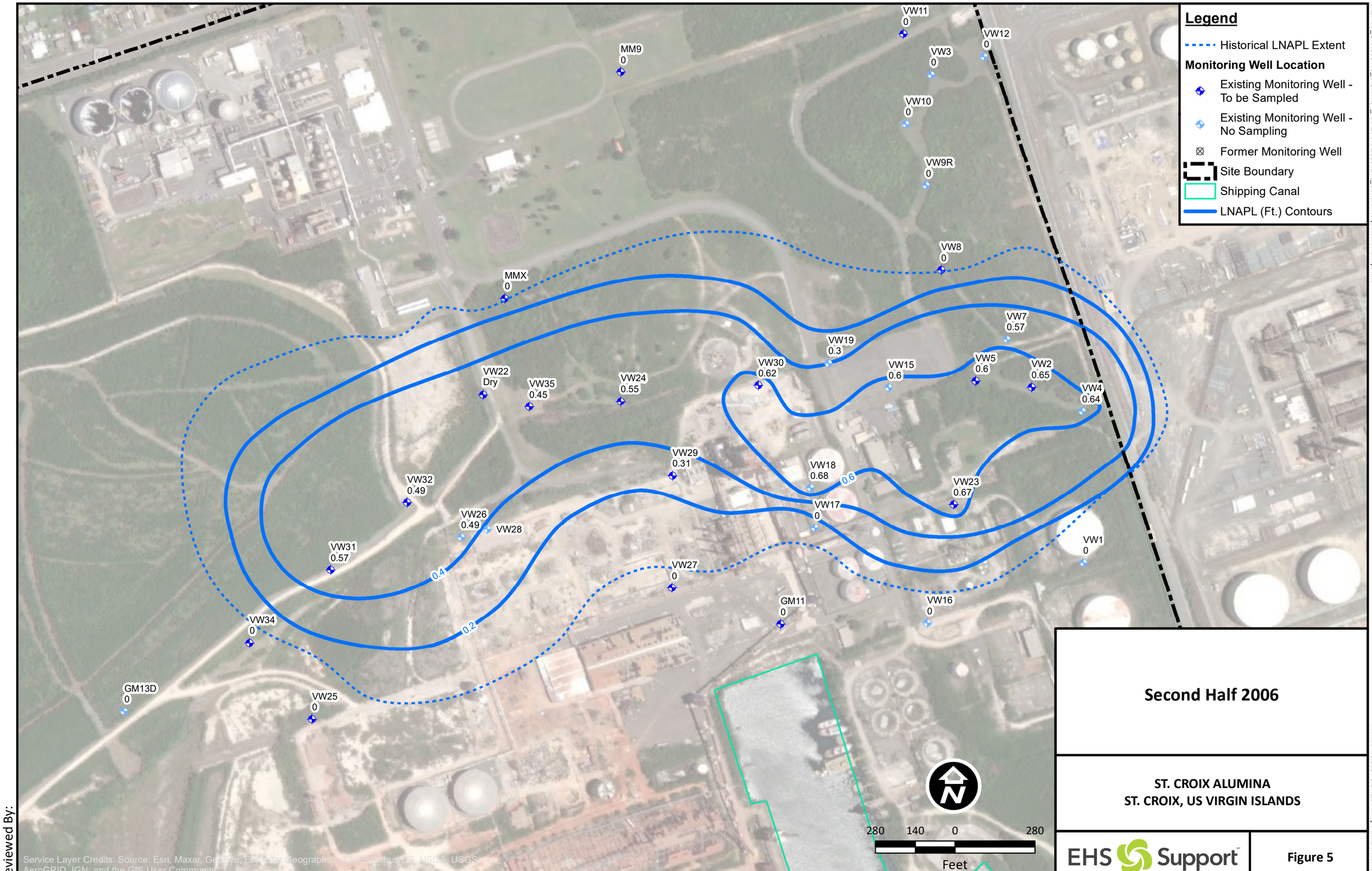

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Second Half 2006

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 5

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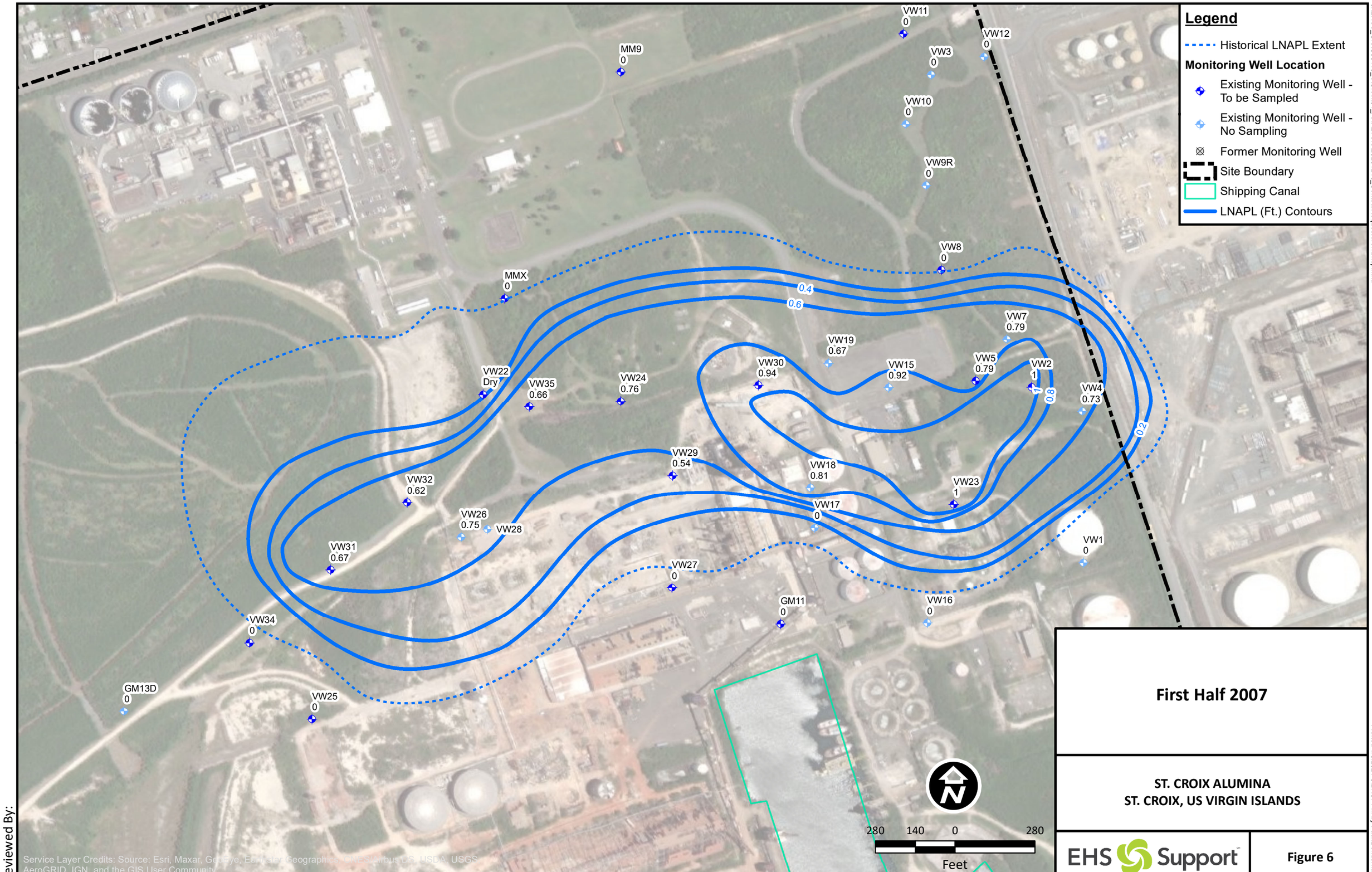

First Half 2007

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 6

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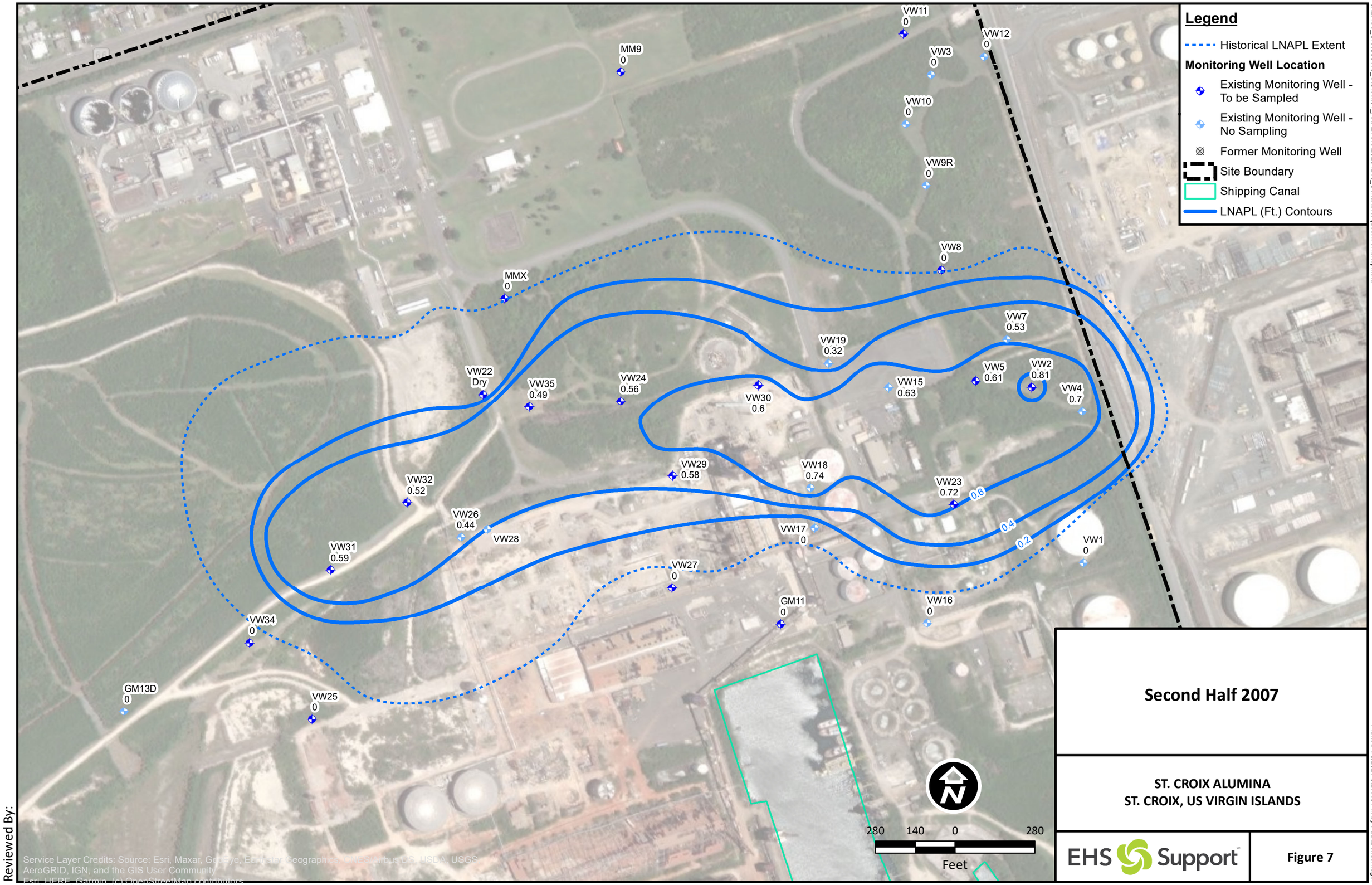

Second Half 2007

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 7

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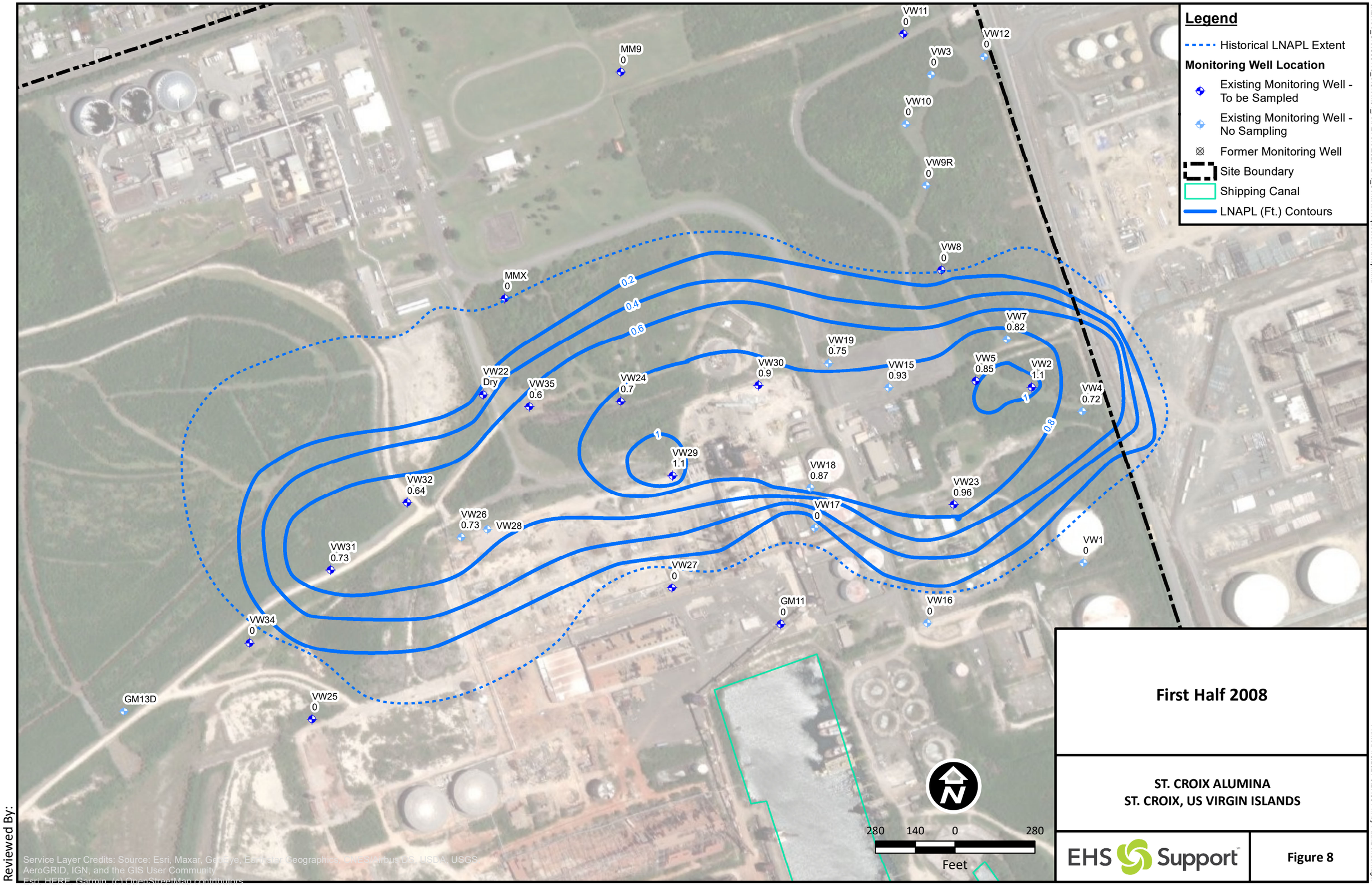

First Half 2008

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

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Figure 8

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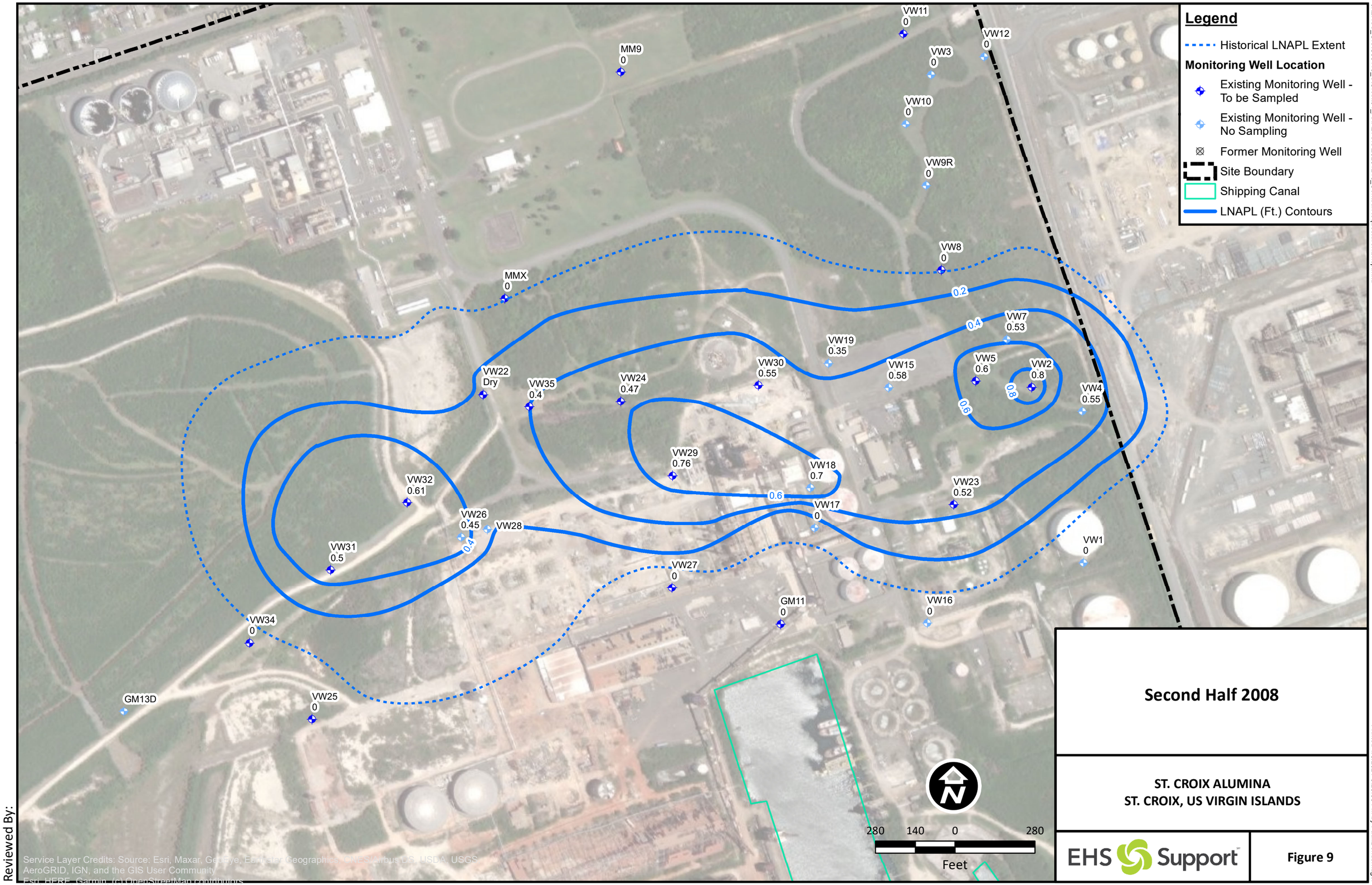

Second Half 2008

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

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Figure 9

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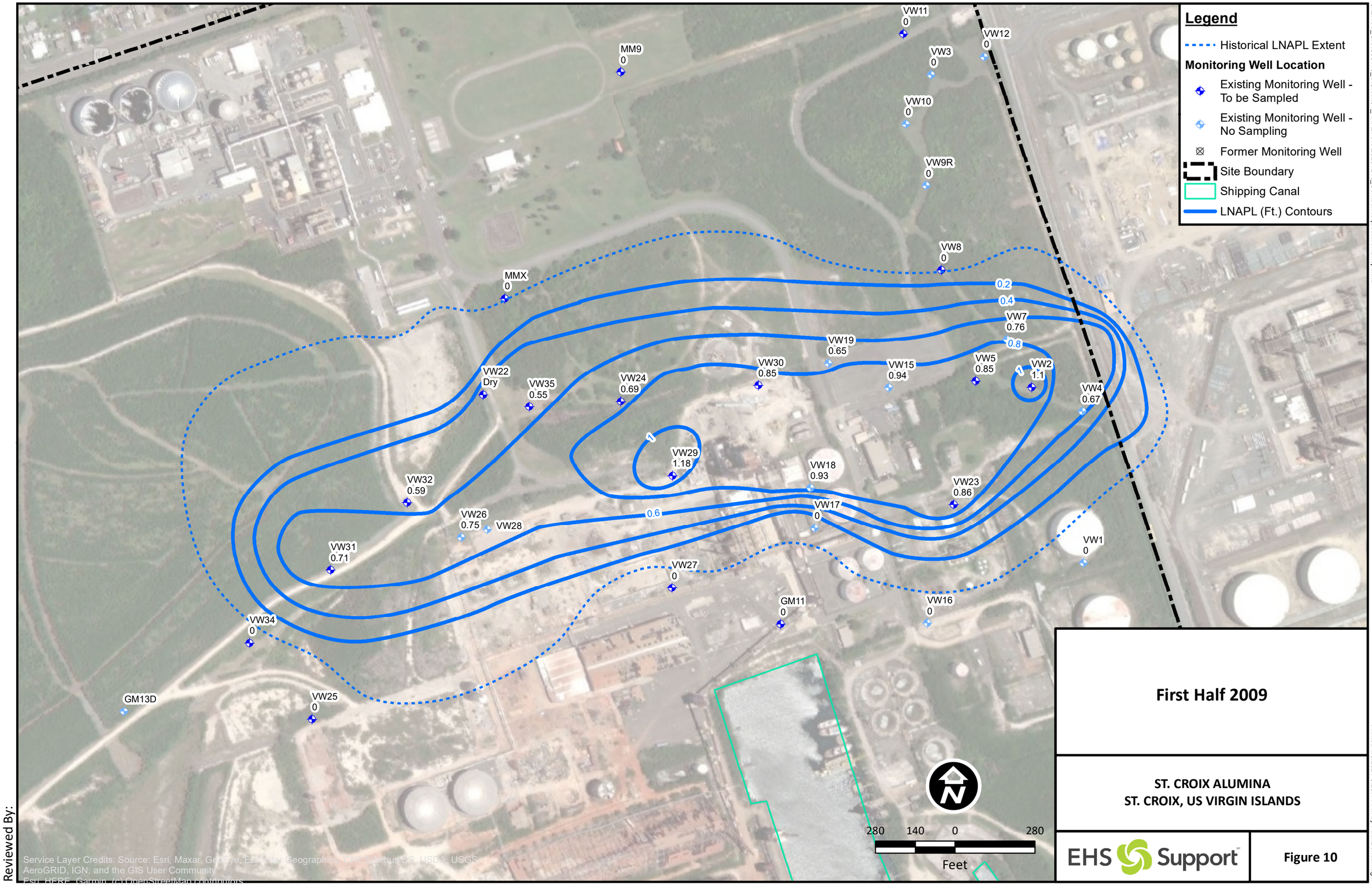

First Half 2009

ST. CROIX ALUMINA
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Figure 10

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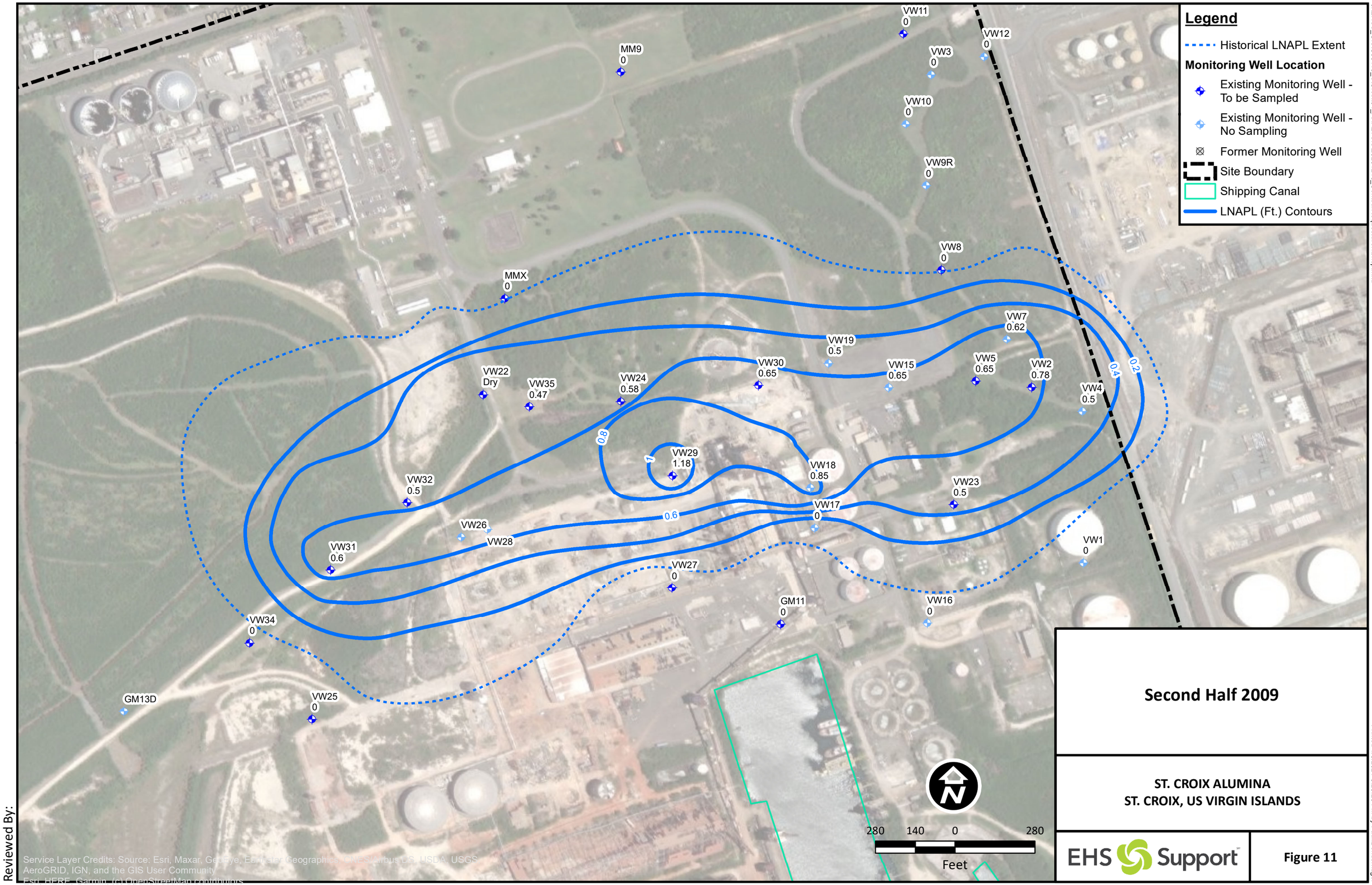

Second Half 2009

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

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Figure 11

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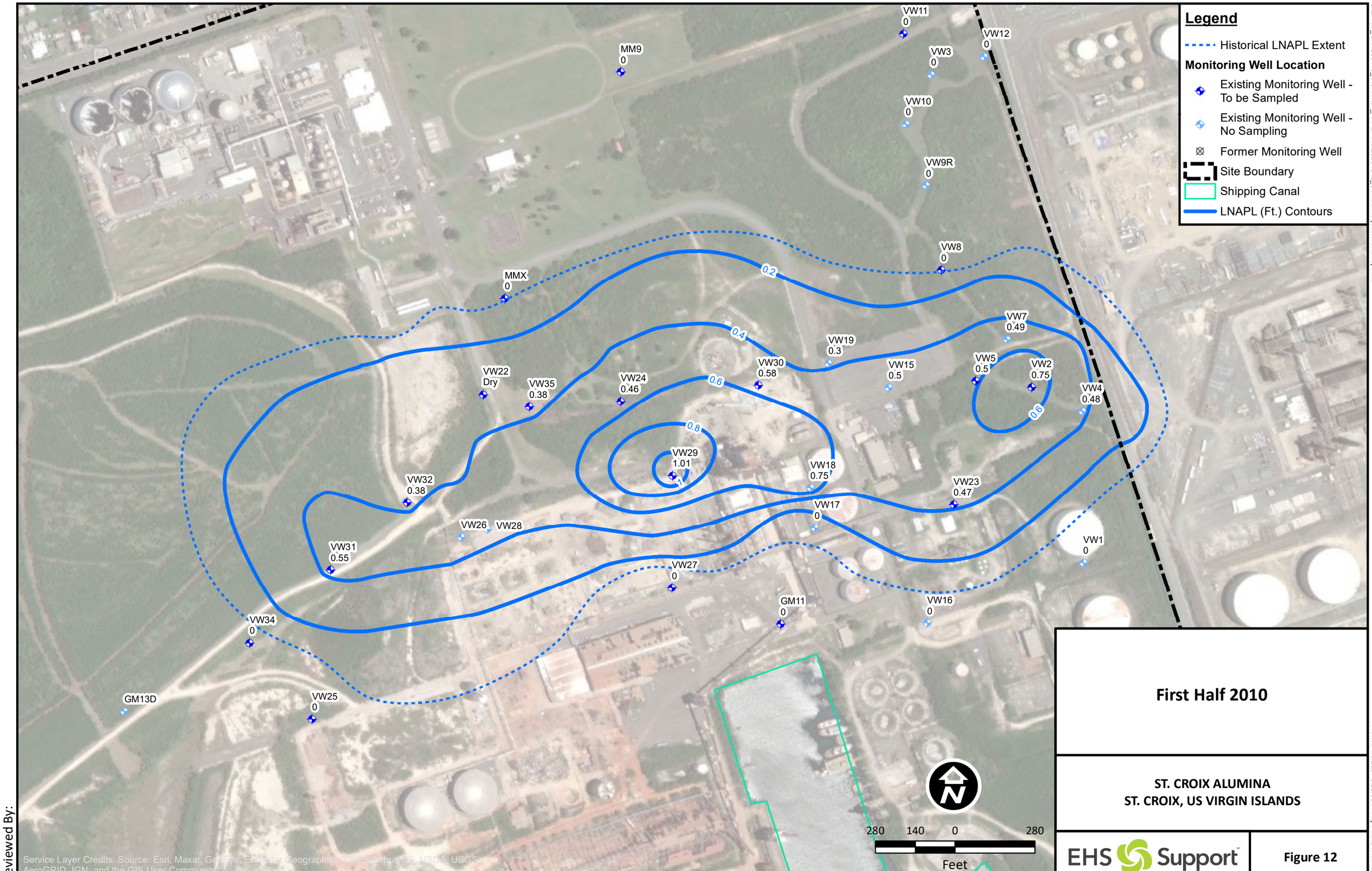

First Half 2010

ST. CROIX ALUMINA
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Figure 12

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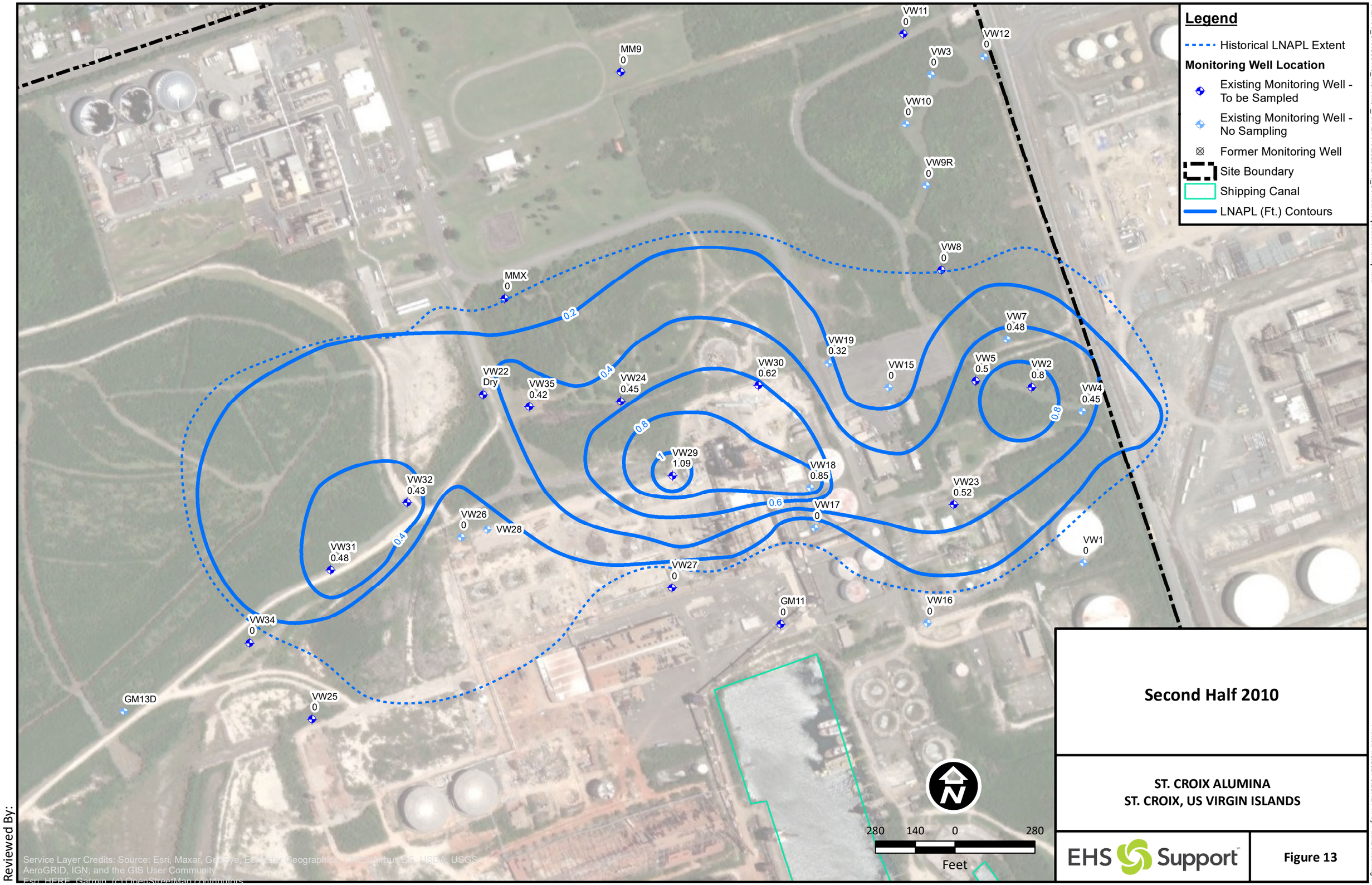
Legend
Historical LNAPL Extent
Monitoring Well Location
Existing Monitoring Well - To be Sampled
Existing Monitoring Well - No Sampling
Former Monitoring Well
Site Boundary
Shipping Canal
LNAPL (Ft.) Contours
MM9 0
VW11 0
VW12 0
VW3 0
VW10 0
VW9R 0
VW8 0
MMX 0
VW7 0.48
VW19 0.32
VW15 0
VW5 0.5
VW2 0.8
VW4 0.45
VW22 Dry
VW35 0.42
VW24 0.45
VW30 0.62
VW29 1.09
VW18 0.85
VW17 0
VW23 0.52
VW32 0.43
VW26 0
VW28
VW31 0.48
VW27 0
VW1 0
GM11 0
VW16 0
VW34 0
GM13D
VW25 0
0.2
0.4
0.6
0.8
1
280 140 0 280
Feet
N
Second Half 2010
ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS
EHS Support
Figure 13
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Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
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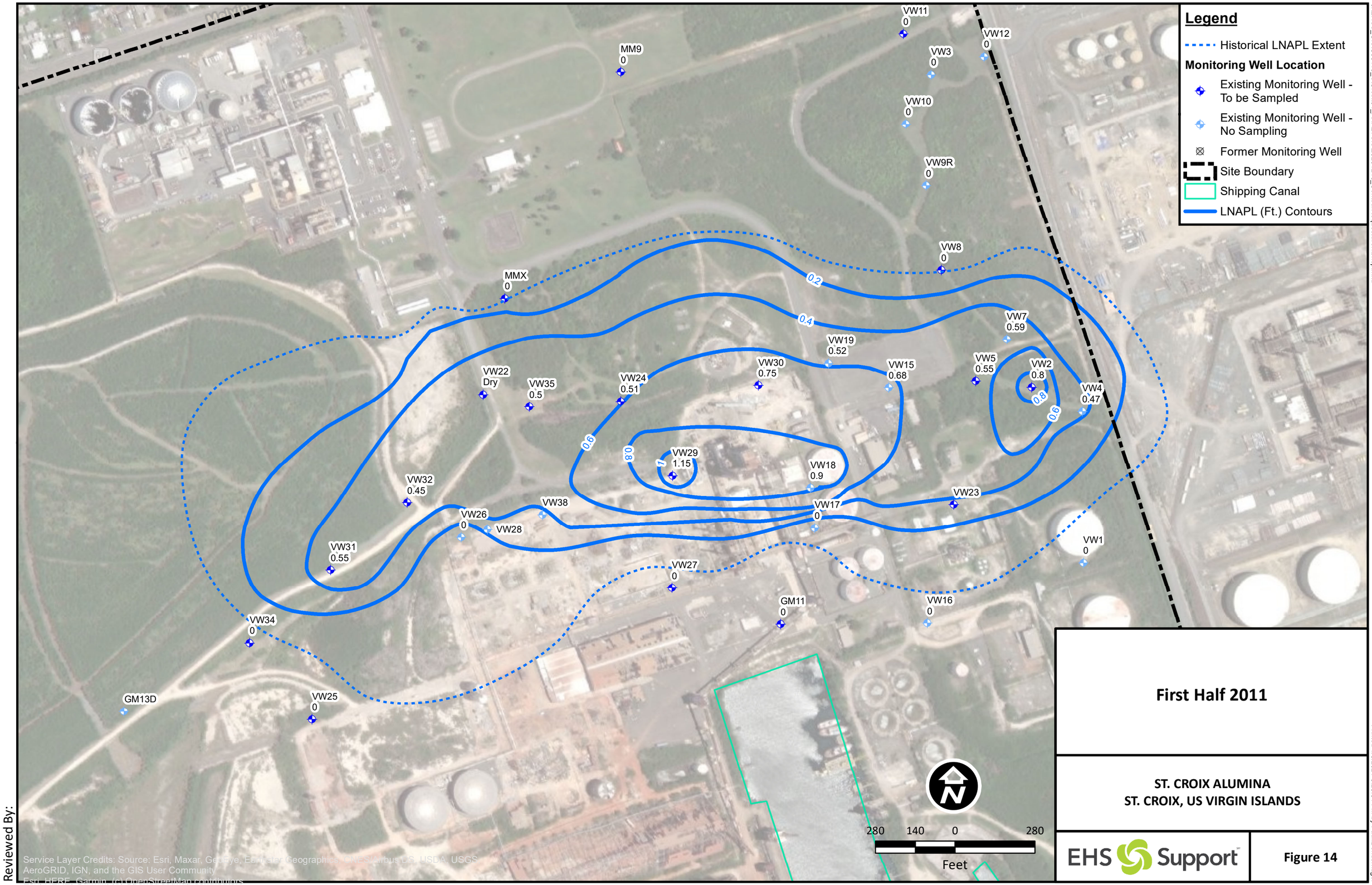

First Half 2011

ST. CROIX ALUMINA
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Figure 14

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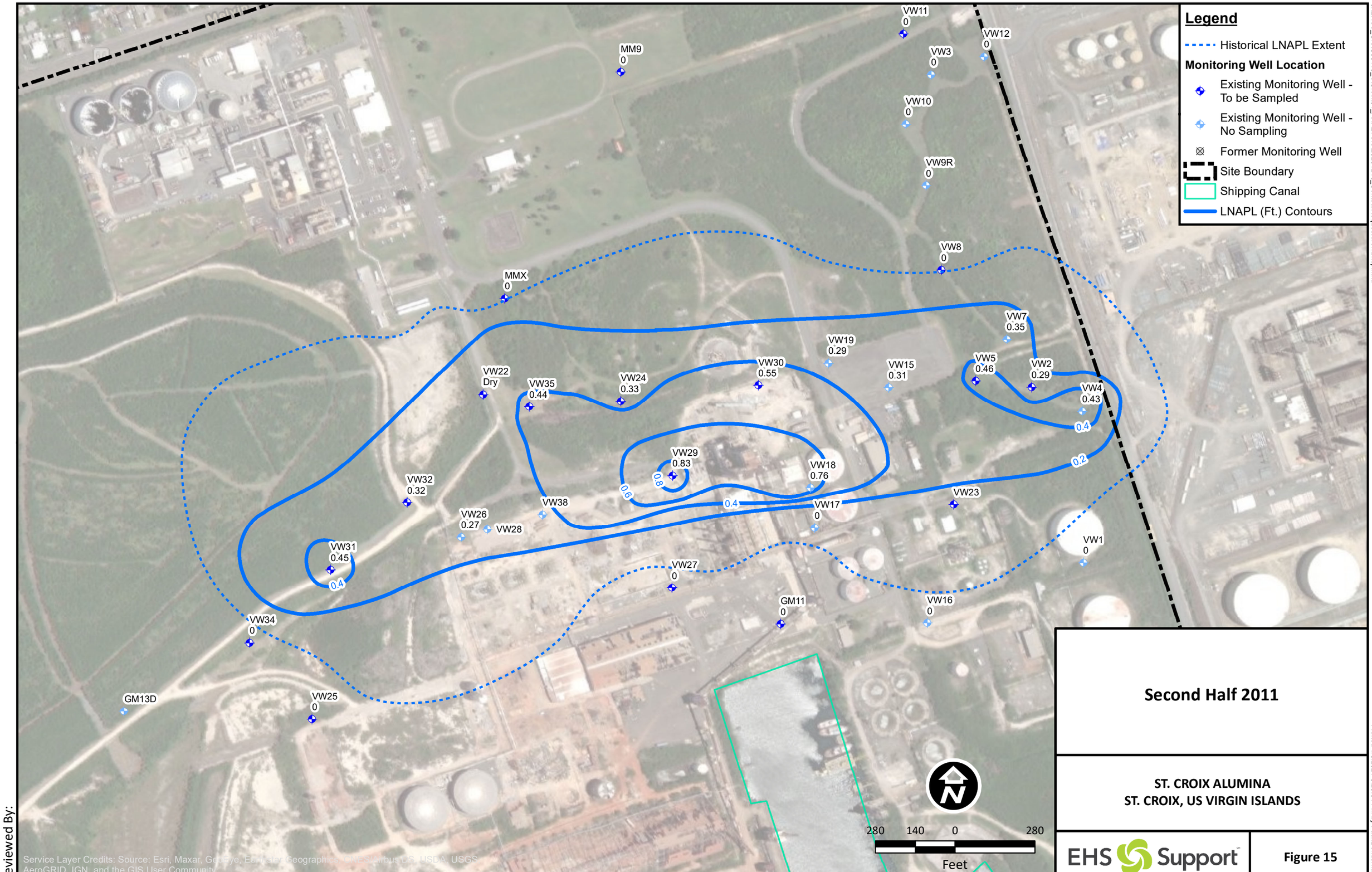

Second Half 2011

ST. CROIX ALUMINA
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Figure 15

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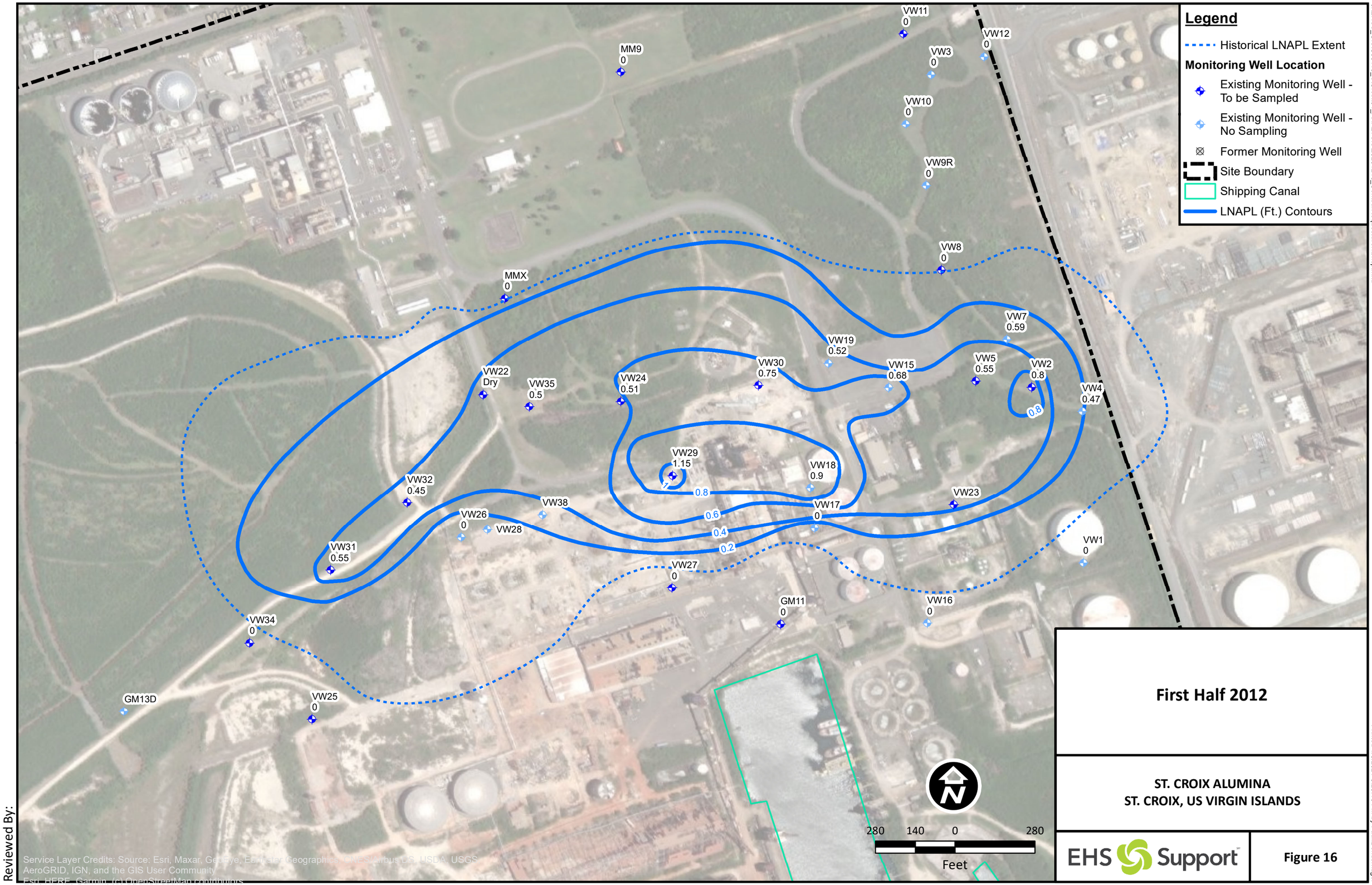

First Half 2012

ST. CROIX ALUMINA
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EHS Support

Figure 16

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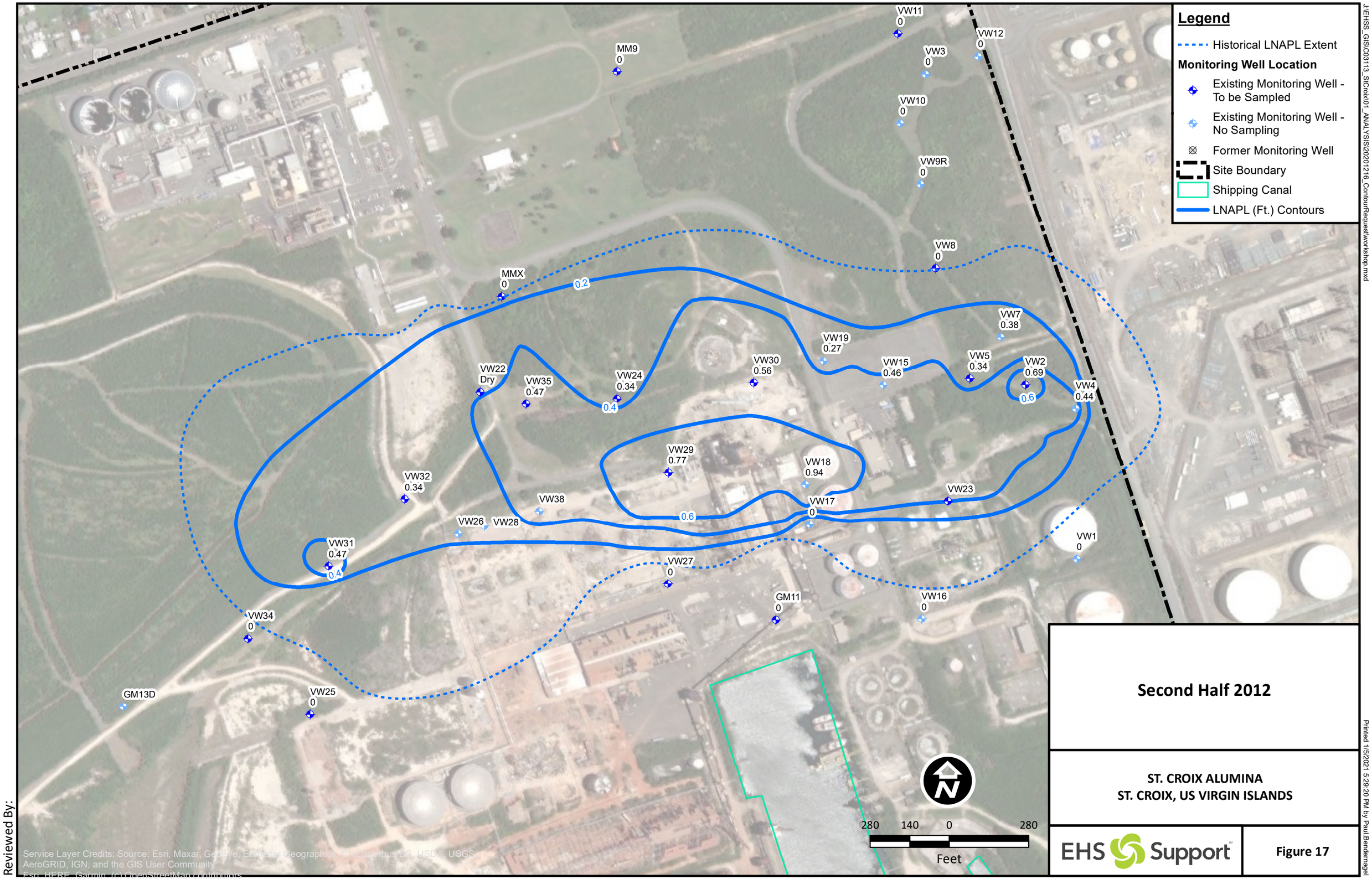

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Second Half 2012

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Figure 17

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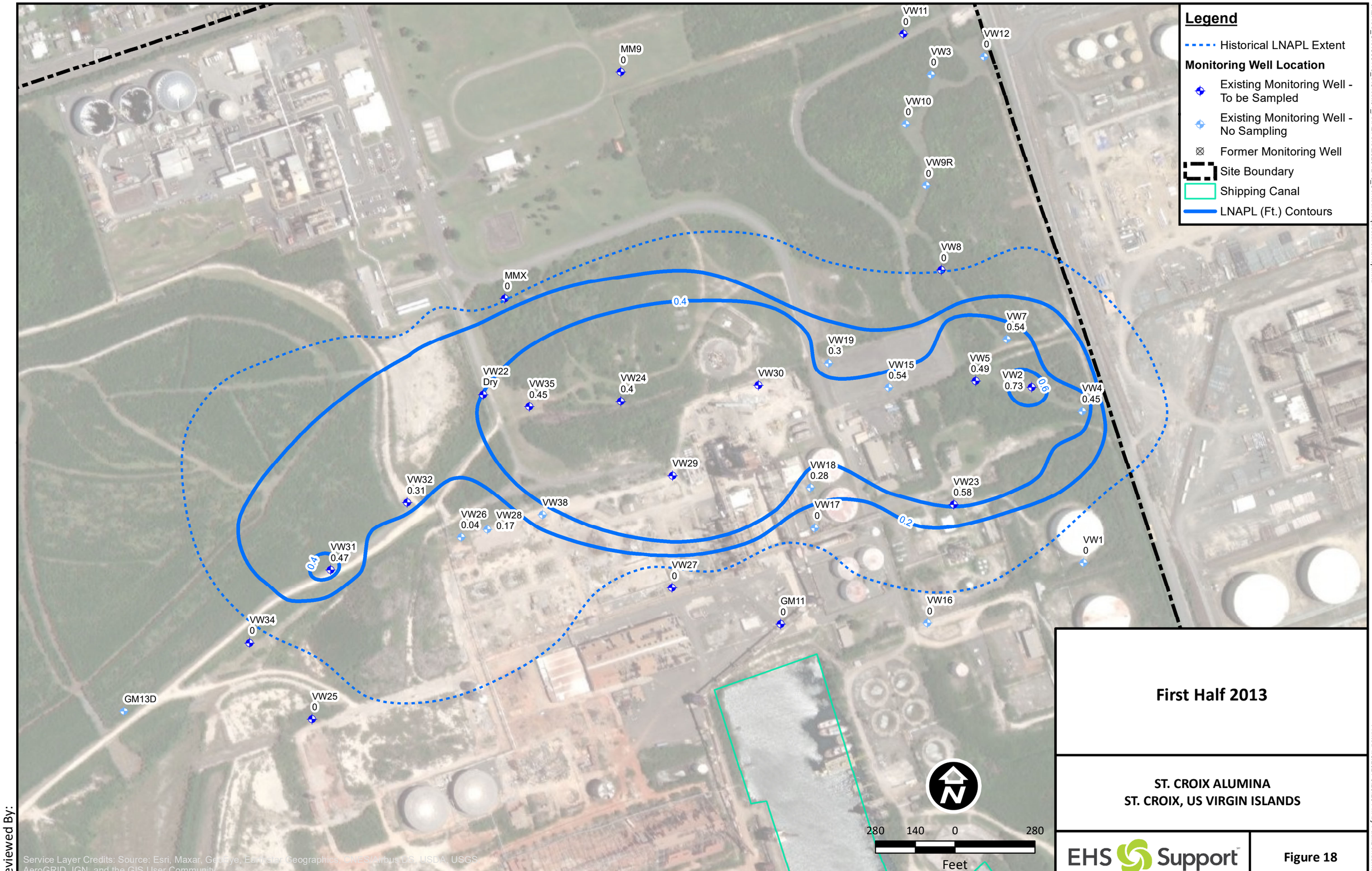

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First Half 2013

ST. CROIX ALUMINA
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Figure 18

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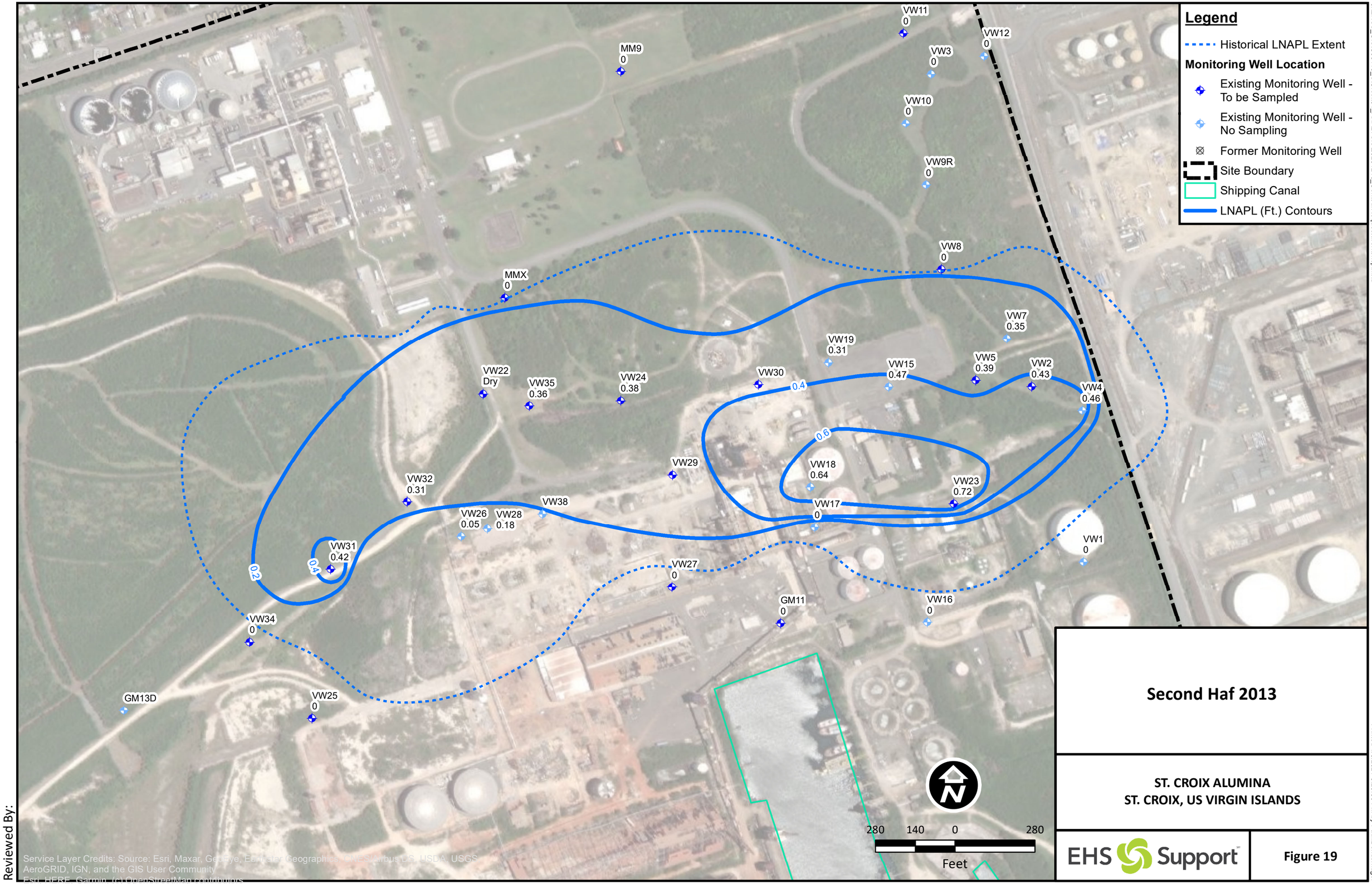

Second Haf 2013

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 19

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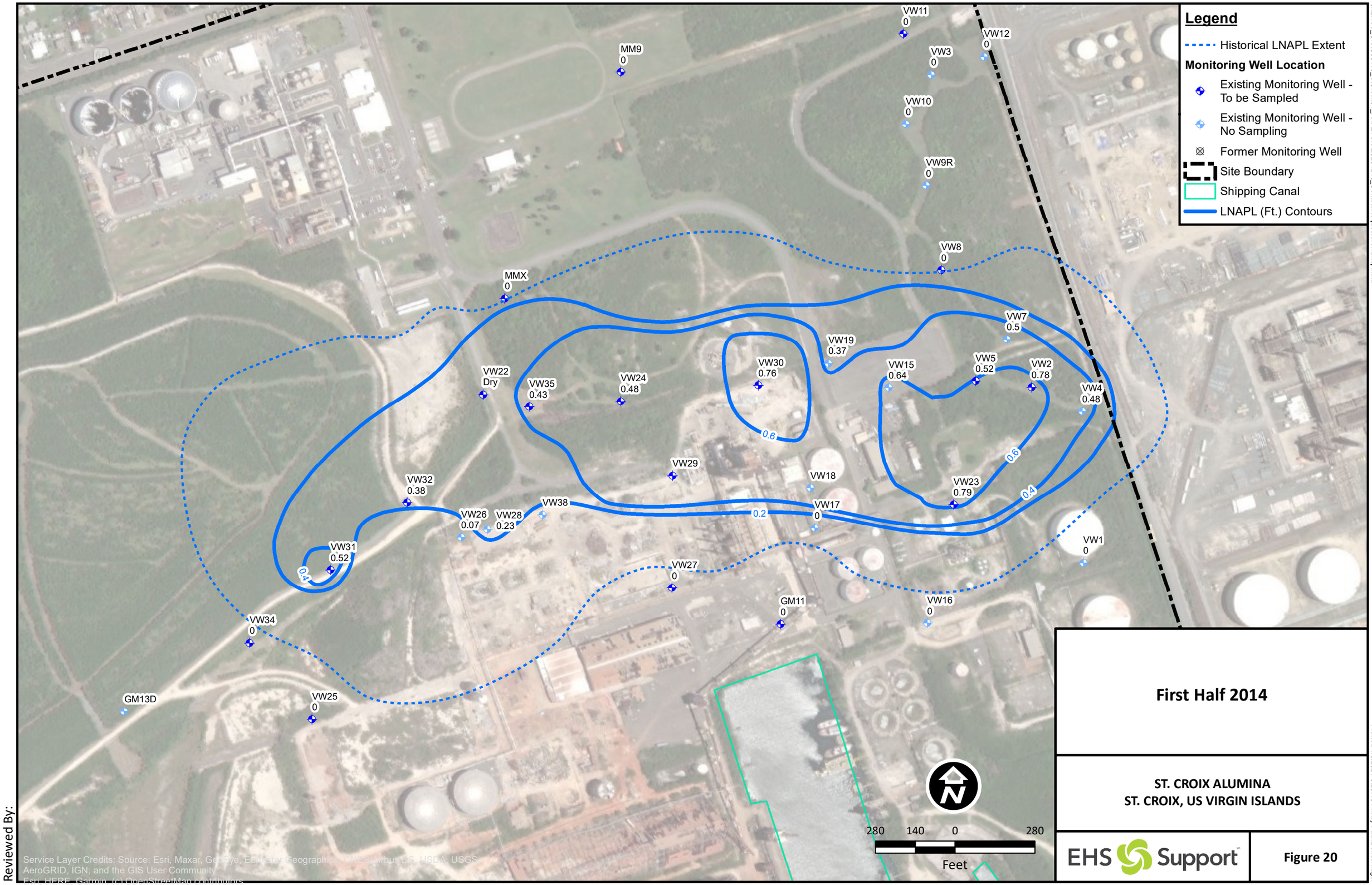

First Half 2014

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 20

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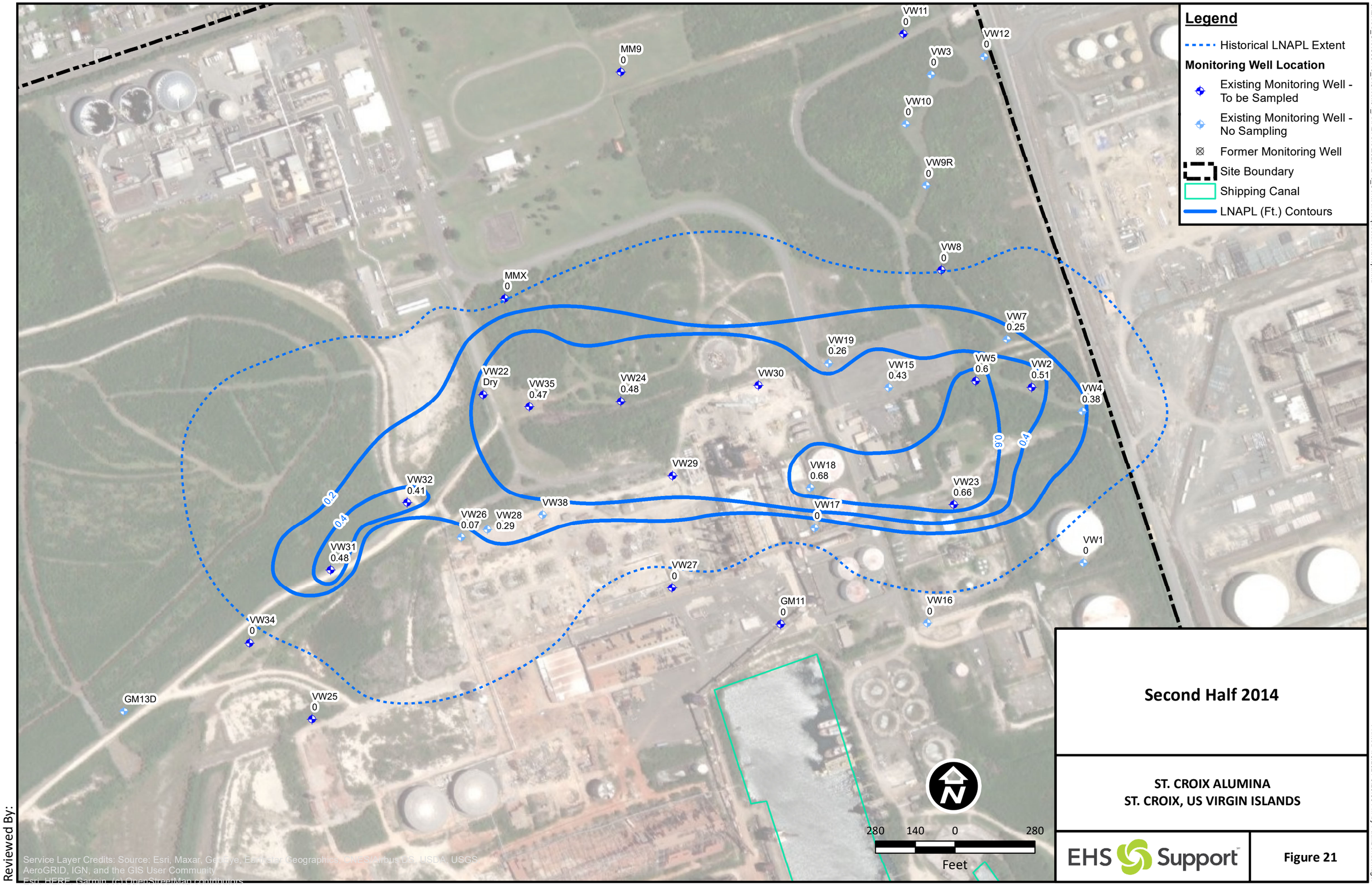
Legend
Historical LNAPL Extent
Monitoring Well Location
Existing Monitoring Well - To be Sampled
Existing Monitoring Well - No Sampling
Former Monitoring Well
Site Boundary
Shipping Canal
LNAPL (Ft.) Contours
VW11 0
VW12 0
MM9 0
VW3 0
VW10 0
VW9R 0
VW8 0
MMX 0
VW7 0.25
VW19 0.26
VW5 0.6
VW2 0.51
VW15 0.43
VW4 0.38
VW22 Dry
VW35 0.47
VW24 0.48
VW30
VW29
VW18 0.68
VW23 0.66
VW32 0.41
VW38
VW17 0
VW26 0.07
VW28 0.29
VW31 0.48
VW1 0
VW27 0
GM11 0
VW16 0
VW34 0
GM13D
VW25 0
0.2
0.4
0.6
0.4
280 140 0 280
Feet
Second Half 2014
ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS
EHS Support
Figure 21
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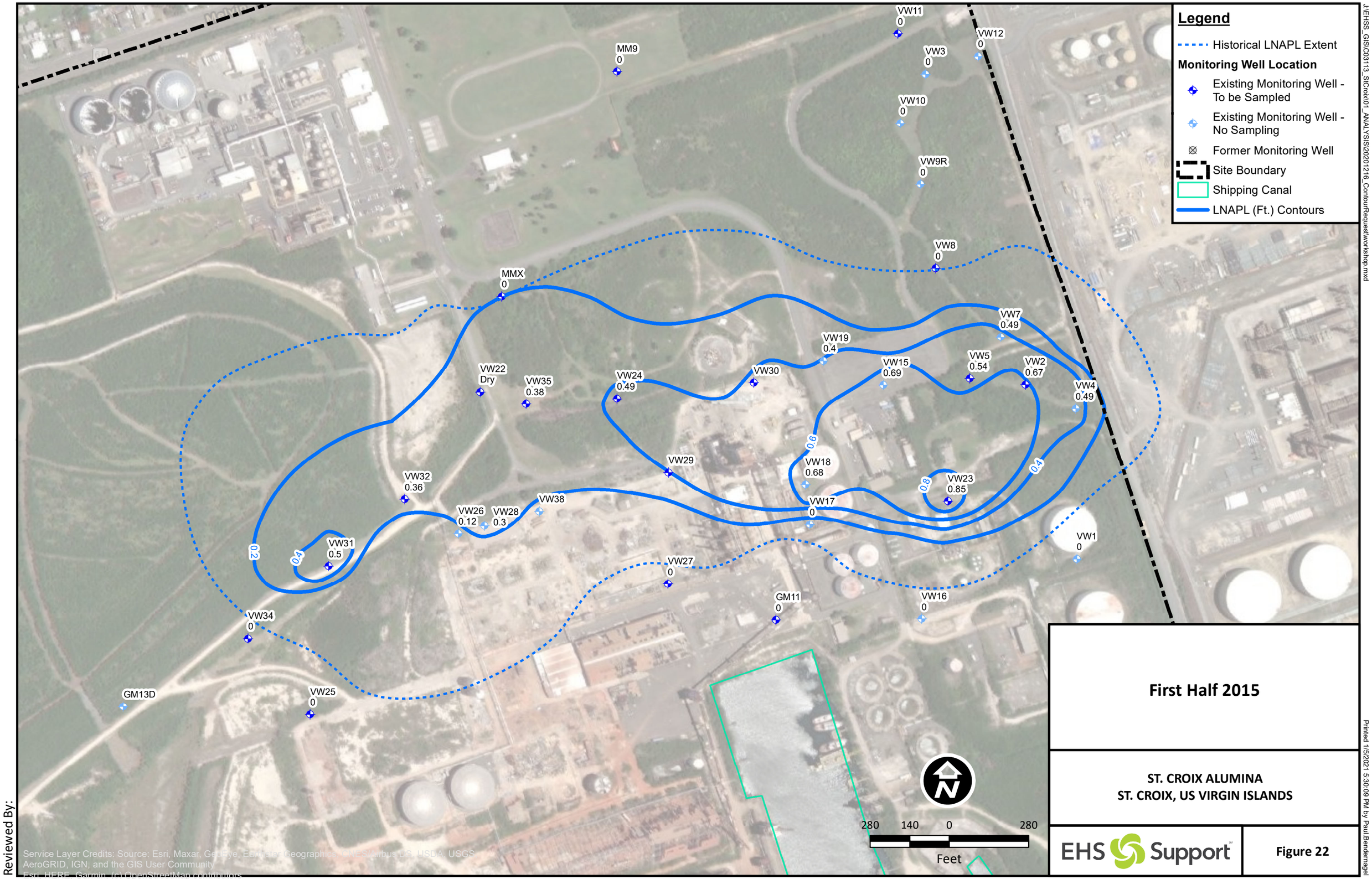

First Half 2015

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

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Figure 22

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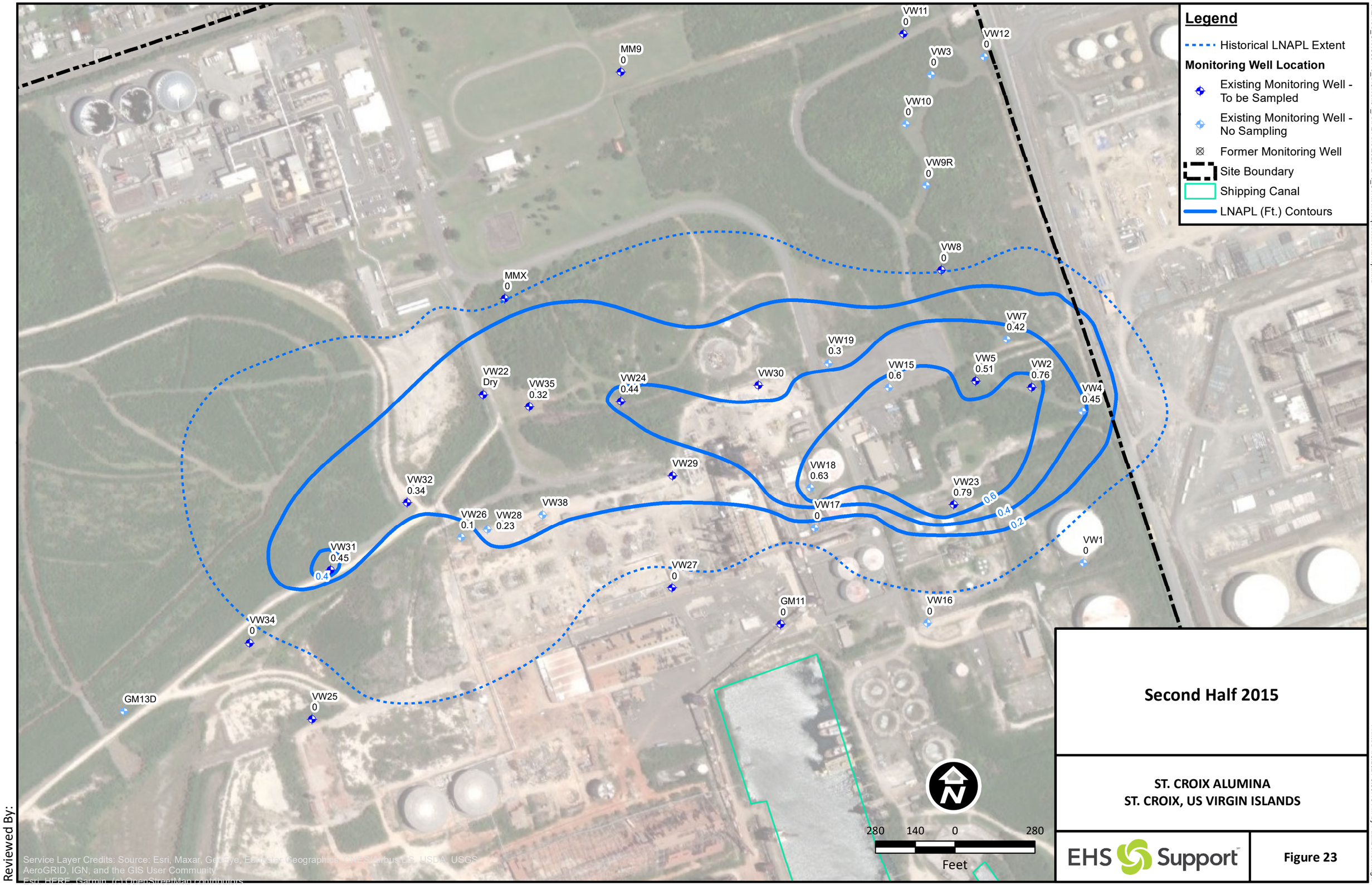

Second Half 2015

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 23

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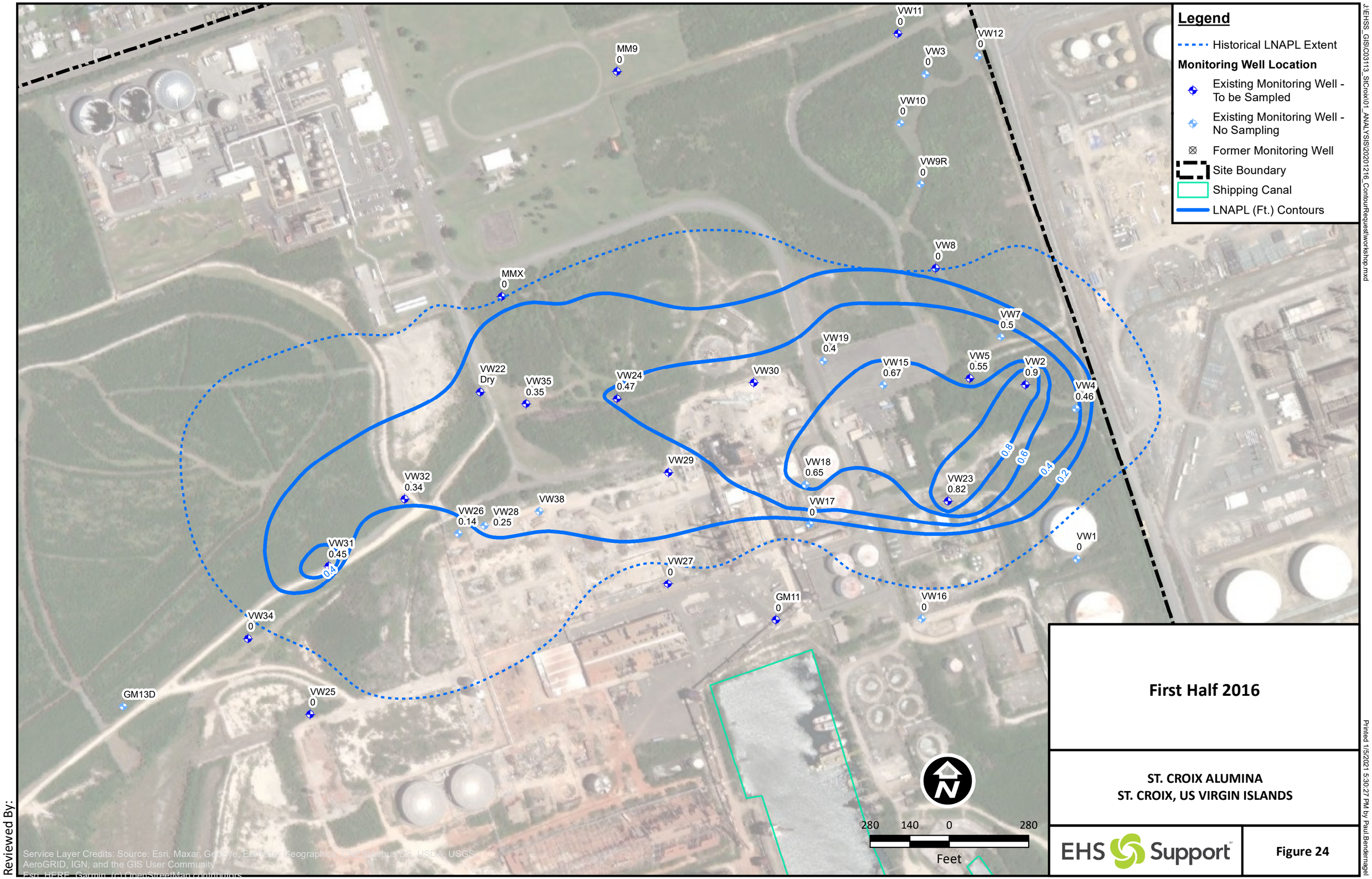

First Half 2016

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 24

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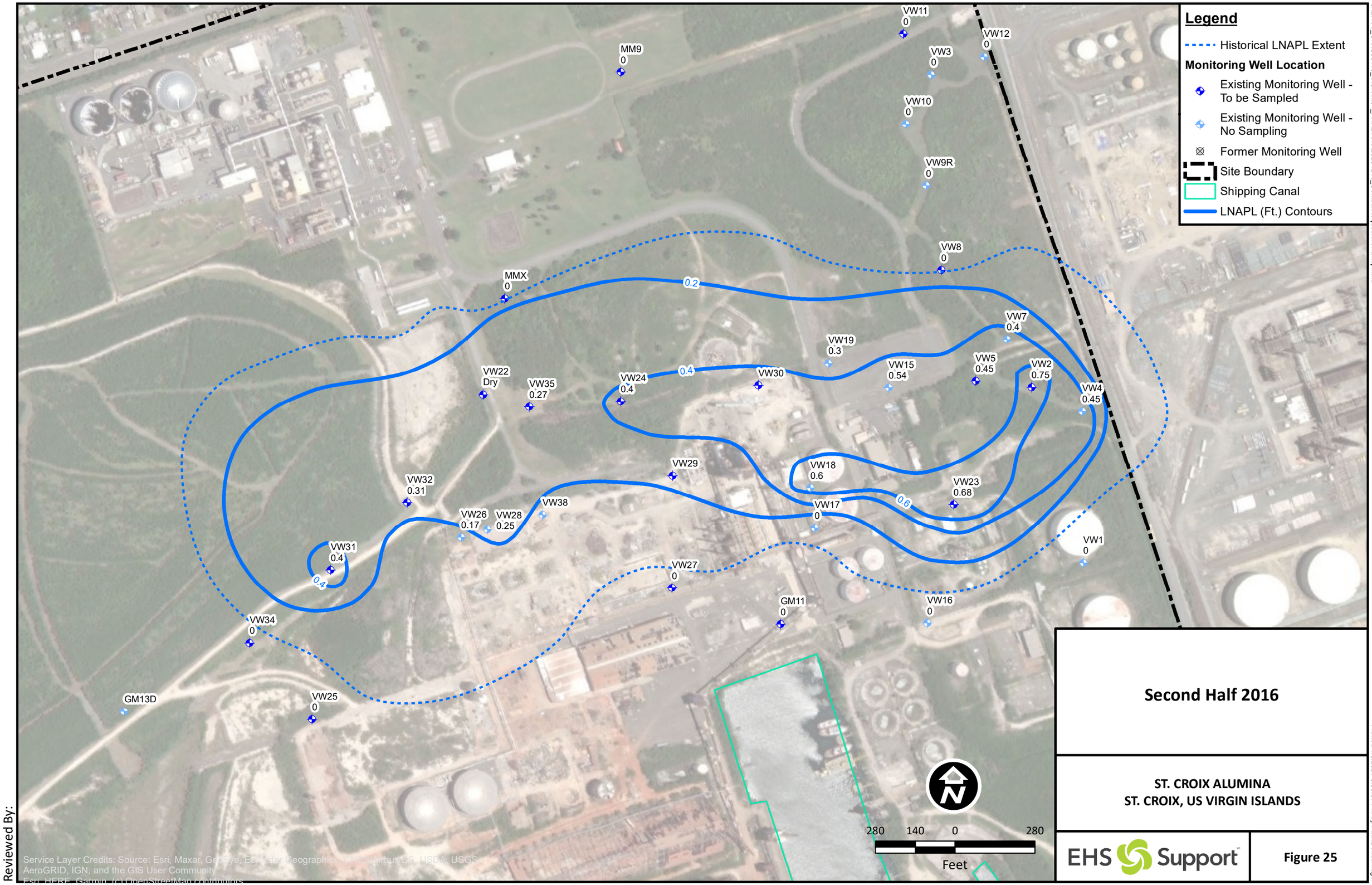
Legend
Historical LNAPL Extent
Monitoring Well Location
Existing Monitoring Well - To be Sampled
Existing Monitoring Well - No Sampling
Former Monitoring Well
Site Boundary
Shipping Canal
LNAPL (Ft.) Contours
VW11 0
VW12 0
MM9 0
VW3 0
VW10 0
VW9R 0
VW8 0
MMX 0
0.2
VW7 0.4
VW19 0.3
VW15 0.54
VW5 0.45
VW2 0.75
VW4 0.45
VW22 Dry
VW35 0.27
VW24 0.4
0.4
VW30
VW29
VW18 0.6
VW23 0.68
VW32 0.31
VW38
VW26 0.17
VW28 0.25
VW17 0
0.6
VW1 0
VW31 0.4
0.4
VW27 0
GM11 0
VW16 0
VW34 0
GM13D
VW25 0
280 140 0 280
Feet
Second Half 2016
ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS
EHS Support
Figure 25
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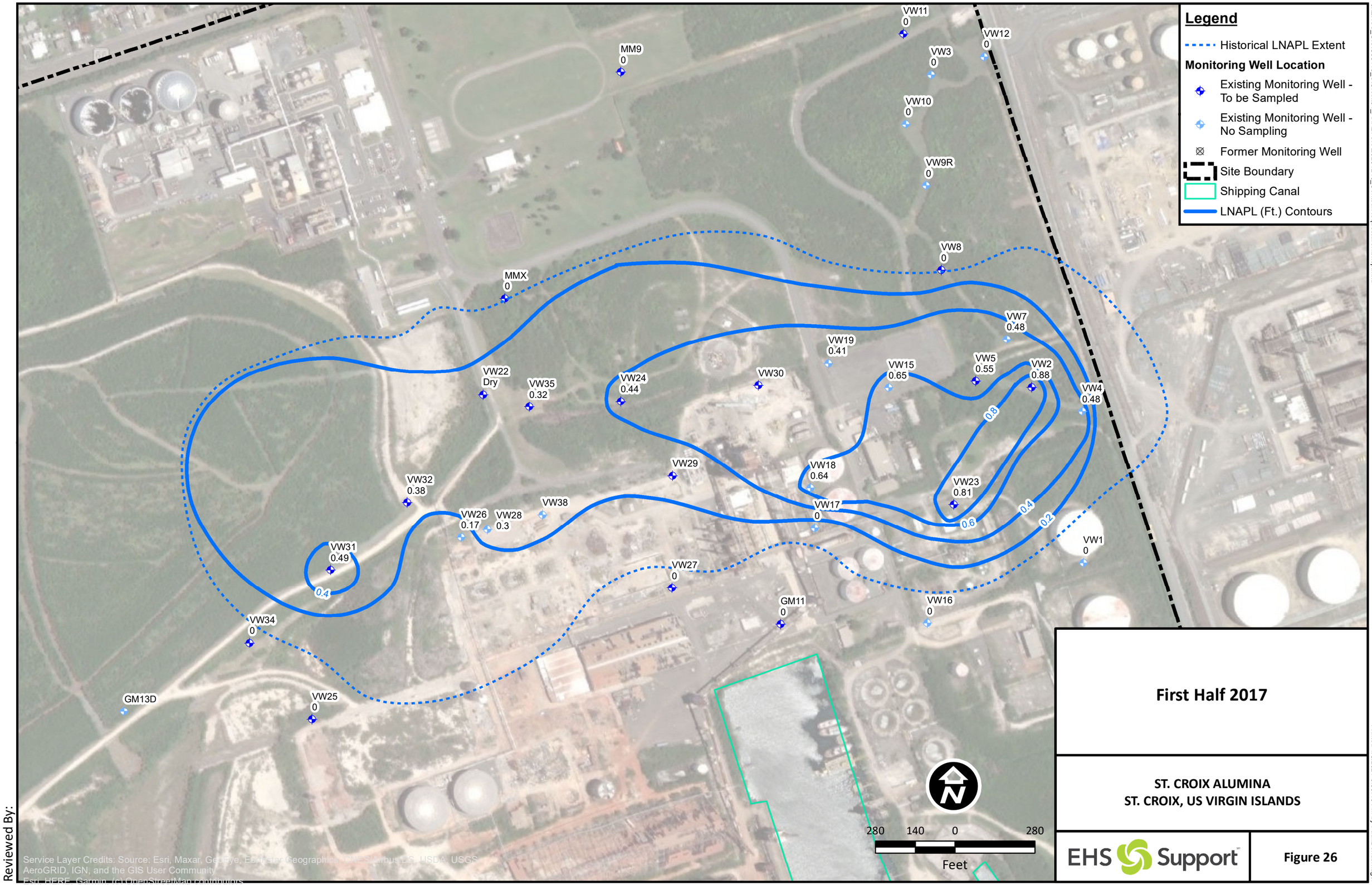

First Half 2017

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 26

Reviewed By:

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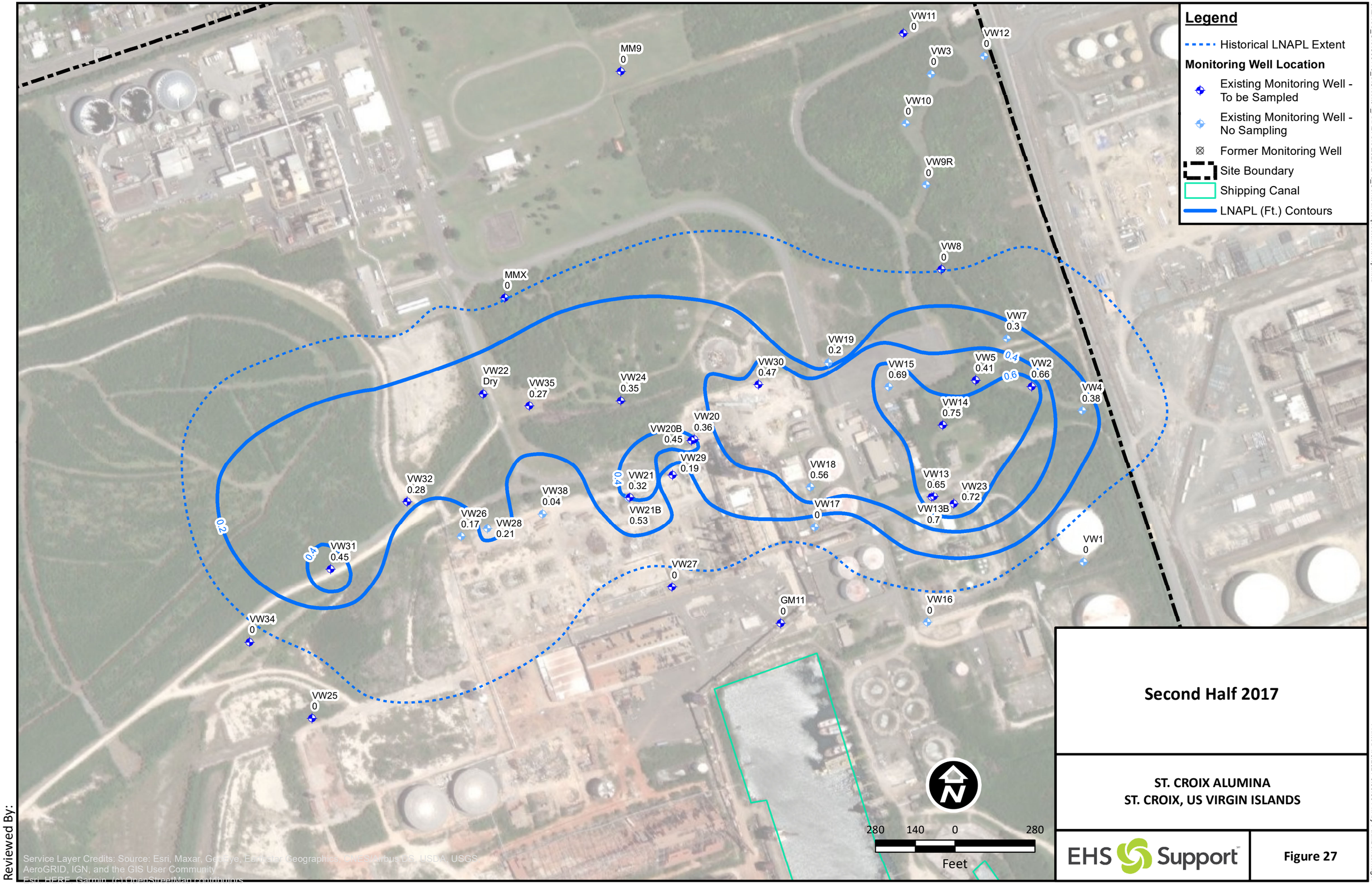

Reviewed By:

Second Half 2017

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 27

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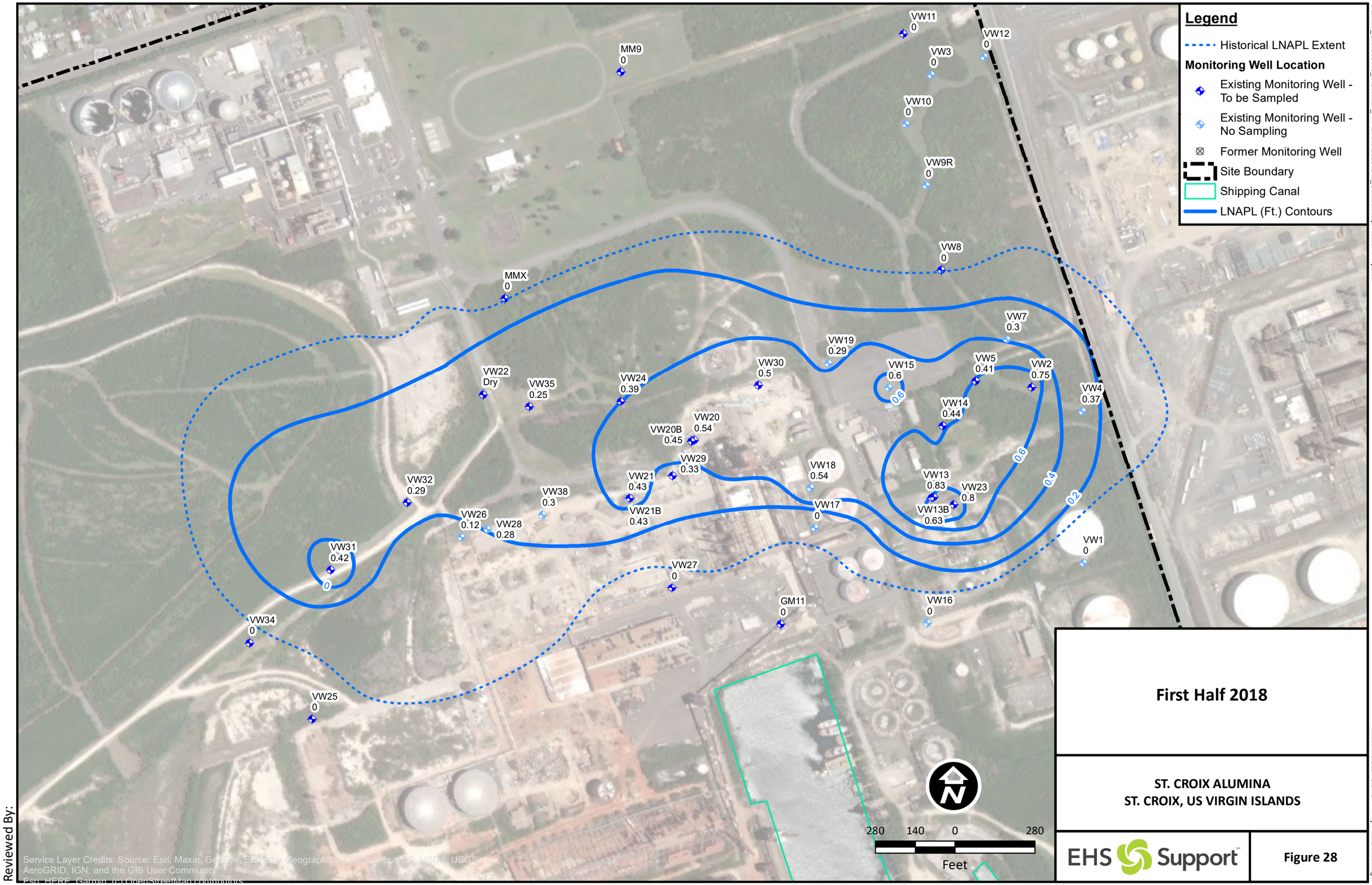

First Half 2018

ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS

EHS Support

Figure 28

Reviewed By:

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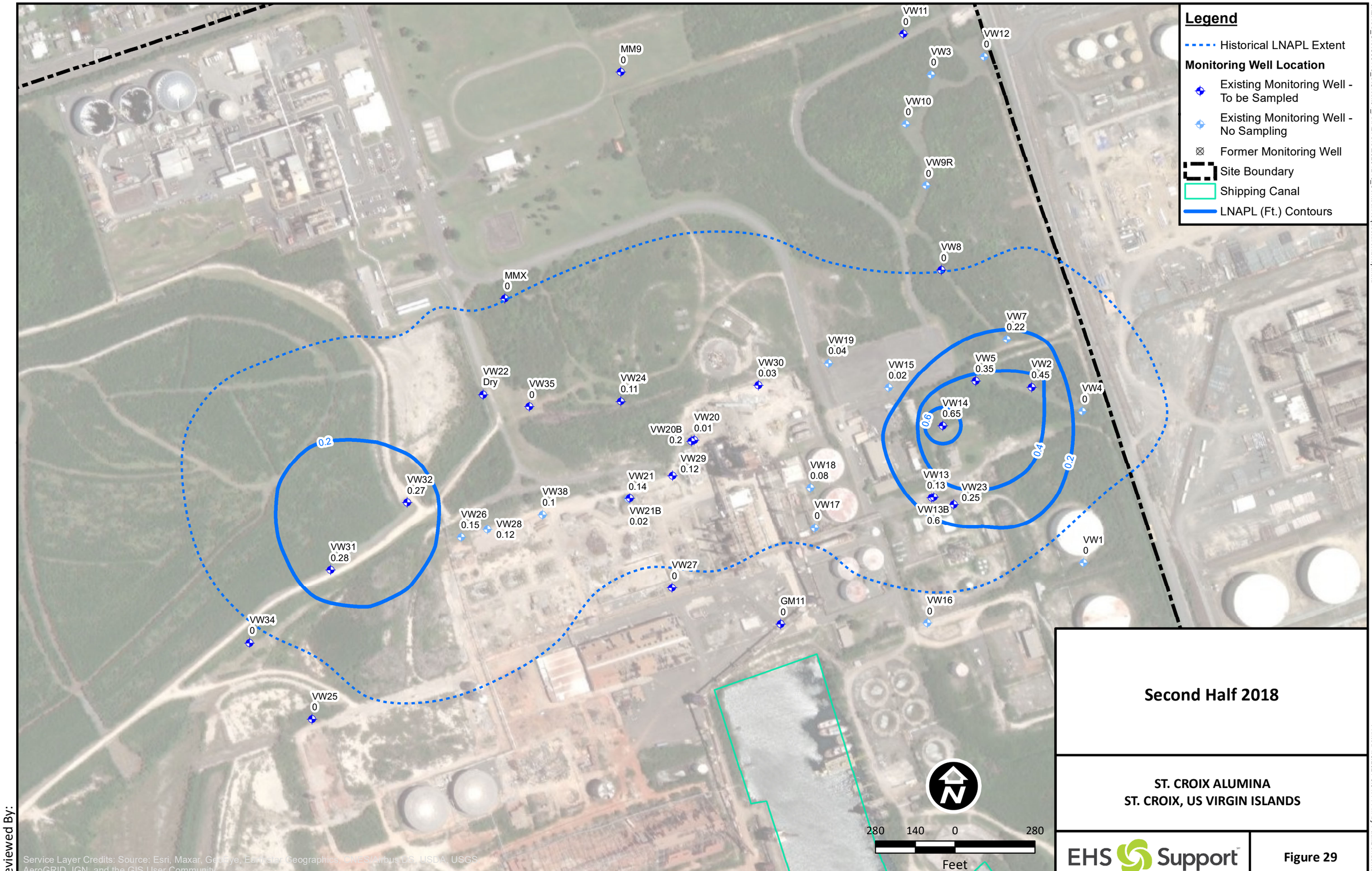
Legend
Historical LNAPL Extent
Monitoring Well Location
Existing Monitoring Well - To be Sampled
Existing Monitoring Well - No Sampling
Former Monitoring Well
Site Boundary
Shipping Canal
LNAPL (Ft.) Contours
MM9 0
VW11 0
VW12 0
VW3 0
VW10 0
VW9R 0
VW8 0
MMX 0
VW7 0.22
VW19 0.04
VW30 0.03
VW15 0.02
VW5 0.35
VW2 0.45
VW4 0
VW22 Dry
VW35 0
VW24 0.11
VW14 0.65
VW20 0.01
VW20B 0.2
VW29 0.12
VW18 0.08
VW13 0.13
VW23 0.25
VW13B 0.6
VW21 0.14
VW38 0.1
VW17 0
VW21B 0.02
VW26 0.15
VW28 0.12
VW32 0.27
VW31 0.28
VW1 0
VW27 0
GM11 0
VW16 0
VW34 0
VW25 0
0.2
0.4
0.6
280 140 0 280
Feet
Second Half 2018
ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS
EHS Support
Figure 29
Reviewed By:
Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
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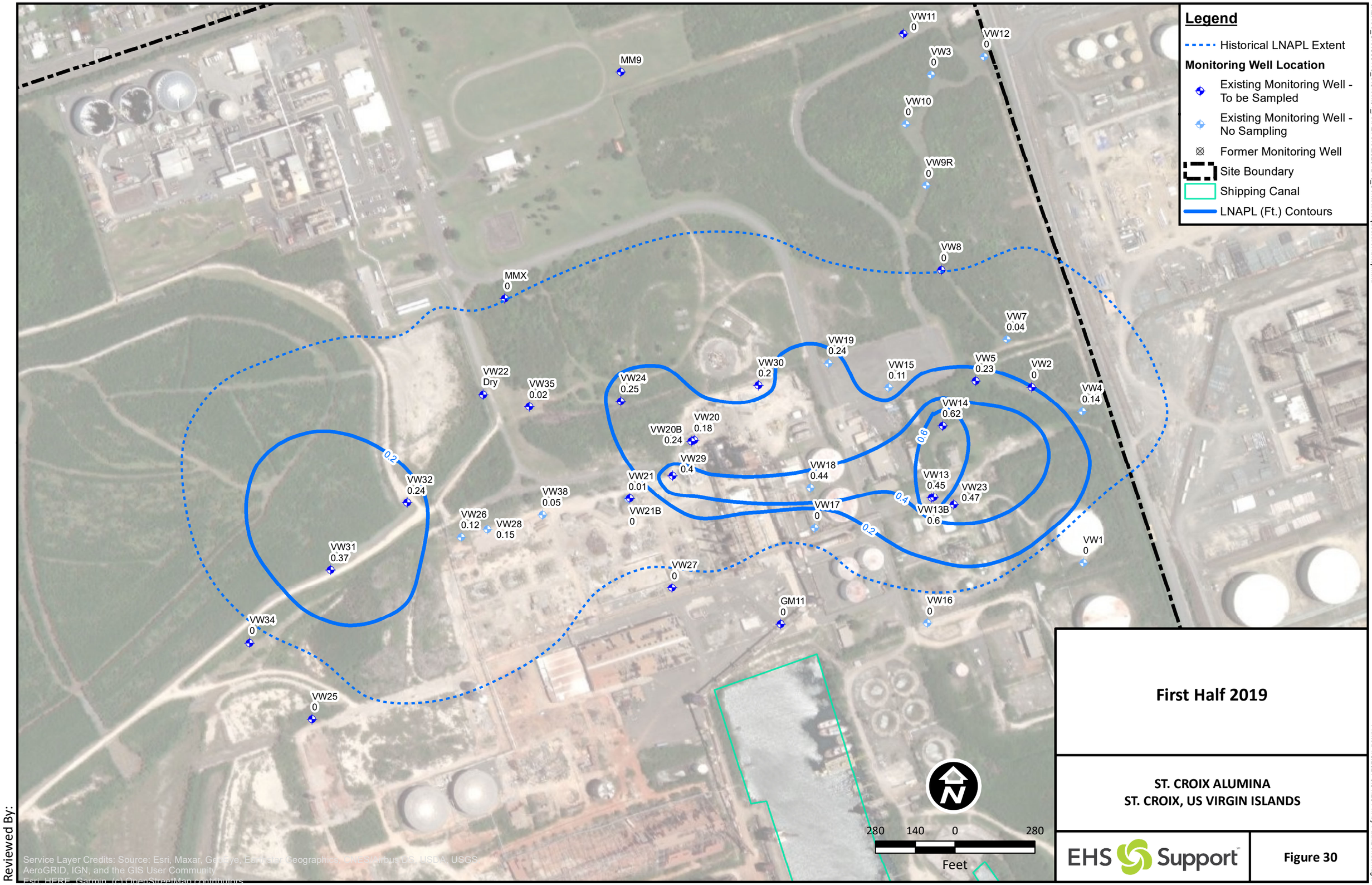
Legend
Historical LNAPL Extent
Monitoring Well Location
Existing Monitoring Well - To be Sampled
Existing Monitoring Well - No Sampling
Former Monitoring Well
Site Boundary
Shipping Canal
LNAPL (Ft.) Contours
VW11 0
VW12 0
VW3 0
MM9
VW10 0
VW9R 0
VW8 0
MMX 0
VW7 0.04
VW19 0.24
VW30 0.2
VW15 0.11
VW5 0.23
VW2 0
VW4 0.14
VW22 Dry
VW35 0.02
VW24 0.25
VW14 0.62
VW20 0.18
VW20B 0.24
VW29 0.4
VW18 0.44
VW21 0.01
VW13 0.45
VW23 0.47
VW38 0.05
VW21B 0
VW17 0
VW13B 0.6
VW26 0.12
VW28 0.15
VW32 0.24
VW31 0.37
VW1 0
VW27 0
GM11 0
VW16 0
VW34 0
VW25 0
0.2
0.4
0.6
280 140 0 280
Feet
N
First Half 2019
ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS
EHS Support
Figure 30
Reviewed By:
Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
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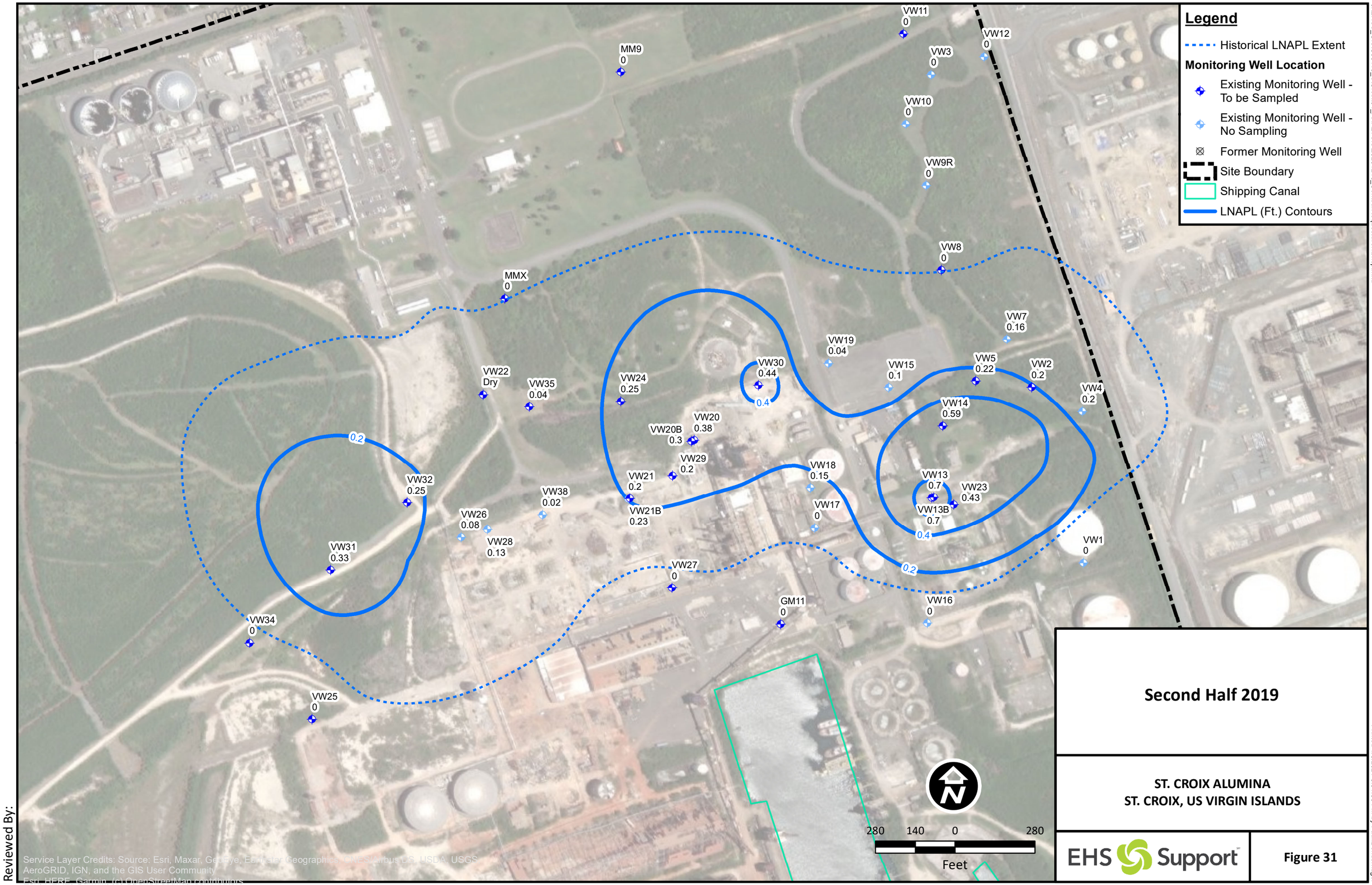
Legend
Historical LNAPL Extent
Monitoring Well Location
Existing Monitoring Well - To be Sampled
Existing Monitoring Well - No Sampling
Former Monitoring Well
Site Boundary
Shipping Canal
LNAPL (Ft.) Contours
VW11 0
VW12 0
MM9 0
VW3 0
VW10 0
VW9R 0
VW8 0
MMX 0
VW7 0.16
VW19 0.04
VW30 0.44
VW15 0.1
VW5 0.22
VW2 0.2
VW4 0.2
VW22 Dry
VW35 0.04
VW24 0.25
VW14 0.59
VW20 0.38
VW20B 0.3
VW29 0.2
VW18 0.15
VW13 0.7
VW23 0.43
VW13B 0.7
VW21 0.2
VW21B 0.23
VW17 0
VW38 0.02
VW32 0.25
VW26 0.08
VW28 0.13
VW31 0.33
VW1 0
VW27 0
GM11 0
VW16 0
VW34 0
VW25 0
0.2
0.4
280 140 0 280
Feet
Second Half 2019
ST. CROIX ALUMINA
ST. CROIX, US VIRGIN ISLANDS
EHS Support
Figure 31
Reviewed By:
Service Layer Credits: Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
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Appendix B2 Well Screen and Historical Water Level Assessment

Table 1
Historic Groundwater Elevations and LNAPL Thickness
St. Croix Alumina Site

Well	Location	Northing	Easting	Top of Casing Elevation (feet msl)	Casing stick Up (feet)	Top of Filter Pack (feet bgs)	Top of Screen (feet bgs)	Bottom of Screen (feet bgs)	Top of Screen (feet msl)	Bottom of Screen (feet msl)	Maximum Historical Groundwater Elevation (feet msl)	Minimum Historical Groundwater Elevation (feet msl)	Maximum Historical LNAPL Elevation (feet msl)	Minimum Historical LNAPL Elevation (feet msl)
VW1	SCA East	9261.9202	7636.3892	31.28	2.00	22.0	24.0	34.0	5.28	-4.72	2.87	1.59	NA	NA
VW2	SCA East	9905.6117	7661.5134	32.86	2.00	27.0	29.0	49.0	1.86	-18.14	3.53	2.08	3.90	2.91
VW3	SCA East	11060.9756	7679.248	78.69	2.00	71.0	73.0	83.0	3.69	-6.31	6.10	2.96	NA	NA
VW4	SCA East	9767.5672	7803.1425	43.73	2.22	28.0	38.0	48.0	3.51	-6.49	2.79	2.04	3.33	2.68
VW5	SCA East	9988.9815	7481.8313	40.12	1.83	30.5	34.0	44.0	4.29	-5.71	2.84	2.08	3.43	2.86
VW 6	SCA East	9766.5878	7520.4738	30.13	3.19	21.0	23.5	33.5	3.44	-6.56	2.77	2.14	3.57	2.23
VW7	SCA East	10092.8334	7632.9962	53.67	2.83	45.0	47.5	57.5	3.34	-6.66	2.86	2.10	3.21	2.67
VW8	SCA East	10397.8527	7492.3997	59.68	2.44	51.5	53.5	63.5	3.74	-6.26	2.83	2.11	NA	NA
VW9R	SCA East	10697.7047	7536.9527	80.83	1.80	63.0	75.5	85.5	3.53	-6.47	4.20	2.25	NA	NA
VW10	SCA East	10924.9844	7538.4744	91.66	2.28	80.0	85.0	95.0	4.38	-5.62	4.70	2.98	NA	NA
VW11	SCA East	11228.09	7635.4075	75.19	2.75	65.7	69.0	79.0	3.44	-6.56	5.43	3.21	NA	NA
VW12	SCA East	11061.0423	7875.9648	75.43	2.85	61.5	68.5	78.5	4.08	-5.92	5.51	3.21	NA	NA
VW13	SCA South	9648.8371	7210.6032	32.66	2.50	22.0	25.5	35.5	4.66	-5.34	2.57	1.72	3.27	2.55
VW13B	SCA South	9649.4646	7204.0179	33.61	2.00	23.0	27.5	47.5	4.11	-15.89	2.52	1.75	3.22	2.38
VW14	SCA South	9877.0682	7321.1501	35.41	3.50	25.0	28.0	38.0	3.91	-6.09	2.57	2.06	3.16	2.71
VW15	SCA South	10065.084	7184.9361	45.72	2.50	36.0	40.0	50.0	3.22	-6.78	3.69	2.08	4.50	2.70
VW16	SCA South	9242.0799	7050.1251	32.07	2.02	20.0	26.5	36.5	3.55	-6.45	2.49	1.66	NA	NA
VW17	SCA Water Plan	9681.0231	6780.1379	38.44							2.89	1.85	2.20	1.89
VW18	SCA Water Plan	9819.9825	6810.7041	38.63	3.00	28.0	32.0	42.0	3.63	-6.37	2.91	2.15	3.70	2.81
VW19	SCA Parking Lot	10213.8602	7010.9961	51.88	3.00	36.0	45.0	55.0	3.88	-6.12	2.87	2.05	3.16	2.54
VW20	SCA Parking Lot	10109.5123	6476.9024	39.69	2.90	26.0	32.0	42.0	4.79	-5.21	3.32	2.83	3.58	3.33
VW20B	SCA West	10108.3031	6465.7951	40.35	3.50	18.0	31.5	51.5	5.35	-14.65	2.92	2.54	3.15	2.98
VW21	SCA West	9987.0588	6191.9721	39.44	2.61	30.0	33.0	43.0	3.83	-6.17	2.76	1.59	3.03	1.60
VW21B	SCA West	9988.185	6197.168	39.54	3.50	22.0	28.5	48.5	7.54	-12.46	2.79	2.62	3.25	2.81
VW22	SCA West	10499.6573	5825.2553	57.94	2.70	24.5	24.5	38.5	30.74	16.74	0.00	0.00	NA	NA
VW23	SCA South	9601.8889	7269.1631	31.89	2.00	22.0	26.5	36.5	3.39	-6.61	2.79	2.08	3.35	2.98
VW24	West of old water tank	10321.5916	6276.5135	69.34	2.95	55.0	62.5	72.5	3.89	-6.11	2.56	1.21	2.71	0.47
VW25	SCA South	9609.3151	4888.4267	37.97	2.30	25.0	31.5	41.5	4.17	-5.83	2.75	1.95	NA	NA
VW26	SCA West	10048.2937	5613.4786	39.41	3.55	27.0	31.5	41.5	4.36	-5.64	2.99	2.18	3.29	2.63
VW27	SCA West	9641.8858	6236.6449	37.79	1.85	21.0	30.0	40.0	5.94	-4.06	2.68	1.42	NA	NA
VW28	SCA West	10044.6965	5686.9818	37.91	2.20	29.0	31.0	41.0	4.71	-5.29	3.02	2.16	3.20	2.77
VW29	SCA West	10015.1369	6366.4531	39.40	2.50	31.0	33.0	43.0	3.90	-6.10	3.20	2.29	4.03	2.82
VW30	SCA North	10219.1776	6752.1836	37.82	2.50	31.0	33.3	43.3	2.02	-7.98	3.36	2.15	3.78	3.04
VW31	SCA South of red mud	10086.4579	5119.091	40.85	2.70	28.0	30.0	40.0	8.15	-1.85	2.73	1.50	3.01	0.50
VW32	SCA South of red mud	10224.4185	5450.6767	41.58	3.00	29.0	31.7	41.7	6.88	-3.12	2.78	1.48	3.05	2.07
VW33	SCA North of red mud	10890.6673	3075.1504	84.26	2.83	72.0	74.0	84.0	7.43	-2.57	4.13	1.96	NA	NA
VW34	SCA South of red mud	9934.6351	4766.1346	26.37	2.26	15.0	17.0	27.0	7.11	-2.89	3.23	1.89	NA	NA
VW35	SCA West	10406.4795	5965.7197	60.13	2.00	51.0	53.0	63.0	5.13	-4.87	3.29	2.10	3.37	0.40
VW36	SCA West	10460.2319	2774.0127	53.14	2.80	45.0	46.5	56.5	3.84	-6.16	4.14	2.63	NA	NA
VW37	SCA West	10191.511	2753.3706	51.79	1.62	46.0	48.5	59.5	1.67	-9.33	2.83	1.86	NA	NA
VW38	SCA West	10044.5541	5791.5325	36.02	3.00	16.0	25.5	45.5	7.52	-12.48	3.03	2.53	3.13	2.75
GM22	SCA South	8586.2873	4367.1417	35.90	4.00	10.0	12.0	27.0	19.90	4.90	19.30	-0.19	NA	NA
GM11	SCA North of Docks	9395.823	6561.2401	37.59	3.28	35.0	37.0	55.0	-2.69	-20.69	29.45	1.44	NA	NA
GM14	SCA West of Docks	8360.2501	6066.4142	9.96	2.60	6.5	8.0	33.0	-0.64	-25.64	4.94	-70.41	NA	NA
MM9	SCA North	11419.8607	6649.6221	84.35	1.10				83.25	83.25	15.28	2.86	NA	NA
MMX	SCA North	10758.6295	6065.4638	64.90	1.20	60.0	60.0	100.0	3.70	-36.30	3.13	2.15	NA	NA
GM7	SCA West	9356.8731	2795.5349	26.04	2.46	25.0	25.0	35.0	-1.42	-11.42	20.50	1.69	NA	NA
GM13D	SCA West	4,344.33	9,759.71	23.12	Unknown	45.0	50.0	90.0	-26.88	-66.88	2.77	1.26	NA	NA

Notes:

	Data not available
NA	Not applicable; LNAPL never present
	Based on quarterly data from October 2002 through December 2019 (excluding data from 2004 and 2005, which are not available)
	VW-24 October 2002 had a reported water level of 16..1 ft msl. This is excluded from the analysis as it is likely erroneous.
	VW-22 May 2003 had a reported water level of 16.11 ft msl. This value is excluded form the analysis as it is likely erroneous.
bgs	below ground surface
LNAPL	light non-aqueous phase liquid
msl	mean sea level

Table 1
Historic Groundwater Elevations and LNAPL Thickness
St. Croix Alumina Site

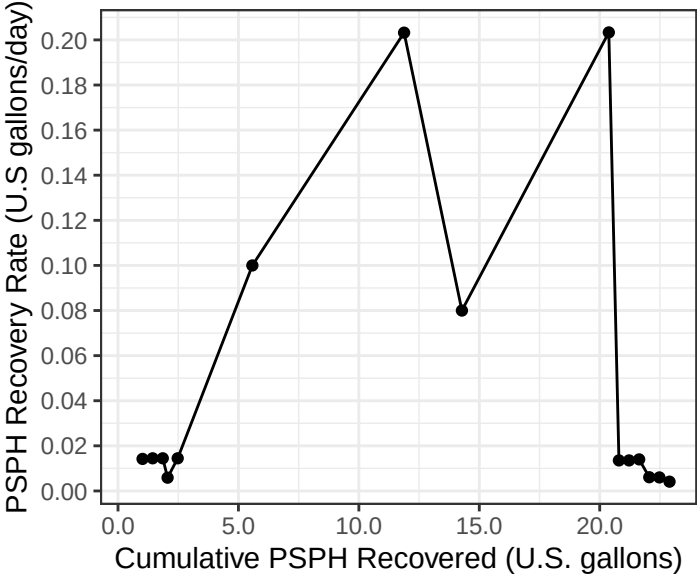
Well	Location	GW Submerged Screen?	Frequency of GW submerged screen (out of 30 events)	LNAPL Submerged Screen?	Frequency of LNAPL submerged screen (out of 30 events)	LNAPL Submerged Filter Pack?	Frequency of LNAPL submerged filter (out of 30 events)
VW1	SCA East	NO		NA		NA	
VW2	SCA East	**YES**	30	**YES**	30	**YES**	1
VW3	SCA East	**YES**	25	NA		NA	
VW4	SCA East	NO		NO		NO	
VW5	SCA East	NO		NO		NO	
VW 6	SCA East	NO		**YES**	2	NO	
VW7	SCA East	NO		NO		NO	
VW8	SCA East	NO		NA		NA	
VW9R	SCA East	**YES**	8	NA		NA	
VW10	SCA East	**YES**	1	NA		NA	
VW11	SCA East	**YES**	29	NA		NA	
VW12	SCA East	**YES**	21	NA		NA	
VW13	SCA South	NO		NO		NO	
VW13B	SCA South	NO		NO		NO	
VW14	SCA South	NO		NO		NO	
VW15	SCA South	**YES**	1	**YES**	5	NO	
VW16	SCA South	NO		NA		NA	
VW17	SCA Water Plan	?		?		?	
VW18	SCA Water Plan	NO		**YES**	2	NO	
VW19	SCA Parking Lot	NO		NO		NO	
VW20	SCA Parking Lot	NO		NO		NO	
VW20B	SCA West	NO		NO		NO	
VW21	SCA West	NO		NO		NO	
VW21B	SCA West	NO		NO		NO	
VW22	SCA West	NO		NA		NA	
VW23	SCA South	NO		NO		NO	
VW24	West of old water tank	NO		NO		NO	
VW25	SCA South	NO		NA		NA	
VW26	SCA West	NO		NO		NO	
VW27	SCA West	NO		NA		NA	
VW28	SCA West	NO		NO		NO	
VW29	SCA West	NO		**YES**	3	NO	
VW30	SCA North	**YES**	30	**YES**	30	NO	
VW31	SCA South of red mud	NO		NO		NO	
VW32	SCA South of red mud	NO		NO		NO	
VW33	SCA North of red mud	NO		NA		NA	
VW34	SCA South of red mud	NO		NA		NA	
VW35	SCA West	NO		NO		NO	
VW36	SCA West	**YES**	3	NA		NA	
VW37	SCA West	**YES**	30	NA		NA	
VW38	SCA West	NO		NO		NO	
GM22	SCA South	NO		NA		NA	
GM11	SCA North of Docks	**YES**	30	NA		NA	
GM14	SCA West of Docks	**YES**	30	NA		NA	
MM9	SCA North	?		?		NA	
MMX	SCA North	NO		NA		NA	
GM7	SCA West	**YES**	30	NA		NA	
GM13D	SCA West	**YES**	30	NA		NA	

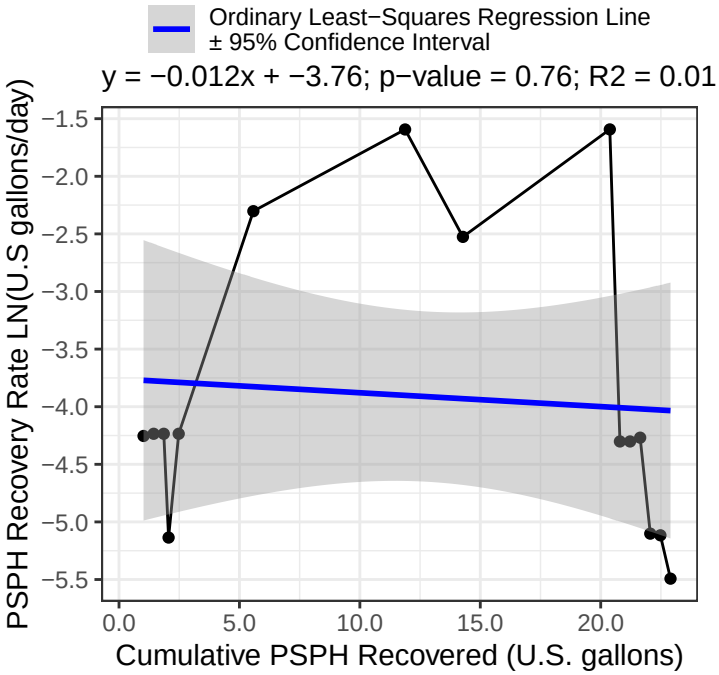
Notes:

	Data not available
NA	Not applicable; LNAPL never present
	Based on quarterly data from October 2002 through December 2019 (excluding data from 2004 and 2005, which are not available)
	VW-24 October 2002 had a reported water level of 16..1 ft msl. This is excluded from the analysis as it is likely erroneous.
	VW-22 May 2003 had a reported water level of 16.11 ft msl. This value is excluded form the analysis as it is likely erroneous.

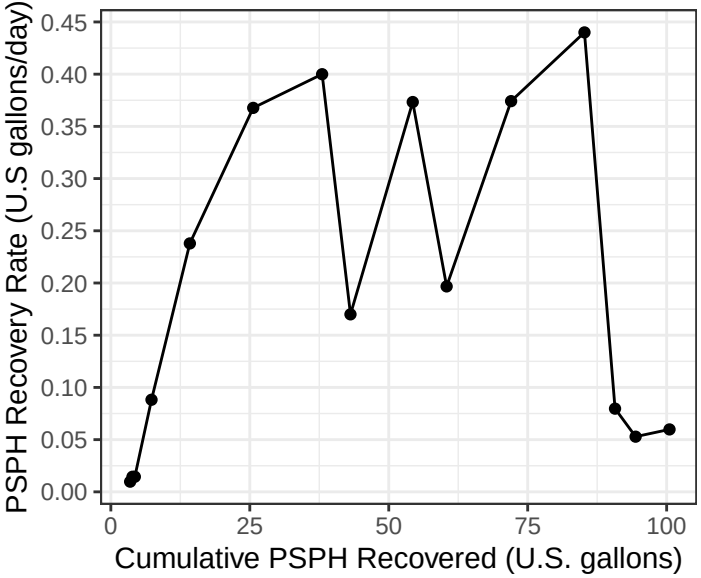
Appendix C Reservoir Decline Curves

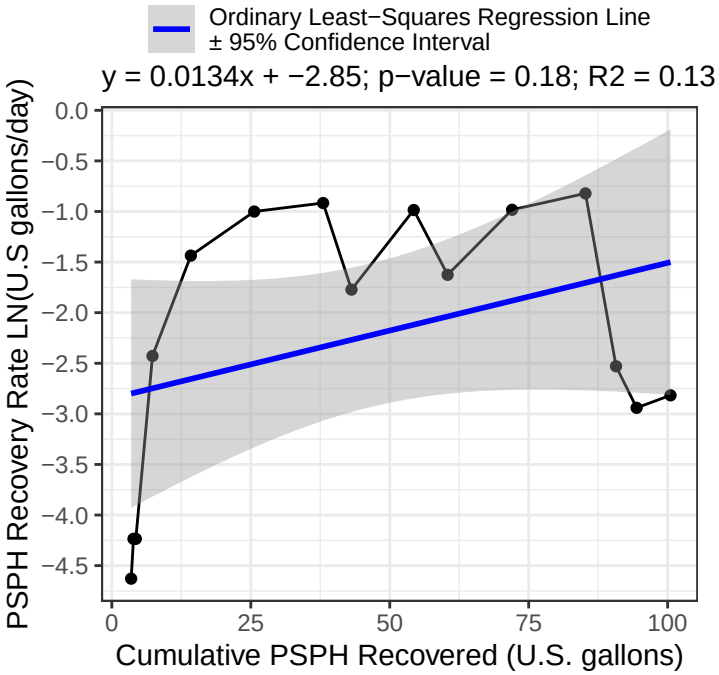
VW2


PSPH Recovery Rate (U.S gallons/day)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0
5.0
10.0
15.0
20.0
Cumulative PSPH Recovered (U.S. gallons)

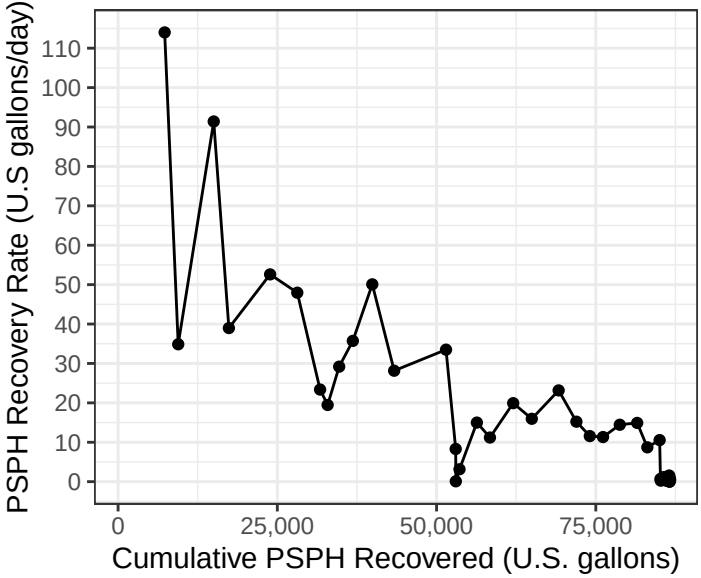

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.012x + −3.76; p−value = 0.76; R2 = 0.01
PSPH Recovery Rate LN(U.S gallons/day)
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
0.0
5.0
10.0
15.0
20.0
Cumulative PSPH Recovered (U.S. gallons)

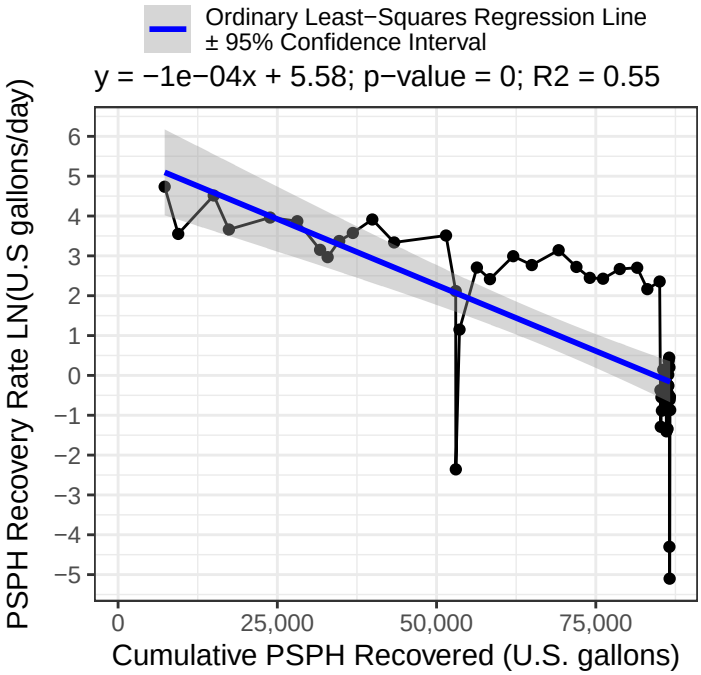
VW5


PSPH Recovery Rate (U.S gallons/day)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
25
50
75
100
Cumulative PSPH Recovered (U.S. gallons)

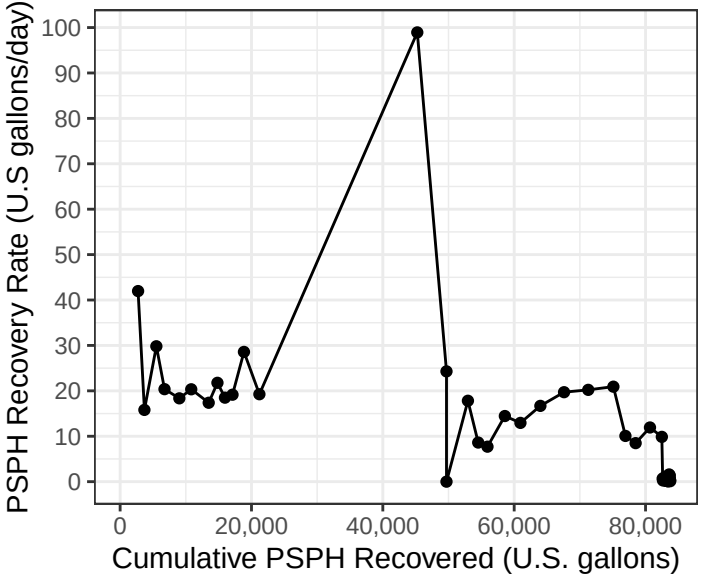

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = 0.0134x + −2.85; p−value = 0.18; R2 = 0.13
PSPH Recovery Rate LN(U.S gallons/day)
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
0
25
50
75
100
Cumulative PSPH Recovered (U.S. gallons)

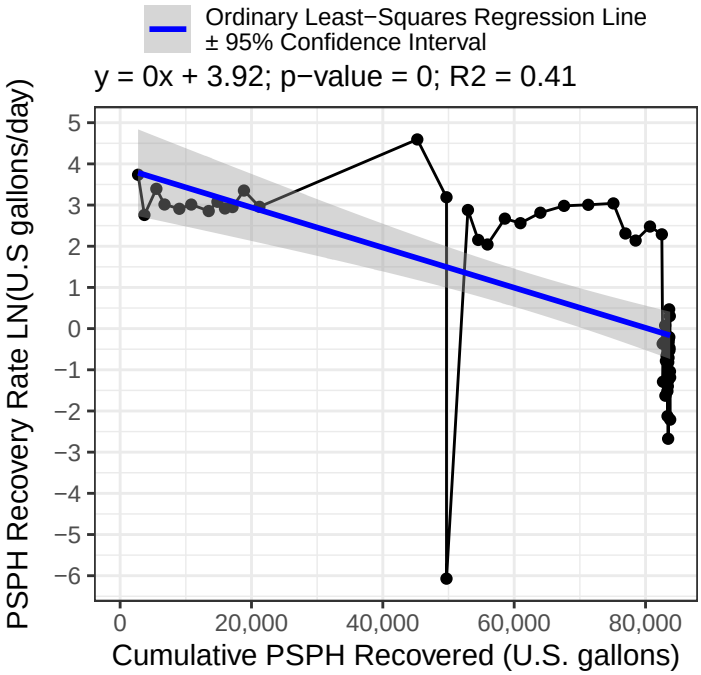
VW6


PSPH Recovery Rate (U.S gallons/day)
110
100
90
80
70
60
50
40
30
20
10
0
0
25,000
50,000
75,000
Cumulative PSPH Recovered (U.S. gallons)

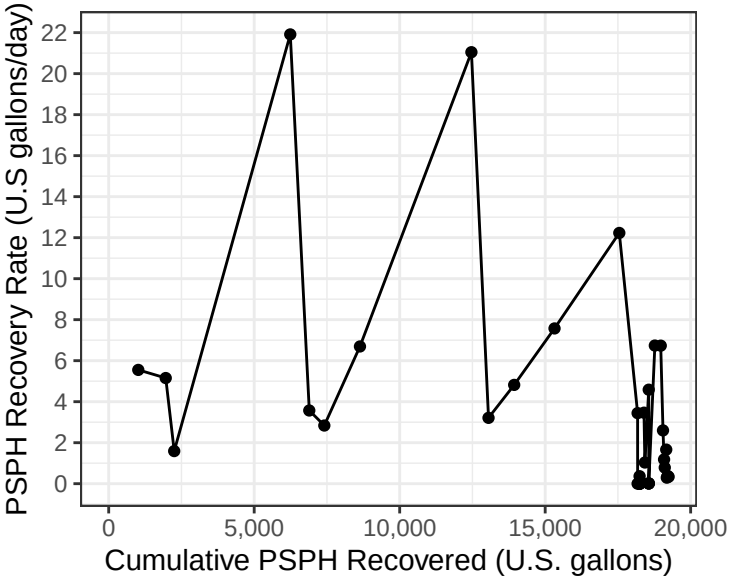

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −1e−04x + 5.58; p−value = 0; R2 = 0.55
PSPH Recovery Rate LN(U.S gallons/day)
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
0
25,000
50,000
75,000
Cumulative PSPH Recovered (U.S. gallons)

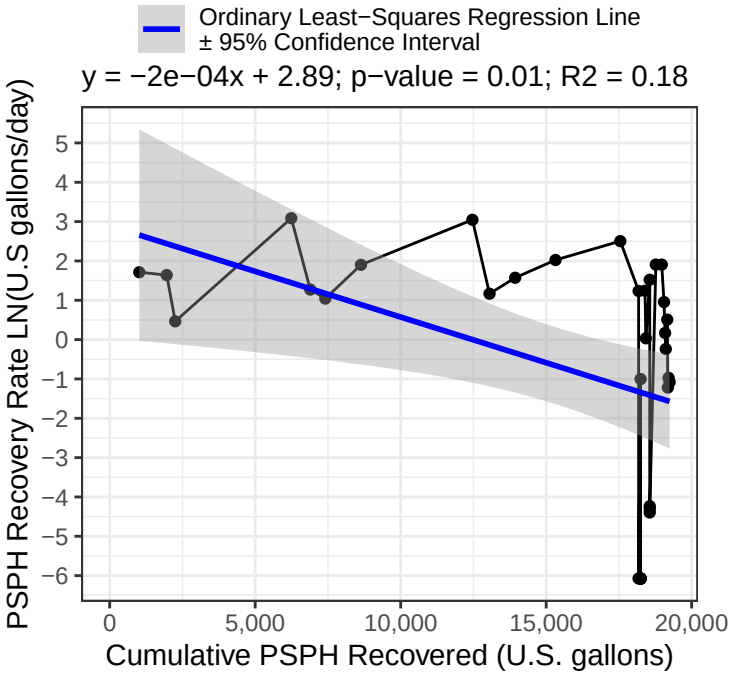
VW13


PSPH Recovery Rate (U.S gallons/day)
100
90
80
70
60
50
40
30
20
10
0
0
20,000
40,000
60,000
80,000
Cumulative PSPH Recovered (U.S. gallons)

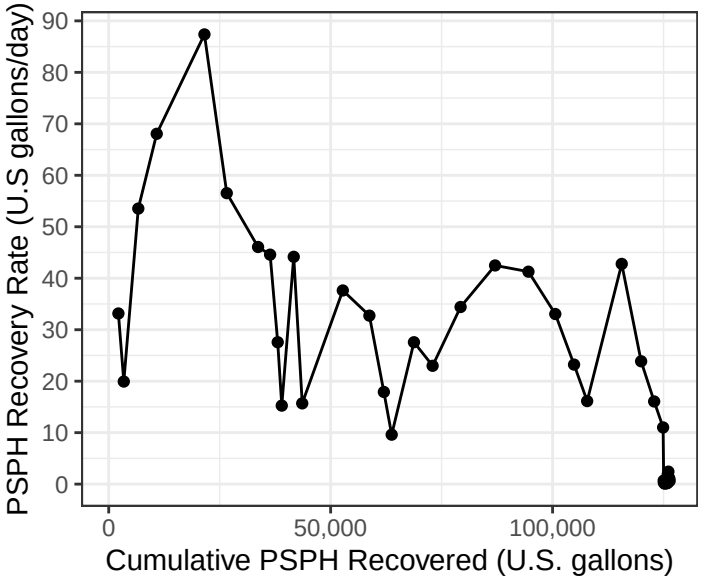

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = 0x + 3.92; p−value = 0; R2 = 0.41
PSPH Recovery Rate LN(U.S gallons/day)
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
0
20,000
40,000
60,000
80,000
Cumulative PSPH Recovered (U.S. gallons)

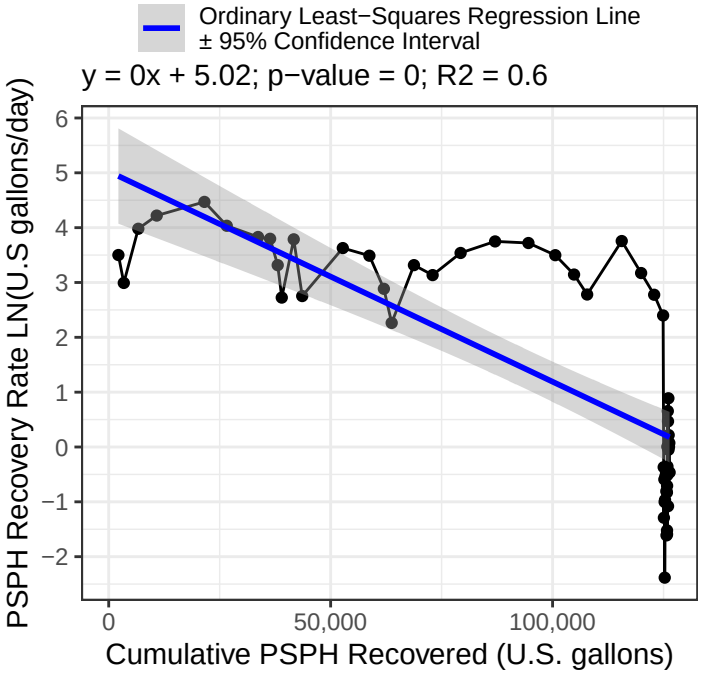
VW13B


PSPH Recovery Rate (U.S gallons/day)
22
20
18
16
14
12
10
8
6
4
2
0
0
5,000
10,000
15,000
20,000
Cumulative PSPH Recovered (U.S. gallons)

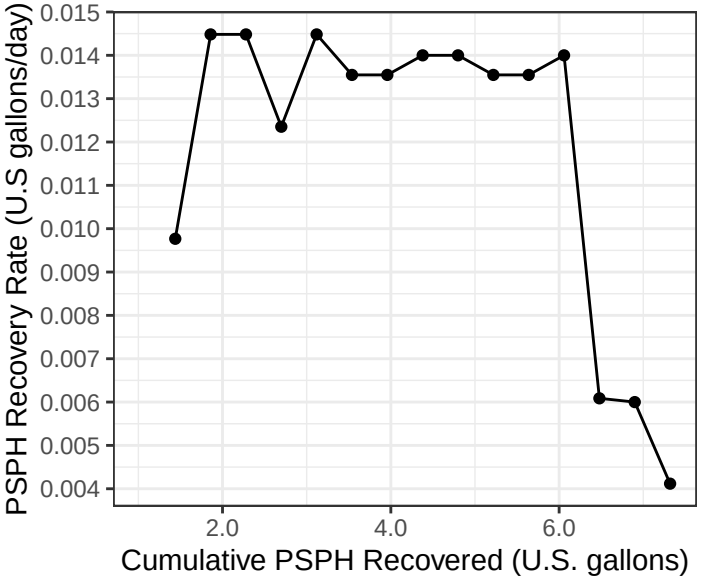

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −2e−04x + 2.89; p−value = 0.01; R2 = 0.18
PSPH Recovery Rate LN(U.S gallons/day)
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
0
5,000
10,000
15,000
20,000
Cumulative PSPH Recovered (U.S. gallons)

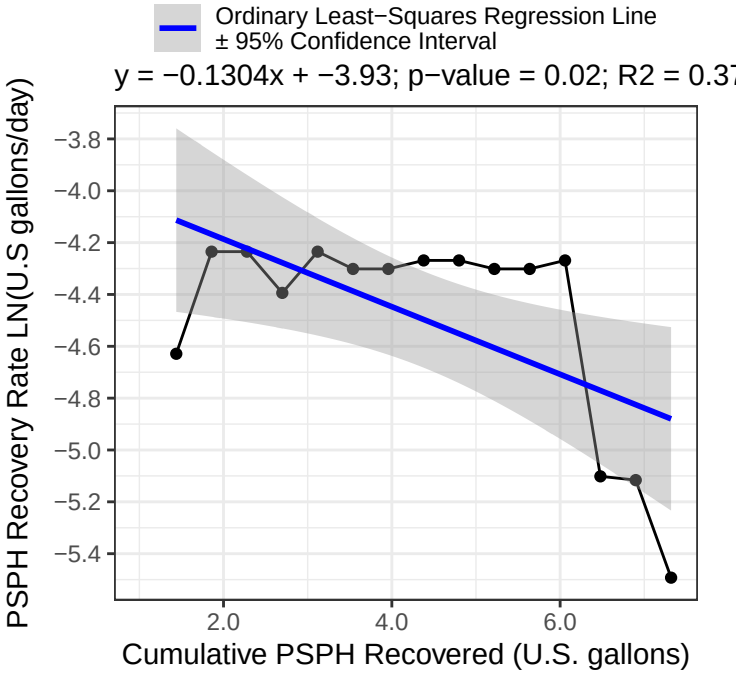
VW14


PSPH Recovery Rate (U.S gallons/day)
90
80
70
60
50
40
30
20
10
0
0
50,000
100,000
Cumulative PSPH Recovered (U.S. gallons)

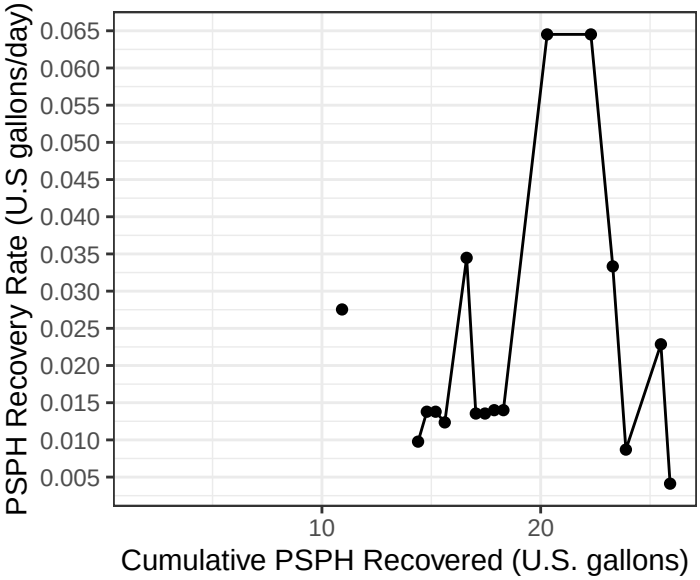

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = 0x + 5.02; p−value = 0; R2 = 0.6
PSPH Recovery Rate LN(U.S gallons/day)
6
5
4
3
2
1
0
−1
−2
0
50,000
100,000
Cumulative PSPH Recovered (U.S. gallons)

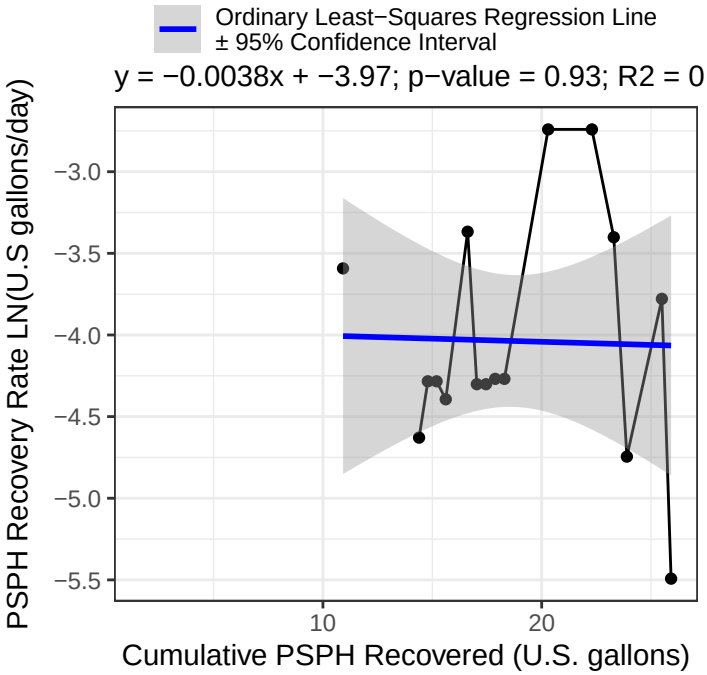
VW15


PSPH Recovery Rate (U.S gallons/day)
0.015
0.014
0.013
0.012
0.011
0.010
0.009
0.008
0.007
0.006
0.005
0.004
2.0
4.0
6.0
Cumulative PSPH Recovered (U.S. gallons)

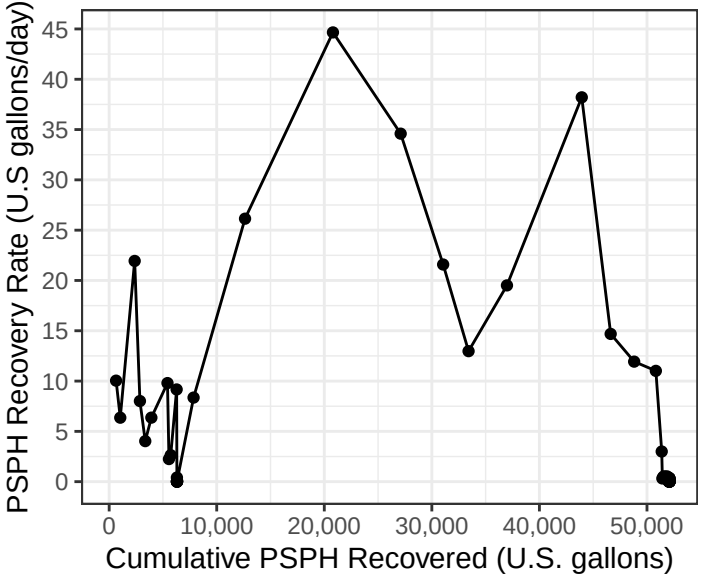

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.1304x + −3.93; p−value = 0.02; R2 = 0.37
PSPH Recovery Rate LN(U.S gallons/day)
−3.8
−4.0
−4.2
−4.4
−4.6
−4.8
−5.0
−5.2
−5.4
2.0
4.0
6.0
Cumulative PSPH Recovered (U.S. gallons)

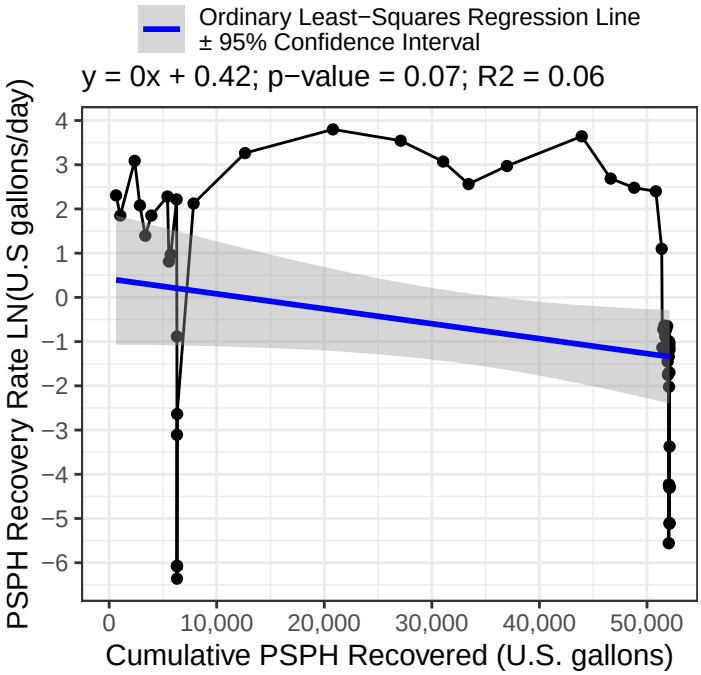
VW18


PSPH Recovery Rate (U.S gallons/day)
0.065
0.060
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
10
20
Cumulative PSPH Recovered (U.S. gallons)

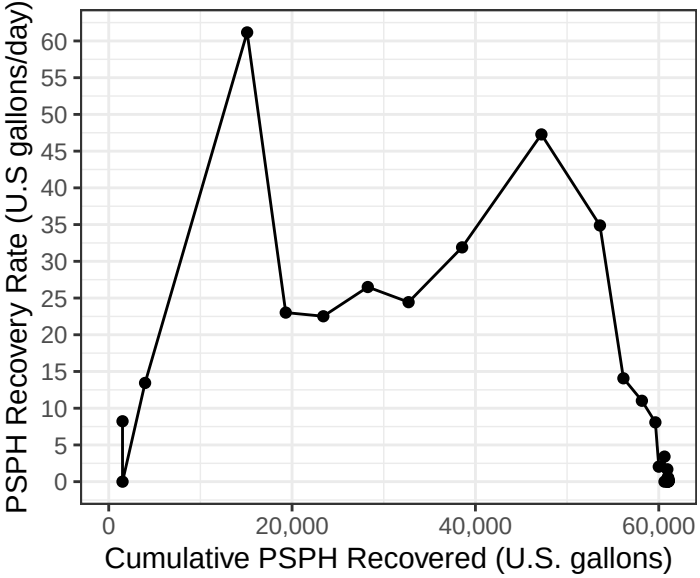

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.0038x + −3.97; p−value = 0.93; R2 = 0
PSPH Recovery Rate LN(U.S gallons/day)
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
10
20
Cumulative PSPH Recovered (U.S. gallons)

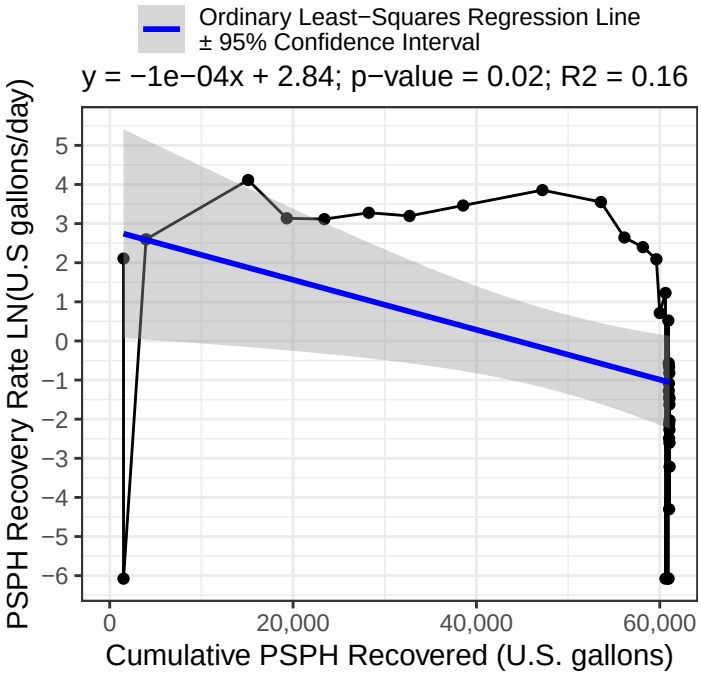
VW20


PSPH Recovery Rate (U.S gallons/day)
45
40
35
30
25
20
15
10
5
0
0
10,000
20,000
30,000
40,000
50,000
Cumulative PSPH Recovered (U.S. gallons)

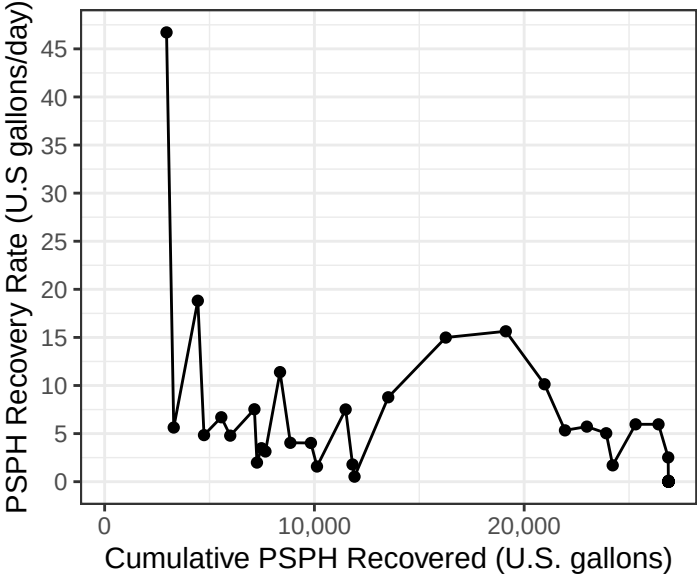

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = 0x + 0.42; p−value = 0.07; R2 = 0.06
PSPH Recovery Rate LN(U.S gallons/day)
4
3
2
1
0
−1
−2
−3
−4
−5
−6
0
10,000
20,000
30,000
40,000
50,000
Cumulative PSPH Recovered (U.S. gallons)

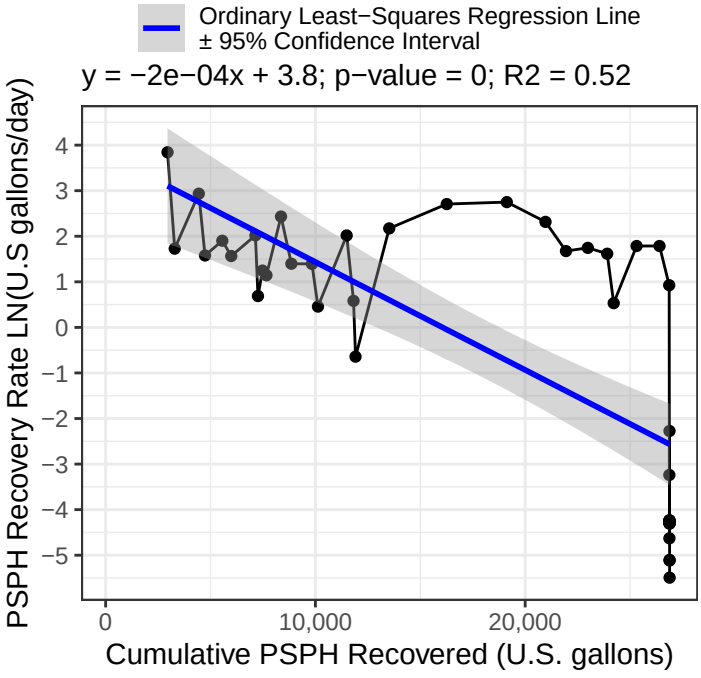
VW20B


PSPH Recovery Rate (U.S gallons/day)
0
5
10
15
20
25
30
35
40
45
50
55
60
0
20,000
40,000
60,000
Cumulative PSPH Recovered (U.S. gallons)

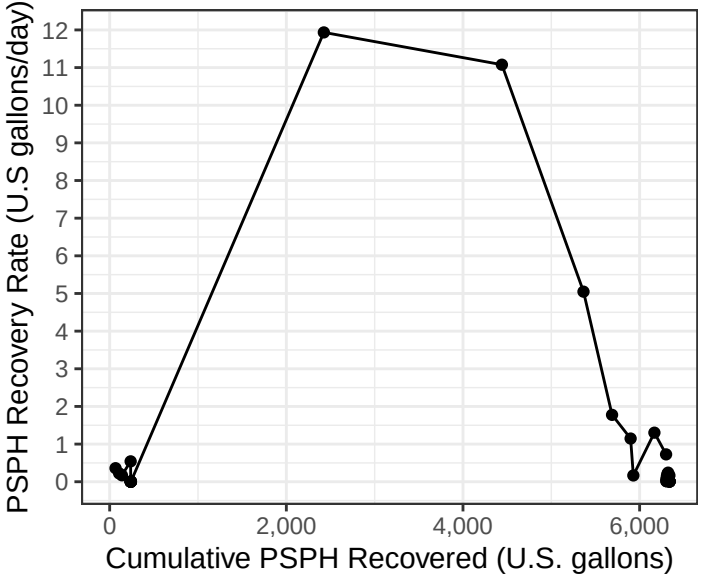

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −1e−04x + 2.84; p−value = 0.02; R2 = 0.16
PSPH Recovery Rate LN(U.S gallons/day)
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
0
20,000
40,000
60,000
Cumulative PSPH Recovered (U.S. gallons)

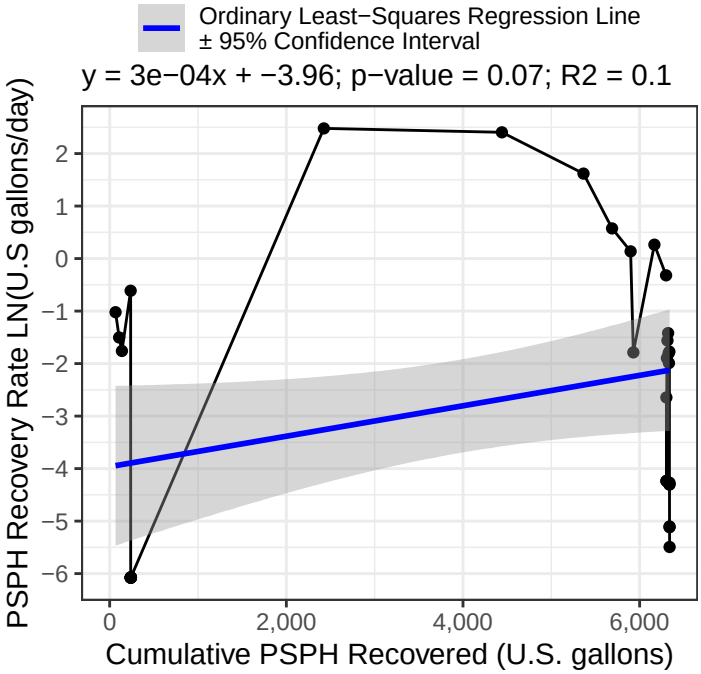
VW21


PSPH Recovery Rate (U.S gallons/day)
45
40
35
30
25
20
15
10
5
0
0
10,000
20,000
Cumulative PSPH Recovered (U.S. gallons)

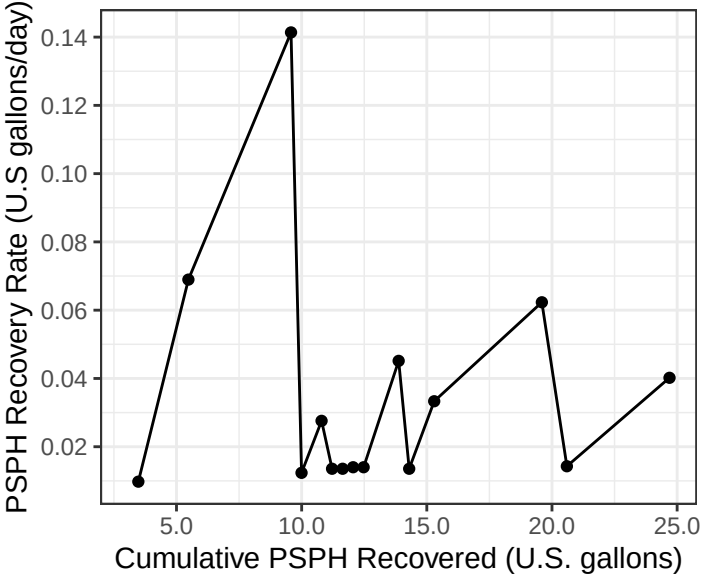

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −2e−04x + 3.8; p−value = 0; R2 = 0.52
PSPH Recovery Rate LN(U.S gallons/day)
4
3
2
1
0
−1
−2
−3
−4
−5
0
10,000
20,000
Cumulative PSPH Recovered (U.S. gallons)

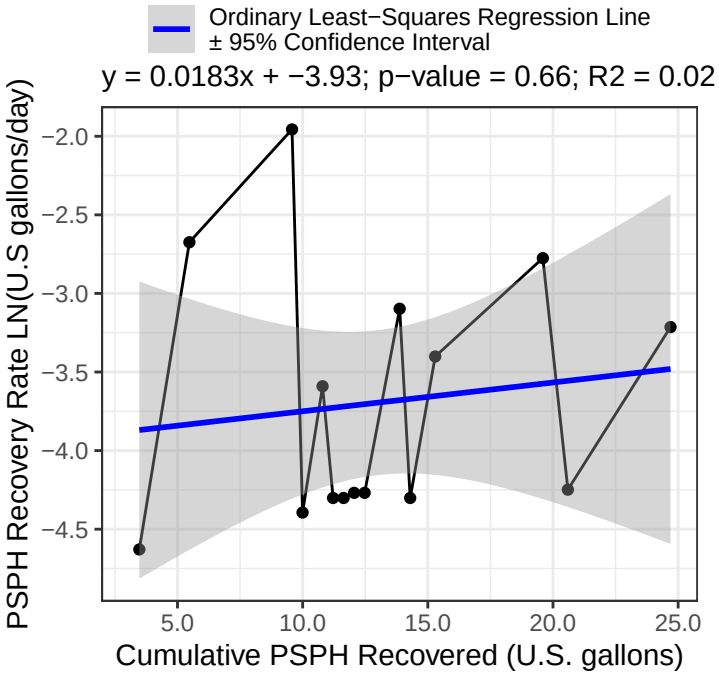
VW21B


PSPH Recovery Rate (U.S gallons/day)
Cumulative PSPH Recovered (U.S. gallons)

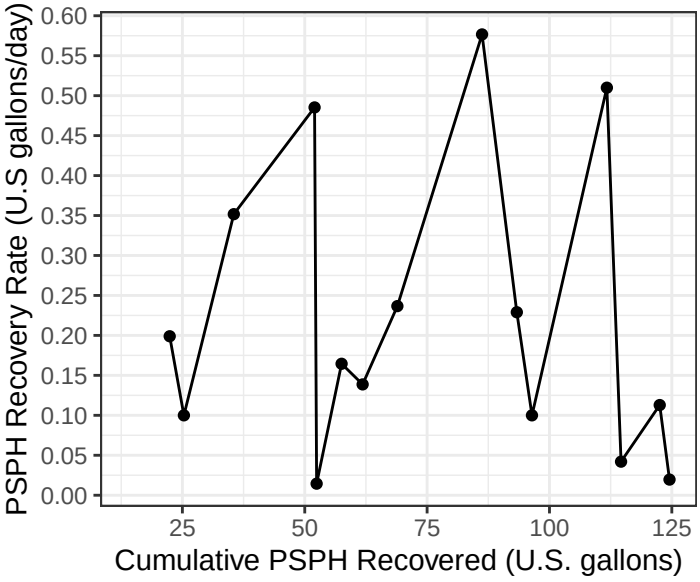

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = 3e−04x + −3.96; p−value = 0.07; R2 = 0.1
PSPH Recovery Rate LN(U.S gallons/day)
Cumulative PSPH Recovered (U.S. gallons)

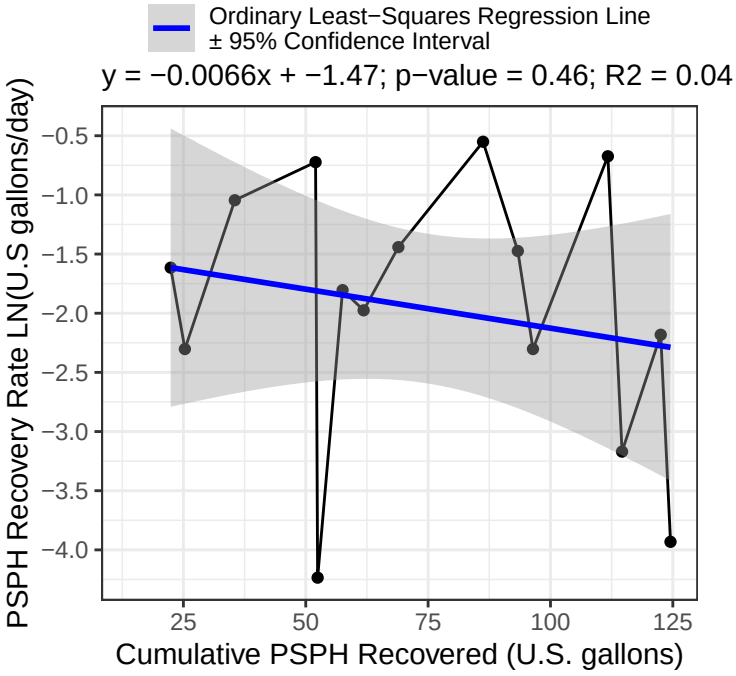
VW23


PSPH Recovery Rate (U.S gallons/day)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
5.0
10.0
15.0
20.0
25.0
Cumulative PSPH Recovered (U.S. gallons)

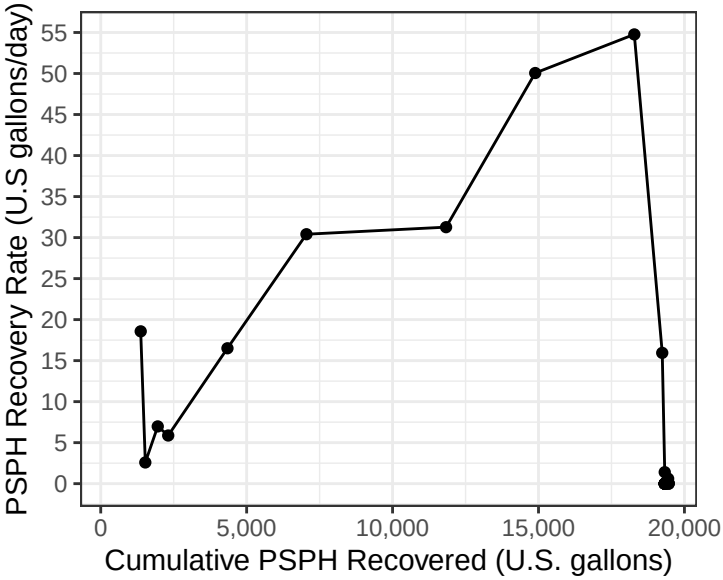

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = 0.0183x + −3.93; p−value = 0.66; R2 = 0.02
PSPH Recovery Rate LN(U.S gallons/day)
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
5.0
10.0
15.0
20.0
25.0
Cumulative PSPH Recovered (U.S. gallons)

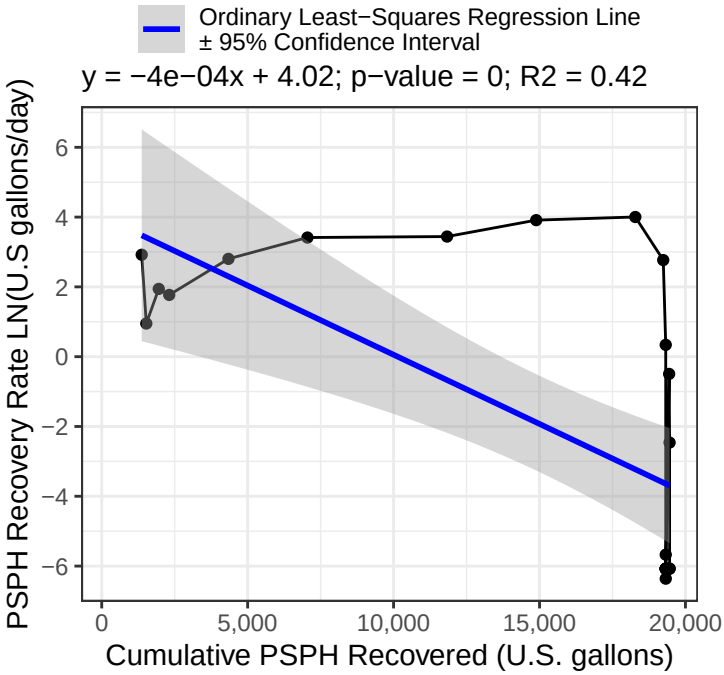
VW24


PSPH Recovery Rate (U.S gallons/day)
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
25
50
75
100
125
Cumulative PSPH Recovered (U.S. gallons)

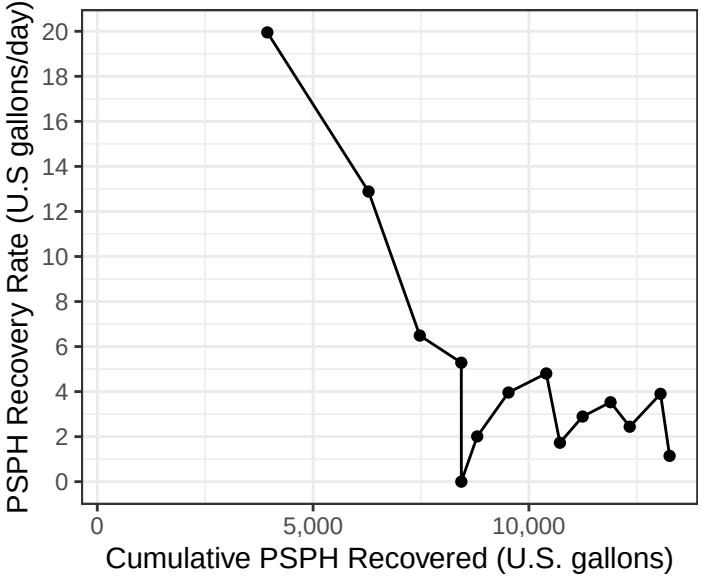

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.0066x + −1.47; p−value = 0.46; R2 = 0.04
PSPH Recovery Rate LN(U.S gallons/day)
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
25
50
75
100
125
Cumulative PSPH Recovered (U.S. gallons)

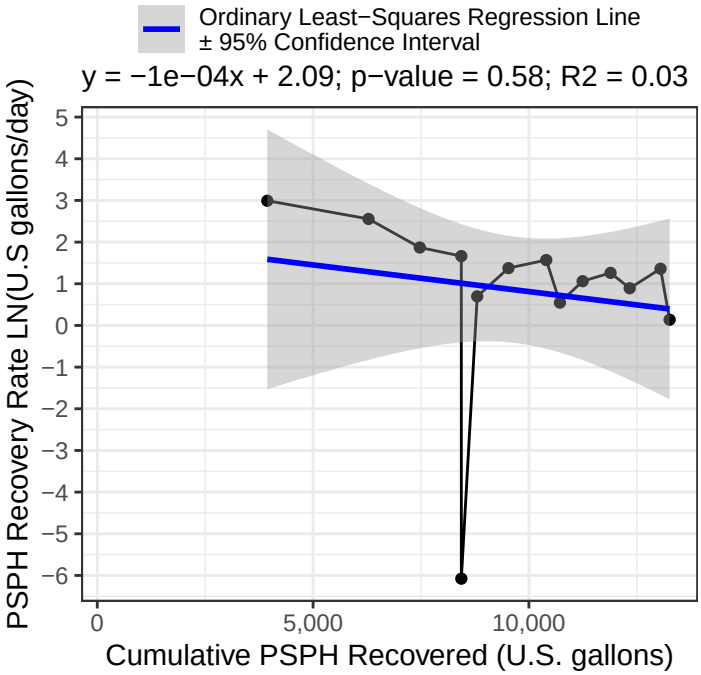
VW26


PSPH Recovery Rate (U.S gallons/day)
55
50
45
40
35
30
25
20
15
10
5
0
0
5,000
10,000
15,000
20,000
Cumulative PSPH Recovered (U.S. gallons)

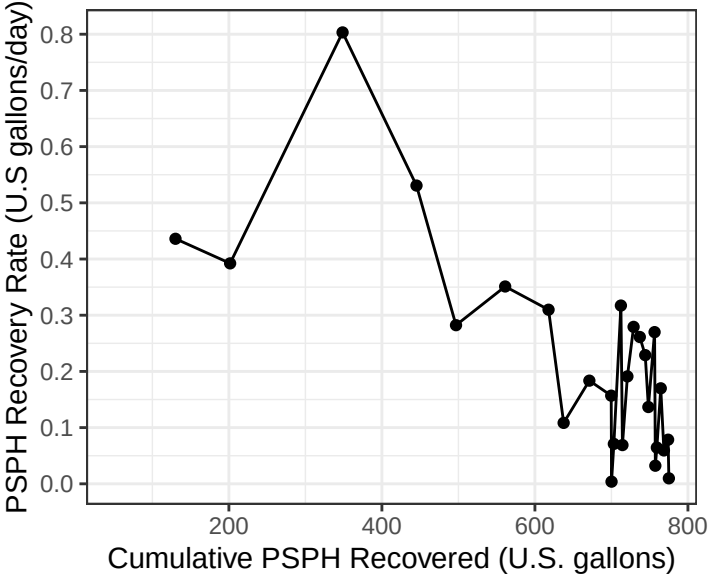

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −4e−04x + 4.02; p−value = 0; R2 = 0.42
PSPH Recovery Rate LN(U.S gallons/day)
6
4
2
0
−2
−4
−6
0
5,000
10,000
15,000
20,000
Cumulative PSPH Recovered (U.S. gallons)

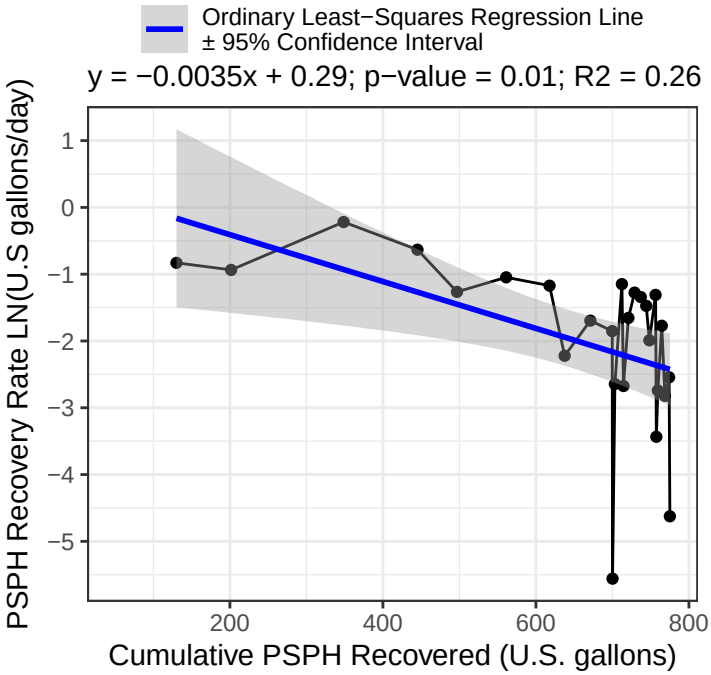
VW28


PSPH Recovery Rate (U.S gallons/day)
20
18
16
14
12
10
8
6
4
2
0
0
5,000
10,000
Cumulative PSPH Recovered (U.S. gallons)

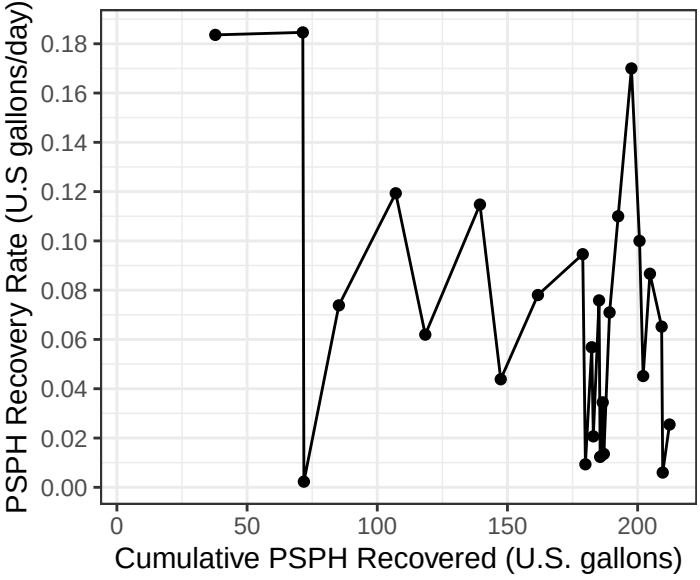

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −1e−04x + 2.09; p−value = 0.58; R2 = 0.03
PSPH Recovery Rate LN(U.S gallons/day)
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
0
5,000
10,000
Cumulative PSPH Recovered (U.S. gallons)

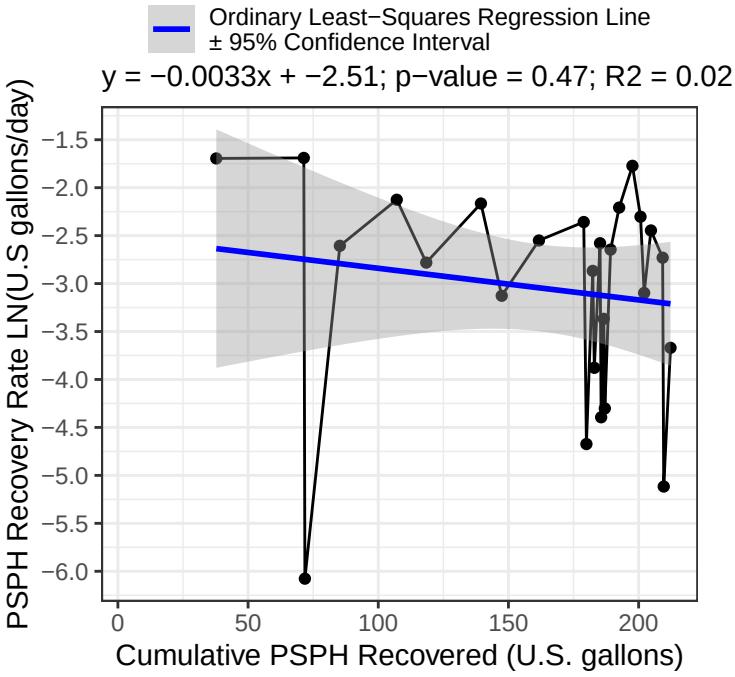
VW29


PSPH Recovery Rate (U.S gallons/day)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
200
400
600
800
Cumulative PSPH Recovered (U.S. gallons)

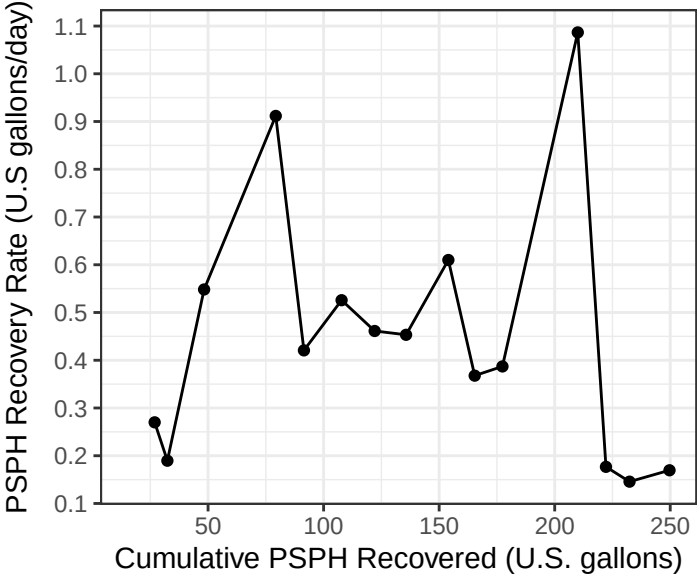

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.0035x + 0.29; p−value = 0.01; R2 = 0.26
PSPH Recovery Rate LN(U.S gallons/day)
1
0
−1
−2
−3
−4
−5
200
400
600
800
Cumulative PSPH Recovered (U.S. gallons)

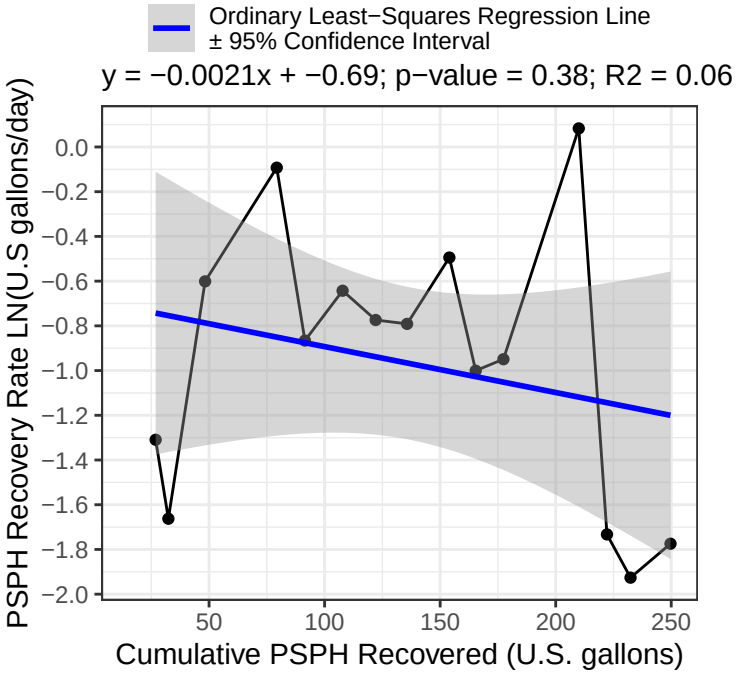
VW30


PSPH Recovery Rate (U.S gallons/day)
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200
Cumulative PSPH Recovered (U.S. gallons)

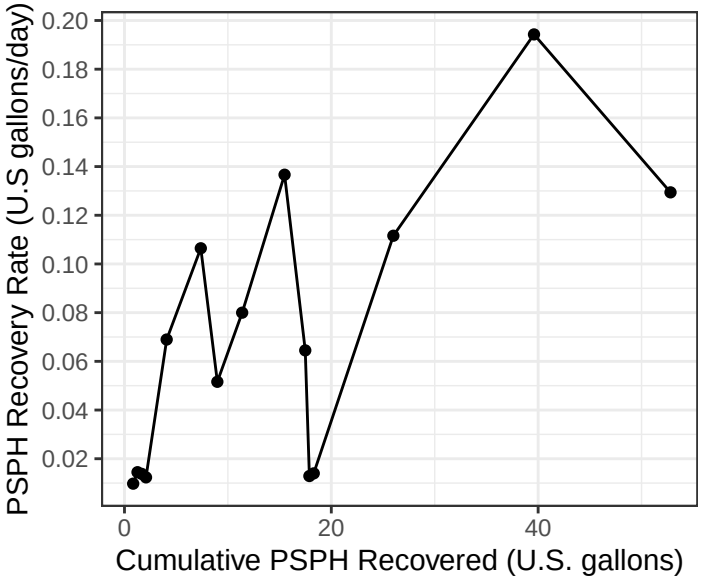

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.0033x + −2.51; p−value = 0.47; R2 = 0.02
PSPH Recovery Rate LN(U.S gallons/day)
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5
−6.0
0
50
100
150
200
Cumulative PSPH Recovered (U.S. gallons)

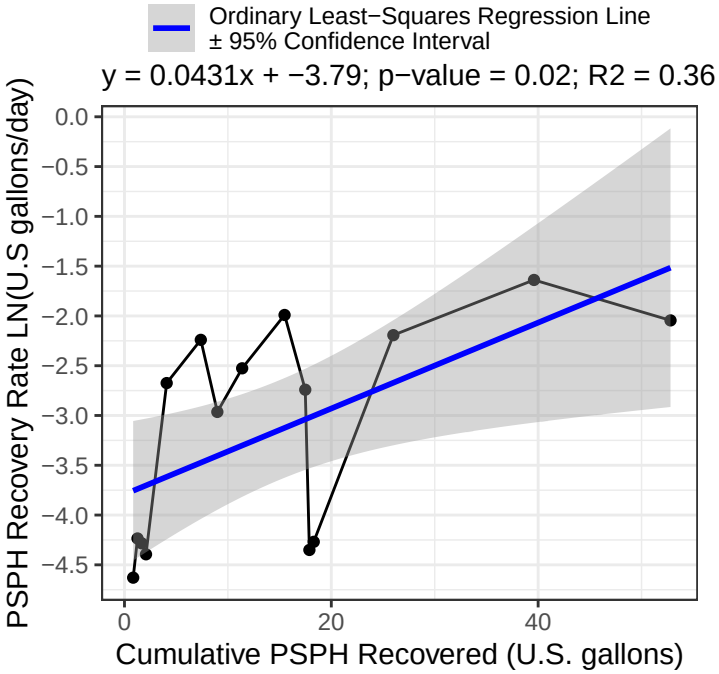
VW31


PSPH Recovery Rate (U.S gallons/day)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
50
100
150
200
250
Cumulative PSPH Recovered (U.S. gallons)

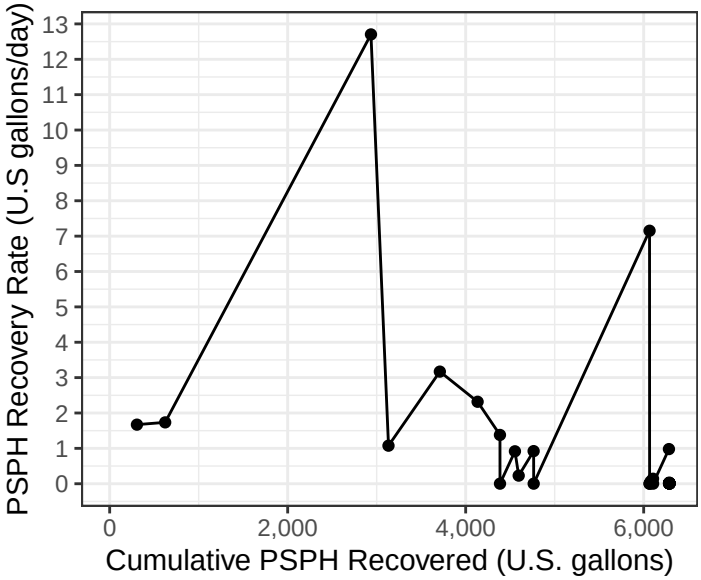

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.0021x + −0.69; p−value = 0.38; R2 = 0.06
PSPH Recovery Rate LN(U.S gallons/day)
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6
−1.8
−2.0
50
100
150
200
250
Cumulative PSPH Recovered (U.S. gallons)

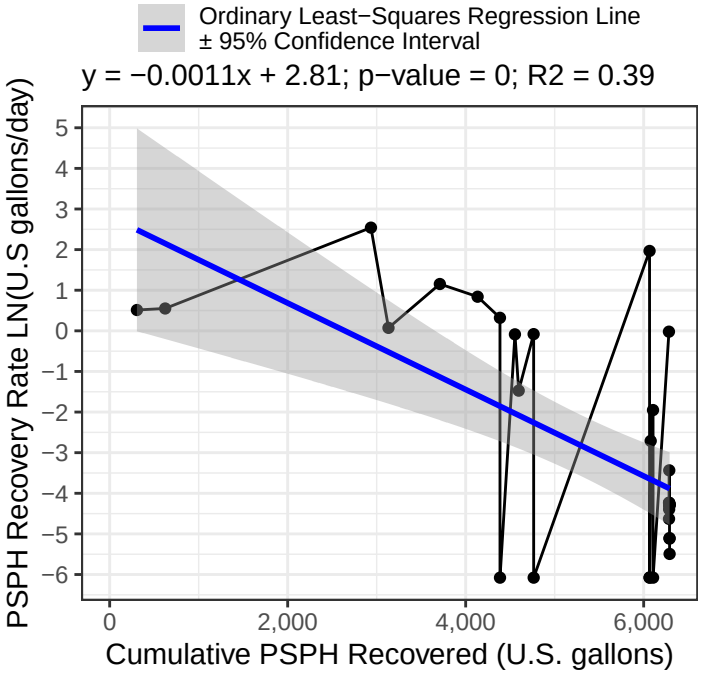
VW32


PSPH Recovery Rate (U.S gallons/day)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
20
40
Cumulative PSPH Recovered (U.S. gallons)


Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = 0.0431x + −3.79; p−value = 0.02; R2 = 0.36
PSPH Recovery Rate LN(U.S gallons/day)
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
0
20
40
Cumulative PSPH Recovered (U.S. gallons)

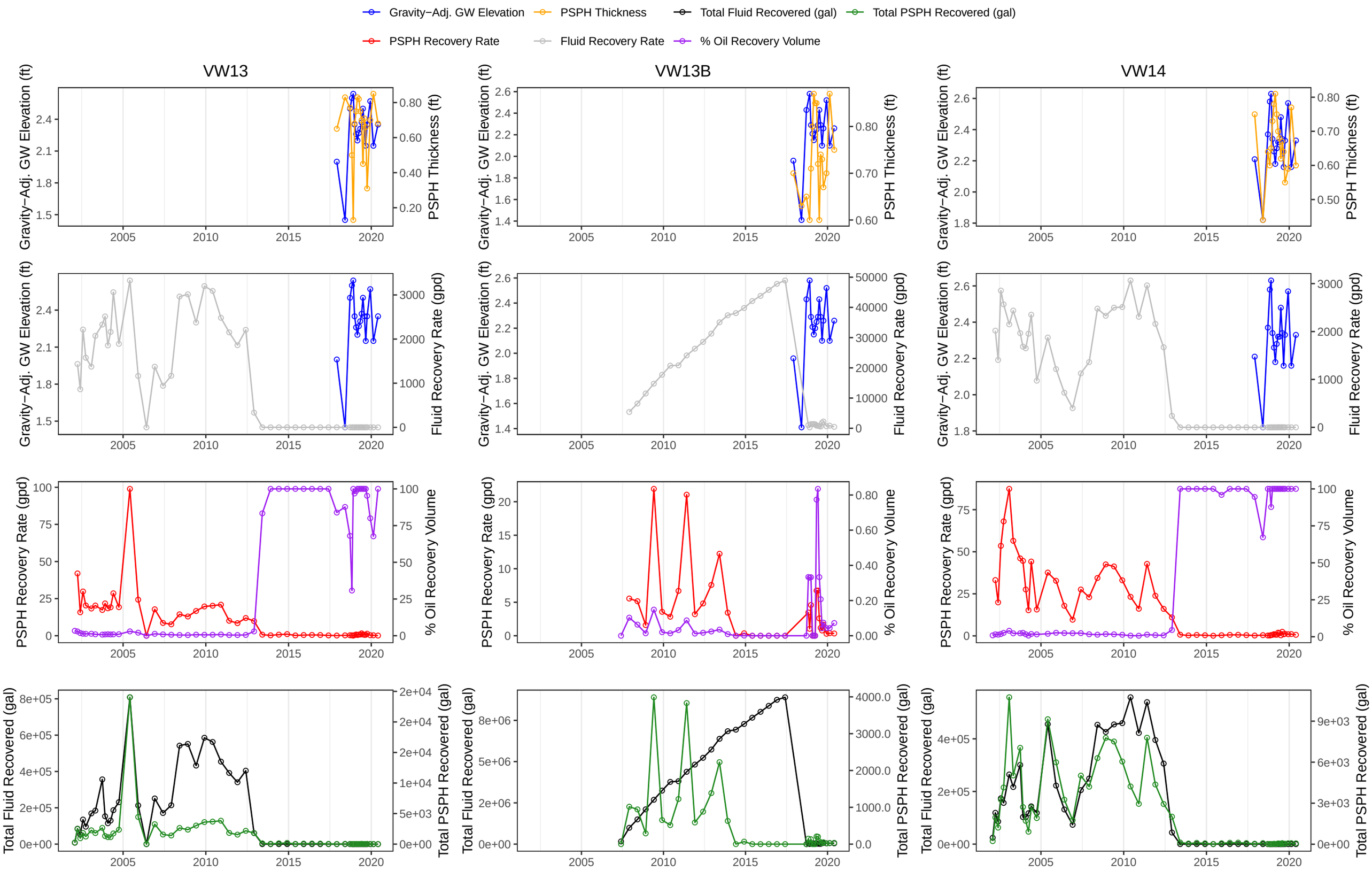
VW38


PSPH Recovery Rate (U.S gallons/day)
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
2,000
4,000
6,000
Cumulative PSPH Recovered (U.S. gallons)

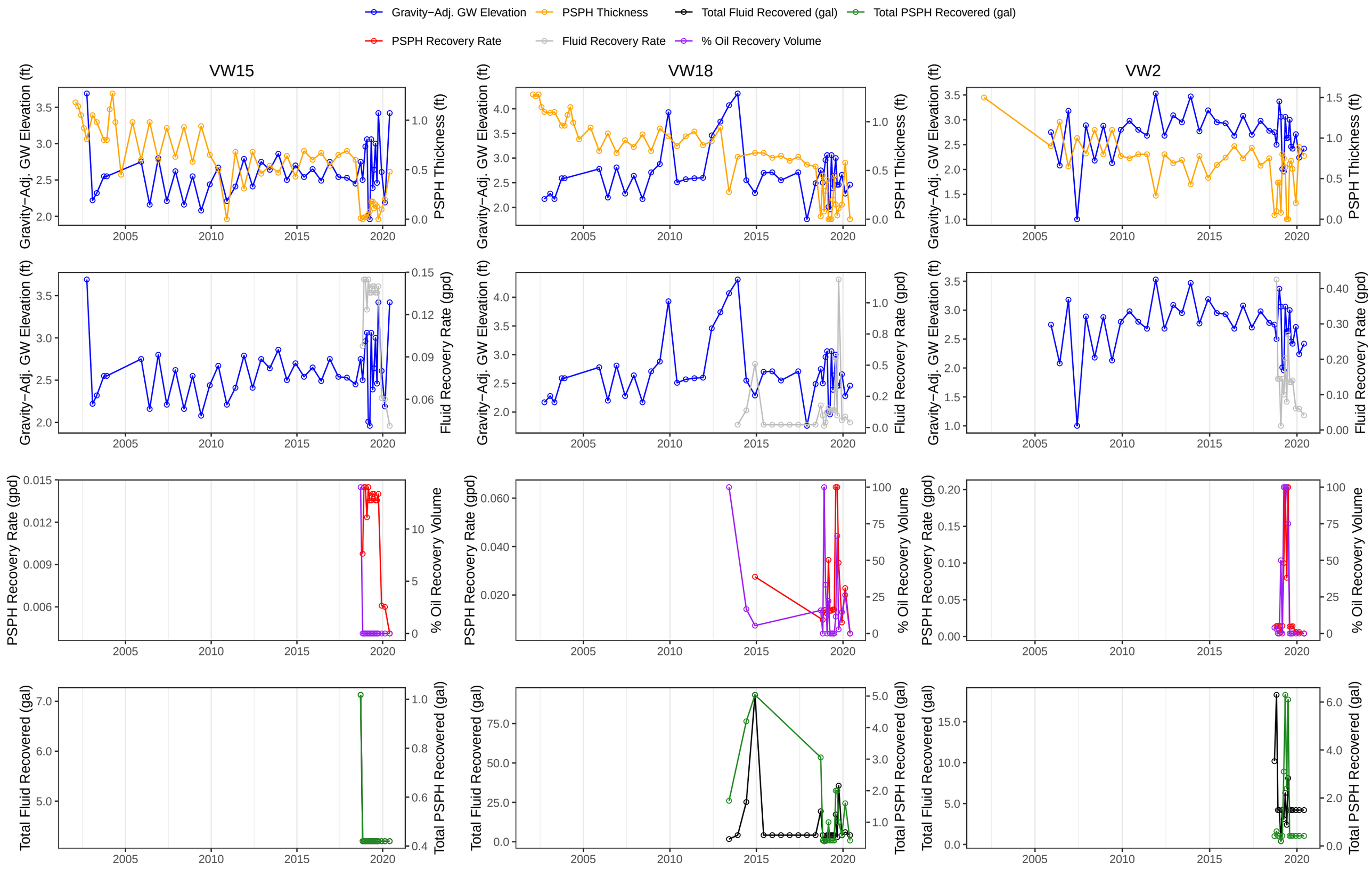

Ordinary Least−Squares Regression Line
± 95% Confidence Interval
y = −0.0011x + 2.81; p−value = 0; R2 = 0.39
PSPH Recovery Rate LN(U.S gallons/day)
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
0
2,000
4,000
6,000
Cumulative PSPH Recovered (U.S. gallons)

Appendix D Time Series Figures

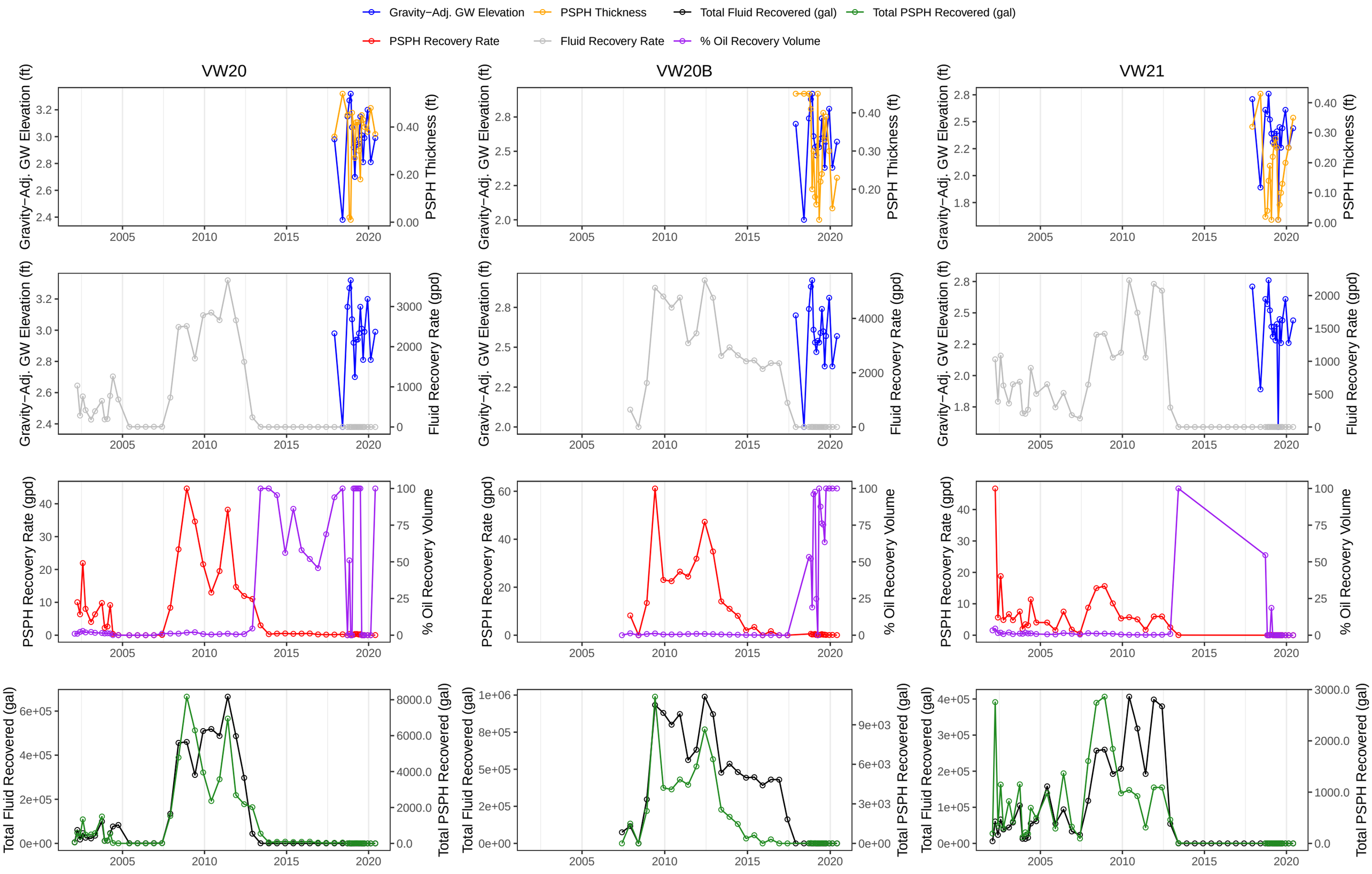
Recovery Wells



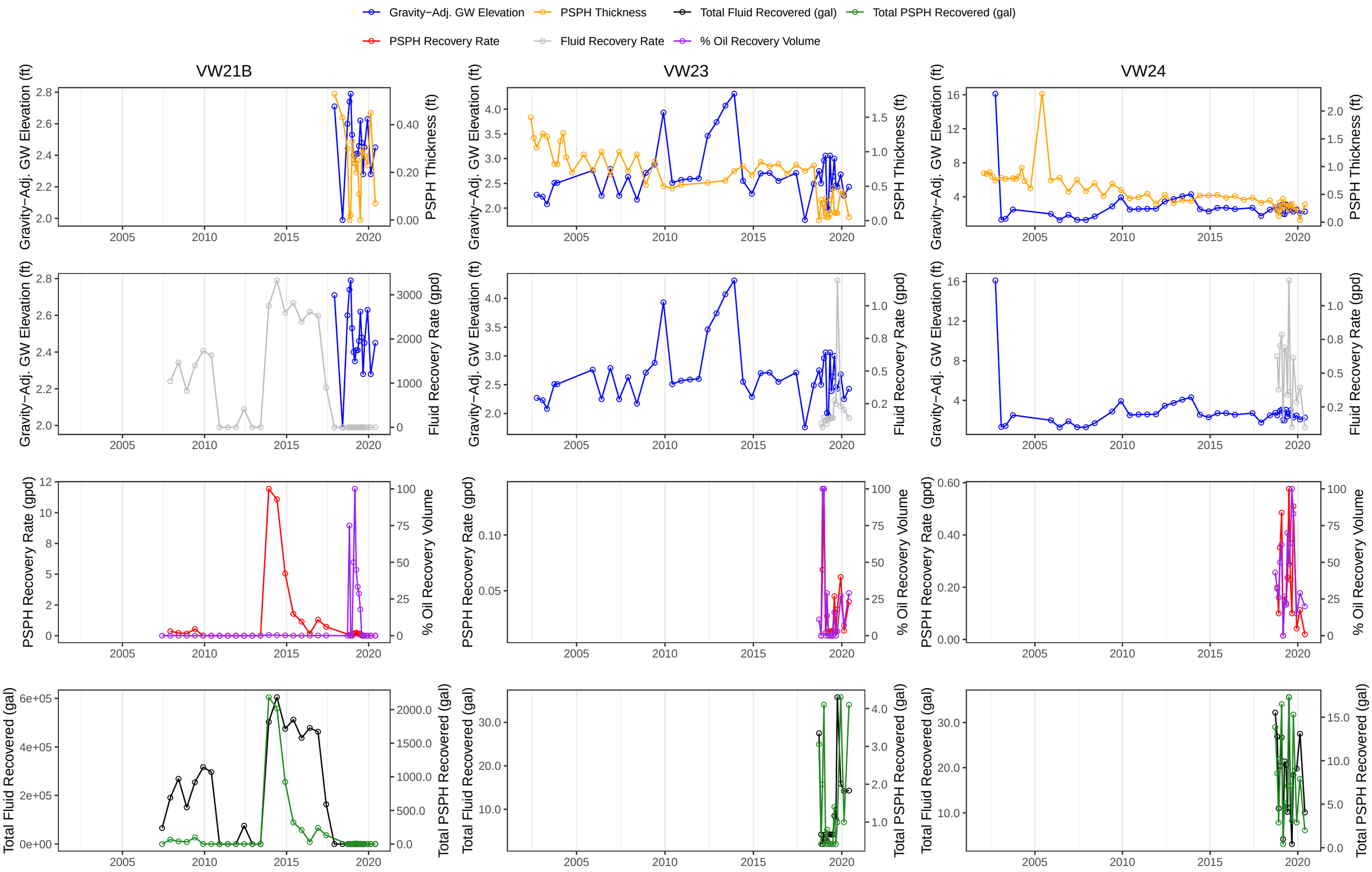
Recovery Wells



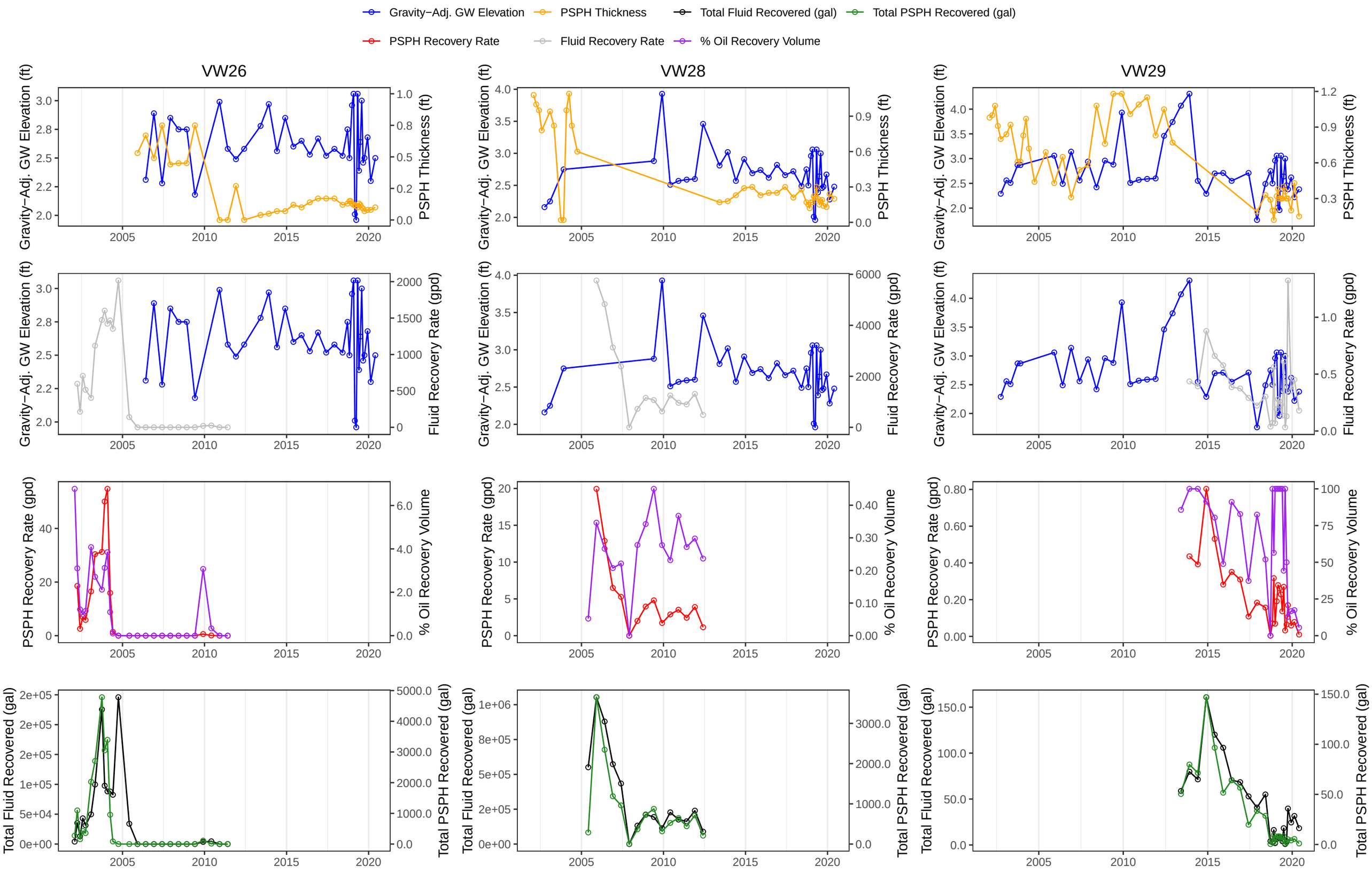
Recovery Wells



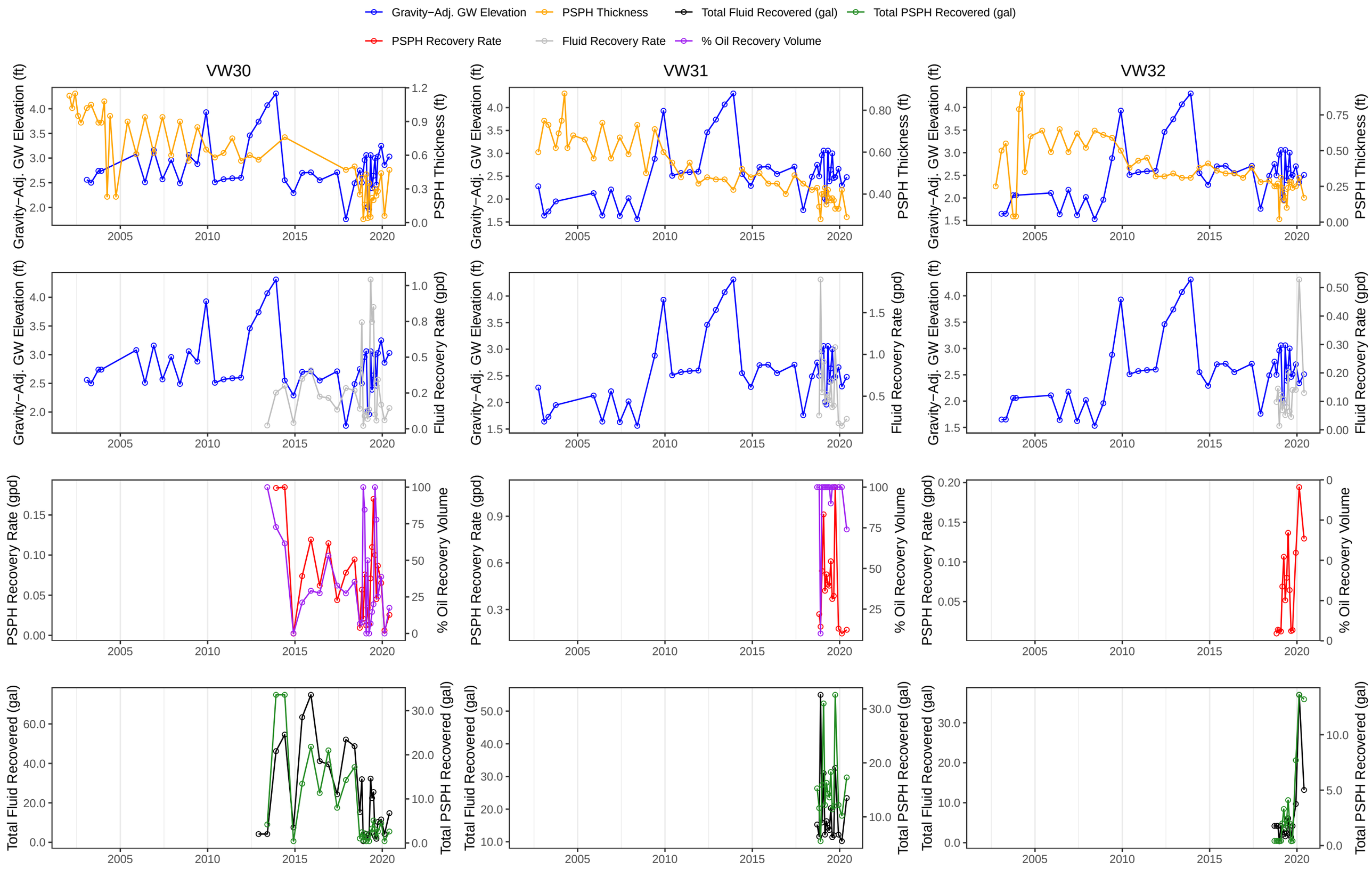
Recovery Wells



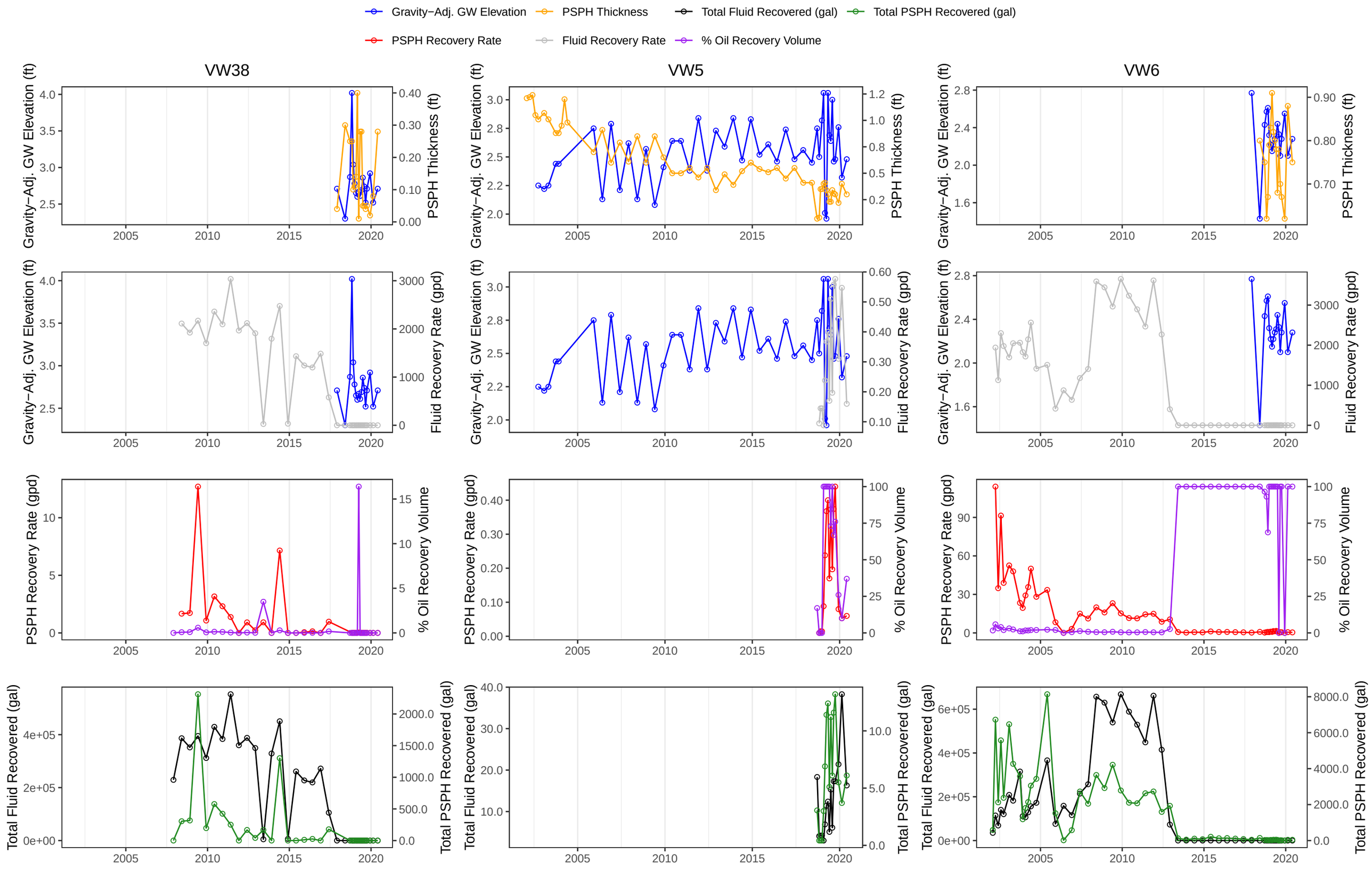
Recovery Wells



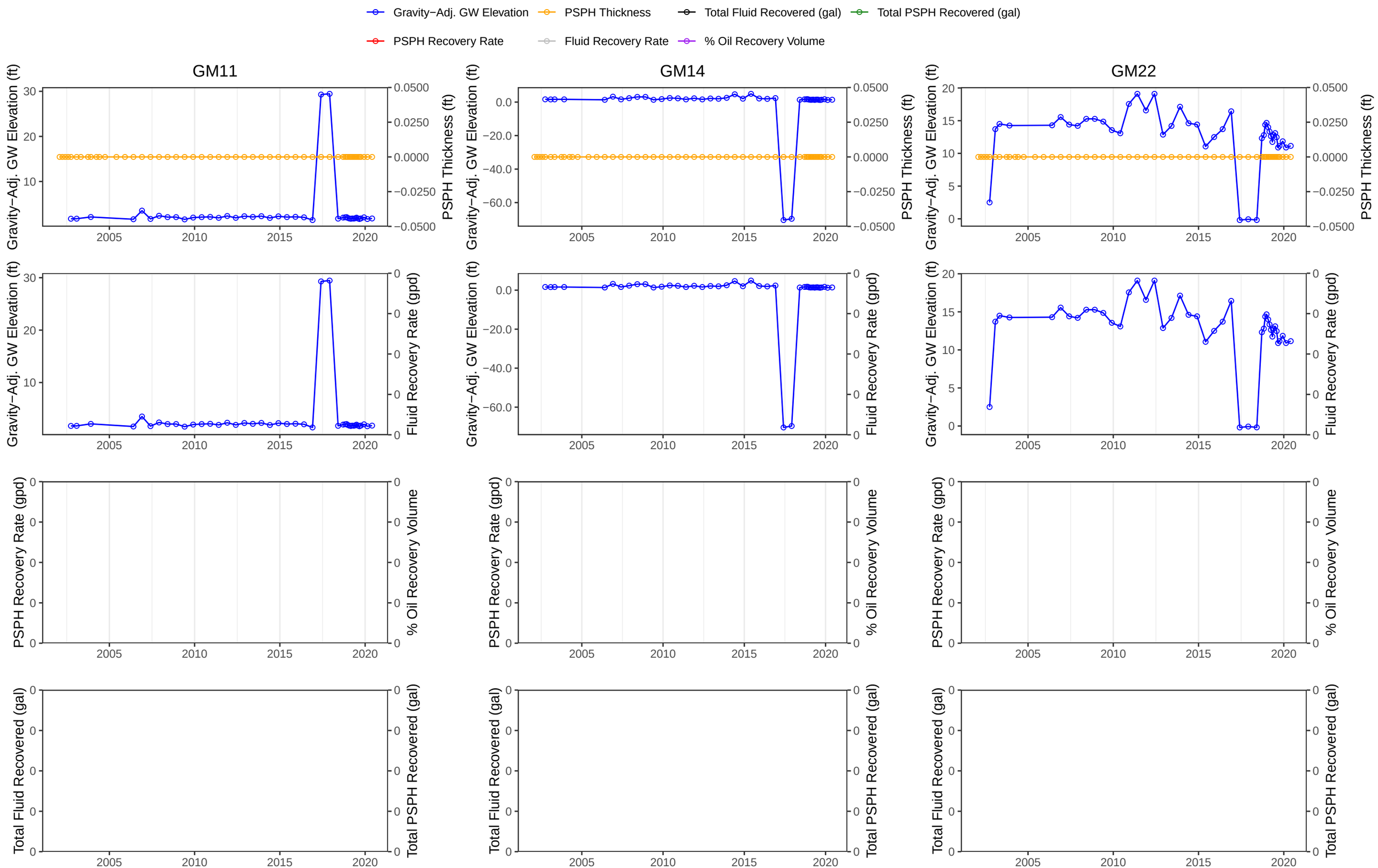
Recovery Wells



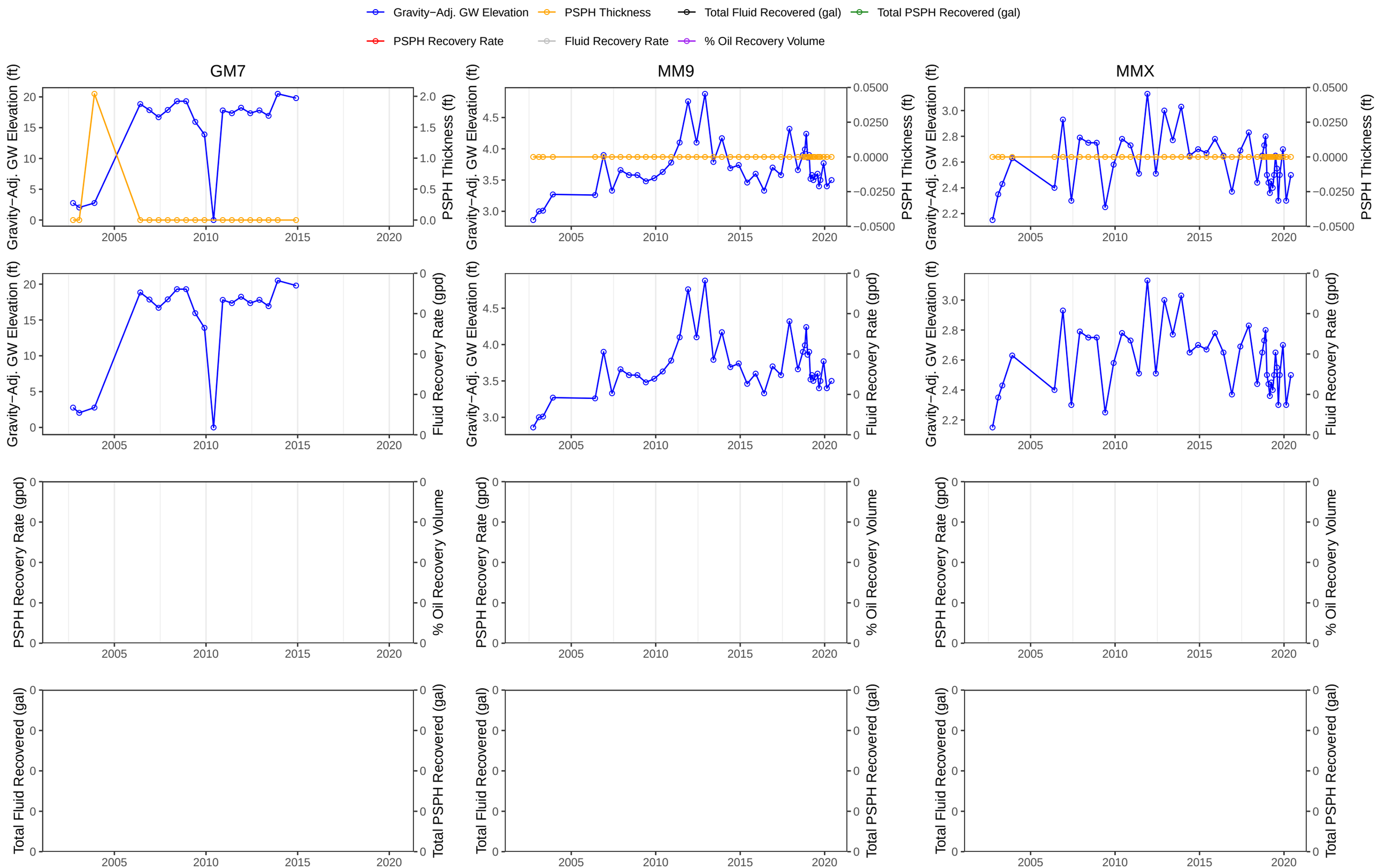
Recovery Wells



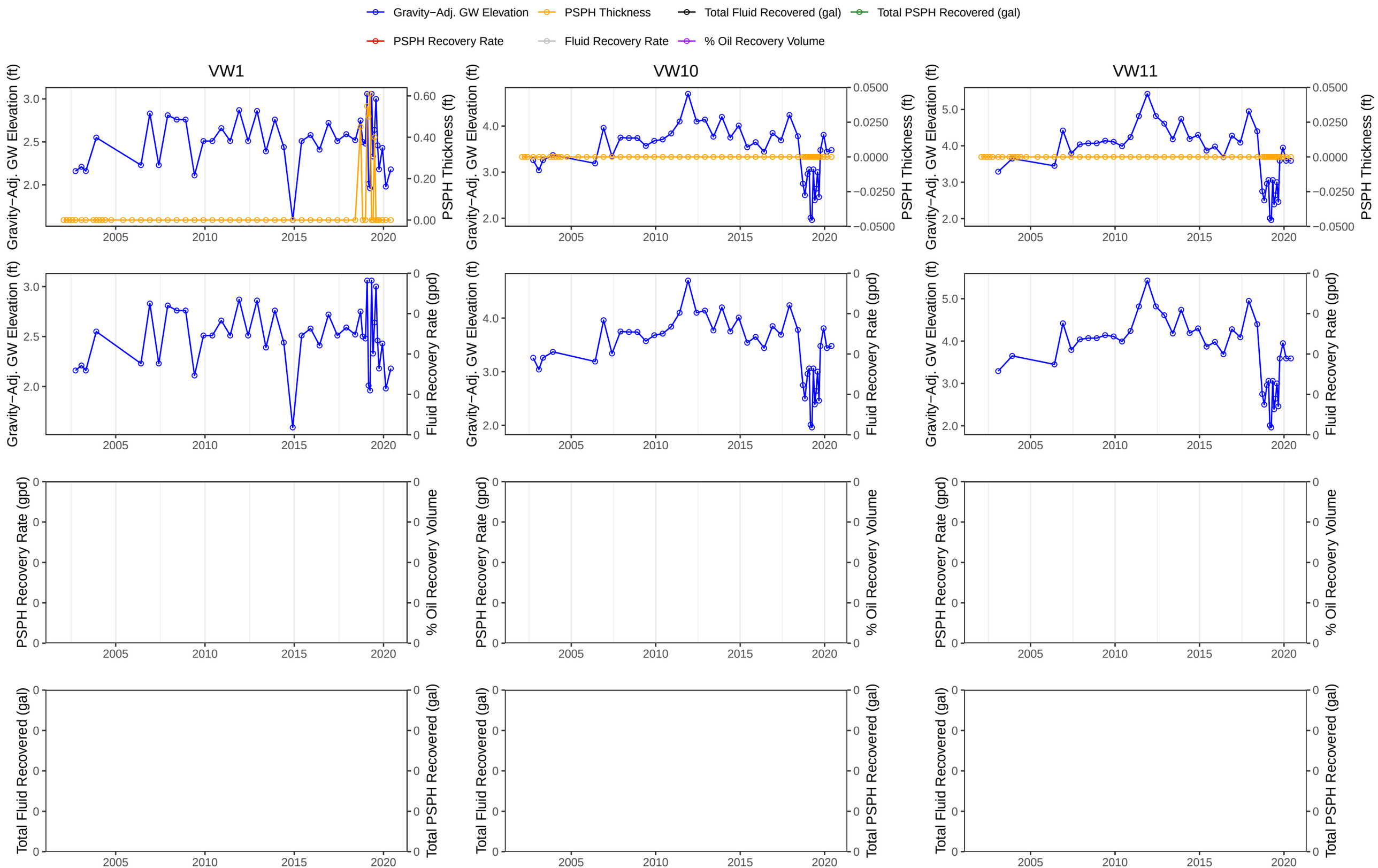
Monitoring Wells



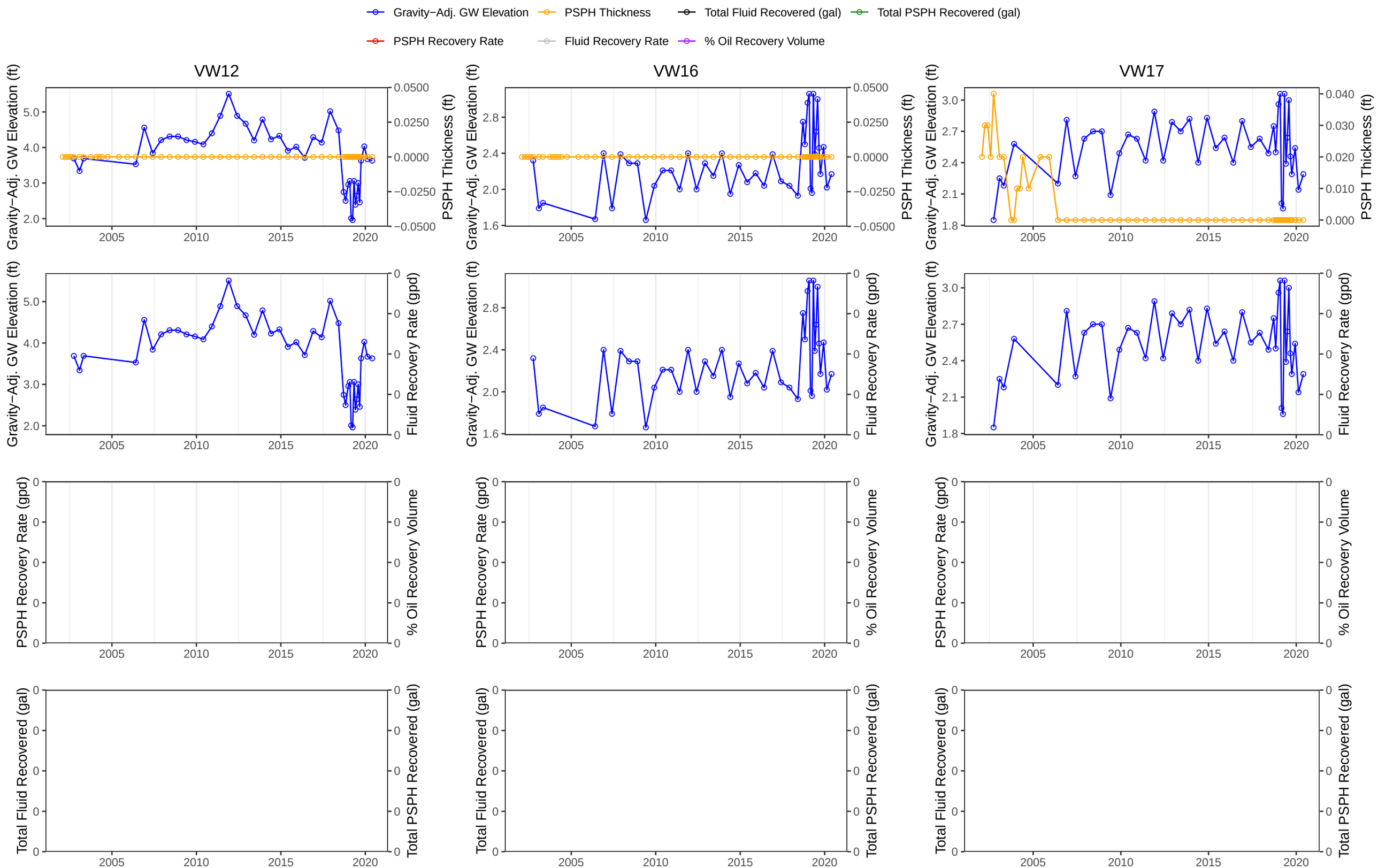
Monitoring Wells



Monitoring Wells



Monitoring Wells



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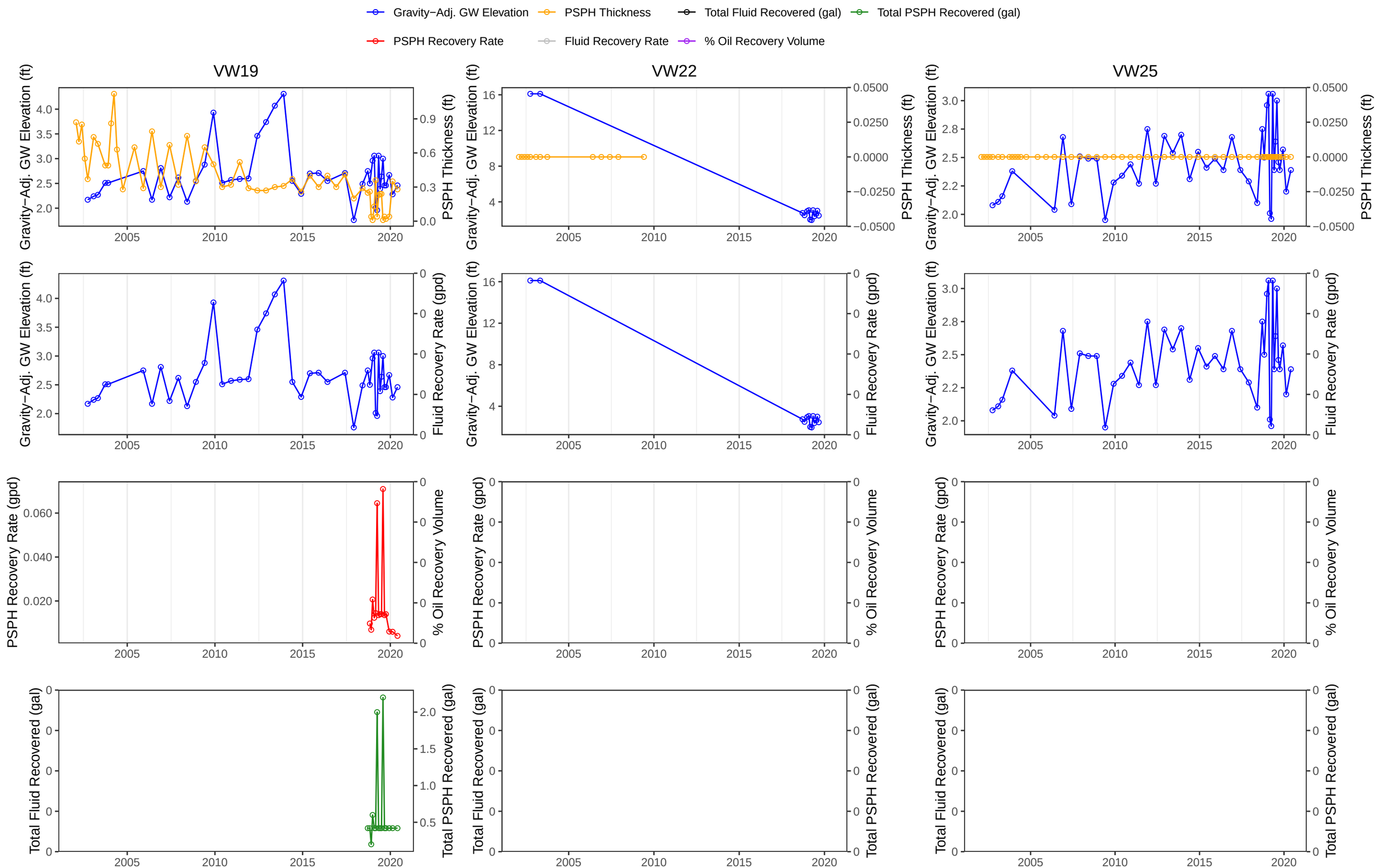
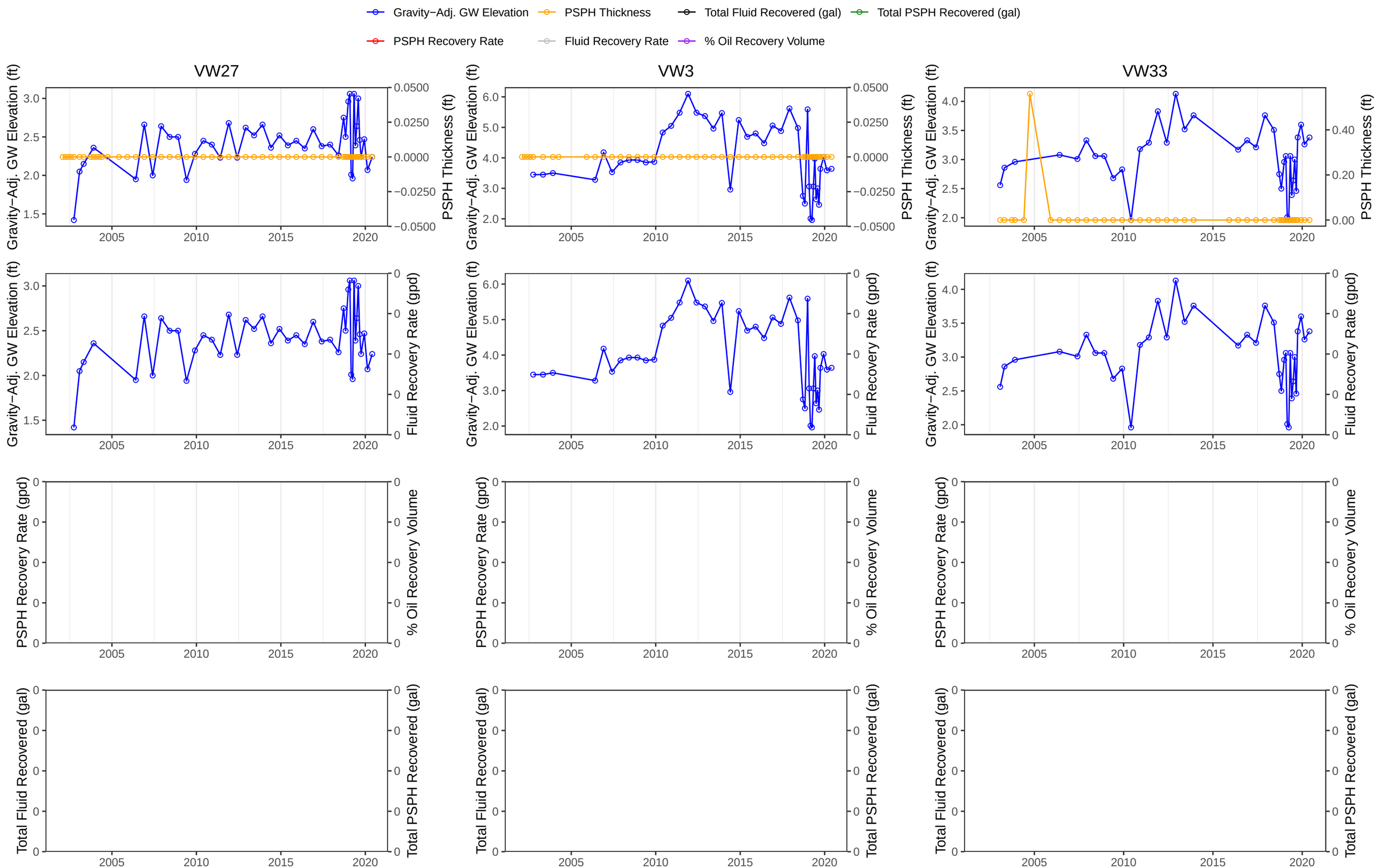
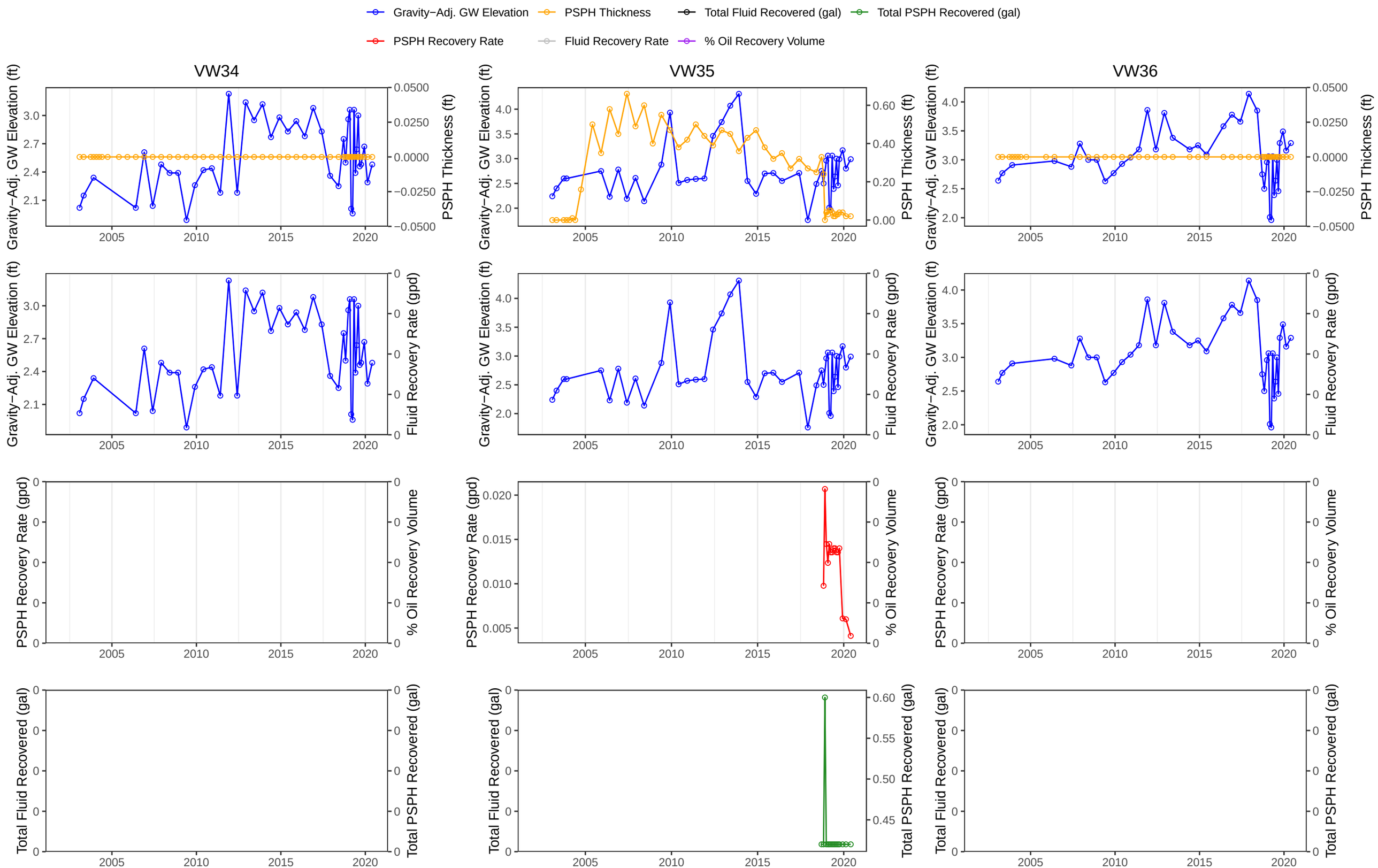


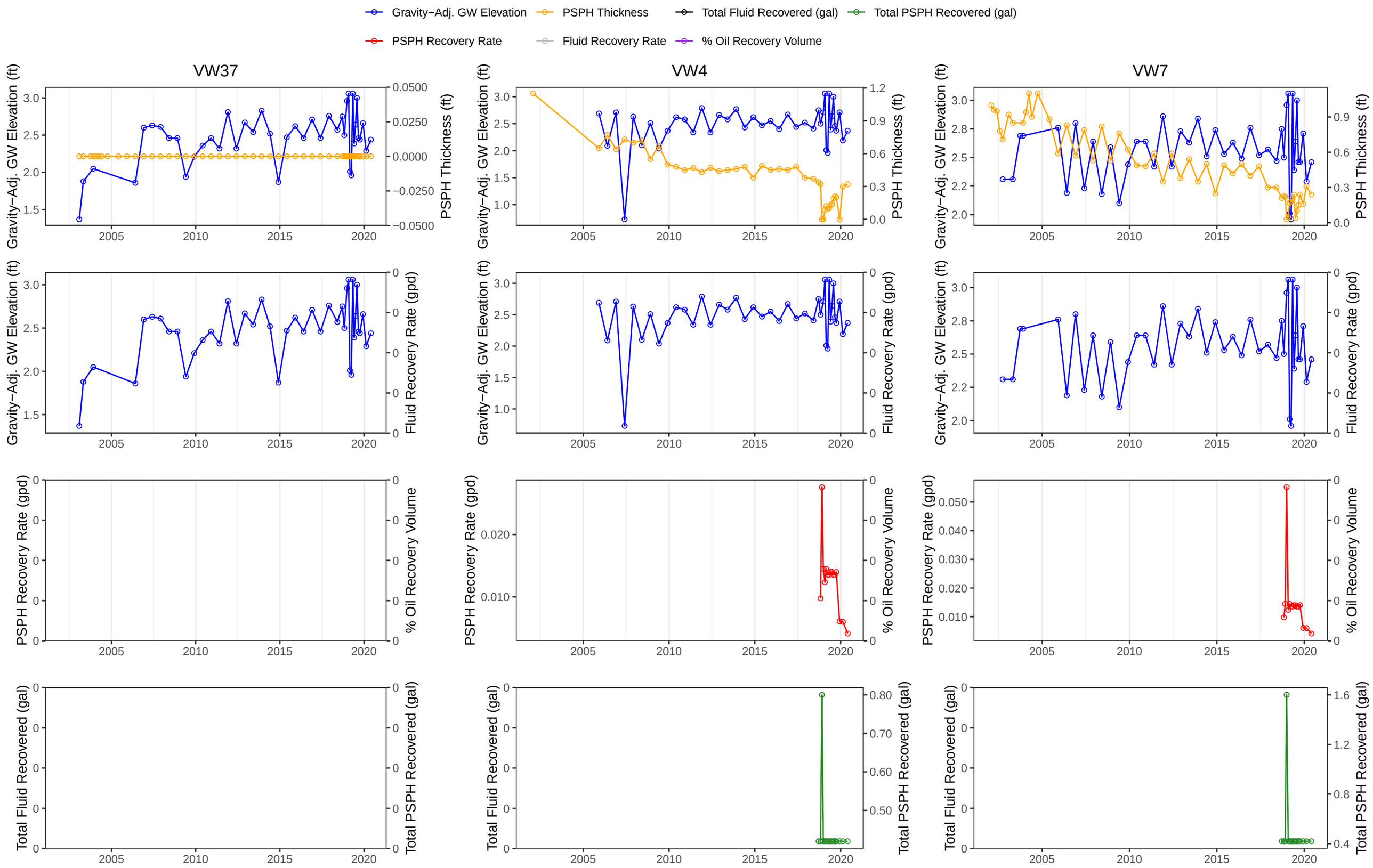
Monitoring Wells



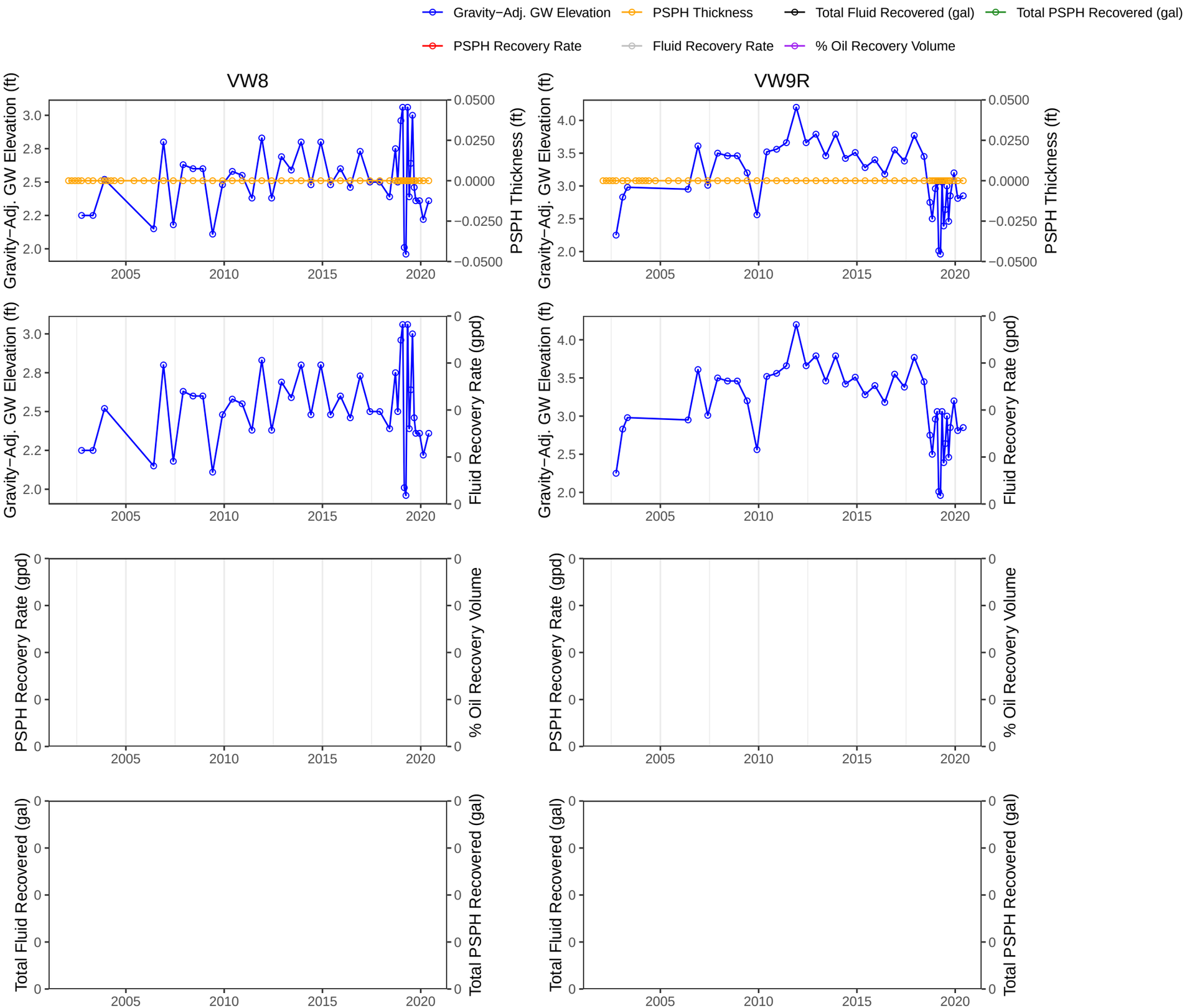
Monitoring Wells



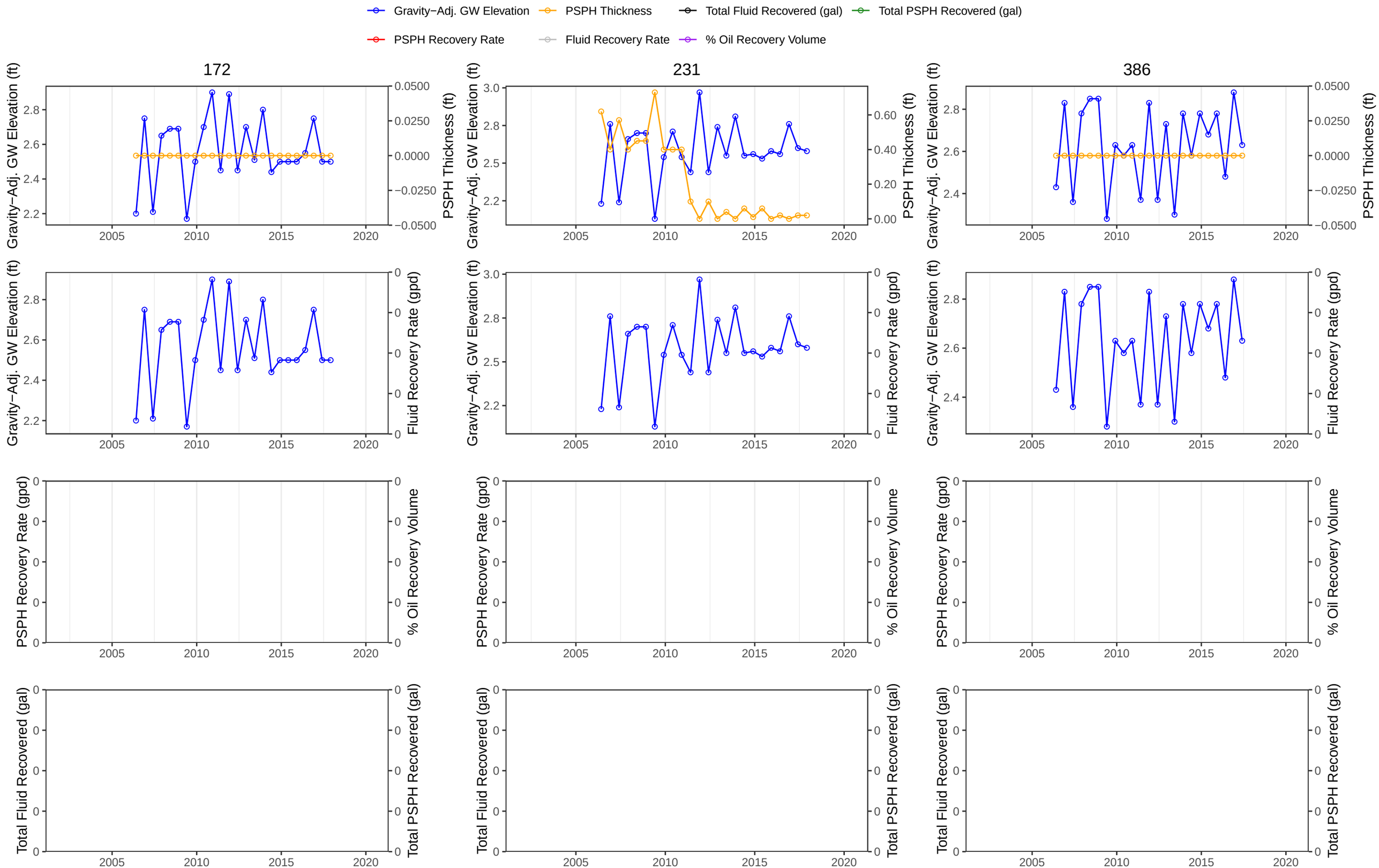
Monitoring Wells



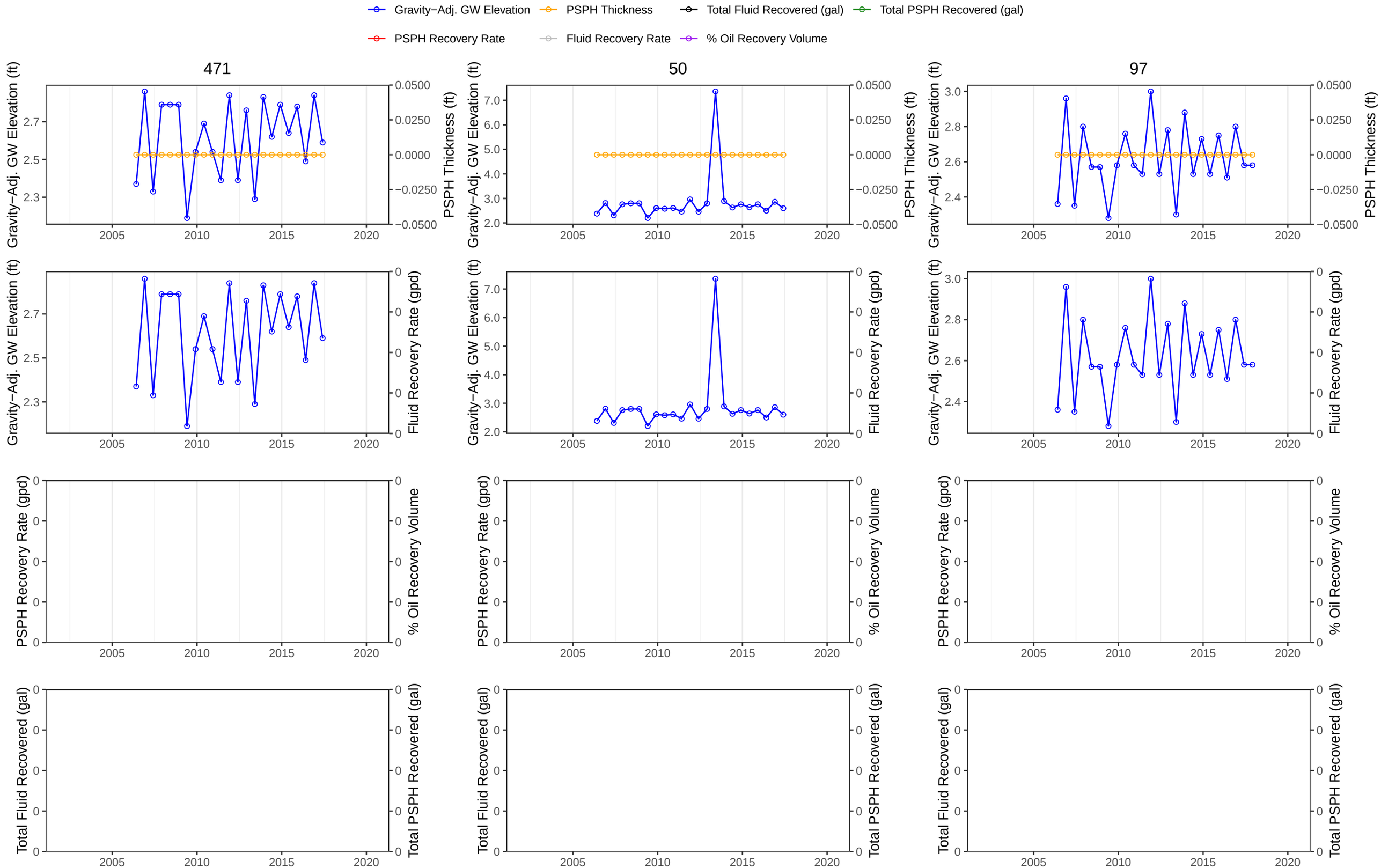
Monitoring Wells



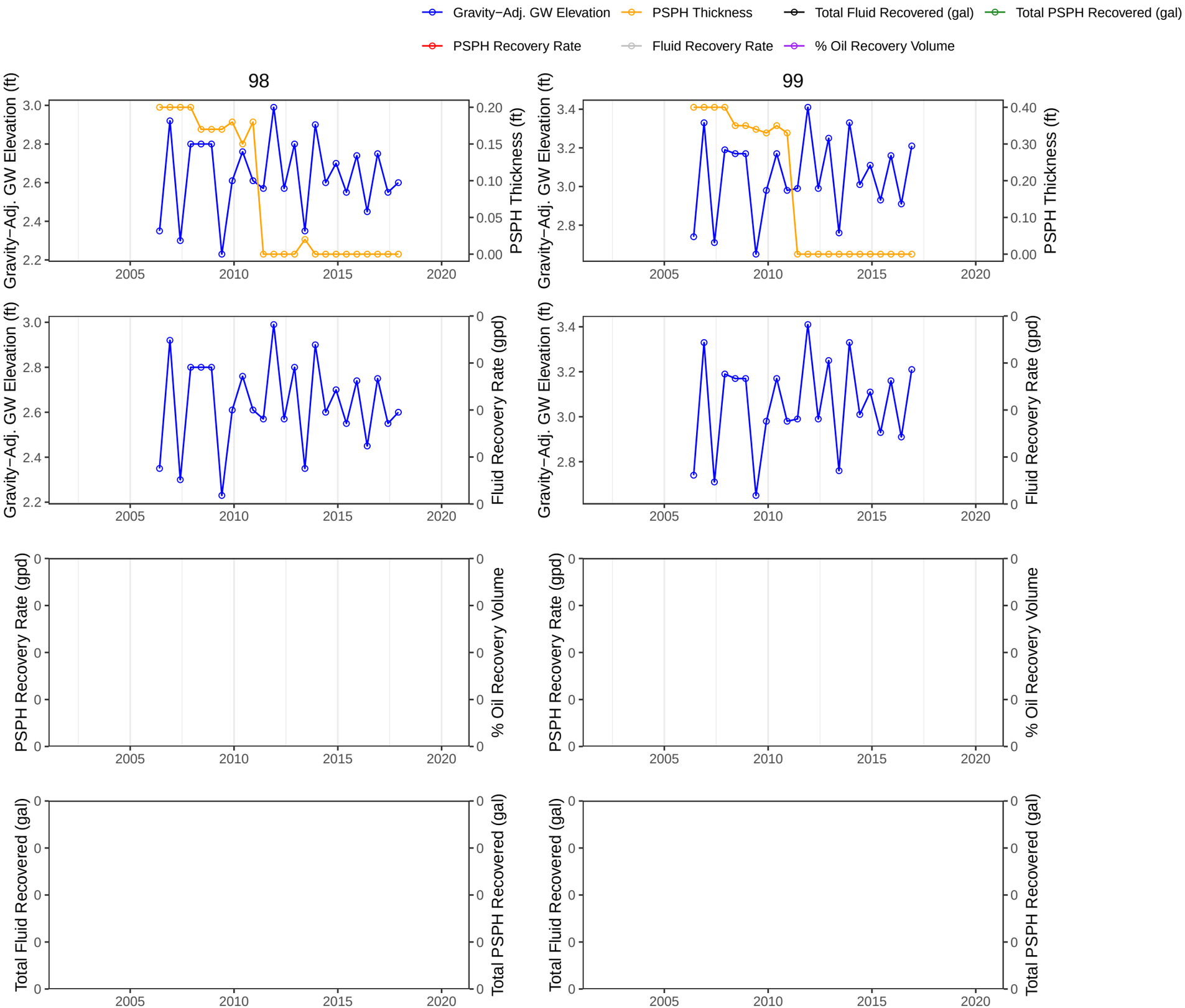
Offsite Monitoring Wells



Offsite Monitoring Wells



Offsite Monitoring Wells



Appendix E USEPA Comments and POC Responses on LNAPL CSM and NSZD Work Plan.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 2
290 BROADWAY
NEW YORK, NY 10007-1866

December 14, 2020

Mr. Brian Epperson,
Director, Environmental Health & Safety
HOVIC
1501 McKinney Street
Director, EHS Houston, Texas 77010

Re: Review of the draft LNAPL CSM and Revised Remedial Action Work Plan, St. Croix Alumina Groundwater Plume, U.S. Virgin Islands, dated July 2020,
EPA ID Number: VID090302084

Dear Mr Epperson:

EPA has reviewed the *LNAPL CSM and Remedial Action Work Plan* for the St. Croix Alumina groundwater plume, located in St. Croix, U.S. Virgin Islands. While we understand that many of our questions may have been addressed verbally at the November 18, 2020 conference call with the Project Operating Committee, the enclosed written comments address the report which is lacking the detail we need to evaluate the efficacy of the proposal.

Additionally, as discussed in our conference call of November 25, 2020, EPA would be interested in discussing with you several recommendations for optimizing the solar sipper system. Finally, as noted in the enclosed comments, EPA is not in concurrence at this time with a final goal of 80% removal of recoverable LNAPL, or with the final transmissivity and corresponding 1-gallon per day recovery criteria for discontinuation of active remediation. These assumptions are dependent upon the plume being stable, which has not yet been established for this site. Further coordination with EPA would be warranted to evaluate the proposed criteria following collection of supporting data.

Should you have any questions, please feel free to contact me via telephone at 212-637-4181, or via email at stein.carol@epa.gov

Sincerely,

Carol A. Stein

Carol A. Stein, PE
Environmental Engineer
Land and Resources Programs Branch

Enclosure

cc: Austin Callwood, Director, USVI-DPNR-DEP (electronic copy)
Syed Syedali, USVI-DPNR-DEP (electronic copy)
Brad Martin, Toeroek (electronic copy)

TECHNICAL REVIEW
LNAPL CSM AND REMEDIAL ACTION WORK PLAN
ST. CROIX, U.S. VIRGIN ISLANDS
ST CROIX ALUMINA SITE
DATED JULY 2020

GENERAL COMMENTS:

General Comment 1*:* The *LNAPL CSM and Remedial Action Work Plan, St. Croix, U.S. Virgin Islands, St. Croix Alumina Site*, dated July 2020 (Work Plan), summarizes the Tier I and Tier II risk assessment reports that were prepared in 2002 and 2003 for the St. Croix Alumina Site. EPA is reviewing these risk assessments to determine whether updates are warranted to reflect both the current Conceptual Site Model (CSM) and the potential for vapor intrusion impacts for any projected or potential reuse of the property. EPA will be contacting you regarding the results of this review. Additionally, please ensure the references to the risk assessments are accurate. In at least one instance (page 45, last paragraph), the date of the Tier 1 risk assessment is incorrectly cited as ES&T 2012 which leads the reader to assume the risk assessment is more recent; However, the date of the reference needs to be corrected to read ES&T 2002.

General Comment 2*:* The Work Plan does not provide specific actionable remedial goals in Step 4 of Section 6.2 for the proposed transition from LNAPL recovery to natural source zone depletion (NSZD) that accounts for the anticipated uncertainty and variability in NSZD, including the variability of a calculated NSZD depletion rate in a well-by-well basis. Without this information, the adequacy of the Work Plan cannot be assessed, and a complete list of data gaps cannot be determined to transition from phase separated petroleum hydrocarbon (PSPH) recovery to NSZD. Please revise the Work Plan to incorporate more details on Step 4 and a cross-walk showing how the proposed NSZD will be evaluated against LNAPL recovery. Also, please note that the transmissivity and corresponding 1-gallon per day criteria (noted in Section 6.2 and elsewhere in the document) is a starting point for evaluating when sippers may no longer be effective tools for removing LNAPL. However, this is dependent on the plume being stable, which has not yet been established at this site. The reason for the apparent instability of the plume may be related to the secondary porosity features present at the site and the buoyancy

changes in the system created by LNAPL pumping activity. We anticipate that further information regarding NSZD and plume stability may be available after additional vapor probe investigations are conducted.

General Comment 3*:* The Work Plan proposes to provide additional visual comparisons of the LNAPL plumes. To ensure the information is readily comparable, ensure the images provided include the following:

Consistent presentation of information in sufficient size and scale to allow for direct comparison of historical and current LNAPL extent.

Consistent labeling of LNAPL contour intervals for ease of understanding of the information presented.

Development of current figures for all information presented.

Revise the Work Plan to address this issue.

General Comment 4*:* Throughout the Work Plan, reference is made to the potential impacts of calcification and an apparent reduction in the inherent porosity of the limestone beneath the Site. However, boring logs are generally poor quality and there are no data provided which substantiate that porosity and permeability in the limestone is restricted to secondary porosity features. Evidence for the statements made regarding secondary porosity is not provided in the Work Plan. The presence of evaporites is only indicated on Figure 4-6 in wells outside the LNAPL treatment areas (specifically in wells VW-33, VW-37, VW-35, VW-3), yet the extent of mapped evaporites is shown near extraction well VW-13B. Based on the data shown on Figure 4-6, it is unclear how the extent of the potential infilling of reef carbonate porosity because of evaporite deposition and calcification was developed.

Also, large scale geologic cross-sections shown in Figure 4-3 do not cut through the majority of the LNAPL treatment area and do not show the juxtaposition or even the presence of any evaporite facies. Smaller scale treatment-area specific geologic cross-sections that show the relationship between the limestone and evaporite

facies are needed. Cross-sections are needed along with the salient extraction well completions showing the LNAPL extent to support the project specific CSM for the Site.

Further, the cross-sections need to indicate the approximate location of the water table in critical extraction wells such that the thickness of LNAPL can be evaluated relative to changes in the relationships between geology and well completions and the apparent thicknesses of LNAPL. The relationship of geology to well screens and the water table can have major impacts on LNAPL removal efficiencies and apparent thicknesses of the LNAPL measured in the field. Please revise the Work Plan such that it incorporates site-specific data capable of supporting the LNAPL CSM as discussed above. In the event such data do not exist, then identify the necessary steps to fill the data gaps to ensure the presented CSM is substantiated by site-specific data.

General Comment 5*:* Throughout the Work Plan the weathered nature of the LNAPL at the Site is noted as potentially impacting viscosity and the transmissivity of the LNAPL, but no viscosity data is provided. The authors imply that the effective solubility data for the LNAPL at the Site resembles a fresh diesel and No.2 fuel oil as provided in Tables 5-2 and 5-3. Please explain how the effective solubilities for the LNAPL at the Site can be similar to fresh diesel and No.2 fuel oil while the LNAPL can be described as highly weathered. Viscosity data for the LNAPL and other geochemical information is needed to substantiate that weathering has impacted the transmissivity of the LNAPL at the Site. Further, if the geochemical data substantiate that the hydrocarbons are weathered, additional lines of evidence regarding the appropriate effective solubility for the site hydrocarbon releases is needed.

General Comment 6*:* In Section 5.5, LNAPL Mobility and Recoverability, reference is made to previous studies that indicate seepage rates at the Site for LNAPL are 0.1 foot/day. Reference to dissolved phase monitoring results as an indication of plume stability also is cited. Substantiation of the mobility of the LNAPL plume needs

to be presented separately from any determination of the stability of the dissolved phase plume. LNAPL buoyancies and the orientation of main secondary fracture zones will control LNAPL mobility and host rock storativity. Neither of these two factors are adequately defined for the Site. Without information regarding the orientation of the primary and secondary fracture zones or LNAPL buoyancy, the recoverability of the LNAPL and the stability of the LNAPL plume cannot be adequately established. Please revise the Work Plan to address these data gaps.

Additionally, in Appendix B, NAPL Thickness Maps, the extent of LNAPL is shown for 2002 and 2003, and then from 2006 through 2019. A review of the plume maps indicates the LNAPL thickness has varied over time. The shifting LNAPL thicknesses shown on these images do not support the interpretation that the plume is stable. Revise the discussion of plume stability to address the shifting configuration of the LNAPL plume.

General Comment 7: The presence of reducing conditions capable of substantiating the potential for reductive MNA processes to act on the LNAPL were only measured in dissolved phase monitoring wells shown in Table 5-4. The results in monitoring wells are variable as shown in Table 1 of the *37th Groundwater Monitoring Event and 1st Semiannual 2020 Status Report for the St. Croix Alumina Groundwater Remediation Project, Geomonitoring Services (GMS), August 31, 2020.* Some data presented in this table suggest the presence of reductive conditions while other wells have values for oxygen reductive potential (ORP) and dissolved oxygen (DO) which are positive and higher respectively, which is indicative of more oxygenated conditions in the groundwater sampled. It is noted in the first sentence of the second paragraph on page 45 of the Work Plan that "Extensive assessment of natural attenuation processes has not been conducted at the site." Additional ORP and DO measurements are needed from wells and associated groundwater beneath the LNAPL plume to evaluate geochemical conditions in groundwater beneath the LNAPL plume and the potential for MNA processes to reduce LNAPL volumes over time. Currently, the lack of geochemical data represents a significant data gap in

substantiation that transition to NSZD and MNA is warranted. Ensure the Work Plan adequately addresses this data gap.

General Comment 8*:* In section 5.5.1, Bail Down Tests Assessments of Transmissivity and Mobility, second to the last paragraph, in the last sentence on page 48, the Work Plan notes that additional bail down testing both spatially and temporally is required. Presumably, this is because current modeling results are only based on bail down tests from three out of approximately 21 wells inside the mapped LNAPL plume. The Work Plan calls for bail down tests at the extraction wells in the proposed network. It is unclear how many, where, and in what wells additional bail down tests will be performed. Please revise the Work Plan to present the locations of additional bail down testing and ensure the selection of those locations considers geologic setting, the presence or absence of fractures, LNAPL thickness, and water table elevation.

General Comment 9*:* LNAPL recoveries shown in Table 5-6 show inconsistent expected LNAPL transmissivity values that exceed the practicality limits provided in the ITRC (2018) guidance and calculated by the authors of greater than 1 gallon per day (gpd) based on an expected transmissivity value of 0.8 foot squared/day. Based on this data. it is unclear how long it might be before individual wells might consistently fall below this estimated practical recovery limit. Many more wells have consistent recovery values that exceed the 0.5 gallon per day recovery limit in this table. Optimization of the solar sipper systems followed by operation of the systems for an additional period of time is warranted before the system can be established as not providing additional value in terms of LNAPL removal rates and total volumes. Solar sippers that can be cycled more regularly allowing for recharge of LNAPL and the addition of additional fluid storage at each location may change the observed recoveries. EPA would be interested in further exploring with the ERT ways to optimize the solar sipper systems. Additionally, changes in the LNAPL removal methods may also change LNAPL recoveries shown in Table 5-6, which is attached at end of the draft Work Plan.

General Comment 10*:* Section 6.2 discusses the proposed framework for LNAPL recovery well shutdown. Four steps are listed, but Step 4 indicates that Steps 2 and 3 would not have to be met when the POC concludes that the active remediation is no more effective than NSZD, or 'where NSZD processes are particularly robust'. Please note that any deviation to the listed steps would require EPA approval. Please revise the Work Plan to note that the POC is not authorized to discontinue active remediation of the system without prior approval from EPA.

SPECIFIC COMMENTS:

Specific Comment #1 *- Table 5-4, Groundwater Parameters, Page 45:* Data presented in Table 5-4 of the Work Plan indicates that reducing conditions are present in key wells. No basis is provided for how the wells were identified as key in terms of the potential for MNA to occur at the site. The Work Plan suggests that the reducing conditions in these key wells are capable of supporting nitrate and sulfate reduction and methanogenesis of LNAPL constituents. Section 5-4 (p. 45) also cites the GES/ES&T model results which indicate that there are 3,379 barrels of oil remaining in the ground, and that there has been a 91.1% decrease in estimated hydrocarbons. However, insufficient information is provided to substantiate that a 91.1% reduction has occurred as stated in the text. If the POC is interested in continuing to refer to the results of this model, the Work Plan would need to provide sufficient detail about how these modeled estimates were derived to allow for concurrence with the stated results. The oxidation reduction conductivity (ORP) and the dissolved oxygen (DO) data would need to be provided for all wells where LNAPL or dissolved phase contamination is present. Furthermore, the work plan would need to be revised to provide the requested information, to provide the decision logic for the selection

of key wells, and to provide sufficient detail regarding the model used to determine the stated percent reduction to allow for an independent assessment of the information provided.

Specific Comment #2 *Table 5-7, Summary of Recovery August 2018 through to May 2020, Page 53:* Under Section 5.5.3, Table 5-7 provides LNAPL recovery rankings for different wells. However, the Work Plan needs to clarify how theses rankings were established and whether these rankings are based on geological conditions and the resulting amount of PSPH recovered from these wells over time. Additionally, details regarding the calculations of "% of total LNAPL" and "oil/water cut (%)" need to be presented as well as the data used needs to be provided.

Specific Comment #3*: Section 6, Updated Remedial Action Work Plan, Page 63:* Section 6 discusses the scope of the Work Plan, which is an updated version of the previously EPA approved July 23, 2001 document. One of the stated objectives of the Work Plan (a.k.a., the updated work plan) is the optimization of LNAPL recovery efforts in order to cease LNAPL recovery. How "optimization" will be determined, what lines of evidence will be used to perform the optimization, and how it will be determined that the system has been optimized to the degree possible is not defined. Site specific performance goals and decision thresholds need to be defined to achieve consensus for the proposed approach. A decision tree and a contingency plan are recommended for integration into the Work Plan, to help determine which decision criteria to use to move the site forward through the optimization process. A decision tree is outlined in *" A Decision-Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquids (LNAPL), EPA 542-R-04-001, March 2005* [and a similar decision tree is outlined in LNAPL-3: LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies, ITRC, March 2018).

Specific Comment #4: Section 6.1, LNAPL Recovery Activities, first paragraph, Page 63: The Work Plan indicates that active measures to manage the LNAPL at the Site should only proceed until June 2021. No rationale is presented for this date. Revise the Work Plan such that the firm date of June 2021 is removed, and lines of evidence are presented that will be attained prior to the cessation of LNAPL recovery.

Specific Comment #5 - Section 6.1, LNAPL Recovery Activities, Bullet 1 Page 64: In the second to last paragraph, it is noted that solar sipper systems will be visited monthly. Because of the low transmissivities of wells at the site, sippers should be checked and cycled more often and on a regularly frequency during the optimization process to assure maximum recoveries are obtained. Weekly assessments, at least during start up, could potentially increase system efficiencies and be used to evaluate the viability of reducing the frequency of system checks and optimization activities. Revise the Work Plan to allow for more frequent initial visits for optimization related activities.

Specific Comment #6: Section 6.2, Proposed Framework for LNAPL Recovery Well Shutdown, Bullet 3, Page 65; and Section 6.2.1, Rationale and Methodology for Reservoir Decline Curve Analysis, Page 66: In Section 6.2, a goal of 80 percent removal of the recoverable LNAPL is proposed. However, few details are provided regarding how this criterion will be applied to the Site. The Work Plan needs to be revised to include specifics regarding how this criterion would be developed and used for decision making purposes before it can be adopted for use at the Site. Additionally, EPA is not in concurrence that this should be the end goal for removal. We would be interested in exploring with the POC ways to increase the removal of recoverable LNAPL beyond 80% removal.

Specific Comment #7 Section 6.2.1, Rationale and Methodology for Reservoir Decline Curve Analysis, Page 66: In Section 6.2.1, in the second to the last sentence, a criterion for R^2 squared of 0.1 is suggested for use when

deciding to perform data analyses and estimating trends. The basis for suggesting this criterion is presented as being based on the inherent variability within geostatistical data sets. Provide a literature reference indicating that use of 0.1 is preferred for analyzing geostatistical data trends. A review of the current regression analyses, provided in Appendix C, Reservoir Decline Curves, suggests that many other factors may influence the observed results, such as changes in extraction methods and protocols or even changes in extraction technologies and equipment. The nature and distribution of results and other statistical assumptions must be considered and the appropriate methods for performing trend analyses used based on data set characteristics. Revise the Work Plan to provide the decision logic used for the use of R^2 as the preferred data assessment metric.

*Specific Comment # 8 : According to Section 6.2.3 (page 67 of report) – "*Reductions in the frequency of monitoring is anticipated (initially to annual) but this will not occur until after all LNAPL recovery activities has ceased at the site and sufficient time has elapsed since termination of recovery (anticipated to be 4 semi-annual events) that plume stability (post recovery termination) has been demonstrated. Ultimately all groundwater monitoring will cease when the Tier II SSTLs are achieved in all perimeter wells". Please note that additional semi-annual monitoring would be required for several years after the SSTLs are achieved to ensure that the goals have been met. The details regarding the extent of post-remedial monitoring warranted will be the subject of further discussion between EPA and the POC.

Specific Comment #9- Section 6.3, Natural Source Zone Depletion Assessment, Page 71: It is unclear which wells will be analyzed for groundwater geochemistry during the Phase 1 effort. LNAPL wells as well as dissolved phase monitoring wells need to be included in the Phase 1 sampling and analysis plan to support MNA evaluations. Revise the Work Plan to specify all wells to be sampled in support of this effort.

Specific Comment #10: Section 6.3, Natural Source Zone Depletion Assessment, Page 71: During Phase II, it is proposed that E-flux and an equivalent E-flux method for carbon dioxide measurements in the subsurface will be

performed using a grid approach. Flux methods depend on reliable estimates of flux through vadose zone media to obtain reliable estimates for expected concentrations of methane and carbon dioxide over time. As noted by ITRC (2018) guidance, it is also possible to use vapor probes properly positioned to emulate flux through differing geologic units at several depths above the LNAPL, but below the surface, to more accurately estimate carbon dioxide and methane concentrations in vadose zone media. This type of application may be more desirable based on the LNAPL CSM for this Site. Less permeable media, which could include limestones with only limited secondary porosity features, alluvium, reef overburden, fill, and evaporite deposits may enhance or drastically reduce the effectiveness of NSZD. Given the variability in the geology at the Site, flux type measurements may be unacceptable for use. It is also unclear why these analyses will not be performed during Phase I, as the collection of this data may be essential to the decision-making process and it will take some time to incorporate the results into the remedial process.

January 8, 2021

Carol A. Stein, PE
Environmental Engineer
Land and Resources Programs Branch

Re: Response to Technical Review, LNAPL CSM and Remedial Action Work Plan, St. Croix, U.S. Virgin Islands, St. Croix Alumina Site, Dated July 2020. EPA ID Number VID090302084

Dear Carol A. Stein,

EHS Support has reviewed the *Response to Technical Review, LNAPL CSM and Remedial Action Work Plan* for the St. Croix Alumina Site, St. Croix, U.S. Virgin Islands (hereafter 'Site'), and prepared the following responses to the comments. For ease of review the comment provided by United States Environmental Protection Agency (USEPA) has been provided and a response in Italics.

We look forward to discussion and resolution of these comments and moving forward with the supplemental assessments so that light non-aqueous phase liquid (LNAPL) mobility/recoverability can be better understood and a decision process (in accordance with Interstate Technology & Regulatory Council [ITRC] and USEPA) can be developed for management of LNAPL recovery and remedial actions with the ultimate goal of achieving restoration of groundwater quality.

General Comment 1*:* The *LNAPL CSM and Remedial Action Work Plan, St. Croix, U.S. Virgin Islands, St. Croix Alumina Site*, dated July 2020 (Work Plan), summarizes the Tier I and Tier II risk assessment reports that were prepared in 2002 and 2003 for the St. Croix Alumina Site. EPA is reviewing these risk assessments to determine whether updates are warranted to reflect both the current Conceptual Site Model (CSM) and the potential for vapor intrusion impacts for any projected or potential reuse of the property. EPA will be contacting you regarding the results of this review. Additionally, please ensure the references to the risk assessments are accurate. In at least one instance (page 45, last paragraph), the date of the Tier 1 risk assessment is incorrectly cited as ES&T 2012 which leads the reader to assume the risk assessment is more recent; However, the date of the reference needs to be corrected to read ES&T 2002.

Response to General Comment 1: *References to risk assessments have been double checked, and the noted error was corrected.*

General Comment 2*:* The Work Plan does not provide specific actionable remedial goals in Step 4 of Section 6.2 for the proposed transition from LNAPL recovery to natural source zone depletion (NSZD) that accounts for the anticipated uncertainty and variability in NSZD, including the variability of a calculated NSZD depletion rate on a well-by-well basis. Without this information, the adequacy of the Work Plan cannot be assessed, and a complete list of data gaps cannot be determined to transition from phase separated petroleum hydrocarbon (PSPH) recovery to NSZD. Please revise the Work Plan to incorporate more details on Step 4 and a cross-walk showing how the proposed NSZD will be evaluated against LNAPL recovery. Also, please note that the transmissivity and corresponding 1-gallon per day criteria (noted in Section 6.2 and elsewhere in the document) is a starting point for evaluating when sippers may no longer

be effective tools for removing LNAPL. However, this is dependent on the plume being stable, which has not yet been established at this site. The reason for the apparent instability of the plume may be related to the secondary porosity features present at the site and the buoyancy changes in the system created by LNAPL pumping activity. We anticipate that further information regarding NSZD and plume stability may be available after additional vapor probe investigations are conducted.

Response to General Comment 2: *Step 4 of Section 6.2 states, that the performance of ongoing recovery relative to natural mass losses will be evaluated. A chart on the following page illustrates that the proposed transition from phase separated petroleum hydrocarbon (PSPH) recovery to natural source zone depletion (NSZD) will occur when natural PSPH mass losses exceed engineered mass losses.*

As requested in the EPA review comment, the following details about how NSZD mass depletion rates will be compared to engineered recovery was included in Step 4 of Section 6.2:

The range of engineered mass losses (gallons per day) for site wells will be tabulated from site recovery operation data as described above. NSZD rates will be calculated at locations where PSPH is present using several approaches to account for potential variability in site conditions (as outlined in greater detail in a forthcoming NSZD Workplan):

- *Aqueous NSZD rates (gallons PSPH per day) will be estimated by comparing maximum, mean, and minimum differences of terminal electron acceptor (TEA) concentrations in groundwater and background wells to source zone (beneath PSPH) and downgradient wells, as outlined in CRC CARE (2018) and ITRC (2009). NSZD assimilative capacity (AC) values will be computed from the maximum, mean, and minimum differences to provide a range of NSZD rates at each location for comparison to engineered mass losses.*
- *Vapor phase and aqueous phase NSZD rates will be estimated using the differential temperature method, by measuring the temperature at specific points within the vadose zone and beneath water table. Heat flux will then be estimated using Fourier's first law of conduction and divided by the enthalpy of formation for a middle distillate fuel oil to yield an NSZD rate (corrected by the heat capacity of water for the aqueous portion of the rate calculation and converted to units of gallons per day).*
- *Based on the outcome of the above assessments, an additional line of evidence will be selected to determine NSZD rates, that may include one or a combination of passive CO_2 traps, use of a dynamic closed chamber, and/or the vadose gas gradient method.*

Given the variability of conditions at the Site, variability in NSZD rates are anticipated at different locations and will be integrated across the maximum extent of LNAPL using a Thiessen Polygon approach for direct comparison to the total engineered PSPH mass loss.

To demonstrate plume stability, figures depicting historical LNAPL thickness and plume extent estimates from previous consultants (Appendix B of the LNAPL CSM and Remedial Action Work Plan) have been updated to facilitate comparisons from the second half of 2002 through second half of 2019 (a 17-year period) – please note: this was also completed to fulfill the request presented in ***General Comment 3*** *(below).*

As is apparent in the revised time-series figures in Appendix B of the LNAPL CSM and Remedial Action Work Plan, and broadly apparent in time series charts of LNAPL thickness in Appendix D of the LNAPL

CSM and Remedial Action Work Plan, the extent of LNAPL has been constant to diminishing over 17 years, and LNAPL thicknesses have decreased overall. Note, apparent shifts in the LNAPL mass are inversely related to minor seasonal fluctuations in water level, where LNAPL drains into wells when the water level drops (i.e., an apparent thickness increase that does not reflect the true distribution of LNAPL in pore space).

General Comment 3: The Work Plan proposes to provide additional visual comparisons of the LNAPL plumes. To ensure the information is readily comparable, ensure the images provided include the following:

- Consistent presentation of information in sufficient size and scale to allow for direct comparison of historical and current LNAPL extent.
- Consistent labeling of LNAPL contour intervals for ease of understanding of the information presented.
- Development of current figures for all information presented.
- Revise the Work Plan to address this issue.

Response to General Comment 3: *As noted above, LNAPL thickness contours presented in Appendix B of the LNAPL CSM and Remedial Action Work Plan have been revised for consistent presentation of information. The revised contours clearly indicate the extent and thickness of LNAPL has remained stable to decreasing over the 17-year time frame.*

General Comment 4: Throughout the Work Plan, reference is made to the potential impacts of calcification and an apparent reduction in the inherent porosity of the limestone beneath the Site. However, boring logs are generally poor quality and there are no data provided which substantiate that porosity and permeability in the limestone is restricted to secondary porosity features. Evidence for the statements made regarding secondary porosity is not provided in the Work Plan. The presence of evaporites is only indicated on Figure 4-6 in wells outside the LNAPL treatment areas (specifically in wells VW-33, VW-37, VW-35, VW-3), yet the extent of mapped evaporites is shown near extraction well VW-13B. Based on the data shown on Figure 4-6, it is unclear how the extent of the potential infilling of reef carbonate porosity because of evaporite deposition and calcification was developed.

Also, large scale geologic cross-sections shown in Figure 4-3 do not cut through the majority of the LNAPL treatment area and do not show the juxtaposition or even the presence of any evaporite facies. Smaller scale treatment-area specific geologic cross-sections that show the relationship between the limestone and evaporite facies are needed. Cross-sections are needed along with the salient extraction well completions showing the LNAPL extent to support the project specific CSM for the Site.

Further, the cross-sections need to indicate the approximate location of the water table in critical extraction wells such that the thickness of LNAPL can be evaluated relative to changes in the relationships between geology and well completions and the apparent thicknesses of LNAPL. The relationship of geology to well screens and the water table can have major impacts on LNAPL removal efficiencies and apparent thicknesses of the LNAPL measured in the field. Please revise the Work Plan such that it incorporates site-specific data capable of supporting the LNAPL CSM as discussed above. In the event such data do not exist, then identify the necessary steps to fill the data gaps to ensure the presented CSM is substantiated by site-specific data.

Response to General Comment 4: *As this comment from EPA contains several elements, the response is parsed into the following categories for clarity:*

1. *Calcification and original porosity/permeability*
2. *The presence of evaporite minerals, particularly in relation to VW-13B*
3. *Cross section location*
4. *Relationship between limestone and evaporites*
5. *Water table on cross sections*

1. Evidence for reduction in primary porosity in limestone at the Site is provided by the Geraghty and Miller, Inc., (1982) study. In addition to their own observations, information from geological and geotechnical studies carried out at the plant site and surrounding area by U.S. Geological Survey (USGS) and researchers from various universities was incorporated.

During their investigation, Geraghty and Miller, Inc., (1982) documented the following, which has been introduced in Section 4.3. of the LNAPL CSM and Remedial Action Work Plan for clarity:

> *"Weathering and percolating subsurface waters have altered the original texture of the limestones in places. In many instances' porosity has been destroyed by the alteration of sand grains to micrite (carbonate clay) and by infilling of the interstices between grains with crystalline calcite. In other places, percolating water has increased the porosity by dissolving cement between grains, and by creating cavities and caverns."*

2. It is important to clarify that evaporites are not the same as calcification of primary (and potentially secondary) porosity. Calcite that reprecipitated in pore spaces identified at the Site by Geraghty and Miller, Inc., (1982) is (geologically speaking) a relatively recent process whereby groundwater supersaturated with respect to calcium carbonate precipitates calcite in cavities/porosity in the modern aquifer.

The deepest locations of evaporite minerals at the Site (calcite [$CaCO_3$], gypsum [$CaSO_4$], and chert [amorphous SiO_2]) are inferred to be depositional in origin (primary chemical sedimentary rocks) due to the occurrence of chert identified on some logs (e.g., VW-13B immediately above an interval of gypsum), which forms from diatom frustules and is indicative of shallow lagoon/strandline depositional environment where marine evaporites may form. Because this common evaporite sequence is identified on the log for VW-13B, an area of evaporites is drawn around VW-13B on Fig. 4-6. Lagoon evaporites are typically associated with low permeability and fine-grained siliciclastic (clay) and/or micrite (carbonate clay) associated with a relatively calm lagoonal/strandline depositional environment. However, the occurrence of an evaporite lagoonal facies does not preclude the presence of secondary porosity features.

The text has been revised to clarify this distinction.

3. A more detailed cross section across the treatment area was drafted (note, large-scale means more detailed and small-scale means less detailed). The new larger scale cross section passes through VW-6 and VW-13B; two wells with historically the thickest LNAPL. The scale here was modified from 1-inch = 50 feet to 1-inch = 25 feet vertically, and from 1-inch = 500 feet to 1-inch = 250 feet horizontally. The new

cross section passes through the treatment area, as indicated on the inset image on the figure that shows the cross-section location with respect to the extent of LNAPL in December 2019. Wells projected onto the section are indicated with dashed lines on this inset image to obviate coverage over the affected area.

4. On the cross sections (Fig 4-3A and 4-3B), locations of evaporite minerals are labeled "caliche" in keeping with the descriptions given on the original boring logs. The cross sections show the relationship of limestone lithologies and evaporite minerals.

5. The location of the water table and LNAPL thicknesses from December 2019 have been added to the new cross section, which incorporates most critical wells at the Site.

General Comment 5: Throughout the Work Plan the weathered nature of the LNAPL at the Site is noted as potentially impacting viscosity and the transmissivity of the LNAPL, but no viscosity data is provided. The authors imply that the effective solubility data for the LNAPL at the Site resembles a fresh diesel and No.2 fuel oil as provided in Tables 5-2 and 5-3. Please explain how the effective solubilities for the LNAPL at the Site can be similar to fresh diesel and No.2 fuel oil while the LNAPL can be described as highly weathered. Viscosity data for the LNAPL and other geochemical information is needed to substantiate that weathering has impacted the transmissivity of the LNAPL at the Site. Further, if the geochemical data substantiate that the hydrocarbons are weathered, additional lines of evidence regarding the appropriate effective solubility for the site hydrocarbon releases is needed.

Response to General Comment 5: *Weathered vs. fresh LNAPL transmissivity vs. effective solubility.*

LNAPL Viscosity data can be collected as part of the NSZD study. Based on the preferential depletion of low molecular weight compounds and in particular paraffins and iso-paraffins, which are the most easily degraded hydrocarbon compounds, LNAPL viscosity is expected to increase over time resulting in changes in further reductions in LNAPL transmissivity. Further detail on impacts of weathering on LNAPL viscosity and transmissivity are provided in ITRC (2018) which has been referenced extensively throughout the document.

In terms of effective solubility, we did not imply that the effective solubility is the same as fresh diesel and No.2 fuel oil. Effective solubility calculations using site specific data are provided in Table 5-1 and show the LNAPL to have low solubility with only naphthalene effective solubility exceeding relevant groundwater criteria. Tables 5-2 and 5-3 were only provided for comparative purposes and we consider that the effective solubility calculations based on LNAPL analytical testing data accurately reflects the properties of the weathered LNAPL at this Site. It is critical to note that effective solubility is the concentration in water in direct contact with oil and is not the concentrations that will be observed in groundwater. The absence of BTEX and naphthalene detections in recent groundwater monitoring data is consistent with the effective solubility of the LNAPL as documented in Table 5-1.

General Comment 6: In Section 5.5, LNAPL Mobility and Recoverability, reference is made to previous studies that indicate seepage rates at the Site for LNAPL are 0.1 foot/day. Reference to dissolved phase monitoring results as an indication of plume stability also is cited. Substantiation of the mobility of the LNAPL plume needs to be presented separately from any determination of the stability of the dissolved phase plume. LNAPL buoyancies and the orientation of main secondary fracture zones will control

LNAPL mobility and host rock storativity. Neither of these two factors are adequately defined for the Site. Without information regarding the orientation of the primary and secondary fracture zones or LNAPL buoyancy, the recoverability of the LNAPL and the stability of the LNAPL plume cannot be adequately established. Please revise the Work Plan to address these data gaps.

Additionally, in Appendix B, NAPL Thickness Maps, the extent of LNAPL is shown for 2002 and 2003, and then from 2006 through 2019. A review of the plume maps indicates the LNAPL thickness has varied over time. The shifting LNAPL thicknesses shown on these images do not support the interpretation that the plume is stable. Revise the discussion of plume stability to address the shifting configuration of the LNAPL plume.

Response to General Comment 6:

Consistent with the means and methods outlined in the ITRC guidance, a number of factors are used to define LNAPL plume stability. These include:

1. *The Interpreted extent of LNAPL. As is shown in the updated figures the extent of LNAPL has declined over time in response to a combination of LNAPL recovery efforts and NSZD.*
2. *The absence of appearance of LNAPL in new wells. There has been no LNAPL occurrence in new wells over more than 10 years. New wells have been installed in areas of known or suspected LNAPL impacts and LNAPL encountered, and LNAPL has been observed to appear and disappear in select wells with changes in groundwater elevation or in response to changes in recovery efforts.*
3. *In the context of sites where dissolved phase impacts are associated with LNAPL impacts it is generally accepted that a stable or decreasing dissolved phase plume extent is an indicator or a pre-requisite for LNAPL stability. Increasing extents of dissolved phase plumes (especially for BTEX constituents which degrade rapidly) is considered a potential indicator of plume expansion and therefore dissolved plume stability is a pre-requisite for stable LNAPL plume.*

A secondary line of evidence is the age of the release and as documented in the ITRC guidance (2018). As stated in the ITRC Guidance,

> *When an LNAPL release occurs, the LNAPL will move vertically downward under the influence of gravity through the permeable pathways (e.g., unconsolidated soil, fractures, and macropores) and, if sufficient LNAPL volume and head is generated by the release, the LNAPL will eventually encounter the water table. During the downward movement of LNAPL through the soil, the presence of confining layers, subsurface heterogeneities, or other preferential pathways may result in irregular and complex lateral spreading and/or perching of LNAPL before the water table is encountered. Once at the water table, the LNAPL will spread laterally in a radial fashion as well as penetrate vertically downward into the saturated zone, displacing water to some depth proportional to the driving force of the vertical LNAPL column (or LNAPL head). The vertical penetration of LNAPL into the saturated zone will continue to occur as long as the downward force produced by the LNAPL head or pressure from the LNAPL release exceeds the counteracting forces produced by the resistance of the soil matrix and the buoyancy resulting from the density difference between LNAPL and groundwater.* ***Once the release of LNAPL is terminated, the areal extent of the LNAPL body will continue to expand for a relatively short***

> ***time, and eventually stop once the resistive forces in the soil balance the driving force of the diminishing LNAPL head. When the LNAPL body reaches this state, the LNAPL body has stabilized in extent, and will not typically expand further unless additional releases or significant subsurface hydraulic changes occur.*** *(ITRC Guidance Section 3.2.1, emphasis added- 3. Key LNAPL Concepts – LNAPL Update (itrcweb.org))*

Consistent with the description above and given the considerable time that has elapsed since operations, it is reasonable to assume that the LNAPL plume has stabilized. There is no data to indicate that there have been new releases at the Site and/or that further migration of the LNAPL Plume has occurred.

LNAPL thickness changes in mature plumes are not an indicator of plume mobility. Rather they are simply indicators of changes in local scale conditions associated with water table elevation changes (drops in groundwater elevation resulting in vertical drainage of LNAPL in the formation into the well) and or changes in stressors such as recovery activities within the well or adjacent wells.

Commentary is provided by USEPA on the factors affecting LNAPL migration, notably, "LNAPL buoyancies and the orientation of main secondary fracture zones will control LNAPL mobility and host rock storativity". To clarify, the variability in the geology (including secondary porosity features and the degree of cementing) impacted on the historical migration of LNAPL at the Site. There is no ongoing migration of the plumes (consistent with the comments above) and so in the context of this site these features are important in understanding the variability in LNAPL transmissivity, total LNAPL recovery volumes and current LNAPL recovery rates.

In the context of the study moving forward, our near-term focus is on NAPL transmissivity and recovery across the plume and correlating this with subsurface conditions. In the context of the site, the POC considers that the primary goals of plume delineation and plume containment have been achieved and demonstrated through years of groundwater monitoring. The focus of our efforts moving forward are on recovery of LNAPL to the extent practical and ultimately (through NSZD processes after recovery becomes impractical) achieving restoration of the aquifer.

General Comment 7: The presence of reducing conditions capable of substantiating the potential for reductive MNA processes to act on the LNAPL were only measured in dissolved phase monitoring wells shown in Table 54. The results in monitoring wells are variable as shown in Table 1 of the *37th Groundwater Monitoring Event and 1st Semiannual 2020 Status Report for the St. Croix Alumina Groundwater Remediation Project, Geomonitoring Services (GMS), August 31, 2020.* Some data presented in this table suggest the presence of reductive conditions while other wells have values for oxygen reductive potential (ORP) and dissolved oxygen (DO) which are positive and higher respectively, which is indicative of more oxygenated conditions in the groundwater sampled. It is noted in the first sentence of the second paragraph on page 45 of the Work Plan that "Extensive assessment of natural attenuation processes has not been conducted at the site." Additional ORP and DO measurements are needed from wells and associated groundwater beneath the LNAPL plume to evaluate geochemical conditions in groundwater beneath the LNAPL plume and the potential for MNA processes to reduce LNAPL volumes over time. Currently, the lack of geochemical data represents a significant data gap in substantiation that transition to NSZD and MNA is warranted. Ensure the Work Plan adequately addresses this data gap.

Response to General Comment 7: *It is duly noted that further assessment of groundwater geochemistry is needed to document and confirm monitored natural attenuation (MNA) processes at the Site. As noted in the response to General Comment 2, an extensive assessment of groundwater geochemistry is outlined in greater detail in the recently submitted NSZD Workplan, including field parameter measurements and samples of groundwater from beneath LNAPL.*

Table 5-4 presents some field parameter data from dissolved phase wells outside and immediately downgradient of the LNAPL footprint. These wells are clearly suboxic to anoxic in terms of dissolved oxygen (DO) measurements, considering the resolution of most instruments is in the 0.2 to 0.5 mg/L range. Additionally, most DO results are below 0.5 milligrams per Liter (mg/L) in Table 1 of the 37th Groundwater Monitoring Event and 1st Semiannual 2020 Status Report for the St. Croix Alumina Groundwater Remediation Project, Geomonitoring Services (GMS), August 31, 2020.

Very generally speaking, oxidation-reduction potential (ORP) values less than +50 millivolts (mV) (relative to an Ag/AgCl electrode) suggest a reductive pathway is possible, and values less than -100 mV suggest a reductive pathway is likely (Wiedemeier et al, 1998[1]). Very generally, ORP values of +50 to -50 mV are indicative of NO_3^- reduction, -50 to -250 mV of SO_4^{2-} reduction, and -175 to -400 mV of CH_4 production. Stabilized ORP values of most wells are in a range suggestive of a reductive pathway in Table 1 of the 37th Groundwater Monitoring Event and 1st Semiannual 2020 Status Report for the St. Croix Alumina Groundwater Remediation Project, GMS, August 31, 2020.

Indeed, current data are strongly suggestive of reductive microbial respiration in the LNAPL affected area relative to background areas, and Table 5-4 and the associated text has been revised to capture this. The only wells with stabilized DO and ORP values that do not fall in a favorable range for reductive degradation are VW-25, VW-37, GM-14, and MMX.

- *VW-25 is at the westernmost edge of the LNAPL.*
- *VW-37 is over 2000 feet side-gradient from the LNAPL.*
- *GM-14 is located adjacent to the shipping canal and is affected by oxygenated seawater as is apparent from the elevated conductivity value.*
- *MMX is located about 800 feet upgradient of the LNAPL.*

General Comment 8: In section 5.5.1, Bail Down Tests Assessments of Transmissivity and Mobility, second to the last paragraph, in the last sentence on page 48, the Work Plan notes that additional bail down testing both spatially and temporally is required. Presumably, this is because current modeling results are only based on bail down tests from three out of approximately 21 wells inside the mapped LNAPL plume. The Work Plan calls for bail down tests at the extraction wells in the proposed network. It is unclear how many, where, and in what wells additional bail down tests will be performed. Please revise the Work Plan to present the locations of additional bail down testing and ensure the selection of those locations considers geologic setting, the presence or absence of fractures, LNAPL thickness, and water table elevation.

Response to General Comment 8:

[1] Wiedemeier, T.H., et al. 1998. Technical protocol for evaluating natural attenuation of chlorinated solvents in groundwater. EPA/600/R-98/128.

As documented in the work plan, a range of methods can be used to assess remedy performance relative to ITRC's LNAPL transmissivity limits. This includes baildown tests where LNAPL Transmissivity values are estimated and conversion of LNAPL recovery rates to LNAPL Transmissivity. The proposed approach is to opportunistically collect LNAPL transmissivity data over time in wells at the Site through a combination of the following:

1. *Measure LNAPL thickness rebound over time in wells during the process of solar sipper pump removal for routine maintenance and/or relocation to another well. Effectively this is considered opportunistic as LNAPL thicknesses will already be depressed in the well due to operation of the skimmer. LNAPL thickness will be allowed to rebound (and rate of increase of LNAPL thickness in well will be measured), and once equilibrated the accumulated LNAPL will be evacuated again and the rebound in LNAPL thicknesses measured over time.*
2. *Baildown testing in wells that are not part of the current LNAPL recovery program but may be incorporated into the program if LNAPL transmissivity in the wells is higher than that measured in other wells and above the ITRC practicality threshold.*

A minimum of one baildown test will be collected from the following wells (although multiple tests may be conducted on select wells over time). The wells proposed for baildown testing (assuming minimum LNAPL thickness threshold of 0.25 feet is present prior to bail-down test) are summarized in the table below.

PROPOSED WELLS FOR BAILDOWN TESTING

Well Id	*Operational Status of Well*	*Additional Comments*
VW6	*Continuous Solar Sipper Operation in high yielding wells*	*Opportunistic baildown test to be completed during removal of pump for routine inspection/maintenance. Solar sipper to be replaced in well after completion. Multiple baildown tests likely to be conducted over time.*
VW13		
VW13B		
VW14		
VW31		
VW5	*Continuous solar sipper operation in low to moderate LNAPL recovery rate wells*	*Baildown tests to be conducted at the end of a 6-month operational period and used to determine if solar sippers will be retained at these well locations.*
VW20		
VW20B		
VW24		
VW29		
VW32		
VW21B	*Periodic solar sipper operations in low LNAPL recovery wells. Solar sippers may be moved from these wells to other historic low yield wells (see list below)*	*Baildown test to be conducted upon removal of solar sipper*
VW23		
VW24		
VW2	*LNAPL wells with insufficient LNAPL for initial recovery*	*Baildown tests to be conducted on all wells which exceed the*
VW7		

Well Id	*Operational Status of Well*	*Additional Comments*
VW15	*actions by solar sippers. Solar sippers may be implemented in wells based on baildown test data.*	*minimum LNAPL thickness threshold*
VW18		
VW19		
VW21		
VW26		
VW28		
VW30		
VW35		

General Comment 9: LNAPL recoveries shown in Table 5-6 show inconsistent expected LNAPL transmissivity values that exceed the practicality limits provided in the ITRC (2018) guidance and calculated by the authors of greater than 1 gallon per day (gpd) based on an expected transmissivity value of 0.8 foot squared/day. Based on this data, it is unclear how long it might be before individual wells might consistently fall below this estimated practical recovery limit. Many more wells have consistent recovery values that exceed the 0.5 gallon per day recovery limit in this table. Optimization of the solar sipper systems followed by operation of the systems for an additional period of time is warranted before the system can be established as not providing additional value in terms of LNAPL removal rates and total volumes. Solar sippers that can be cycled more regularly allowing for recharge of LNAPL and the addition of additional fluid storage at each location may change the observed recoveries. EPA would be interested in further exploring with the ERT ways to optimize the solar sipper systems. Additionally, changes in the LNAPL removal methods may also change LNAPL recoveries shown in Table 5-6, which is attached at end of the draft Work Plan.

Response to General Comment 9: *We agree that the LNAPL recovery rates in Table 5-6 show variability over time associated with operation of the solar sippers (pumping being turned on and off and adjusted). To mitigate this variability and provide more consistent recovery rates (that can be used for reservoir decline curve analysis) we have proposed adjustments to the Operation and Maintenance (O&M) program including installation of ISO/Totes to provide longer operational times and instructing our field staff to not make adjustments to elevation and setting of the solar sippers.*

We consider that the capacity of the solar sippers is sufficient to keep LNAPL thicknesses at the desired minimum threshold of 0.1 to 0.25 feet in the recovery wells (some LNAPL is required in the well to provide continuity between the well and formation in order for LNAPL to enter the well). Use of the larger ISO containers will allow for prolonged operation of the high yield wells to demonstrate the effectiveness (sufficient pumping capacity) of the solar sippers.

General Comment 10*:* Section 6.2 discusses the proposed framework for LNAPL recovery well shutdown. Four steps are listed, but Step 4 indicates that Steps 2 and 3 would not have to be met when the POC concludes that the active remediation is no more effective than NSZD, or 'where NSZD processes are particularly robust'. Please note that any deviation to the listed steps would require EPA approval. Please revise the Work Plan to note that the POC is not authorized to discontinue active remediation of the system without prior approval from EPA.

Response to General Comment 10: *Comment is noted, any proposed permanent shutdown of recovery wells will only be conducted with USEPA approval.*

Specific Comment #1 *- Table 5-4, Groundwater Parameters, Page 45:* Data presented in Table 5-4 of the Work Plan indicates that reducing conditions are present in key wells. No basis is provided for how the wells were identified as key in terms of the potential for MNA to occur at the site. The Work Plan suggests that the reducing conditions in these key wells are capable of supporting nitrate and sulfate reduction and methanogenesis of LNAPL constituents. Section 5-4 (p. 45) also cites the GES/ES&T model results which indicate that there are 3,379 barrels of oil remaining in the ground, and that there has been a 91.1% decrease in estimated hydrocarbons. However, insufficient information is provided to substantiate that a 91.1% reduction has occurred as stated in the text. If the POC is interested in continuing to refer to the results of this model, the Work Plan would need to provide sufficient detail about how these modeled estimates were derived to allow for concurrence with the stated results. The oxidation reduction conductivity (ORP) and the dissolved oxygen (DO) data would need to be provided for all wells where LNAPL or dissolved phase contamination is present. Furthermore, the work plan would need to be revised to provide the requested information, to provide the decision logic for the selection of key wells, and to provide sufficient detail regarding the model used to determine the stated percent reduction to allow for an independent assessment of the information provided.

Response to Specific Comment 1:

The MNA data for key wells is discussed in the response for General Comment 7. Please note, Table 5-4 was updated with the most recent round of monitoring data and text was added to the LNAPL CSM document to clarify this issue.

Our approach does not rely on historic modelling as there are fundamental flaws with that type of modelling in this setting. The reference to 91.1% reduction reflects the conclusions of past reports which is supported by other lines of evidence include the declines in recovery rate over time, thicknesses in wells and the lateral extent of LNAPL impacts.

Our approach moving forward will be focused on collection of empirical data on LNAPL transmissivity and LNAPL recovery and natural source zone depletion rates. A NSZD Work Plan has been prepared and submitted to USEPA which documents the extent of this proposed program of work.

Specific Comment #2 *Table 5-7, Summary of Recovery August 2018 through to May 2020, Page 53:* Under Section 5.5.3, Table 5-7 provides LNAPL recovery rankings for different wells. However, the Work Plan needs to clarify how these rankings were established and whether these rankings are based on geological conditions and the resulting amount of PSPH recovered from these wells over time. Additionally, details regarding the calculations of "% of total LNAPL" and "oil/water cut (%)" need to be presented as well as the data used needs to be provided.

Response to Specific Comment 2: *The rankings provided in Table 5-7 were simply based on the total volume of LNAPL recovered over the trial period of August 2018 through to May 2020. Well VW13B with the largest LNAPL recovery volume over this period (1197.10 gallons) was ranked as number 1. The other calculations were:*

- *% of total LNAPL being the % from the well over the period relative to the total volume of LNAPL over the period (for example VW13B was 1191.10 gallons relative to a total volume recovered of 4566.37 gallons which is 26.22%).*

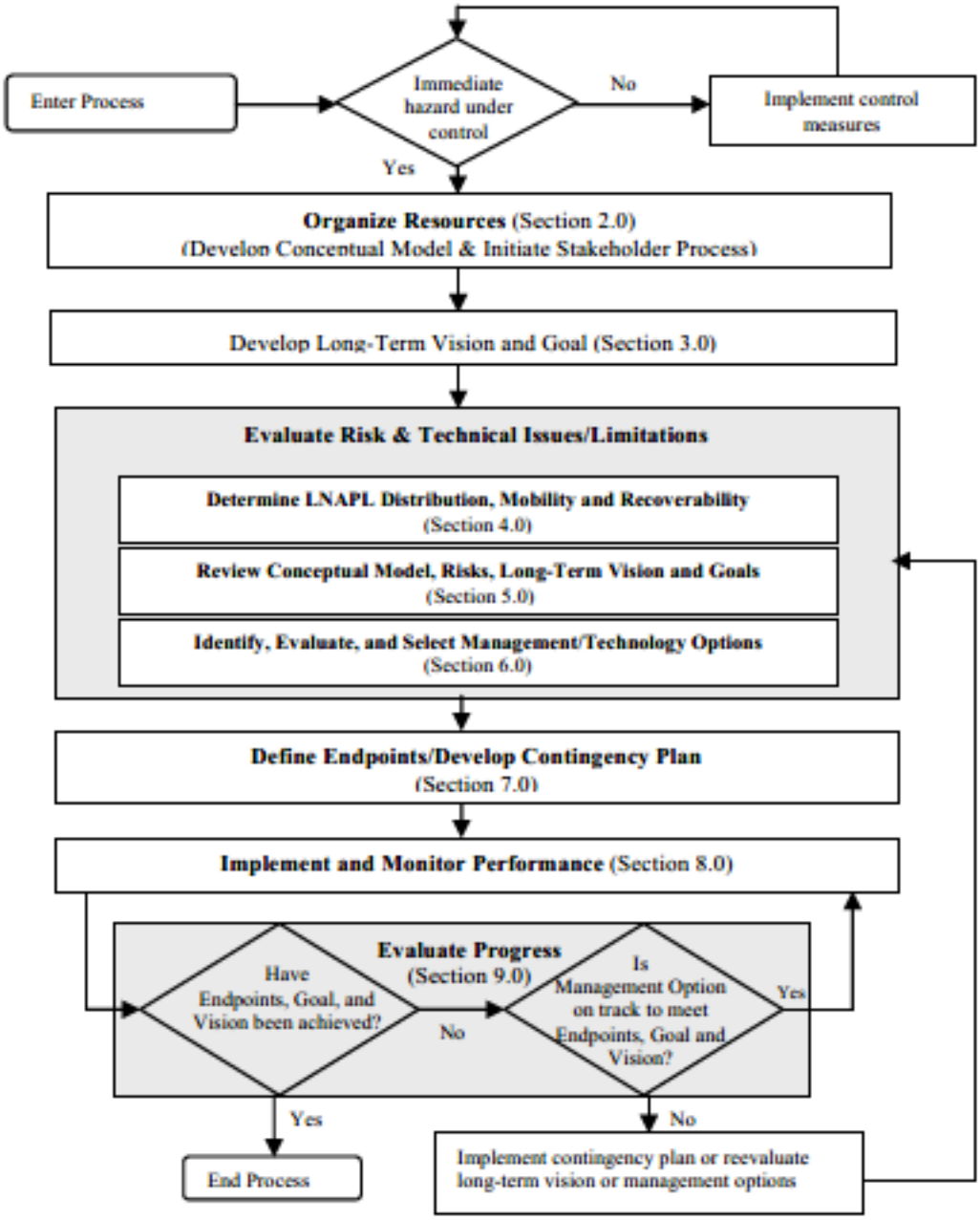
- *% oil/water cut was calculated as the volume of oil removed from the well relative to the volume of water. % oil/water cut is an indicator of efficiency and as LNAPL transmissivity declines over time the % oil/water cut is expected to decline (assume same technology and approach applied over the period).*

Footnotes will be added to the table to document how these calculations were made.

***Specific Comment #3**: Section 6, Updated Remedial Action Work Plan, Page 63:* Section 6 discusses the scope of the Work Plan, which is an updated version of the previously EPA approved July 23, 2001 document. One of the stated objectives of the Work Plan (a.k.a., the updated work plan) is the optimization of LNAPL recovery efforts in order to cease LNAPL recovery. How "optimization" will be determined, what lines of evidence will be used to perform the optimization, and how it will be determined that the system has been optimized to the degree possible is not defined. Site specific performance goals and decision thresholds need to be defined to achieve consensus for the proposed approach. A decision tree and a contingency plan are recommended for integration into the Work Plan, to help determine which decision criteria to use to move the site forward through the optimization process. A decision tree is outlined in *"A Decision-Making Framework for Cleanup of Sites Impacted with Light Non-Aqueous Phase Liquids (LNAPL), EPA 542-R-04-001, March 2005* [and a similar decision tree is outlined in LNAPL-3: LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies, ITRC, March 2018).

***Response to Specific Comment #3**. We agree that a decision-making process can be developed for the benefit of USEPA but inherently the purpose of this work plan was to outline our approach, reach some consensus of practical endpoints, and collect data to validate and finalize the CSM. Consistent with the ITRC (2018) Guidance and USEPA (2006), (as shown below), a CSM must be developed prior to the endpoint determination. Given that NSZD is considered a critical component of the remedial approach moving forward, this assessment must be completed before we can define our final endpoint vision and*

The purpose of the document was to frame some endpoint considerations which can be assessed as part of the supplemental investigation scope of work. From review of USEPA comments we see that there is no objection to using the ITRC (2018) guidance framework and inherently then the mobility/recoverability practicality endpoints for LNAPL. Similarly, USEPA is in apparent agreement that NSZD is a component of the remedial approach for the Site. What is uncertain is whether we have reached a point at certain locations that NSZD should be considered as the approach moving forward, what will be the restoration time frame with NSZD, where hydraulic recovery of LNAPL will continue in the short term and what are the contingency plan and associated triggers.


Enter Process
Immediate hazard under control
No
Implement control measures
Yes
Organize Resources (Section 2.0)
(Develop Conceptual Model & Initiate Stakeholder Process)
Develop Long-Term Vision and Goal (Section 3.0)
Evaluate Risk & Technical Issues/Limitations
Determine LNAPL Distribution, Mobility and Recoverability
(Section 4.0)
Review Conceptual Model, Risks, Long-Term Vision and Goals
(Section 5.0)
Identify, Evaluate, and Select Management/Technology Options
(Section 6.0)
Define Endpoints/Develop Contingency Plan
(Section 7.0)
Implement and Monitor Performance (Section 8.0)
Evaluate Progress
(Section 9.0)
Have Endpoints, Goal, and Vision been achieved?
No
Is Management Option on track to meet Endpoints, Goal and Vision?
Yes
Yes
No
End Process
Implement contingency plan or reevaluate long-term vision or management options

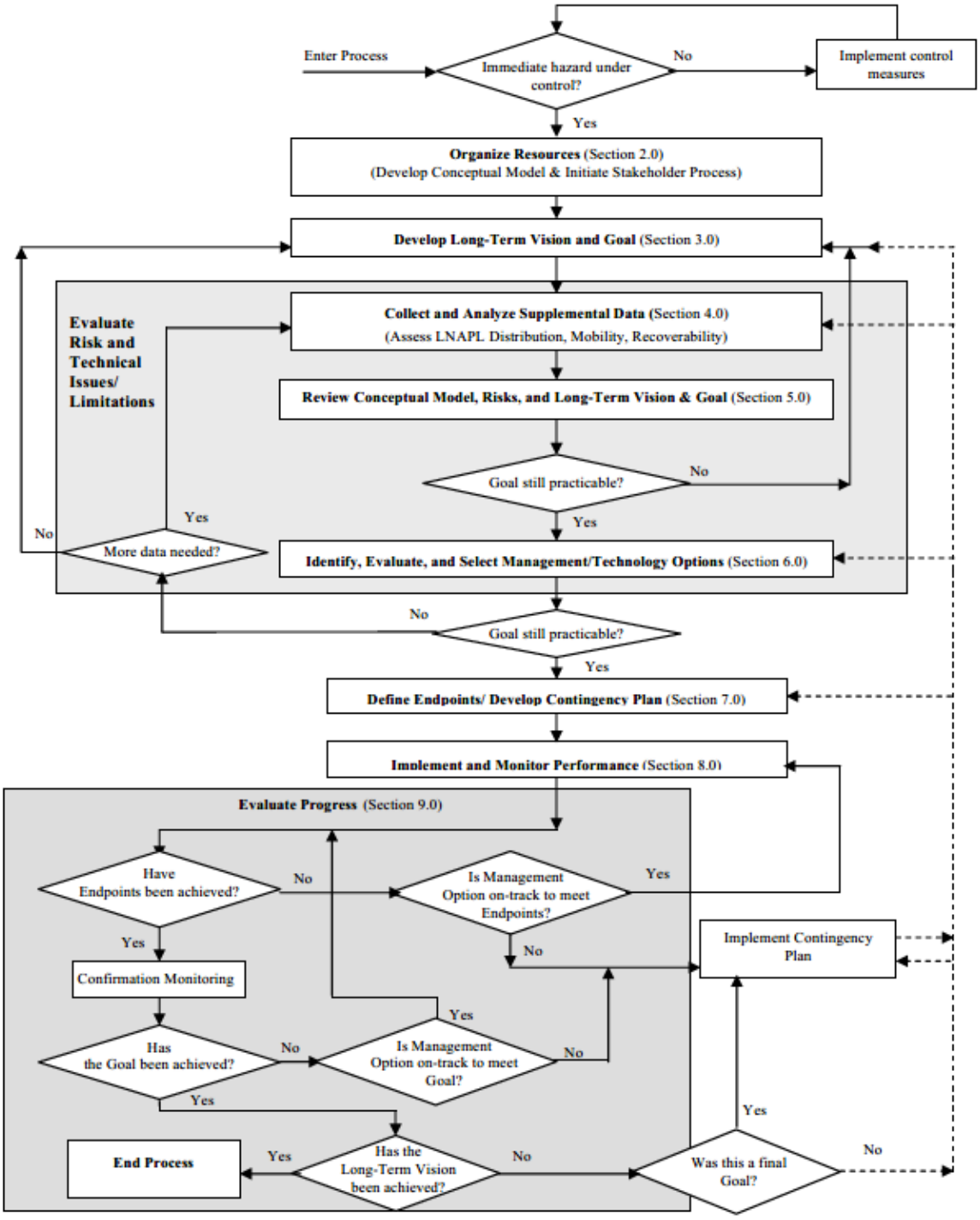


Figure 1. NAPL Management Decision-Making Framework Process

Specific Comment #4*: Section 6.1, LNAPL Recovery Activities, first paragraph, Page 63*: The Work Plan indicates that active measures to manage the LNAPL at the Site should only proceed until June 2021. No rationale is presented for this date. Revise the Work Plan such that the firm date of June 2021 is removed, and lines of evidence are presented that will be attained prior to the cessation of LNAPL recovery.

Response to Specific Comment #4*. As documented in this section, we propose to operate the system without interruption until June 2021 to enable collection of data for more detailed analysis of LNAPL transmissivity and LNAPL reservoir (recovery) decline curves. As stated in the document,*

> *"At this time, it is anticipated that sufficient data will be available to support systematic shutdown of recovery wells and a transition to MNA/NSZD processes in accordance with the framework described below. It should be noted that this assessment will be done on a well-by-well basis and the number of recovery wells that are shutdown after June 2021 will be informed by the data collected during this period and the process described below."*

What is being stated here is the data we have collected will determine if and what wells may not warrant further recovery actions and that any such decisions will be made on a well-by-well basis. Further and consistent with USEPA's comments, recommendations for shutdown will be provided to USEPA for approval.

It is anticipated that some wells will still be recovering sufficient LNAPL that LNAPL recovery actions will be continuing after June 2021. It should be noted that this date can be revised based on the approval date of this workplan and the NSZD work plan as it is critical that we have both LNAPL transmissivity and NSZD data in order to complete the assessments and provide recommendations for ongoing operations.

Specific Comment #5 *- Section 6.1, LNAPL Recovery Activities, Bullet 1 Page 64:* In the second to last paragraph, it is noted that solar sipper systems will be visited monthly. Because of the low transmissivities of wells at the site, sippers should be checked and cycled more often and on a regularly frequency during the optimization process to assure maximum recoveries are obtained. Weekly assessments, at least during start up, could potentially increase system efficiencies and be used to evaluate the viability of reducing the frequency of system checks and optimization activities. Revise the Work Plan to allow for more frequent initial visits for optimization related activities.

Response to Comment #5 – Routine inspections of the well will be conducted to confirm that the pumps are operational and functioning. However, no adjustments to the pump elevation and operation will be made during this test period. Constant tinkering and adjustments to the pump are the direct cause of the data variability that made data analysis challenging (as noted in USEPA's comments) and it is critical that we get constant operations.

The solar sipper is equipped with a floating intake, and as such water table elevation adjustments are not required. The pumping rate will be dialed in to minimize the amount of LNAPL in the well (target 0.1 to 0.25 feet in the well) but will not be adjusted once set. This may mean that the pump activates and pumps some air to surface. Consistency is key during this part of the evaluation.

Specific Comment #6: *Section 6.2, Proposed Framework for LNAPL Recovery Well Shutdown, Bullet 3, Page 65; and Section 6.2.1, Rationale and Methodology for Reservoir Decline Curve Analysis, Page 66:* In Section 6.2, a goal of 80 percent removal of the recoverable LNAPL is proposed. However, few details are provided regarding how this criterion will be applied to the Site. The Work Plan needs to be revised to include specifics regarding how this criterion would be developed and used for decision making purposes before it can be adopted for use at the Site. Additionally, EPA is not in concurrence that this should be the end goal for removal. We would be interested in exploring with the POC ways to increase the removal of recoverable LNAPL beyond 80% removal.

Response to Specific Comment #6: *Consistent with the discussion provided in Section 6.2.1, this is only one of the goals for the recovery systems. The primary determinant is an LNAPL transmissivity less than 0.8 ft^2/day (based on ITRC defined goals). Each Step in the process addresses key considerations and some of the comments provided by USEPA above.*

- ***Is the well being operated efficiently?*** *Step 1 of the process asks are LNAPL recovery operations being optimized to ensure that LNAPL is effectively removed from the well (LNAPL thicknesses measured in wells are maintained as much as possible below 0.25 feet during active recovery) thereby ensuring that the LNAPL recovery rates (on a well by well basis) continue to decrease over time.*
- ***Have we reached practical endpoint for hydraulic recovery?*** *Step 2 in the process uses ITRC (2018) recommended transmissivity value of 0.8 ft^2/day to define this decision point. Baildown tests (as discussed above) and LNAPL recovery rates will be used to determine if this end point has been reached. This is the primary metric to determine the practical endpoint for recovery, however Step 3 evaluates another.*
- ***Since LNAPL Transmissivity is Limiting Further Recovery can natural processes facilitate restoration of the aquifer in a reasonable period of time?*** *Whatever the endpoint for hydraulic recovery is at some point in time natural processes will be relied upon to facilitate restoration of the aquifer. Once the magnitude of these NSZD processes becomes known, the time period for restoration of the aquifer can be estimated.*

If the LNAPL transmissivity is > 0.8 ft^2/day then recovery will continue whether the reservoir decline curve analysis demonstrates that 80%, 90% or 95% of the potentially recoverable has been recovered.

Specific Comment #7 *Section 6.2.1, Rationale and Methodology for Reservoir Decline Curve Analysis, Page 66:* In Section 6.2.1, in the second to the last sentence, a criterion for R^2 squared of 0.1 is suggested for use when deciding to perform data analyses and estimating trends. The basis for suggesting this criterion is presented as being based on the inherent variability within geostatistical data sets. Provide a literature reference indicating that use of 0.1 is preferred for analyzing geostatistical data trends. A review of the current regression analyses, provided in Appendix C, Reservoir Decline Curves, suggests that many other factors may influence the observed results, such as changes in extraction methods and protocols or even changes in extraction technologies and equipment. The nature and distribution of results and other statistical assumptions must be considered and the appropriate methods for performing trend analyses used based on data set characteristics. Revise the Work Plan to provide the decision logic used for the use of R^2 as the preferred data assessment metric.

Response to Specific Comment #7*. The 0.1 R^2 coefficient is a minimum that is used to determine if there is some additional data processing required. The text will be revised accordingly. Consistent with the*

reservoir/recovery decline curve analysis methodology a best fit line needs to be established for the relationship between recovery rate and total recoverable volume. A discussion of this method is provided in the ITRC (2018) guidance. Regression coefficients are the accepted tool for assessing the quality of fit.

The scatter in the data was identified as a key constraint for analysis and recommendations for modifications to operations and monitoring for the solar sippers. As noted on the conference call with USEPA, the collection of recent data on a high frequency (relative to historical monitoring frequencies) creates an inherent bias (all data points are given the same weighting in correlation and regression coefficients) and impacts on the assessment and establishment of best fit lines. A range of methods exist for addressing these issues including outlier analysis (Cooks D Statistic or other outlier test) as well as time weighted averaging of recent data to ensure later time record data has the same periodicity of measurement as older data.

It is recommended that as more data are collected, a range of statistical tools will be used to determine how best to improve the fit of the best fit line.

***Specific Comment # 8**: According to Section 6.2.3 (page 67 of report)* – "Reductions in the frequency of monitoring is anticipated (initially to annual) but this will not occur until after all LNAPL recovery activities has ceased at the site and sufficient time has elapsed since termination of recovery (anticipated to be 4 semi-annual events) that plume stability (post recovery termination) has been demonstrated. Ultimately all groundwater monitoring will cease when the Tier II SSTLs are achieved in all perimeter wells". Please note that additional semi-annual monitoring would be required for several years after the SSTLs are achieved to ensure that the goals have been met. The details regarding the extent of post-remedial monitoring warranted will be the subject of further discussion between EPA and the POC.

***Response to Specific Comment #8**. Comment is noted. It is anticipated that an LNAPL Management Plan will be developed after completion of both the supplemental assessments and NSZD study. This LNAPL management plan will provide a decision-making framework for LNAPL consistent with the referenced ITRC and USEPA guidance and will be supported by a monitoring plan. This monitoring plan will consider the monitoring requirements associated with ongoing LNAPL recovery (if occurring) and natural source zone depletion and will demonstrate stability of the LNAPL and dissolved phase plumes. It is recognized monitoring and management will be required until Tier II site specific target levels (SSTL's) have been demonstrated to have been achieved.*

***Specific Comment #9**- Section 6.3, Natural Source Zone Depletion Assessment, Page 71:* It is unclear which wells will be analyzed for groundwater geochemistry during the Phase 1 effort. LNAPL wells as well as dissolved phase monitoring wells need to be included in the Phase 1 sampling and analysis plan to support MNA evaluations. Revise the Work Plan to specify all wells to be sampled in support of this effort.

***Response to Specific Comment # 9:** The text in Section 6.3 has been updated to list wells to be analyzed for geochemical parameters during the Phase 1 NSZD effort. An NSZD workplan with additional details has been provided to USEPA for review and does include this information.*

Specific Comment #10: *Section 6.3, Natural Source Zone Depletion Assessment, Page 71:* During Phase II, it is proposed that E-flux and an equivalent E-flux method for carbon dioxide measurements in the subsurface will be performed using a grid approach. Flux methods depend on reliable estimates of flux through vadose zone media to obtain reliable estimates for expected concentrations of methane and carbon dioxide over time. As noted by ITRC (2018) guidance, it is also possible to use vapor probes properly positioned to emulate flux through differing geologic units at several depths above the LNAPL, but below the surface, to more accurately estimate carbon dioxide and methane concentrations in vadose zone media. This type of application may be more desirable based on the LNAPL CSM for this Site. Less permeable media, which could include limestones with only limited secondary porosity features, alluvium, reef overburden, fill, and evaporite deposits may enhance or drastically reduce the effectiveness of NSZD. Given the variability in the geology at the Site, flux type measurements may be unacceptable for use. It is also unclear why these analyses will not be performed during Phase I, as the collection of this data may be essential to the decision-making process and it will take some time to incorporate the results into the remedial process.

Response to Specific Comment 10: *Given the effort and expense for implementing E-flux traps and need to quantify the spatial variability in NSZD processes occurring at the Site, it is proposed to first assess geochemical indicators (among other factors), subsurface soil gases and temperature profiles in existing wells to better understand NSZD variability across the site. A NSZD workplan with additional details on the proposed Phase 1 and II work has been submitted to USEPA for review.*

The process of NSZD assessments is complex and all methods have limitations. There are numerous questions that need to be answered first as part of the assessment to define the preferred approach. E-Flux (if all methane is converted to carbon dioxide) is a good methane measurement as it provides temporal averaging and captures advective (for example diurnal temperature and pressure movements of subsurface soil gases) and diffusive processes. Equally vertical transects of soil gas probes using Ficks First Law of Diffusion can look at a broad range of soil gases but only involves snap shots of soil gas concentration. Before we finalize our means and method and consistent with the NSZD Work Plan submitted to USEPA which involves a multiple lines of evidence approach, we are proposing to conduct a Phase 1 program of works to assess the following:

1. *Are the geochemical conditions supportive of sulfate reduction and methanogenesis (note these windows of degradation overlap)?*
2. *In terms of methane is complete degradation to carbon dioxide occurring or anticipated to occur in the unsaturated zone?*
3. *Do other data sets indicate variability in NSZD rates across the site and how should the sampling program be modified to reflect this variability?*
4. *Are there background methane and carbon dioxide sources that need to be considered?*

Based on the Phase 1 program, recommendations for the Phase 2 NSZD Studies will be provided to USEPA for approval.

Sincerely,
EHS Support Corporation

Respectfully,

Nigel Goulding
Senior Vice President

Dr. Andrew Fowler
Senior Hydrogeologist

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 2
290 BROADWAY
NEW YORK, NY 10007-1866

January 29, 2021

Mr. Brian Epperson,
Director, Environmental Health & Safety
HOVIC
1501 McKinney Street
Houston, Texas 77010

Re: Review of the draft LNAPL Natural Source Zone Depletion Work Plan, St. Croix Alumina Groundwater Plume, U.S. Virgin Islands; EPA ID Number: VID090302084

Dear Mr Epperson:

EPA has reviewed the *LNAPL Natural Source Zone Depletion Work Plan,* dated November 2020, for the St. Croix Alumina groundwater plume, located in St. Croix, U.S. Virgin Islands. The enclosed comments specify the additional information needed. They include input from EPA Region 2's Laboratory Services & Applied Science Division, as well as from our RCRA contractor, Toeroek. If you have any questions regarding these comments, please feel free to contact me via telephone at 212-637-4181, or via email at stein.carol@epa.gov

Sincerely,

Carol A. Stein

Carol A. Stein, PE
Environmental Engineer
Base Program Management Section
Land and Resources Programs Branch

Enclosure

cc: Austin Callwood, Director, USVI-DPNR-DEP (electronic copy w/enclosure)
Syed Syedali, USVI-DPNR-DEP (electronic copy w/enclosure)
Brad Martin, Toeroek (electronic copy w/enclosure)

ENCLOSURE

COMMENTS ON DRAFT LNAPL NATURAL SOURCE ZONE DEPLETION WORK PLAN ST CROIX ALUMINA GROUNDWATER PLUME, NOVEMBER 2020 ST CROIX, USVI

I. QUALITY ASSURANCE PROJECT PLAN (QAPP)

Comment #1 - QAPPs normally have a lifecycle of 5 years. The QAPP included as Appendix C to the Work Plan is outdated and needs to be resubmitted. Any new scopes of work will also require the submission of a new QAPP. Please also note that the submitted QAPP was used for the work associated with the dissolved phase petroleum hydrocarbon. Whereas the work proposed under the draft LNAPL NSZD work plan is for assessing the LNAPL source zone depletion. Hence, a separate QAPP would be needed for LNAPL sampling and analysis. In addition, please note that EPA Region 2 has adopted the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) format for QAPP documentation. Additional information can be found at the following EPA webpage: https://www.epa.gov/fedfac/assuring-quality-federal-cleanups. The UFP-QAPP Manual and the accompanying Optimized Worksheets are available for reference in the same webpage. The UFP-QAPP, which contains 37 worksheets, is designed to be a standalone document for project personnel to carry out their responsibilities. After the work plan is updated in accordance with the comments noted in this letter, it would be sufficient to cite in each of the QAPP worksheets where each of the requested items are located (section, page) within the revised work plan.

Comment #2 - For the Key Study Questions in Section 3.3 and Data Quality Objectives (DQO's), please use the EPA's 7-step DQO process in order capture the decisions that will be made and the required level of data quality with corresponding acceptance criteria. With the UFP-QAPP, the Optimized Worksheet #11 should be used to document this information.

Comment #3 - Key investigation questions are provided in Table 3-1 (included in the body of the Work Plan), but the questions lack specificity. The questions need to be expanded to present the specific logic and decisions that will be made regarding the NSZD monitoring effort. Table 1 (included in the Table section) provides some clarification in terms of how data will be used, but does not provide adequate cross-references to appropriate sections of the Work Plan for ease in understanding and identification of decision criteria that might be considered during decision making. As noted above, please revise the Work Plan to ensure the DQO development is consistent with the approach outlined in the UFP-QAPP.

II. General Questions

a. Section 3.2 - The rationale for selection of monitoring wells to be used in the Phase I monitoring program are not adequately discussed in the text and associated tables, specifically Table 3. The Phase I program is noted as being conducted in conjunction with the semiannual monitoring event, but the omission of certain wells historically inside the light non-aqueous phase liquid (LNAPL) plume (i.e., wells VW-15, VW-17, VW-18, VW-19, VW-26, VW-28 and VW-38) are excluded from the proposed well network. The rationale for excluding these wells but including others needs to be provided in the Work Plan. Please revise Table 3 of the Work Plan to include, as part of the data quality objectives (DQOs), the intended informational purpose for each well location selected.
b. Please specify where the temperature profiling and well head space soil gas measurements will be collected.
c. (Section 2) - Important elements of the Natural Source Zone Depletion (NSZD) conceptual site model (CSM) including the depth of the groundwater table relative to well screens, location and thickness of LNAPL, and geology across well screen intervals are not provided in the associated maps and cross-sections. Data is available to define these features in the LNAPL NSZD CSM. The NSZD CSM serves an important role in evaluating the reliability of proposed data to be collected during the Phase I and II programs. Please revise the Work Plan to include a more detailed site NSZD CSM for critical wells and portions of the NSZD study area.
d. Section 4.2.1 – The first paragraph of this section indicates that the presence of methane and carbon dioxide above baseline concentration in the vadose zone provide a strong line of evidence that hydrocarbon degradation and mass loss are occurring. Please clarify when the baseline concentration was determined. In addition, please explain what the basis is for the selecting which efflux gas measurement methods (passive flux trap or dynamic closed chamber method) will be used.
e. Decision Criteria: The decision criteria that will be used to decide how grids for surface samples collected using either E-flux passive samples (E-flux) or dynamic closed chamber (DCC) samplers is not presented. The decision logic for establishment of the sampling point grids needs to be presented in a flow chart/decision tree that can be used to understand how decisions will be made to select one method and establish the associated grid to be used during Phase II of the NSZD evaluation program. Please revise the Work Plan to include this information.
f. Groundwater Flow Direction*:* As noted in the Work Plan, the cause for the anomalous groundwater elevation at well GM-22 is currently unknown. Arrows showing estimated flow directions on the piezometric surface map provided in the Work Plan appear to be erroneous at key locations. Groundwater flow beneath the plume is not always south to southeast as suggested in the CSM and the map

arrows. The piezometric surface high surrounding VW-30 and VW-35 as mapped beneath the LNAPL plume suggests that although groundwater gradients in this area are low, groundwater flow could be radially outward to the northwest and southeast of these groundwater highs or mounds and could very well explain, in part, the historical geometry of the LNAPL plume (See Figure 4). The CSM that focuses on the areas where NSZD is to be further evaluated, needs to be revised to include a more detailed and corrected piezometric surface map and a discussion of possible localized flow directions for groundwater beneath the historic LNAPL plume.

g. Because a multiple lines of evidence approach will be used during decision making after completion of Phases I and II, it is essential that a formal weight of evidence approach be described including a flow chart that supports the proposed decision-making process in the Work Plan. The decision logic needs to identify the benefits and limitations of decision criteria used at critical points of the program. This decision process needs to also indicate what parameters have the greatest potential for introducing errors to the decision process for estimating NSZD rates identified in the Work Plan and in subsequent deliverables. Please revise the Work Plan to include the decision logic to be used.

h. The Work Plan calls for the use of a gradient method that combines soil gas readings from inside wells near the water table with shallow one-foot below ground surface (bgs) soil gas measurements adjacent to the paired wells. Because of the complexity of the geology at the site it may not be adequate to use only two points to verify changing conditions in the vadose zone, particularly where secondary porosity features may influence advective flow in the subsurface. American Petroleum Institute (API) NSZD Guide (2017) suggests that multiple levels of soil gas probes may be needed when water tables are greater than five feet below ground surface (bgs) to better define the limits of vapor phase diffusion coefficients and NSZD rates using a gradient method. The depth to groundwater at the site appears to range up to 40 feet bgs. The Work Plan needs to describe how the proposed gradient method can be considered representative of site conditions.

i. Also, gradient methods assume that diffusion is the only soil gas distribution mechanism above an LNAPL plume. Given that secondary diagenetic features such as calcification and bedding planes are potentially controlling mechanisms for advection (i.e., flow) beneath the site, it is not clear how these potential influences will be overcome using the simple two point gradient test proposed in the LNAPL NSZD Work Plan. The Cooperative Centre for Contamination Assessment and Remediation of the Environment (CRCCARE) in Technical Report No. 44, Technical measurement guidance for LNAPL NSZD (CRCCARE Guide), suggests in Figure 9 of this report that gradient methods in limestone sites should be carefully considered prior to use. Table 6 of the CRCCARE guidance indicates gradient methods should include soil gas probes installed below 1.5 meters bgs to avoid root zones. Moisture content in the subsurface may also have

a substantial influence on any calculated NSZD rates calculated using gradient and other soil gas measurement methods. The Work Plan needs to address how the current designs can be reliably used given site conditions. How and when moisture content issues related to NSZD activities will be addressed needs to be integrated more specifically into the site decision logic and sampling plan discussed in the Work Plan. Please revise the Work Plan to address these issues.

j. The decision whether to use DCC as opposed to passive E-flux meters during Phase II will depend on whether methane is completely digested at a specific location and across the site. Given the flux of soil gas through the E-flux sampler can only be estimated, it is essential that flux rates are estimated as closely as is possible under site conditions during NSZD testing. Please revise the Work Plan to include sufficient information on how flux rates will be estimated should E-flux be proposed for use at the site during Phase II. Further, the Work Plan should also discuss how the potential for excessive winds to over-estimate NSZD rates when using E-flux will be addressed.

k. Section 4.3.9.2 – For the dynamic closed chamber method, it is not clear how the CO_2 detection limit is determined and the process/method that will be used for data validation. Since weather condition is a factor in efflux measurements calculations, it is not clear what type of weather-related information will be collected and/or instrumentation used.

III. LABORATORY QA/QC

a. Section 4.3.9.1 – Please provide the name of the laboratory that will be analyzing the traps for CO_2, as well as the method to be used and the laboratory's reporting limit. In addition, information regarding acceptance criteria for the duplicates should also be included.

b. Section 5.7 – It is not clear what will be the acceptance criteria to evaluate the specified QA/QC samples. In addition, the collection frequency for the QA/QC samples was not included. Please provide.

c. Section 5.8 – For the specified laboratory analysis, it is not clear what are the project's required reporting limits and whether there are there any criteria that are being used for comparing the results. Please also provide the laboratory's accreditation information for these analyses (type of accreditation and expiration date).

   In addition, please provide the method specifications that will be used for the dissolved gases. Please also include the filter size that will be used to collect the sample for dissolved metals; please note that a consistent filter size is needed for consistent results, and that 0.45 microns is a typical filter size for dissolved metals.

d. Section 6.0 – Please clarify which procedures will be used for validating the data generated and the process for assessing the data usability. Also, please include any SOPs that will be used. The type of decision that will be made with the data will typically dictate the level of validation.

IV. SPECIFIC COMMENTS

Specific Comment 1: Section 1.1 last paragraph, Figure 2: As noted in the last sentence, potential source areas are located on the west side of the site. The location of these potential source areas needs to be shown on Figure 2 as they could impact where samplers are placed and the geochemistry of the soil gas near these impacted surface materials. Please revise Figure 2 accordingly.

Specific Comment 2: Section 1.2 Paragraph 4, Figure 3: In this paragraph it is noted that the groundwater table is broadly consistent with the Kingston Limestone. However, Figure 3 does not support this statement. The depth to the water table and relationship of well screens in the LNAPL NSZD study area needs to be described more accurately in this section and on Figure 3 of the Work Plan. Careful inspection of Figure 3 also shows that boring logs from some wells such as VW-14 and projected well VW-18 were not honored on the cross-section. Some explanation, perhaps as a footnote to Figure 3, of why these well logs were not included in the cross-section is needed. An updated set of cross-sections, specifically for the LNAPL plume study area, are needed in the Work Plan to demonstrate the spatial relationships between well screened intervals, LNAPL, geologic, and hydrogeologic features. Also, the cross-sections shown on Figure 3 need to be updated to include detailed LNAPL study-specific well diagrams that support verification of the LNAPL transmissivity bail down tests.

Specific Comment 3: Section 1.3, first paragraph, Figure 4: In this paragraph groundwater flow is noted as generally to the south-southwest and south towards the sea. Inspection of Figure 4 indicates that localized flow beneath the plume may occur radially to the northwest and southeast away from several groundwater highs in the vicinity of wells VW30 and VW35. These features suggest a very flat gradient beneath the LNAPL plume and potentially variable flow directions that could explain, in part, the geometry of the historical LNAPL plume. A more detailed piezometric surface map underlain by the most extensive historical plume map, such as those provided in Appendix A of the Work Plan is needed. The extent of historical subsurface contamination needs to be presented along with the interpreted localized groundwater elevations beneath the LNAPL plume. The locations of potential source areas also needs to be identified on Figure 4 or another more detailed piezometric surface map prepared for the LNAPL NSZD plume study area.

Specific Comment 4: Section 3.2.2: The scope of the Phase 2 program is poorly defined. This section of the Work Plan needs to be more detailed to allow for a better idea of the number of

samplers of various types which may be used along with dimensions of any proposed study areas. Other information that needs to be included in this section includes whether geochemistry parameters collected during Phase 1 will be repeated in subsequent phases or monitoring events, and whether temperature monitoring will be included in Phase 1 and subsequent well sampling events as a means for long term monitoring of NSZD.

Specific Comment 5: ***Section 3.2.2, Last Bullet:*** In the last Bullet, it is suggested that during Phase 2, analysis of wells for carbon fractionation using compound specific isotopic methods for carbon will be performed to determine if a background correction can be applied successfully to remove the impacts of carbon signatures from native carbonate rocks from signatures from NSZD of the LNAPL. It would be beneficial to perform these analyses as soon as possible to assure that passive Flux or DCC soil gas sampling data will be representative of NSZD of the LNAPL and not biased high because of contributions from native carbonate contributions to carbon dioxide values. Ensure the Work Plan allows for the collection of this data at the earliest step.

Specific Comment 6: ***Section 3.2.3***: This section does not provide a specific time frame for reporting Phase 1 results to EPA. Please modify the Work Plan to provide more specific timing for the Phase 1 report.

Specific Comment 7: Table 3-1 includes general data quality objectives. These DQOs are based on the content in Appendix B of the Technical Measurement Guidance for LNAPL Natural Source Zone Depletion (CRC-CARE Technical Report No. 44) (CRCCARE). The checklists included in Appendix B of the CRCCARE report are intended to be used as place holders to prompt the development of site-specific DQOs. However, the Work Plan needs to develop site specific DQO's that define how the data from Phase 1 and 2 will be used to bound decision making concerning the evaluation of NZSD at the site. Development of the specific DQOs can occur in Table 1 of the Work Plan and should be consistent with those presented in Worksheet #11 of the associated UFP-QAPP.

Further, the information included in Table 1 of the Work Plan includes site specific principal study questions in a format that is more in tune with EPA's DQO approach, but Table 1 does not provide an adequate cross-walk between applicable sections of the Work Plan and the Table contents for the column heading "Data Use Objective". Information in Table 1 should be consistent with UFP-QAPP, Optimized Worksheet #17 which supports the information included in Worksheet #11. Please revise Table 1 to include references to the supporting information within the Work Plan as well as UFP-QAPP Worksheet#17 or its equivalent. Additionally, please ensure that the Work Plan includes a diagram or flow chart indicating the intended decision logic to be used during data assessment. As cited in the reference section at the end of the Work Plan, the Interstate Technology & Regulatory Council (ITRC) updated its LNAPL guidance: ITRC 2018. *Light Non-Aqueous Phase Liquid (LNAPL)* Site *Management: LCSM*

Evolution, Decision Process, and Remedial Technologies, LNAPL-3. Washington, D.C. https://lnapl-3.itrcweb.org (LNAPL-3). Hence the list of references cited at the bottom of Table 1 needs to include the ITRC's LNAPL-3. Appendix B of LNAPL-3 includes examples of site-specific decision logic diagrams to guide the decision-making process. Please ensure that the Work Plan includes a site-specific decision logic diagram or flow chart consistent with the ITRC LNAPL-3 guidance.

Specific Comment 8: ***Table 3:*** This table identifies the wells in the proposed LNAPL plume monitoring network, as well as those wells selected as being indicative of background and down gradient. No rationale is provided for how and why the background wells were selected. Presumably, their selection is based on location and proximity to the study area and past monitoring and sample analyses performed at these locations. Additional detail is needed in the Work Plan concerning how the background wells were selected. A review of down gradient well locations given the current piezometric surface provided in Figure 4 indicates that many of these wells are upgradient or cross-gradient of the study area. Understanding there may be a significant data error/anomaly in the reported groundwater value for GM22, Table 3 will need to be reevaluated before the wells listed in it can be considered representative for LNAPL NZSD study purposes as either down-gradient or upgradient.

Additionally, the work on the redetermination of the casing elevation of GM22 and other wells should be considered during Phase 1 to better inform the CSM.

Specific Comment 9: ***Figure 7:*** The Figure shows potential locations for E-flux samplers. However, it is unclear how the configuration shown in the figure was developed and why there is not a figure which also shows potential locations for DCC samplers should they be selected for use. Please include this information. It also would be useful to include a presentation of where gradient evaluations may be performed.

EVALUATION OF RESPONSE TO USEPA COMMENTS

DATED DECEMBER 14, 2020

ON THE

LNAPL CSM AND REDEDIAL ACTION WORK PLAN

ST. CROIX, U.S. VIRGIN ISLANDS

DATED JULY 2020

In general, the Response to Comments (RTCs) addressed EPA's comments and are acceptable with the following considerations. The following evaluation includes only responses where additional information or clarification is required.

A revised version of the Light Non-Aqueous Phase Liquid (LNAPL) Conceptual Site Model (CSM) and Remedial Action Work Plan (Work Plan) was not provided, and as such an evaluation of the whether the RTCs were incorporated into the Work Plan was not able to be completed. A revised Work Plan incorporating the proposed revisions is needed.

EVALUATION OF RESPONSES TO GENERAL COMMENTS:

***Evaluation of the Response to General Comment 1 (Risk Evaluation)*:** As noted in our conference call of February 3, 2021, the risk assessment will need to be updated to address current conditions. Additionally, an evaluation currently is being conducted to provide input to help determine if the Site Specific Target Levels (SSTLs) need to be updated for the SCA plume site.

Evaluation of the Response to General Comment 2 (Remedial Goals): The response partially addresses the concerns expressed. The interpretation of transmissivity sits at the crux of the assessment of LNAPL recovery. Transmissivity assessment is made on a well-by-well basis. Assurances that each well used to determine transmissivity is appropriately screened to support such an assessment needs to be demonstrated. As such, the cross-section presented in Figure 4-3B omits the presentation of the screen interval with respect to the water table, the historical high-water level, the historical low-water level, and the currently known LNAPL thickness in the well screen. Any well included as part of the transmissivity assessment needs to have a well screen which straddles all of the high, low, and LNAPL levels. Also, changes in apparent product thickness may change the LNAPL transmissivities measurements planned for collection during Phase 1 activities. Any significant changes in groundwater levels and associated apparent product thicknesses may necessitate additional transmissivity measurements. Please revise the Work Plan to ensure it presents well logs showing the following for each well: the historical high-water level, the historical low-water level, and the currently known LNAPL thickness in the well screen. Also, include a contingency for additional transmissivity measurements based on observed changes to LNAPL thicknesses.

EVALUATION OF RESPONSES TO SPECIFIC COMMENTS

Evaluation of the Response to Specific Comment 3 (*Section 6, Updated Remedial Action Work Plan, Page 63)* **:** The last sentence in the first paragraph of this response is incomplete and needs to be revised. The purpose of providing a non site-specific decision logic diagram in the response is unclear.. A Site-specific decision logic diagram needs to be prepared and discussed with the EPA prior to moving

forward, even if some of the steps are contingent upon the finalization of the CSM. CSM contingent decision steps could be uniquely noted as such in the site-specific decision tree configuration.

Evaluation of the Response to Specific Comment 6 (*Section 6.2, Proposed Framework for LNAPL Recovery Well Shutdown, Bullet 3, Page 65; and Section 6.2.1, Rationale and Methodology for Reservoir Decline Curve Analysis, Page 66)****:***

The following rules-of-thumb are noted in Appendix C of the Interstate Technology Regulatory Council 2018 LNAPL guidance (ITRC-3), Section 1.1:

- *LNAPL transmissivity between the range of 0.1 to 0.8 ft^2/day may be used as a decision point for remedial system operation or technology transitions. While LNAPL transmissivity is useful for evaluating LNAPL hydraulic recovery potential, it should not be used as a sole means to determine whether an LNAPL remedy for a site is necessary or unnecessary.*
- *A threshold LNAPL transmissivity value, typically representative of an LNAPL saturation that is nominally above the residual LNAPL saturation for the formation, may be established at the outset of the LNAPL recovery action and used as a trigger for stopping LNAPL recovery. The decision on whether to implement an LNAPL remedial action should be based on the broader site LNAPL CSM rather than LNAPL transmissivity alone.*
- *It should be noted that LNAPL transmissivity measurements often vary in both space and time. For example, groundwater fluctuations can occur such that the LNAPL fluctuates from unconfined to confined conditions. In that situation, it may be necessary to measure LNAPL transmissivity values under both conditions.*

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EPA recognizes that your response to comments indicates that additional goals will be evaluated. However, more details are needed to justify these goals. Appendix C, Section 1.2 of ITRC-3 notes the following:

There are a number of methods that can be used individually or in combination to demonstrate that free product has been removed to the maximum extent possible. According to Appendix C, Section 1.2 of the LNAPL-3 document, these include:

- *comparing mobile LNAPL mass to the mass of LNAPL in the smear zone,*
- *analyzing LNAPL recovery data and determining that future recovery will not be meaningful,*
- *showing that LNAPL thicknesses are small and/or intermittently observed,*
- *modeling future potential LNAPL recovery using a multiphase model,*
- *demonstrating that the LNAPL body is stable and that stability will not change in the future, and*
- *presenting information that shows an unreasonable cost per gallon or pound of LNAPL recovered.*

The current plan does not clearly define what multiple lines of evidence have been or will be used in the future to support a decision to turn existing wells off in terms of performing continued product removal. At present insufficient data and conclusions have been presented to EPA to support the proposed decision criteria and decision logic. Specifically, more information is needed in terms of explaining the basis for why a transmissivity criterion of 0.8 foot squared/day or 1 gallon per day LNAPL recovery criteria should be agreed upon for use at the site. Please ensure that the Work Plan outlines how these issues will be addressed going forward.

Memo

To: Brian Epperson, Hess Corporation

From: Nigel Goulding EHS Support LLC
Dr. Andrew Fowler EHS Support LLC

CC: Brad Freeman, Geo Monitoring Services

Date: February 19, 2021

Re: Response to January 29, 2021 United States Environmental Protection Agency (USEPA) Review of the draft light non-aqueous phase liquid (LNAPL) Natural Source Zone Depletion (NSZD) Work Plan, St. Croix Alumina Groundwater Plume, U.S. Virgin Islands, EPA ID Number: VID090302084

EHS Support LLC ("EHS Support") has prepared this response to the United States Environmental Protection Agency (USEPA) review of the draft light non-aqueous phase liquid (LNAPL) Natural Source Zone Depletion (NSZD) Work Plan (Work Plan) for St. Croix Alumina U.S. Virgin Islands site (Site), dated January 29, 2021.

From our review of USEPA comments, we recognize that there is general alignment that multiple lines of evidence are needed to assess NSZD at the Site. We also note that that there are no comments on the calculations and technical aspects of the methodology that we proposed as these align with Interstate Technology and Resource Council (ITRC) and Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) guidance.

In development of the NSZD Work Plan, it was evident that the work needed to be phased so that preliminary information could be used to better define the work scope and address potential concerns associated with: (a) background carbon dioxide; (b) heterogeneity of NSZD process and geology across the LNAPL affected area, which would impact the study design, and (c) the potential that all methane was not being converted to carbon dioxide prior to fluxing to atmosphere. This was explicitly discussed in the Work Plan and the strengths and weaknesses of various quantification methods was explored in the context of those uncertainties. The lack of definition for the Phase II program of works simply reflected the group's desire to collect preliminary data (as Phase I) and provide a more informed study design for the more expensive flux-based methods (E-flux or dynamic closed chamber using a LI-COR meter).

During the routine January 2021 monitoring and sampling event at the Site, we obtained some supplemental field measurements. The intention for the work was to, coupled with the comments provided by USEPA, help refine work proposed for Phase I and Phase II in a revised NSZD Work Plan. As described below, the supplemental measurements provide strong qualitative evidence for ongoing NSZD

occurring in the LNAPL source area at the Site and indicate that the proposed assessment is a critical component in development of the remedial strategy for this Site. In addition, the supplemental measurements indicate there is relatively low spatial heterogeneity in the manifestations of NSZD at the Site, despite the observed geologic and hydrogeologic heterogeneity. Based on these results, we propose to modify our approach to include additional wells for temperature profiling and head space measurements. Wells VW4, VW7, VW15, and VW18 will be added to the Phase I temperature profiling program, and Phase I well headspace gas measurements will be made at all wells where temperature profiles are to be measured. Additionally, the density of temperature measurements will be increased from three measurements per well to five per well to better capture vertical heterogeneity.

This letter is divided into two sections: **Section 1** a brief summary of the supplemental measurement methodology and results, and **Section 2** direct responses to USEPA comments on the draft NSZD Work Plan. To facilitate review of our direct responses in '2)', USEPA comments are shown in black text and our responses are shown in blue text.

1 Supplemental Measurements

Supplemental measurements were collected on January 26, 2021 during the routine monitoring event. Vadose and saturated zone temperature profiles along with monitoring well headspace gas concentrations were measured. Vadose zone temperatures were measured 2 feet below ground surface (bgs), half-way to the water table, and 1-foot above groundwater. Saturated zone temperatures were measured 1 foot below groundwater, 5 feet below groundwater, and 10 feet below groundwater. Headspace gases were measured 2 feet below top of casing and 1-foot above groundwater.

Supplemental measurements were collected from the following locations:

- Source area wells where LNAPL was present (VW2, VW5, VW6, VW13, VW13B, VW14, VW15, VW23, VW31, and VW32).
- One downgradient well where LNAPL was absent (VW17)

Groundwater temperature data collected from background monitoring wells MMX and VW37 as part of the routine field parameter suite were used to compare with those obtained from the supplemental measurements.

The following observations were made from the supplemental data:

1. Vadose zone temperatures qualitatively indicate NSZD. Vadose temperatures are elevated above the maximum daily air temperature (28.9 degrees Celsius [^{o}C]) on the sampling date (in-text **Figure 1A**).
2. Groundwater temperatures qualitatively indicate NSZD. Groundwater temperatures are elevated beneath the LNAPL by up to 3.1 ^{o}C compared to background groundwater at wells MMX and VW37 (27.6 ^{o}C) (in-text **Figure 1A**).
3. Temperature distributions qualitatively indicate NSZD. Groundwater temperatures increase in the downgradient direction beneath LNAPL, indicating progressive addition of heat as groundwater passes beneath the source zone (in-text **Figure 1B**).

4. Well headspace gas concentrations 1 foot above the liquid level qualitatively indicate NSZD processes. Gases indicative of NSZD processes (methane [CH_4], hydrogen sulfide [H_2S] and carbon dioxide [CO_2]) are present at notable concentrations (in-text **Figures 2A** and **2B**).
5. As shown on the in-text Figures, virtually all locations in the LNAPL affected area show temperature changes and gas concentrations in the same direction (i.e., elevated), except possibly in the vadose zone at VW-6. Additionally, the CO_2 and CH_4 concentrations are all largely within the same order of magnitude. This observation suggests that variations in geology and hydrogeology at the site may not have a particularly large effect on the NSZD processes that are occurring at the Site, and a Thiessen polygon approach to calculate cumulative NZSD processes will likely be adequate.

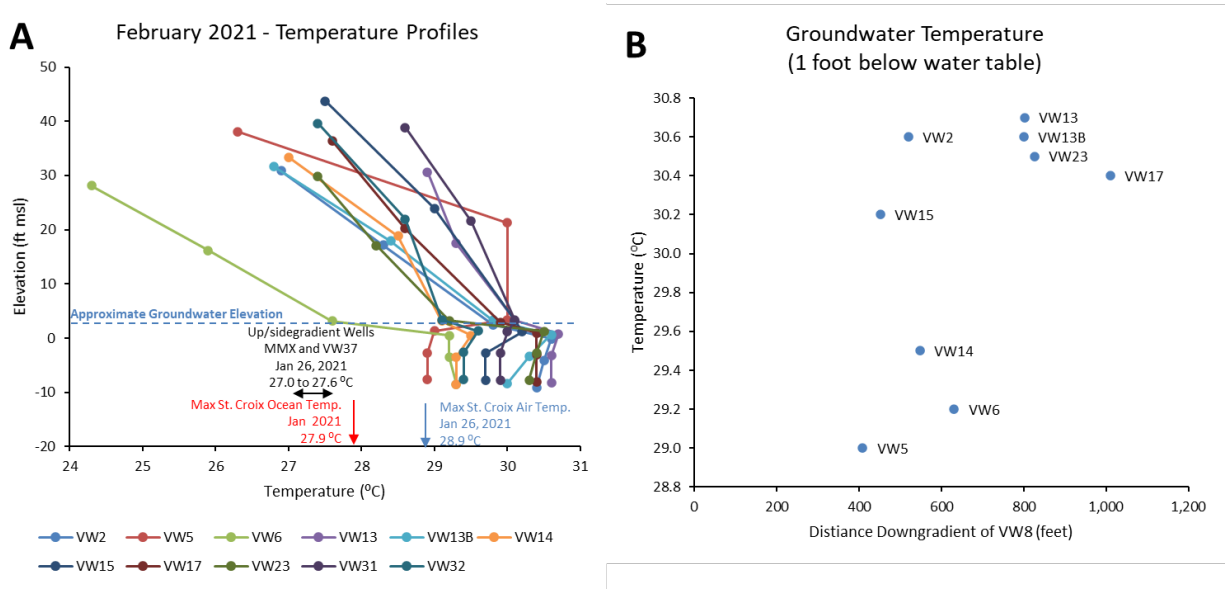

Figure 1 Results for the supplemental temperature survey. A) Down hole temperature survey results compared to background and ambient values. B) Temperatures beneath the western LNAPL lobe as a function of downgradient distance from upgradient well VW8.

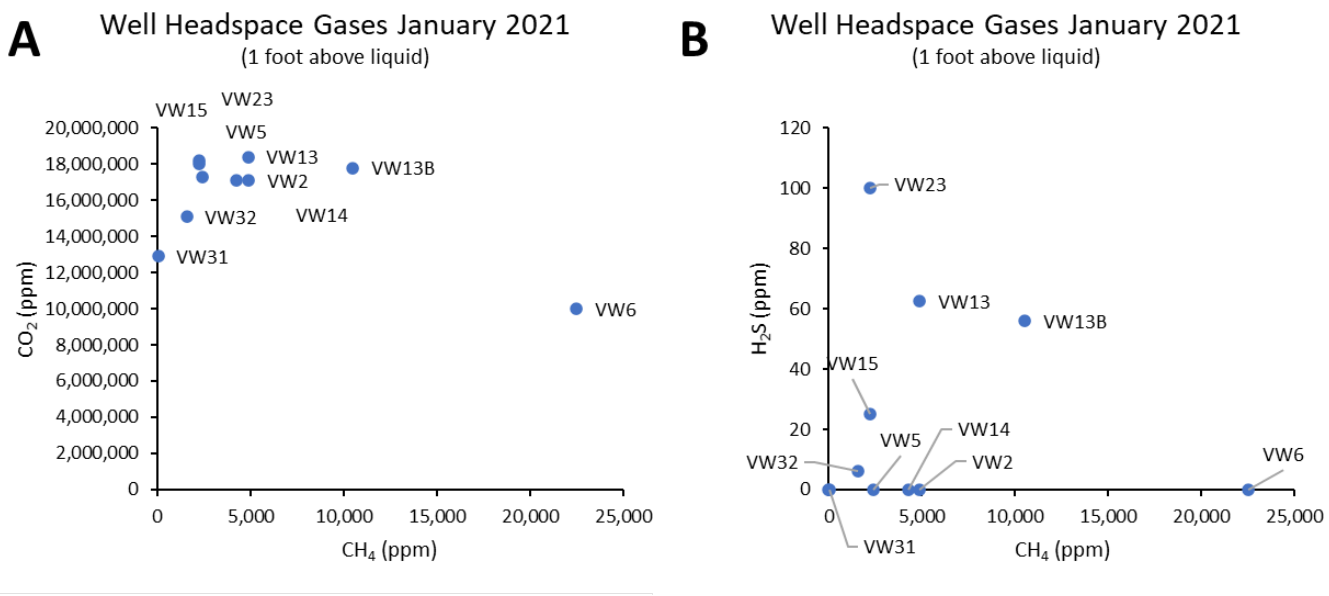

Figure 2 Results for well head space readings taken 1 foot above the liquid level in the well. A) CO2 and CH4 are elevated in wells where LNAPL is present, but absent in VW17 where LNAPL is absent. This supports that background concentrations of these gases are low and that appreciable volumes are produced by NSZD processes. B) The presence of H2S and methane provides evidence of sulfate reduction and methanogenesis may also contribute to NSZD. This contention is also supported by historic dissolved oxygen and ORP measurements of groundwater in wells downgradient of the LNAPL plume.

2 Responses to USEPA Comments on the Draft NSZD Work Plan

I. QUALITY ASSURANCE PROJECT PLAN (QAPP)

Comment #1 - QAPPs normally have a lifecycle of 5 years. The QAPP included as Appendix C to the Work Plan is outdated and needs to be resubmitted. Any new scopes of work will also require the submission of a new QAPP. Please also note that the submitted QAPP was used for the work associated with the dissolved phase petroleum hydrocarbon. Whereas the work proposed under the draft LNAPL NSZD work plan is for assessing the LNAPL source zone depletion. Hence, a separate QAPP would be needed for LNAPL sampling and analysis. In addition, please note that EPA Region 2 has adopted the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) format for QAPP documentation. Additional information can be found at the following EPA webpage: https://www.epa.gov/fedfac/assuring-quality-federal-cleanups. The UFP-QAPP Manual and the accompanying Optimized Worksheets are available for reference in the same webpage. The UFP-QAPP, which contains 37 worksheets, is designed to be a standalone document for project personnel to carry out their responsibilities. After the work plan is updated in accordance with the comments noted in this letter, it would be sufficient to cite in each of the QAPP worksheets where each of the requested items are located (section, page) within the revised work plan.

2.1 Response to Comment #1

We acknowledge that a revised QAPP based on the Uniform Federal Policy for Quality Assurance Project Plans (UFP-QAPP) format is required. As stated above, the QAPP will only be required for the LNAPL sampling and analysis. We propose to update the QAPP for both LNAPL, dissolved phase, and other groundwater geochemistry testing that will be required to implement this scope of work and long-term groundwater monitoring (including monitored natural attenuation [MNA] and NSZD performance monitoring). As we understand, field-based methods such as field screening of soil gas concentrations, downhole soil gas monitoring and the E-flux and Flux Chamber LI-COR monitoring will not be included in the QAPP.

Once agreement is reached on the means and methods proposed in the draft NSZD Work Plan, a revised QAPP will be submitted to USEPA for review.

Comment #2 - For the Key Study Questions in Section 3.3 and Data Quality Objectives (DQO's), please use the EPA's 7-step DQO process in order capture the decisions that will be made and the required level of data quality with corresponding acceptance criteria. With the UFP-QAPP, the Optimized Worksheet #11 should be used to document this information.

2.2 Response to Comment #2

USEPA's 7-step DQO process has been incorporated into attached **Table 1** of the Work Plan and the key study questions in Section 3.3 of the Work Plan have been updated and provided for your review.

Comment #3 - Key investigation questions are provided in Table 3-1 (included in the body of the Work Plan), but the questions lack specificity. The questions need to be expanded to present the specific logic and decisions that will be made regarding the NSZD monitoring effort. Table 1 (included in the Table section) provides some clarification in terms of how data will be used, but does not provide adequate

cross-references to appropriate sections of the Work Plan for ease in understanding and identification of decision criteria that might be considered during decision making. As noted above, please revise the Work Plan to ensure the DQO development is consistent with the approach outlined in the UFP-QAPP.

2.3 Response to Comment #3

Attached **Table 1** has been updated by adding reference to the relevant sections of the work plan. In-text **Table 3-1** of the Work Plan (Key Questions) has been updated to include specific statements and has been provided as an attachment for review.

II. General Questions

a. Section 3.2 - The rationale for selection of monitoring wells to be used in the Phase I monitoring program are not adequately discussed in the text and associated tables, specifically Table 3. The Phase I program is noted as being conducted in conjunction with the semiannual monitoring event, but the omission of certain wells historically inside the light non-aqueous phase liquid (LNAPL) plume (i.e., wells VW-15, VW-17, VW-18, VW-19, VW-26, VW-28 and VW-38) are excluded from the proposed well network. The rationale for excluding these wells but including others needs to be provided in the Work Plan. Please revise Table 3 of the Work Plan to include, as part of the data quality objectives (DQOs), the intended informational purpose for each well location selected.

2.4 Response to General Question II.a.

Source area wells were selected as those that most recently had LNAPL present. Upgradient and downgradient wells were selected to be representative geology/hydrogeology variations, historical chemistry data, and provide geographical coverage without committing to sampling all Site wells. **Table 3** (attached) has been revised to include a column that specifies the rationale behind each location and has been provided for review.

b. Please specify where the temperature profiling and well head space soil gas measurements will be collected.

2.5 Response to General Question II.b.

Well headspace measurement and temperature profiling intervals are provided in Section 3.2.1 of the Work Plan, specifically:

- Vadose zone temperatures will be measured 2 feet bgs, half-way to the 1-foot above groundwater, and three equally spaced intervals in between.
- Saturated zone temperatures will be measured 1 foot below groundwater, 5 feet below groundwater, and 10 feet below groundwater.
- Headspace gases will be measured 1-foot above groundwater.

c. (Section 2) - Important elements of the Natural Source Zone Depletion (NSZD) conceptual site model (CSM) including the depth of the groundwater table relative to well screens, location and thickness of LNAPL, and geology across well screen intervals are not provided in the associated maps and cross-sections. Data is available to define these features in the LNAPL NSZD CSM. The NSZD CSM serves an

important role in evaluating the reliability of proposed data to be collected during the Phase I and II programs. Please revise the Work Plan to include a more detailed site NSZD CSM for critical wells and portions of the NSZD study area.

2.6 Response to General Question II.c.

We propose to update the NSZD Work Plan by incorporating the following elements from the LNAPL Conceptual Site Model (CSM) provided to in response to USEPA comments on the LNAPL CSM dated January 8, 2021:

- Revised cross sections have been developed and submitted to USEPA in response to comments on the Site LNAPL CSM. The revised cross sections indicate location and thickness of LNAPL and will be included in a revised NSZD Work Plan. The revised cross sections (new **Figure 3A** and **Figure 3B** in the revised Work Plan) are attached.
- Figure 5 (Geology across well screens) was included in the draft Work Plan that was submitted. Coupled with the revised cross sections, this is expected to adequately address the request for information about geology across well screens.

d. Section 4.2.1 – The first paragraph of this section indicates that the presence of methane and carbon dioxide above baseline concentration in the vadose zone provide a strong line of evidence that hydrocarbon degradation and mass loss are occurring. Please clarify when the baseline concentration was determined. In addition, please explain what the basis is for the selecting which efflux gas measurement methods (passive flux trap or dynamic closed chamber method) will be used.

2.7 Response to General Question II.d.

The statement here is not intended to be site specific and is a general statement that the presence of carbon dioxide and methane indicate NSZD is occurring. A reference to the ITRC guidance where this information was sourced will be inserted for clarification.

Consistent with USEPA's comments on the LNAPL CSM and Remedial Action Plan, decision logic diagrams have been prepared to support the assessment of the NSZD data collection and analysis (**Figure A4** and **Figure A5** of the package of LNAPL and NSZD decision logic diagrams included with the latest response to comments on the LNAPL CSM). This decision logic considers that the NSZD process may not be uniform across the Site and that the various methods (as described by ITRC and CRC Care have limitations). Criteria that will be evaluated to identify if passive trap or dynamic closed chamber (DCC) methods will be used include:

- If methane is detected at ground surface, the dynamic closed chamber will be favored as latest instruments are capable of measuring methane for incorporation into an NSZD rate calculation, whereas passive traps do not measure methane.
- Text will be added to state that weather will be a consideration of the utility of the passive trap method. Specifically, data for wind speed and duration downloaded from the National Oceanic and Atmospheric Administration (NOAA) data bases (or equivalent) from the region will be assessed in context of manufacturer recommendations as to the utility of the method. Note that a NOAA weather station is located less than 1.5 miles from the Site. Also please note that background and source area locations will be equally affected by wind, assuming the traps have

equivalent exposure. Therefore, the effect of wind will be minimized during the background correction.

- The passive trap method will be utilized if there are indications that high and/or variable concentrations of carbon dioxide are identified in background locations. In this situation, passive traps will be employed to obtain stable and radiogenic carbon isotope data to quantify background carbon dioxide concentrations that are not attributable to NSZD processes.
- Based on the outcome of supplemental measurements taken in January 2021, we recognize that geological variability may preclude use of either passive trap or DCC methods if gases produced by NSZD are not representative at the ground surface where these methods are employed.

Therefore, to assess the bulleted points above, we revised the NSZD Work Plan to propose installing three soil vapor monitoring locations in the source areas and one at a background well location during Phase 1. Specific locations will be determined based on access considerations during site reconnaissance but will generally target the center of each of the three main lobes of the LNAPL plume. The clusters will be adjacent to an existing monitoring well so that a well can be used to collect a deep soil gas measurement immediately above the liquid level in the well (as performed during collection of supplemental measurements described in this letter). The generalized construction of each soil vapor monitoring location will consist of sampling points installed 5 feet above the groundwater table (targeting the sand unit present at or above most screened intervals), midway between the ground surface and top of well screen (approximately 20 feet below ground surface [bgs] in most locations) and one 5 feet bgs.

e. Decision Criteria: The decision criteria that will be used to decide how grids for surface samples collected using either E-flux passive samples (E-flux) or dynamic closed chamber (DCC) samplers is not presented. The decision logic for establishment of the sampling point grids needs to be presented in a flow chart/decision tree that can be used to understand how decisions will be made to select one method and establish the associated grid to be used during Phase II of the NSZD evaluation program. Please revise the Work Plan to include this information.

2.8 Response to General Question II.e.

The decision logic to be used in defining the grid spacing and placement is provided in **Figure A4** and **Figure A5**. The variability in NSZD rates estimated via the temperature methodology as well as differences in groundwater geochemistry and soil gas concentrations down well will inform the grid spacing and locations which best capture the subsurface processes contributing to NSZD at the Site. It is understood that additional sampling and monitoring points may be required following field reconnaissance at the site and evaluation of Phase I results. A preliminary layout of Phase II E-Flux or LI-COR sampling locations has been provided but updates to this are anticipated.

The following potential outcomes from the evaluation of Phase I data could indicate:

- A uniform grid is appropriate for application at the Site.
- The grid spacing as provided in the preliminary layout is appropriate.
- The grid spacing should be smaller than that proposed layout provided on the figure.
- The grid spacing and locations should be modified to reflect key subsurface features/conditions contributing to NSZD rates.
- Locations should be avoided where surface cover or soil water saturation could result in a high or low bias and/or an inability to collect data.

f. Groundwater Flow Direction: As noted in the Work Plan, the cause for the anomalous groundwater elevation at well GM-22 is currently unknown. Arrows showing estimated flow directions on the piezometric surface map provided in the Work Plan appear to be erroneous at key locations. Groundwater flow beneath the plume is not always south to southeast as suggested in the CSM and the map arrows. The piezometric surface high surrounding VW-30 and VW-35 as mapped beneath the LNAPL plume suggests that although groundwater gradients in this area are low, groundwater flow could be radially outward to the northwest and southeast of these groundwater highs or mounds and could very well explain, in part, the historical geometry of the LNAPL plume (See Figure 4). The CSM that focuses on the areas where NSZD is to be further evaluated, needs to be revised to include a more detailed and corrected piezometric surface map and a discussion of possible localized flow directions for groundwater beneath the historic LNAPL plume.

2.9 Response to General Question II.f.

We concur that groundwater flow at GM-22 is a data gap and is identified as such in the NSZD Work Plan. We have subsequently verified that the survey data at this location is accurate and the mound is likely real. We note the following:

- We identified that GM-22 is within the footprint of the former red mud pond (see **Figure 3**below).
- Nearby and former well GM-10 (see **Figure 3** below) historically had anomalously high groundwater elevations, which was attributed to artificial recharge from a former cooling pond that was 10 feet above sea level and filled with seawater for cooling a power plant and residual brine from a desalinization plant (Geraghty and Miller, 1982)[1].
- Well GM-7 (see **Figure 3** below) was shown to be dry on Figure 4 of the draft NSZD Work Plan. The top of casing at GM-7 is 26.04 feet above sea level, and the well is 35 feet deep. Therefore, the groundwater mound is not present in this location.
- We identified a complex wastewater treatment system that recharges the groundwater system with reclaimed water is located to the west of wells GM-10 and GM-22. The system contains a network of subsurface pipes that may also potentially leak.

We expect that groundwater at GM-22 (and GM-10) is perched due the buried features and/or abundant clay in these locations from the historic Krause Lagoon that was present where these wells are sited. The source of the water is conceivably from the groundwater recharge system or leaking infrastructure, which has been in place for decades. We intend to sample GM-22 for cations, anions, and alkalinity, to verify if the water type at this location is geochemically distinct to verify this.

Once the cause of the mound has been identified, future groundwater contour maps will be revised accordingly.

FIGURE 3 REVIEW OF GERAGHTY AND MILLER (1982)[1] SHOWS THAT GM-22 IS WITHIN THE FORMER RED MUD POND AREA.

g. Because a multiple lines of evidence approach will be used during decision making after completion of Phases I and II, it is essential that a formal weight of evidence approach be described including a flow chart that supports the proposed decision-making process in the Work Plan. The decision logic needs to identify the benefits and limitations of decision criteria used at critical points of the program. This decision process needs to also indicate what parameters have the greatest potential for introducing errors to the decision process for estimating NSZD rates identified in the Work Plan and in subsequent deliverables. Please revise the Work Plan to include the decision logic to be used.

2.10 Response to General Question II.g.

Decision logic diagrams have been provided as **Figure A4** and **Figure A5**. In the context of the ITRC and CRC Care guidance, highest weight will be assigned to the Phase II assessment methods (unless key limitations to the application of these methods are identified in Phase 1).

The key decisions that need to be determined as part of this process include:

[1] Geraghty and Miller, Inc., 1982. Installation of a ground-water monitoring network for Martin Marietta Alumina, St. Croix, U.S. Virgin Islands. June.

1. Do the background (upgradient) CO_2 concentrations indicate that naturally occurring CO_2 could impact the analysis of the data? If background $CO_2$is 10 percent of the concentrations observed in the source area, then this impact is significant, and a correction will need to be applied to the calculations. Where detectable concentrations are observed to be less than this threshold, a correction may not be required, and the presence of background sources of carbon dioxide will be discussed in the uncertainty section of the data analysis.
2. Is CH_4 elevated in shallow soil gas sampling locations such that use of the E-Flux approach would result in a low bias in NSZD rate estimates? If CH_4in shallow soil gas (at 5 feet bgs) is greater than 10 percent of the CO_2 concentration (normalized for molecular weight of carbon in both molecules) then the potential bias is considered significant and either an alternative method (flux chamber and LI-COR meter or additional vertical soil gas profiles) will need to be utilized.
3. Identify the areas where hard sand is present that may lead to the accumulation of soil gases. These areas will have to be avoided for Phase II testing methods and sampling grids and locations modified accordingly.
4. Identify the areas where water ponding or water-logged soils may exist that could act to impede the vertical migration of gases. These areas will have to be avoided for Phase II testing methods and sampling grids and locations will be modified accordingly.

h. The Work Plan calls for the use of a gradient method that combines soil gas readings from inside wells near the water table with shallow one-foot below ground surface (bgs) soil gas measurements adjacent to the paired wells. Because of the complexity of the geology at the site it may not be adequate to use only two points to verify changing conditions in the vadose zone, particularly where secondary porosity features may influence advective flow in the subsurface. American Petroleum Institute (API) NSZD Guide (2017) suggests that multiple levels of soil gas probes may be needed when water tables are greater than five feet below ground surface (bgs) to better define the limits of vapor phase diffusion coefficients and NSZD rates using a gradient method. The depth to groundwater at the site appears to range up to 40 feet bgs. The Work Plan needs to describe how the proposed gradient method can be considered representative of site conditions.

2.11 Response to General Question II.h.

Please see our proposed revisions to the gas gradient method in our Response to General Question II.d (**Section 2.7**).

i. Also, gradient methods assume that diffusion is the only soil gas distribution mechanism above an LNAPL plume. Given that secondary diagenetic features such as calcification and bedding planes are potentially controlling mechanisms for advection (i.e., flow) beneath the site, it is not clear how these potential influences will be overcome using the simple two point gradient test proposed in the LNAPL NSZD Work Plan. The Cooperative Centre for Contamination Assessment and Remediation of the Environment (CRCCARE) in Technical Report No. 44, Technical measurement guidance for LNAPL NSZD (CRCCARE Guide), suggests in Figure 9 of this report that gradient methods in limestone sites should be carefully considered prior to use. Table 6 of the CRCCARE guidance indicates gradient methods should include soil gas probes installed below 1.5 meters bgs to avoid root zones. Moisture content in the subsurface may also have a substantial influence on any calculated NSZD rates calculated using gradient and other soil gas measurement methods. The Work Plan needs to address how the current designs can

be reliably used given site conditions. How and when moisture content issues related to NSZD activities will be addressed needs to be integrated more specifically into the site decision logic and sampling plan discussed in the Work Plan. Please revise the Work Plan to address these issues.

2.12 Response to General Question II.i.

Consistent with the framework provided in the work plan, the NSZD Work Plan uses an extensive range of methods to determine what methods can best quantify NSZD rates at this Site and ultimately be included into a long-term monitoring program. The limitations of the various methods were recognized in the development of the program and as such a range of methods were employed. Every method has limitations and short comings; consequently, our program of works attempted to facilitate early data collection with higher resolution lower quality methods to inform the sampling design for the Phase II high quality testing methods. The approach proposed by the group is consistent with the Triad approach and is designed to aid the group and USEPA in making informed decisions on modifications to the Phase II program of works. In the context of limestone geology, the surface-based flux measurement methods (E-Flux and LI-COR) involve sampling in the upper 6 inches of the subsurface which in all cases is unconsolidated media (and in many cases fill). In this context these methods will be not affected by the presence of secondary diagenetic features. In the event that site heterogeneity (including secondary diagenetic features) results in major differences in subsurface soil gas and temperature profiles, (work completed as part of Phase I) revisions to sampling density and locations will be made in accordance with the decision logic diagrams referenced above.

Further, our proposed revisions to the gas gradient method in our Response to General Question II.d. go part way to addressing this issue; through the installation of nested soil vapor probes we hope to better constrain the spatial and vertical distribution of gases in the subsurface. We are aware of issues related to elevated moisture and surface cover exist and as part of the Phase I activities (refer decision logic diagram), therefore, detailed site reconnaissance will be completed and revisions to the Phase II scope of work will be required. To support the further understanding of soil vapor diffusivity (including moisture effects), the tracer method will be used to quantify soil vapor diffusivity at vadose gas monitoring points. This proposed additional testing is included in the work plan.

j. The decision whether to use DCC as opposed to passive E-flux meters during Phase II will depend on whether methane is completely digested at a specific location and across the site. Given the flux of soil gas through the E-flux sampler can only be estimated, it is essential that flux rates are estimated as closely as is possible under site conditions during NSZD testing. Please revise the Work Plan to include sufficient information on how flux rates will be estimated should E-flux be proposed for use at the site during Phase II. Further, the Work Plan should also discuss how the potential for excessive winds to over-estimate NSZD rates when using E-flux will be addressed.

2.13 Response to General Question II.j.

The work plan has been revised to include more information on how passive E-flux rates are estimated by the vendor. Please note that a detailed description of the calculation method and equations are already provided in Section 4.3.9.1 of the work plan . By quantifying the mass of CO_2 on the sorbent media and knowing the time over which the trap was deployed flux rate is estimate (mass/time – for example grams per day/grams per hour etc.). Specifically, the vendor (E-Flux; www.soilgasflux.com) analyzes traps and

provides a rate estimate. The specific method is outlined in McCoy et al. (2014)[2], which is properly referenced in the Work Plan but will be expanded upon in the revised submission. Additionally, a Standard Operating Procedure (SOP) that describes the method is included in the appendices of the work plan. Consideration of excessive winds were addressed as described in our Response to General Question II.d (**Section 2.7**) and will be a factor in the decision to use E-flux technology.

k. Section 4.3.9.2 – For the dynamic closed chamber method, it is not clear how the CO2 detection limit is determined and the process/method that will be used for data validation. Since weather condition is a factor in efflux measurements calculations, it is not clear what type of weather-related information will be collected and/or instrumentation used.

2.14 Response to General Question II.i.

Text is provided on attached **Table 1** to clarify how detection limits are verified using the DCC method. The detection limit is measured on a chamber that is sealed off. 60 measurements are made on the sealed chamber. The detection limit is simply the mean value of the measurements plus three times the standard deviation, a typical method commonly used to quantify detection limits.

Text will be updated to specify that weather-related information will be obtained from the nearby NOAA station "LTBV3 - 9751401 - Lime Tree Bay, St. Croix, VI", which is located approximately 1.5 miles southeast of the site.

III. LABORATORY QA/QC

a. Section 4.3.9.1 – Please provide the name of the laboratory that will be analyzing the traps for CO2, as well as the method to be used and the laboratory's reporting limit. In addition, information regarding acceptance criteria for the duplicates should also be included.

2.15 Response to III.a.

If passive traps are selected for use, they will be obtained from E-Flux (www.soilgasflux.com). E-Flux uses industry-accepted practices and methodologies, including quality assurance and quality control protocols. In combination with their proprietary technology, the carbonate and ^{14}C analyses are based on two ASTM methods:

- D4373-14, Standard Test Method for Rapid Determination of Carbonate Content of Soils.
- D6866-18, Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis (includes stable carbon isotope analysis).

This information has been included in the revised attached **Table 1**. E-Flux completes their own quality assurance/quality control (QA/QC) checks in accordance with these standard methods and will provide statements about data quality and useability in their reports (**Appendix E**).

[2] McCoy, K., Zimbron, J., Sale, T. and Lyverse, M., 2015. Measurement of natural losses of LNAPL using CO2 traps. Groundwater, 53(4), pp.658-667.

b. Section 5.7 – It is not clear what will be the acceptance criteria to evaluate the specified QA/QC samples. In addition, the collection frequency for the QA/QC samples was not included. Please provide.

2.16 Response to III.b.

Attached **Table 1** has been updated to include quality control procedures. The following QA/QC strategies are utilized in the technique:

- A travel blank that accompanies the samples during shipping to and from the Site. CO_2 detected in the travel blank is subtracted from the primary samples.
- Radiocarbon/stable carbon isotope corrections for non-NSZD gases inputs.
- Deployment of an upgradient/background trap to account for contributions from wind/weather or background sources not captured in the isotope analysis.
- One duplicate trap per 10 deployments. For the duplicate trap, the results will be compared and a target of +/- 30 percent will be established as a preliminary goal. No formal quality control metrics have been proposed in the guidance or by the vendor.

c. Section 5.8 – For the specified laboratory analysis, it is not clear what are the project's required reporting limits and whether there are there any criteria that are being used for comparing the results. Please also provide the laboratory's accreditation information for these analyses (type of accreditation and expiration date). In addition, please provide the method specifications that will be used for the dissolved gases. Please also include the filter size that will be used to collect the sample for dissolved metals; please note that a consistent filter size is needed for consistent results, and that 0.45 microns is a typical filter size for dissolved metals.

2.17 Response to III.c.

We have requested this information from E-Flux and will include the requested documentation in the revised Work Plan as (**Appendix E**). We will specify that a 0.45 micron filter will be used.

d. Section 6.0 – Please clarify which procedures will be used for validating the data generated and the process for assessing the data usability. Also, please include any SOPs that will be used. The type of decision that will be made with the data will typically dictate the level of validation.

2.18 Response to III.d.

An updated QAPP is being developed for the routine groundwater sampling and the targeted LNAPL and groundwater sampling proposed as part of the NSZD Assessment. In terms of the Phase II E-Flux assessment, it is assumed that reference to the literature (McCoy et al., 2014[3] & CRC CARE, 2018[4])

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[3] McCoy, K., Zimbron, J., Sale, T. and Lyverse, M., 2015. Measurement of natural losses of LNAPL using CO2 traps. Groundwater, 53(4), pp.658-667.

[4] CRC CARE. 2018. Technical measurement guidance for LNAPL natural source zone depletion. CRC CARE Technical Report 44. Adelaide, Australia: CRC for Contamination Assessment and Remediation of the Environment.

would be adequate. We will extract the relevant information and provide it in the revised text (Section 4.3.9.1.1). Specifically, (from CRC CARE):

"*QA/QC procedures are important in evaluating the accuracy and precision of the data collected. One duplicate trap location every 10 locations is recommended to evaluate consistency between installation procedures and replication of results. Place the duplicate trap approximately 0.3 m from the parent location and install it in an area of similar ground cover. Statistics such as the calculation of a relative percent difference (RPD) from the parent and duplicate sample data can be performed to assess data quality. An elevated RPD of greater than 30% is typically used as a criterion to re-evaluate the soil receiver pipe installation procedures to ensure a good seal with the subsurface was attained. However, heterogeneities in the subsurface impact the ability to achieve an RPD of less than 30% at many sites, therefore the 30% criterion may not be achieved in all cases.*

As discussed above, a TB must be provided by the passive flux trap supplier and analyzed along with the samples for each field event. The TB accounts for CO2 not associated with flux from the subsurface that either came from manufacturing or sorbed from atmosphere (through the caps) during the shipment.

*The detection limit of a passive CO2 trap is dictated by the detection limit of the analytical method. The detection limit of the analytical method is found by multiplying a typical coefficient of variation of 3% on trap CO2 analyses, and a typical blank trap CO2 content of 1% by weight by five (i.e., 3% cv * 1% CO2 by weight * 5). The detection limit of the analytical method of CO2 trap is approximately 0.15% CO2 by weight of the sorbent (API 2017). Then using deployment time, the area exposed to efflux, and the quantity of sorbent material the detection limit of the CO2 trap can be determined. The detection limit is typically 0.1 µmol/m2/s for a 15-day deployment time, a cross-sectional diameter of 10.16 cm of the Schedule 40 polyvinyl chloride (PVC) receiver pipe, and 40 g of sorbent material A decrease in deployment time of 4 days would result in approximately a 5-fold increase in the detection limit (0.5 µmol/m2/s). Note that if laboratory results are less than the specified analytical detection limit, the resulting detection limit of the CO2 traps must be considered non-detect."*

For the LI-COR and soil gas vertical profile methods, field-based meters will be utilized. QA/QC will be achieved through calibration of the instrument against calibration standards in the field. It is proposed that consistent with the E-Flux methodology described above duplicate testing will be conducted at 10% of the locations. This will comprise completion of a duplicate sampling location with 2 feet of the primary sample location. As no laboratory testing will be conducted no other QA/QC processes are proposed.

IV. SPECIFIC COMMENTS

Specific Comment 1: Section 1.1 last paragraph, Figure 2: As noted in the last sentence, potential source areas are located on the west side of the site. The location of these potential source areas needs to be shown on Figure 2 as they could impact where samplers are placed and the geochemistry of the soil gas near these impacted surface materials. Please revise Figure 2 accordingly.

2.19 Response to Specific Comment 1.

Figure 2 has been revised and provided for review.

Specific Comment 2: Section 1.2 Paragraph 4, Figure 3: In this paragraph it is noted that the groundwater table is broadly consistent with the Kingston Limestone. However, Figure 3 does not support this statement. The depth to the water table and relationship of well screens in the LNAPL NSZD study area needs to be described more accurately in this section and on Figure 3 of the Work Plan. Careful inspection of Figure 3 also shows that boring logs from some wells such as VW-14 and projected well VW-18 were not honored on the cross-section. Some explanation, perhaps as a footnote to Figure 3, of why these well logs were not included in the cross-section is needed. An updated set of cross-sections, specifically for the LNAPL plume study area, are needed in the Work Plan to demonstrate the spatial relationships between well screened intervals, LNAPL, geologic, and hydrogeologic features. Also, the cross-sections shown on Figure 3 need to be updated to include detailed LNAPL study-specific well diagrams that support verification of the LNAPL transmissivity bail down tests.

2.20 Response to Specific Comment 2.

The Work Plan states "*An interval of gravels, sands, silt, and clay within the Kingshill Limestone is identified beneath the central portion of the Site that is broadly coincident with the location of the water table and intervals over which most Site wells are screened*."

Revised cross sections (Work Plan Figures 3A and 3B) showing the location of the water table relative to various lithology features has been provided to support our statement.

Specific Comment 3: Section 1.3, first paragraph, Figure 4: In this paragraph groundwater flow is noted as generally to the south-southwest and south towards the sea. Inspection of Figure 4 indicates that localized flow beneath the plume may occur radially to the northwest and southeast away from several groundwater highs in the vicinity of wells VW30 and VW35. These features suggest a very flat gradient beneath the LNAPL plume and potentially variable flow directions that could explain, in part, the geometry of the historical LNAPL plume. A more detailed piezometric surface map underlain by the most extensive historical plume map, such as those provided in Appendix A of the Work Plan is needed. The extent of historical subsurface contamination needs to be presented along with the interpreted localized groundwater elevations beneath the LNAPL plume. The locations of potential source areas also needs to be identified on Figure 4 or another more detailed piezometric surface map prepared for the LNAPL NSZD plume study area.

2.21 Response to Specific Comment 3.

We have partly addressed this comment in our Response to General Question II.f (**Section 2.9**). We intend to revise contour maps once geochemical fingerprinting of groundwater at GM-22 is available, a task that will be implemented in Phase 1 of the proposed work. We will include the footprint of historical LNAPL distributions on the revised groundwater contour map as requested.

Specific Comment 4: Section 3.2.2: The scope of the Phase 2 program is poorly defined. This section of the Work Plan needs to be more detailed to allow for a better idea of the number of samplers of various types which may be used along with dimensions of any proposed study areas. Other information that needs to be included in this section includes whether geochemistry parameters collected during Phase 1 will be repeated in subsequent phases or monitoring events, and whether temperature monitoring will be included in Phase 1 and subsequent well sampling events as a means for long term monitoring of NSZD.

2.22 Response to Specific Comment 4.

The scope of work proposed for Phase II is necessarily vague due to the need for information from Phase 1 to inform the program. However, we expect that our response to Comment #2 (**Section 2.2**, revising DQOs) provides the additional detail that is requested. As noted above, the decision logic diagrams describe how information from the Phase 1 scope of works will inform scoping and implementation of Phase II.

Specific Comment 5: Section 3.2.2, Last Bullet: In the last Bullet, it is suggested that during Phase 2, analysis of wells for carbon fractionation using compound specific isotopic methods for carbon will be performed to determine if a background correction can be applied successfully to remove the impacts of carbon signatures from native carbonate rocks from signatures from NSZD of the LNAPL. It would be beneficial to perform these analyses as soon as possible to assure that passive Flux or DCC soil gas sampling data will be representative of NSZD of the LNAPL and not biased high because of contributions from native carbonate contributions to carbon dioxide values. Ensure the Work Plan allows for the collection of this data at the earliest step.

2.23 Response to Specific Comment 5.

We propose collecting well headspace readings from upgradient locations (where NSZD is not expected to be occurring) during Phase 1 to identify if gases are present in the subsurface at concentrations that warrant the expense of employing compound specific carbon isotope analysis. If no gases are present in the subsurface at upgradient and side gradient locations, we believe the urgency for employing this technique will be reduced or eliminated.

Specific Comment 6: Section 3.2.3: This section does not provide a specific time frame for reporting Phase 1 results to EPA. Please modify the Work Plan to provide more specific timing for the Phase 1 report.

2.24 Response to Specific Comment 6.

Timing for implementation of Phase 1 will be provided once agreement is reached on the proposed scope of work. We anticipate completing a report within 90 days of completion of the Phase 1 field work.

Specific Comment 7: Table 3-1 includes general data quality objectives. These DQOs are based on the content in Appendix B of the Technical Measurement Guidance for LNAPL Natural Source Zone Depletion (CRC-CARE Technical Report No. 44) (CRCCARE). The checklists included in Appendix B of the CRCCARE report are intended to be used as place holders to prompt the development of site-specific DQOs. However, the Work Plan needs to develop site specific DQO's that define how the data from Phase 1 and 2 will be used to bound decision making concerning the evaluation of NZSD at the site. Development of the specific DQOs can occur in Table 1 of the Work Plan and should be consistent with those presented in Worksheet #11 of the associated UFP-QAPP. Further, the information included in Table 1 of the Work Plan includes site specific principal study questions in a format that is more in tune with EPA's DQO approach, but Table 1 does not provide an adequate cross-walk between applicable sections of the Work Plan and the Table contents for the column heading "Data Use Objective". Information in Table 1 should be consistent with UFP-QAPP, Optimized Worksheet #17 which supports the information included in Worksheet #11. Please revise Table 1 to include references to the supporting information within the Work

Plan as well as UFP-QAPP Worksheet#17 or its equivalent. Additionally, please ensure that the Work Plan includes a diagram or flow chart indicating the intended decision logic to be used during data assessment. As cited in the reference section at the end of the Work Plan, the Interstate Technology & Regulatory Council (ITRC) updated its LNAPL guidance: ITRC 2018. Light Non-Aqueous Phase Liquid (LNAPL) Site Management: LCSM Evolution, Decision Process, and Remedial Technologies, LNAPL-3. Washington, D.C. https://lnapl-3.itrcweb.org (LNAPL-3). Hence the list of references cited at the bottom of Table 1 needs to include the ITRC's LNAPL-3. Appendix B of LNAPL-3 includes examples of site-specific decision logic diagrams to guide the decision-making process. Please ensure that the Work Plan includes a site-specific decision logic diagram or flow chart consistent with the ITRC LNAPL-3 guidance.

2.25 Response to Specific Comment 7.

We have partly addressed this comment in our response to Comment #2 (**Section 2.2**) and Comment #3 (**Section 2.3**), and **Table 3-1** has been updated and provided for review. USEPA has recommended that decision-logic diagrams be included in both the LNAPL CSM and NSZD Assessment. In review of the ITRC guidance no specific decision logic diagram is provided for assessment and analysis of NSZD data.

A site-specific decision logic diagram based on NSZD 14 has been developed and is included with the response to comments on the LNAPL CSM (this response was provided at the same time as this response) as **Figure A1**and decision logic diagrams for the evaluation of Phase I and Phase II NSZD data is provided as **Figure A4** and **Figure A5** (and duplicated in this response to comment).

Specific Comment 8: Table 3: This table identifies the wells in the proposed LNAPL plume monitoring network, as well as those wells selected as being indicative of background and down gradient. No rationale is provided for how and why the background wells were selected. Presumably, their selection is based on location and proximity to the study area and past monitoring and sample analyses performed at these locations. Additional detail is needed in the Work Plan concerning how the background wells were selected. A review of down gradient well locations given the current piezometric surface provided in Figure 4 indicates that many of these wells are upgradient or cross-gradient of the study area. Understanding there may be a significant data error/anomaly in the reported groundwater value for GM22, Table 3 will need to be reevaluated before the wells listed in it can be considered representative for LNAPL NZSD study purposes as either down-gradient or upgradient.

Additionally, the work on the redetermination of the casing elevation of GM22 and other wells should be considered during Phase 1 to better inform the CSM.

2.26 Response to Specific Comment 8.

This comment is addressed in our Response to General Question II.a (**Section 2.4**). **Table 3** (attached) has been revised to include rationale for selecting wells.

Specific Comment 9: Figure 7: The Figure shows potential locations for E-flux samplers. However, it is unclear how the configuration shown in the figure was developed and why there is not a figure which also shows potential locations for DCC samplers should they be selected for use. Please include this

information. It also would be useful to include a presentation of where gradient evaluations may be performed.

2.27 Response to Specific Comment 9.

Rational for selecting E-flux sampling locations will be added to the text in Section 4.2 of the Work Plan, as requested. However, as noted in Response to General Question II.e (**Section 2.8**), grid spacing will ultimately be dependent on the Phase 1 sampling results. Specific data points that will be used are provided in the revised **Table 1** (attached), and revised **Table 3-1** (attached). The preliminary concept for sampling locations for the DCC locations will be identical to the E-Flux sampling locations. E-flux is the favored method as it provides time weighted averages. However, if methane is not being fully degraded before discharging to the atmosphere, and the mass balance of carbon equivalent concentrations indicates the error could be larger than 10 percent, then DCC may have to be used. It is recognized that the soil gas vertical gradient methods and temperature methods will provide a line of evidence and that data evaluation that must address this concern and E-Flux measurements still could be used as the primary high quality evaluation method.

The ITRC document does consider an iterative approach as proposed by the group as stated in ITRC-3 Appendix B.

> *"The required data density depends on multiple variable: site heterogeneity (including ground cover, soil type and stratigraphy, depth to groundwater/LNAPL) across the LNAPL footprint, LNAPL distribution as well as the data use objectives and costs. The practitioner might consider an iterative process in which the LCSM is informed in earlier stages with high data density of lower data quality, and lower data density of higher quality at the later stages. This is common practice in environmental remediation, as exemplified by the EPA Triad Approach (for example, see (Johnson 2010)).*"

We have completed a preliminary assessment using temperature profiles and head space readings in wells and propose to complete the Phase 1 testing program using the wells specified to understand the Site heterogeneity using lower data quality analysis methods. Based on the results from this testing, a method of high-resolution testing will be selected, and sampling density determined for application to the Site.

The decision process that will guide the analysis of data is provided in **Figure A4** and **Figure A5** and an updated sampling program for the Phase II will be prepared after completion of Phase I. As described above, this will involve changes in sample grid density and sampling locations based on data collected from the Phase I program. Phase II of the testing program will not commence until USEPA review of the Phase I data and approval of the proposed Phase II sampling program.

Memo

To: Brian Epperson, Hess Corporation

From: Nigel Goulding EHS Support LLC
Dr. Andrew Fowler EHS Support LLC

CC: Brad Freeman, Geo Monitoring Services

Date: February 18, 2021

Re: Response to February 08, 2021 US EPA Review of POCs Response to December 14, 2020 Comments on the LNAPL CSM and Remedial Action Work Plan, St. Croix Alumina Site, U.S. Virgin Islands, EPA ID Number: VID090302084

EHS Support LLC ("EHS Support") has prepared this response to the February 8, 2021 United States Environmental Protection Agency (USEPA) Review of Point of Contacts (POCs) Response to the December 14, 2020 comments on the Light Non-Aqueous Phase Liquid (LNAPL) Conceptual Site Model (CSM) and Remedial Action Work Plan ("LNAPL CSM and Work Plan") for the St. Croix Alumina U.S. Virgin Islands site ("site").

From our review of USEPA comments, we understand that USEPA is in general acceptance of the LNAPL CSM and Work Plan following EHS Support's responses, provided some additional information for clarification is made.

To facilitate review of our responses, USEPA comments are shown in black text and our responses are shown in blue text.

Responses to USEPA Comments on the LNAPL CSM and Work Plan:

EVALUATION OF RESPONSE TO USEPA COMMENTS

DATED DECEMBER 14, 2020

ON THE

LNAPL CSM AND REMEDIAL ACTION WORK PLAN

ST. CROIX, U.S. VIRGIN ISLANDS

DATED JULY 2020

In general, the Response to Comments (RTCs) addressed EPA's comments and are acceptable with the following considerations. The following evaluation includes only responses where additional information or clarification is required.

A revised version of the Light Non-Aqueous Phase Liquid (LNAPL) Conceptual Site Model (CSM) and Remedial Action Work Plan (Work Plan) was not provided, and as such an evaluation of the whether the RTCs were incorporated into the Work Plan was not able to be completed. A revised Work Plan incorporating the proposed revisions is needed.

EVALUATION OF RESPONSES TO GENERAL COMMENTS:

***Evaluation of the Response to General Comment 1 (Risk Evaluation)*:** As noted in our conference call of February 3, 2021, the risk assessment will need to be updated to address current conditions. Additionally, an evaluation currently is being conducted to provide input to help determine if the Site Specific Target Levels (SSTLs) need to be updated for the SCA plume site.

Response to Evaluation of the Response to General Comment 1

We understand that the risk assessment will need to be updated to reflect current conditions. Given that the plume extent has retracted and further weathering of the LNAPL has occurred over time, we do not consider major changes to the findings and conclusions of the risk assessment. We await receipt of USEPA's review and comments on the need to update the Site Specific Target Levels (SSTLs).

Evaluation of the Response to General Comment 2 (Remedial Goals): The response partially addresses the concerns expressed. The interpretation of transmissivity sits at the crux of the assessment of LNAPL recovery. Transmissivity assessment is made on a well-by-well basis. Assurances that each well used to determine transmissivity is appropriately screened to support such an assessment needs to be demonstrated. As such, the cross-section presented in Figure 4-3B omits the presentation of the screen interval with respect to the water table, the historical high-water level, the historical low-water level, and the currently known LNAPL thickness in the well screen. Any well included as part of the transmissivity assessment needs to have a well screen which straddles all of the high, low, and LNAPL levels. Also, changes in apparent product thickness may change the LNAPL transmissivities measurements planned for collection during Phase 1 activities. Any significant changes in groundwater levels and associated apparent product thicknesses may necessitate additional transmissivity measurements. Please revise the Work Plan to ensure it presents well logs showing the following for each well: the historical high-water level, the historical low-water level, and the currently known LNAPL thickness in the well screen. Also, include a contingency for additional transmissivity measurements based on observed changes to LNAPL thicknesses.

Response to Evaluation of the Response to General Comment 2

We have prepared **Table 1** (**Enclosure A**) to demonstrate well screen elevations vs. historic water and LNAPL levels from October 2002 through December 2019. Please note the following regarding wells where LNAPL has historically been detected:

- Five wells where LNAPL was historically present have had screens submerged at some point in the past (VW2, VW6, VW15, VW18, VW29, and VW30).
- Of these wells, only VW2 and VW30 screens have consistently been submerged below the LNAPL.
- Of these wells, only VW-2 had a filter pack submerged below the LNAPL. This occurred on one occasion at which time the LNAPL elevation was equal to the filter pack elevation.

- Of these wells, only VW2 and VW30 had screens submerged below the LNAPL during the last three quarters.

Please note the following regarding wells where LNAPL has *not* historically been detected:

- Three wells (VW3, VW11, and VW12) screens are submerged by groundwater during most monitoring events. These three wells are co-located at the upgradient site boundary where LNAPL is not expected. Additionally, wells VW7, VW8, VW9R, and VW10 are located between the LNAPL source area and the location of these wells. These wells delineate the extent of LNAPL impacts upgradient of the LNAPL plume.
- The screen for VW37 is consistently submerged. This well is up/side-gradient from the LNAPL source area and near VW-36, which has only had a submerged screen three times.
- GM11, GM14, GM7, and GM13D consistently have groundwater submerged screens. These wells monitor the dissolved-phase plume in deeper groundwater intervals beyond the network of shallower monitoring wells that do not have submerged screens.

We note that ASTM E2856-13 "Standard Guide for Estimation of LNAPL Transmissivity" does not exclude wells that historically had well screens submerged by LNAPL, only those with submerged screens at the time of testing. Consequently, VW2 and VW30 are the only wells that should be excluded from transmissivity testing based on the analysis above.

EVALUATION OF RESPONSES TO SPECIFIC COMMENTS

Evaluation of the Response to Specific Comment 3 (*Section 6, Updated Remedial Action Work Plan, Page 63)* ***:*** The last sentence in the first paragraph of this response is incomplete and needs to be revised. The purpose of providing a non site-specific decision logic diagram in the response is unclear. A Site-specific decision logic diagram needs to be prepared and discussed with the EPA prior to moving forward, even if some of the steps are contingent upon the finalization of the CSM. CSM contingent decision steps could be uniquely noted as such in the site-specific decision tree configuration.

Response to Evaluation of the Response to Specific Comment 3

Based on the interlinkages between Response to Specific Comment 3 and 6, a detailed response is incorporated below in the Response to Specific Comment 6. This response includes a site-specific decision logic diagram for monitoring wells in which LNAPL has been observed and active recovery wells where the decision to transition to natural source zone depletion (NSZD) is being evaluated.

Evaluation of the Response to Specific Comment 6 (*Section 6.2, Proposed Framework for LNAPL Recovery Well Shutdown, Bullet 3, Page 65; and Section 6.2.1, Rationale and Methodology for Reservoir Decline Curve Analysis, Page 66)****:***

The following rules-of-thumb are noted in Appendix C of the Interstate Technology Regulatory Council 2018 LNAPL guidance (ITRC-3), Section 1.1:

- *LNAPL transmissivity between the range of 0.1 to 0.8 ft^2/day may be used as a decision point for remedial system operation or technology transitions. While LNAPL*

transmissivity is useful for evaluating LNAPL hydraulic recovery potential, it should not be used as a sole means to determine whether an LNAPL remedy for a site is necessary or unnecessary.

- *A threshold LNAPL transmissivity value, typically representative of an LNAPL saturation that is nominally above the residual LNAPL saturation for the formation, may be established at the outset of the LNAPL recovery action and used as a trigger for stopping LNAPL recovery. The decision on whether to implement an LNAPL remedial action should be based on the broader site LNAPL CSM rather than LNAPL transmissivity alone.*

- *It should be noted that LNAPL transmissivity measurements often vary in both space and time. For example, groundwater fluctuations can occur such that the LNAPL fluctuates from unconfined to confined conditions. In that situation, it may be necessary to measure LNAPL transmissivity values under both conditions.*

EPA recognizes that your response to comments indicates that additional goals will be evaluated. However, more details are needed to justify these goals. Appendix C, Section 1.2 of ITRC-3 notes the following:

There are a number of methods that can be used individually or in combination to demonstrate that free product has been removed to the maximum extent possible. According to Appendix C, Section 1.2 of the LNAPL-3 document, these include:

- *comparing mobile LNAPL mass to the mass of LNAPL in the smear zone,*
- *analyzing LNAPL recovery data and determining that future recovery will not be meaningful,*
- *showing that LNAPL thicknesses are small and/or intermittently observed,*
- *modeling future potential LNAPL recovery using a multiphase model,*
- *demonstrating that the LNAPL body is stable and that stability will not change in the future, and*
- *presenting information that shows an unreasonable cost per gallon or pound of LNAPL recovered.*

The current plan does not clearly define what multiple lines of evidence have been or will be used in the future to support a decision to turn existing wells off in terms of performing continued product removal. At present insufficient data and conclusions have been presented to EPA to support the proposed decision criteria and decision logic. Specifically, more information is needed in terms of explaining the basis for why a transmissivity criterion of 0.8 foot squared/day or 1 gallon per day LNAPL recovery criteria should be agreed upon for use at the site. Please ensure that the Work Plan outlines how these issues will be addressed going forward.

Response to Evaluation of the Response to Specific Comment 6

USEPA has noted that the Group needs to complete an evaluation relative to the decision logic process outlined in the ITRC (2018) Guidance. For purposes of advancing the discussion and to address USEPA comments on both the LNAPL CSM and Work Plan and the NSZD Work Plan, the following document systematically uses the information contained in Appendix B of the ITRC guidance to evaluate metrics of success and provide a decision logic process for consideration.

The flowcharts from the NSZD guidance are provided below and the LNAPL CSM and NSZD Work Plans are discussed in the context of this guidance document. A number of data gaps and uncertainties were identified in the LNAPL CSM for which supplemental assessment and monitoring were proposed. Issues identified by EHS Support and USEPA included the temporal variability of solar sipper recovery rates (during the trial), which impacted the regression coefficients for the recovery decline curve analysis as well as potential operational issues (larger LNAPL thicknesses in the recovery wells than anticipated during operation of the pumps). This variability was attributed to the program of operation and maintenance activities being implemented during this period and revisions to the approach were proposed in the report, discussed with USEPA, and have been implemented in the field.

In addition, it was noted in discussions with USEPA that data smoothing/averaging (reflective of the high frequency of recent data relative to the older data sets) was required to more accurately complete trend analysis and improve the regression coefficients. This is proposed to be completed after completion of the optimization activities using the additional recovery data which will be collected from the recovery wells.

In the context of the decision logic diagram that USEPA has requested we develop, there are numerous decision logic diagrams provided in the ITRC guidance. A number of diagrams are associated with development of the initial LNAPL CSM and selection of technologies while others have been specifically developed for mature sites (such as St. Croix) where decisions associated with the possible transition to NSZD are being considered. Given the maturity of this site (i.e., where large volumes of LNAPL have been recovered, LNAPL plume extent and thicknesses have declined over time, and the limited risk [either based on the chemistry of the LNAPL or incomplete exposure pathways]), the focus has increasingly been on demonstrating recovery to the extent practical and achieving the long- term goal of groundwater restoration. Decision logic flowchart Figure NSZD-14 (**Enclosure B**) is considered the most appropriate starting framework for development of a site- specific "interim" decision logic diagram. It is understood that based on the findings from the supplemental LNAPL mobility/recoverability evaluations and NSZD evaluation, modifications to this process may be required.

A range of potential metrics were identified in the LNAPL CSM and were also provided in USEPA's most recent comments; they are listed below with additional clarification and discussion provided. USEPA has also specifically referenced the rules of thumb provided in Appendix C of ITRC-3 (2018) guidance. In review of these rules of thumb there is alignment between the group and USEPA on the use of the LNAPL transmissivity thresholds (upper bound of 0.8 ft^2/day). The other rules of thumb provided USEPAs evaluation of the groups response to comments are more challenging to apply or are a key qualitative/semi-quantitative consideration. For example, the rule of thumb listed below is not quantitative using terms like "nominally above" and inherently does not provide a quantitative link between laboratory saturation data and LNAPL transmissivity:

> *"A threshold LNAPL transmissivity value, typically representative of an LNAPL saturation that is nominally above the residual LNAPL saturation of the formation, may be established at the outset of the LNAPL recovery action and used as a trigger for stopping LNAPL recovery".*

In application of criteria such as this, terminology and test methods need to be considered. Permeability to oil can be estimated in petrophysical testing but transmissivity is not. Further, air displacing oil and water displacing oil imbibition tests can evaluate pore fluid drainage relative to applied stress but do not

provide LNAPL transmissivity. In this context most practitioners have reverted to using petrophysical tests to define in porous media LNAPL saturations at which "drainage can occur" and relying on field measurements to assess LNAPL transmissivity, mobility and recovery.

Commonly, practitioners have relied on the ITRC transmissivity value referenced above, LNAPL recovery rates from wells (as noted above 1 gallon per day [gpd] has been used at numerous refineries), reservoir decline curve analysis (recovery relative to total theoretical recoverable volume) and recovery efficiency (oil/water cuts and using this ratio to estimate LNAPL transmissivity from groundwater transmissivity).

In addition to these rules of thumb, USEPA also lists a number of methods that can be used individually or in combination to demonstrate that free product has been removed to the maximum extent possible (Section 1.2 of the LNAPL-3 document). Commentary on the application of these criteria to the site is provided after each item

- *Comparing mobile LNAPL mass to the mass of LNAPL in the smear zone*. This assessment method usually involves coring and petrophysical testing. Pore fluid saturations (oil and water phase) and water displacing oil imbibition tests (for LNAPL in saturated zone) are conducted to define the potentially mobile and immobile fractions. The methods are typically applied to porous media but can be modified to consolidated materials (if LNAPL is in secondary porosity of limestone).
- *Analyzing the LNAPL recovery data and determining that future recovery will not be meaningful*. This was proposed in our approach with the use of reservoir/recovery decline curve analysis. Typical application of this criteria has included percent recovery relative to the maximum theoretical recovery, a recovery rate metric aligned with LNAPL Transmissivity and oil/water percentages for total fluid recovery systems. As described further in **Table 2** (**Enclosure A**) the table below 80 percent and 90 percent of the maximum theoretical recovery has been used as a metric aligned with industry experience in upstream oil and gas. The proposed 1 gpd metric included in our report has been calculated based on the ITRC transmissivity threshold, and oil/water percentages are not applicable metrics for skimming.
- *Showing that LNAPL thicknesses are small and/or intermittently observed.* Routine gauging and groundwater sampling activities are conducted at the site. This data has demonstrated reductions in LNAPL thicknesses over time and a number of wells were LNAPL is only intermittently observed. As discussed extensively in the ITRC guidance, LNAPL thickness is not the primary determinant of LNAPL recoverability. LNAPL saturation and site geology are the critical controls on LNAPL transmissivity and in homogeneous geology LNAPL thickness is correlated with LNAPL transmissivity. Based on the complexity of the site geology (as described in the LNAPL CSM) LNAPL transmissivity at this site is more controlled by geology than thickness. Use of an LNAPL thickness metric is not recommended for this site and LNAPL baildown testing is considered a more reliable tool for assessing LNAPL transmissivity and recoverability.
- *Modeling future potential LNAPL recovery using a multi-phase model.* The American Petroleum Institute's (API) LNAPL Distribution and Recovery Model (LDRM) can be used to model the recoverability of LNAPL and provide future predictions. The model relies on the physical properties of soil, literature input values (potentially sourced from the API database), LNAPL saturation inputs or estimates, and estimates of LNAPL transmissivity. The models should be calibrated to current LNAPL recovery rates.

- *Demonstrating that the LNAPL body is stable and that stability will not change in the future.* Routine groundwater gauging and sampling is being conducted at the site and demonstrates that the plume is stable. Based on the hydraulic gradients at the site and that recovery efforts are focused on skimming, significant changes in groundwater conditions are not anticipated to occur. Long-term monitoring will be implemented when recovery activities are terminated at the site.
- *Presenting information that shows an unreasonable cost per gallon or pound of LNAPL recovered.* The cost of recovery at the site has significantly increased over time in response to the reduction in LNAPL recovery volumes. Early recovery efforts removed large volumes of LNAPL providing a low cost of removal. A graph of expenditures over time in dollars/gallon is provided (**Enclosure C**).

Decision Flowcharts

Detail decision *logic diagrams* using a hierarchy of decisions for both monitoring wells and recovery wells are provided (**Figure A1** through **Figure A5** in **Enclosure D**). The general decision process for a combined LNAPL and NSZD remedial approach is provided as **Figure A1**. Specific decision logic diagrams for LNAPL recovery wells (which should be incorporated into the process shown on **Figure A1**) are provided as **Figure A2** and the decision logic diagram for monitoring wells is provided as **Figure A3**.

For the decision logic diagram provided for monitoring wells (**Figure A3**), note that this flowchart is not applicable to recovery wells which are part of the permanent or temporary recovery program (see **Figure A2**). Once recovery and bail down tests have been completed and it has been determined that LNAPL has been recovered to the extent practical, recovery wells will be converted to long-term monitoring wells. The focus of the long-term monitoring program will be on demonstrating a *stable* LNAPL plume and that NSZD processes are continuing. As part of the process, changes in LNAPL thickness and extent will be evaluated to determine if recovery activities need to be reinstated in select wells.

For the active recovery wells at the site, **Figure A2** has been prepared and integrated into the decision logic provided by ITRC Figure NSZD-14 (**Enclosure B**). We consider this decision flowchart to best reflect the life stage of this project and the desired outcome of integrating NSZD processes into the existing LNAPL recovery program. The following key information (which is required to complete a site specific flowchart) is provided below:

<u>Remedial Action Objectives and Goals</u>

The cleanup criteria for LNAPL was described in the USEPA-approved Phase Separated Petroleum Hydrocarbon Plume Remediation Work Plan.[1]

> *The clean-up criteria for PSPH are based on two independent factors: risk and mobility. Corrective measures for PSPH will be complete when it is determined that PSPH:*

[1] Hess. 2001. Phase Separated Petroleum Hydrocarbon Plume Remediation Work Plan.

- *Poses no unacceptable risk to human health and the environment, or*
- *Is below the Practical Limits of Mobility (PLM) and is not likely to impact a receptor in the future."*

Define Performance Metrics, End Points and Transition Criteria

A range of metrics have been tracked over the years but no formal endpoints and transition criteria have been contextualized in documents. Proposed Criteria include:

- ***End Point – Restoration of Groundwater Quality.*** *As we understand the desired outcome is "restoration of groundwater" which will require no mobile/observable LNAPL in wells and achievement of water quality standards suitable for the future beneficial use of groundwater.*
- ***Performance Metrics –*** *A range of performance metrics are inherent with USEPA comments and EHS Supports LNAPL CSM these include:*
  - ***Ensure that the LNAPL plume is stable and not migrating.*** *Associated metrics would include:*
    - *No measurement of LNAPL in new wells (wells that have not historically had LNAPL)*
    - *LNAPL thicknesses measured in wells consistent with historic observations (and considering the potential effects of groundwater elevation fluctuations)*
  - ***Are the skimming pumps being effectively operated:***
    - *Are the intakes of the pumps within the LNAPL layer?*
    - *Are routine operational and maintenance activities being conducted to ensure high operational uptimes?*
    - *Do oil/water cuts (> 25%) support effective operation of the skimmer pump.*
    - *Are the LNAPL thicknesses in wells maintained below 0.33 feet (4 inches) – effective operational thickness.*
  - ***Recovery to the Maximum Extent Practicable (Practical Limits of Mobility) in individual wells (recovery will be terminated on a well by well basis) as defined by (in order of priority):***
    - *Baildown test LNAPL Thresholds in individual wells below the upper bound of ITRC Thresholds and not inconsistent with the observed LNAPL thickness in the well and geology/hydrogeology at that location. USEPA has requested a justification for use of the ITRC transmissivity value but has also asked us to use the ITRC guideline. The use of this guideline value is predicated on these values being the only defined quantitative guideline included in the guidance and its extensive use on other sites to define a point at which LNAPL recovery may be impractical.*
    - *LNAPL recovery rates less than 1 gpd (to be validated by baildown tests immediately conducted on suspension of recovery). This value as demonstrated in the LNAPL CSM equates to the LNAPL transmissivity threshold provided above. The use of an LNAPL recovery rate (as a surrogate for LNAPL Transmissivity) provides for ease of application but is metric which guides actions such as*

completing a baildown test or reservoir decline curve analysis (see decision logic diagram)

- *Reservoir decline curve analysis demonstrating that a minimum of 90% of the maximum theoretical LNAPL recovery volume has been achieved. It should be noted in the application of this criteria even if > 90% of the theoretical recoverable volume has been removed termination of recovery will be determined based on the measured transmissivity.*
- *In the event that the reservoir decline curve analysis does not yield a strong regression coefficient after application of common data filtering methods (spline functions, time weighted averages to standardize the temporal records over time or other smoothing algorithms) then other methods such as comparison on mobile and residual mass (using petrophysical testing) may be required.*

- ***Further recovery of LNAPL is uneconomic.*** *If USEPA wants to utilize the ITRC recommendations we can also include a metric around cost effectiveness and leverage a metric of $/gallon. Typically costs that have been utilized at other sites have included (a) costs in excess of the value of the product (b) costs a factor of 10 fold more than the value of the product. These metrics in many cases are arbitrary and we consider that they should be a consideration, not a formal metric.*

- ***Transition Criteria – In addition to achievement of recovery to the extent practicable. Transition criteria will be linked to the key concepts:***
  - ***Natural Mass Losses are greater than engineered mass losses.*** *This is focused on the concept that the natural processes must be sufficiently robust that the incremental gains of continued recovery (once the maximum extent practicable metrics are achieved) are limited*
  - ***Natural source zone depletion can facilitate restoration of the aquifer within a "reasonable" period of time.*** *This would require quantification of NSZD mass loss rates and quantification of mass in place to support calculation.*

The approach proposed by the group is also aligned with other guidance contained within ITRC **Figure NSZD-15** (**Enclosure B**) which includes the considerations discussed in the context of the site in **Table 2** (**Enclosure A**). We request that USEPA consider that the group is still seeking to collect and collate data for this site. Consistent with **Figure A2**, the magnitude of NSZD rates and assessment of risk are important considerations in the context of defining recovery to the extent practical. The group does understand that the metrics and goals provided will have to be refined and if reservoir/recovery decline curve analysis is constrained in its application then alternative methods may have to be incorporated into the approach.

Enclosures:

Enclosure A	Tables
Enclosure B	NSZD Figures
Enclosure C	Expenditures Figure
Enclosure D	Decision Logic Diagram Figures

TOEROEK
ASSOCIATES, INC.

April 8, 2021

Ms. Carol Stein, PE, MBA
U.S. Environmental Protection Agency, Region 2
290 Broadway
New York, NY 10007-1866

Re: **Contract #68HERH19D0018, TO 68HE0220F0069; Corrective Action and Permit Support for Hovensa and St. Croix Alumina Plume;: Draft Technical Evaluation of the Response to February 8, 2021 USEPA Review of POC's Response to December 14, 2020 Comments, dated March 24, 2021, on the LNAPL CSM and Remedial Action Work Plan, St. Croix, U.S. Virgin Islands, St. Croix Alumina Site, dated July 2020**

Dear Ms. Stein:

Toeroek Associates, Inc. (Toeroek) is pleased to present this draft technical evaluation of the Response to February 8, 2021 USEPA Review of POC's Response to December 14, 2020 Comments, dated March 24, 2021 (RTCs) on the *LNAPL CSM and Remedial Action Work Plan, St. Croix, U.S. Virgin Islands, St. Croix Alumina Site*, dated July 2020 (Work Plan). A revised version of the Work Plan was not provided, and as such an evaluation of the whether the RTCs were incorporated into the Work Plan was not able to be completed. This deliverable was reviewed as part of our quality assurance program under our Quality Management Plan for the REPA 6 Zone 3 contract. The letter serves as the deliverable and is attached in both MS Word and portable document format (PDF) files for your convenience.

The RTCs addressed EPA's comments and are acceptable. Please note, Toeroek did not review the Response General Comment 1 as this was prepared by EPA. Also of note, for the Response to Specific Comment 6, the financial comparison information to justify a process for mechanical removal of light non-aqueous phase liquid (LNAPL) in Attachment C are still under development and could not be reviewed. Further, Toeroek did have comments on the decision logic diagrams provided; however, as we already provided these comments to EPA on the evaluation of the PTPLLC Responses to EPA's January 29, 2021 Review, dated March 10, 2021 (Response to Comments [RTCs]) of the Light Non-Aqueous Phase Liquid (LNAPL) Natural Source Zone Depletion (NSZD) Work Plan, St. Croix, U.S. Virgin Islands, St. Croix Alumina Site, dated November 4, 2020, we have therefore not repeated the comments herein.

Finally, the Response to Specific Comment 6, provided an adequate process to evaluate the mass of LNAPL present in the vadose zone as compared to that immediately above and in the saturated zone. However, this issue remains unresolved until data is provided.

205 West Wacker Drive, Suite 1810
Chicago, IL 60606
Phone: 312-212-0934

Please contact Brad Martin, Toeroek Project Manager, directly at 312•212-0934 should you have any questions.

Sincerely,

Paul Kieler
REPA 6 Program Manager

cc: B. Martin, Toeroek
C. Dare, Toeroek
R. Howe, Toeroek
P. Rosa, EPA Region 2
Toeroek Project Files

EVALUATION OF THE

PTPLLC RESPONSES TO EPA'S JANUARY 29, 2021 REVIEW

DATED MARCH 10, 2021

OF THE

DRAFT LIGHT NON-AQUEOUS PHASE LIQUID (LNAPL)

NATURAL SOURCE ZONE DEPLETION (NSZD) WORK PLAN

ST. CROIX ALUMINA GROUNDWATER PLUME, U.S. VIRGIN ISLANDS

DATED NOVEMBER 4, 2020

In general, the Response to Comments (RTCs) addressed EPA's comments and are acceptable with the following considerations. The following evaluation includes only responses where additional information or clarification is required.

A revised version of the Light Non-Aqueous Phase Liquid (LNAPL) Natural Source Zone Depletion Work Plan (Work Plan) was not provided, and as such an evaluation of the whether the RTCs were incorporated into the Work Plan was not able to be completed. A revised Work Plan incorporating the proposed revisions is needed.

Additional data was collected and presented as part of these RTCs. No additional comments concerning the additional data presented were noted in this evaluation.

Evaluation of the Response to Comment 1: The response is partially acceptable. Field-based measurement technology manufacturer instruction and other measurement quality evaluations to be performed in the field should be provided as part of the revised quality assurance project plan (QAPP) in accordance with the Unified Federal Policy (UFP) format. Typically, Worksheets #20, #21, and #22 address field measurements. Field-based measurements will be an essential portion of the field program and as such additional duplicate measurements may be needed to ensure data quality over the guidelines suggested in a manufacturer's direction on how test kits and field measurement are evaluated prior to use in directing additional field efforts. Please ensure these worksheets are completed to address collection of field measurements.

Evaluation of the Response to Comment 2: The response is partially acceptable. The proposed changes to Table 1 are generally acceptable but should reference the appropriate sections of the revised UFP-QAPP once it is completed. It is noted that the Optimized UFP-QAPP Worksheet #11 includes text that cross references, at a minimum, content from Worksheet #17 as well as Worksheets #19, 20, 24, 25, 26, 27, 28, and 30. Field-based measurement requirements for both precision and accuracy and not just precision should be addressed in the UFP-QAPP and Table 1. The need for additional calibration checks is anticipated and should be included in the event the suggested manufactures guidelines are inadequate for supporting decision making in the field.

Evaluation of the Response to Comment 3: The response is acceptable; however, the table should be amended and included appropriate reference to specific sections of the UFP-QAPP as noted in the Evaluation of the Response to Comment 2 above.

Evaluation of the Response to General Question II.c.: Revised Table 1 is acceptable, but the figures are missing information. Although the Legend for Cross Section 3A includes a thin blue line noted as approximate groundwater elevation, no blue line could be identified on the cross section. Cross Section 3B shows well specific elevations, but still does not provide an interpreted groundwater elevation within the cross section that clearly shows the water levels in the wells. Further, cross-section 3B provided as Figure 5 does provide the needed water levels, but still does not properly indicate that wells like MW-13B and others are projected onto the cross-section line. Appropriate symbology that alerts the reviewer that some of the wells are projected onto the cross-section and are not "in-line" with the cross-section cut needs to be developed and applied to the image. Please review the cross-sections to identify any additional errors and omissions as this list is not inclusive.

Evaluation of the Response to General Question II.g.: The response is partially acceptable. It is assumed that the reference in "key decision 3" to "hard sand" should instead say "caliche cemented sands." Please revise this terminology as noted for clarity where needed in associated text and tables. These substances differ in several properties, including transmission of gases.

Evaluation of the Response to General Question II.k.: The response is acceptable. Please note that the comment response is mislabeled as response to General Question II.i. instead of II.k. This typographical error needs to be corrected, but response is acceptable for General Question II.k.

Evaluation of the Response to Laboratory QA/QC Question III.a.: The response is acceptable. Please ensure that some level of secondary review/data validation of the lab data/results will be performed when data is used to make critical decisions along with the results of any secondary/data usability reviews provided in the associated results reports.

Evaluation of the Response to Laboratory QA/QC Question III.b.: The response is acceptable.

Evaluation of the Response to Laboratory QA/QC Question III.c.: The response is acceptable contingent on verifying that the revised Appendix E of the revised Work Plan provides the information as stated in this comment response.

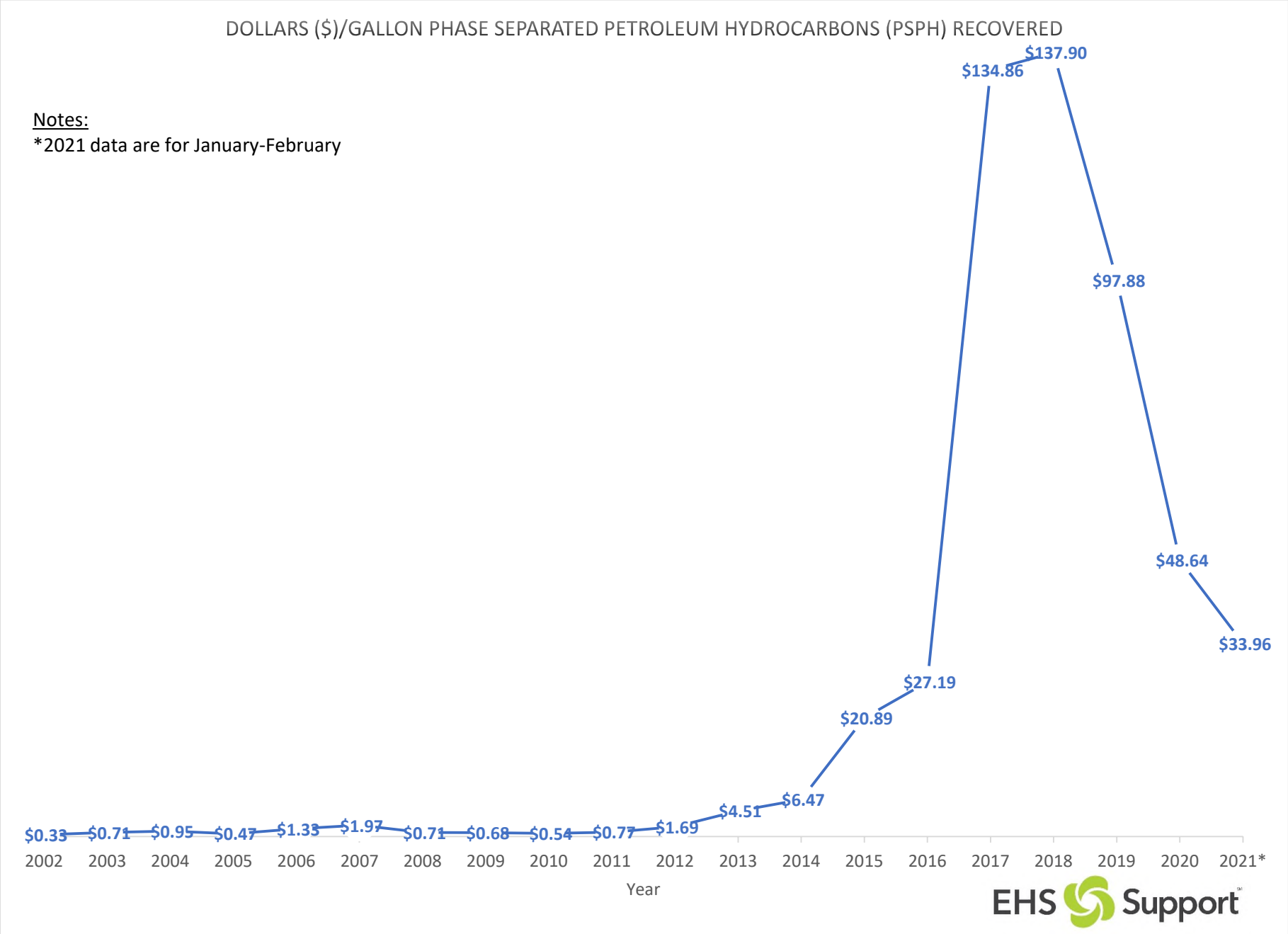
Evaluation of the Response to Laboratory QA/QC Question III.d.: The response is partially acceptable. The response indicates the performance of field duplicate QC samples at a rate of 10 percent and duplicate performance criteria of 30 percent. It does not however, address the primary question, which was how much of the data from field efforts will be validated and by whom and how the results of any validation will be used (i.e., at a minimum to assess training needs or the need for a secondary review of results) to assure the usability of the results. This type of information is still needed and should be provided in the revised UFP-QAPP and summarized in the Work Plan.

Evaluation of the Response to Specific Comment 2: The response is partially acceptable. Figure 3A still needs to be modified to clearly show the groundwater elevations and geology from projected wells as previously indicated. Also numerous projected wells are not identified on Figure 3B as noted previously in General Question Response II.c.

Evaluation of the Response to Specific Comment 7: The response is partially acceptable. The decision logic diagrams provided in Appendix A-are a good-start, but they do not clearly define the decision steps. Simplifying the diagrams and condensing them would make their use of critical decision points more

readily performed. The flowcharts need to be more clearly defined and simplified in order to clearly show what the decision steps are. Figure A1 (in Attachment D of your response) follows most closely the typical flow-charting symbology protocols with some notable issues. Other flowcharts are less clear. As a general rule of thumb, please note that ovals are normally used for start and stop points, rectangles are used for actions, and diamonds are used to indicate decision statements. For more information on formats when creating decision logic diagrams the following simple reference might be helpful (Flowchart Basics: How to Create Flowcharts like a Process Analysis Expert (creately.com). None of the other proposed decision logic diagrams follow the standard conventions used in decision logic diagrams and need to be modified before a careful review can be performed of the logic process outlined in each diagram.

Appendix F Dollars ($) per Gallon Phase Separated Petroleum Hydrocarbons (PSPH) Recovered


DOLLARS ($)/GALLON PHASE SEPARATED PETROLEUM HYDROCARBONS (PSPH) RECOVERED
Notes:
*2021 data are for January-February
$0.33
$0.71
$0.95
$0.47
$1.33
$1.97
$0.71
$0.68
$0.54
$0.77
$1.69
$4.51
$6.47
$20.89
$27.19
$134.86
$137.90
$97.88
$48.64
$33.96
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2021*
Year
EHS Support