Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility

JOINT BASE PEARL HARBOR-HICKAM, O‘AHU, HAWAI‘I

Administrative Order on Consent in the Matter of Red Hill Bulk Fuel Storage Facility, EPA Docket Number RCRA 7003-R9-2015-01 and DOH Docket Number 15-UST-EA-01, Attachment A, Statement of Work Section 6 Investigation and Remediation of Releases, and Section 7 Groundwater Protection and Evaluation

July 27, 2018
Revision 00

NAVFAC
Naval Facilities Engineering Command
NAVFAC HAWAII

Comprehensive Long-Term Environmental Action Navy
Contract Number N62742-17-D-1800, CTO18F0126

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Prepared for:

Defense Logistics Agency Energy
8725 John J Kingman Rd Suite 4950
Fort Belvoir, VA 22060-6222

Prepared by:

AECOM Technical Services, Inc.
1001 Bishop Street, Suite 1600
Honolulu, HI 96813-3698

Prepared under:

NAVFAC Naval Facilities Engineering Command NAVFAC HAWAII

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ACRONYMS AND ABBREVIATIONS

[redacted]	redacted: Navy infrastructure data
µg/L	microgram per liter
AOC	Administrative Order on Consent
BTEX	benzene, toluene, ethylene, and xylene
CDPH	California Department of Public Health
COC	chemical of concern
COPC	chemical of potential concern
CSM	conceptual site model
DO	dissolved oxygen
DoD	Department of Defense
DON	Department of the Navy, United States
DW	drinking water
EAL	Environmental Action Level
EPA	Environmental Protection Agency, United States
ft	foot/feet
GMS	Groundwater Modeling System
GWPP	*Groundwater Protection Plan*
IRR	Investigation and Remediation of Releases Report
JP	Jet Fuel Propellant
LNAPL	light non-aqueous-phase liquid
LTM	long-term monitoring
MCL	maximum contaminant level
mg/L	milligram per liter
mgd	million gallons per day
MNA	monitored natural attenuation
mV	millivolt
NAP	natural attenuation parameter
NGS	Next Generation Sequencing
NSZD	natural source-zone depletion
ORP	oxidation reduction potential
PAH	polynuclear aromatic hydrocarbon
PID	photoionization detector
ppbv	parts per billion by volume
ppm	parts per million
PT-MC	Particle Tracking, Monte Carlo
QSM	*Quality Systems Manual*
RBDC	risk-based decision criteria
RCRA	Resource Conservation and Recovery Act
RHS	Red Hill Shaft
RSL	Regional Screening Level
SME	subject matter expert
SSRBL	site-specific risk-based level
TIC	tentatively identified compound
TOC	total organic carbon
TPH	total petroleum hydrocarbons
TPH-d	total petroleum hydrocarbons – diesel range organics
TPH-g	total petroleum hydrocarbons – gasoline range organics
TPH-o	total petroleum hydrocarbons – residual range organics (i.e., TPH-oil)

U.S.	United States
UCM	unresolved complex mixture
USGS	United States Geological Survey

WELL NAME CROSS-REFERENCE TABLE

Well ID	DLNR ID	USGS Site ID	Known Aliases
Fort Shafter Monitor	2053-10		
Moanalua Deep	2153-005	212123157535501	Moanalua Fresh Water Mon. Well
TAMC1	2153-007		
TAMC2	2153-008		
Manaiki T24	2153-009		Moanalua T24 (DLNR)
Moanalua 1	2153-010		
Moanalua 2	2153-011		
Moanalua 3	2153-012		
TAMC-MW2	2153-013	212144157534701	TAMC MW2 TAMC-MW-2
Moanalua DH43	2253-002	212225157533001	
Hālawa Deep Monitor Well (2253-03)	2253-003	212241157535501	Hālawa Deep HDMW HDMW2253-03
Hālawa Deep Monitor Well Chase Tube	2253-003	212241157535502	Hālawa Deep Chase Tube
RHMW06	2253-004	212226157534101	
RHMW07	2253-005	212222157535201	
RHMW08	2253-007	212216157535801	
RHMW09	2253-008	212209157535201	
RHMW10	2253-009	212213157533901	
RHMW11	2253-011	212226157535001	
Red Hill Shaft	2254-001	212225157542601	Red Hill Shaft (S11) RHMW2254-01 Navy Supply Well 2254-01
UMW-1	2254-02M	212229157541501	South Hālawa Alluvium MW-1 HCF shallow monitoring well Hālawa Correctional Facility MW
‘Aiea Hālawa Shaft	2255-032	212253157554301	Hālawa Shaft (S5) Navy Hālawa Shaft
Hālawa T-45	2255-033		
Hālawa BWS Deep Monitor	2255-040	212233157552302	Hālawa TZ Well Hālawa deep monitor well near Hālawa T45 (2255-33)
‘Aiea Navy	2256-010	212238157561101	‘Aiea US Navy (187-B) ‘Aiea boat harbor well
Pearl City III	2257-003		
Hālawa Shaft	2354-001	212305157542601	Hālawa Shaft (S12)
Ka‘amilo Deep	2355-015	212340157552301	Ka‘amilo Deep Monitor
OWDFMW01		212214157542601	OWDFMW08 (former name) OWDFMW1
RHMW01		212214157535401	
RHMW02		212216157534701	
RHMW03		212219157533901	
RHMW04		212231157532901	
RHMW05		212210157540201	

1. Introduction

This technical memorandum was prepared to present the Navy's interim environmental analysis of current data and an initial framework and analysis of potential environmental risks as part of executing the *Administrative Order on Consent* (AOC) *In the Matter of Red Hill Bulk Fuel Storage Facility* ("the Facility").

1.1 PURPOSE

The purpose of this technical memorandum is to provide an interim environmental analysis of current data, and presents an initial framework and analysis of potential environmental risks in preparation for the AOC Statement of Work Section 6.3 deliverable, *Investigation and Remediation of Releases Report*, and the AOC Statement of Work Section 7.1 deliverable, *Groundwater Flow Model Report*, to be submitted to the Regulatory Agencies in December 2018. Information sources include but are not limited to the following:

- Past investigations conducted in the region and in the vicinity of Red Hill (e.g., geologic, hydrogeologic, environmental)
- Facility information
- Fuel types and releases
- Groundwater and vapor monitoring data
- Geologic and hydrogeologic data
- Seismic studies data
- Hydraulic recharge and water balance
- Light non-aqueous-phase liquid (LNAPL) and hydrocarbon-based fuel forensic studies
- Natural source-zone depletion (NSZD) and natural attenuation studies
- Water supply well design and pumping rates
- Water level elevations
- Interim groundwater modeling of migration of groundwater from underneath the Facility, and of the source water zones for key public supply wells and shafts

The recently released *Conceptual Site Model* (CSM) for the Facility is the primary reference for detailed information for this document and is extensively referenced herein.

1.2 OBJECTIVES

Key objectives for the interim environmental analysis include the following:

1. Protect public health and environment.
2. Meet Department of Defense (DoD) Operational Requirements for the Red Hill Facility.
3. Comply with the AOC.
4. Comply with government regulations.
5. Meet acceptable environmental performance criteria and risk reduction defined as: Localized limited impact such that any contamination from Red Hill will be evaluated to determine if:

(1) it may adversely impact a water supply well and (2) if so, that appropriate contingencies are in place so that water pumped from such a supply well will meet federal maximum contaminant levels (MCL) as well as State of Hawaiʻi Department of Health (DOH) criteria. In addition, the interim risk assessment will also evaluate other potential chemicals of concern (COCs) from a drinking water perspective to ensure that human health is protected relative to use of potable water.

This memorandum is intended to provide sound, objective, defensible and relevant information to document the interim environmental analysis.

2. Conceptual Site Model Summary

The generalized physical and environmental setting is comprehensively addressed in the Red Hill CSM and includes information regarding (1) current monitoring network; (2) Facility information; (3) subsurface geology, hydrogeology; and (4) migration, degradation, and characteristics of released fuels. As with any CSM, this CSM will continue to evolve over time as new information is obtained that will further improve understanding of the area. The current initial CSM (DON 2018) is summarized below. The CSM fully details the current understanding of the physical and environmental setting and is intended to be updated as new data are added. Therefore, the CSM is considered an important companion reference to this document. The CSM is referenced extensively in subsequent sections of this document, with the formal "(DON 2018)" citation omitted for brevity.

The Facility and vicinity are shown on Figure 2-1. Due to the complexity of the site, the comprehensive CSM was divided into seven modules, as reflected on the initial pictorial CSM (Figure 2-2):

A. **Physical Setting and Current Monitoring Network.** The 144-acre underground fuel storage Facility is located in south-central Oʻahu approximately 2–3 miles east of Pearl Harbor, within the Red Hill ridge that divides South Hālawa Valley from Moanalua Valley on southwest flank of Oʻahu's Koʻolau Mountain Range. The Facility's twenty 12.5-million-gallon fuel storage tanks store and supply fuel for military operations in Hawaiʻi and throughout the Pacific. The tank bottoms are situated approximately 100–130 feet (ft) above an underlying basal aquifer that is a major municipal and military drinking water source and is considered an irreplaceable resource with a high vulnerability to contamination. Water supply wells located near the Facility tank farm that pump from this basal aquifer include the Navy's Red Hill Shaft (2254-01, approximately 2,600 ft west), the Honolulu City and County Board of Water Supply's (BWS) Hālawa Shaft (2354-01, approximately 4,400 ft northwest), and the BWS Moanalua Wells (2153-10, -11, -12, approximately 6,650 ft south).

Below the surface soil and saprolite of Red Hill ridge, geologic formations consist largely of basalt with varying layers of materials exhibiting high and low permeability, containing occasional voids. In the surrounding valleys, sedimentary deposits are underlain by weathered basalt (saprolite) and unweathered basalt. In the Red Hill area, the basal aquifer water table lies at approximately 20 ft mean sea level (msl). Groundwater in the Pearl Harbor vicinity generally flows toward the harbor, although potential exists for variances in localized flow directions depending on geologic formations and other factors. Subsurface cross sections of the Red Hill area are based on available boring and tank barrel logs and are presented on CSM Figures 5-2 through 5-9.

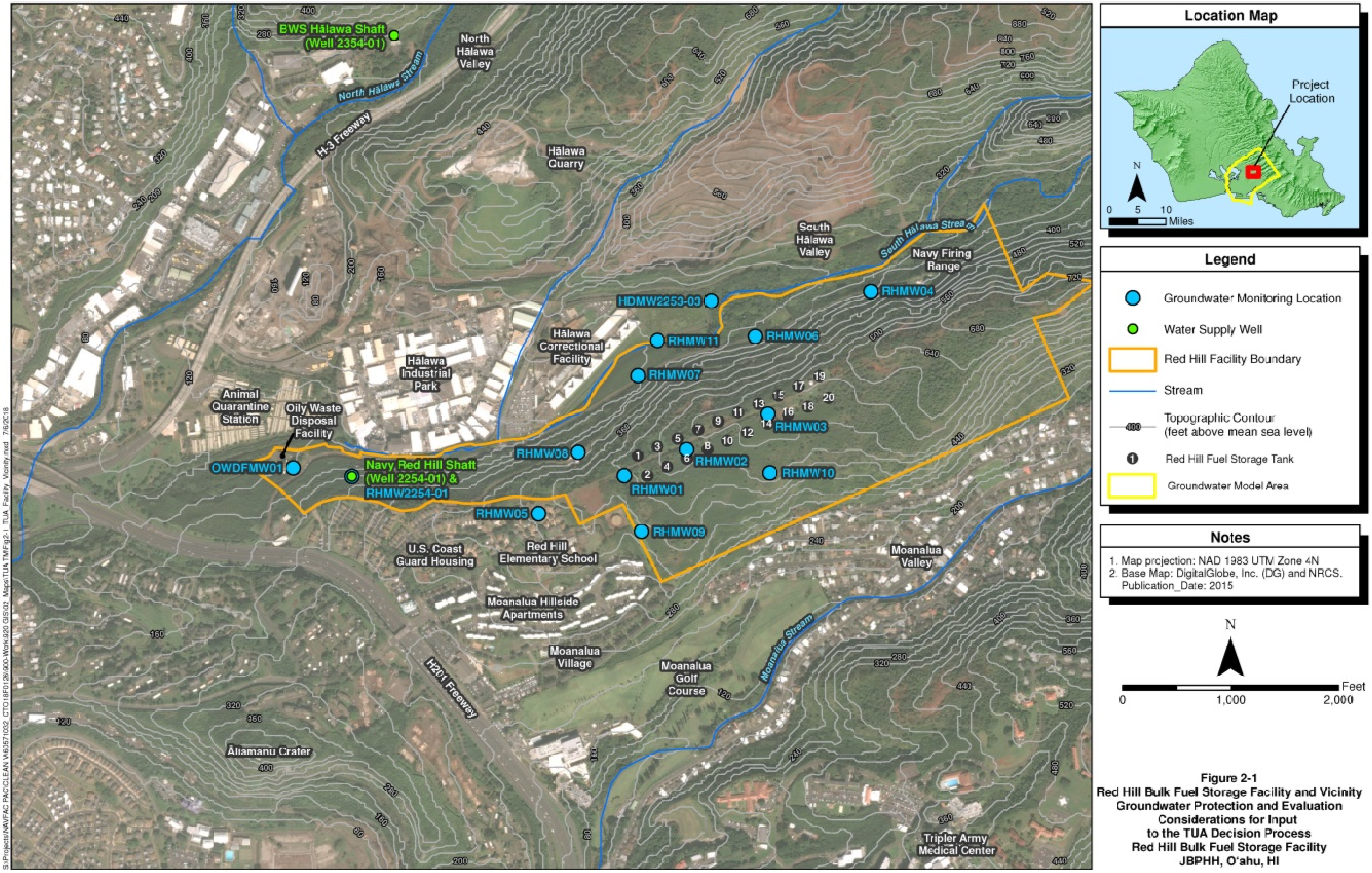


Figure 2-1: Red Hill Bulk Fuel Storage Facility and Vicinity

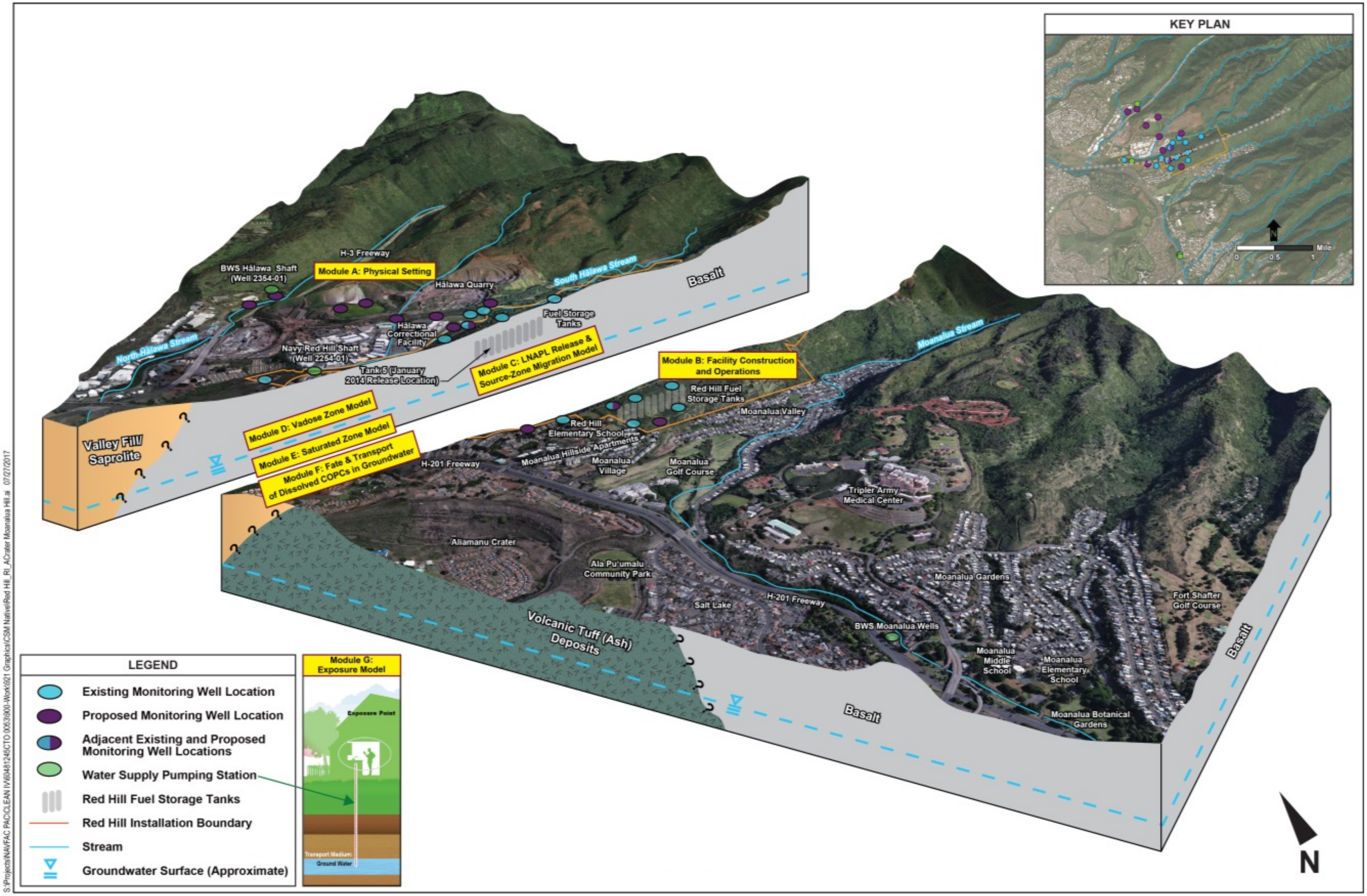


Figure 2-2: Pictorial CSM

Currently, a network of 14 groundwater monitoring locations is established at and around Red Hill (Figure 2-1), and an expansion of the network is planned (Section 3.1). Groundwater from the monitoring network is sampled quarterly at a minimum and analyzed for a list of chemicals of potential concern (COPCs) established by the Regulatory Agencies. Additionally, soil vapor monitoring points are installed under each of the Facility's 18 active fuel storage tanks (Tanks 1 and 19 are inactive and do not contain fuel) and are monitored monthly. Results of both groundwater and soil vapor monitoring events are regularly reported to Hawaiʻi DOH.

B. Facility Construction and Operations. The Facility's 20 fuel storage tanks were field-constructed of steel-lined concrete in the early 1940s. They are connected to a fuel pumping station at Pearl Harbor via a tunnel system. Kerosene-based jet fuels stored at the Facility have included Jet Fuel Propellant (JP)-5, JP-8, and NATO-grade F-24; the tanks currently contain kerosene-based JP-5 and F-24 and diesel-based F-76 Diesel Fuel-Marine.

C. LNAPL Release and Source-Zone Migration Model. During Tank 5 refilling operations following a routine 3-year inspection and refurbishment process conducted every 20 years, a release of approximately 27,000 gallons of JP-8 was confirmed and reported to DOH in writing on January 23, 2014. During that month, a fuel hydrocarbon seep confirmed to be JP-8 was observed on a tunnel wall below Tank 5, and soil vapor monitoring points installed beneath the tank exhibited a sharp increase in hydrocarbon vapor concentrations. Potential migration pathways include through gaps between the tank's steel lining and inner side of its concrete shell, and through cracks in the concrete shell into higher-permeability rock surrounding the concrete.

Subsequent analysis indicated the cause of the release to be defective workmanship in welding by the tank refurbishment contractor, poor inspection, and ineffective quality control.

D. Vadose Zone Model. The Facility tanks are surrounded by rock in the vadose (i.e., unsaturated) zone, which consists primarily of basalt flows in complex, alternating layers. These heterogeneous layers vary from extremely high to extremely low permeability, with a corresponding varying ability to transmit or hold LNAPL depending on the layer's type and micro-pore structure (i.e., high ability in high-permeability aʻā and thin pāhoehoe flows; low ability in massive aʻā and massive pāhoehoe flows; limited transmissivity but high holding capacity in aʻā clinker zones). Geologic and water saturation characteristics in the rock surrounding the tanks will cause LNAPL to spread as it moves through the rock. As LNAPL moves through the larger pore spaces, some of it will be trapped in poorly connected fractures and blocked by capillary tension of moisture, especially water held in the smaller pores.

Hawaiian volcanic rocks vary in porosity and permeability depending on the emplacement process, lava type, genesis, flow thickness, flow rate, extent, cooling rate, and weathering. Permeability is typically highest in the relatively thick, unweathered rubbly aʻā clinker zones and intensely fractured zones or lava tubes of pāhoehoe flows. Permeability is much lower in the interior portions of massive flows, weathered interflows, intrusive rocks (dikes/sills), ash beds, and weathered rocks (saprolite)/soil horizons, which can impede vertical flow and horizontally flow across valleys. Generally, the vertical permeability of the basalt is often orders of magnitude lower than the horizontal permeability. Horizontal permeability is significantly higher in the direction that the lava flowed.

E. Saturated Zone Model. Groundwater flow and solute transport are controlled by the hydraulic and physical properties of the hydrogeologic units (HGUs), including hydraulic conductivity, effective porosity, specific yield, specific storage, and dispersivity.

Fresh groundwater inflow originates as deep infiltration of precipitation and seepage from surface water features. According to the United States Geological Survey (USGS), estimates of recharge for Oʻahu for recent conditions (2010 land cover and 1978–2007 rainfall) differ from predevelopment recharge values by only a few percent (Izuka et al. 2018). Spatial distribution of recharge mimics the orographic rainfall pattern—recharge is highest on windward slopes and mountain peaks below the top of the trade-wind inversion.

Groundwater outflow includes withdrawals from wells and natural groundwater discharge to springs, streams, wetlands, and submarine seeps. Under predevelopment conditions, groundwater withdrawal was negligible and natural groundwater discharge probably was approximately equal to recharge. Under recent conditions, natural groundwater discharge has been reduced by the pumping well withdrawals. Data collected by the USGS for groundwater levels, saltwater/freshwater interface, spring flow, and stream base-flow indicate an overall reduction in aquifer storage for most areas where groundwater has been extracted; this has caused groundwater levels to decline (Izuka et al. 2018).

Recharge from multiple sources including precipitation, stream recharge, and recharge from the Hālawa Quarry/cement plant area north of South Hālawa Valley may increase groundwater recharge rates locally, and create zones of shallow water (e.g., perched zone at the prison).

F. Fate and Transport of LNAPL and Dissolved COPCs in Groundwater. Attenuation studies, in the vadose zone as NSZD and in the dissolved groundwater plume as monitored natural attenuation (MNA), provide strong evidence of biodegradation. Occurrence of LNAPL is primarily limited to a depth of 30 ft beneath wells RHMW02 and RHMW03 and is being biodegraded based on thermal, soil vapor, and carbon trap studies. Attenuation of dissolved-plume COPCs in the saturated zone limits the extent of the existing dissolved plume before reaching Red Hill Shaft under present conditions and within the context of historical releases. Spatial and temporal trends in COPCs, natural attenuation parameter (NAP) data, and fuel studies provide strong evidence that active attenuation processes are responsible for degradation of COPCs within the groundwater plume under the tank farm.

Profiles of total petroleum hydrocarbons–diesel-range organics (TPH-d) from site data are consistent with soluble components of jet fuel. The available chromatograms from RHMW02 groundwater samples are all consistent with chromatograms for biodegraded kerosene-type fuels (e.g., JP-5 and JP-8). Petroleum fuels are composed primarily of hydrocarbons (nonpolar) that have distinctive chromatographic profiles. The majority of the fuel is not water soluble, and the chromatographic profiles are useful in distinguishing LNAPL from biodegraded material that is polar and indicating ongoing biodegradation.

G. Exposure Model. Historical releases (prior to 2005) are considered the main source of impacts to groundwater at the Facility. Other releases (e.g., spills or leaks in the fuel system) may have occurred or may occur in the future. Potentially contaminated media are unconsolidated materials, volcanic rock within the tunnels, soil/rock vapor within the tunnels, tunnel air, groundwater beneath the Facility, and offsite surface waters (e.g., Pearl Harbor, springs) where groundwater may discharge. Offsite surface waters are considered too far away to pose a significant concern for ecological receptors. Human receptors that may contact onsite or offsite Facility-impacted media are Facility occupational workers, construction workers, and visitors, and offsite residents. Among the potentially complete exposure pathways identified, the primary one is offsite residents using tap water sourced from the Red Hill Shaft water supply well. While residents using water sourced from Red Hill Shaft may likely be a receptor, these criteria are also protective of residents deriving water from other water supply wells (such as Hālawa Shaft). These receptors could be exposed to chemicals in tap water via direct ingestion and dermal contact, and via inhalation while showering/bathing. Exposure by ecological receptors is considered incomplete or insignificant.

As stated above, the CSM is an evolving tool that will continue to be updated as new information becomes available. The initial 2018 CSM indicates that LNAPL released from Red Hill fuel storage tanks has entered the vadose zone at various areas beneath Red Hill. LNAPL entering the vadose encounters a complex geology in the surrounding volcanic layers that vary significantly in their permeability and overall geometry. Consequently, LNAPL will migrate laterally through high-permeability zones underlain by low-permeability layers. Vertical migration is likely manifested through clinker bridges, and highly fractured zones. As LNAPL moves through the pore spaces, some of it will be trapped in poorly connected fractures, voids, and pores. The LNAPL tends to preferentially migrate toward the predominant dip direction of 10–12 degrees to the south-southwest (between 190 and 210 degrees). Once the LNAPL encounters the water table, its vertical migration potential is minimized due to the density difference between LNAPL and water. Soluble components (monitored by analyzing groundwater samples for COPCs) will enter the groundwater through either dissolution from LNAPL in the vadose zone due to infiltrating water or through dissolution of LNAPL in the saturated zone close to the water table. Currently, no LNAPL has been measured in the water table monitoring wells, and analytical data are inconclusive as to the presence of LNAPL in the saturated zone. Even if some LNAPL had migrated to the saturated zone, the source would be very small, as evidenced by the depletion in naphthalene concentrations after the 2014 release. The thermal study conducted in October 2017 shows evidence that residual LNAPL is primarily limited to a depth of 30 ft beneath wells RHMW02 and RHMW03 and is being biodegraded. COPC concentrations in groundwater suggest that there is not a significant source of LNAPL at the water table. General transport of COPCs in the dissolved plume is in the southwest direction toward Red Hill Shaft. Migration to the southeast and northwest is limited by the extent of lower-permeability materials (valley fill and saprolite) extending below the water table in the valleys bounding the Facility. Attenuation of COPCs in the dissolved plume in the saturated zone limit the extent of the existing dissolved plume before reaching Red Hill Shaft under present conditions and within the context of historical releases.

3. LNAPL Properties and Distribution

This section covers (1) the detection and history of fuel releases at the Facility, (2) the distribution of LNAPL fuel in the subsurface, and (3) evidence of LNAPL weathering. The intent of this section is to highlight key elements of the CSM related to LNAPL distribution and properties as described in CSM Sections 2.12, 4, 7.1, 7.2, and 7.3.

3.1 RELEASE DETECTION

Leak detection has evolved over time since the tanks entered service in 1943. The initial tank design included a system of tell tales for leak detection; however, these were removed from most tanks in 1977 due to operational problems. A soil vapor monitoring system is now used as one of several release detection measures.

The Red Hill Long-Term Monitoring (LTM) Program, initiated in 2005, provided an additional mechanism for the detection of releases. The LTM consists of groundwater monitoring (beginning in

2005; Figure 3-1) and soil vapor monitoring (beginning in 2008; Figure 3-2). The LTM monitoring results can be used to identify releases that result in an increase in fuel vapors below the tanks and/or increased impacts to groundwater. The LTM program is conducted pursuant to the Red Hill *Groundwater Protection Plan* (GWPP) (DON 2014). As shown on Figure 3-1, plans are underway to expand the Red Hill groundwater monitoring network.

3.2 RELEASE HISTORY

The occurrence of historical fuel releases (i.e., releases that may have occurred before 1998–2002) has been characterized through the completion of angle borings below each active tank between 1998 and 2002 (DON 2002). These results indicate historical LNAPL releases from several of the tanks; however, the timing and magnitude of these releases cannot be determined. As shown on Figure 3-3:

- LNAPL staining and/or sheens were observed below Tanks 1, 9, 11, 13, 14, and 16.
- Petroleum odors (but no staining or sheens) were observed below Tanks 2, 3, 4, 5, 6, 7, 8, 12, 18, 19 and 20.
- No evidence of petroleum impacts were observed below Tanks 10, 15 and 17.

The LTM monitoring dataset indicates that impacts to groundwater are most likely attributable to historical releases rather than releases since 2005 (when monitoring started), and only one recent release impacted the below-tank soil vapor wells since 2008 (i.e., the 2014 release from Tank 5). As discussed in CSM Section 7.2, groundwater monitoring conducted since 2005 has consistently shown (1) no consistent presence of LNAPL in any of the monitoring wells and no evidence of LNAPL since 2014, (2) no more than trace levels of benzene, toluene, ethylbenzene, and xylene (BTEX) in any groundwater samples, (3) concentrations of naphthalenes that have varied over time but have remained within the historical range observed early in the monitoring period, and (4) chromatograms consistent with dissolved constituents originating from a biodegraded/weathered source. Together, these results indicate an absence of recent (i.e., since 2005) LNAPL releases that have migrated to groundwater. Monthly photoionization detector (PID) monitoring conducted since 2008 indicates a single LNAPL release (2014) during the monitoring period that resulted in an impact within the vadose zone directly below the fuel tanks. Section 6.1.1 provides a more detailed overview of soil vapor monitoring results and conclusions.

3.3 LNAPL PROPERTIES

Kerosene type jet fuels (Jet A, JP-5, JP-8) are middle distillates from crude oil characterized by a wide variety of hydrocarbons. Typically, about 80% are aliphatic hydrocarbons (straight, branched, and cyclic alkanes) and 20% are aromatic hydrocarbons (monoaromatics like xylenes and diaromatics like naphthalene and methylnaphthalenes). Hydrocarbon molecular structure is important in partitioning into water and weathering of the fuels once released to the environment. Aliphatic hydrocarbons have relatively very low water solubility compared to aromatic hydrocarbons. For instance, pure xylenes (eight carbons) are >200× more soluble in water than pure n-octane. A relatively small portion of jet fuel (aromatics) partitions to water based on the effective solubility of the individual compounds with effective overall water solubility of ~5 milligrams per liter (mg/L). BTEX can account for ~3 mg/L and substituted benzenes and naphthalenes are the rest of the dissolved components. The chromatographic profile or fingerprint of jet fuel is quite different from the corresponding fingerprint of dissolved jet fuel in water. As the fuel weathers, older releases may be dominated by heavier substituted benzenes, naphthalenes and metabolites (degradation products of biodegradation). Refer to CSM Appendix B.7 Section 3.

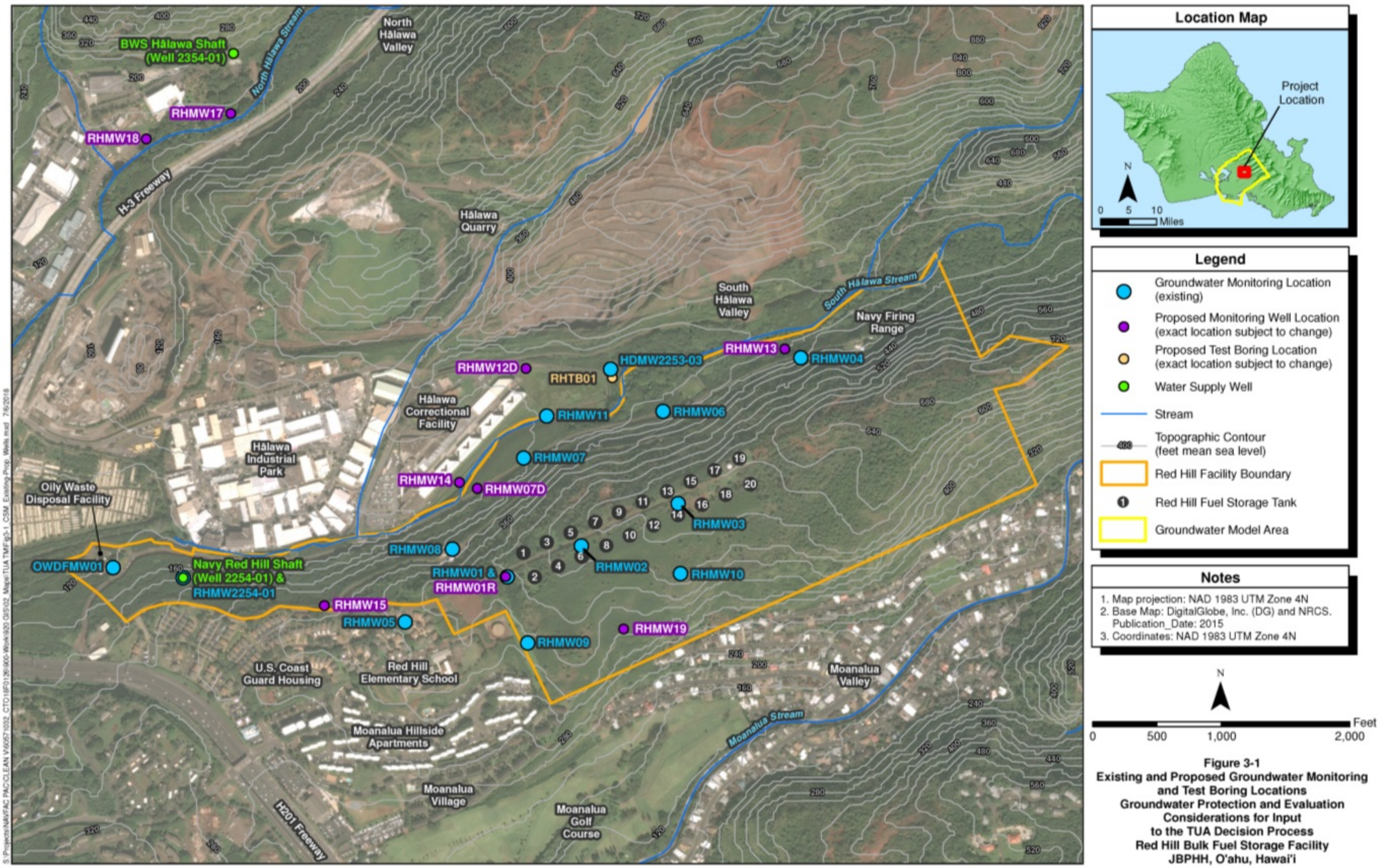
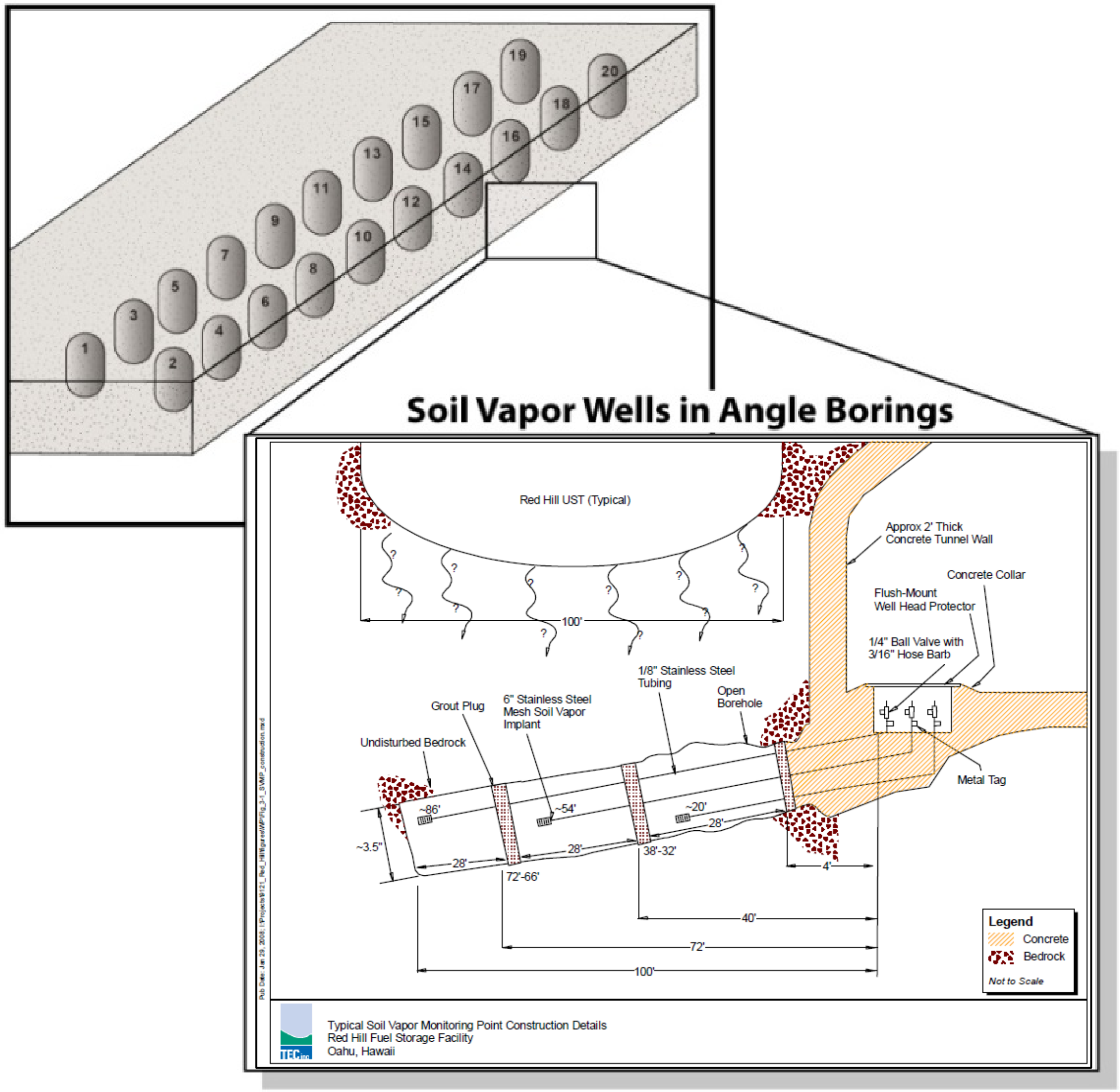


Figure 3-1: Existing and Proposed Groundwater Monitoring and Test Boring Locations



Tank	Number of Soil Vapor Wells
1	0 (Tank out of Service)
2	3
3	3
4	3
5	3
6	2
7	3
8	3
9	3
10	2
11	2
12	3
13	3
14	3
15	3
16	3
17	3
18	2
19	0 (Tank out of Service)
20	3

Figure 3-2: Red Hill Soil Vapor Monitoring Network

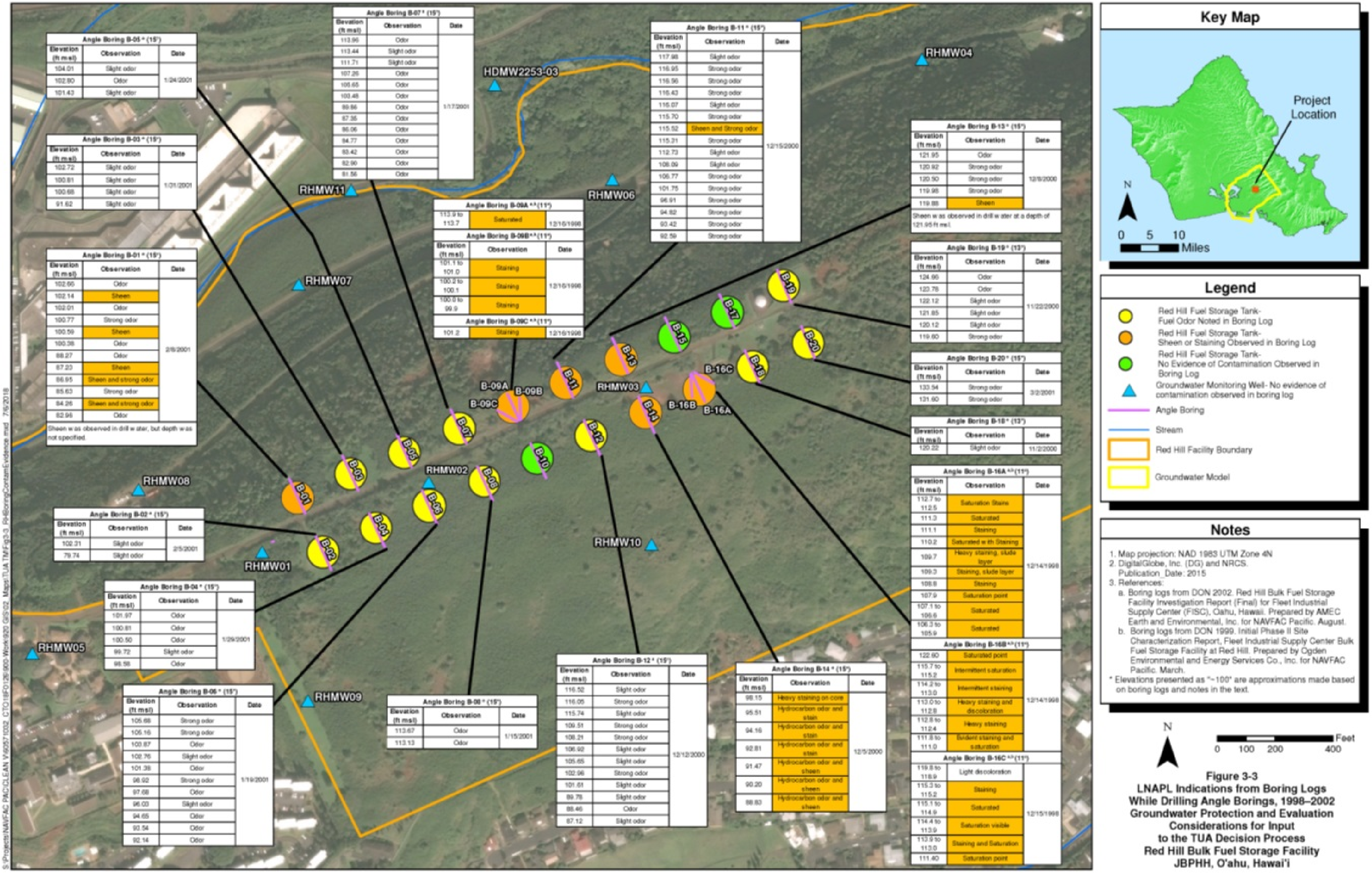


Figure 3-3: LNAPL Indications from Boring Logs While Drilling Angle Borings, 1998–2002

3.4 LNAPL DISTRIBUTION

LNAPL Distribution in the Vadose Zone: The distribution of LNAPL within the vadose zone has been inferred based on the results of the thermal NSZD study conducted in Fall 2017 (CSM Appendix B.1). In summary, when bacteria biodegrade LNAPL, they produce heat, and therefore, in an aerobic environment, the LNAPL-containing interval within the vadose zone can be determined based on the interval of heat generation (Figure 3-4). Based on the temperature profiles for Facility wells, LNAPL is inferred to be present within the top one-third of the unsaturated zone between the Facility's lower access tunnel and the water table (i.e., within a depth interval of 70–110 ft msl (Figure 3-5).

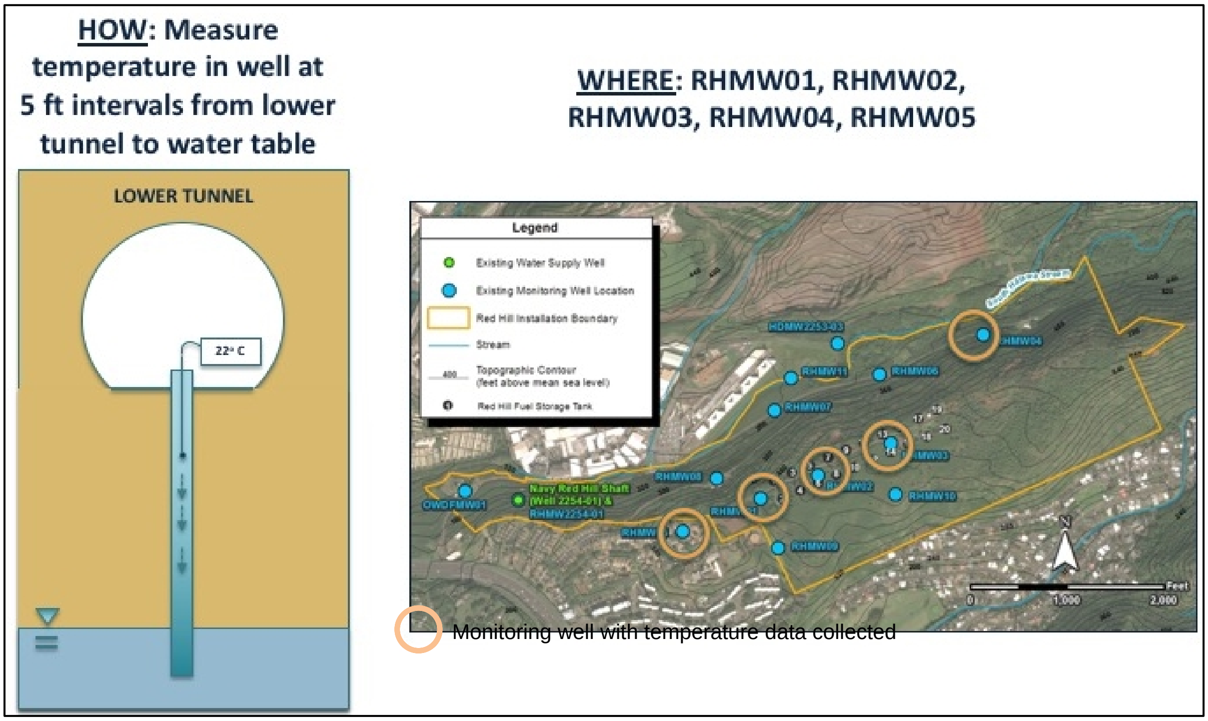


Figure 3-4: Collection of Temperature Data for Identification of LNAPL-Containing Interval

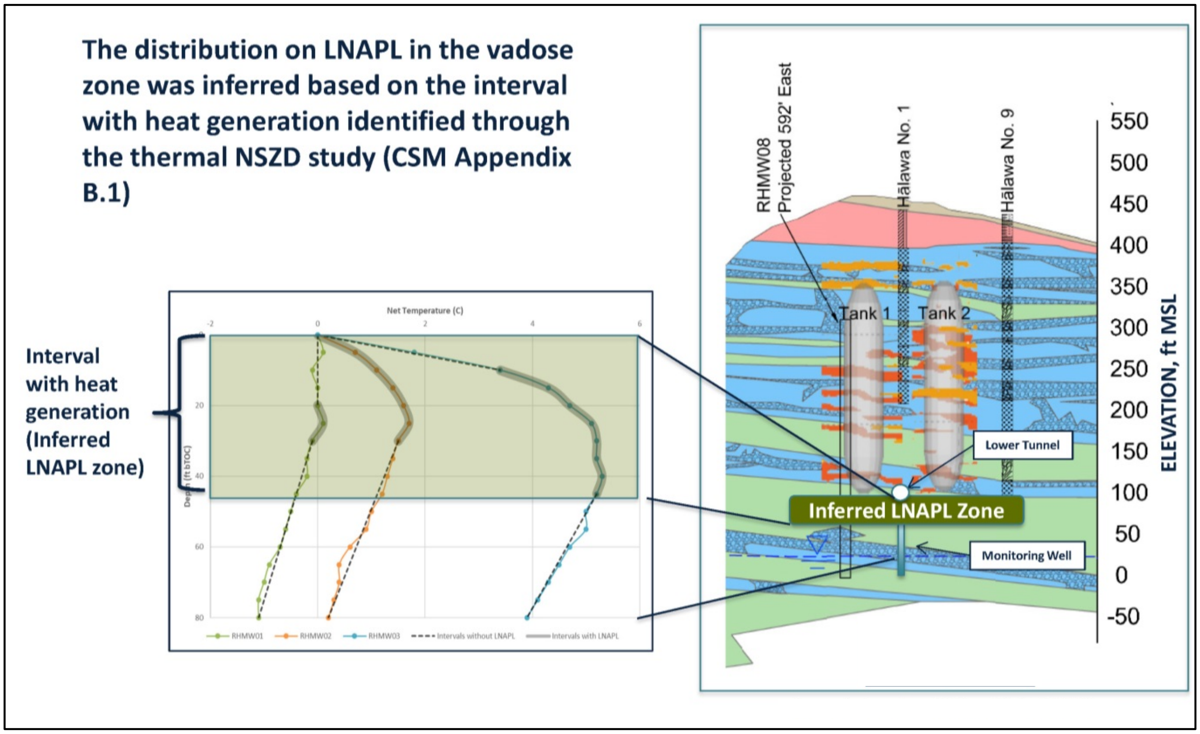


Figure source: CSM Figure 6-5

Cross section sources: Hālawa No. 1, 9: (Macdonald 1941); red and orange around tanks represent clinker identified in As-Built Barrel Logs (DON 1943)

measured groundwater elevation

Figure 3-5: Groundwater Protection and Evaluation Considerations for the Interim Environmental Analysis

LNAPL Distribution within Groundwater: No LNAPL has been measured in any Red Hill monitoring well since 2014 (i.e., after the January 2014 Tank 5 release event). Prior to 2014, the available records regarding LNAPL observations (in RHMW02) do not provide a clear indication of the presence or absence of LNAPL in individual wells; however, it was frequently noted that water purged from the well had a yellow tint and naphthalene odor in sampling events conducted in 2006 and 2007 (email from Bob Whitter to John Kronen dated June 26, 2018). Section 4 provides a detailed explanation.

Dissolved-phase concentrations of COPCs in groundwater and chromatographic profiles of TPH analysis may be useful as indirect indicators in evaluating the presence of LNAPL in groundwater or in close proximity to specific monitoring wells when used collectively as multiple lines of evidence. Based on the visual evaluation of the chromatograms, there is no evidence that LNAPL was present in any of the groundwater samples collected from Red Hill monitoring wells. For the four monitoring wells located adjacent to or immediately downgradient from the tanks, the dissolved-phase COPC concentrations support the following observations:

- In monitoring well RHMW03, total dissolved-phase concentrations of fuel constituents are relatively low (< 0.5 mg/L since 2005), with limited depletion of groundwater electron acceptors (oxygen, nitrate, and sulfate) and no measurable methane production. The groundwater data in this area suggest the presence of a low-concentration dissolved plume, potentially one that is driven by infiltration/leaching processes, and do not indicate the presence of LNAPL in the saturated zone upgradient of RHMW03.

- Monitoring well RHMW02 exhibits the highest total dissolved-phase fuel constituent concentrations among Red Hill monitoring wells (approximately 2–7 mg/L since 2005). Much of these concentrations are in the form of polar compounds associated with the biodegradation of petroleum. The concentrations of naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene are equal to or greater than the expected concentration based on the effective solubility of these compounds in jet fuel. However, BTEX concentrations are very low (generally less than 1 microgram per liter [µg/L]). Although COPC concentrations have varied over time, the observed concentration ranges are similar for the monitoring periods before and after the 2014 Tank 5 release. The MNA sampling parameters indicate high levels of biodegradation occurring in the vicinity of this well, as key electron acceptors are depleted and high concentrations of dissolved methane are present (sometimes greater than 10 mg/L). Taken together, these data suggest the presence of weathered LNAPL (i.e., pre-2005) in the immediate vicinity of RHMW02 or within the saturated zone upgradient from this well. Based on the angle boring investigations conducted in 1998–2002, this LNAPL may have originated from Tank 9, 11, or 13. Based on an assessment of overall trends and data forensics, the monitoring data indicate that impacts to groundwater are likely from historical releases and are not associated with the 2014 Tank 5 release.
- Monitoring well RHMW01 exhibits the next-highest dissolved-phase fuel constituent concentrations (approximately 0.1–1 mg/L since 2005); RHMW01 may have some hydraulic connection to monitoring well RHMW02 located upgradient. Electron acceptors are depleted, and methane is present in the 0.2–7 mg/L range since 2005. These data are consistent with the natural attenuation of dissolved constituents in groundwater and do not suggest the presence of LNAPL within the saturated zone between RHMW02 and RHMW01.
- Monitoring well RHMW05 is located between the tank farm area and the Red Hill Shaft water development tunnel. Groundwater at this location exhibits low concentrations of fuel hydrocarbons (typically less than 0.05 mg/L). These data do not suggest the presence of LNAPL within the saturated zone between RHMW01 and RHMW05.

3.5 EVIDENCE OF LNAPL WEATHERING

The available monitoring data indicate that the LNAPL present in the subsurface has undergone physical weathering (i.e., volatilization of light-end constituents) and biological weathering. This is reflected in soil vapor samples collected from below the tanks (CSM Appendix B.3), and LNAPL from the vadose zone below some of the tanks in angle borings completed in 1998–2002 (Figure 3-3). Section 6.3 provides detailed discussions of this topic.

3.6 CONCLUSIONS

The available site investigation and monitoring results support the following conclusions regarding the presence and distribution of LNAPL at the Facility:

- Since the initiation of LTM in 2005, the monitoring data indicate only one detectable release of LNAPL: the release of approximately 27,000 gallons of JP-8 from Tank 5 in 2014.
- The angle boring investigations from 1998 to 2002 indicate LNAPL releases from other tanks prior to this time.
- Based on the temperature profiles for Facility wells, LNAPL is inferred to be present within the top one-third of the unsaturated zone between the lower access tunnel (70 ft msl) and the water table (110 ft msl).

- Monitoring data suggest the presence of weathered LNAPL (i.e., pre-2005) in the immediate vicinity of RHMW02 or within the saturated zone upgradient from this well.
- The LNAPL present at the Facility has undergone significant physical and biological weathering consistent with natural attenuation of these historical releases.
- Available data suggest that the LNAPL from the 2014 Tank 5 release is likely being retained in the unsaturated zone, and has been and is being attenuated via NSZD. Based on current data and detailed forensic analyses, only weathered constituents have been observed within the Red Hill monitoring network, and COPC concentrations have generally remained within recent historical ranges.
- Based on existing data, it appears that LNAPL from the 2014 release has not reached groundwater. There were also no discernable changes in dissolved constituents in groundwater before and after the 2014 release, indicating that dissolved constituents from that release likely did not impact groundwater and impacts to groundwater are most likely attributable to historical releases.

4. Dissolved Fuel Constituents in Groundwater and Analytical Considerations

This section summarizes key points from CSM Sections 6.7, 7.2, and Appendix B.7. LNAPL has not been measured in any Facility monitoring well since 2014 (i.e., after the January 2014 Tank 5 release event). Prior to 2014, the available records regarding LNAPL observations do not provide a clear indication of the presence or absence of LNAPL in individual wells. Discussions with DOH (Bob Whittier, pers. comm. 2018) indicate that a small sheen may have been present in an early sampling event for RHMW02 prior to the 2014 release (CSM Section 7.1.2.1). Therefore, dissolved constituents were evaluated to identify the type of source fuel, assess natural attenuation in the groundwater at the Facility, and investigate evidence of impact to groundwater since the onset of the LTM program in general and from the 2014 JP-8 release in particular.

Dissolved COPCs include individual target compounds including TPH measurements. There are analytical issues that should be considered when interpreting individual concentrations of the COPCs in each well with time. For example, low-level COPC detections near and below the limit of detection and well below the limit of quantitation should be reviewed carefully, particularly when analyses were done by multiple laboratories with varying reporting limits. These results should be evaluated carefully along with other site information to determine actual presence of the COPCs in groundwater that fits the current understanding of the CSM. Furthermore, interpretation of TPH results is not straightforward because TPH is defined by the method used to measure it. Inherent limitations and variability associated with TPH analysis should be considered in evaluating trends over time. Further discussion of TPH and naphthalenes analytical considerations and usability of low-level detections is presented in CSM Appendix B.7 Sections 5.2.1, 5.2.2, and 5.2.6 and Attachments B.7.2, B.7.3, and B.7.4.

4.1 DISSOLVED CONSTITUENTS IN GROUNDWATER

Dissolved-phase concentrations of COPCs in groundwater are summarized in CSM Section 7.2 and Appendix B.7 Sections 4 and 5.1.2. Cumulative historical groundwater monitoring results and COPC graphs are included in CSM Appendix A.1 and A.2. Other than for RHMW02 and to a much lesser extent RHMW01, most site wells have very low concentrations of COPCs. Close scrutiny of the data indicates that many of the detected compounds are very low estimated concentrations, often also detected in the laboratory and/or field blanks. The frequency of low-level estimates can be correlated to particular laboratories within certain time periods. Multiple lines of evidence were used to evaluate the validity of the data as further described in the CSM Appendix B.7 Sections 5.2.1, 5.2.2, and 5.2.6 and Attachments B.7.2, B.7.3, and B.7.4.

4.1.1 RHMW02

Groundwater samples from this monitoring well have the highest concentrations reported at the site since the LTM program began in 2005. Concentrations of TPH and naphthalenes have varied somewhat over time, but concentration ranges were similar for the monitoring periods immediately before and after the 2014 Tank 5 release. This well has had a continuous presence of TPH-d and naphthalenes. The TPH-d chromatographic signature and the results of the TPH-d with silica gel treatment analysis indicate that the reported TPH-d results are a mixture of jet-fuel-soluble components (substituted benzenes and naphthalenes) and biodegradation by-products. Up to 85% of the TPH-d is removed by silica gel (which removes polar organic compounds, including metabolites from biodegradation of hydrocarbons). Metabolites are shown on Figure 4-1 by the presence of a "hump" (unresolved complex mixture) that is largely removed by silica gel. The MNA sampling parameters also indicate high levels of biodegradation occurring in the vicinity of this well, as key electron acceptors are depleted and high concentrations of dissolved methane are present (sometimes greater than 10 mg/L). Taken together, these data suggest the presence of weathered LNAPL (i.e., pre-2005 release) in the immediate vicinity of RHMW02 or within the saturated zone upgradient from this well. Further discussion is presented in CSM Sections 7.1 and 7.2 and Appendix B.7 Section 4.

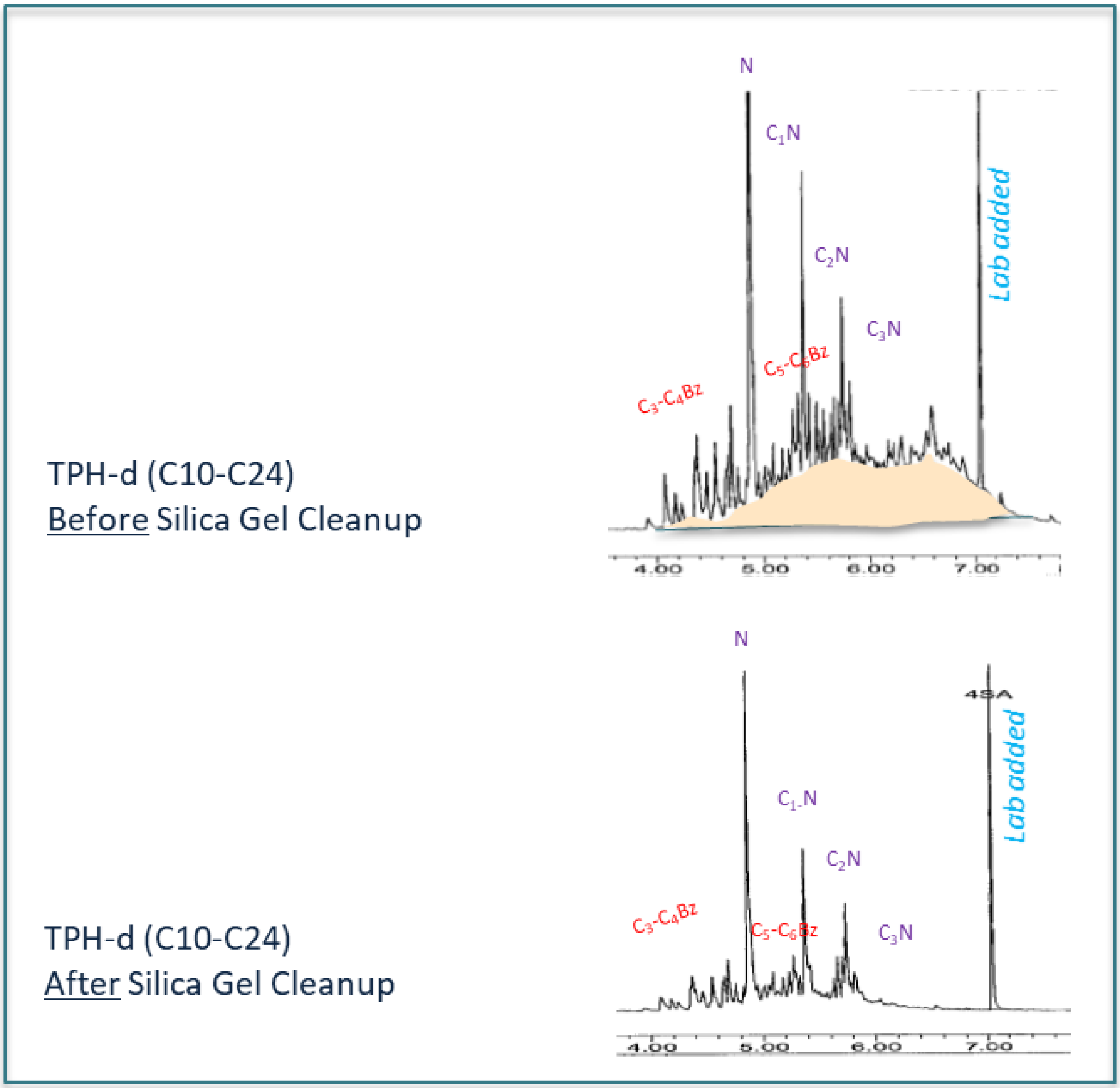
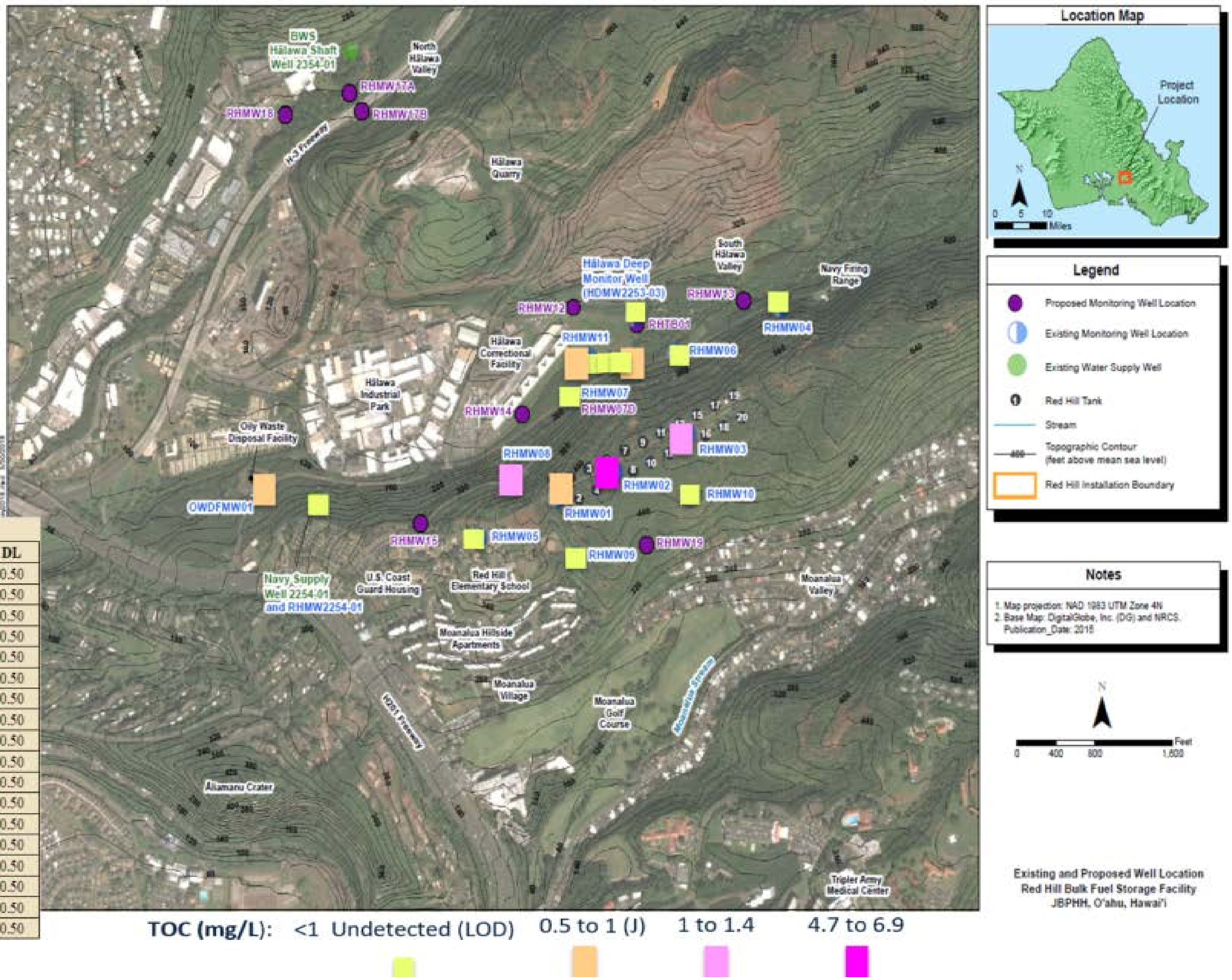


Figure 4-1: Chromatographic Fingerprints of TPH-d in Groundwater from RHMW02 (January 2017) Before and After Silica Gel Treatment (CSM Appendix B.7 Section 4.1.1, Figure 4-2)

It is evident that detected COPCs and metabolites in groundwater at RHMW02 are attenuated and do not reach other monitoring wells (CSM Appendix B.4 Section 3.4). This is reaffirmed by total organic carbon (TOC) measurements. TOC is a good indicator of total organic matter in groundwater, and its spatial distribution is shown on Figure 4-2. TOC is in the 5–7 mg/L range in RHMW02; in the 0.5–1.4 mg/L range in RHMW01, RHMW03, RHMW08, RHMW11, and OWDFMW01; and below detection in RHMW2254-01, RHMW04, RHMW05, RHMW06, RHMW07, RHMW09, RHMW10, and HDMW2253-03.



TOC, mg/L

	Oct-17		Apr-18		LOQ	DL
RHMW2254-01	<1	U	<1	U	1.0	0.50
RHMW01	0.77	J	0.59	J	1.0	0.50
RHMW02	6.9		4.7		1.0	0.50
RHMW03	1.4		1.3		1.0	0.50
RHMW04	<1	U	<1	U	1.0	0.50
RHMW05	<1	U	<1	U	1.0	0.50
RHMW06	<1	U	<1	U	1.0	0.50
RHMW07	<1	U	<1	U	1.0	0.50
RHMW08	1.1		0.87	J	1.0	0.50
RHMW09	<1	U	<1	U	1.0	0.50
RHMW10	<1	U	<1	U	1.0	0.50
OWDFMW01	0.68	J	0.51	J	1.0	0.50
HDMW2253-03	<1	U	<1	U	1.0	0.50
RHMW11-01	NA		0.67	J	1.0	0.50
RHMW11-02	NA		<1	U	1.0	0.50
RHMW11-03	NA		<1	U	1.0	0.50
RHMW11-04	NA		<1	U	1.0	0.50
RHMW11-05	NA		0.95	J	1.0	0.50

Figure 4-2: Total Organic Carbon in Groundwater

4.1.2 Dissolved Constituents in Other Red Hill Wells

Other than RHMW02, most wells have very low levels and/or infrequent detections of COPCs well below screening criteria (i.e., risk-based decision criteria [RBDC], which is further discussed in Section 7). Evaluation of historical quality control data indicates that some pre-October 2016 results were affected by matrix interferences, and that some results may be attributable to field or laboratory artifacts based on concurrent detections reported in laboratory and field blanks; further information is presented in CSM Section 7.2, Appendix B.7 Section 5, and Attachments B.7.2, B.7.3, and B.7.4. Particular issues with low-level detections of naphthalene by different laboratories are discussed in detail in CSM Appendix B.7 Section 5.2.6 and Attachment B.7.4.

RHMW01 is an inside-tunnel monitoring well and is located near Tanks 1 and 2. RHMW01 had frequent detection of TPH-d and TPH-residual range organics (TPH-o), but recent TPH-d and TPH-o with silica gel cleanup data indicate that the detections in this well and all other wells are mostly due to polar material and not hydrocarbons. Many reported values for other COPCs are estimates below the limit of quantitation.

RHMW2254-01 is a sampling point located inside the water development tunnel of Navy Supply Well 2254-01 (Red Hill Shaft). Detections of TPH-gasoline range organics (TPH-g), TPH-d, TPH-o, and naphthalenes occurred occasionally during monitoring events between 2005 and 2017, but COPCs have not been detected above the screening criteria. Toluene was detected during four monitoring events, but may be attributed to field or laboratory artifact based on reported trip blank contamination during the October 2015 and January 2016 events. Very low levels of naphthalene have been reported in this well (all below 0.1 µg/L) prior to March 2014. Due to the uncertainty associated with these low-level detections, detection of less than 0.1 µg/L do not necessarily indicate impacts from the Facility without additional supporting lines of evidence. Further information is presented in Section 4.2.2 and in CSM Attachment B.7.2 and B.7.4.

RHMW04 is an outside-tunnel monitoring well located northeast of the tank farm and was installed in 2005 as a background monitoring location. TPH-d, TPH-o, benzene, toluene, and naphthalenes were occasionally detected below screening criteria, but none have been detected after July 2016. These few reported COPCs are mostly below quantitation limits, and many are also found in corresponding laboratory and field blanks, indicating potential sample cross-contamination. Refer to CSM Appendix B.7.3 and B.7.4 for additional details.

4.2 Analytical/QA Considerations

4.2.1 TPH

TPH measurements are method/laboratory-dependent and may include naturally occurring organics and biodegradation metabolites along with petroleum hydrocarbons. The variability of TPH results is expected to be significantly higher than for single-component measurements like BTEX. This is reflected in relatively wide ranges of acceptance criteria for laboratory controls and calibration standards. The DoD *Quality Systems Manual* (QSM) Version 5.1.1 specifies control limits for the TPH-d laboratory control sample (LCS) of 36% to 132% of the expected value (DoD and DOE 2018). The LCS control limits for BTEX are tighter, in the range of 78% to 121%. Additionally, TPH-d performance testing samples from vendors have acceptance criteria of 30% to 125% recovery of the spiked concentrations.

Numerical results of dissolved TPH-d alone are not suitable as a diagnostic tool to assess the presence of LNAPL in groundwater, based on the chemistry of fuels as discussed in detail in CSM Appendix B.7 Sections 3.1 and 3.2. TPH-d measurements are further complicated by biodegradation of the fuels that produces polar/metabolites that tend to be more water-soluble than the aliphatic parent compounds (CSM Appendix B.7 Sections 3.3 and 4.1.1).

Figure 4-3 (also see CSM Appendix B.7 Figures 5-1 and 5-2) shows the historical TPH-d concentrations in RHMW02 over time (top graph), showing that there is scatter in the data as expected for this type of analysis. The bottom graph shows the same data with the laboratories identified. There is clearly more variability based on the absolute TPH results for various laboratories over time. This figure shows that it is not feasible to evaluate trends solely on TPH without understanding the limitations of this parameter. When TPH-d concentrations change from one monitoring event to the next, the significance of the change should be evaluated in the context of changes in the characteristics of the chromatograms and changes in the mixture of individual dissolved constituents. Figure 4-3 also shows results for split samples that were analyzed by APPL (current Navy laboratory for the Facility) and the United States (U.S.) Environmental Protection Agency (EPA) Region 9 laboratory from January 2017 to April 2018. The 2017 results from these sampling events showed that APPL results were significantly different from EPA results (EPA Region 9 and DOH 2017 and CSM Appendix B-7). Protocols used for extraction and analysis were similar at both laboratories but there were some differences, primarily in the extraction method that appeared to have significant impact in the extraction of polars/metabolites that are the bulk of the TPH-d. Changes in extraction were made at APPL and the 2018 results are more comparable as indicated. This is another example of how TPH-d results are difficult to compare across laboratories.

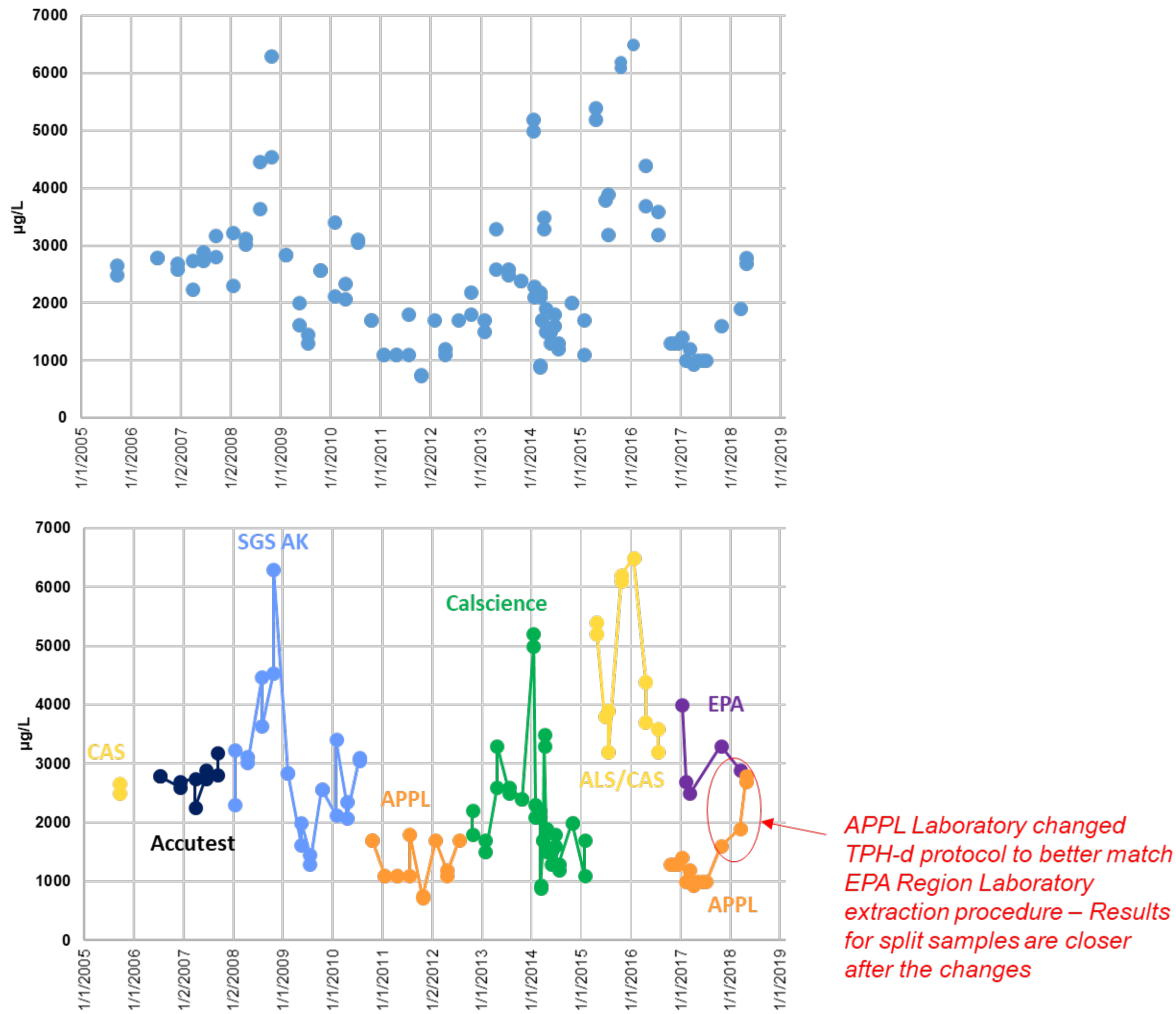


Figure 4-3: RHMW02 TPH-d Results over Time with Laboratories Identified (CSM Appendix B.7 Figures 5-1 and 5-2)

Other issues with TPH at low levels include detections of TPH in blanks. Refer to CSM Appendix B.7 Attachments B.7.2 and B.7.3 for more detail.

4.2.2 Naphthalenes

In general, there is lack of precision in naphthalene results for some duplicate samples. This is reflected in the DoD QSM (DoD and DOE 2018) with acceptance criterion for the LCS in the same range as TPH-d (40% to 121%). Similar to TPH-d, trend analysis based solely on naphthalene results can be unreliable (CSM Appendix B.7 Section 5.2.2). CSM Attachment B.7.4 presents an evaluation of low-level detections of naphthalenes that seem to be in many wells across the site during the same time period. Concurrent low-level detections of naphthalene in outlying wells are not consistent with LNAPL transport through either the vadose or saturated zones. Therefore, detections of less than 0.1 µg/L for naphthalenes (i.e., 1-methylnaphthalene, 2-methylnaphthalene, and/or naphthalene) for these data sets should not be considered as evidence of impacts from the Facility without additional supporting lines of evidence. Other than for RHMW01 and RHMW02, there have been less than

10 detections of naphthalenes above 0.1 µg/L in any of the other wells, all below 0.17 µg/L (the risk-based decision criterion for naphthalenes; see Section 7).

4.3 EVALUATION OF 2014 RELEASE

The historical groundwater monitoring data (i.e., 2005 to March 2018) have been reviewed to evaluate if LNAPL is likely present in groundwater in the vicinity of Red Hill monitoring wells and to assess if the 2014 JP-8 Tank 5 release event resulted in an impact to groundwater. The evaluation was based on presence or absence of LNAPL and changes in the composition and concentration of dissolved COPCs in the monitoring wells.

LNAPL was not measured in any of the monitoring wells after the 2014 Tank 5 release. Dissolved-phase concentrations of COPCs in groundwater and chromatographic profiles of TPH analysis may be useful as indirect indicators in evaluating the presence of LNAPL in groundwater or in close proximity to specific monitoring wells when used collectively as multiple lines of evidence. Based on the visual evaluation of the chromatograms, there is no evidence that LNAPL was present in any of the groundwater samples collected from monitoring wells at the Facility. For the four inside-tunnel monitoring wells located nearest to the tanks, the dissolved-phase COPC concentrations do not show any significant changes before and after the 2014 release.

Multiple lines of evidence (listed in Table 4-1) evaluated for RHMW02 (also see CSM Appendix B.7 Table 5-1) indicate that it is likely that the 2014 release did not impact the groundwater and impacts to the groundwater are more likely attributable to historical leaks. Furthermore, no impact to the Red Hill Shaft groundwater monitoring location (RHMW2254-01) from the 2014 release was noted.

Table 4-1: Evidence of Impact to Groundwater from 2014 Release: Summary of Lines of Evidence

Description		Key Points	Evidence of Impact to Groundwater from 2014 Release
TPH-d	Laboratory changes	Variability for TPH-d from laboratory to laboratory precludes reliable trend analyses.	Unreliable
	Chromatographic profiles	Primarily polar/metabolites and naphthalenes consistent with dissolved weathered material.	Not Apparent
	Chromatographic profiles and naphthalene ratios	Chromatographic profiles and naphthalene ratios show weathered material regardless of concentration changes.	Not Apparent
Naphthalenes and naphthalene ratios		Ratios of 1+2 methylnaphthalenes to naphthalene < 2 indicate a weathered source. Imprecision in naphthalene results have been observed in previous data validation reports.	Not Apparent
TPH-g		No significant change in TPH-g after 2014 release, some variability coincides with laboratory changes and method variability, not unexpected for TPH measurements.	Not Apparent
Benzene		No significant changes in benzene after 2014 release.	Not Apparent
Toluene		No significant change in toluene after 2014 release.	Not Apparent
Ethylbenzene		No significant changes in ethylbenzene after 2014 release.	Not Apparent
Xylenes		No significant changes in xylenes after 2014 release.	Not Apparent

5. Interim Groundwater Flow Model

5.1 PURPOSE

The objectives of this interim modeling study are to:

1. Develop an understanding of the hydrogeologic system behavior and prepare for development of a comprehensive final groundwater flow and transport model.
2. Evaluate the zones of source water for key pumping wells/shafts within the modeling domain, including an understanding of timing and trajectory. The key water supply locations include Hālawa Shaft, Red Hill Shaft, and the Moanalua Wells.
3. Evaluate the forward migration (flow only) of groundwater underlying the Facility including timing and trajectory.
4. Evaluate the impact of uncertainty and model approximations on the source water zones for key wells and on forward migration of groundwater from underneath the Facility.

The migration of groundwater underlying the Facility and the source water zones of the key supply wells were evaluated by the interim modeling effort to provide input/information as part of the interim environmental analysis. The interim modeling effort also provides information and insights to assist with developing potential groundwater protection strategies and preliminary contingency plans. These decisions will be finalized with the help of the final groundwater flow and solute transport models that will be subsequently developed using all the insights gained from the interim model and additional information and data collected at the site. Appendix A describes the interim model in detail.

5.2 AGENCY AND STAKEHOLDER INPUT TO MODEL DEVELOPMENT

The model was developed following review of previous models for the site and vicinity, and with input from agency, stakeholder, and USGS subject matter experts (SMEs). Collaboration with these SMEs was completed through a series of Groundwater Flow Modeling Working Group Meetings. These meetings were initiated in June 2017, and to date, 12 meetings have been held. The model has been developed based on information and feedback provided during the meetings. A summary of meeting dates as well as a synopsis of outcomes are provided in Table 5-1.

Table 5-1: Groundwater Flow Modeling Working Group Meetings

Meeting #	Date	Synopsis
1	6/6/2017	**Groundwater Flow Modeling Purpose:** “The purpose…is to refine the existing groundwater flow model and improve the understanding of the direction and rate of groundwater flow within aquifers around the [Red Hill Bulk Fuel Storage] Facility.” **Discussion topics:** Groundwater modeling status; modeling milestones; target development periods; proposed numerical model boundary conditions and locations.
2	6/26/2017	**Discussion topics:** Model boundary conditions update; HGUs; and model layer update.
3	8/17/2017	**Discussion topics:** Hydrogeological CSM and newly acquired data; groundwater flow modeling activities and decision points; lateral boundary conditions; decision to preclude SW12 from Navy model; Navy decision to utilize ModFlow-USG; proposed model layering approach; model calibration targets; interim modeling efforts.

Meeting #	Date	Synopsis
4	9/22/2017	**Modeling objectives:** The objective of groundwater modeling will be to help ascertain potential risk to water supply wells as a result of a potential range of releases from the Red Hill Bulk Fuel Storage Facility under a range of reasonable pumping conditions within the model domain. The results of this modeling effort will then be used to inform decisions related to potential remediation options. **Discussion topics:** Review of Navy's modeling approach (interim and final) and timeline; review of Navy's decision to use MODFLOW USG and to use MODFLOW NWT/MT3D for fate and transport validation; USGS update on the Synoptic Water Level Study; review of Navy's southwest (Ocean) boundary and deep boundary approach and decision to preclude SWI2; Navy's approach for model calibration and uncertainty.
5	11/17/2017	**Discussion topics:** Apparent gradients near Red Hill based on South Hālawa barrier; water typing; updated groundwater elevations; model layering; calibration approach and targets; comparison of USGS May 2015 Hālawa Shaft pumping test data to 2007 model simulations; updated boundaries; groundwater discharge rates in model area; groundwater balance schematic showing all groundwater inflow and outflow components and average annual flow rates; modeling code (discuss access to transport code); pumping schedules; critical data needs and data sharing.
6	12/20/2017	**Discussion topics:** Water level data assimilation; calibration targets, weights and error; parameter values and ranges; recharge and pumping stresses; conceptual groundwater budget estimates; model construction, water level contours.
7	1/11/2018	**Discussion topics:** Field data collection update; groundwater potentiometric map; interim modeling; LNAPL modeling.
8	2/12/2018	**Discussion topics:** Field data collection update; interim modeling calibration; particle tracking; sensitivity analysis.
9	3/16/2018	**Discussion topics:** Interim modeling sensitivity analysis; interim model evaluations; Final Groundwater Flow Model – December 5, 2018; contaminant fate and transport considerations.
10	4/13/2018	**Discussion topics:** Interim modeling issues and action items; sensitivity analyses - low hydraulic conductivity of the caprock; influence of GHB stage along the northwest boundary of the model; saprolite with same properties as basalt; integrating Red Hill and Hālawa Shafts (revised) elevations; low hydraulic conductivity rind on caprock.
11	6/7/2018	**Discussion topics:** CSM: Red Hill Area Groundwater Flow System; issues and action items - modeling approach for basalt; saprolite extent and hydraulic properties; model layering; uncertainty in modeling; steady-state modeling assumptions; discussion of the base-case model and changes for the December 2018 flow model; discussion of groundwater level measurement procedures for Red Hill and Hālawa Shafts to properly filter and analyze concurrent pumping and groundwater elevation data; lateral boundary fluxes relative to sensitivity analyses; addition of Red Hill monitoring wells to the Screen Elevations and Related Model Layers summary table; integration of conservative assumptions into interim modeling; incorporation of RHMW11 data; considerations of local flow gradients within the regional groundwater flow system; summary of the sensitivity analyses/multiple models to evaluate the impact of uncertainty.
12	7/12/2018	**Discussion topics:** Increasing efficacy of working group; working group goals, current challenges and member contribution; improve communication; meeting format and best practices; foster engagement.

5.3 MODELING APPROACH

This modeling effort considered available regional and site data as well as information derived from previous models, as described in the CSM. A modeling effort for this area, for the current objectives, is challenging due to extremely flat water level gradients, high hydraulic conductivities, large local-scale heterogeneities, and scarcity of model-wide synoptic data. Therefore, along with conservative assumptions of model development, calibration and application, a multi-model evaluation was conducted to assess the impact of uncertainty in conceptualization, numerical implementation, parameter values, water levels, and synchronous stresses on groundwater flow. All models were then considered in the groundwater migration and source water zone analyses. The simulation results were further collated to provide probability maps of migration from the Facility and of source water zones for the key water supply locations. This addresses the fourth objective discussed above, concerning uncertainty. In addition, very conservative/protective models were considered in further evaluations for the relevant objectives.

Groundwater flow models were developed and calibrated to site information available at the time the models were being developed. Conservative assumptions were implemented in developing the models so as to be protective of the key water supply locations. These models were valuable in providing a better understanding of the complex hydrogeologic system which will provide greater focus on development of the final model for the study as required by the first objective discussed above. Groundwater flow was simulated using the MODFLOW-USG code (Panday et al. 2013), which is an unstructured grid version of the USGS modular finite-difference flow model, MODFLOW.

The models were applied toward evaluating the migration of groundwater from beneath the Facility and toward estimating the source water zones of the key water supply locations. Extreme conditions of pumping at the key water supply locations were implemented for this evaluation, to provide conservative predictions. Particle tracking analyses were conducted using the forward tracking approach to evaluate migration of water from beneath the Facility, and the backward tracking approach from the key water supply wells for evaluating source water zones. This addresses the second and third objectives discussed above. Particle tracking was initially simulated using the Mod-PATH3DU code (SSPA 2014), which is a particle-tracking model developed for unstructured grids and applicable to MODFLOW-USG. A later version of Mod-PATH3DU (SSPA 2018) was used for several simulations toward the end of the interim modeling study, as noted in Appendix A. Groundwater Modeling System (GMS) (Aquaveo LLC.) was used as the pre and post processor and as the user interface to the MODFLOW-USG model and Mod-PATH3DU software.

5.4 Model Development, Calibration, and Application

The model domain and grid are shown on Figure 5-1. The domain covers an area of about 9 miles by 6 miles and extends from just downstream of the dike intruded area in the mountains, to Pearl Harbor and the ocean. The grid is oriented along the general direction of lava flow and has higher resolution underneath the Facility, around water-supply wells and shafts, adjacent to lateral boundaries, and beneath the valleys. The model includes 5 numerical layers to represent the caprock and valley fill materials (numerical layer 1), and the basalt (numerical layers 2–5). Saprolite underlying the valley fill was simulated in numerical layers 2 and 3. Multiple model layers were implemented for the basalt aquifer to provide vertical resolution with a finer grid spacing near the water table, and does not coincide (or need to coincide) with geological layering.

In most models that were developed for the current study, the caprock, valley fill, saprolite, and basalt were simulated as homogeneous materials, as noted by previous regional studies of the area. Basalt properties were anisotropic in the lateral and vertical directions to include the smaller-scale heterogeneities resulting from geologic considerations in lava flow, basalt aquifer formation, and weathering. Local scale heterogeneities were also evaluated by some of the models including conceptual representations of clinker zones underneath Red Hill, of saprolite presence beneath the water table, and of caprock zonation into upland alluvial sediments and coastal marine sediments.

The model was calibrated to steady-state and transient conditions.

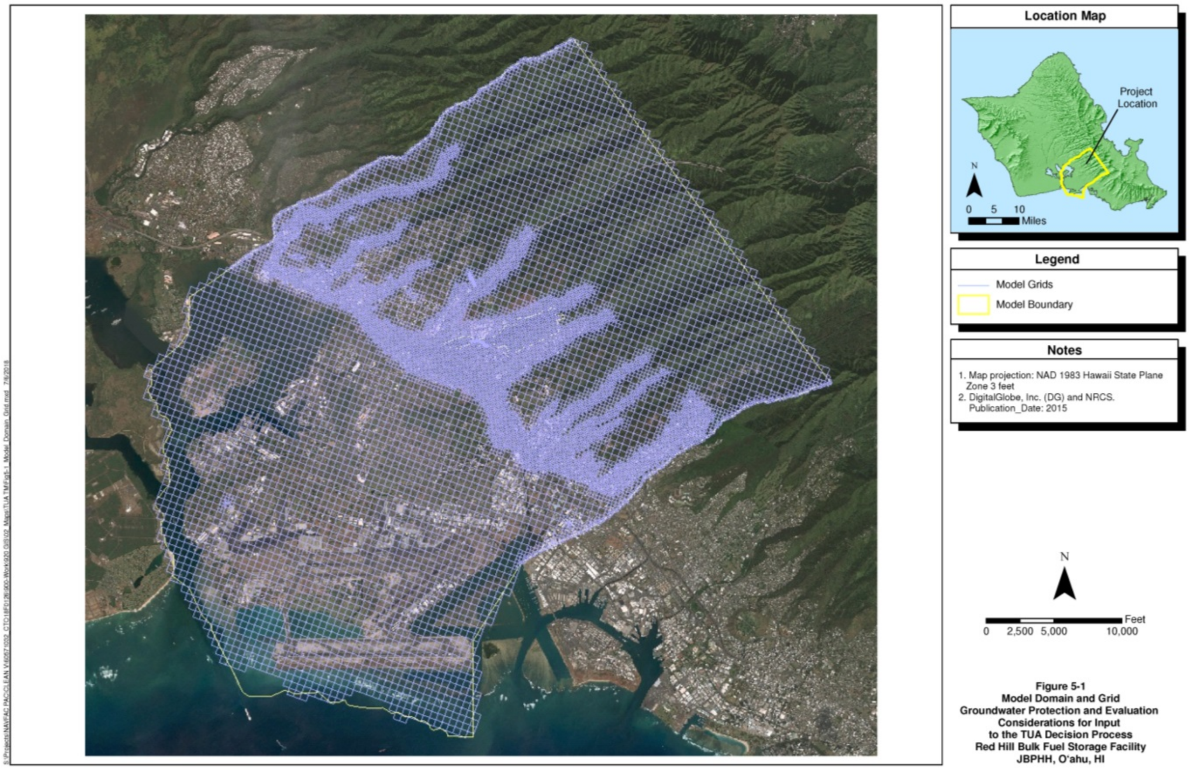


Figure 5-1: Model Domain and Grid

Three steady-state evaluations were conducted representing annual average conditions for different years – 2006, 2015, and 2017. Typical modeling projects only establish one steady-state flow field within one time span for calibration that is appropriate for the modeling objectives. Water level data and fluxes at major springs within the domain were first processed to evaluate long-term calibration targets for model comparison. The simulated water levels, differences in water levels between wells, and apparent hydraulic gradients matched observed conditions regionally, when the regional evaluations were performed with a consistent methodology between observed and simulated information. The impact of local heterogeneities due to presence of clinker materials beneath the Facility was captured by one of the models that included a localized conceptual representation of the clinker zone.

Transient responses of water levels at the Facility (and in its vicinity) to changes in pumping at Red Hill Shaft and Hālawa Shaft were also simulated to establish the hydraulic connectivity between the pumping locations and water level measurement points. This was conducted for two synoptic pumping and water level measurement studies that were conducted in 2006, and in 2015. The 2017/2018 synoptic study information will be integrated into the final flow model.

Conservative assumptions were included in development and calibration of the model. Saprolite, which can act as a barrier to flow, is known to extend for several hundred feet beneath the water table in areas adjacent to and southwest of the Facility within North and South Hālawa Valleys, as well as Moanalua Valley, however, the lateral extent and depth were greatly reduced in the model. This conservative sensitivity analyses had saprolite in model layers 2 and 3 (to a depth of 60 ft below the water table vs the seismic profile indicating saprolite depth at approximately 200 feet below the water table), and used K values as relatively low permeability as well as the same permeability as the basalt. The calibrated models were further evaluated to note water level differences between the Facility and the key water supply locations. Larger water level differences between the Facility and measurement points create larger driving forces between them and the models, where biased, were conservative to the key water supply locations. Also, different models were protective of different objectives and therefore evaluations were conducted with the more conservative model as appropriate. Various models were developed in this manner and calibrated if possible. The models were then used to estimate groundwater migration and source water zones. These computations were conducted under extreme conditions for pumping at the key locations to provide very conservative evaluations. Two primary scenarios were considered in this regard:

1. Maximum pumping at Hālawa Shaft (16 million gallons per day [mgd]), with average pumping Red Hill Shaft ([redacted] mgd), and Moanalua Wells (3.7 mgd)
2. Maximum pumping at Hālawa Shaft (16 mgd) and average pumping Moanalua Wells (4.66 mgd) with no pumping at Red Hill Shaft

The first scenario is referred to as the "RHS Pumping Scenario,", while the second scenario is referred to as the "RHS Not Pumping Scenario". These scenarios depict extreme conditions that are not sustainable in practice. Also, the evaluations were conducted for steady-state flow fields resulting from the above pumping regimes and therefore neglect the buffering effects of transient conditions.

5.5 Sensitivity Analyses and Uncertainty Evaluation

A multi-model approach was used in this study to evaluate the impact of parameter uncertainty, different conceptual representations, and numerical approximations, on modeling flow and migration of groundwater from beneath Facility, and on the source water zones for the key wells. A total of 43 steady-state (31) and transient (12) models were developed to evaluate flow behavior and response to pumping. These models conservatively bracketed the estimated parameter ranges for the aquifer materials, the observed long-term water level elevations in monitoring wells and water level changes observed during the synoptic studies. Each of the steady-state models was further used with specified conservative pumping scenarios at key wells, to evaluate the response in terms of migration of water and source water zone evaluations.

A parameter sensitivity to calibration analysis was conducted as part of the multi-model approach, whereby parameter values were varied to their probable lower and upper bounds and sensitive parameters were noted. The models were then recalibrated, if possible, by varying other model parameters within their probable ranges. The recalibrated models were then evaluated to note whether they are conceptually appropriate and if the water budget terms are reasonable. Models that were deficient in this regard were provided a lower weighting in the subsequent uncertainty analysis.

Sensitivity of parameters was further noted toward the simulation objectives for each of the application scenarios (RHS Pumping and RHS Not Pumping), and for each of the objectives (specifically the source water zones of each of the water supply shafts/wells and the migration behavior of water from beneath Facility). The sensitivity analyses were categorized based on ASTM classifications to identify data significance, as detailed in Appendix A.

Uncertainty analysis was conducted on groundwater migration from beneath the Facility and on the source water zones of key wells. Similar to the multi-model spaghetti-plots shown on TV depicting the uncertainty in projected paths of hurricanes, the particle tracks for each model were examined to evaluate their collective story, as detailed in Appendix A. The uncertainty in migration and source water zone evaluations was also quantified from this set of models.

This uncertainty quantification was performed in a manner similar to the "Particle Tracking, Monte Carlo" (PT-MC) approach (Frind and Molson 2018; Anderson, Woessner, and Hunt 2015). In this approach, hundreds of equally probable values of a single input parameter are obtained based on the parameter's underlying statistical distribution, which is combined randomly with other parameters obtained in a similar manner, and a model is created for each combination. The models may be further evaluated depending on conceptual reasonableness and whether they calibrate to observed conditions. Particle tracking is then performed for each selected model and particle-tracking results from all models are combined to create a capture frequency or capture probability map. Weighting of the various models may also be performed considering their goodness of fit to data and the appropriateness of conceptualization or water budgets.

The approach used is similar to PT-MC, however, instead of creating hundreds of models with random combinations of material parameters, models were deliberately selected in a focused manner. Monte Carlo realizations are not practical for timely production of meaningful results for the current study, and do not consider the hydrogeologist's expert understanding. Also, performing deliberate simulations with focused sets of parameters provides an understanding of the impact of the ranges of individual model parameters and parameter combinations, as well as of various conceptualizations and numerical or boundary approximations which are difficult to implement into a Monte Carlo framework.

5.6 MODELING RESULTS

The key results from the interim modeling effort are the following:

- Red Hill Shaft intercepts all groundwater that migrates from the Facility when it is pumping at an average of [redacted] mgd. This was indicated by all the models evaluated in this study.
- It would require over 10 mgd of pumping at Hālawa Shaft with Red Hill Shaft turned off for a sustained period of over 6 years for there to be any threat to Hālawa Shaft from groundwater beneath the Facility. A close examination of the models further indicated that the potential was largest for conditions of extreme drought with reduced lateral boundary inflows and recharge to groundwater.
- The scenario with Hālawa Shaft pumping at 16 mgd with Red Hill Shaft being off showed a higher probability of migration of groundwater from beneath the Facility to Hālawa Shaft with a minimum travel time of 3 years, the worst case again being for the model with extreme drought with reduced lateral boundary inflows and recharge. During the Groundwater Modeling Working Group Meeting held in June 2018, BWS also indicated that Hālawa Shaft would not be able to pump at this extreme rate for an extended period of time. Also, it is not anticipated that Red Hill Shaft would be off for this extended period of time under a severe extended drought. Thus, while this scenario has been evaluated in an effort to be very conservative and understand the extremes, it is not likely this scenario would occur.
- Provide focus and guidance for development of the final model.

Probability distribution maps for the source water zone of Hālawa Shaft are shown on Figure 5-2 and Figure 5-3 for the RHS Pumping Scenario and the RHS Not Pumping Scenario, respectively. The source water zone for Hālawa Shaft lies to the northeast of the shaft for both scenarios.

The probability distribution map for the source water zone of Red Hill Shaft is shown on Figure 5-4 for the RHS Pumping Scenario. The source water zone for Red Hill Shaft covers the Facility in all cases.

Probability distribution maps for migration of groundwater from beneath the Facility are shown on Figure 5-5 and Figure 5-6 for the RHS Pumping Scenario and the RHS Not Pumping Scenario, respectively. With Red Hill Shaft pumping, groundwater from beneath the Facility is entirely captured by Red Hill Shaft. With Red Hill Shaft not pumping, groundwater from beneath the Facility first migrates in a southwest direction and then in a northwest direction toward Pearl Harbor. There is a small probability of groundwater from beneath the Facility to migrate toward Hālawa Shaft for this scenario. It is further noted that groundwater does not migrate directly (as the crow flies) between the Facility and Hālawa Shaft. The difference in capture at Hālawa Shaft between Figure 5-3 and Figure 5-6 is a limitation in GMS on how particles are seeded, as discussed further in Appendix A.

Probability distribution maps for the source water zone of Moanalua Wells are shown on Figure 5-7 and Figure 5-8 for the RHS Pumping Scenario and the RHS Not Pumping Scenario, respectively. For both scenarios, the source water zone does not underlie the Facility. Furthermore, these wells extract water from deeper in the basalt in numerical model layer 5. On comparing Figure 5-7 and Figure 5-8, it was noted that the source water zone of Moanalua Wells was not impacted by pumping at Red Hill Shaft.

Several models had one particle that tracked from the Facility to Hālawa Shaft when Hālawa Shaft was simulated with pumping at a steady 16 mgd for the Red Hill Shaft Not Pumping Scenario. This caused the probability distribution map of Figure 5-6 to show some probability of migration toward Hālawa Shaft. Therefore, an additional scenario was simulated using all the models to calculate the cut-off pumping rate at Hālawa Shaft where that does not happen. This Scenario included Hālawa Shaft pumping at a steady 10 mgd with Red Hill Shaft not pumping. The probability distribution map for migration of groundwater from beneath the Facility for this Scenario is shown on Figure 5-9, indicating that it is not likely for groundwater from beneath the Facility to migrate toward Hālawa Shaft under this scenario. This scenario is also an unlikely case with extreme conditions for pumping at Hālawa Shaft and Red Hill Shaft that are not likely to be sustained in the field. Furthermore, interim model development and calibration involved conservative and protective assumptions for the various objectives, when data were sparse or not easily quantified.

The interim modeling effort also provides focus and indicates a more reliable path forward for the final model development effort. The discretization and particle tracking approaches of the interim model help with planning the discretization for a flow and transport model. The various conceptualizations and parameter representations evaluated by the interim modeling effort help direct attention toward significant parameters and conceptualizations and away from those that may not be of consequence to the modeling objectives related to fate and transport of potential solutes. Recently collected data (e.g., 2017/2018 synoptic data and geophysical information on saprolite extent) and an associated refined model conceptualization will also be incorporated into the final groundwater flow model to refine and fill the data gaps of the interim model.

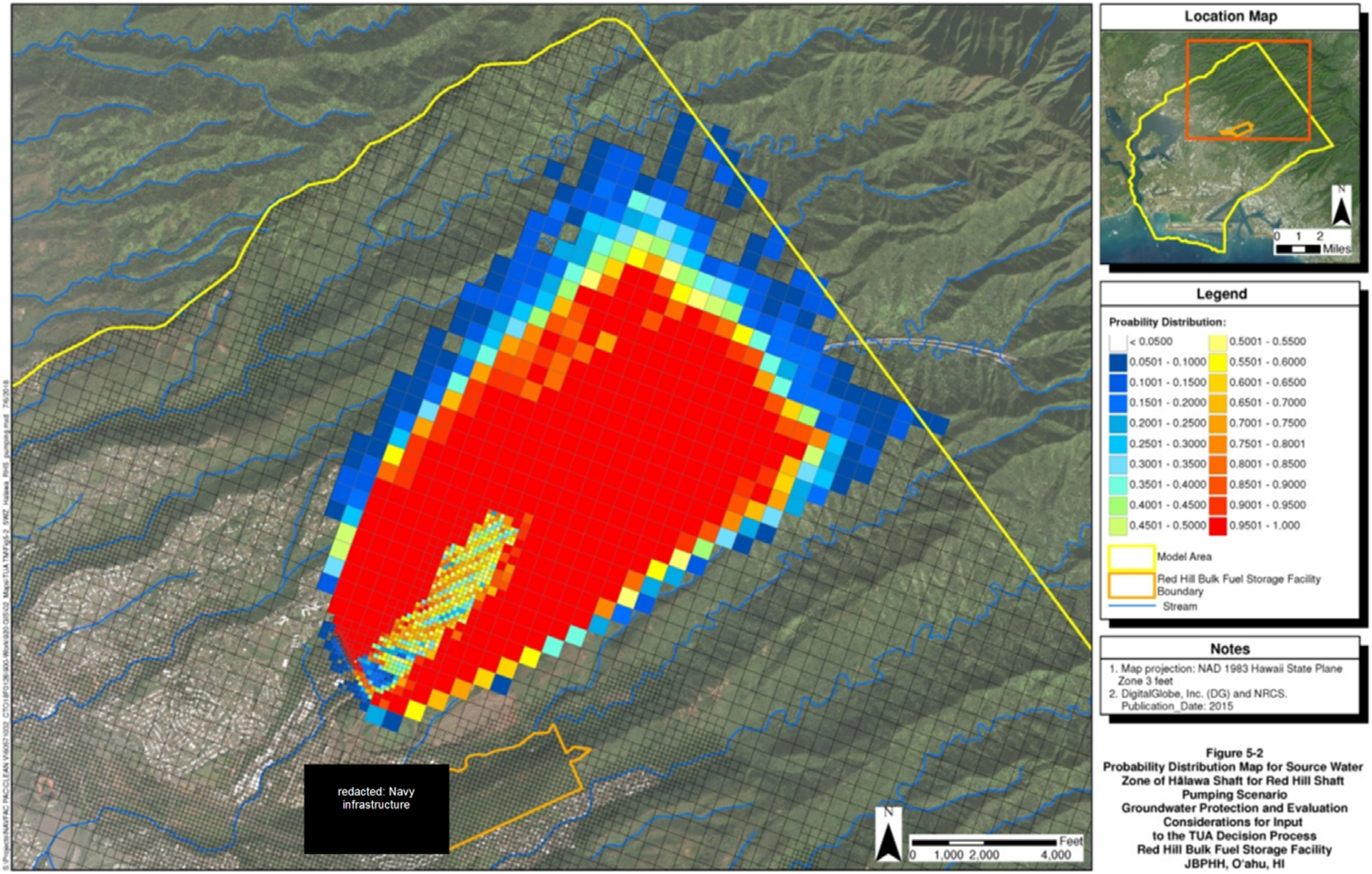


Figure 5-2: Probability Distribution Map for Source Water Zone of Hālawa Shaft for Red Hill Shaft Pumping Scenario

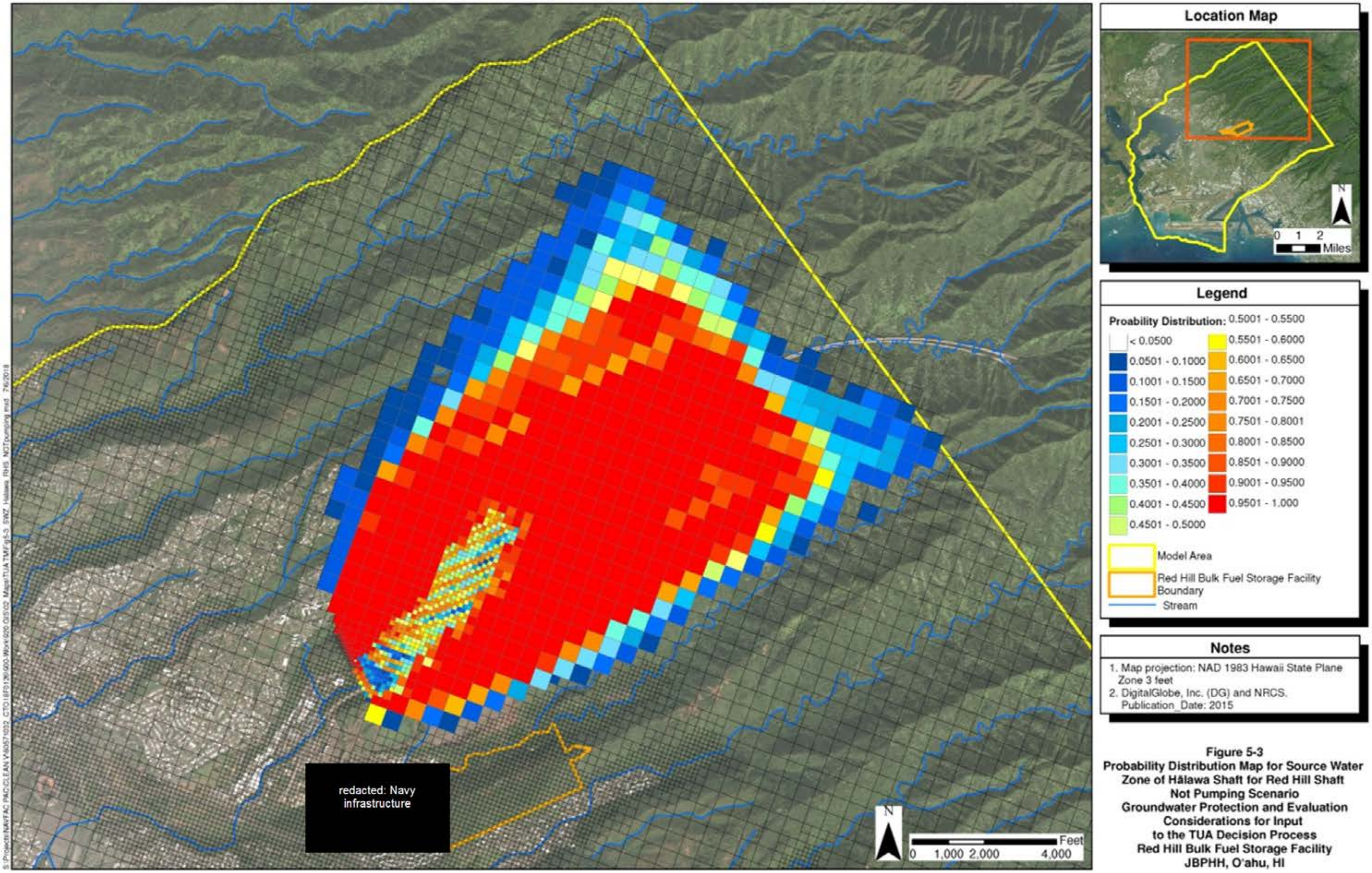


Figure 5-3: Probability Distribution Map for Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping Scenario

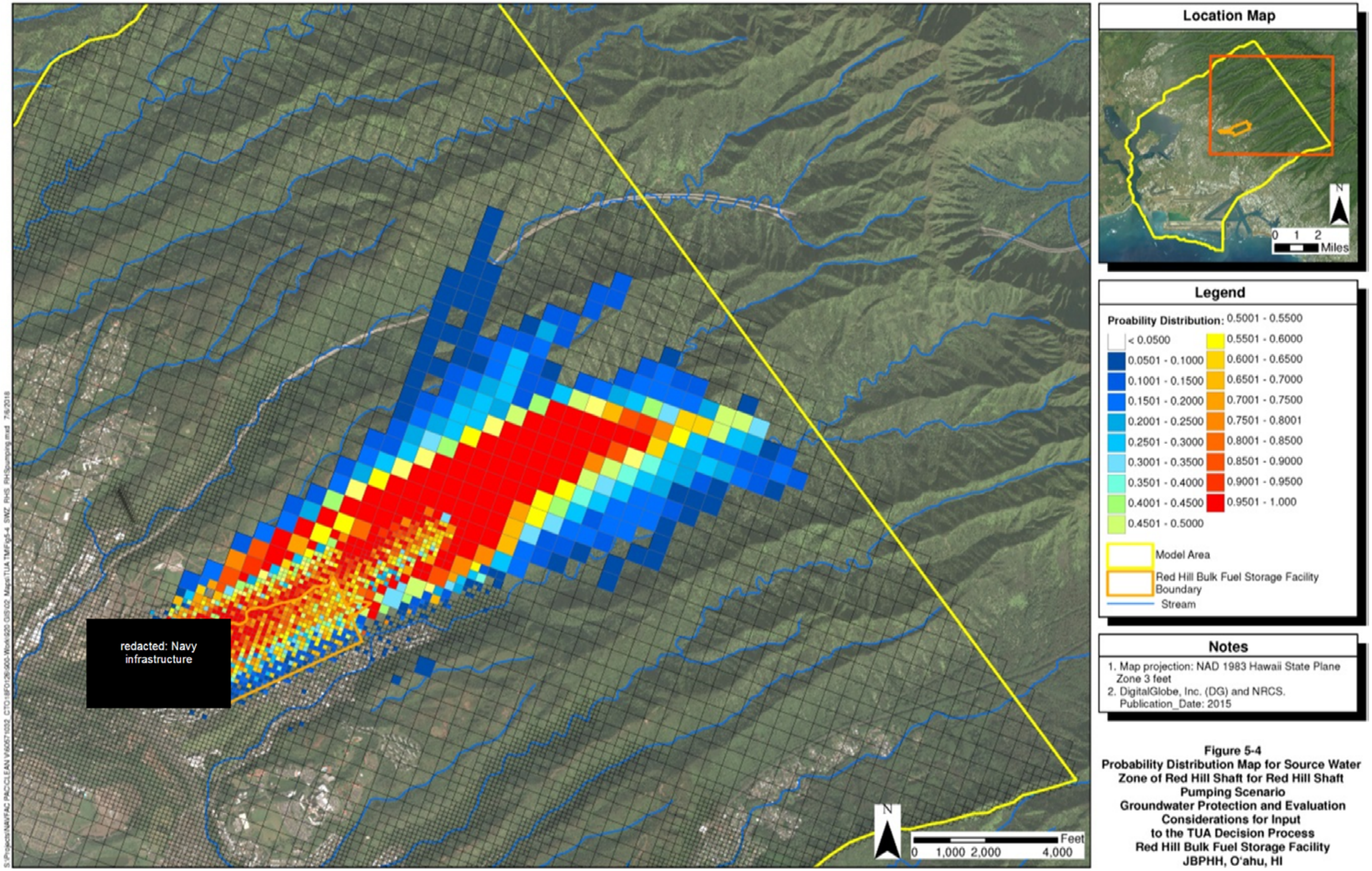


Figure 5-4: Probability Distribution Map for Source Water Zone of Red Hill Shaft for Red Hill Shaft Pumping Scenario

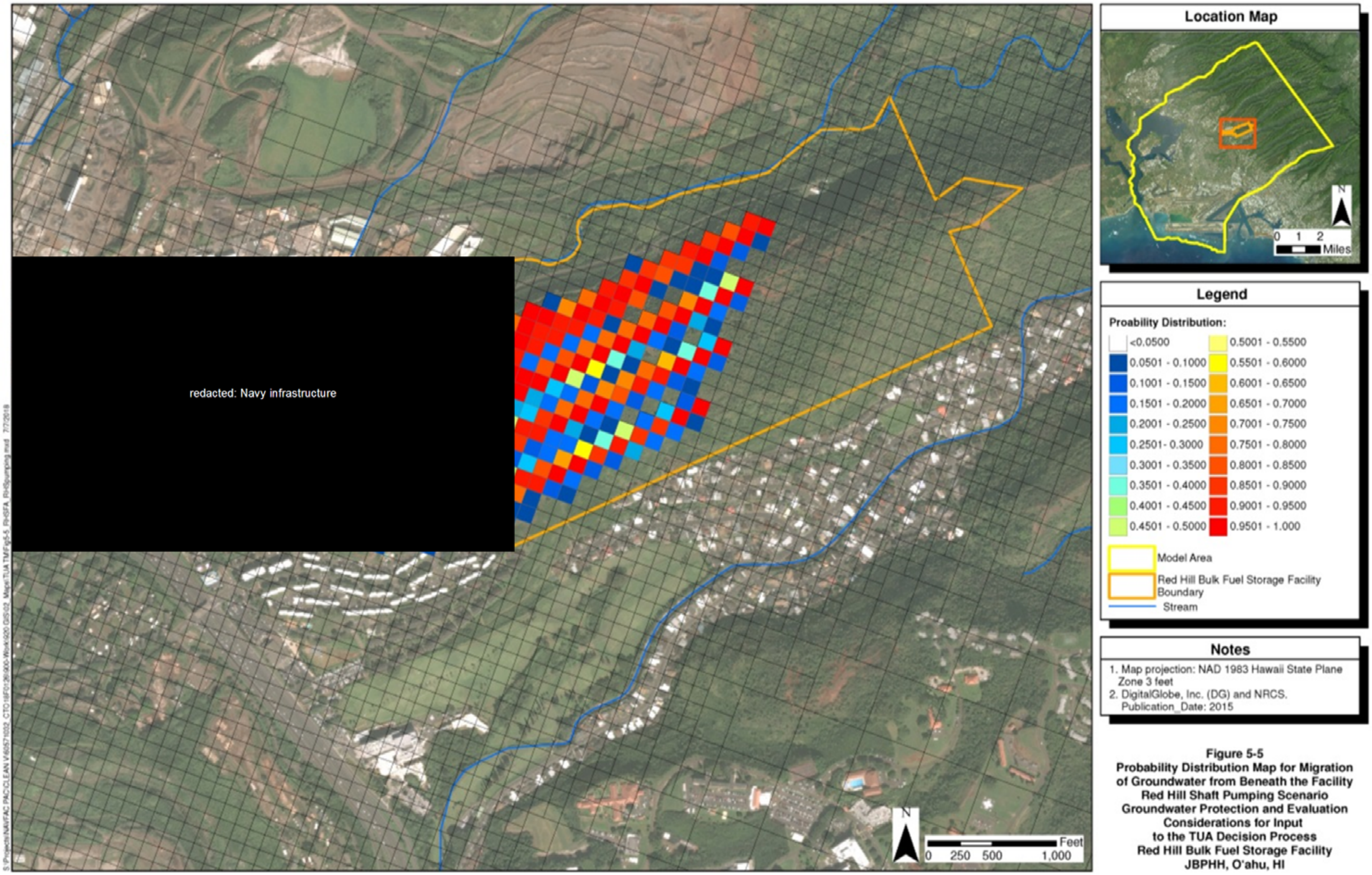
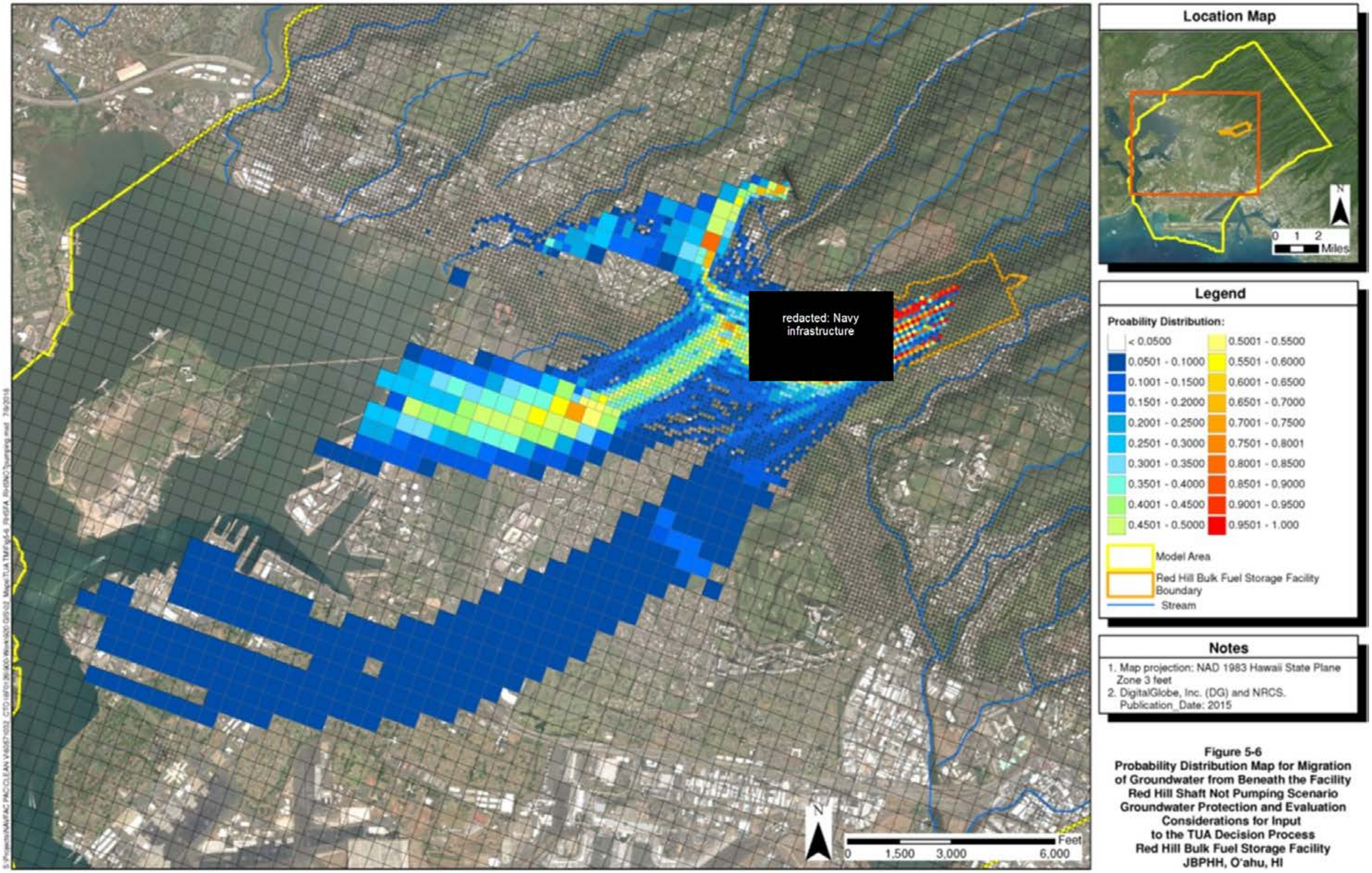


Figure 5-5: Probability Distribution Map for Migration of Groundwater from Beneath the Facility for Red Hill Shaft Pumping Scenario



1 **Figure 5-6: Probability Distribution Map for Migration of Groundwater from Beneath the Facility for Red Hill Shaft Not Pumping Scenario**

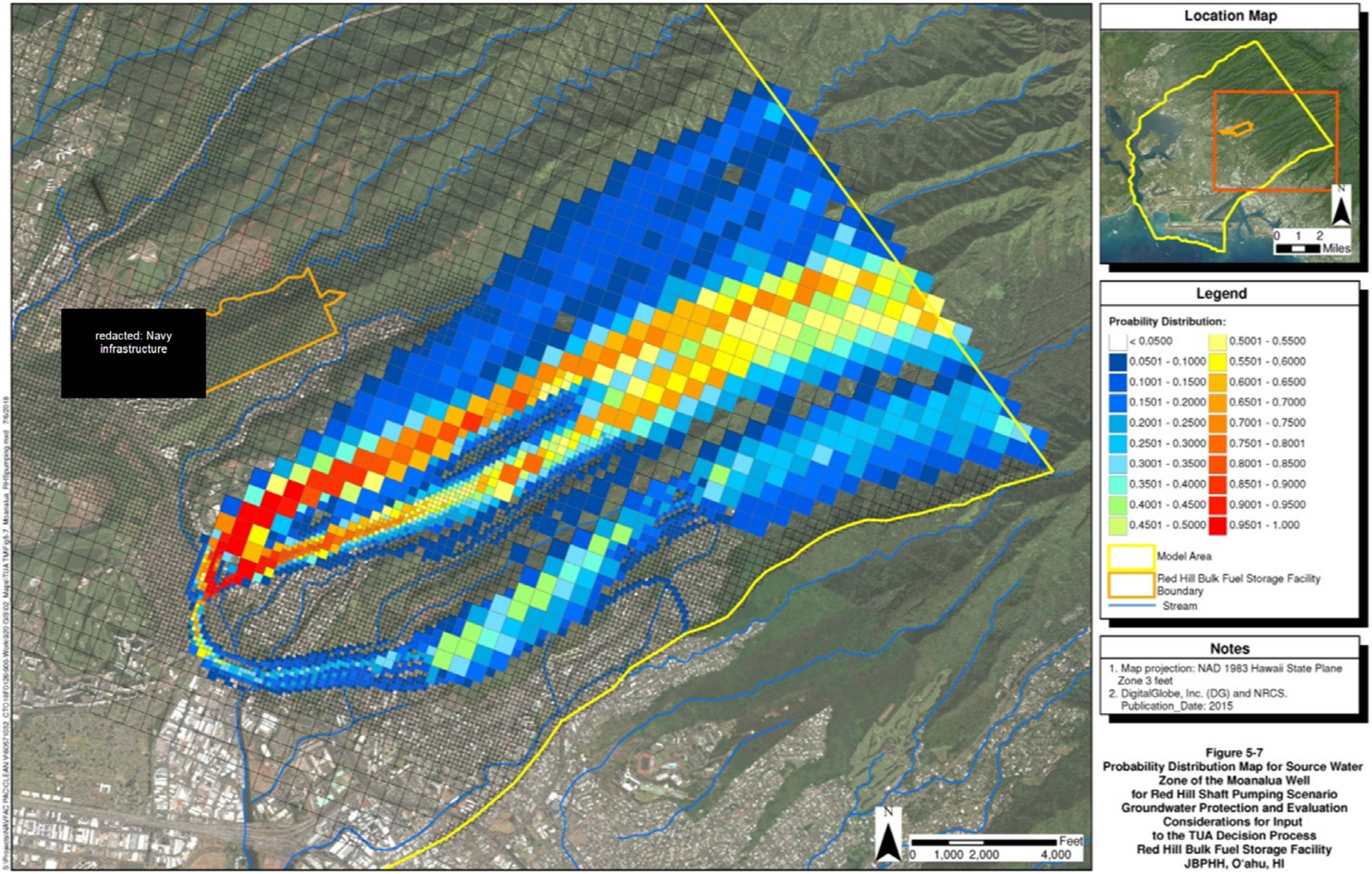


Figure 5-7: Probability Distribution Map for Source Water Zone of the Moanalua Wells for Red Hill Shaft Pumping Scenario

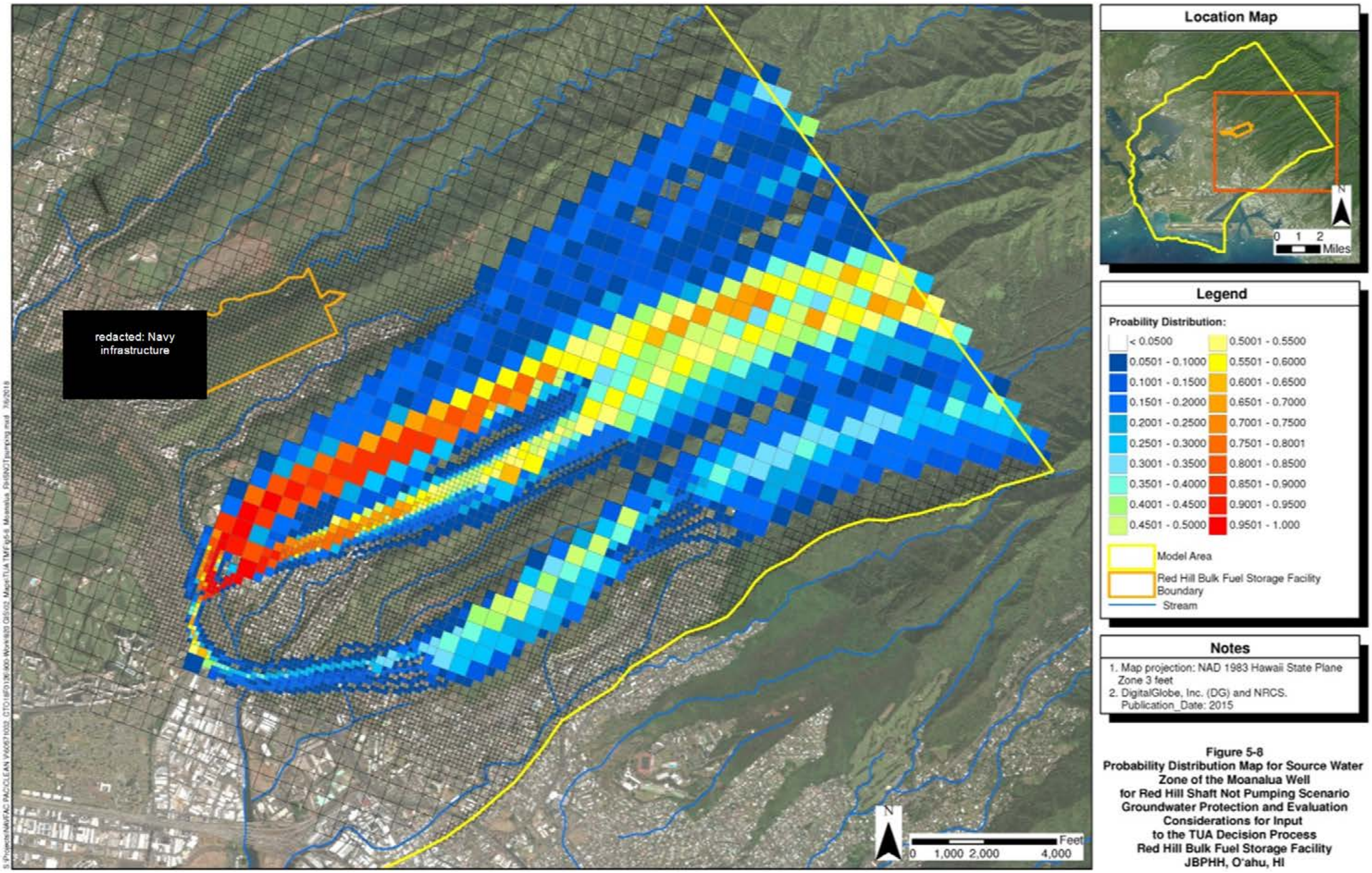


Figure 5-8: Probability Distribution Map for Source Water Zone of the Moanalua Wells for Red Hill Shaft Not Pumping Scenario

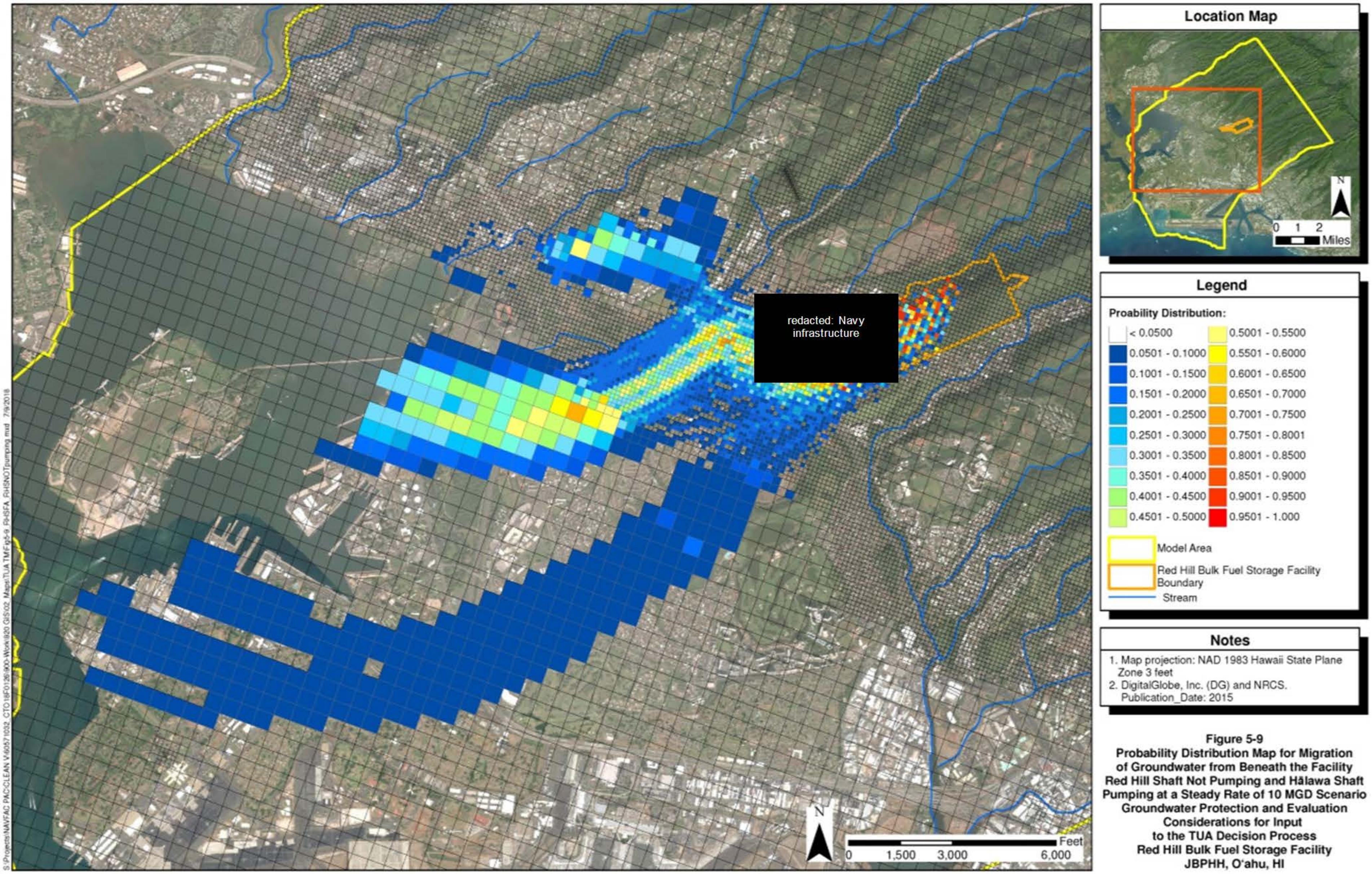


Figure 5-9: Probability Distribution Map for Migration of Groundwater from Beneath the Facility for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at a Steady Rate of 10 MGD Scenario

6. Natural Attenuation

This section highlights key elements related to natural attenuation as described in CSM Sections 7.3 and Appendix B. LTM results and supplemental investigations serve to document the natural breakdown of LNAPL and COPCs at the Facility including: (1) NSZD, which involves attenuation of LNAPL source zones, and (2) natural attenuation, which is focused on the attenuation of dissolved constituents in plumes. The natural attenuation investigations confirm that both NSZD and natural attenuation processes are active at the Facility. NSZD and natural attenuation are serving to remove mass from LNAPL source zones within the Facility and control the migration of COPCs leaving the Facility.

In the unsaturated zone, NSZD is ongoing as demonstrated by:

- Based on a thermal NSZD analysis, heat being generated by biodegradation processes was measured in three of the monitoring wells located within the tank farm, corresponding to an NSZD rate per area ranging from 140 (at RHMW01) to 1,500 (at RHMW03) gallons per acre per year, a range consistent with many other hydrocarbon release sites (CSM Appendix B.1). These individual measurements suggest that between 2,600 and 17,300 gallons of fuel hydrocarbons are being biodegraded per year by NSZD from the entire Facility.
- Carbon dioxide emissions from petroleum hydrocarbon biodegradation have been detected leaving Red Hill at both the ground surface and via the Facility tunnel ventilation system, indicating the current total NSZD ranges from 4,400 and 7,400 gallons of LNAPL (fuel hydrocarbons) being biodegraded per year from the entire Facility. This range is consistent with the range estimated using thermal measurements.
- Throughout the vadose zone, high oxygen concentrations (generally >19%) support aerobic biodegradation. Oxygen has been consumed and carbon dioxide has been generated as demonstrated by soil vapor sampling.
- The forensics analysis on the soil vapor shows high concentrations of weathered petroleum hydrocarbon vapors below Tank 5, the site of the 2014 jet fuel release, and a mixture of fresh and weathered petroleum vapors underlying the rest of the tanks. Note the fresh petroleum vapors at present at very low concentrations, which likely originate from routine operations of the Facility and not LNAPL releases.

In the saturated zone, biodegradation of released fuel and COPCs is ongoing as demonstrated by:

- Patterns in the groundwater geochemistry show that biodegradation is occurring, with consumption of dissolved oxygen, nitrate, and sulfate and production of metabolic by-products ferrous iron and methane.
- Reduction of dissolved hydrocarbon as one travels downgradient from the high concentration groundwater near monitoring well RHMW02 due to attenuation processes that control the overall length of the dissolved plume at the Facility.
- Laboratory microcosm studies and multiple microbial parameters show that aerobic bacteria are present in groundwater underlying the Facility that can readily degrade key COPCs at the site. These same tests identified evidence of anaerobic degradation potential, but limited results available to-date from anaerobic microcosms suggest slower rates under these conditions (however, this may be related to long acclimation periods for anaerobic bacteria).

Overall these processes conclusively demonstrate that NSZD is degrading LNAPL sources in the unsaturated and saturated zone, and that natural attenuation processes are controlling the migration of the dissolved fuel constituents.

6.1 NATURAL SOURCE ZONE DEPLETION IN THE VADOSE ZONE

NSZD is a term used to describe the collective, naturally occurring processes of dissolution, volatilization, and biodegradation that result in mass losses of LNAPL petroleum hydrocarbon constituents from the subsurface. Background information on NSZD is provided in CSM Section 7.3.1. NSZD within the Facility vadose zone has been documented and quantified through: (1) soil vapor monitoring and (2) carbon trap and temperature measurements.

6.1.1 Soil Vapor Monitoring

The soil vapor monitoring network consists of two to three soil vapor monitoring wells installed in angled borings below each of the Facility's 18 active fuel tanks. The available soil vapor monitoring data include (1) monthly PID screening of the soil vapor monitoring wells below each fuel storage tank and (2) a detailed soil vapor testing program conducted at the Facility in October 2017 where the composition of the gas in the soil vapor probes underlying the tanks was measured using EPA Air Method, Toxic Organics-15 (TO-15).

The monthly soil vapor monitoring data generally show low total vapor concentrations (generally <10,000 parts per billion by volume [ppbv]) in the soil vapor wells consistent with weathered LNAPL. Soil vapor concentrations generally decreased from the initiation of monitoring in March 2008 through 2013, consistent with ongoing attenuation of prior LNAPL releases (Figure 6-1). In January 2014, PID readings in the Tank 5 soil vapor wells increased dramatically corresponding to the release of approximately 27,000 gallons of JP-8 from Tank 5. PID readings peaked at 450,000 ppbv in June 2014. Smaller increases in PID readings were observed below each of the adjacent tanks (i.e., Tanks, 3, 6, and 7) indicating that the existing soil vapor monitoring network provides a robust means for evaluating releases. Since 2014, PID readings at Tank 5 have decreased over time, consistent with rapid weathering of this new LNAPL release.

Field measurements and laboratory analysis of soil vapor samples collected from the soil vapor wells in October 2017 provided additional evidence of NSZD. High oxygen concentrations (13% to 21%) and non-detect methane concentrations (<0.1%) indicate aerobic conditions below all tanks. The chromatograms for the soil vapor samples do not exhibit the typical sequence of n-alkanes characteristic of unweathered fuel but, instead, are dominated by an unresolved "hump" or unresolved complex mixture (UCM) visible at the end of the chromatogram characteristic of biological weathering (Figure 6-5). Although all soil vapor samples exhibit the characteristics of biological weathering, the chromatogram from the Tank 5 sample shows the broadest unresolved hump consistent with a more recent fuel release. For the samples from the other tanks, the hump starts later (i.e., further right on the chromatogram) consistent with more extensive weathering expected for older releases. As discussed in CSM Appendix B.3, in addition to evidence of weathered LNAPL, many of the soil vapor samples exhibited an alkane distribution consistent with very low concentrations of unweathered jet fuel vapors. Small vapor-phase releases can occur through joints, valves, and gaskets as well as during tank filling and fuel transfer operations. These types of small vapor-phase releases are difficult to completely eliminate and may be contributing to this chromatographic signature.

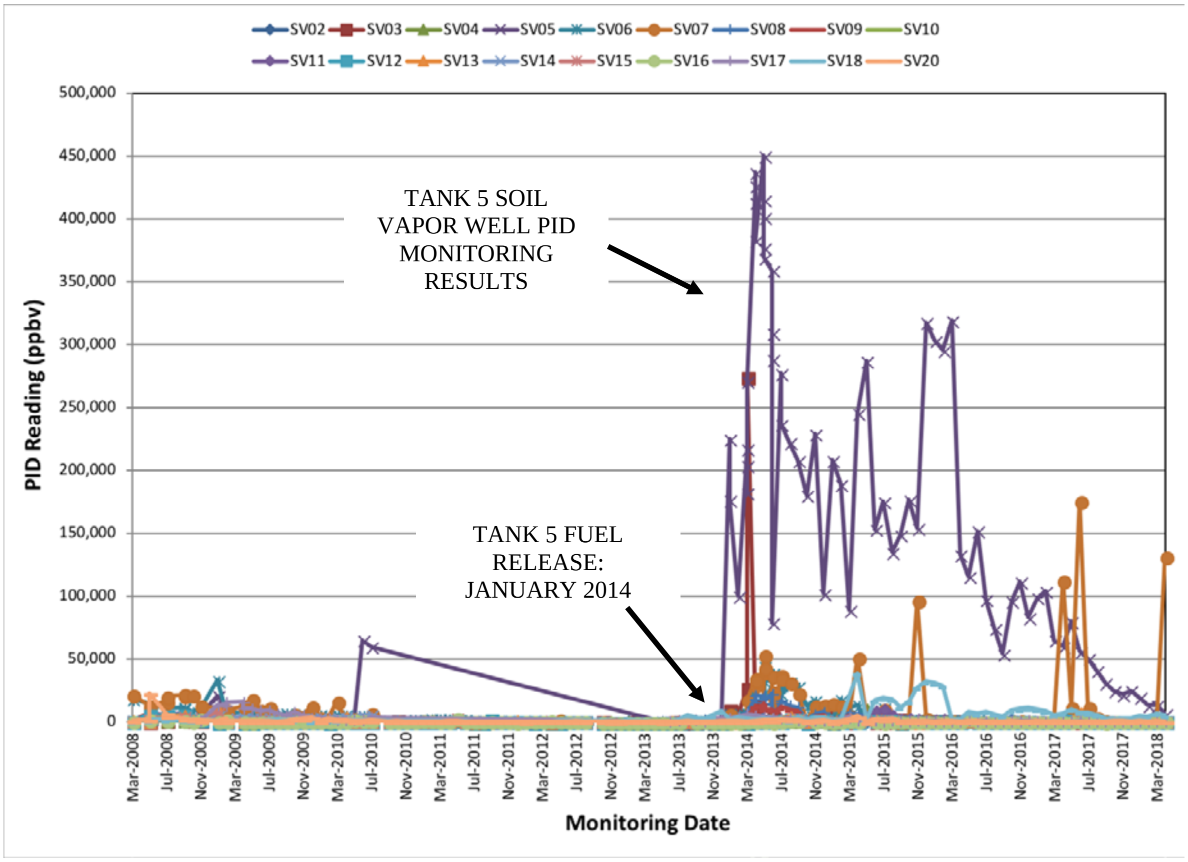


Figure 6-1: Monthly PID Monitoring Results for Below Fuel Tank Soil Vapor Wells

6.1.2 NSZD Rates Measured Using Temperature Measurements and Carbon Traps

NSZD rates have been measured at many LNAPL sites and can be quantified by measuring indicators of biodegradation processes such as heat generation and carbon dioxide generation. Two different methods were able to measure NSZD rates at the Facility: a thermal NSZD analysis and deployment of carbon dioxide traps.

Thermal NSZD rates were established at the Facility using vertical temperature profiles obtained from existing monitoring wells. This included monitoring wells (RHMW01, RHMW02, and RHMW03) located within the area likely impacted by prior releases, and one background well located within the Lower Tunnel (RHMW05; Figure 3-4). A vertical temperature profile was also obtained from well RHMW04, but this location was not suitable for use as a background location due to differences between temperature profiles in this well and the lower access tunnel wells, and thus well RHMW05 served as the sole background well for this evaluation. These profiles were then used to quantify NSZD rates at the tank farm. Two methods were employed to obtain temperature measurements at each well: Well Air Temperature Method and Wall Temperature Method, and three calculation approaches were also applied. The investigation methods and data analysis are documented in CSM Appendix B.1.

Results were fairly consistent (within 60% relative percent difference), which increases the confidence in the accuracy of these results.

The resulting NSZD rates per acre per year for the three monitoring wells with hydrocarbon impacts were:

- RHMW01: 140 gallons per acre per year of NSZD
- RHMW02: 640 gallons per acre per year of NSZD
- RHMW03: 1,500 gallons per acre per year of NSZD

Overall, when the NSZD rates are applied over the entire tank farm area, the gross potential NSZD rate from the temperature method is estimated to be between 2,600 and 17,300 gallons of hydrocarbon being biodegraded per year by NSZD in the unsaturated zone.

The second NSZD method that could be applied at the Facility was the carbon dioxide efflux method (or "carbon trap" method) (CSM Appendix B.2). This method measures the amount of carbon dioxide being generated through the biodegradation of LNAPL. The carbon dioxide is captured using two carbon dioxide sorbent elements composed of soda lime (consisting primarily of calcium hydroxides), which are contained in a canister, installed over LNAPL zones (McCoy et al. 2014). Carbon-14 isotope analysis is used to distinguish carbon dioxide from petroleum sources vs. modern sources (such as respiration). Because the ventilation system in the tunnels created a negative pressure gradient within the tank access tunnels, advective gas flow was from the vadose zone into the tunnels. As a result, the tunnels act like a soil vapor extraction system and can capture carbon dioxide generated through biological NSZD occurring in the vadose zone. Therefore, a carbon trap was deployed in the tunnel system to measure the extraction of petroleum-based carbon dioxide being removed by the tunnels, and on the ground surface on Red Hill to measure carbon dioxide that escapes to ground surface (Figure 6-2).

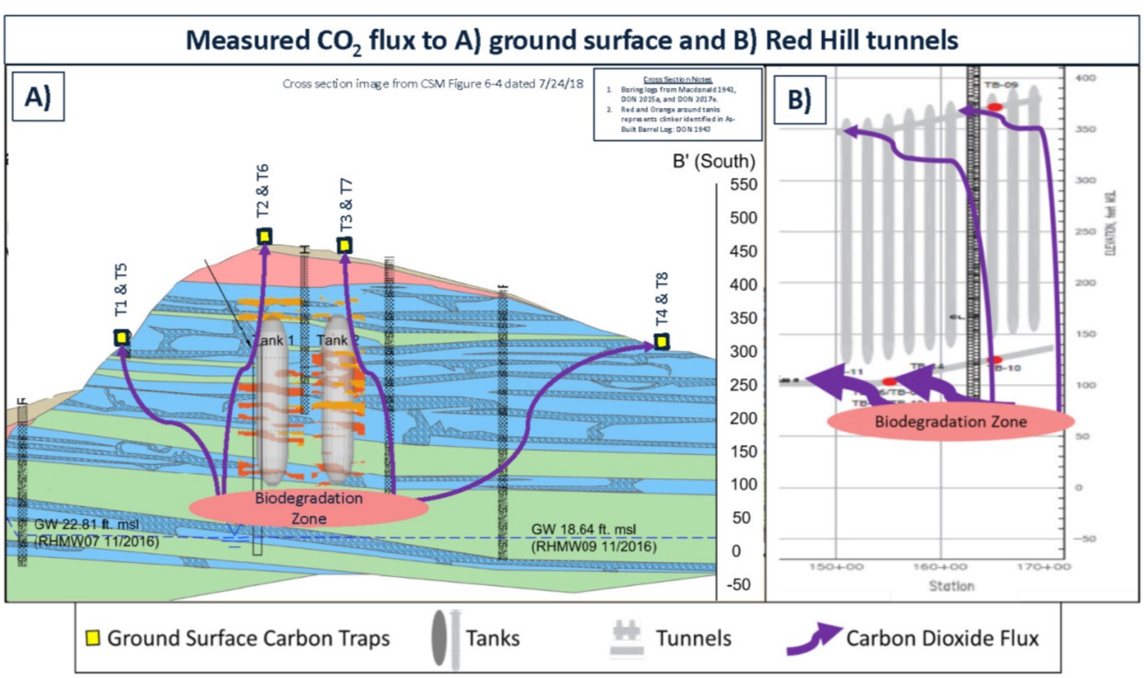


Figure 6-2: Collection of Carbon Trap Data for Quantification of NSZD

The carbon trap data indicated that the NSZD rate attributable to petroleum-based carbon dioxide entering the tunnels was calculated as between 3,400 and 6,400 gallons per year. The ground surface traps indicated an additional NSZD rate of about 1,000 gallons per year attributable to carbon dioxide migration to the ground surface, yielding a total NSZD rate between 4,400 and 7,400 gallons of jet fuel biodegrading per year at the Facility.

A third method to measure NSZD, the gradient method, was attempted but due to the advection associated with the tunnel system, the assumptions underlying this method were violated and therefore it could not be used to measure the NSZD rate at the Facility (CSM Appendix B.3).

The two methods used to measure NSZD rates yielded similar ranges: (1) between 2,600 and 17,300 gallons per year based on heat flux and (2) between 4,400 and 7,400 gallons per year based on carbon dioxide flux. This is the current NSZD rate based on the ongoing biodegradation of historical releases; these rates could decline after most of the LNAPL is removed by NSZD. Alternatively, in the event of additional releases in the future, higher NSZD rates (expressed in terms of gallons per year for the Facility) are likely if they increase the lateral and/or vertical extent of LNAPL in the subsurface.

6.2 NATURAL ATTENUATION IN GROUNDWATER

Natural attenuation covers a variety of physical, chemical, or biological processes that act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in groundwater. A lines-of-evidence approach was used to evaluate the occurrence of natural attenuation of COPCs at the Facility.

6.2.1 Analysis of Geochemical Data (Secondary Evidence of Natural Attenuation)

A detailed discussion related to this section is presented in CSM Appendix B.5. Biodegradation of dissolved petroleum constituents in groundwater results in characteristic changes in concentrations of geochemical indicator parameters. Geochemical and COPC data from October 2016 to April 2018 strongly indicate that active and robust biodegradation of COPCs is occurring within the tank farm area:

- In the area of highest COPC concentrations (RHMW01 and RHMW02), electron acceptors (i.e., dissolved oxygen, nitrate, sulfate) are generally depleted (or have low concentrations) and concentrations of metabolic byproducts (i.e., ferrous iron, methane, TOC) are elevated relative to the monitoring locations outside of the tank farm area (RHMW04 to RHMW10). This spatial pattern of electron acceptor depletion and metabolic byproduct formation is generally consistent over the monitoring period (October 2016 to April 2018; see Figure 6-3 for April 2018 data) and is strong indirect evidence of biodegradation of COPCs in the area near RHMW02.
- Further, at RHMW01 and RHMW02, low dissolved oxygen concentrations (< 1 mg/L) and negative oxidation-reduction potential (ORP) values support anaerobic conditions in this area. For wells outside of tank farm area (RHMW04 to RHMW10), O_2 concentrations were generally greater than 4 mg/L and ORP values were greater than 100 millivolts (mV), consistent with aerobic conditions.

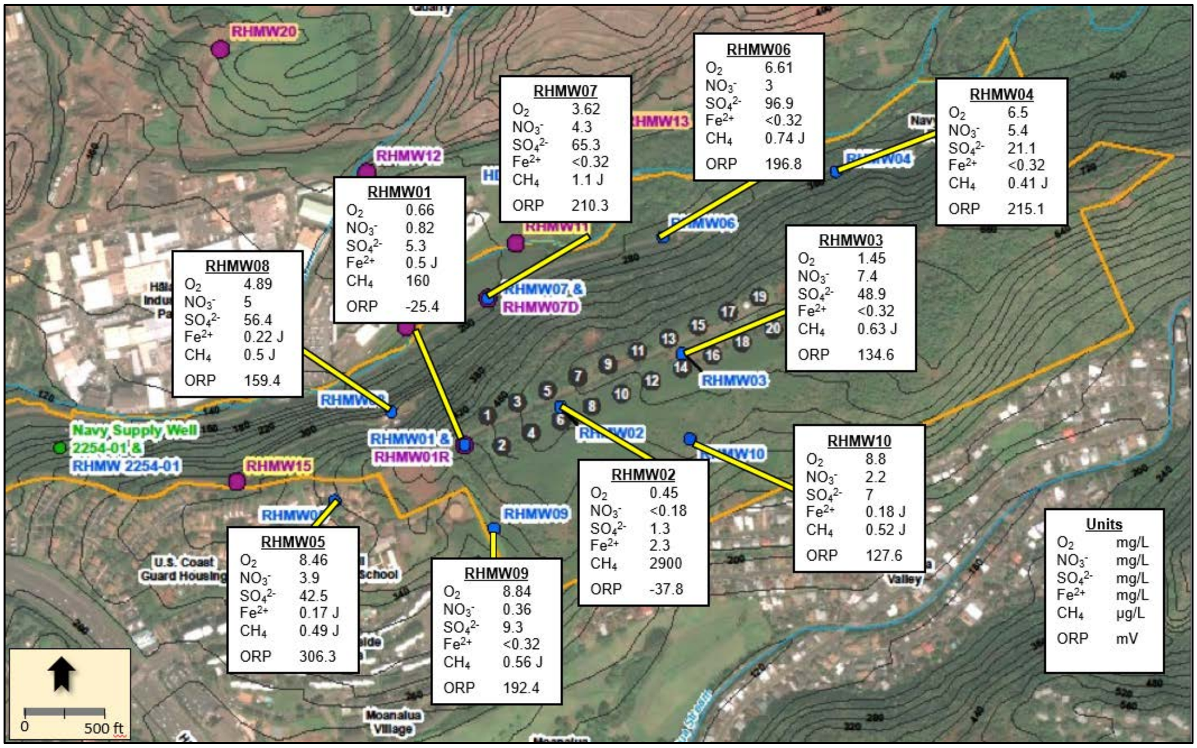
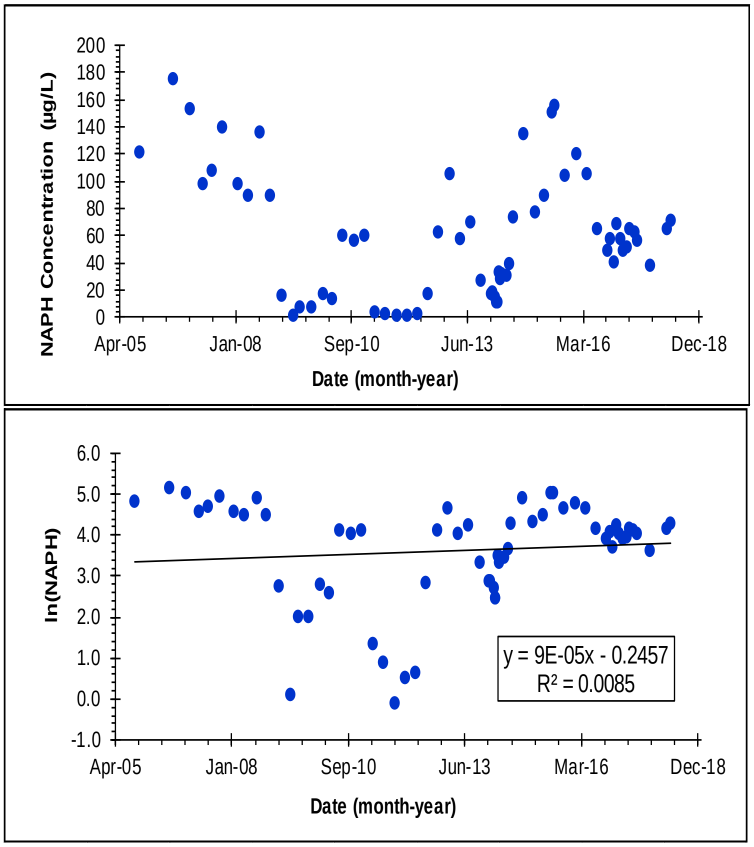


Figure 6-3: Concentrations of O2, NO3-, SO42-, Fe2+, CH4, and ORP from the Facility Groundwater Monitoring Network on April 23–25, 2018

6.2.2 Analysis of COPC Data (Primary Evidence of Natural Attenuation)

A detailed discussion of the material in this section is presented in CSM Appendix B.4. Groundwater monitoring data from the Facility over the monitoring period of 2005 to April 2018 were used to evaluate plume duration and plume attenuation. Plume duration was assessed by evaluating trends in COPC concentrations over time (increasing, stable, or decreasing). Plume attenuation was assessed based on changes in COPC concentrations between different monitoring locations (RHMW02 to RHMW01, and RHMW02 to Red Hill Shaft). Key findings are summarized below.

- **Plume Duration:** COPC concentrations at individual monitoring locations varied over time, exhibiting both increases and decreases in concentration. At RHMW02, the monitoring location with the highest COPC concentrations, most of the COPCs showed little or no long-term concentration trend due to high data variability over the monitoring period. For example, naphthalene concentrations at RHMW02 varied considerably over the monitoring period, resulting in no clear trend over time (Figure 6-4). The observed variability in COPC concentration reflects potential analytical issues as well as the complexity of the LNAPL source (i.e., complex mixture of individual compounds, each with different solubilities and biodegradation potential) and the changing composition of the LNAPL source over time. As a result of the changing LNAPL composition during weathering, stable or increasing dissolved concentrations of less-soluble COPCs such as naphthalene may, in fact, reflect significant depletion of the LNAPL source material. This phenomenon has been observed at other sites such as the USGS Bemidji, MN research site (Baedecker et al. 2011).



k	9.35E-05	d^{-1}
k	0.034	yr^{-1}
$t_{1/2}$	--	yrs
n	63	
R^2	0.0085	
p	0.47	

Figure 6-4: Linear and Natural Log Scale Plots of Naphthalene Concentrations from September 2005 to April 2018 at Monitoring Well RHMW02

- **Plume Attenuation:** COPC concentrations decrease from RHMW02 to downgradient monitoring locations RHMW01 and Red Hill Shaft. Attenuation half-lives ranged from 5 to 14 days (from RHMW02 to RHMW01) while half-lives ranged from 7 to 92 days (from RHMW02 to Red Hill Shaft). Taken together, analysis of RHMW02 to RHMW01 and of RHMW02 to Red Hill Shaft represents the probable range of plume attenuation rates for COPCs in groundwater at the Facility and supports the conclusion that biodegradation is contributing to the natural attenuation of COPCs within groundwater.

6.2.3 Microcosm Studies and Microbial Parameter Analysis

To further evaluate natural attenuation of COPCs in groundwater, a microcosm study is being completed to provide an estimate of the bulk attenuation rate due to biodegradation under aerobic and anaerobic conditions using groundwater from two wells (RHMW01 and RHMW02). In addition, a series of molecular methods for assessing microbial parameters, including QuantArray-Petro and Next Generation Sequencing (NGS), were employed to quantify particular biomarkers of petroleum hydrocarbon degradation in groundwater from four wells (RHMW01, RHMW02, RHMW03, and RHMW04). A full description of these studies is provided in CSM Appendix B.6.

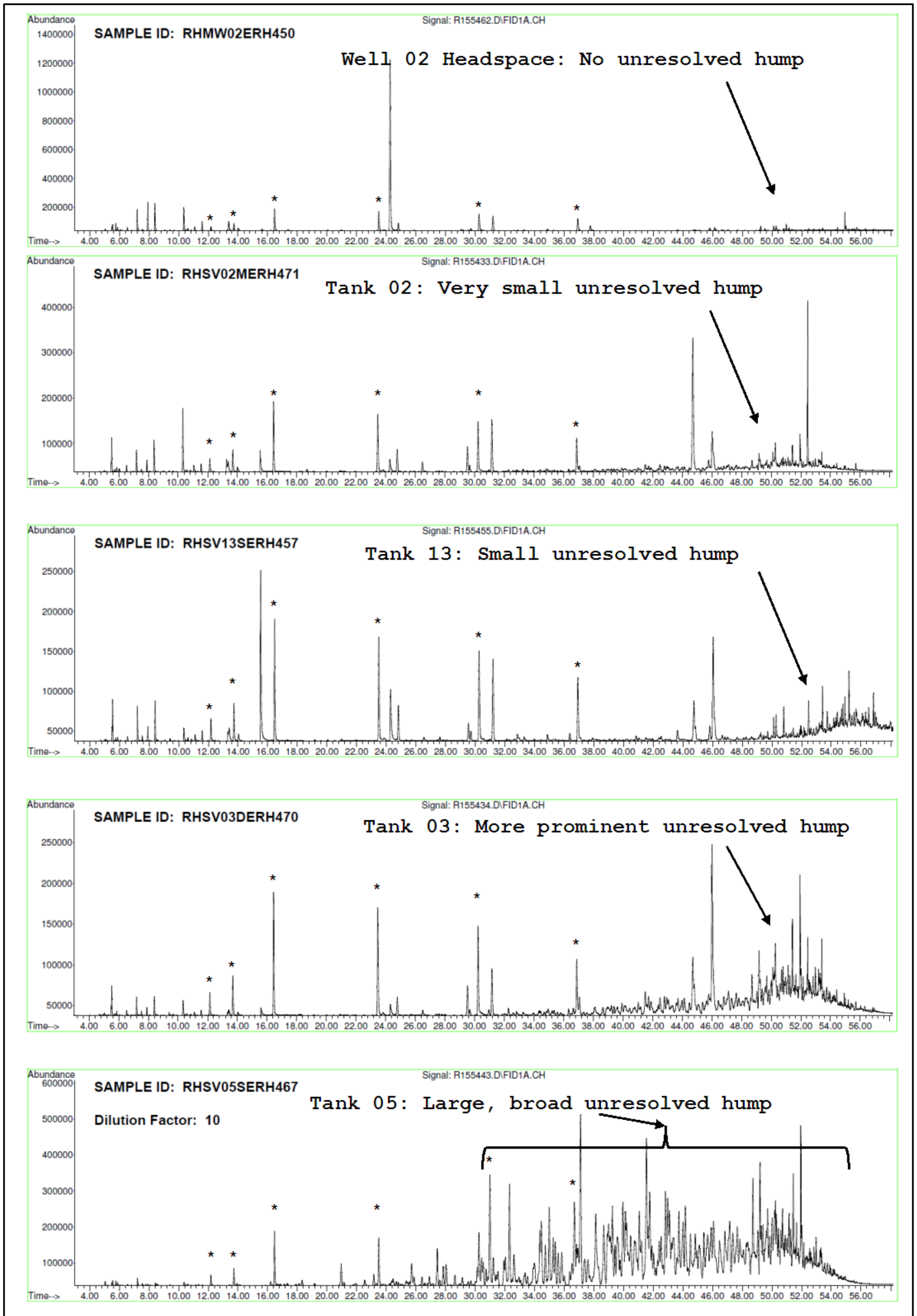
Key findings are summarized below:

- In microcosms maintained under aerobic conditions, rapid degradation of all constituents was observed in RHMW02 (half-life < 7 days for all constituents, including benzene, toluene, xylenes, and polynuclear aromatic hydrocarbons [PAHs]) and RHMW01 (half-lives currently on the order of 8–25 days). Based on the early microcosm results, degradation of these petroleum hydrocarbons is non-conclusive under anaerobic conditions, with little changes in concentration over the first 5 months of testing. Extended ongoing monitoring is being employed for the anaerobic microcosm studies to account for the apparent slower degradation under these conditions and potential extended acclimation times associated with anaerobic biodegradation.

- A suite of different functional genes associated with both aerobic and anaerobic petroleum hydrocarbon degradation were detected in samples from all four well locations. The presence of functional genes for degradation of petroleum hydrocarbons confirms that aerobic and anaerobic microorganisms are both present and active (i.e., the genes would not be expressed if the microorganisms were not active).
- The microbial data are largely consistent with concentration trends and geochemical conditions at the Facility, including evidence that concentrations attenuate significantly in groundwater moving downgradient. The molecular data suggest that a combination of anaerobic and aerobic processes is responsible for this attenuation, although the potential for rapid aerobic degradation (as observed in the microcosms) is restricted somewhat by the low availability of oxygen near wells RHMW02 and RHMW01. Aerobic biodegradation should be a significant factor in wells with dissolved oxygen (DO) higher than 2 parts per million (ppm).

6.3 Evidence of LNAPL Weathering

Natural attenuation is further supported by evidence that the LNAPL present in the subsurface has undergone physical weathering (i.e., volatilization of light-end constituents) and biological weathering. This is reflected in soil vapor samples collected from below the tanks (Figure 6-5; CSM Appendix B.3). In addition, dissolved constituents from groundwater samples collected from RHMW02 (CSM Appendix B.7) also indicate extensive LNAPL weathering. The chromatograms for the soil vapor samples do not exhibit the typical sequence of n-alkanes characteristic of unweathered fuel but, instead, are dominated by an unresolved "hump" (a UCM) visible at the end of the chromatogram characteristic of biological weathering (Figure 6-5). Although all soil vapor samples exhibit the characteristics of physical and biological weathering, the chromatogram from the Tank 5 sample shows the broadest unresolved hump consistent with a more recent fuel release. For the samples from the other tanks, the hump starts later (i.e., further right on the chromatogram) consistent with more extensive weathering expected for older releases. Analysis of two LNAPL samples collected during the angle boring installations indicate the presence of biodegraded jet fuel below Tank 6 at 0.5 ft and biodegraded diesel below Tank 11 at 20.3 ft (DON 2002) (see also CSM Appendix B.7 Section 3.2.2, Figure 3-11).



Note: Asterisk (*) = Internal Standard

Figure 6-5: FID Chromatograms from Representative Soil Vapor Samples Showing Range of Unresolved Hump

The laboratory analysis and TPH chromatographic profiles or fingerprints for groundwater samples collected from RHMW02 show the following evidence of physical and biological weathering:

- An absence of more soluble and readily degradable components of jet fuel such as BTEX constituents. Studies of petroleum LNAPL biodegradation and weathering at other sites indicated that these constituents become depleted from LNAPL as a result of biological weathering (Baedecker et al. 2011).
- Higher concentrations of compounds that are relatively resistant to biodegradation are typically found in low concentrations in unweathered fuel, but become relatively enriched in the weathered fuels as the more degradable compounds are consumed. These compounds include naphthalene, 1-methylnaphthalene and 2-methylnaphthalene as well as some of the compounds detected as tentatively identified compounds (TICs) such as naphtheno-benzenes. The detection of these TICs in RHMW02 indicates that the dissolved-phase plume is originating from weathered fuel.
- Chromatographic profiles consistent with soluble components of jet fuel. The presence of naphthalene, C1-naphthalenes, as well as C2+naphthalenes is evident. The available chromatograms from RHMW02 groundwater samples are all consistent with chromatograms for biodegraded kerosene-type fuels (e.g., JP-5 and JP-8 are kerosenes with special additives). There is also evidence of C4-benzenes. Lighter components are partially lost in the extraction and concentration of the extract prior to analysis; thus, lighter substituted benzenes, if present, would not be detected in the TPH-d analysis.
- Presence of a "hump" in the chromatograms that extends beyond the end of the jet/kerosene carbon range (C16+) (see CSM Appendix B.7 Figure 3-11 and associated discussion). Unweathered petroleum fuels are composed primarily of hydrocarbons (nonpolar) that have distinctive chromatographic profiles seen as evenly distributed peaks spanning the carbon range of the fuel. The presence of a hump with unevenly distributed peaks beyond the fuel carbon range is likely due to polar matter that could be metabolites from biodegradation. Silica gel treatment (used to remove polar material) of the groundwater extract used for measuring TPH-d removes between 40% and 85% of the RHMW02 dissolved TPH-d concentration, indicating that a significant amount of polar compounds is present in the groundwater. The dissolved organics in RHMW02 are a mixture of hydrocarbons and polar metabolites, indicating ongoing biodegradation.

6.4 CONCLUSIONS

The available site investigation and monitoring results support the following conclusions regarding the occurrence of NSZD and natural attenuation:

- Evidence of NSZD includes (1) decreasing soil vapor concentrations over time below the Facility fuel tanks, (2) laboratory analysis indicating that the vadose zone LNAPL is highly weathered, (3) high oxygen concentrations in the vadose zone indicative of aerobic conditions, and (4) measurement of excess temperature and carbon dioxide associated with biodegradation of petroleum constituents.
- The rate of carbon dioxide emission and heat generation from the vadose zone indicates that between 2,600 and 17,300 gallons of hydrocarbon are being biodegraded per year by NSZD from the entire Facility.
- Evidence of natural attenuation within the groundwater includes reduced concentrations of electron acceptors (i.e., dissolved oxygen, nitrate, sulfate) and increased concentrations of

metabolic byproducts (i.e., ferrous iron, methane, TOC) in the area of highest dissolved COPC concentrations (i.e., RHMW02 and RHMW01). In addition, microcosm studies documented the rapid aerobic biodegradation of all COPCs evaluated.

- COPC concentrations decrease from RHMW02 to downgradient monitoring locations RHMW01 and Red Hill Shaft. Attenuation half-lives ranged from 5 to 14 days from RHMW02 to RHMW01, while half-lives ranged from 7 to 92 days from RHMW02 to Red Hill Shaft.
- The LNAPL present at the Facility as undergone significant physical and biological weathering consistent with natural attenuation of these historical releases.

7. Risk-Based Decision Criteria

7.1 DEFINITION AND PURPOSE OF RBDC AND SSRBLS

The main concern for human health risk for the Facility and surrounding area is the potential impact of an inadvertent fuel release to groundwater that is the source of drinking water at Navy Supply Well 2254-01 (and other water supply wells as appropriate). Therefore, conservative RBDC were developed to ensure that drinking water at this supply well is protected from potential releases at the Facility.

RBDC are risk-based screening values for drinking/domestic use water that are protective of human health, safety, and the environment, specifically considering exposure of human receptors to chemicals of potential concern (COPCs) in the public water supply through ingestion of tap water, dermal contact, and inhalation of volatile chemicals while bathing/showering. RBDC are intended to be protective of the most sensitive human receptor population, which is child residents using tap water originating from groundwater at Navy Supply Well 2254-01 (Red Hill Shaft), which supplies potable water to JBPHH. RBDC are also intended to protect people using water from other drinking water supply systems within the study area.

RBDC have been developed as detailed in the *RBDC Development Plan* (DON 2017a) to support the investigation and remediation of releases at the Red Hill Bulk Fuel Storage Facility ("the Facility") at Joint Base Pearl Harbor-Hickam (JBPHH), Hawai'i. The RBDC are intended to update the Red Hill GWPP (DON 2014), ensuring that drinking water receptors are protected. The RBDC are also used in the development of Site-Specific Risk-Based Levels (SSRBLs) for the sentinel monitoring well network, as described in the *Sentinel Well Network Development Plan* (DON 2017b).

The purpose of the SSRBLs is to use the LTM system of identified sentinel monitoring wells (to be determined at a future date) to identify the magnitude of any releases in areas downgradient of the Facility and determine the potential for COPCs in groundwater migrating to the public water supply to exceed RBDC and pose a potential risk to human health. SSRBLs are target groundwater concentrations for individual sentinel monitoring wells, and back-calculated from the RBDC using mass flux analyses. An appropriate contingency plan (e.g., Updated GWPP) will be developed to address SSRBL exceedances and will describe what additional contingency action (e.g., further evaluation, more frequent monitoring, treatment) needs to be taken, so that the RBDC will not be exceeded at the tap. If the concentration of a COPC in groundwater at a given monitoring well location does not exceed the SSRBL, then the concentration of that COPC should not exceed the RBDC at the tap.

SSRBLs will be established for each sentinel monitoring well by back-calculating a concentration from the RBDC through a mass flux-based approach. The RBDC will be applied to the tap water source, and the back-calculation will factor in mass flux to establish the SSRBL concentration for each sentinel monitoring well. The SSRBL will be used as an indicator that the RBDC may be exceeded at the tap water source if the SSRBL is exceeded.

7.2 RBDC BASIS

Because the RBDC are intended to protect people who are likely to have the greatest exposure to groundwater, the RBDC for most COPCs will be the lower of the EPA (2018) Regional Screening Levels (RSLs) or the DOH (2017) Environmental Action Levels (EALs) for drinking water. The RBDC are based on various endpoints, and the EPA RSLs are based on cancer (target cancer risk of 1E-06) or non-cancer health effects (target non-cancer hazard quotient of 0.1).

The RBDC will be used to evaluate total (unfiltered) groundwater data as a conservative approach. This is consistent with DOH guidance for evaluation of groundwater for potable water uses (DOH [(2017)] Volume 2, Page 5-1).

RBDC have been developed for the COPCs presented in the AOC Statement of Work Sections 6 and 7 scoping completion letter dated February 4, 2016 (EPA Region 9 and DOH 2016), as shown in the shaded cells of Table 7-1.

Additional COPCs may be added to the current list, based on changes in fuels stored at the Facility in the future, other possible chemical sources identified at the Facility, or future data that will reflect ongoing advancements in the analysis and evaluation of TPH-related chemicals. For all COPCs, separate comparisons will be performed using health-based criteria as well as taste- and odor-based EALs.

Table 7-1: EPA Regional Screening Levels and DOH Environmental Action Levels for COPCs

	EPA (2018) RSL		DOH (2017) EALs						
	THQ=0.1		Table F-1a (Drinking Water)					Table F-3b (Risk-Based Screening Levels for Tapwater)	
COPC	Tap Water (µg/L)	Basis	Groundwater EAL (µg/L)	Basis	DW Toxicity	Basis	Gross Contamination	Risk-Based	Basis
Benzene	0.46	c	5	DW toxicity	5	Primary MCL	170	0.48	carcinogenic
Ethylbenzene	1.5	c	7.3	Aquatic Habitat Goal	700	Primary MCL	30	1.7	carcinogenic
Toluene	110	n	9.8	Aquatic Habitat Goal	1000	Primary MCL	40	1400	noncancer
Xylenes	19	n	13	Aquatic Habitat Goal	10,000	Primary MCL	20	210	noncancer
Methylnaphthalene, 1-	1.1	c	2.1	Aquatic Habitat Goal	27	carcinogenic	10	27	carcinogenic
Methylnaphthalene, 2-	3.6	n	4.7	Aquatic Habitat Goal	24	noncancer	10	24	noncancer
Naphthalene	0.17	c	12	Aquatic Habitat Goal	17	CDPH notification level	21	0.17	carcinogenic
TPH-g (gasolines)	—	—	300	DW toxicity	300	noncancer	500	300	noncancer
TPH-d (middle distillates)	—	—	400	DW toxicity	400	noncancer	500	400	noncancer
TPH-o (residual fuels)	—	—	500	Gross Contamination	2,400	noncancer	500	2,400	noncancer
2-[2-methoxyethoxy]-ethanol	80	n	—	—	—	—	—	—	—
Phenol	580	n	5	Gross Contamination	6,000	noncancer	5	6,000	noncancer

Shaded cell lowest relevant screening value
— not established
c cancer
CDPH California Department of Public Health
DW drinking water
MCL Maximum Contaminant Level
n non-cancer

7.3 USE OF RBDC AND SSRBLS

The RBDC and SSRBLs are action levels to determine if additional contingency action is needed to protect the drinking water supply. Because of the conservative nature of the RBDC and SSRBLs, an exceedance of the SSRBLs will not necessarily suggest an unacceptable risk or hazard exists at the tap water source. In addition to monitoring sentinel wells, water from sampling point RHMW2254-01 adjacent to Navy Supply Well 2254-01 (Red Hill Shaft) will also be monitored to ensure that RBDC at the supply well are met. RBDC associated with COPCs may be evaluated further as new information related to toxicity and risk assessment for these COPCs becomes available.

The need to address exceedances of SSRBLs at the sentinel wells will be a two-step process, i.e., it will not be based solely on the comparison of site concentrations with SSRBLs. If the concentration of a COPC in groundwater at a given monitoring well location does not exceed the SSRBL, it is likely that as groundwater migrates from that well to Navy Supply Well 2254-01, the concentration of that COPC will not exceed the RBDC. These screening values will be used as follows:

- If the detected concentration of a COPC exceeds the back-calculated SSRBL at a monitoring well location, this will indicate that the concentration in drinking water could exceed RBDC that are protective of residential tap water use, in which case Red Hill Shaft discharge water will be monitored to ensure that concentrations do not exceed an appropriate risk-based level (as described below). However, the need to address exceedances of SSRBLs at the monitoring well locations will be a two-step process, i.e., it will not be based solely on the comparison of site concentrations with SSRBLs.
- If there are no exceedances of the SSRBLs, then cancer risks and non-cancer hazards associated with COPC exposure will be considered unlikely and cumulative risk/hazard calculations will not be needed.
- If there are exceedances of the SSRBLs, then cumulative risks and hazards will be calculated to determine if the exceedances suggest actual potential risk. If cumulative cancer risk estimates are greater than 1×10^{-6} or cumulative non-cancer hazard indexes are greater than 1, then the need for additional contingency action (e.g., further evaluation, more frequent monitoring, treatment) will be determined to address the exceedance.

8. Mass Flux and Sentry Well Considerations

Sentry wells will be used as an early warning system in conjunction with other release detection methods to help ensure that water supply wells are not adversely impacted from a release. These wells will consist of a combination of specifically identified existing monitoring wells along with additional monitoring wells that will be installed as deemed appropriate for this purpose. These wells will be located in areas that are most likely to be in the flow path from the tank farm to Red Hill Shaft (and other water supply wells as appropriate). RBDC will be used as part of a mass flux approach. Through this approach, SSRBLs will be determined for each sentry well to ensure that drinking water is protected at the tap. The SSRBL will account for mass flux and COPC concentration at the well. The SSRBL will be used as an indicator (early warning system) in determining if contingency action (e.g., further evaluation, more frequent monitoring, treatment) is needed to prevent COPC concentrations at the drinking water tap from exceeding the RBDC if the SSRBL is exceeded. Establishing SSRBLs through this approach is consistent with ASTM (2015) Risk-Based Corrective Action guidance. The approach is currently more conceptual in nature (due to current uncertainties) and will be solidified as the final groundwater model is developed.

8.1 Mass Flux and Trigger Levels

Sentinel monitoring wells will have established SSRBLs based on an integration of the RBDC described in the *RBDC Development Plan* (DON 2017a) combined with a back-calculation of concentrations at the exposure point (tap water) that can be determined based on mass flux and plume concentration, as noted in the following:

Mass Flux/Mass Discharge

$$C_{rhsw} = (M_d/Q_{rhs})Cf$$

Where:

C_{rhsw}	=	concentration of contaminant "x" in Water Supply Well (parts per billion)
M_d	=	mass discharge (grams per day)
Q_{rhs}	=	flow rate (gallons per minute [gpm]) of water supply well necessary to achieve capture
CF	=	conversion factor (184 micrograms-gallon-day [μg-gal-day]/grams-liter-min [g-L-min])

In the equation above, mass discharge considerations (aquifer cross section with contaminant flow near each sentry well) will be established so that appropriate SSRBLs concentrations can be determined. This evaluation will be based on concentration of a COPC in a well (SSRBL) that results in a mass flux that does not exceed the RBDC (C in the equation) for a well with a pumping rate (Q) that establishes an appropriate capture zone.

8.2 RBDC and SSRBL Integration

As described in the *Sentinel Well Network Development Plan* (DON 2017b), sentinel monitoring wells will be used to:

- Ensure that a sufficient capture zone is created if needed to contain a release by pumping Navy Supply Well 2254-01 to contain COPCs.
- Determine if COPC concentrations (SSRBLs) at the sentinel monitoring wells indicate that additional contingency action is needed to ensure that drinking water remains safe for residential use.

The RBDC and SSRBLs will be identified as action levels that will be presented in the forthcoming Red Hill GWPP Update to determine if additional contingency action is needed to protect the drinking water supply.

Because of the conservative nature of the RBDC and SSRBLs, an exceedance of the SSRBLs will not necessarily suggest an unacceptable risk or hazard exists at the tap water source. Water from sampling point RHMW2254-01 adjacent to Navy Supply Well 2254-01 will also be monitored as part of a contingency plan to ensure that RBDC at the supply well are met. The need to address exceedances of SSRBLs at the monitoring wells will be a two-step process, i.e., it will not be based solely on the comparison of site concentrations with SSRBLs.

8.3 Sentry Well Considerations

The overall objective of the Sentinel Well Network Program is to establish a network of monitoring wells that provides an early trigger level-based warning system of potential impacts from the Facility to protect drinking water and other receptors. Specifically, the sentinel monitoring well network will be used to accomplish two primary objectives:

- Demonstrate that a capture zone is maintained that will contain COPCs, if needed.
- Evaluate COPC concentrations upgradient from drinking water production wells to determine the need for additional contingency action (e.g., further evaluation, more frequent monitoring, treatment) to protect the water supply.

8.3.1 Sentinel Well Identification, Evaluation, and Selection

The *Sentinel Well Network Development Plan* (DON 2017b) outlines a process to identify, evaluate, and select sentinel monitoring wells. Two primary functions of the sentinel monitoring well network are needed to meet the overall objectives; (1) hydraulic head/groundwater flow gradients to provide confirmation that the capture zone developed during the capture zone analysis is effective, and (2) effective monitoring of SSRBL concentrations for the selected COPCs. The sentinel monitoring wells SSRBLs will be based on an integration of the RBDC combined with a back-calculation of concentrations at the exposure point (tap water) that can be determined based on mass flux and plume concentration as described in Section 8.1.

The sentinel well selection process will initially consider (1) all existing monitoring wells within Red Hill monitoring network, (2) future proposed and newly constructed monitoring wells for the Red Hill monitoring network, and (3) other wells outside of the current and future monitoring network that may have relevance to the objectives of the sentinel well network. The *Sentinel Well Network Development Plan* (DON 2017b) details screening criteria, ranking, and selection of sentinel wells. Following the selection, an analysis to identify limitations and additional monitoring locations will be conducted if needed.

8.3.2 Establishment of Sentinel Well Network Program

The establishment of the Sentinel Well Network Program will follow the decision matrix outlined in the AOC Statement of Work, where a *Groundwater Monitoring Well Network Report* will be prepared 12 months after Regulatory approval of the *Groundwater Flow Model Report*. The documents will present the recommendations and conclusions of the sentinel monitoring well evaluation and selection process described above. The report will also present the proposed Sentinel Well Network Program.

The program will also include the following elements:

- Regulatory framework under U.S. EPA, Resource Conservation and Recovery Act (RCRA), and DOH programs
- COPCs (as previously agreed upon by AOC parties and developed under the *RBDC Development Plan*)
- Locations and frequency of sampling (based on integration with the leak detection system)
- Integration of SSRBLs based on mass flux and RBDC
- Contingency plans for exceedances and releases
- Optimization and modification of the Sentinel Well Network Program

The *Groundwater Well Network Report* will provide a basis for a Decision Meeting prescribed under the AOC Statement of Work that is to be held 60 days after the *Groundwater Monitoring Well*

Network Report is approved. Sixty (60) days following the Decision Meeting, a *Groundwater Monitoring Well Decision Document* will be prepared to provide final documentation of the decision process. Based on the *Groundwater Monitoring Well Decision Document,* the Red Hill GWPP (DON 2014) will be updated.

9. Hypothetical Future Release Scenarios

To better understand hypothetical risks, a quantitative calculation of the ability for Red Hill to hold fuel (LNAPL) in the case of a hypothetical fuel tank release from the Facility has been conducted. Two separate holding capacity calculations were performed:

- The LNAPL holding capacity for a hypothetical large, sudden release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. The calculations and results of this analysis are described in Appendix B.
- The LNAPL holding capacity for a hypothetical small chronic release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. This calculation is dependent on the NSZD rate at the Facility and is described in Appendix C.

9.1 HYPOTHETICAL LARGE SUDDEN RELEASE

Historical results from the LTM and other Facility investigations (as well as the CSM) have been used to evaluate the fate of prior releases from the Facility tanks including the 2014 release of approximately 27,000 gallons of JP-8 from Tank 5. These data in turn, have been used to estimate the possible impact of a hypothetical future sudden release from a tank. Specifically, a hypothetical future sudden release volume has been estimated that would be protective of Red Hill Shaft and other water supply wells (i.e., no exceedances of RBDC from well discharge). The likely fate and transport of a future sudden release was evaluated based on two interpretations of the 2014 Tank 5 release:

- *Evaluation 1, Vadose Zone Retention Capacity:* Available monitoring data indicate that the 2014 release of approximately 27,000 gallons of JP-8 from Tank 5 was likely retained within the top one-third of the vadose zone between the lower tunnel and the water table with no significant impact to groundwater. Based on this finding, the 2014 release was used to estimate the vadose zone holding capacity for LNAPL along with site-specific geologic data and data from the scientific literature. This holding capacity was then used to evaluate the LNAPL volume that would be retained mostly or exclusively in the vadose zone for a hypothetical future release resulting in no significant impact to groundwater. A Monte Carlo model was used to obtain a range of release volumes accounting for uncertainty in vadose zone holding capacity and other site parameters.
- *Evaluation 2, Possible Impact to Groundwater:* Based on feedback from DOH, the fate and transport of a hypothetical future release was evaluated based on a second interpretation of the 2014 release. For this interpretation, a conservative approach was taken where the 2014 release was assumed to have impacted groundwater at the Facility and variations in dissolved COPC concentrations following the release were attributed to this release even though forensic analysis of the data does not indicate this is the case. The likely impact of a hypothetical future release was evaluated assuming a linear relationship between release volume and magnitude of impact to Red Hill Shaft.

Under either evaluation of the 2014 Tank 5 release, the 27,000-gallon release of jet fuel:

- Did not result in the observation of LNAPL in any of the monitoring wells and the Facility.
- Did not result in any measurable increase in COPC concentrations in Red Hill Shaft.

These observations indicate that a hypothetical future sudden release from a Facility fuel tank would have to be larger than the 2014 release in order to result in an exceedance of RBDC in Red Hill Shaft and other water supply wells. The two evaluations focused on understanding and quantifying this "margin of safety" associated with the 2014 release in order to estimate the volume of a hypothetical future sudden release that would not result in an exceedance of the RBDC at Red Hill Shaft (Table 9-1).

Table 9-1: Volume of a Hypothetical Future Sudden Release that Would be Protective of Red Hill Shaft

Estimate Type	Evaluation 1 (gallons)	Evaluation 2 (gallons)
More-Conservative and Protective Low-End Volume	48,000	27,000
Conservative and Protective Mid-Range Volume	**150,000**	**88,000**
Less-Conservative High-End Volume	400,000	920,000

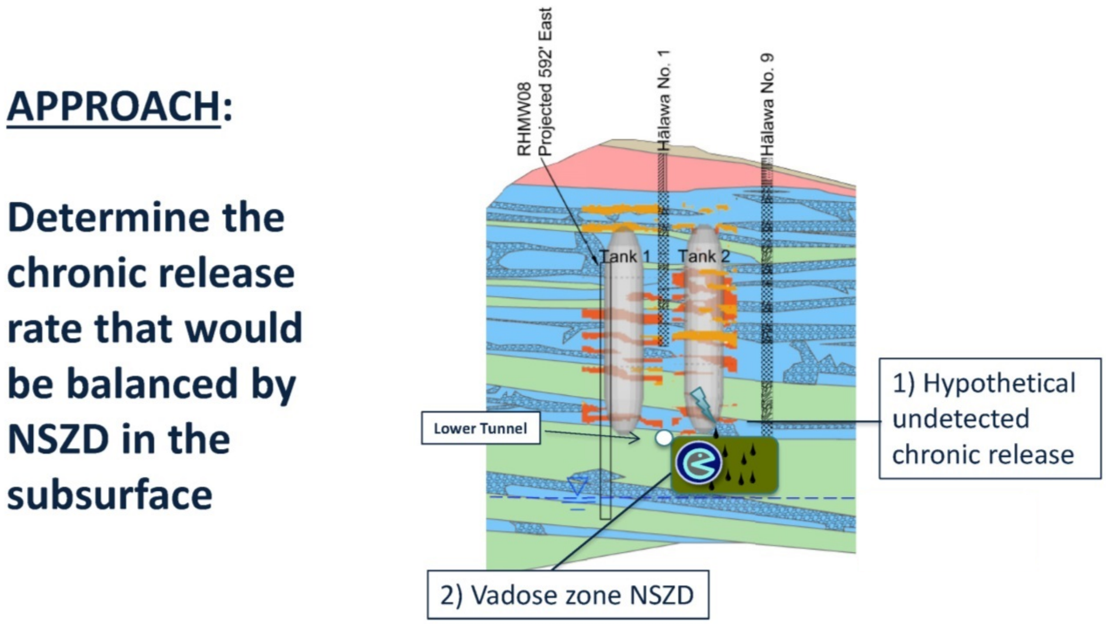
- The more-conservative volume estimate is based on a combination of conservative assumptions that serve to significantly overestimate the potential for a hypothetical future release to cause an unacceptable impact; therefore, this volume should be considered protective for all tanks with a very high degree of confidence.
- The reasonably conservative mid-range estimate is based on a mix of conservative and realistic assumptions that serve to provide a reasonably conservative overestimation of the potential for a hypothetical future release to cause an unacceptable impact; therefore, this volume should be considered protective for all tanks with a high degree of confidence.
- The less-conservative estimate utilizes realistic assumptions and accounts for uncertainly in input parameters using a less conservative approach. Due to the layout of the Facility, the less-conservative volume is likely to be protective for a hypothetical release from a tank located farther away from Red Hill Shaft (e.g., Tanks 11 to 20).

The following is recommended to account for prior release:

- *Tanks with Strong Evidence of Prior Releases* (Tanks 5, 9, 11, 13, 14, and 16): Reduce the hypothetical future release volume by 25%.
- *Tanks with Weaker Evidence of Prior Releases* (Tanks 2, 3, 4, 5, 6, 7, 8, 12, 18, and 20): Reduce the hypothetical future release volume by 10%.

9.2 HYPOTHETICAL SMALL CHRONIC RELEASE

Site monitoring data indicate that historical LNAPL releases at the Facility are being biodegraded in the vadose zone. The observed NSZD rate for these prior releases has been used to estimate the rate at which a hypothetical future release would be degraded. The hypothetical small chronic release rate was determined as the release rate that is off-set by biodegradation so that, at steady-state, the amount of LNAPL being released every day would be equal to the amount of LNAPL being degraded in the vadose zone such that the overall extent of impact would not increase over time (Figure 9-1).



Cross section sources: Hālawa No. 1, 9: (Macdonald 1941); red and orange around tanks represent clinker identified in As-Built Barrel Logs (DON 1943)

measured groundwater elevation

Figure 9-1: Conceptual Approach for Determination of the Hypothetical Chronic Release Rate

The hypothetical small chronic release rate was estimated based on the following observations and assumptions:

- Ongoing NSZD within the vadose zone has been documented and quantified using two measurements: heat flux (CSM Appendix B.1) and carbon dioxide flux (CSM Appendix B.2). Expressed in volumetric terms, the observed NSZD rate is up to 9.8×10^{-4} gallons per ft^3 per year (Appendix B).
- Based on the inferred LNAPL impact area within the vadose zone following the 2014 Tank 5 release, a hypothetical small chronic release for an individual tank would invade 2.3 million ft^3 of basalt within the vadose zone before migrating to the water table (i.e., based on an impact volume of 150 ft × 150 ft × 103 ft; Appendix C).

Based on this NSZD rate and vadose zone volume, a hypothetical chronic release of 2,300 gallons of LNAPL per tank per year (i.e., 9.8×10^{-4} gallons per ft^3 per year * 2.3×10^6 ft^3, or about 6.3 gallons of LNAPL per tank per day) would be balanced by biodegradation within the vadose zone preventing an impact to groundwater. Because biodegradation is an ongoing process, such release could continue over a time scale of tens to hundreds of years without impact.

LTM data confirm additional biodegradation of dissolved constituents within the saturated zone to be on-going at the Facility based on the loss of mass between monitoring wells RHMW02 and RHMW01 and/or Red Hill Shaft (CSM Appendix B.4), geochemical indicators (CSM Appendix B.5), and microcosm data (CSM Appendix B.6). Although not quantified, if a hypothetical chronic release were to impact the water table, this additional biodegradation within the saturated zone would also serve to prevent impacts to Red Hill Shaft and other groundwater receptors.

9.3 Conclusions

Two separate holding capacity calculations were performed:

- The LNAPL holding capacity for a hypothetical large, sudden release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. The calculations and results of this analysis are described in Appendix B.
- The LNAPL holding capacity for a hypothetical small chronic release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. This calculation is dependent on the NSZD rate at the Facility and is described in Appendix C.

The resulting reasonable conservative volume estimates that would be protective with a high confidence are:

- A hypothetical sudden future release of approximately 120,000 gallons of LNAPL would have, at most, a minimal impact to groundwater and would not cause an RBDC exceedance in Red Hill Shaft.
- An indefinite hypothetical chronic release of 2,300 gallons per tank per year (6.3 gallons per tank per day) would be degraded within the vadose zone, resulting in, at most, a minimal impact to groundwater and would not cause an RBDC exceedance in Red Hill Shaft.

10. Summary and Conclusions

All available data to date have been integrated into the current CSM, and the evaluation of data and determination of conclusions are reasonably conservative. The conservatism is based on highly probable outcomes and/or conclusions as identified by current data. The following subsections describe the key points from various sections of this document.

10.1 LNAPL Distribution and Properties

- LNAPL has been observed in the vadose zone below some of the fuel tanks (i.e., in angle borings completed in 1998–2002). Thermal monitoring data show that when LNAPL is indicated in the vadose zone, it is located primarily within the upper one-third of the vadose zone between the lower tunnel and the water table (i.e., within the depth interval of 70–110 ft msl).
- No LNAPL has been measured on any of the Red Hill monitoring wells. Weathered LNAPL from a release prior to 2005 may be present in the immediate vicinity of RHMW02 or within the saturated zone upgradient from this well.
- The mixture of dissolved constituents in groundwater and the mixture of constituents in soil vapor samples are consistent with weathered/biodegraded fuel.
- A 27,000-gallon release of jet fuel from Tank 5 in January 2014 did not appear to impact any of the Facility's monitoring wells or Red Hill Shaft located approximately 1,500 ft downgradient.

10.2 DISSOLVED FUEL CONSTITUENTS IN GROUNDWATER AND ANALYTICAL CONSIDERATIONS

- Dissolved components in groundwater are consistent with soluble (aromatic hydrocarbons) components and polar material (likely metabolites) from fuels consistent with biodegraded jet fuel.
- Available data suggest the presence of weathered LNAPL (i.e., pre-2005) in the immediate vicinity of RHMW02 or within the saturated zone upgradient from this well. Multiple lines of evidence indicate that strictly biodegraded/weathered material (likely not associated with the 2014 release) is present in groundwater and COPC concentrations have generally remained within recent historical ranges.
- Analytical results of dissolved TPH-d alone are not suitable as a diagnostic tool to assess presence of LNAPL in groundwater. Biodegradation products of soluble fuel components are polar and are generally more water soluble than the aliphatic parent compounds. Furthermore, changes in TPH-d concentrations should be carefully evaluated as they can be due to changes in laboratory (methods and laboratory to laboratory) and to inherent limitations of TPH measurement. When TPH-d concentrations change from one monitoring event to the next, the significance of the change should be evaluated in the context of changes in the characteristics of the chromatography and changes in the mixture of individual dissolved constituents.

10.3 INTERIM GROUNDWATER FLOW MODEL

- As described in Section 5.3, dozens of groundwater models, utilizing various conceptualizations and stresses (e.g., boundary fluxes, material properties, heterogeneity considerations, geometries) have been developed and none of these models (with one exception) show groundwater flow from Red Hill to any of the BWS wells, even with extreme pumping conditions. The exception represents a drought condition under which Red Hill Shaft is not pumping and Hālawa Shaft pumps continuously at 16 mgd for several years (steady state conditions). For this case, it took a minimum of 3 years of continuous drought and extreme pumping conditions for groundwater to migrate to Hālawa Shaft from beneath the Facility. While this scenario has been evaluated in an effort to be very conservative, the likelihood of this scenario occurring is negligible.
- When operating under normal pumping conditions ([redacted] mgd), Red Hill Shaft captures all groundwater flow from beneath the tanks underlying Red Hill even when Hālawa Shaft is pumping at 16 mgd and Moanalua Valley wells are pumping at 3.7 mgd.
- All models indicate that groundwater flow from beneath the Facility is toward Red Hill Shaft even when Red Hill Shaft is not pumping.
- A conservative model (shortest travel time) with clinker indicates that flow from RHMW02 to Red Hill Shaft is on the order of 45 days. Slower travel times are over 90 days. The more conservative of these values were implemented into evaluations of mass flux and natural attenuation.

10.4 NATURAL ATTENUATION

- Excess carbon dioxide (measured by carbon traps) and heat are being generated at the Facility, confirming that NSZD of LNAPL is active in the vadose zone. For the entire tank farm, the NSZD rate is likely between 2,600 and 17,300 gallons per year.

- Soil vapor monitoring and fingerprinting analysis show that rapid weathering of petroleum is occurring in the vadose zone.
- Both the MNA Primary Lines of Evidence (concentration reduction in the plume) and Secondary Lines of Evidence (geochemical analyses and microcosm studies) confirm that aerobic and anaerobic biodegradation of dissolved petroleum hydrocarbons is occurring in groundwater. Based on available data, the plume attenuation half-lives for dissolved constituents are likely on the order of 10–100 days.

10.5 Risk-Based Decision Criteria

- Contaminants of potential concern were previously agreed upon by the AOC Parties and include benzene, ethylbenzene, toluene, total xylenes, naphthalene, 1-methylnaphthalene, 2-methylnaphthalene, TPH-g, TPH-d, TPH-o, 2-(2-methoxyethoxy)-ethanol, and phenol.
- RBDC have been developed for these COPCs as conservative, initial screening criteria that are protective of drinking and domestic water use.

10.6 Mass Flux and Sentry Well Considerations

- Mass flux considerations are widely used in evaluating potential impacts to pumping wells from chemical concentrations in aquifers (monitoring wells).
- A mass flux approach is being utilized to evaluate potential impacts from COPCs in groundwater to Red Hill Shaft. This approach will also be utilized in establishing sentry well trigger levels as part of the release response plan. Utilization of mass flux of COPCs from upgradient sources, Red Hill Shaft pumping rates, and RBDC help to ensure that drinking water at Red Hill Shaft (and other wells) is adequately protected.
- Sentry well locations will be further evaluated after the current synoptic water level information is evaluated along with the final contaminant fate and transport model. Consideration will be given to transient fluctuations related to potential gradient changes due to changes such as pumping or recharge.

10.7 Release Scenarios

- The current understanding of LNAPL distribution and attenuation rates at the Facility have been used to evaluate the possible environmental impacts of a hypothetical future chronic or sudden release of jet fuel from the Facility.
- Based on the observed attenuation of LNAPL in the vadose zone and at the water table, an undetected chronic release of 2,300 gallons per year per tank would be biodegraded in the vadose zone, prior to reaching groundwater.
- Based on the LNAPL retention capacity in the subsurface (estimated based on data from prior releases), a sudden release of approximately 120,000 gallons of LNAPL would likely be retained in the vadose zone and/or at the water table without causing an exceedance of RBDC at Red Hill Shaft. Within the range of uncertainty, a sudden release of less than 38,000 gallons would be very unlikely to cause an impact. Depending on the release location (e.g., a higher elevation within a tank and/or a higher numbered tank further away from Red Hill Shaft) and accounting for uncertainty regarding LNAPL retention capacity, it is possible that a release as large as 700,000 gallons would not cause an exceedance of RBDC at Red Hill Shaft. However, there is less confidence that the higher-end release volume would be protective.

- To reduce monitoring variability, unnecessary changes to sampling methods and laboratory analysis procedures should be avoided. Due to inherent limitations of TPH measurement, indicators of new releases should be based on multiple lines of evidence. Changes in TPH-d concentrations between monitoring events should be evaluated in the context of changes in the characteristics of the chromatogram and changes in the mixture of individual dissolved constituents.

10.8 PATH FORWARD

The information provided in the CSM and this technical memorandum will help with a better current understanding of potential environmental issues given that additional data has been collected since the signing of the AOC. Given the results of the interim environmental analysis of current data, conditions are reasonably bounded by the current monitoring well network. Additional monitoring wells are planned to be installed to further improve resolution of site conditions. As new data become available (e.g., synoptic water level study data), those data will be integrated into an updated CSM for use in developing the *Investigation and Remediation of Releases Report (IRR)*, *Groundwater Flow Model Report*, and the *Contaminant Fate and Transport Model Report*. These reports can be used to further inform stakeholders on potential risks and to identify options for managing those potential risks. Specifically, the information presented in the CSM and this technical memorandum will be used to assist with the IRR and subsequent decision-making pursuant to the AOC. The IRR will include an evaluation and determination of the feasibility of alternatives (e.g., enhanced monitored natural attenuation, capture zone analysis) for investigating and remediating potential releases from the Facility to the maximum extent practicable. If another leak occurs prior to the completion of the environmental investigation and decisions regarding remedial alternatives for potential releases from the Facility, the current GWPP (DON 2014) will be followed accordingly.

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Appendix A:
Interim Groundwater Flow Model

CONTENTS

FIGURES (INCLUDED AT END OF APPENDIX)

TABLES

ACRONYMS AND ABBREVIATIONS

AOC	Administrative Order on Consent
ASTM	ASTM International
BWS	Board of Water Supply, City and County of Honolulu
CLN	Connected Linear Network
CSM	conceptual site model
DOH	Department of Health, State of Hawaiʻi
EPA	Environmental Protection Agency, United States
ft/d	foot/feet per day
ft/ft	foot per foot
ft^2/d	square foot/feet per day
GHB	general head boundary
GMS	Groundwater Modeling System
GWMWG	Groundwater Modeling Working Group
HANI	horizontal anisotropy
Kh	horizontal hydraulic conductivity
Kv	vertical hydraulic conductivity
LPF	Layer Property Flow
MAE	mean absolute error
ME	mean error
mgd	million gallons per day
msl	mean sea level
Navy	Department of the Navy, United States
Obs	observation
PEST	PEST Parameter Estimation software
PT-MC	particle tracking with a Monte Carlo framework
QA	quality assurance
QC	quality control
RHS	Red Hill Shaft (Navy well 2254-01)
RMS	root mean square
TEC	TEC, Inc.
U.S.	United States
USGS	United States Geological Survey
WLE	water level elevation

1. Introduction and Literature Review

1.1 BACKGROUND AND OBJECTIVES

The Red Hill Bulk Fuel Storage Facility (“the Facility”) is located along the Red Hill Mountain Ridge between South Hālawa Valley and Moanalua Valley on the island of O‘ahu, Hawai‘i, as shown on Figure 1.1.1. The Facility includes 20 concrete underground storage tanks with steel liners that store jet fuel (and other fuels such as marine diesel) in the unsaturated zone above the water table. Previous investigations have indicated evidence of petroleum hydrocarbons in the rock surrounding the tanks and in the underlying aquifer. A release of approximately 27,000 gallons of Jet Propellant 8 from Tank 5 was reported in January 2014.

The *Administrative Order on Consent* (AOC) *In the Matter of Red Hill Bulk Fuel Storage Facility* (EPA Region 9 and DOH 2015) was issued in September 2015 following the 2014 release, and requires the United States (U.S.) Department of the Navy (Navy) and Defense Logistics Agency to take actions, subject to State of Hawai‘i Department of Health (DOH) and U.S. Environmental Protection Agency (EPA) approval, to address fuel releases and implement infrastructure improvements to protect human health and the environment.

To fulfill the requirements of the AOC Statement of Work, an environmental investigation and groundwater flow and transport modeling are being conducted as described under the following subsections within Sections 6 (Investigation and Remediation of Releases) and 7 (Groundwater Protection and Evaluation) of the AOC Statement of Work:

- 6.2 Investigation and Remediation of Releases SOW
- 7.1.2 Groundwater Flow Model SOW
- 7.2.2 Contaminant Fate and Transport (CF&T) Model SOW
- 7.3.2 Groundwater Monitoring Well Network SOW

The current investigation is being conducted to evaluate risk to the underlying aquifer and to public supply wells, and to support Sections 6 and 7 of the AOC Statement of Work. The findings of the investigation are being used to prepare and support the following AOC Statement of Work reports:

- 6.3 Investigation and Remediation of Releases Report
- 6.5 Investigation and Remediation of Releases Decision Document and Implementation
- 7.1.3 Groundwater Flow Model Report
- 7.2.3 CF&T Model Report
- 7.3.3 Groundwater Monitoring Well Network Report
- 7.3.5 Groundwater Monitoring Well Network Decision Document and Implementation

Environmental investigations have been conducted at the Facility since 1998, and long-term monitoring has been conducted since 2005. The groundwater monitoring well network at and surrounding the Facility has continued to expand including the installation of two wells (RHMW06 and RHMW07) in 2014 following the Tank 5 release. The current investigation has included the installation of four new wells (RHMW08 through RHMW11) since 2016 with current plans to install additional new wells. Additional investigation activities have included various sampling and investigation activities to support evaluations of groundwater flow and the effects of pumping local water supply wells on the flow field, natural source zone depletion, and natural attenuation.

The interim groundwater flow model has been developed to assist with evaluating flow and migration from the water table beneath the Facility and to assess the source water zones of key water supply wells. The objective of groundwater modeling is to help ascertain potential risk to water supply wells as a result of a potential range of releases from the Facility under a range of reasonable pumping conditions within the model domain. The interim model will continue to be developed into the groundwater flow model that will be presented in the *Groundwater Flow Model Report* described under Section 7.1.3 of the AOC Statement of Work, which is due in December 2018.

This appendix reports the interim groundwater flow model development and application. The interim modeling effort is being used to assist with the following:

- Provide input to the interim environmental analysis.
- Inform decisions related to potential remedial alternatives and monitoring.
- Develop a final groundwater flow model and fate and transport models of potential release scenarios and water supply pumping conditions to evaluate potential migration, attenuation, and risk to water supply wells, all of which will be used to inform changes to the *Groundwater Protection Plan* (DON 2014).

1.2 REVIEW OF MODELS

Several groundwater flow models have been developed that cover the area of interest. The most updated of these models include a saltwater intrusion study by the U.S. Geological Survey (USGS) (Oki 2005), and models developed for the Source Water Assessment Program by the DOH in 2004, later modified by TEC, Inc. (TEC) in 2007.

This section reviews these models and the associated reports as pertinent to the current modeling efforts and objectives within the current study area (which is generally within the model domain but with more focus on the Red Hill area). These studies, including the simulations and sensitivity analyses, contain significant information on the behavior of the hydrogeologic system. It is important to build on the information obtained from the reported successes and to understand issues faced in those studies.

1.2.1 SUTRA Model by USGS (Oki 2005)

A modeling study of the aquifer in the Pearl Harbor area was conducted by the USGS (Oki 2005) to evaluate the impact of valley-fill barriers and of redistribution of groundwater withdrawals on water levels and salinity in the aquifer. A density-dependent groundwater flow and solute transport model was developed using a finite element code SUTRA (version 2D3D.1), which is appropriate for evaluating saltwater intrusion in coastal systems. This section presents an evaluation of this model and the associated report with a focus on the current modeling objectives and domain.

The Oki (2005) SUTRA model builds on a model by Gingerich and Voss (2005). The Gingerich and Voss (2005) model did not represent details of hydrogeological features. A two-dimensional model by Souza and Voss (1987) was used to initially parameterize the aquifer system.

The model by Gingerich and Voss (2005) was isotropic horizontally and was not calibrated. The model indicated that the interface as computed by the Ghyben-Herzberg Principle was generally shallower than the 50 percent saltwater contour line with largest differences occurring at times of highest pumping. The difference was attributed to pressure drop and to vertical flow components. Fluctuations in the simulated interface position were small mainly because of low vertical hydraulic conductivity (Kv) of the aquifer that dampened the pressure changes with depth.

Souza and Voss (1987) noted that only six parameters control the complex flow and saltwater intrusion behavior of the system. These parameters include the Kh and Kv of the basalt aquifer, hydraulic conductivity of the confining caprock layer, leakance below the caprock, specific yield, and aquifer matrix compressibility.

1.2.1.1 Aquifer Properties

The basalt aquifer in the area of interest was formed by gently dipping lava flows with a generally high hydraulic conductivity due mainly to clinker zones, voids along contacts between lava flows, cooling joints, and lava tubes associated with pāhoehoe flows. The regional horizontal hydraulic conductivity (Kh) value is large and ranges from hundreds to thousands of feet per day (ft/d), resulting in relatively flat water table gradients.

Horizontal anisotropy (HANI) of the basalt aquifer can be large with the hydraulic conductivity several times higher in the longitudinal direction of lava flows than in the perpendicular (transverse) direction; the modeled estimate of longitudinal Kh was 4,500 ft/d, while transverse Kh was 1,500 ft/d. The Kv may be hundreds of times less than the Kh; the modeled estimates were around 7.5 ft/d. These values were also used by other researchers. Uniform properties for basalt were used to calibrate the model.

There are a number of geologic controls to groundwater flow. Low-permeability valley-fill deposits and weathered volcanic rock (saprolite) beneath the valley-fill deposits impede groundwater movement and can create differences in groundwater levels on opposite sides of the valley. Nearer the coast, the valleys may contain terrestrial sediments inter-fingered with marine sediments and limestone units. Inland, above an altitude of around 30 feet, the base of the valley-fill material typically consists of older alluvium that may be hundreds of feet thick in lower altitudes but non-existent above altitudes of 400 to 600 feet.

In the Kalihi Stream Valley along the southeastern boundary of the current study area, the thickness of valley-fill deposits likely exceeds 1,000 feet, forming an effective barrier to flow. A site beneath Waiawa Stream Valley along the northwestern boundary of the current study area reportedly had weathered basalt extending to depths of 50 to 100 feet below sea level. Valley-fill barriers and underlying weathered basalt associated with Waimalu and North Hālawa Streams within the current study area may impede the flow of groundwater. Waimalu Stream Valley reportedly contains sedimentary material and weathered basalt to depths greater than 200 feet below mean sea level (msl), while North Hālawa Stream Valley reportedly contains alluvial and colluvial material at depths below sea level with weathered basalt extending even further below.

Older alluvium deposits in the valleys have a low hydraulic conductivity reportedly estimated at between 0.013 ft/d to 1.08 ft/d (three samples), while alluvium without reference to weathering was reportedly estimated to have a hydraulic conductivity ranging from 0.019 to 0.37 ft/d. Valley-fill barriers were assigned an isotropic value for hydraulic conductivity of 0.058 ft/d in the Oki (2005) model.

Weathering of the basalt was dominated by chemical processes that are enhanced by percolating water in high rainfall areas and under streams where the saprolite (weathered basalt) thicknesses are greater. Weathered basalt hydraulic conductivity was reportedly estimated to be 0.083 ft/d to 0.128 ft/d, although higher values (283 ft/d) and lower values (0.0028 ft/d) were also reportedly estimated that were attributed to variability in macro-porosity among samples.

Coastal sedimentary deposits and underlying weathered basalt form a confining unit called caprock above the basalt aquifer. The caprock includes zones of low to high hydraulic conductivity; however, the overall effect is that of a low hydraulic conductivity modeled at 0.15 ft/d by Souza and Voss (1987). The Oki (2005) model simulates the caprock as an upper limestone (Kv and Kh values of 25 and 2,500 ft/d, respectively) and a low-permeability unit (isotropic hydraulic conductivity value of 0.6 ft/d).

Porosity of the aquifer ranges from less than 5 percent associated with massive features, including dense flows and aʻā cores, to more than 50 percent associated with clinker zones. Effective porosity may be up to an order of magnitude less than the total porosity. The basalt (including clinker zones and surrounding basalt) in the current study area had a modeled effective porosity of 0.04, the upper limestone unit had an effective porosity of 0.2, and all other rock types had an effective porosity value of 0.1.

Storage properties of the basalt aquifer are related to the porosity. The specific storage was computed to range from 7.5×10^{-6} ft^{-1} to 7.8×10^{-6} ft^{-1} for effective porosity values ranging from 0.02 to 0.2.

1.2.1.2 Groundwater Flow

The main groundwater flow system in the basalt aquifer consists of a freshwater lens overlying saltwater. Recharge to the freshwater lens system occurs due to infiltration of rainfall and inflow into the area of interest from upstream areas.

Recharge was estimated using reported relationships between annual recharge and annual rainfall depending on agricultural conditions. Maps of the area as presented by Oki (2005) indicate that there is little if any cultivation within the current study area since the mid-1970s. Recharge for the transient model was averaged over periods ranging from 5 to 20 years.

Freshwater discharge occurs as groundwater pumping, discharge to onshore springs, and diffuse discharge through the caprock to Pearl Harbor and the ocean.

Groundwater pumping from the basalt aquifer increased through the 1970s and declined thereafter following closure of sugarcane plantations. Withdrawal from the caprock was mainly from its upper limestone unit and is currently used mainly for landscape and golf course irrigation or industrial purposes.

The major Pearl Harbor Springs within the current study area include Kalauao Spring with Waiau-Waimano Springs located just outside of the model domain. Main spring discharge occurs from areas where the basalt is exposed or where there is a break in the land surface. Reported relationships between spring discharge and water level measured at a Pearl Harbor well were used to quantify discharge; there was a high correlation for Waiawa and Waimano-Waiau Springs and a reasonable correlation for Kalauao Spring.

Diffuse seeps also occur where the caprock is thin.

The freshwater lens thickness is described by the Ghyben-Herzberg Principle as 40 times the water table elevation at that location above msl, with the assumption that flow is horizontal. Flow is generally horizontal except for near springs or through the caprock where vertical flow components exist.

The salinity of water withdrawn from wells in the area was expected to increase with depth, proximity to the coast, and withdrawal rate, although exceptions to this generalization were reported. Saltwater intrusion was a problem at older high-capacity irrigation wells because of the great depth to which they were drilled and the high withdrawal rates.

The water table elevation is less than a few tens of feet above sea level in the upstream reaches of the current study area. Nearer to the coastline, the shallow caprock wells indicate water levels close to msl. The water table elevation increases inland within the basalt aquifer at a rate of about 1 foot per mile with local variations due to springs or pumping wells.

Water levels fluctuated by as much as 5 feet seasonally during the peak cultivation period with a long-term downward trend. However, reported seasonal fluctuations seem to be half that in the later (1990–2000) timeframe with an apparent stabilization or even a slight increase noticed in the long-term trend. Barometric pressures also affect water level measurements. On a weekly to annual time scale, migratory low- or high-pressure systems can cause relatively large pressure variations (in excess of 0.3 foot of water).

1.2.1.3 Model Details

The model domain covers the current study area, with the southeast boundary lying approximately at the same location as the current interim model domain's southeast boundary. The model extends into Pearl Harbor and into the ocean to sufficiently capture the saltwater flow dynamics.

The model was discretized into 56 rows, 72 columns, and 76 layers of nodes. The rows and columns were deformed such that the elements are boundary-fitted to the simulation domain, while the layers are stacked vertically. Variable grid spacing was provided for fine discretization in the upper part of the aquifer and near areas of groundwater discharge. Figure 1.2.1 shows the simulation domain of the SUTRA model in relation to the current study area.

The top of the model is at msl; therefore, the model is truncated below the water table that can be tens of feet above msl. The overall aquifer transmissivity was noted to be underestimated by less than 1 percent with this assumption.

The model extends to a depth of 5,906 feet below msl to include the saltwater system up to an assumed aquifer bottom. Inflow of freshwater from lateral upgradient boundaries occurs between altitudes of -3 feet and -984 feet with no-flow conditions further below.

Uniform aquifer properties were used in the model for each of the geologic units. This was done to avoid creating an overly complex model that could not be justified based on existing information. Equivalent properties at a grid-block scale, therefore, included anisotropy in all directions to account for the complex local-scale geology. Numerical stability was enhanced by using multiple nodes to simulate the horizontal well shafts and by creating high dispersivity zones near discharge zones in the Pearl Harbor Springs.

The longitudinal hydraulic conductivity of the top layer of the model was extracted and is shown on Figure 1.2.2. The simulated longitudinal Kh of basalt was 4,500 ft/d. The caprock was sub-divided into an upper limestone unit with a simulated Kh of 2,500 ft/d, and a low-permeability caprock unit with a hydraulic conductivity value of 0.6 ft/d within the current model domain. A band of the lower hydraulic conductivity was noted at the intersection of caprock and basalt in layer 1, in upland areas of the caprock where the coastal upper limestone unit is absent. The upper limestone sub-unit of the caprock extended to different depths and through different layers as derived based on existing structural contours that were extrapolated to the east and in offshore areas.

Figures 1.2.3 and 1.2.4 show the simulated water table elevation at the end of the simulation (in 2000), as extracted from the base case model results for model layers 1 and 21, respectively. Model layer 1 simulated caprock nearer to the coast and basalt in upland regions of the model. Model layer 21 simulated basalt within the current model domain in upland regions and underlying caprock nearer to the coast. The simulated water levels are at msl near the coastline within the caprock and deeper in the basalt. As shown on Figure 1.2.3, the simulated water levels in caprock rise up to about 4 feet within the upper limestone sub-unit. Water levels then rapidly increase within the lower-permeability unit band due to the higher resistance simulated therein. Water levels are as high as 15 to 20 feet just upstream of this lower hydraulic conductivity band in the basalt regions of the model. Water levels increase more gradually further inland within the basalt aquifer where it is unconfined. Higher water levels were also simulated in the North Hālawa Valley fill sediments, resulting from additional mounding of recharge within the lower hydraulic conductivity valley-fill material.

Water levels in basalt confined beneath the caprock (Figure 1.2.4) increase rapidly from the coastline where the basalt is confined. Where the basalt is unconfined, the water level gradients are similar to those simulated in layer 1 (Figure 1.2.3) and are about 1 foot lower.

Figure 1.2.5 shows the simulated elevation of the saltwater interface (50 percent salinity contour) within the current study area at the end of the simulation (in 2000), as extracted from the base case model results. The saltwater interface elevation is similar to that obtained by the Ghyben-Herzberg Principle in the Red Hill area and along the northeastern boundary of the study area. The calculated interface depth decreases rapidly within the caprock nearer the shoreline and surfaces at the coastline.

Sensitivity to valley-fill barriers was reported to be about a few tenths of a foot difference in water levels within the current study area when the barriers were deepened or when the barriers were absent as compared to the base case simulation.

Sensitivity of saltwater intrusion to reducing pumping in Hālawa Shaft by 5.66 million gallons per day (mgd) and increasing pumping in Pearl City III well by the same amount indicated a change in the interface elevation of less than 15 feet under both these locations. For the case of moving the Hālawa Shaft pumping to well Kunia III (2401-04), the 50 percent salinity depth change was less than 10 feet at Hālawa Shaft.

Sensitivity of saltwater intrusion to reducing pumping in Hālawa Shaft by 5.66 mgd with and without valley-fill barriers indicated that the saltwater intrusion impact due to pumping changes in Hālawa Shaft is larger when there is no valley-fill barrier than when the simulation included or deepened the valley-fill barrier.

1.2.1.4 CONCLUSIONS RELEVANT TO INTERIM MODEL

The following points highlight the system behavior as reported by Oki (2005):

- The document provides ranges of parameter values appropriate for the site:

  - The regional Kh value is large, resulting in relatively flat water table gradients.
  - The hydraulic conductivity is several times higher in the longitudinal direction of lava flows than in the perpendicular (transverse) direction.
  - The Kv may be hundreds of times less than the Kh.
- Water levels in caprock and basalt are close to msl in offshore areas. Where the basalt is not overlain by caprock, the water table elevation increases inland at a rate of about 1 foot per mile with local variations due to springs or pumping wells.
- The saltwater interface, as represented by the 50 percent seawater concentration, was simulated to be approximately at the ocean shoreline. The interface depth increased rapidly further inland, within the caprock, and where basalt is confined. The interface depth was 850 to 900 feet in the Red Hill area, which is consistent with estimates using the Ghyben-Herzberg Principle.
- Truncating the aquifer below the water table had a negligible impact on transmissivity. Therefore, transmissivity of freshwater is not sensitive to freshwater depth under Red Hill. Pumping changes of [redacted] mgd move the saltwater interface depth by less than 15 feet, which also has a similar negligible impact on the freshwater transmissivity.
- Valley fill and underlying weathered basalt form low hydraulic conductivity barriers that control flow and water levels across the barrier:
  - The bottom of the alluvium filling Hālawa Stream Valley was estimated by Izuka (1992) to be near sea level at a channel altitude of about 150 feet. Weathered basalt was assumed to extend 200 feet beneath the alluvium and maintained at that elevation in downstream areas up to where the contact with caprock was also at 200 feet below sea level.
  - The bottom of the Waimalu valley-fill barrier was estimated based on well logs to extend to about 330 feet below sea level just upstream of Pearl Harbor. The barrier bottom was extrapolated further upstream with a 3 percent slope up to where the barrier bottom was at sea level.
  - In the Kalihi Stream Valley along the southeastern boundary of the study area, the thickness of valley-fill deposits likely exceeds 1,000 feet, forming an effective barrier to flow.
- Seasonal water level fluctuations were about 2.5 feet after 2000. Water level errors as large as 0.3 foot can occur due to barometric fluctuations within a matter of a week.
- A uniform material property value for each of the geologic units was adequate to calibrate the model to water levels and chlorides measured at select wells.
- Calibration was not sensitive to presence/absence or deepening of the valley-fill barriers.

1.2.2 TEC Groundwater Flow Model (TEC 2007; Rotzoll 2014)

A modeling study of the area around Red Hill was conducted by TEC (TEC 2007, 2010) for a flow and transport assessment to evaluate current and potential future risk to human health associated with petroleum compounds from past or future releases to the environment. This model generally overlies the current study area and was designed for similar objectives.

The model was developed in two stages. First, the regional island-wide model of Oʻahu's Source Water Assessment Program was modified to represent the more recent period from 1996–2005 by updating land use, recharge, pumping rates, and observed water levels. The model was then used to provide boundary conditions to a local-scale model of Red Hill and adjacent areas. Figure 1.2.6 shows the domains of the TEC models and of the current model.

1.2.2.1 Aquifer Properties

The aquifer descriptions provided here are similar to those presented by the USGS (Oki 2005), which are discussed in Section 1.2.1. Additional specific discussions pertinent to the current study include site-specific issues that were not of concern in the USGS saltwater intrusion study.

Streams on Oʻahu have generally short reaches with steep gradients, causing high peak flows and little base flow. Streambed elevations are generally higher than the water table in the basalt aquifer except nearer to the coast. North Hālawa Stream flows over deeply weathered rock and reportedly loses water to a perched system formed by underlying alluvium. This mounding was noted in the SUTRA model heads in layer 1 (Figure 1.2.3).

1.2.2.2 Groundwater Flow

Discussions of groundwater flow are similar to those presented by the USGS (Oki 2005), which are provided in Section 1.2.1. Additional details included herein pertain to the specific objectives of the TEC (2007) study.

There was not much fluctuation of water levels between 1996 and 2005, and therefore, the average was a good representation of the simulated time period. However, modeled pumping rates were far below the allocated pumping rates.

1.2.2.3 Model Details

There were two models created by TEC (2007): the regional island-wide model and the small-scale local model.

The regional model had a grid size that varied from 150 feet in the region of Red Hill to 1,000 feet in the outer regions of the model. The model consisted of two numerical layers.

The regional model indicated a good match with observed conditions; misfit between observed and simulated water levels was attributed partially to small-scale heterogeneity not represented in the coarse model, and to inconsistent water level measurements as compared to the conceptualized hydraulic gradient.

The regional model treated the valley fill using the hydraulic flow barrier conditions available in MODFLOW. The local model simulated the valley fill explicitly in the five major valleys in the area (Waimalu, North Hālawa, South Hālawa, Moanalua, and Kalihi Valleys).

The local model had a grid size that varied from 30 feet in the region of Red Hill to 600 feet in the outer regions of the model. The model consisted of seven numerical layers.

Calibrated hydraulic parameters for the local model were similar to those of the USGS model by Oki (2005). However, the caprock was simulated as a homogeneous unit sub-divided into the marine limestone unit and upper alluvial sediments. Basalt hydraulic conductivities were 4,428 ft/d, 1,476 ft/d, and 7.4 ft/d for the longitudinal horizontal, transverse horizontal, and vertical directions, respectively. Isotropic hydraulic conductivity values were assigned to the valley fill and caprock at 0.066 ft/d and 115 ft/d, respectively.

Cross sections of the valley topography were analyzed to evaluate the depth of incision of the valley fill for the local model. The predicted bottom of the valley fill was consistent with reported borehole observations including the low-permeability weathered basalt.

Sensitivity analyses of the hydraulic conductivity of the valley fill indicated little difference in the water table except for right beneath the valley. Increasing the conductivity removed the elevated water table that was otherwise noted within the valley fill.

A transient calibration was also conducted with the local model for synoptic water level studies conducted between May 10 and June 1, 2006. The simulation was conducted for a period of 17 days. Pumping at Red Hill Shaft (RHS) (Navy well 2254-01) was varied in a controlled manner, and resulting water level responses were noted at several surrounding wells (reproduced on Figure 1.2.7).

Figures 1.2.8 through 1.2.11 reproduce the pumping rate at RHS, and simulated and observed water level signals at the observation wells as shown on Figure 1.2.7. The calibration is noted to be good for all wells except for RHS where simulated responses were more muted than observed. This was because RHS is also a pumping well, while the simulated water level was for the groundwater grid-block that contains the simulated well. The simulated response at the Hālawa wells (Figure 1.2.10) was noted to be larger than observed, indicating a larger effective simulated connectivity between RHS and these wells than indicated by the observations. Deepening the valley fill and including one extra layer for low-permeability weathered basalt were expected to improve the fit of observed drawdown from the Red Hill pumping response on the other side of the valley fill for North Hālawa Valley.

Capture zones created from the calibrated steady-state simulation indicated that capture at the Hālawa Shaft was not intersecting Red Hill and that capture at the RHS was from beneath the fuel storage facility for pumping of average and maximum conditions over the 10-year time period.

In 2014, Rotzoll used the model to further evaluate the impact of flow in the aquifer resulting from a simulated shutdown of the Navy RHS pumping (Rotzoll 2014). Capture zones developed for this simulation also indicated that capture at the Hālawa Shaft was not intersecting the Facility footprint. Figure 1.2.12 shows the 10-year capture zones computed by the TEC (2007) simulation with RHS on, and by the Rotzoll (2014) simulation with RHS off.

Rotzoll (2014) recommended updating the groundwater flow model with current and updated information to achieve a higher degree of certainty. Rotzoll (2014) also recommended improving the subsurface geology representation to better simulate the lower connectivity between RHS and the Hālawa observation wells shown on Figures 1.2.7 through 1.2.11.

1.2.2.4 Conclusions Relevant to Interim Model

The following points highlight the system behavior as modeled by TEC (2007) and Rotzoll (2014):

- There was not much change in water levels between 1995 and 2005.
- Calibrated hydraulic parameter values for the local model are similar to those of other models including the Oki (2005) model discussed Section 1.2.1. Caprock was simulated as one homogeneous unit.
- Sensitivity to hydraulic conductivity of valley fill showed little impact to water levels except immediately within the valley fill.
- A transient simulation to a controlled pumping with synoptic water level measurement study in 2006 indicated that the simulated valley fill material of North Hālawa Valley had a greater connectivity than was observed. Thus, the model was more conservative in that direction than was observed for the given flow conditions.
- Particle capture simulations indicated that the Facility was within the capture zone of RHS and that the Hālawa Shaft capture zone did not extend to the Facility with or without pumping of the RHS.

1.2.3 Navy (2007) Final Technical Report

The Navy (2007) final technical report included details of site characterization activities as well as modeling studies and risk assessments conducted by TEC with regards to the Facility. This section presents elements of the study that are significant to understand the site and develop a model.

Soils in the vicinity of the Facility generally consist of clays and clayey gravels to a depth of 10 feet below ground surface. Alternating layers of clay and fractured basalts were encountered beneath the surface soils. The western slope of Hālawa Valley is generally barren of soil and consists of outcropping basalt lava flows to the valley floor.

Valleys approaching 600 meters in depth were cut into the basalt during the volcanic quiet period. Sediments consisting of silt and sand accumulated in the valley floors. Pāhoehoe and a‘ā lava flows are present. Pāhoehoe lava is characterized by relatively thin-bedded basalt flows, while a‘ā lava is jagged, blocky, and contains clinker beds that are more permeable than the rest of the basalt. The a‘ā lava may act as a localized confining layer that is generally limited in extent.

An aquifer test conducted in 2006 is also presented. The test was used to calibrate the localized groundwater flow model. RHS was first completely turned off for the period of a week followed by pumping rates that alternated between [redacted] mgd. Hālawa Shaft and Moanalua wells maintained their regular pumping patterns. Wells in Red Hill, Hālawa, and Moanalua Valleys were monitored to note the aquifer test response.

Groundwater gradients computed using data from wells RHMW02, RHMW03, and RHMW04 during the aquifer test indicated varying gradients and directions for different pumping conditions of RHS. When the pump was cycling, the gradient ranged from 0.00046 foot per foot (ft/ft) to 0.00054 ft/ft with an angle of 204 to 245 degrees. Thus, the hydraulic gradient between these wells was southwestward when RHS was pumping and southward when the well was turned off.

The current groundwater risk was evaluated at the RHS. No petroleum compounds were observed in samples from this well. RHMW01 and RHMW03 exceeded their respective DOH drinking water Environmental Action Levels, but contaminants were naturally degraded to below detectable levels before entering RHS. The fate and transport simulations indicated that a Jet Propellant 5 light non-aqueous-phase liquid plume would need to extend to within 1,099 feet from RHS for benzene to exceed Federal Maximum Contaminant Levels and DOH Environmental Action Levels. It was estimated that a release of 16,000 gallons from the Facility could cause this exceedance at RHS within 5 to 6 years of such a release.

1.2.3.1 Conclusions Relevant to Interim Model

The following points highlight the system behavior as discussed by the Navy (2007):

- The groundwater conditions in the basalt are mainly unconfined in the Red Hill area.
- Valleys in the basalt are filled with low hydraulic conductivity sediments.
- The local groundwater gradient direction under the Facility was southwestward when RHS was pumping.
- The local groundwater gradient direction under the Facility was southward when RHS was off.

1.2.4 TEC (2010) Re-evaluation Letter Report

In 2010, TEC re-evaluated the groundwater gradients and directions from the 2006 aquifer test study. A resurvey of well casing elevations was performed to more accurately evaluate groundwater elevations. Also, the gradient calculations were performed using wells RHMW02, RHMW03, RHMW04, and OWDFMW01 (OWDFMW01 replaced RHS in the analysis). Results indicated a consistent water level gradient direction of 270 degrees (i.e., from east to west) as compared with the varying directions evaluated in the 2007 analysis. Water level gradients vary from 0.00015 ft/ft to 0.000089 ft/ft (i.e., a foot drop in 1.2 to 2.1 miles).

A contouring approach was also presented using a larger set of wells (seven wells total) with more regional coverage including wells in the Moanalua Valley. Results from contouring indicated a west-northwest regional flow component with a local southwest flow component at Red Hill when RHS was pumping at normal [redacted] mgd) or maximum ([redacted] mgd) capacity.

1.2.4.1 Conclusions Relevant to Interim Model

The following points highlight the system behavior as modeled by TEC (2010):

- Using the EPA gradient calculator, the local water level gradient direction under the Facility is to the west.
- A contouring approach with wells in Moanalua Valley indicated regional water level gradient directions in the vicinity of the Facility to the west-northwest with a local southwest direction when RHS was pumping.

1.2.5 Souza and Voss (1987)

The basalt aquifer in the region of interest is composed of thin lava flow layers that are a meter to several meters thick and tens to hundreds of meters wide, dipping about 5 to 10 degrees from the upland recharge areas to the ocean. The basalt outcrops along the sea bottom more than 40 kilometers offshore. The overlapping basalt layers, laid down by a single geological process, are generally undisturbed aside from some compaction. Therefore, the aquifer is fairly homogeneous on a regional scale.

Groundwater discharge occurs at a line of springs at the boundary of the basalt and caprock near the perimeter of Pearl Harbor and at pumping centers. Some diffuse discharge occurs through the caprock though the quantity is likely small.

A cross sectional model was developed in the north-northeast by south-southwest direction through Pearl Harbor.

Modeling results were insensitive to the recharge distribution along the inflow boundary, and water recharged at greater or lesser depth rose or dove to an even distribution within the freshwater lens in a short horizontal distance.

Simple distributions and single parameter values gave good model matches to field data. Only six parameters were identified that control the complex hydraulic and chloride behavior. The steady-state behavior was controlled by Kh and Kv of the basalt aquifer, hydraulic conductivity of the confining caprock layer, and leakance below the caprock. The transient behavior of the system was controlled by the specific yield, the specific storativity, and the horizontal to vertical anisotropy of the basalt.

Porosity was estimated to be less than 5 percent in dense lava flows and up to 50 percent in clinker zones. Average bulk porosity was measured at about 26 percent. The simulations assumed that the total volumetric porosity, the effective porosity, and the specific yield were the same.

The hydraulic conductivity of the lateral seaward boundary beneath the caprock controlled system behavior at a long-time scale (1880 to 1980) but did not impact short-term transient behavior lasting a few months or less, nor the steady-state behavior of the system.

The simulated 50 percent chloride value was generally about 75 meters shallower after 78 years of pumping in the 1880–1980 time-period simulation.

Seasonal variations in pumping due to high agricultural demand in summer months caused the consistent yearly variations in water levels.

1.2.5.1 Conclusions Relevant to Interim Model

The following points highlight the system behavior as described and modeled by Souza and Voss (1987):

- The basalt aquifer is fairly homogeneous on a regional scale. The beds dip at an angle of 5 to 10 degrees and can be several meters thick to hundreds of meters wide.
- Groundwater discharge occurs due to pumping at Pearl Harbor Springs. Diffuse discharge through the caprock was expected to be small.
- Only six parameters control the complex flow and saltwater intrusion behavior (the Kh and Kv of the basalt aquifer, hydraulic conductivity of the confining caprock layer, leakance below the caprock, specific yield, and aquifer matrix compressibility). Simple parameter values gave good matches to field data.

1.2.6 Nichols, Shade, and Hunt (1996)

Nichols, Shade, and Hunt (1996) provide an analysis of groundwater flow in southern O'ahu.

Mean annual precipitation was approximately apportioned as 40 percent groundwater recharge, 16 percent runoff, and 44 percent evapotranspiration. Precipitation varies areally with steep orographic gradients ranging from about 275 inches/year near the crest of the Ko‘olau Range to less than 25 inches/year over the southwestern lowlands.

Streamflow is flashy with high flood peaks and little baseflow. Streams are perennial at high altitudes where rainfall is persistent or near sea level where they intercept shallow groundwater.

Hydraulic conductivity of the basalt has been evaluated from aquifer tests at various field scales. Aquifer thickness is not well known and impacts the estimates of hydraulic conductivity. A small range of hydraulic conductivity values has been applied to groundwater models on O‘ahu.

Figure 30 of the report by Nichols, Shade, and Hunt (1996) indicates that 23 mgd of inflow occurs along the northeast boundary of the current study area.

2. Numerical Groundwater Flow Model

The objectives of developing a model for groundwater flow and transport are to evaluate the migration pathways of groundwater from beneath the Facility and the source water zones of public supply wells in the region to evaluate potential risk. This section provides an overview of the model and serves as a guide to the rest of this appendix.

A model is any calculation or quantitative interpretation of the behavior of a natural system. In that regard, simple tables or spreadsheets (analytical solutions) that consider the general site hydrogeological behavior of a system are considered models. Tiered approaches to modeling and decision making, in fact, start by examining the overarching behavior with details and complexity appropriately included, by considering objectives and available site information. The model developed here has far greater complexity and detail than offered by simple analytical solutions and is considered appropriate and adequate to address the objectives of concern at the intended resolution.

2.1 Scales of Discussion

The modeling objectives, geologic variability, and simulation results are evaluated at various spatial scales during data assimilation, model conceptualization, numerical model development, and reporting. These scales are subjective, typically depending on domain size and modeling objectives.

For this study, a ***domain-wide scale*** encompasses the entire modeled area depicted on Figure 1.1.1 and includes portions (about a couple of miles) outside of the model domain to evaluate possible boundary conditions and impacts.

The ***regional scale*** at the Facility is defined as the area encompassing Red Hill, and including a couple of valleys on either side; past Moanalua Stream to the southeast, and past North Hālawa Stream to the northwest. This is the scale of interest for major objectives of the flow model evaluation, specifically to determine migration pathways from the water table underneath the Facility, and to estimate the source water zones of the significant water supply wells/shafts in the area. The closest significant water supply withdrawals to the Facility are the RHS to the southwest, the Hālawa Shaft (Well 2354-01) to the northwest, and the Moanalua Wells (2153-10, -11, and -12) to the southeast of the Facility.

The ***local scale*** at the Facility is defined as the Facility outline itself. This is about 1.5 miles down the spine of Red Hill Ridge and encompasses the area beneath the tanks and RHS. This scale is the most studied, with the densest data availability with regards to geology and water levels.

The ***grid-block scale*** is the size of a couple of grid-blocks used to discretize the numerical model; the numerical groundwater flow model discretizes the three-dimensional model domain into grid-blocks or cells that represent the respective volumes in the groundwater flow calculations. Model discretization is typically finer in areas where a greater resolution is required at the grid-block scale. Greater resolution is required typically to capture steep water level gradients, in locations of high variability in modeled stresses or parameters, or around regions of interest. Model gridding is discussed later in the report; however, grid-block sizes range from 30 to 500 feet in the current study.

The ***scale of the well/water supply shaft*** is modeled explicitly in the current study. The MODFLOW-USG code selected for the modeling effort accommodates well representations using the Connected Linear Network (CLN) Package. A water supply well is represented as a vertical cylindrical conduit extending from the screened-interval top, to the screened-interval bottom, and encompasses all numerical model layers in between. This conduit is a distinct numerical cell that interacts with the surrounding groundwater model cells using analytical well-drawdown solutions to calculate flows and water levels within pumping wells that interact with the groundwater. Water supply shafts are represented by horizontal cylindrical conduits with known bottom elevation, length, and radius. This scale is therefore explicitly represented by use of the MODFLOW-USG CLN package and does not pose additional discretization concerns.

The ***sub-grid-block scale*** is smaller than a numerical grid-block size. In numerical modeling, heterogeneities that occur at a sub-grid-block scale are represented by use of equivalent material properties at the grid-block scale. Associated sub-grid-block scale processes are averaged at the grid-block scale, or may be conceptualized as additional components of the mathematical formulation. For instance, sub-grid-block scale heterogeneity is quantified for flow simulations using grid-block scale anisotropy such that equivalent hydraulic conductivity parameters represent the significant characteristics of flow in each direction. Particle tracking or solute transport simulations account for sub-grid-block scale heterogeneities using the primary porosity to evaluate migration. Solute transport evaluations include additional terms for sub-grid-block scale processes including a retardation term to quantify solute adsorption onto soil within the primary porosity zones, and matrix diffusion to account for solute retention within lower-permeability sediments.

Even though anticipated solute transport simulations require evaluations at the regional scale, there will be considerations at all scales. Heterogeneity at the local scale affects physical dispersion. Discretization at the grid-block scale affects numerical dispersion. Matrix diffusion processes that occur at the sub-grid-block scale will be represented via a dual-porosity transport conceptualization.

2.2 SUMMARY OF FLOW MODEL CONCEPTUALIZATION

An evaluation of the conceptual site model (CSM) in view of the modeling objectives provides the framework for developing the numerical flow model. A review of previous modeling efforts also provides guidance on model construction and expected hydrogeologic behavior. The CSM report details its development from geological and geophysical data and hydrogeological information, and Section 1.2 provides a summary of pertinent information from previous modeling efforts.

2.2.1 Geologic CSM

The major subsurface geologic features within the model domain include a deep basalt aquifer that was formed by a long period of lava flows over hundreds of thousands of years ago. The lava flows had a general south-southwest orientation within the model domain. At the regional scale, the basalt aquifer behaves as a fairly homogeneous system with a higher hydraulic conductivity (by several times) in the direction of lava flows than in the transverse direction. Kv can be orders of magnitude lower. At the local scale at Red Hill, variability has been noted in geologic and water level data indicating presence of highly transmissive localized clinker zones that may impact flow. Clinker zones are known to be a few feet to tens of feet in height, tens to hundreds of feet in width, and thousands or tens of thousands of feet in length. Localized lava tubes may also cause sub-grid-block scale transmissive pathways; however, their density and cross sectional area are spatially infrequent and small relative to the model grid blocks.

Stream valleys formed within the basalt over thousands of subsequent years. Alluvial and marine deposits accumulated in the stream valleys comprising a lower hydraulic conductivity (compared to the basalt valley-fill material). Chemical weathering of the basalt beneath the valley fill, resulting from percolating water underneath the streams, produced a low-permeability saprolite material that can extend hundreds of feet beneath the water table. The saprolite is differentially weathered with less weathering at depth. The low hydraulic conductivity of these materials in comparison to the basalt, however, cause them to behave as hydrogeologic flow barriers with higher flow likely to occur beneath them than through them.

Further toward the coast, there exists a caprock layer that thickens seaward and is comprised of terrestrial alluvium, marine sediments, calcareous reef deposits, and pyroclastic rocks of the Honolulu Volcanics that have significantly lower permeability than the basalt. This caprock layer forms a confining unit over the basalt aquifer. Interbedded limestone aquifer units are present within the caprock toward the coast.

2.2.2 Hydrogeologic CSM

Hydrogeologic data is explored in Section 3. Information from previous modeling efforts summarized in Section 1.2 is also pertinent to understanding the hydrogeologic behavior of the modeled system.

Freshwater generally flows within the basalt from the mountains toward the sea. The basalt aquifer is several thousand feet thick with freshwater floating on top of the denser saltwater for depths of up to hundreds of feet within the model area. The depth of freshwater was estimated via simplified hydrogeologic conditions and evaluated against previous modeling efforts. The freshwater/saltwater interface becomes rapidly shallower within the caprock and exits the subsurface slightly offshore from the coastline to the south.

Inflow of freshwater occurs mostly as a result of recharge of precipitation over the model domain and lateral subsurface inflow from the dike-intruded area to the northeast. The water table within the upper reaches of the basalt aquifer, and locally at Red Hill, is fairly flat resulting from the high longitudinal hydraulic conductivity of basalt. Water levels are generally in the 15- to 20-foot range in this area. However, recharge mounding or perching has been noted on the lower hydraulic conductivity valley fill or in underlying saprolite material.

Freshwater is confined within the basalt underneath the caprock as it flows toward the sea. Outflow of freshwater occurs as a result of pumping from wells and shafts within the basalt, at springs at the caprock/basalt interface, and as diffuse discharge through the caprock to Pearl Harbor and the ocean.

The localized limestone aquifer within the caprock is not generally pumped in any substantial manner. Water levels within this unit are pretty flat, generally 1 to 5 feet and rarely rising to within 10 feet of sea level.

2.3 NUMERICAL MODEL FRAMEWORK

The CSM provides an understanding of the hydrogeological system under study, considering the available geologic and hydrogeologic information. The following pertinent information was examined and detailed by the CSM:

- The geologic structure, hydrogeologic properties, and heterogeneity were described at various scales.
- Water flow patterns and temporal water level behavior were established from various wells, and the density of this information was evaluated.
- Recharge patterns were established considering precipitation trends, estimated recharge distribution, land cover, and topography.
- Discharge patterns were estimated from pumping records, spring-flux observations, and water balance calculations.

The numerical model is an implementation of these CSM elements into a physically based, mass balance framework. The groundwater flow equations provide a physically based, spatially distributed representation of how groundwater behaves under natural and anthropogenic stresses. The numerical model, therefore, further simplifies the CSM to implement significant elements that affect modeling objectives.

The numerical groundwater flow model discretizes a three-dimensional model domain into grid-blocks or cells that represent the respective volumes in the groundwater flow calculations. Areal discretization is governed by considerations of required resolution. Model layering also considers stratigraphic and hydrogeologic influences. Sections 4.1 and 4.2 provide details about model discretization.

A model grid was first constructed to represent the subsurface geological conditions. The geologic CSM was then translated onto the numerical grid such that the effective cell properties are representative of the aggregate of the rock that is contained within the cell volume. Anisotropic properties allow for flow conditions to be different in the lateral, transverse, and vertical directions to consider impacts of sub-grid-block scale heterogeneity. Large anisotropy also represents the impact of thin clinker beds in the basalt that are generally oriented in the direction of lava flow. Water flow and migration were modeled to occur only within the primary porosities such as the clinker bed portions of the grid-block. Section 4.3 provides a discussion of model parameterization.

Calibration and verification metrics and targets for the intended objectives were also established. The model was then calibrated and evaluated against the various qualitative and quantitative metrics pertinent to the study. The impact of errors and assumptions of the model were also evaluated in terms of whether the model behavior was consistent, conservative, or unduly protective in relation to site conditions and objectives. Section 5 details the model calibration effort.

The model was applied to evaluate the migration of groundwater from beneath the Facility under various regional pumping conditions. Extreme conditions were evaluated to provide conservative evaluations. Specifically, water migration and source zones of supply wells/shafts were evaluated for when RHS pumps at average conditions with Hālawa Shaft and Moanalua Wells pumping at maximum levels. Migration and source zone evaluations were also conducted for maximum pumping conditions at Hālawa Shaft and Moanalua Wells, with zero pumping at RHS.

Sensitivity analyses were conducted to evaluate the impact of parameter uncertainty/error/simplifications on model calibration as well as on particle migration and capture. Sensitivity analyses were performed on parameter value bounds, conceptual uncertainties, and boundary stresses. Thus, multiple model predictions provided a range of outcomes considering the range of uncertainty in model parameters or stresses. Section 6 details the model application effort.

All aspects of model development and application for the current modeling effort have been guided by the modeling objectives stated in Voss (2011) as follows: *"…the best way to go forward with practical management is to rise above groundwater models as final products, and instead, empower hydrologists to provide advice by using groundwater models in simple ways that are intended to elucidate understanding."* Therefore, the model is considered as a tool for decision making and is useful if it can provide meaningful interpretations of flow behavior and an understanding of observed conditions in the region of interest pertaining to the modeling objectives. With an understanding of the cause-and-effect impacts, the model may be used to establish effects of various parameter ranges or model conceptualizations. Model complexity of the current effort was appropriate to provide this understanding.

The current modeling effort has been conducted within a regulatory framework. Therefore, the analyses were conducted in a conservative manner to err on the side of caution. Simplifications of the CSM in the numerical framework reflect reasonably conservative assumptions considering modeling objectives and available data. Model calibration was also biased toward conservative representations of the hydrogeology where possible. Alternate conceptualizations and parameterizations were explored to evaluate the impact of uncertainty and error. Even model application evaluated the impacts of extreme cases that are not consistent with current operations or even possible without infrastructure changes. Model calibration, application, parameter ranges, and alternate conceptualizations were evaluated with consideration of input from a technical Groundwater Modeling Working Group (GWMWG) that included experts representing regulators and stakeholders.

There have been several lessons learned from the interim model. Also, there has been additional data collected and information obtained to refine the CSM in critical areas. This understanding and new information will be implemented into a refinement of the interim model to develop the final flow model, which will be further used to evaluate solute fate and migration. The stepwise (or tiered) modeling approach gives the flexibility to evaluate and add complexity appropriately while still establishing and conducting conservative analyses for decision making within a regulatory framework.

2.4 NUMERICAL MODEL CODE SELECTION

Several criteria were considered in selection of the groundwater modeling software. First and foremost, the software should be capable of simulating project objectives and handling site-related complexities. The modeling code should also be robust to handle extreme parameter values that may be used to examine model sensitivity or extreme stresses that may be simulated to evaluate solute migration or influence zones of wells under dire conditions; a robust simulator allows focus on hydrogeology and calibration, and enables an understanding of model behavior rather than evaluating/correcting for convergence or dry cell issues. Furthermore, the code should be efficient to enable multiple simulations within a reasonable time period as required for model calibration and application. Finally, the model should be easy to access, develop, and process; a graphical user interface that works with the model code greatly facilitates input and output of complex spatial and temporal information.

The MODFLOW-USG groundwater modeling code (S. Panday et al. 2013) was selected to develop the numerical groundwater flow model. MODFLOW-USG is an open-source, public domain groundwater flow modeling code that was released by the USGS in 2013 to accommodate the flexibility of unstructured grids. The code has the ability to meet all simulation objectives and the capability to accommodate the CSM. The upstream weighting formulation with Newton Raphson linearization provides robustness available in the MODFLOW-NWT (Niswonger, Panday, and Ibaraki 2011) version of the MODFLOW suite of codes. Unstructured grids accommodate nested grids and quad-tree grid-block refinement, providing resolution only where required for optimal simulation efficiency. A public domain particle tracking routine for MODFLOW-USG available from SSPA (2014) was used to evaluate migration pathways or source water zones for public supply wells/shafts via forward and reverse particle tracking. Transport simulation capabilities are accommodated by USG-Transport (Sorab Panday 2017), which is also available as an open-source, public domain software from the GSI Environmental website. The software is further interfaced with the PEST Parameter Estimation software (PEST) (Doherty 2015), which was used to assist with model calibration. MODFLOW-USG is also interfaced with several commercial Graphical User Interfaces (GUIs) including the U.S. Army Corps of Engineers' Groundwater Modeling System (GMS). The GMS graphical user interface was used for model construction and evaluation for this work and allows for easy switching between different numerical model grids or between different simulators as needed.

2.5 Selection of Model Calibration Time Periods for Evaluating Steady-State and Transient Model Behavior

The model was developed and calibrated against water level and flow data from different time periods to constrain the system using different datasets for different hydrologic conditions. All available data in the domain was implemented into the calibration strategy. However, data earlier than 1999 were not considered because this earlier data represent a hydrologic system under conditions that were different from the current state of the aquifer.

The model was first calibrated for steady-state annual average conditions. Three different time periods (2006, 2015, and 2017) were selected to evaluate different hydrologic conditions. These years also coincide with aquifer test studies conducted in the region.

The model was next evaluated against transient data obtained during synoptic pumping and water level measurement studies conducted in the region. These studies evaluated the change in water levels at monitoring wells resulting from a change in pumping at one or more of the key water supply wells in the region. In effect, the synoptic studies were multi-well aquifer tests. This information is valuable in constraining the model because it establishes the hydraulic connectivity between monitoring and pumping wells. If water levels in a well respond significantly to pumping, then there is sufficient connectivity between the pumping and observation well (i.e., high transmissivity and/or low storage properties of the aquifer). However, if the response is weak or muted, the connectivity is low resulting from a lower effective hydraulic conductivity between the pumping and observation well.

The synoptic water level studies were conducted in May 2006, September 2015, and November–December 2017 (ongoing). To evaluate the response for different conditions, the synoptic studies of 2006 and 2015 were evaluated using the model. Transient simulations were initiated using the steady-state simulated water levels for that year. The 2017 synoptic water level study was not evaluated as part of the interim modeling effort because data for this study were not available in time to be implemented into the current modeling effort.

3. Hydrogeologic Data Assimilation

Hydrogeologic data within the domain was evaluated to understand what information was available and how the information may be used in developing and calibrating the numerical groundwater flow model that addresses current issues and concerns in the region. This data included water level information, pumping data, evaluation of water level gradients, spring fluxes, groundwater recharge, and boundary flows for the domain.

3.1 Water Levels

Monitoring wells within the model domain were identified, available water level elevation (WLE) data were collected, and a quality assurance/quality control (QA/QC) check was performed on the data.

3.1.1 Objectives of Water Level Data Assimilation

The objectives of the water level data assimilation were as follows:

1. Evaluate and QA/QC the available groundwater elevation data.
2. Extract trends from noisy WLE observations. Specifically, extract long-term trends, determine monthly fluctuations, and establish confidence intervals in available data around the long-term trend.
3. Use annual and monthly trends to fill data gaps and project available water level information onto time periods evaluated by the model. This information is useful for providing flow model calibration targets and evaluating the spatial distributions of the water levels.
4. Use the spatial distribution of water levels to assist with:
    a. Understanding the gradients and/or anomalies in the water level distributions within the modeling domain.
    b. Implementing the general head boundaries (GHBs) along the northwest and southeast of the model domain.
    c. Evaluating the freshwater/saltwater interface elevations within the model domain using the Ghyben-Herzberg Principle to provide the bottom elevation for the freshwater flow system.

3.1.2 Data Availability and Quality

A total of 234 wells were identified within the modeled area. Data for these wells were obtained from a variety of sources including the City and County of Honolulu Board of Water Supply (BWS), Naval Facilities Engineering Command, Hawaii, the Commission on Water Resource Management, the State of Hawai'i Department of Land and Natural Resources, the Navy, the National Groundwater Monitoring Network, and the USGS. General characteristics of the data collected are presented in Table 3.1.2-1. As shown in Table 3.1.2-1, data were available from as early as 1921 for some of the wells. Wells within the local or regional scale around Red Hill are identified in a different color in the table. The number of observations at a well within the local or regional scale around Red Hill could range from just a handful to hundreds of thousands, with measurement frequency ranging from 10 minutes to monthly and several wells having no specific measurement frequency.

To assist further with data analysis, monitoring wells with available data were categorized and color-coded based on both the quality and quantity of the available WLE data:

- *Pink and Orange:* Wells with data unavailable after 1999 were assigned pink and orange colors (had no data at all in the available dataset). These wells were considered as not having any useful information and were not used in further evaluations. Most of these wells were within the caprock in downstream reaches of the model.
- *Red:* Wells that had data available after 1999, but the number of observations was very sparse (e.g., only a few measurements were available), were assigned a red color. Most of these wells were also within the caprock in downstream reaches of the model.
- *Green:* Wells with long historical data after 1999, but with sparse monthly measurements throughout each year, were colored green. Wells within the Facility mainly fell in this group.
- *Blue:* Wells with long historical records after 1999 and sufficient monthly measurements throughout each year were assigned a blue color. These wells were in the basalt and scattered throughout the model domain.
- *Yellow:* Wells with sufficient monthly water level data available after 1999, but only over a short duration, were colored yellow. For example, the Hālawa Shaft observations available at the time of model development fell in this group.

Figure 3.1.2-1 shows the water level data quality and availability distribution throughout the model domain, using the color categorization scheme discussed above.

3.1.3 Evaluation of Long-Term Trends

The long-term temporal variability in WLE data was evaluated by plotting WLE hydrographs between 1999 and 2017 and evaluating the trend within Excel. The resulting linear slope provided an estimate of how the WLEs varied over that period of time. Because of the availability of long temporal records of water level data, only the blue and green color-coded wells were used to evaluate long-term trends; the blue wells are in the basalt and are scattered throughout the model domain, while the green wells are located at the Facility. Water level hydrographs and the resulting linear trends for each of the 20 blue color-coded wells are shown on Figure 3.1.3-1. A domain-wide average rise in water levels of 0.00016 ft/d (1 foot in a little over 17 years) was obtained from this analysis. This is also consistent with the observation by TEC (2007) that water levels had not changed significantly in the recent past.

Table 3.1.2-1: General Characteristics of Water Level Data

		GW Elevation Data Characteristics			
Well ID	Well Name	Start Date	End Date	# of Data Points	Measurement Frequency
1954-01M	Honolulu Airport	10/28/1987	N/A	1	N/A
1955-03M	Honolulu Airport	10/28/1987	N/A	1	N/A
1956.01-01	Unknown	12/29/1972	N/A	1	N/A
3-1959-005	Fort Weaver Road	11/19/1968	10/1/2006	9,467	Daily
3-2051-002	Kamehameha School B	2/22/2000	—	1	N/A
3-2052-002	Kalihi	—	—	—	—
3-2052-008	Kalihi Shaft	—	—	—	—
3-2052-009	Fort Shafter	—	—	—	—
3-2052-010	Kapālama	1/31/2007	1/31/2015	110	~ Quarterly
3-2052-012	Jonathan Springs	6/1/1981	6/12/1981	2	NSMF
3-2052-013	Kapālama 2	11/25/1996	—	1	N/A
3-2052-014	Kapālama 1	1/6/1997	—	1	N/A
3-2052-015	Kalihi Shaft Deep Monitor	—	—	—	—
3-2053-001	Fort Shafter	—	—	—	—
3-2053-002	Fort Shafter	—	—	—	—
3-2053-003	Kalihi	—	—	—	—
3-2053-004	Fort Shafter	—	—	—	—
3-2053-005	Kalihi	—	—	—	—
3-2053-006	Fort Shafter	—	—	—	—
3-2053-007	Fort Shafter	—	—	—	—
3-2053-008	Kalihi	Apr-10	9/26/2013	143	NSMF
3-2053-009	Kalihi	—	—	—	—
3-2053-010	Fort Shafter Monitor	Dec-15	5/10/2017	284	Monthly
3-2053-011	Fort Shafter	11/16/1960	4/6/2017	109	Monthly
3-2053-012	Kalihi	—	—	—	—
3-2053-013	Fort Shafter	4/28/1995	5/3/1995	90	Hourly
3-2054-001	Pu'uloa Rd.	—	—	—	—
3-2054-002	Pu'uloa Rd.	—	—	—	—
3-2054-003	Pu'uloa Rd.	4/19/1965	N/A	1	N/A
2055.01-03	Unknown	10/19/1972	N/A	1	N/A
3-2055-001	Nimitz Hwy	9/26/1929	N/A	1	N/A
3-2055-002	Hickam A F Base	—	—	—	—
3-2055-003	Hon Intl Airport	—	—	—	—
3-2056-001	Hickam A F Base	—	—	—	—
3-2056-002	Hickam A F Base	—	—	—	—
3-2056-003	Hickam A F Base	—	—	—	—
3-2056-004	Valkenburgh 1	2/28/1989	N/A	1	N/A
3-2056-005	Valkenburgh 2	2/27/1989	N/A	1	N/A
3-2057-001	Hickam A F Base	—	—	—	—
3-2057-002	Hickam A F Base	—	—	—	—
3-2057-003	Hickam A F Base	—	—	—	—
3-2057-004	Hickam A F Base	—	—	—	—
3-2057-005	Hydrogen	—	—	—	—
3-2153-001	Moanalua	—	—	—	—
3-2153-002	Moanalua	Apr-10	9/26/2013	1,161	NSMF
3-2153-003	Ft Shafter	—	—	—	—
3-2153-004	Moanalua	—	—	—	—
3-2153-005	Moanalua Deep Monitor	3/13/1981	11/18/2016	8,721	Daily, 10 min
3-2153-006	Moanalua	—	—	—	—
3-2153-007	TAMC 1	5/1/2008	4/6/2017	102	Monthly
3-2153-008	TAMC 2	4/27/1945	5/10/2017	236	Monthly
3-2153-009	Moanalua	12/29/1945	11/18/2016	11,242	Daily, 10 min
3-2153-010	Moanalua 1	—	—	—	—
3-2153-011	Moanalua 2	—	—	—	—
3-2153-012	Moanalua 3	—	—	—	—
3-2153-013	TAMC-MW-2	4/29/2015	12/10/2017	184	Daily
3-2154-001	Honolulu International Country Club	10/24/1929	4/22/1969	3	NSMF
3-2155-001	Makalapa	—	—	—	—
3-2155-002	Makalapa	—	—	—	—
3-2155-003	Makalapa	—	—	—	—
3-2155-004	Makalapa	6/22/1941	N/A	1	N/A
3-2155-005	Makalapa	7/23/1948	N/A	1	N/A
3-2156-001	Makalapa	11/2/1933	N/A	1	N/A
3-2156-002	Makalapa	11/2/1933	N/A	1	N/A
3-2156-003	Makalapa	—	—	—	—
3-2156-004	Makalapa	—	—	—	—
3-2157-001	Pearl Harbor	—	—	—	—
3-2157-002	Pearl Harbor	1/10/1928	N/A	1	N/A
3-2157-004	Pearl Harbor	—	—	—	—
3-2250-001	Kalihi Aerator	—	—	—	—
3-2250-002	Kalihi II	—	—	—	—
3-2253-001	Red Hill	—	—	—	—
3-2253-002	Moanalua DH 43	1/5/1951	11/18/2016	6,036	10 min
3-2253-003	Hālawa Deep Monitor	5/15/2003	10/31/2017	41	NSMF
3-2253-004	RHMW06	4/22/2015	11/14/2017	17	NSMF
3-2253-005	RHMW07	4/23/2015	10/25/2017	4,181	~ Monthly, 10 min (2015 USGS study)
3-2253-009	RHMW10	5/4/2017	10/25/2017	4	Monthly

Well ID	Well Name	GW Elevation Data Characteristics			
		Start Date	End Date	# of Data Points	Measurement Frequency
3-2254-001	Red Hill Shaft	10/31/2002	10/24/2017	130	NSMF
3-2254-002	Hālawa	—	—	—	—
3-2255-001	Hālawa	—	—	—	—
3-2255-002	Hālawa	—	—	—	—
3-2255-003	Hālawa	—	—	—	—
3-2255-004	Hālawa	—	—	—	—
3-2255-005	Hālawa	9/24/1979	9/26/2017	3	~Daily
3-2255-006	Hālawa	—	—	—	—
3-2255-007	Hālawa	—	—	—	—
3-2255-008	Hālawa	—	—	—	—
3-2255-009	Hālawa	—	—	—	—
3-2255-010	Hālawa	—	—	—	—
3-2255-011	Hālawa	—	—	—	—
3-2255-012	Hālawa	—	—	—	—
3-2255-013	Hālawa	—	—	—	—
3-2255-014	Hālawa	—	—	—	—
3-2255-032	‘Aiea Hālawa Shaft	—	—	—	—
3-2255-033	Hālawa Obs.	1/5/1956	8/22/2017	12,019	Daily
3-2255-034	‘Aiea TH	—	—	—	—
3-2255-035	‘Aiea Refinery 1	1989	1994	2	NSMF
3-2255-036	‘Aiea Refinery 2	1989	N/A	1	N/A
3-2255-037	Hālawa 2	—	—	—	—
3-2255-038	Hālawa 3	—	—	—	—
3-2255-039	Hālawa 1	—	—	—	—
3-2255-040	Hālawa-BWS Deep Monitor	12/16/1996	1/23/2017	51	NSMF
3-2256-010	‘Aiea Navy	1/16/1928	3/15/2017	237,242	15 min
3-2256-011	‘Aiea	1/16/1928	1/15/1946	2	Daily
3-2256-012	‘Aiea	1/16/1928	9/3/2003	173	~ Bimonthly
3-2256-013	‘Aiea	3/12/1943	N/A	1	N/A
3-2354-001	Hālawa Shaft	4/1/2015	7/21/2015	16,444	10 min
3-2355-001	‘Aiea	—	—	—	—
3-2355-002	‘Aiea	—	—	—	—
3-2355-003	‘Aiea Gulch 1	—	—	—	—
3-2355-004	‘Aiea Gulch B	—	—	—	—
3-2355-005	‘Aiea Gulch 2	—	—	—	—
3-2355-006	‘Aiea 1	—	—	—	—
3-2355-007	‘Aiea 2	—	—	—	—
3-2355-008	Kalauao	—	—	—	—
3-2355-009	Kalauao P1	—	—	—	—
3-2355-010	Kalauao P4	—	—	—	—
3-2355-011	Kalauao P2	—	—	—	—
3-2355-012	Kalauao P3	—	—	—	—
3-2355-013	Kalauao P5	—	—	—	—
3-2355-014	Kalauao P6	—	—	—	—
3-2355-015	Ka‘amilo Deep Monitor	8/18/2012	11/14/2017	31,106	10 min
3-2355-016	WG Minami 2007	10/16/2007	10/19/2007	3	~ Daily
3-2356-044	‘Aiea	—	—	—	—
3-2356-049	Waimalu I-1	—	—	—	—
3-2356-050	Waimalu I-2	—	—	—	—
3-2356-051	Pearl Harbor	—	—	—	—
3-2356-052	Pearl Harbor	—	—	—	—
3-2356-053	Waimalu III	10/13/1959	4/26/2012	10	NSMF
3-2356-054	Pearl Country Club Golf	—	—	—	—
3-2356-055	Kaonohi I-2	—	—	—	—
3-2356-056	Kaonohi I-1	—	—	—	—
3-2356-057	Waimalu	11/14/1990	8/22/2017	12,277	Daily
3-2356-058	Ka‘amilo 1	—	—	—	—
3-2356-059	Ka‘amilo 2	—	—	—	—
3-2356-060	Waimalu II-1	—	—	—	—
3-2356-061	Kaonohi II-1	—	—	—	—
3-2356-062	Kaonohi II-2	—	—	—	—
3-2356-063	Waimalu II-2	—	—	—	—
3-2356-064	Waimalu II-3	—	—	—	—
3-2356-065	Kaonohi II-3	—	—	—	—
3-2356-066	Pearlridge B	—	—	—	—
3-2356-067	Pearlridge J	—	—	—	—
3-2356-068	Pearlridge K	—	—	—	—
3-2356-069	Pearlridge K1	—	—	—	—
3-2356-070	Lau Farm	5/15/1989	N/A	1	N/A
3-2357-001	Pearl Harbor	—	—	—	—
3-2357-003	Kalauao	—	—	—	—
3-2357-006	Waiau	—	—	—	—
3-2357-007	Waiau	—	—	—	—
3-2357-008	Waiau	—	—	—	—
3-2357-019	Waiau	—	—	—	—
3-2357-020	Waiau	—	—	—	—
3-2357-021	Waiau	4/4/1963	10/27/1981	159	~ Monthly
3-2357-022	Kalauao	—	—	—	—
3-2357-023	Ka‘ahumanu I-2	—	—	—	—

		GW Elevation Data Characteristics			
Well ID	Well Name	Start Date	End Date	# of Data Points	Measurement Frequency
3-2357-024	Kaʻahumanu I-1	—	—	—	—
3-2358-002	Pearl City	Apr-10	11/20/1974	967	~ Monthly
3-2358-019	Pearl City Peninsula	4/24/1944	10/28/2005	131	~ Bimonthly
3-2451-001	North Hālawa-DOT	9/19/1991	—	1	N/A
3-2455-001	Upper Waimalu	10/31/2002	2/28/2017	113	Monthly
3-2455-002	Waimalu	—	—	—	—
3-2455-003	Waimalu	—	—	—	—
3-2456-004	Newtown Deep Monitor	10/31/2000	6/12/2012	23	NSMF
3-2456-005	Waimalu Deep Monitor	2005	4/26/2012	4	NSMF
3-2457-004	Punanani DMW	11/26/1968	10/22/2013	92	NSMF
3-2558-010	Waiawa Shaft	2/1/2005	5/11/2017	2,936	Monthly
N/A	OWDFMW01	4/28/2006	10/26/2017	4,187	~ Monthly, 10 min (2015 USGS study)
N/A	RHMW01	2/17/2005	11/21/2017	147	~ 2x per month
N/A	RHMW02	9/8/2005	11/15/2017	159	~ 2x per month
N/A	RHMW03	9/7/2005	11/21/2017	152	~ 2x per month
N/A	RHMW04	7/26/2005	10/24/2017	4,173	~ Monthly, 10 min (2015 USGS study)
N/A	RHMW05	Jul-09	10/25/2017	130	~ 2x per month
N/A	RHMW08	10/19/2016	7/4/2017	12	Monthly
N/A	RHMW09	10/25/2016	10/24/2017	10	~ Monthly

— no data
N/A not applicable

3.1.4 Evaluation of Seasonal Trends

In addition to long-term temporal variability, WLE data show seasonal variations. Evaluation of seasonal changes was performed only on the blue color-coded wells because of their larger frequency of data collection through the year. The seasonal variability was evaluated on a monthly basis using a methodology that de-trends the long-term trends at a well as follows:

1. Compute the monthly WLE averages for each well. For this purpose, all relevant WLE data for each well were sorted by sampled month. Data for each month were then averaged to provide a monthly WLE average for all years of available data at the well.
2. Calculate an annual average WLE for each well by averaging the monthly averages.
3. Derive a Monthly WLE Deviation from Annual Average (Monthly WLE Deviation) for each well to determine how the monthly averages compared to the annual average. For this purpose, the annual average obtained in Step 2 was subtracted from the monthly average obtained in Step 1. Positive deviations indicate monthly observations are higher than the annual average WLE, while negative values indicate that the observation for the month was lower than the annual average.

The resulting Monthly WLE Deviation provided a measure for correcting the seasonal WLE variation in a well to the annual average conditions. Figure 3.1.4-1 shows the average monthly water level deviation for all the wells. Trends are more noticeable at wells where data density is large. In general, water levels are higher than the annual average for January through April and lower than the annual average for August through November.

A map of the annual trends and monthly deviations is shown on Figure 3.1.4-2. Long-term trends can be positive or negative throughout the model domain; however, the change is typically small. Seasonal fluctuations also vary among locations and deviations can be higher than half a foot from the annual average. The proximity of the measurements to pumping wells or shafts (or whether the measurement was in a pumping well) also affects the fluctuations.

3.1.5 Estimating Annual Average Water Levels for 2006, 2015, and 2017

WLE projections for annual average conditions were made at all well locations for the years 2006, 2015, and 2017 based on the long-term temporal trends corrected for seasonal variations. Water level availability at focus area wells for these years is shown in Table 3.1.5-1. Projected WLE for 2006, 2015, and 2017 are shown on Figures 3.1.5-1, 3.1.5-2, and 3.1.5-3, respectively. These projected water levels were used for contouring and as calibration targets for the model.

Table 3.1.5-1: Water Level Availability at Focus Area Wells

Well Name	2006	2015	2017
OWDFMW01	Measured	Measured	Measured
RHMW01	Measured	Measured	Measured
RHMW02	Measured	Measured	Measured
RHMW03	Measured	Measured	Measured
RHMW04	Measured	Measured	Measured
RHMW05	Interpolated	Measured	Measured
RHMW08	Interpolated	Interpolated	Measured
RHMW09	Interpolated	Interpolated	Measured
Hālawa Deep Monitor	Measured	Measured	Measured

Well Name	2006	2015	2017
RHMW06	Interpolated	Measured	Measured
RHMW07	Interpolated	Measured	Measured
RHMW10	Interpolated	Interpolated	Measured
Red Hill Shaft	Measured	Measured	Measured
Hālawa Shaft	Interpolated	Measured	Interpolated

Annual averages were computed for blue-shaded wells where the data were available for the year of interest. Because of the paucity of observed WLE data in all other wells, annual WLE projections were made as detailed below.

3.1.5.1 Blue-Shaded Wells

For blue-shaded wells, annual projections were estimated by the following procedure:

1. Using monthly deviations, adjust the available observed monthly average WLE to the annual average for the closest year of available data.
2. Using the long-term trend, adjust the WLE from the closest available year to 2006, 2015, and 2017 conditions.

3.1.5.2 Other Wells

For all other wells (green, yellow, and red color-coded wells that do not have data for the specific year), WLE projections were based on the average long-term temporal and seasonal trends of all 20 blue color-coded wells. The following procedure was used to estimate the WLEs:

1. Compute domain-wide monthly deviations as an average of the monthly deviations from all 20 blue color-coded wells.
2. Using the domain-wide monthly deviations, adjust the available observed monthly average WLE to the annual average for the closest year of available data.
3. Compute domain-wide long-term WLE trend as an average of the long-term WLE trend from all 20 blue color-coded wells.
4. Using the domain-wide long-term trend, adjust the WLE from the closest available year to 2006, 2015, and 2017 conditions.

3.1.6 Water Level Errors and Uncertainties

WLEs fluctuate over time. Fluctuations as much as 3 feet were observed at pumping wells depending on whether the pumps were on or off. In addition, monthly deviations from annual average conditions were noted to be more than half a foot at several monitoring wells. To evaluate the variation in data from the annual average conditions, the 95 percent confidence interval was estimated around the long-term trend line for each of the blue- and green-shaded wells. This confidence interval is presented in Table 3.1.6-1. The value reflects the two standard deviation range of the measurements, about a well's annual average WLE. Calibration target values should lie within this range. Considering that this range is large for the relatively flat reported water table gradients, multiple models were developed with different parameter ranges and alternate conceptualizations. Also, model calibration further investigated errors and biases and whether the simulations were protective of the various modeling objectives.

Table 3.1.6-1: Water Level Target Confidence Interval

Well ID	± 95% Confidence of WLE Deviation from Regression Line (ft msl)
1959-05	1.61
2052-10	1.33
2053-08	2.00
2053-10	1.84
2053-11	0.98
2153-02	1.83
2153-05	0.36
2153-07	0.95
2153-08	1.71
2153-09	0.55
2253-03	2.03
2254-01	2.99
2255-33	0.73
2255-40	1.46
2256-10	0.85
2355-15	0.36
2356-57	1.68
2358-19	1.55
2455-01	1.08
2457-04	2.42
2356-53	0.70
2456-04	2.79
OWDFMW01	0.38
RHMW01	1.30
RHMW02	1.70
RHMW03	1.73
RHMW04	0.27
RHMW05	0.99
RHMW06	0.57
RHMW07	0.12
RHMW08	0.37
RHMW09	0.71

Other errors and uncertainties in WLE measurements may include:

- Measurement errors
- Inaccuracies in datum elevations
- Extrapolating sparse measurements
- Random errors
- Transducer drift
- Daily barometric fluctuations (can be as much as 0.3 foot)

- Tidal fluctuations near the coast
- Localized errors
- Multiple measuring point elevations in a single well
- Well alignment

3.1.7 Water Level Contouring over Model Domain for 2006, 2015, and 2017

Using the projected WLE data obtained as described in the preceding sections, potentiometric surface maps were estimated by contouring the domain-wide data. Contouring was performed using the Surfer Software. A couple of iterations were performed, including adding six control points along the northwest and northeast boundary of the domain, to provide contours that were generally consistent with the regional interpretation of flow in the domain. Previous modeling efforts helped to guide the control point values. Water level contours for 2006, 2015, and 2017 are shown on Figures 3.1.7-1, 3.1.7-2, and 3.1.7-3, respectively. Water levels for 2017 were also used to evaluate the saltwater/freshwater interface depth.

What was indicated from the contours is that freshwater flow occurs from mountain to sea with shallow gradients within the basalt aquifer, and steeper gradients within the caprock. There is a cone of depression around Hālawa Shaft pumping. WLEs in the unconfined regions of the basalt aquifer are generally about 15 to 20 feet. There are several localized variations in WLE measurements within the caprock. The variations can be over 5 feet in short horizontal distances and may be attributed to localized variations in the caprock limestone aquifer, high vertical gradients within the caprock alluvial sediments, different measurement depths, and localized pumping within the caprock for golf course or landscape irrigation.

3.2 PUMPING

Pumping wells and water supply shafts within the model domain were identified, available pumping data was collected, and a QA/QC check was performed on the data.

3.2.1 Available Data within Model Area

Table 3.2.1-1 shows the general characteristics for the pumping data available for wells within the model domain. Data were obtained from a variety of sources including the BWS, Naval Facilities Engineering Command, Hawaii, the Commission on Water Resource Management, the State of Hawai‘i Department of Land and Natural Resources, the Navy, the National Groundwater Monitoring Network, and USGS. The table includes WLE data characteristics to compare the relative availability and frequency of measurements of the two datasets.

The pumping rates in the majority of wells were reported either monthly or more frequently; some were even reported at 10-minute intervals. On the other hand, the WLE information was obtained at more sparse time intervals and the time of data collection was often not noted. The data was further analyzed to evaluate data synchronicity and the impact of changes in extraction on water levels at the pumping well itself.

Table 3.2.1-1: Pumping Rate Data Characteristics

		GW Elevation Data Characteristics				Pumping Rate Data Characteristics				
Well ID	Well Name	Start Date	End Date	# of Data Points	Measurement Frequency	Start Date	End Date	# of Data Points	Measurement Frequency	GW and Pumping Rate Data Dates Overlap?
1954-01M	Honolulu Airport	10/28/1987	N/A	1	N/A	—	—	—	—	N/A
1955-03M	Honolulu Airport	10/28/1987	N/A	1	N/A	—	—	—	—	N/A
1956.01-01	Unknown	12/29/1972	N/A	1	N/A	—	—	—	—	N/A
3-1959-005	Fort Weaver Road	11/19/1968	10/1/2006	9,467	Daily	—	—	—	—	N/A
3-2051-002	Kamehameha School B	2/22/2000	—	1	N/A	1/2/2001	5/1/2017	197	Monthly	No
3-2052-002	Kalihi	—	—	—	—	—	—	—	—	N/A
3-2052-008	Kalihi Shaft	—	—	—	—	6/30/1937	8/1/2017	189,307	Monthly; 10 min	N/A
3-2052-009	Fort Shafter	—	—	—	—	—	—	—	—	N/A
3-2052-010	Kapālama	1/31/2007	1/31/2015	110	~ Quarterly	—	—	—	—	N/A
3-2052-012	Jonathan Springs	6/1/1981	6/12/1981	2	NSMF	12/1/1987	6/1/1997	102	Monthly	No
3-2052-013	Kapālama 2	11/25/1996	—	1	N/A	1/31/2004	2/1/2017	158	Monthly	No
3-2052-014	Kapālama 1	1/6/1997	—	1	N/A	5/1/2001	2/1/2017	82	Monthly	No
3-2052-015	Kalihi Shaft Deep Monitor	—	—	—	—	N/A	N/A	N/A	N/A	N/A
3-2053-001	Fort Shafter	—	—	—	—	—	—	—	—	N/A
3-2053-002	Fort Shafter	—	—	—	—	7/1/1929	12/31/1957	342	Monthly	N/A
3-2053-003	Kalihi	—	—	—	—	7/1/1929	12/31/1946	210	Monthly	N/A
3-2053-004	Fort Shafter	—	—	—	—	—	—	—	—	N/A
3-2053-005	Kalihi	—	—	—	—	1/1/1947	11/30/1988	473	Monthly	N/A
3-2053-006	Fort Shafter	—	—	—	—	7/1/1929	12/31/1958	354	Monthly	N/A
3-2053-007	Fort Shafter	—	—	—	—	—	—	—	—	N/A
3-2053-008	Kalihi	Apr-10	9/26/2013	143	NSMF	7/1/1929	5/13/2017	381	Monthly	Yes
3-2053-009	Kalihi	—	—	—	—	7/1/1929	6/30/1991	714	Monthly	N/A
3-2053-010	Fort Shafter Monitor	Dec-15	5/10/2017	284	Monthly	N/A	N/A	N/A	N/A	N/A
3-2053-011	Fort Shafter	11/16/1960	4/6/2017	109	Monthly	7/1/1927	4/30/2017	1,047	Monthly	Yes
3-2053-012	Kalihi	—	—	—	—	5/1/1968	6/30/1990	76	Monthly	N/A
3-2053-013	Fort Shafter	4/28/1995	5/3/1995	90	Hourly	2/1/2008	4/30/2008	3	Monthly	No
3-2054-001	Pu'uloa Rd	—	—	—	—	7/1/1929	7/31/1942	157	Monthly	N/A
3-2054-002	Pu'uloa Rd	—	—	—	—	7/1/1963	9/30/1964	15	Monthly	N/A
3-2054-003	Pu'uloa Rd.	4/19/1965	N/A	1	N/A	7/1/1965	6/30/1990	150	Monthly	No
2055.01-03	Unknown	10/19/1972	N/A	1	N/A	—	—	—	—	N/A
3-2055-001	Nimitz Hwy	9/26/1929	N/A	1	N/A	7/1/1929	12/31/1934	66	Monthly	Yes
3-2055-002	Hickam A F Base	—	—	—	—	—	—	—	—	N/A
3-2055-003	Hon Intl Airport	—	—	—	—	—	—	—	—	N/A
3-2056-001	Hickam A F Base	—	—	—	—	—	—	—	—	N/A
3-2056-002	Hickam A F Base	—	—	—	—	—	—	—	—	N/A
3-2056-003	Hickam A F Base	—	—	—	—	—	—	—	—	N/A
3-2056-004	Valkenburgh 1	2/28/1989	N/A	1	N/A	1/1/1990	12/31/2016	3	NSMF	No
3-2056-005	Valkenburgh 2	2/27/1989	N/A	1	N/A	1/1/1990	12/31/2016	3	NSMF	No
3-2057-001	Hickam A F Base	—	—	—	—	—	—	—	—	N/A
3-2057-002	Hickam A F Base	—	—	—	—	—	—	—	—	N/A
3-2057-003	Hickam A F Base	—	—	—	—	—	—	—	—	N/A
3-2057-004	Hickam A F Base	—	—	—	—	1/1/1990	5/31/2017	8	Monthly	N/A
3-2057-005	Hydrogen	—	—	—	—	3/1/2013	2/27/2014	7	NSMF	N/A
3-2153-001	Moanalua	—	—	—	—	7/1/1929	8/31/1958	350	Monthly	N/A
3-2153-002	Moanalua	Apr-10	9/26/2013	1,161	NSMF	7/1/1929	5/31/2017	696	Monthly	Yes
3-2153-003	Ft Shafter	—	—	—	—	—	—	—	—	N/A
3-2153-004	Moanalua	—	—	—	—	7/1/1929	12/31/1951	270	Monthly	N/A
3-2153-005	Moanalua Deep Monitor	3/13/1981	11/18/2016	8,721	Daily, 10 min	4/1/2015	6/30/2015	64	Daily	Yes
3-2153-006	Moanalua	—	—	—	—	10/1/1929	11/30/1967	458	Monthly	N/A
3-2153-007	TAMC 1	5/1/2008	4/6/2017	102	Monthly	7/1/1945	4/30/2017	831	Monthly	Yes
3-2153-008	TAMC 2	4/27/1945	5/10/2017	236	Monthly	—	—	—	—	N/A
3-2153-009	Moanalua	12/29/1945	11/18/2016	11,242	Daily, 10 min	4/1/2001	4/30/2001	1	N/A	Yes
3-2153-010	Moanalua 1	—	—	—	—	12/1/1974	2/28/2017	507	Monthly	N/A
3-2153-011	Moanalua 2	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2153-012	Moanalua 3	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2153-013	TAMC-MW-2	4/29/2015	12/10/2017	184	Daily	N/A	N/A	N/A	N/A	N/A
3-2154-001	Honolulu International Country Club	10/24/1929	4/22/1969	3	NSMF	7/1/1929	4/17/2017	825	~ Monthly	Yes
3-2155-001	Makalapa	—	—	—	—	—	—	—	—	N/A
3-2155-002	Makalapa	—	—	—	—	—	—	—	—	N/A
3-2155-003	Makalapa	—	—	—	—	—	—	—	—	N/A
3-2155-004	Makalapa	6/22/1941	N/A	1	N/A	1/1/1943	12/31/1977	420	Monthly	No
3-2155-005	Makalapa	7/23/1948	N/A	1	N/A	—	—	—	—	N/A
3-2156-001	Makalapa	11/2/1933	N/A	1	N/A	—	—	—	—	N/A
3-2156-002	Makalapa	11/2/1933	N/A	1	N/A	—	—	—	—	N/A
3-2156-003	Makalapa	—	—	—	—	—	—	—	—	N/A
3-2156-004	Makalapa	—	—	—	—	—	—	—	—	N/A
3-2157-001	Pearl Harbor	—	—	—	—	—	—	—	—	N/A
3-2157-002	Pearl Harbor	1/10/1928	N/A	1	N/A	—	—	—	—	N/A
3-2157-004	Pearl Harbor	—	—	—	—	—	—	—	—	N/A
3-2250-001	Kalihi Aerator	—	—	—	—	7/1/1990	2/28/2017	101	Monthly	N/A
3-2250-002	Kalihi II	—	—	—	—	—	—	—	—	N/A
3-2253-001	Red Hill	—	—	—	—	—	—	—	—	N/A
3-2253-002	Moanalua DH 43	1/5/1951	11/18/2016	6,036	10 min	—	—	—	—	N/A
3-2253-003	Hālawa Deep Monitor	5/15/2003	10/31/2017	41	NSMF	—	—	—	—	N/A
3-2253-004	RHMW06	4/22/2015	11/14/2017	17	NSMF	N/A	N/A	N/A	N/A	N/A

Well ID	Well Name	GW Elevation Data Characteristics				Pumping Rate Data Characteristics				GW and Pumping Rate Data Dates Overlap?
		Start Date	End Date	# of Data Points	Measurement Frequency	Start Date	End Date	# of Data Points	Measurement Frequency	
3-2253-005	RHMW07	4/23/2015	10/25/2017	4,181	~ Monthly, 10 min (2015 USGS study)	N/A	N/A	N/A	N/A	N/A
3-2253-009	RHMW10	5/4/2017	10/25/2017	4	Monthly	N/A	N/A	N/A	N/A	N/A
3-2254-001	Red Hill Shaft	10/31/2002	10/24/2017	130	NSMF	7/1/1942	5/31/2017	198,563	Hourly	Yes
3-2254-002	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-001	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-002	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-003	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-004	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-005	Hālawa	9/24/1979	9/26/2017	3	~Daily	—	—	—	—	N/A
3-2255-006	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-007	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-008	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-009	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-010	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-011	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-012	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-013	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-014	Hālawa	—	—	—	—	—	—	—	—	N/A
3-2255-032	ʻAiea Hālawa Shaft	—	—	—	—	4/26/2015	5/31/2015	4	NSMF	N/A
3-2255-033	Hālawa Obs.	1/5/1956	8/22/2017	12,019	Daily	N/A	N/A	N/A	N/A	N/A
3-2255-034	ʻAiea TH	—	—	—	—	—	—	—	—	N/A
3-2255-035	ʻAiea Refinery 1	1989	1994	2	NSMF	1/1/1957	12/31/1996	447	Monthly	Yes
3-2255-036	ʻAiea Refinery 2	1989	N/A	1	N/A	—	—	—	—	N/A
3-2255-037	Hālawa 2	—	—	—	—	7/1/1961	2/28/2017	668	Monthly	N/A
3-2255-038	Hālawa 3	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2255-039	Hālawa 1	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2255-040	Hālawa-BWS Deep Monitor	12/16/1996	1/23/2017	51	NSMF	N/A	N/A	N/A	N/A	N/A
3-2256-010	ʻAiea Navy	1/16/1928	3/15/2017	237,242	15 min	—	—	—	—	N/A
3-2256-011	ʻAiea	1/16/1928	1/15/1946	2	Daily	1/1/1924	12/31/1959	431	Monthly	Yes
3-2256-012	ʻAiea	1/16/1928	9/3/2003	173	~ Bimonthly	—	—	—	—	N/A
3-2256-013	ʻAiea	3/12/1943	N/A	1	N/A	—	—	—	—	N/A
3-2354-001	Hālawa Shaft	4/1/2015	7/21/2015	16,444	10 min	4/1/1943	8/1/2017	192,169	10 min	Yes
3-2355-001	ʻAiea	—	—	—	—	—	—	—	—	N/A
3-2355-002	ʻAiea	—	—	—	—	—	—	—	—	N/A
3-2355-003	ʻAiea Gulch 1	—	—	—	—	1/1/1956	2/28/2017	734	Monthly	N/A
3-2355-004	ʻAiea Gulch B	—	—	—	—	—	—	—	—	N/A
3-2355-005	ʻAiea Gulch 2	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2355-006	ʻAiea 1	—	—	—	—	1/1/1956	2/28/2017	734	Monthly	N/A
3-2355-007	ʻAiea 2	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2355-008	Kalauao	—	—	—	—	—	—	—	—	N/A
3-2355-009	Kalauao P1	—	—	—	—	11/1/1965	2/28/2017	615	Monthly	N/A
3-2355-010	Kalauao P4	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2355-011	Kalauao P2	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2355-012	Kalauao P3	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2355-013	Kalauao P5	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2355-014	Kalauao P6	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2355-015	Kaʻamilo Deep Monitor	8/18/2012	11/14/2017	31,106	10 min	N/A	N/A	N/A	N/A	N/A
3-2355-016	WG Minami 2007	10/16/2007	10/19/2007	3	~ Daily	6/9/2013	12/31/2016	34	Monthly	No
3-2356-044	ʻAiea	—	—	—	—	1/1/1945	12/31/1955	132	Monthly	N/A
3-2356-049	Waimalu I-1	—	—	—	—	1/1/1959	2/28/2017	514	Monthly	N/A
3-2356-050	Waimalu I-2	—	—	—	—	7/31/1956	2/28/2017	182	Monthly	N/A
3-2356-051	Pearl Harbor	—	—	—	—	—	—	—	—	N/A
3-2356-052	Pearl Harbor	—	—	—	—	—	—	—	—	N/A
3-2356-053	Waimalu III	10/13/1959	4/26/2012	10	NSMF	—	—	—	—	N/A
3-2356-054	Pearl Country Club Golf	—	—	—	—	7/1/1966	5/31/2017	572	Monthly	N/A
3-2356-055	Kaonohi I-2	—	—	—	—	10/1/1969	2/28/2017	569	Monthly	N/A
3-2356-056	Kaonohi I-1	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2356-057	Waimalu	11/14/1990	8/22/2017	12,277	Daily	—	—	—	—	N/A
3-2356-058	Kaʻamilo 1	—	—	—	—	1/1/1975	2/28/2017	468	Monthly	N/A
3-2356-059	Kaʻamilo 2	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2356-060	Waimalu II-1	—	—	—	—	4/1/1978	2/28/2017	221	Monthly	N/A
3-2356-061	Kaonohi II-1	—	—	—	—	1/1/2004	2/28/2017	59	Monthly	N/A
3-2356-062	Kaonohi II-2	—	—	—	—	10/1/2014	2/28/2017	29	Monthly	N/A
3-2356-063	Waimalu II-2	—	—	—	—	10/1/2014	2/28/2017	29	Monthly	N/A
3-2356-064	Waimalu II-3	—	—	—	—	10/1/2014	2/28/2017	29	Monthly	N/A
3-2356-065	Kaonohi II-3	—	—	—	—	4/1/1978	2/28/2017	246	Monthly	N/A
3-2356-066	Pearlridge B	—	—	—	—	—	—	—	—	N/A
3-2356-067	Pearlridge J	—	—	—	—	—	—	—	—	N/A
3-2356-068	Pearlridge K	—	—	—	—	—	—	—	—	N/A
3-2356-069	Pearlridge K1	—	—	—	—	—	—	—	—	N/A
3-2356-070	Lau Farm	5/15/1989	N/A	1	N/A	7/1/1987	3/28/2017	121	NSMF	No
3-2357-001	Pearl Harbor	—	—	—	—	—	—	—	—	N/A
3-2357-003	Kalauao	—	—	—	—	—	—	—	—	N/A
3-2357-006	Waiau	—	—	—	—	—	—	—	—	N/A
3-2357-007	Waiau	—	—	—	—	1/1/1970	12/23/2016	1	N/A	N/A
3-2357-008	Waiau	—	—	—	—	1/24/1980	1/6/2017	1	N/A	N/A
3-2357-019	Waiau	—	—	—	—	—	—	—	—	N/A

		GW Elevation Data Characteristics				Pumping Rate Data Characteristics				
Well ID	Well Name	Start Date	End Date	# of Data Points	Measurement Frequency	Start Date	End Date	# of Data Points	Measurement Frequency	GW and Pumping Rate Data Dates Overlap?
3-2357-020	Waiau	—	—	—	—	—	—	—	—	N/A
3-2357-021	Waiau	4/4/1963	10/27/1981	159	~ Monthly	7/1/1963	2/1/1976	123	Monthly	Yes
3-2357-022	Kalauao	—	—	—	—	7/1/1967	12/31/1969	30	Monthly	N/A
3-2357-023	Kaʻahumanu I-2	—	—	—	—	6/1/1978	2/28/2017	465	Monthly	N/A
3-2357-024	Kaʻahumanu I-1	—	—	—	—	1/1/2013	2/28/2017	50	Monthly	N/A
3-2358-002	Pearl City	Apr-10	11/20/1974	967	~ Monthly	—	—	—	—	N/A
3-2358-019	Pearl City Peninsula	4/24/1944	10/28/2005	131	~ Bimonthly	—	—	—	—	N/A
3-2451-001	North Hālawa-DOT	9/19/1991	—	1	N/A	—	—	—	—	N/A
3-2455-001	Upper Waimalu	10/31/2002	2/28/2017	113	Monthly	1/1/2001	1/31/2001	1	N/A	No
3-2455-002	Waimalu	—	—	—	—	5/4/2003	12/31/2016	97	Monthly	No
3-2455-003	Waimalu	—	—	—	—	5/4/2003	9/30/2016	90	Monthly	No
3-2456-004	Newtown Deep Monitor	10/31/2000	6/12/2012	23	NSMF	—	—	—	—	N/A
3-2456-005	Waimalu Deep Monitor	2005	4/26/2012	4	NSMF	—	—	—	—	N/A
3-2457-004	Punanani DMW	11/26/1968	10/22/2013	92	NSMF	—	—	—	—	N/A
3-2558-010	Waiawa Shaft	2/1/2005	5/11/2017	2,936	Monthly	1/1/1952	5/31/2017	3,665	Monthly	Yes
N/A	OWDFMW01	4/28/2006	10/26/2017	4,187	~ Monthly, 10 min (2015 USGS study)	—	—	—	—	N/A
N/A	RHMW01	2/17/2005	11/21/2017	147	~ 2x per month	—	—	—	—	N/A
N/A	RHMW02	9/8/2005	11/15/2017	159	~ 2x per month	—	—	—	—	N/A
N/A	RHMW03	9/7/2005	11/21/2017	152	~ 2x per month	—	—	—	—	N/A
N/A	RHMW04	7/26/2005	10/24/2017	4,173	~ Monthly, 10 min (2015 USGS study)	—	—	—	—	N/A
N/A	RHMW05	Jul-09	10/25/2017	130	~ 2x per month	—	—	—	—	N/A
N/A	RHMW08	10/19/2016	7/4/2017	12	Monthly	—	—	—	—	N/A
N/A	RHMW09	10/25/2016	10/24/2017	10	~ Monthly	—	—	—	—	N/A

— no data
N/A not applicable

3.2.2 Average Pumping for 2006, 2015, and 2017

Since the groundwater flow model is run for steady-state annual average 2006, 2015, and 2017 conditions, the available pumping rate data were averaged for the modeled years. Table 3.2.2-1 shows the averaged pumping rates. Zero pumping was applied in the model when data was not available for a particular year. Table 3.2.2-2 shows the screening intervals of the wells and associated modeled layers.

Annual average pumping rates over 7 mgd occur at both Kalihi Shaft and Hālawa Shaft; over 5 mgd occurs at Kalauao P1; and over [redacted] mgd occurs at RHS.

3.2.3 Water Levels and Pumping Rates for Synoptic Studies of 2006 and 2015

Synoptic water level and pumping rate measurements were made at several wells during a short time span in 2006, 2015, and 2017. These synoptic studies provide valuable information on the impact of well pumping at one location, to water levels at several locations regionally. From this impact, the connectivity between a pumping well and the water level observation can be established. The 2017 synoptic study was not available during preparation of the interim model and was therefore not evaluated further in the current modeling effort.

Figures 3.2.3-1 and 3.2.3-2 show the synoptic pumping and water level changes at the various wells for the 2006 and 2015 synoptic studies, respectively. This information will be used to evaluate the transient modeled behavior. Specifically, the modeled impact of pumping changes will be compared to observed impacts to note the simulated connectivity in relation to observations for various parts of the domain.

3.3 DRAWDOWN AND PUMPING IN HĀLAWA SHAFT AND RED HILL SHAFT

Pumping data was available for time increments as small as 10 minutes at RHS and Hālawa Shaft. Also, pumping rates at RHS can change at sub-daily time increments (pumping can cycle between on and off in as little as 8-hour periods), although changes at Hālawa Shaft were not that often. However, water level measurements at the shafts were not that frequent; therefore, it is important to understand the relationship between water level and pumping rates at the shafts themselves. This will have implications to steady-state model calibration, which considers annual average pumping at the public supply well locations for the years simulated (i.e., 2006, 2015, and 2017), while the average pumping rates during the water level measurements within the shafts may be different.

3.3.1 Synoptic Data Evaluation at Critical Water Supply Locations

Synoptic measurements of water level and pumping data at Hālawa Shaft and RHS were isolated and analyzed against pumping rates at the two shafts to determine the correlation between drawdown and pumping. In this analysis, there was very little synoptically measured data at either of these water supply shafts available at the time of interim model development. RHS data was infrequently scattered over the years and the timing of WLE measurements was often not clear. Hālawa Shaft data was focused within the short span of a month with thousands of synoptic measurements for pumping and water levels at a very high frequency.

Table 3.2.2-1: Annual Average Pumping Rate Statistics

Well Name	Well ID	Year	[redacted]	# of Data Points	Measurement Frequency	Measurement Start Date	Measurement End Date
Kalihi Shaft	2052-08	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	52,560	10 minutes	1/1/2015	12/31/2015
		2017	[redacted]	30,529	10 minutes	1/1/2017	8/1/2017
Kalihi	2053-08	2006	[redacted]	—	—	—	—
		2015	[redacted]	—	—	—	—
		2017	[redacted]	—	—	—	—
Fort Shafter	2053-11	2006	[redacted]	12	Monthly	1/1/206	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	4	Monthly	1/1/2017	4/30/2017
Hickam AF Base	2057-04	2006	[redacted]	—	—	—	—
		2015	[redacted]	—	—	—	—
		2017	[redacted]	5	Monthly	1/4/2017	5/31/2017
Moanalua	2153-02	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	5	Monthly	1/1/2017	5/31/2017
Moanalua	2153-05	2006	[redacted]	—	—	—	—
		2015	[redacted]	64	Daily	4/1/2015	6/30/2015
		2017	[redacted]	—	—	—	—
TAMC 1	2153-07	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	4	Monthly	1/1/2017	4/30/2017
Moanalua 1	2153-10	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Moanalua 2	2153-11	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Moanalua 3	2153-12	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
HNL Intl CC	2154-01	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	2	3 and 9.5 months	2/4/2015	10/14/2015
		2017	[redacted]	1	Once	1/28/2017	4/17/2017
Kalihi Aerator	2250-01	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Red Hill Shaft	2254-01	2006	[redacted]	8,760	Hourly	1/1/2006	12/31/2006
		2015	[redacted]	11,639	Hourly then 5 minutes	1/1/2015	12/31/2015
		2017	[redacted]	1,944	Hourly	1/1/2017	3/22/2017
Navy Hālawa	2255-32	2006	[redacted]	—	—	—	—
		2015	[redacted]	4	Weekly	5/7/2015	5/22/2015
		2017	[redacted]	—	—	—	—
Hālawa 2	2255-37	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Hālawa 3	2255-38	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Hālawa 1	2255-39	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Hālawa Shaft	2354-01	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	55,473	10 minutes	1/1/2015	12/31/2015
		2017	[redacted]	30,530	10 minutes	1/1/2017	8/1/2017
ʻAiea Gulch 1	2355-03	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
ʻAiea Gulch 2	2355-05	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
ʻAiea 1	2355-06	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
ʻAiea 2	2355-07	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kalauao P1	2355-09	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kalauao P4	2355-10	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kalauao P2	2355-11	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kalauao P3	2355-12	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kalauao P5	2355-13	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017

Well Name	Well ID	Year	[redacted]	# of Data Points	Measurement Frequency	Measurement Start Date	Measurement End Date
Kalauao P6	2355-14	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
WG Minami 2007	2355-16	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	—	—	—	—
Waimalu I-1	2356-49	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	monthly	1/1/2017	2/28/2017
Waimalu I-2	2356-50	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Pearl Country Club	2356-54	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	9	Monthly	1/1/2015	9/30/2015
		2017	[redacted]	3	1 and 2 months	1/1/2017	5/31/2017
Kaonohi I-2	2356-55	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kaonohi I-1	2356-56	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Ka'amilo 1	2356-58	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Ka'amilo 2	2356-59	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Waimalu II-1	2356-60	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kaonohi II-1	2356-61	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kaonohi II-2	2356-62	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Waimalu II-2	2356-63	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Waimalu II-3	2356-64	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Kaonohi II-3	2356-65	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Lau Farm	2356-70	2006	[redacted]	—	—	—	—
		2015	[redacted]	—	—	—	—
		2017	[redacted]	1	One time	3/1/2017	3/28/2017
Waiau	2357-08	2006	[redacted]	—	—	—	—
		2015	[redacted]	—	—	—	—
		2017	[redacted]	—	—	—	—
Ka'ahumanu I-2	2357-23	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Ka'ahumanu I-1	2357-24	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Waimalu	2455-02	2006	[redacted]	10	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	—	—	—	—
		2017	[redacted]	—	—	—	—
Waimalu	2455-03	2006	[redacted]	10	Monthly (skipping July & Aug)	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	—	—	—	—
Newtown 1	2456-01	2006	[redacted]	12	Monthly	1/1/2006	12/31/2006
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Newtown 2	2456-02	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	2/28/2017
Newtown 3	2456-03	2006	[redacted]	—	—	—	—
		2015	[redacted]	12	Monthly	1/1/2015	12/31/2015
		2017	[redacted]	2	Monthly	1/1/2017	8/1/2017

— no data

Table 3.2.2-2: Pumping Well Characteristics

Well Name	Well ID						Related Model (CLN cell) Layers
Kalihi Shaft	2052-08						2
Kalihi	2053-08						1
Fort Shafter	2053-11						2, 3, 4
Hickam AF Base	2057-04						1
Moanalua	2153-02						2, 3, 4
Moanalua Deep	2153-05						3, 4, 5, and below
TAMC 1	2153-07						2, 3, 4, 5
Moanalua 1	2153-10						4, 5
Moanalua 2	2153-11						4, 5
Moanalua 3	2153-12						4, 5
HNL Intl CC	2154-01						2, 3, 4
Kalihi Aerator	2250-01						1
Navy Hālawa	2255-32						2
Hālawa 2	2255-37						3, 4
Hālawa 3	2255-38						3, 4
Hālawa 1	2255-39						3, 4
‘Aiea Gulch 1	2355-03						2, 3
‘Aiea Gulch 2	2355-05	0					2, 3
‘Aiea 1	2355-06						3, 4
‘Aiea 2	2355-07						3, 4
Kalauao P1	2355-09						3, 4, 4
Kalauao P4	2355-10						3, 4, 5
Kalauao P2	2355-11						3, 4, 5
Kalauao P3	2355-12						3, 4, 5
Kalauao P5	2355-13						3, 4, 5
Kalauao P6	2355-14						3, 4, 5
WG Minami 2007	2355-16						2, 3
Waimalu I-1	2356-49						3, 4, 5
Waimalu I-2	2356-50						3, 4, 5,
Pearl CC	2356-54						3, 4
Kaonohi I-2	2356-55						3, 4, 5
Kaonohi I-1	2356-56						3, 4, 5
Ka‘amilo 1	2356-58						3, 4
Ka‘amilo 2	2356-59						3, 4
Waimalu II-1	2356-60						3, 4
Kaonohi II-1	2356-61						4, 5
Kaonohi II-2	2356-62						4, 5
Waimalu II-2	2356-63						3, 4, 5
Waimalu II-3	2356-64						3, 4
Kaonohi II-3	2356-65	0					4, 5
Lau Farm	2356-70						4
Waimalu	2455-02						1, 2, 3
Waimalu	2455-03						1, 2, 3
Hālawa Shaft	2354-01						3
Red Hill Shaft	2254-01						2

3.3.2 Relation between Drawdown and Pumping at Hālawa Shaft

Synoptic groundwater elevations and pumping rate measurements at the Hālawa Shaft were available for the November 2015 time period at time intervals as small as 10 minutes. These elevations were plotted against pumping rates as shown on Figure 3.3.2-1. Several observations lie on the same point in the chart, and therefore, there are over 700 synoptic data values in the figure. An excellent correlation of drawdown with pumping was observed. The good correlation between drawdown and water levels can also be attributed to a negligible time-lag noted between pumping and water level changes, and to the short duration of synoptic information such that weather influences were not reflected in the water level data. Figure 3.3.2-1 indicates a 4.38 feet water level drop for every 10 mgd increase of pumping at Hālawa Shaft (slope of the regression line).

Water level data for Hālawa Shaft was not available for 2006 and 2017, as noted in Table 3.1.5-1, and was estimated using model-wide trends. These projected water levels may not reflect those for average annual pumping conditions used in the model for each of the years. This unknown will reflect in calibration errors for water levels at Hālawa Shaft.

3.3.3 Relation between Drawdown and Pumping at Red Hill Shaft

At the RHS, very few synoptic data were available for each of the three modeled time periods. Although multiple synoptic measurements were available for 2015 and 2017, only two measurements were available for 2006 (which was within a 2-week period).

Similar to the Hālawa Shaft synoptic information, the water levels for RHS were plotted against the synoptic pumping rates as shown on Figure 3.3.3-1. The 2006 and 2017 data indicate 3.51 and 3.69 feet water level drop for every [redacted] mgd increase of pumping in RHS, respectively. However, the 2015 data showed a flatter relationship of 1.45 feet water level drop for [redacted] mgd increase in pumping. Upon closer examination of the data, several of the water level data had spurious measurement time values and the synchronicity of the measurements with pumping could not be determined. Thus, it is possible that many of the 2015 measurements were taken when the pumps were off for a period of time even though they were plotted for pumping conditions.

Table 3.3.3-1 shows the pumping and water level information obtained synoptically and for annual average conditions at RHS. The pumping rates at times when water levels were synoptically measured were higher than the annual average pumping rates. This lack of synchronicity will reflect in calibration errors at RHS. The issue is not alleviated even if transient simulations were performed with sub-daily time-steps for time periods beyond the synoptic studies performed in the region.

Table 3.3.3-1: Synoptic Pumping and Water Level Evaluation at Red Hill Shaft

Year	2006	2015	2017
Average WLE (ft)	16.68	16.87	18.76
Average Synoptic Pumping (mgd)	[redacted]	[redacted]	[redacted]
Average Annual Pumping (mgd)	[redacted]	[redacted]	[redacted]

3.4 WATER LEVEL GRADIENT AND DIRECTION

A key aspect of the current study is evaluation of water level gradients and directions because this controls how water from beneath the Facility would migrate in the domain and determines the source water zone for public supply wells in the region. Hydraulic gradient, in conjunction with hydraulic conductivity and anisotropy of the aquifer material, controls the flow of groundwater within an aquifer.

Hydraulic gradients and direction were evaluated at a local scale at Red Hill and at the regional scale surrounding Red Hill. At the local scale, a three-point gradient calculation approach was used, which represents the water levels between three wells as a plane. A contouring approach was applied to regional water level information to determine the regional water level gradients and directions. This contouring is separate from the model-wide contouring discussed in Section 3.1.7 and only evaluates the regional setting at Red Hill; domain-wide information or control points were not used. Structural controls can still impact flow at this scale, and the contours are simply interpolations of observed data.

3.4.1 Triangulation using November 2016 Synoptic Data and Annual Average 2006, 2015, and 2017 Water Levels

Under the three-point approach, a geometric plane is defined between three wells using the well coordinates and observed water level data. The maximum downward slope of this plane represents the hydraulic gradient while the direction of maximum slope is the direction in which water levels are declining.

For all wells at the local scale at Red Hill, the three-point solution method was used to evaluate the hydraulic gradients and directions using the EPA On-Line Tools for Site Assessment. The three-point gradients between trios of wells were evaluated using: https://cfpub.epa.gov/si/si_public_record_report.cfm? dirEntryId=287064. The average gradient of a best-fit plane through all of the wells was also computed using: https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/gradient4plus-ns.html.

These evaluations were performed for groundwater elevation data from the November 2016 synoptic study as well as for the annual average 2006, 2015, and 2017 conditions being evaluated by the model. 12 monitoring wells were used to create 15 different planes used for the evaluation. As shown on Figures 3.4.1-1 through 3.4.1-4, the monitoring wells included OWDFMW01, RHMW01 through RHMW09, and HDMW2253-03.

Overall, the local groundwater flow direction at the site is hard to interpret. As shown on Figures 3.4.1-1 through 3.4.1-4, a significant local spatial variation was observed, likely due to high localized heterogeneities compounded by flat hydraulic gradients. In general, however, flow directions for the various years are mostly similar to those of the synoptic study from November 2016. Therefore, there is consistency in directions between interpreted and measured synoptic data and between patterns of flow through the years.

Due to the high variability of flow directions at the local scale, the groundwater flow model will be used to further evaluate the general groundwater flow direction and magnitude at a local scale on Red Hill. Sensitivity analyses will provide a means to study the impact of uncertainty including different conceptual settings under extreme pumping conditions.

3.4.2 Contouring using 2006 Synoptic Data; Average 2006, 2015, and 2017 Water Levels; and 2006, 2015, and 2017 Steady-State Simulated Water Levels using a Consistent Methodology

TEC (2010) used a contouring approach to evaluate regional water level gradients at Red Hill using synoptic aquifer test data collected in May 2006. As noted in Section 1.2.4, their evaluation determined that there were regional water level gradient directions in the vicinity of the Facility to the west-northwest with a local southwest direction when RHS was pumping. TEC's (2010) approach was applied here to the 2006 synoptic data as well as to 2006, 2015, and 2017 annual average data to evaluate this approach and estimate regional long-term water level gradients as per this approach.

The synoptic data evaluated by TEC (2010) consisted of three distinct periods when RHS was not pumping, RHS was pumping at a maximum rate of [redacted] mgd, and RHS was pumping at an average rate of [redacted] mgd. Figure 3.4.2-1 shows the water level contouring for these three time periods, which is very similar to those of TEC (2010). Thus, the current study was able to reproduce the TEC (2010) results. These results can be interpreted as having regional northwest pointing gradients when RHS is not pumping with a local southwest pointing gradient when RHS is pumping.

Figure 3.4.2-2 shows the water level contours for 2006, 2015, and 2017 annual average conditions using the same set of wells and the same contouring methodology as was used for the May 2006 synoptic data. The annual average water level gradients and directions are similar to those in the synoptic study with regional northwest pointing gradients and a local southwest component along Red Hill. Therefore, at the regional scale, annual average flow directions for the various years are generally similar to those of the synoptic study from 2006 and there is consistency in directions between interpreted and measured synoptic data and between patterns of flow through the years.

Contouring of water levels does not account for subsurface flow conditions that are controlled by subsurface heterogeneity that includes the saprolite beneath the valleys. Therefore, the groundwater flow model will be used to evaluate the flow gradients at a regional scale around Red Hill. Sensitivity analyses will provide a means to study the impact of uncertainty including different conceptual settings under extreme pumping conditions.

3.5 SPRING LOCATIONS AND FLUXES WITHIN MODEL DOMAIN

Although 16 natural springs are located in the general vicinity of the site, only two springs (Pearl Harbor Spring at Kalauao and Kalauao Spring) are located within the modeling domain. Both of these springs were modeled as drainage conditions with a drain elevation of 10 feet. The drain conductance was a calibration parameter. Figure 3.5-1 shows the location and average flows of the individual springs. Figure 3.5-2 shows a close-up of the modeled Pearl Harbor and Kalauao springs.

To develop spring-flow targets for the 2006, 2015, and 2017 steady-state calibration periods, a regression was first evaluated between available flow data and groundwater elevations at the Navy 'Aiea well. Good correlations were noted at several springs by USGS studies including Oki (2005). Figures 3.5-3 and 3.5-4 show the scatterplot of water level at the Navy 'Aiea well versus spring-flow at Pearl Harbor Spring at Kalauao, and Kalauao Spring, respectively. There is a good correlation with flows at the Pearl Harbor Spring at Kalauao, and a reasonable correlation with flows at Kalauao Spring. Although the correlation is not as good, flow at Kalauao Spring itself is a small value and of small significance to the water budget in the domain.

Average water levels for the years 2006, 2015, and 2017 at the Navy 'Aiea well were then extracted from the database. This well has a long period of observation (since 1928) with frequency as high as 15 minutes (Table 3.1.2-1). The regression line equation gives corresponding spring-flow rates for the calibration stress periods as shown in Table 3.5-1.

Table 3.5-1: Spring-Flow Calibration Targets

Year	2006	2015	2017
WLE at Navy 'Aiea Well (ft msl)	18.28	16.26	18.03
Spring 22 – Pearl Harbor Spring at Kalauao (mgd)	12.123	9.556	11.805
Spring 25 - Kalauao Spring (mgd)	0.328	0.224	0.315

3.6 GROUNDWATER RECHARGE

Groundwater recharge estimates were developed for 2006, 2015, and 2017 to develop water budget estimates and provide input to the model. A recent study by the USGS provides average groundwater recharge estimates within the domain area (Izuka et al. 2018). This recharge distribution was scaled in accordance to annual precipitation to provide the stresses to the model. Scaling assumes that the precipitation of a year affects groundwater recharge within that same year, while other factors may also have an impact.

3.6.1 Average Recharge Distribution within Model Domain

The recharge distribution within the model domain was available from maps produced by the USGS (USGS 2017) as shown on Figure 3.6-1. The metadata for this map indicated that the distribution was representative of a dry period with updated land use information.

3.6.2 Estimating Recharge Scaling Factors for 2006, 2015, and 2017

To estimate groundwater recharge for the calibration stress periods, the distribution shown on Figure 3.6-1 was scaled according to observed rainfall in the modeled years 2006, 2015, and 2017. Scaling factors were developed as described below.

The precipitation data within the domain was evaluated to develop scaling factors for recharge for the modeled stress periods. Precipitation data were collected from four gaging stations in the general vicinity of the modeled area. The stations (station USC00510123, station 212428157511201, station 212359157502601, and station USC00516395) shown on Figure 3.6.1-1 were selected because they are located upstream in areas with higher rainfall and because they had data available from 2006 through 2017.

The scaling factors were developed as follows:

1. Average daily precipitation rates were obtained for the years 2005–2017 at each gaging station and are shown in Table 3.6.1-1.
2. An average of the 2005-2017 time period was also computed for each gaging station as shown in Table 3.6.1-1.
3. Recharge scaling factors were then estimated for each year at each gaging station as the ratio of the daily average obtained in Step 1 to the overall average obtained in Step 2. The recharge scaling factors were then averaged over all gage stations shown in Table 3.6.1-2.

The recharge scaling factors of 1.21, 1.19, and 0.85, respectively for 2006, 2015, and 2017, were used as initial values for distributing the USGS annual recharge shown on Figure 3.6-1. These factors were used to conceptualize the water budgets within the model domain and were adjusted during model calibration.

Table 3.6.1-1: Domain-Wide Rain Gage Precipitation Record

	Precipitation	Precipitation	Precipitation	Precipitation	
Year	USC00510123	212428157511201 (North Hālawa Rain Gage)	212359157502601 (Moanalua Rain Gage)	USC00516395	Daily Average
2005	0.18	0.36	0.18	0.09	in/day
2006	0.19	0.46	0.47	0.11	in/day
2007	0.18	0.34	0.31	0.09	in/day
2008	0.17	0.33	0.31	0.08	in/day
2009	0.11	0.38	0.38	0.06	in/day
2010	0.16	0.38	0.48	0.09	in/day
2011	0.20	0.39	0.37	0.11	in/day
2012	0.13	0.31	0.30	0.06	in/day
2013	0.16	0.45	0.44	0.10	in/day
2014	0.15	0.45	0.42	0.10	in/day
2015	0.18	0.48	0.45	0.11	in/day
2016	0.15	0.46	0.43	0.08	in/day
2017	0.13	0.32	0.33	0.08	in/day
Average	0.16	0.39	0.37	0.09	in/day

Table 3.6.1-2: Recharge Scaling Factors

	Factor	Factor	Factor	Factor	Average Factor
Year	USC00510123	212428157511201 (North Hālawa Rain Gage)	212359157502601 (Moanalua Rain Gage)	USC00516395	Average of gages
2005	1.120	0.917	0.482	1.009	0.882
2006	1.182	1.171	1.257	1.233	1.211
2007	1.120	0.866	0.829	1.009	0.956
2008	1.057	0.840	0.828	0.897	0.906
2009	0.684	0.958	1.018	0.672	0.833
2010	0.995	0.972	1.275	1.009	1.063
2011	1.244	0.997	0.982	1.233	1.114
2012	0.809	0.777	0.815	0.672	0.768
2013	0.995	1.135	1.169	1.121	1.105
2014	0.933	1.155	1.118	1.121	1.082
2015	1.120	1.218	1.194	1.233	1.191
2016	0.933	1.179	1.150	0.897	1.040
2017	0.809	0.815	0.883	0.897	0.851

3.7 NORTHEAST BOUNDARY INFLOW

Groundwater inflow from the northeast model boundary represents inflow from the dike intruded area. The lateral inflow was assumed to include all groundwater recharge that occurs between the northeast model boundary and the topographic divide. Integrating the recharge rate of Figure 3.6-1 over the area between the northeast model boundary and the topographic divide gives a volumetric rate of 22.4 mgd. Values in the range of 22 to 28 mgd were estimated using precipitation-based estimation methods and local rainfall data as shown in Table 3.7-1.

Table 3.7-1: Recharge Through Northeast Lateral Boundary from Dike Intruded Area

Resources/References	Precipitation Rate (in/year)	Calculated Volumetric Rate [c] (mgd)
Recharge Based on USGS Recharge Estimates (Engott et al. 2015)	124.72	22.4
Recharge Estimate from USGS North Hālawa Rainfall Data [a, c]	146.0	26.6
Recharge Estimate from USGS Moanalua Valley Rainfall Data [b, c]	138.7	24.3
Recharge Estimate from USGS Rainfall Data at Waiawa (Nichols, Shade, and Hunt Jr. 1996)	147.7	27.2

[a] USGS gauge #212428157511201.
[b] USGS gauge #212359157502601.
[c] Estimated for the area between the northeast boundary and the topographic divide.

The northeast boundary inflow was applied uniformly along the northeast boundary of the model.

3.8 CONCEPTUAL WATER BUDGET

The water budget for the model domain was estimated for annual average 2006, 2015, and 2017 conditions. Inflow and outflow from the various groundwater boundaries were evaluated to establish the water budget components of the domain.

Groundwater recharge and inflow from the northeast lateral boundary, discussed in Sections 3.6 and 3.7, respectively, are the only inflow components to the model domain.

Inflow and outflow from the lateral northwest and southeast boundaries were assumed to be negligible. This is because the stream valleys and underlying saprolite form low hydraulic conductivity barriers that are estimated to be several hundreds of feet below the water table in the valleys along the model's northwest and southeast boundaries.

Groundwater outflow is via pumping (discussed in Section 3.2), spring-flow (discussed in Section 3.5), and via diffuse seepage from the caprock into Pearl Harbor and the ocean. The diffuse seepage term was estimated from the water balance of the domain. Table 3.8-1 shows the annual water budget components for the simulation stress periods. Spring-flow was lowest in 2015 when water levels at the Navy ‘Aiea well were also lowest. Pumping approximately equaled areal recharge in 2006 and 2017 but was lower than recharge in 2015.

Table 3.8-1: Conceptual Water Balance Over the Model Domain

Year	2006	2015	2017
Recharge	43.11	42.40	30.30
NE Inflow	22.4	22.4	22.4
NW Inflow	0	0	0
SE Inflow	0	0	0
Well Discharge	43.12	37.93	31.46
Pearl Harbor Spring at Kalauao Discharge	12.12	9.56	11.81
Kalauao Spring Discharge	0.328	0.224	0.315
Seafloor Discharge	9.94	17.09	9.12

Note: Units are in mgd.

4. Numerical Model Development

The interim model was developed to assist with evaluation of the migration of potential solutes from the water table at the Facility and the source water zones of key nearby water supply wells and shafts. The modeling effort considers uncertainty in parameter and conceptual representations of the hydrogeologic system by evaluating several different conceptual models, boundary stresses, and parameter values that bracket the range of expected values at the site, via a sensitivity analysis that was calibration-constrained where possible. All models developed in this study were evaluated to understand the impact of uncertainty in model parameters or stresses on model calibration as well as on modeling results. Specific evaluations of migration and source water zones utilized models that were protective of the various potential receptor locations. In addition, extreme case pumping scenarios were considered for the model applications as a conservative approach.

MODFLOW-USG, the unstructured grid version (S. Panday et al. 2013) of the USGS modular finite-difference flow model (MODFLOW), was used to simulate the flow of groundwater. MODFLOW is a three dimensional, cell-centered, finite difference, saturated flow model that simulates both steady-state and transient groundwater flow. MODFLOW-USG, the unstructured grid version of MODFLOW, provides greater flexibility for gridding than prior versions. The model can provide additional resolution as required by use of nested grids. Linear features, such as wells and streams, and other complexities that affect groundwater flow can also be accommodated. GMS (Aquaveo LLC) was used as the pre- and post-processor and as the user interface to the MODFLOW-USG model.

Key model attributes, assumptions, and input data for the MODFLOW-USG models are listed below.

4.1 Domain and Horizontal Gridding

The model domain measured approximately 9 miles by 6 miles (Figure 4.1-1). The top of the model is the topographic surface and the bottom of the model was at the calculated location of the freshwater/saltwater interface. The model grid was oriented 200 degrees from north to align with the principal direction of anisotropy. A maximum grid size of 500 feet was employed for the parent grid, with quadtree refinements performed along the northwest and southeast lateral boundaries, through the valleys, along Red Hill, around the pumping wells, and along the RHS and Hālawa Shaft.

Quadtree refinement is a procedure used to focus grid resolution along points or line segments of interest. Based on the notion that any grid cell can be divided into four equally-sized cells (Sorab Panday et al. 2017), it allows for an efficient gridding, with finer resolution applied only where needed. In quadtree refinement, a one-level quadtree refinement implies splitting a grid cell into four equally-sized cells; a two-level refinement implies the further splitting of a one-level refined cell into four cells, etc. (Figure 4.1-2).

Quadtree refinement allows for a more accurate representation of known variations in hydraulic properties or boundary conditions and a better representation of hydraulic gradients around hydraulically important features (Sorab Panday et al. 2017). In GMS, the refinement procedure refines the grid in all layers. Therefore, the same refinement was maintained through all five model layers.

A two-level quadtree refinement was applied along the northwest and southeast lateral boundaries, decreasing the cell size from 500 to 125 feet. A two-level refinement was also used through the valleys and Red Hill to provide resolution on the saprolite thickness. A three-level refinement was used around the pumping wells, providing a cell size of 62.5 feet near the wells. To capture the groundwater interactions, a four-level quadtree refinement was applied along the Red Hill and Hālawa Shafts, reducing the grid size from 500-foot cells to 31.25-foot cells. Figure 4.1-3 depicts examples of the refinements around these features. The Discretization Package of MODFLOW-USG was used to define the model cells.

4.2 Model Layering

The modeled domain was divided into five layers as shown schematically on Figure 4.2-1.

Layer 1 discretizes the caprock in the downstream areas and the valley fill in the valleys. In regions where caprock or valley fill do not exist, the layer 1 cells were made inactive (i.e., layer 1 is not simulated). Topographic surface elevations served as the top of Layer 1 (or the top of Layer 2 where Layer 1 was absent). Figure 4.2-2 shows the topographic surface elevation across the model domain.

Top elevations of the weathered basalt (saprolite) underneath the valleys and of basalt beneath the caprock represented the bottom elevations for Layer 1. The active grid area of Layer 1 is shown on Figure 4.2-3 (Panel A). The inactive areas in Layer 1 are regions where basalt is unconfined. Layer 1 thickness contours are shown on Figure 4.2-4.

The saprolite and basalt were discretized into Layers 2, 3, 4, and 5. Saprolite was simulated to exist only underneath the valleys, with the remaining area simulated as unweathered basalt. Also, the model was conservatively constructed so that the saprolite was present only in layers 2 and 3 with unweathered basalt underneath. The bottom elevation of layer 3 beneath the valleys, which represents the bottom of the saprolite, was simulated at about 60 feet below the water table. This is a conservative estimate for the depth of the saprolite barrier because saprolite beneath South Hālawa Valley was noted to be considerably deeper near the Facility and is expected to be deeper still nearer to the coast.

Multiple model layers in the saturated portions of the basalt were used to provide a finer vertical resolution for capturing vertical flow gradients. A finer vertical discretization was provided near the water table to accommodate better resolution for groundwater flow and transport near the water table. The maximum saturated thickness of the numerical model layers increased with depth to reduce the total number of cells in deeper regions that are of less interest to the current study.

Layer 2 top elevations were defined by the bottom elevations of Layer 1 where Layer 1 is present, and by the topographic surface elevations in areas where Layer 1 is inactive. The bottom elevations of Layers 2, 3, and 4 follow the basalt-caprock interface where the basalt is confined, and follow the approximate water table elevation where caprock is absent. This allows for maintaining a fine vertical cell-size resolution near the water table and limits the number of dry cells above the water table. The dip in the basalt structure is slightly larger; however, MODFLOW equations strictly represent groundwater flow in the horizontal and vertical directions. Therefore, the dip in the layering of unconfined basalt is not consequential. Furthermore, vertical freshwater level gradients were relatively small except within saprolite, across the caprock, or near pumping locations as also noted in the USGS (Oki 2005) model.

Layer thicknesses of Layers 2, 3, 4, and 5 varied as shown on Figures 4.2-5, 4.2-6, 4.2-7, and Figure 4.2-8, respectively. The thickness of these layers pinches out toward the coast where the saltwater interface is above the layer surface as noted on the schematic of Figure 4.2-1. Model cells that lie below the bottom of the domain were inactivated as noted on Figure 4.2-3 (Panels B, C, D, and E). The bottom elevation of the model domain is shown on Figure 4.2-9.

4.3 Model Parameterization

The major stratigraphic units delineated within the model include the caprock, valley fill, saprolite, and basalt. The stratigraphic interface elevations were estimated as detailed in the CSM report and summarized in Section 2.2.1. These elevations were used to delineate the material layers for caprock and valley fill, from the basalt in the model.

Homogeneous material properties were assigned to the caprock in most of the model evaluations that were conducted for the current study. The material was modeled as horizontally isotropic with vertical anisotropy resulting from the alluvial and marine depositional environments of the aquifer sub-units that form the caprock. This is similar in conceptualization to the TEC (2007) study. Sensitivity studies were also conducted to determine the impact of uncertainty in the parameter values. A sensitivity study further zoned the caprock into inland alluvial sediments and coastal marine sediments (as was done by the USGS, 2005 model) to note the impact on calibration and on the migration/source zone evaluations.

Most of the model evaluations that were conducted for the current study used homogeneous properties to represent the basalt. There are data available at Red Hill indicating local scale heterogeneities; however, there is not much information available to indicate how these propagate at the regional scale. Information at the regional scale is obtained from the geologic CSM, which indicates that the basalt has a regional anisotropy with higher hydraulic conductivities in the direction of lava flow (to the southwest) that are several times higher than in the directions transverse to lava flow (to the northwest or southeast) – contributing factors also include the clinker zones that are generally aligned with the direction of lava flow. Information at the site (local scale beneath the Facility) is also obtained from a historical hydrogeologic log of the RHS water development tunnel and from other borings, which are integrated in the hydrogeologic conceptual model, that indicate a clinker zone under the Facility that extends to the RHS. Also, the main modeling objectives for the interim model are at the regional scale – whether water from beneath the Facility is captured by the regional pumping wells and not about flow variations locally beneath the Facility itself. Past studies (Souza and Voss 1987; Gingerich and Voss 2005; Oki 2005; TEC 2007, 2010) have indicated that homogeneous parameterization, along with strong anisotropy in the southwest direction, was adequate to describe the aquifer conditions at the regional scale. These studies also guided initial model parameter values that were then changed during model calibration.

After developing the first of the models, sensitivity analyses were conducted to evaluate the impact of parameter uncertainty on the model results. Sensitivity analyses also included evaluation of the impact of local scale heterogeneities at Red Hill. Specifically, a sensitivity model was developed that included a clinker zone conceptualized to exist under Red Hill. Indicators of the presence of this clinker zone include very flat water level gradients upstream of the RHS and an unusually high water production zone intercepted by the water development tunnel connected to RHS. This model is more protective of RHS because the high conductive clinker zone directs flow along it toward the shaft thus providing a worst-case scenario for RHS. The other models are, however, more protective of Hālawa Shaft because they do not explicitly include a clinker zone beneath Red Hill that could cause groundwater to more likely flow to toward RHS, thereby reducing the opportunity for simulating flow in the transverse direction toward Hālawa Shaft or the Moanalua wells.

Basalt was simulated as horizontally and vertically anisotropic. The basalt lateral Kh along the direction of lava flows is several times greater than in the transverse direction to the lava flows (Oki 2005). This is because of local scale and grid-block scale heterogeneities, which include clinker formations that are much longer in the longitudinal direction and have small vertical thickness. A HANI of 0.33 was simulated to provide a hydraulic conductivity in the lateral direction that was

3 times larger than in the transverse direction for most of the models. Kv was orders of magnitude lower than the longitudinal Kh. Sensitivity analyses were also conducted to analyze the impact of varying these parameters.

The valley fill and saprolite were modeled as horizontally isotropic. The Kv value of these units was lower than the Kh. The saprolite, where it exists, was modeled as having a lower hydraulic conductivity at shallower depths (in layer 2) than at deeper depths (in layer 3). Around Red Hill, the shallower saprolite zone in layer 2 was up to about 30 feet below the water table and the deeper zone was another 60 feet below the water table as per the numerical model grid layering beneath the valley. Valley fill and saprolite material properties were estimated from literature and calibrated to a qualitative evaluation of the water levels within, as there were few observations within them; furthermore, their material values did not significantly impact simulated water levels or gradients in the basalt. Most models used the higher hydraulic conductivity estimates for saprolite that would provide less of a barrier effect to be conservative in terms of allowing simulated flow to occur through the saprolite barriers. Sensitivity analyses further determined the impact of variations in these material property values.

The Layer Property Flow (LPF) package of MODFLOW was used to parameterize the model. The LPF package includes capability for horizontal and vertical anisotropy. The upstream weighted scheme of the LPF package was used to solve the groundwater flow equations. This approach helps with convergence and dry-cell issues as compared to the other options.

Particle tracking simulations also require estimates of the effective transport porosity to determine travel times. Previous modeling studies and literature estimates were used to quantify the effective porosity of the modeled geologic materials. Sensitivity simulations were not conducted to evaluate the impact of porosity values because it is straightforward. The travel time is linearly related to porosity (doubling the porosity of a material zone doubles the travel time within that zone); however, there is no impact of porosity to flow directions.

4.4 MODEL BOUNDARY CONDITIONS

Model boundary conditions include inflow of water to the domain, and outflow of water from the domain. Inflow occurs as a result of areal groundwater recharge and inflow from lateral model boundaries. Outflow occurs as a result of pumping, seeps and springs, and diffuse seepage into Pearl Harbor and the ocean.

Groundwater recharge was estimated for annual average 2006, 2015, and 2017 conditions using a recharge distribution map prepared by the USGS and scaling factors for each year depending on precipitation, as detailed in Section 3.6. The scaling factors were adjusted during calibration. The calibrated recharge values were used for the respective annual average conditions as well as for the synoptic studies in the respective years and applied in the model using the RCH: Recharge Package of MODFLOW. Sensitivity analyses determined the impact of a range of recharge values applied to the model.

A flux boundary condition was applied along the northeast lateral model boundary using the WEL package of MODFLOW. Inflow from the northeast boundary was estimated by considering groundwater recharge up to the topographic divide, as detailed in Section 3.7 and shown on Figure 3.6-1. The flux was assumed to be the same for 2006, 2015, and 2017 as being controlled by the more stable water levels behind the dike intruded area than the precipitation of that year. Sensitivity models also evaluated the impact of this boundary uncertainty. Prescribing heads (via constant head or GHB conditions) were not applied along this boundary as that would constrain the model to the estimated head values at the boundary.

Water flow across the lateral northwest and southeast boundaries is relatively small since they parallel the conceptualized flow direction from mountain to sea. This flow could be in or out depending on pumping and gradients of water levels near the boundary. The northwest and southeast lateral boundaries were simulated using the GHB Package of MODFLOW to allow water to flow in and out. For most models, the GHB head values were set according to the water level contouring discussed in Section 3.1.7. A low GHB conductance was set for several of the models to provide minimal flows across this. Sensitivity analyses were also conducted to determine the impact of these flows due to uncertainty in this boundary condition, in terms of the boundary head as well as GHB conductance.

The springs within the model domain were represented using the DRN: Drain Package of MODFLOW. Spring fluxes that were estimated in Section 3.5 were used to calibrate the model. A drain elevation of 10 feet above msl was used at both Kalauao Spring and Pearl Harbor Spring at Kalauao, which are within the model domain.

Water supply wells and shafts within the model domain were simulated using the CLN package of MODFLOW-USG, which simulates vertical or horizontal conduit features such as wells and shafts. The wells may be screened in multiple model layers, and shafts may cross multiple model cells. Withdrawals are then applied to the CLN cell using the WEL package of MODFLOW. The "AUTOFLOWREDUCE" option of the well package was used to prevent water levels from going below the well bottom elevation, and model outputs were checked to ensure that all pumping was appropriately simulated. Pumping information within the model domain was assimilated as detailed in Section 3.2 for input to the model.

Diffuse discharge into Pearl Harbor and offshore regions of the model domain was simulated using the GHB Package of MODFLOW. The GHB head of 0 feet was provided and the GHB conductance was a calibration parameter.

4.5 SIMULATION SETUP

The model was run in steady-state mode for three stress periods representing annual average 2006, 2015, and 2017 conditions.

The model was also run in transient mode for the 2006, 2015, and 2017 synoptic studies. Starting water levels for the synoptic study evaluations were obtained from the respective steady-state simulation results. Stress periods and time stepping for evaluation of the 2006 and 2015 synoptic studies are shown in Tables 4.5-1 and 4.5-2, respectively. The 2006 synoptic study simulation time-stepping and stress periods follow those used in the TEC (2007) study.

The XMD linear solver option of the Sparse Matrix Solver Package of MODFLOW-USG was used in the simulations. A Newton-Raphson linearization scheme was used to resolve nonlinearities in a robust manner. The Sparse Matrix Solver parameters used for the simulations are shown in Table 4.5-3.

Table 4.5-1: Stress Periods and Time Stepping for Simulation of 2006 Synoptic Study

Stress Period No.	Start (day)	Length (day)	Number of Time Step	Multiplier
1	0	131.5801311	1	1.45
2	131.5801411	6.7981056	10	1.45
3	138.3782567	0.0328964	3	1.45
4	138.4111631	0.0668766	6	1.45
5	138.4780497	0.0479703	5	1.45
6	138.52603	0.2292258	8	1.45
7	138.7552658	0.3125274	10	1.45
8	139.0678032	0.3542731	10	1.45
9	139.4220863	0.6794786	15	1.45
10	140.1015749	0.4297708	10	1.45
11	140.5313557	0.4722764	10	1.45
12	141.0036421	0.5478208	13	1.45
13	141.5514729	0.4520771	10	1.45
14	142.00356	0.5574205	13	1.45
15	142.5609905	0.0024648	2	1.45
16	142.5634653	0.0476774	3	1.45
17	142.6111527	0.1058743	5	1.45
18	142.717037	0.3721338	10	1.45
19	143.0891808	0.4846893	10	1.45
20	143.5738801	0.4401681	10	1.45
21	144.0140582	0.6765815	14	1.45
22	144.6906497	0.3368678	8	1.45
23	145.0275275	0.478543	10	1.45
24	145.5060805	0.005578	3	1.45
25	145.5116685	0.9528402	20	1.45
26	146.4645187	0.0726372	6	1.45
27	146.5371659	2.5967783	25	1.45

Table 4.5-2: Stress Periods and Time Stepping for Simulation of 2015 Synoptic Study

Stress Period No.	Start	Length (day)	Number of Time Step	Multiplier
1	4/30/2015 0:00	1	1	1
2	5/1/2015 0:00	1	1	1
3	5/2/2015 0:00	1	1	1
4	5/3/2015 0:00	1	1	1
5	5/4/2015 0:00	1	1	1
6	5/5/2015 0:00	1	1	1
7	5/6/2015 0:00	1	1	1
8	5/7/2015 0:00	1	1	1
9	5/8/2015 0:00	1	1	1
10	5/9/2015 0:00	1	1	1
11	5/10/2015 0:00	1	1	1
12	5/11/2015 0:00	1	1	1
13	5/12/2015 0:00	1	1	1
14	5/13/2015 0:00	1	1	1
15	5/14/2015 0:00	1	1	1
16	5/15/2015 0:00	1	1	1
17	5/16/2015 0:00	1	1	1
18	5/17/2015 0:00	1	1	1
19	5/18/2015 0:00	1	1	1
20	5/19/2015 0:00	1	1	1
21	5/20/2015 0:00	1	1	1
22	5/21/2015 0:00	1	1	1
23	5/22/2015 0:00	1	1	1
24	5/23/2015 0:00	1	1	1
25	5/24/2015 0:00	1	1	1
26	5/25/2015 0:00	1	1	1
27	5/26/2015 0:00	1	1	1
28	5/27/2015 0:00	1	1	1
29	5/28/2015 0:00	1	1	1
30	5/29/2015 0:00	1	1	1
31	5/30/2015 0:00	1	1	1
32	5/31/2015 0:00	1	1	1

Table 4.5-3: Input Parameters for SMS Solver

MODFLOW SMS Solver

Comments (Text):

Solver options: Show all solver input rows

Max head change between outer iterations (L) (HCLOSE)	0.0001
Max head change between inner iterations (L) (HICLOSE)	1.0e-006
Max number of outer nonlinear iterations for problem (MXITER)	500
Max number of inner linear iterations for problem (ITER1)	600
Print additional info to listing file (IPRSMS)	(1) print summary
Nonlinear solution method (NONLINMETH)	(1) Newton with Delta-Bar-Delta
Linear matrix solver (LINMETH)	(1) xMD
Options (OPTIONS)	SPECIFIED
Delta-bar-delta learning rate reduction factor (THETA)	0.7
Delta-bar-delta learning rate increment (AKAPPA)	0.1
Delta-bar-delta memory term factor (GAMA)	0.02
Nonlinear fraction history added (AMOMENTUM)	0.0
Maximum residual backtracking iterations (NUMTRACK)	20
Residual change tolerance (BTOL)	1.2
Residual change reduction size (BREDUC)	0.2
Residual reduction limit (RESLIM)	1.0
Acceleration method (IACL)	(1) ORTHOMIN
Ordering scheme (NORDER)	(0) original ordering
ILU decomposition level of fill (LEVEL)	12
Number of orthogonalizations for ORTHOMIN accel. (NORTH)	14
Reduced system (IREDSYS)	(0) do not apply
Residual tolerance criterion (RRCTOL)	0.0
Perform drop tolerance (IDROPTOL)	(1) perform
Drop tolerance value (EPSRN)	0.0001

5. Groundwater Flow Model Calibration

The interim model was designed to evaluate the movement of groundwater from underneath the Facility and the source water zone of water supply wells and shafts in the area. A multi-model approach was used to evaluate impacts of conceptual and numerical approximations and parameter or boundary uncertainties as detailed later. The models were developed and calibrated based on the best available estimates of input parameters, material properties, hydrogeologic data, and boundary conditions.

Calibration is the process of adjusting model parameters until the differences between modeled outputs and site-specific data are reduced to an acceptable level. Both quantitative and qualitative comparisons were made between the model and site-specific information. Quantitative comparisons included statistical evaluations of simulated conditions as compared to observations. Qualitative comparisons included comparison of simulated groundwater level contours with interpolated and conceptual water level distributions, and of changes in water levels in the transient simulations.

Examination of calibration of a model is subjective even though quantitative calibration metrics are prescribed. The calibrated models were therefore examined further to note the impact of errors on the flow-field and to evaluate if the simulated flow-field was conservative/protective (or not) for the various modeling objectives.

5.1 MODEL CALIBRATION AND SENSITIVITY APPROACH

5.1.1 Steady-State Model Calibration

Calibration was conducted using an expert interactive (manual trial-and-error) approach as well as automatic parameter estimation using PEST:

1. First, an expert interactive calibration was performed to average steady-state conditions for 2006, 2015, and 2017. This allowed for an assimilation of long-term trends for three different years, an understanding of the modeled groundwater flow dynamics, and a preliminary evaluation of parameter sensitivities. Expert interactive calibration also helped to evaluate simulation behavior, tune solver parameters, and provide a rough preliminary calibration.
2. Next, using the insights obtained from the manual calibration, an automated calibration was performed using the parameter estimation code PEST. PEST is a non-linear inverse modeling program that automatically runs the MODFLOW-USG model multiple times, by varying selected input parameters and performing optimization, until the difference between the model outputs and the site-specific observation targets is minimized. PEST was employed to fine-tune manual calibrations, explore the impacts of different calibration targets (by adjusting their weights), and evaluate the significance of various material parameters. Parameters calibrated using PEST included:
    a. The Kh and Kv in the basalt
    b. The Kh and Kv in the caprock
    c. Recharge factors for annual average 2006, 2015, and 2017 conditions
    d. The GHB conductances for two zones, one within Pearl Harbor and the other outside the bay to the south

5.1.2 Capturing Model Uncertainty

A modeling effort for this area, for the current objectives, is challenging due to extremely flat water level gradients, high hydraulic conductivities, large local-scale heterogeneities, and scarcity of model-wide synoptic water level and pumping data. Therefore, along with reasonably conservative assumptions of model development and calibration, a multi-model evaluation was conducted to assess the impact of uncertainty in conceptualization, numerical implementation, parameter values, water levels, and synchronous stresses on groundwater flow. All models were then considered in the groundwater migration and particle tracking analyses and conservative/protective models were considered in further evaluations for the relevant objectives with the understanding that different models may be more protective of the different objectives.

The first calibrated model (Model #1) was the most probable case depicting average site conditions at the time it was developed. Model parameters for Model #1were within established ranges for the various hydrogeologic properties of the aquifer materials as determined from prior field investigations and modeling studies. Therefore, additional models that were developed for this study investigated the impact of extreme values for specific model parameters while recalibrating remaining parameters, still within established ranges. Yet other models examined the impact of local scale heterogeneities and conceptual uncertainties of various boundary conditions and stresses. As further models were developed, they considered the experience gained from prior models, as well as an improved understanding of the system obtained from more recent data collection efforts and analyses provided by the GWMWG. Therefore, the multi-model approach provides a collection of probable models that explain the data and flow conceptualization within the domain, and attempts to address various questions and concerns that arose in GWMWG meetings during analyses of the complex available local hydrogeologic data still being collected at Red Hill.

Development of the multiple models for the interim modeling study was conducted in a systematic manner. A traditional sensitivity analysis was first conducted on an individual parameter (or set of parameters) by changing the values to reasonable lower and/or upper bounds considering hydrogeologic judgment and past reporting, and noting the associated impact on calibration. Sensitivity analyses were also conducted on alternate conceptual representations or boundary uncertainties in a similar manner. If the model was sensitive, it was roughly recalibrated to 2006, 2015, and 2017 conditions by varying specific other parameter values within reasonable limits. The model was considered acceptable if a reasonable calibration could be obtained with the modified setup or conceptualization. The model behavior was further reviewed to note whether the flow-field was generally consistent with the conceptual model and to evaluate whether the model was conservative/protective of the various simulation objectives.

5.1.3 Transient Model Evaluations

Transient model calibration was conducted using data from the synoptic studies of 2006 and 2015 rather than the sparsely available long-term data. These synoptic studies were the only available data where water levels and pumping were known simultaneously and fairly continuously to enable quantification of effective hydraulic parameters between pumping and observation wells. Calibration to long-term transient conditions was considered but not performed because it would not provide a better model to address the modeling objectives for the following reasons:

- Available long-term water level measurements are sparse.
- Sub-daily pumping variations employed in a long-term transient model would also be averaged to the time-scale of the simulation as is the case for the steady-state simulations of annual average conditions.
- Although the estimated recharge and pumping rate inputs can be varied and adjusted to match the long-term transient water level data, little is achieved by this in constraining the model.
- Uncertainty in the raw data inputs (synoptic long-term transient water levels and pumping) and of hydrogeologic conditions at the instant data was collected, cause a deviation of the signal from the underlying trends resulting in noise in the information.
- Calibration to long-term transient conditions would not provide any additional insights or increase the applicability of the groundwater flow model for significantly more effort.

Transient model calibration was first conducted using Model #1 with reasonable values of storage parameters as determined by previous modeling efforts (USGS, 2005, DON, 2007). Transient behavior of the system was then compared to those of the 2006 and 2015 synoptic studies.

Multiple models were also evaluated using the transient information from the 2006 synoptic study. First, a traditional sensitivity analysis was conducted to the storage parameters by varying them within reasonable ranges using Model #1 to note if modeled behavior bracketed observed changes in water levels. Select other calibrated models were also evaluated in transient mode to note if their behavior bracketed observed transient changes.

The calibration details of Model #1 are reported below. Several of the alternate models that were developed were not particularly sensitive and therefore all the details are not reproduced for all of these models. Rather, the similarities of the alternate models to Model #1 are noted and differences highlighted, so that the hydrogeologic behavior of these other models can be understood in a comparative manner.

5.2 Calibration Metrics and Targets

The steady-state models were calibrated to average 2006, 2015, and 2017 conditions. Sufficiency of the calibration was based on both qualitative and quantitative metrics.

Qualitative steady-state calibration metrics included evaluation of:

- Potentiometric surfaces compared to the flow patterns in the conceptual model
- Hydraulic gradients using a consistent contouring methodology
- Spring fluxes
- Key head differences
- Spatial bias
- Water budget terms against the conceptual model water budgets

Quantitative steady-state calibration metrics included evaluation of:

- Model-wide water level statistics
  - Mean error (ME)
  - Mean absolute error (MAE)
  - Root mean square (RMS) error
  - Scatterplots
  - Regression coefficients
- Spring flow errors
- Focus area water level statistics (ME, MAE, RMS, scatterplots, and regression coefficients). The focus area is generally considered the regional scale that encompasses the Facility and a couple of valleys on either side including key water supply locations; specifically the Hālawa Shaft, RHS, and Moanalua wells.

A complete evaluation of all calibration metrics was performed using Model #1. With the experience gained as more models were developed, the evaluations were more limited as appropriate. Comparison of the models was performed to evaluate which models were conservative for the various objectives. The differences in modeled versus observed behavior were also examined to note modeled impact on the various simulation objectives as compared to observed conditions.

Annual average WLEs for 2006, 2015, and 2017 were established as noted in Section 3.1.5 and presented on Figures 3.1.5-1, 3.1.5-2, and 3.1.5-3. These water levels were used to evaluate the calibration of all steady-state models. The annual average flow at Pearl Harbor Spring at Kalauao, and at Kalauao Spring was established for 2006, 2015, and 2017 conditions as presented in Section 3.5 and detailed in Table 3.5-1. These flow conditions at the springs were also evaluated during calibration.

Comparison of the model calibration to the transient synoptic studies of 2006 and 2015 was based on qualitative visual evaluation of the hydrographs. This allowed for the assessment of salient similarities and/or differences between observed and simulated water level changes.

5.3 MODEL #1 PARAMETERS

The calibrated model parameters for Model #1 are shown in Table 5.3-1. These values are similar to values of previous modeling studies (Oki 2005; TEC 2007, 2010; Rotzoll 2014). This was expected since the current study is a numerical representation of the same freshwater flow hydrogeologic system. Figure 5.3-1 shows the layer numbers for model calibration target wells in basalt.

Table 5.3-1: Model #1 Calibrated Model Parameters

Material	Kh (ft/day)	Kv (ft/day)	L:T Anisotropy
Caprock (Layer 1)	1,208	0.08	1
Valley Fill (Layer 1)	100	1	1
Saprolite (Layer 2)	0.1	0.01	1
Saprolite (Layer 3)	10	1	1
Basalt (Layer 2, 3, 4, 5)	2,000	20	0.33
Other Parameters			
Recharge Multiplier	1.27 (2006)	0.95 (2017)	0.97 (2017)
GHB Conductance (ft^2/day)	3,416 (Pearl Harbor Bay)	1,242 (South)	10^{-7} (NW/SE)
Drain Conductance (ft^2/day)	1×10^6 (Pearl Harbor Spring at Kalauao)	5,000 (Kalauao Spring)	10 ft msl (elevation)

The calibrated hydraulic conductivity values for the various material units represent average homogeneous conditions within each material zone. Alternate models discussed later evaluated the uncertainty that may be associated with each of these model parameters or associated heterogeneities.

Simulation experience has indicated the following:

- Kv of caprock has a significant influence on water levels in the basalt. Lower values raised the simulated water levels at all observation targets, and vice versa.
- Kh of basalt has a significant influence on water levels and flow gradients within the basalt. Higher Kh values for basalt produced lower levels and flatter gradients, and vice versa.
- Kh and Kv of valley fill control the water levels within the valley fill but have little other impact. Lower values of Kh and Kv of valley fill raise water levels up the valley, and vice versa.
- Kh and Kv of modeled saprolite mainly control water levels within the saprolite and to a lesser degree, the valley fill. Lower values of Kh and Kv of saprolite raise these water levels, and vice versa.

- There is a slight impact of saprolite Kh on water levels within the basalt. Water levels within the basalt were slightly lower with higher Kh of saprolite.
- Localized heterogeneity in basalt can have a considerable impact on local scale water level gradients and directions.
- Heterogeneity in caprock can have a small impact on flow directions from the Facility.

Calibrated recharge multipliers of 1.27, 0.95, and 0.97 were obtained for 2006, 2015, and 2017, respectively. These deviated slightly from the conceptual recharge estimates of 1.21, 1.19, and 0.85 established in Section 3.6.1 and detailed in Table 3.6.1-2. The calibrated recharge multipliers were not changed in any of the alternate models except when evaluating sensitivity of the model to areal recharge. For that case, the entire recharge input was scaled to the upper and lower expected limits without changing the individual multipliers for the specific years. Simulation experience has indicated that areal recharge has a considerable impact on water levels in the basalt and a small impact on associated water level gradients. The same is true for lateral inflow from the northeast boundary.

A GHB conductance of 3,416 ft^2/d was obtained for Pearl Harbor Bay and 1,242 ft^2/d for the southern offshore model boundary. This boundary conductance represents vertical connection of the caprock to the floor of Pearl Harbor Bay and the ocean. Simulation experience has indicated that the Pearl Harbor Bay and offshore GHB conductance has a significant influence on water levels in the caprock and in the basalt. Lower values raised the simulated water levels at all observation targets. The opposite was true up to a certain point.

The GHBs along the northwestern and southeastern lateral boundaries were set to a very low value (10^{-7} ft^2/d) to essentially simulate no lateral flow across those boundaries. This conceptual representation (i.e., flow is parallel to Kalihi Valley along the southeast model boundary, and parallel to the Waimalu Valley along the northwest model boundary) also has some uncertainty. Therefore, a set of alternate models evaluated the conceptual uncertainty of this representation, by using a very high GHB conductance values (10^7 ft^2/d) with different possible combinations of GHB heads along these lateral boundaries. Simulation experience has indicated that these lateral boundary heads can have considerable impact on the simulated water budgets and boundary flows across the lateral boundaries though the impact is small on flow directions from the Facility.

Values of 10^6 ft^2/d and 5,000 ft^2/d were used for the drain conductances of Pearl Harbor Spring at Kalauao and Kalauao Spring, respectively. These are high values and do not create much resistance to drain flow. Alternate models discussed later also evaluated the impact of different drain conductance and flows on the modeling objectives. A drain bottom elevation of 10 feet msl was used for both drains. Simulation experience has indicated that lower values of drain conductance can have moderate impact on drain flows a small impact on water levels or gradient directions in the basalt, except locally around the drain.

5.4 MODEL #1 CALIBRATION STATISTICS

Model calibration was evaluated for the entire model domain as well as only for the focus area wells that include wells along Red Hill, and the key water supply and monitoring wells that lie across Hālawa and Moanalua valleys.

A comparison of the observed and simulated water levels over the entire model domain is shown on Figure 5.4-1. An ME of 0.59 foot msl, MAE of 1.26 feet msl, and RMS error of 2.0 feet msl were obtained over the entire model domain. These errors are less than 10 percent of the overall difference between the maximum and minimum observed water levels of 22 feet msl, which is considered acceptable. A regression coefficient of 0.93 indicates a good correlation between observed and simulated water levels.

A comparison of the observed and simulated water levels over the focus area wells is shown on Figure 5.4-2 (including well RHMW07) and Figure 5.4-3 (excluding well RHMW07). A comparison with and without RHMW07 was conducted to analyze whether water levels within RHMW07 were biasing the results. Considering only the focus area wells, an ME of -0.25 foot msl, a MAE of 0.95 foot msl, an RMS error of 1.23 feet msl, and a regression coefficient value of 0.7 were obtained as shown on Figure 5.4-2. The errors are similar when excluding RHMW07 from the analysis (Figure 5.4-3); the ME was -0.23 foot msl, the MAE was 0.90 foot msl, the RMS was 1.20 feet msl, and the regression coefficient was 0.62. Thus, RHMW07 does not degrade the calibration statistic indicating that there is likely saprolite present that causes the associated higher water levels at that location.

5.5 MODEL #1 SPATIAL DISTRIBUTION OF RESIDUALS FOR 2006, 2015, AND 2017

The distribution of residuals between the observed and simulated water levels over the entire model domain is shown on Figures 5.5-1 through 5.5-6 for the modeled years 2006, 2015, and 2017. Wells within the caprock are noted to have large error variations within small distances that result from unknown depths of measurement and large vertical gradients within the caprock. For wells within the basalt, the model was noted to underestimate water levels in the northwestern portion of the model domain, and overestimate water levels in the southeast portion of the domain. Thus, the simulated model-wide gradients are more tilted toward the northwest than observed causing the model to be conservative in terms of flow from Red Hill toward Hālawa Shaft. At the local scale, the water levels at Red Hill were simulated to be higher than observed, with Hālawa Shaft water levels simulated lower than observed for 2006 and 2017. This is also conservative in terms of flow from Red Hill toward Hālawa Shaft.

5.6 MODEL #1 WATER LEVEL MAPS FOR 2006, 2015, AND 2017

The simulated 2017 water level contours for the caprock and valley fill (model layer 1) are shown on Figure 5.6-1. Water levels are noted to be as high as 40 to 90 feet in the upper reaches of the valleys and drop to about 4 feet in upstream portions of the caprock. Contoured water levels for 2017 shown on Figure 3.1.7-3 do not include any data points in the valleys and therefore are representative of basalt water levels in upstream portions of the domain. Water levels within the caprock are comparable in magnitude but simulated water levels do not show the localized mounds and drawdowns exhibited in interpolated contours, which may result from local heterogeneities, different depths of measurement for the different wells, high vertical gradients within the caprock, and sparse measurements (as noted in Section 3.1.2, most caprock wells had only one water level measurement within the model domain post-1999). Simulated water level results from the model of Oki (2005) shown on Figure 1.2-3 show contours within the caprock similar to the current modeling results.

Figure 5.6-1 also shows the residuals at all well locations within the domain. A low residual indicates under-prediction by the model, while a high residual indicates that the model overestimates the water levels. Also, green indicates that the residuals are within one standard deviation of target value, orange indicates that the residuals are within two standard deviation of the target value, and red indicates that they are beyond two standard deviation of the target value. The two standard deviation (95 percent confidence interval) values are shown in Table 3.1.6-1.

From Figure 5.6-1, it is noted that residuals within the caprock are both positive and negative due to the large variations in localized caprock water levels discussed above. Residuals in the basalt are noted to be within one standard deviation of the observed variations, except for wells near the northwest boundary, where the large negative residuals indicate an under-prediction by the base case model. The implication of this was discussed earlier in Section 5.5 as being conservative in terms of flow from the Facility toward Hālawa Shaft.

Figure 5.6-2 shows the simulated 2017 water level contours for the basalt (model layer 2). The regional water level gradients are from east to west with water perching on the saprolite zones. A comparison with Figure 3.1.7-3 also indicates similar regional gradients in the interpolated values (aside from the simulated mounding within caprock). A comparison with water level results from the model of Oki (2005) shown on Figure 1.2-3 also shows similar regional gradients and further includes mounding on the simulated caprock underlying the valleys. This should be expected since the current study is a numerical representation of the same freshwater flow hydrogeologic system.

Figure 5.6-3 shows the simulated 2017 water level contours for the basalt in model layer 3. The water levels are very similar to those in the basalt in model layer 2 except for the mounding within the saprolite, which is not noticeable in model layer 3 because of the higher hydraulic conductivity of saprolite in layer 3 than in layer 2. Comparing with water levels in layer 2 further indicates that vertical gradients are small except within the saprolite or adjacent to pumping wells or shafts.

Figures 5.6-4 and 5.6-5 show the simulated 2017 water level contours for the basalt in model layers 4 and 5, respectively. Water levels in these deeper layers are similar to those in model layer 3 with small vertical hydraulic gradients except near pumping wells or shafts.

5.7 MODEL #1 SIMULATED GROUNDWATER VOLUMETRIC BUDGETS FOR 2006, 2015, AND 2017

The Model #1 simulated groundwater volumetric budgets for 2006, 2015, and 2017 are shown in Table 5.7-1.

Table 5.7-1: Model #1 Simulated Groundwater Volumetric Budgets

Year	2006	2015	2017
IN (mgd)			
NE Flux	22.4	22.4	22.4
Recharge	48.0	35.8	36.8
GHB Pearl Harbor Bay	0.0	0.0	0.0
GHB South	0.0	0.0	0.0
GHB NW Boundary	0.0	0.0	0.0
GHB SE Boundary	0.0	0.0	0.0
Total IN	**70.4**	**58.2**	**59.1**
OUT (mgd)			
Well Discharge	37.4	28	26.8
GHB Pearl Harbor Bay	14.2	13.1	13.5
Pearl Harbor Spring	10.9	10	11.6
Kalauao Spring	0.1	0.1	0.1
GHB Offshore	8.1	7.2	7.3
GHB NW Boundary	0	0	0
GHB SE Boundary	0	0	0
Total OUT	**70.7**	**58.4**	**59.4**

Comparing these with Table 3.8-1, the total simulated volumetric budget is within 13 percent of the conceptual model water budget. Well discharge was different between the conceptual and numerical models because the conceptual model had included additional pumping wells that were not a part of the numerical model. The largest percent error was noted in the seafloor discharge term, which compensated for the well pumping discrepancy in the conceptual model budgets. The spring flow (correlated with WLEs at the Navy 'Aiea well) was noted to be lowest in 2015 while recharge and pumping were lowest in 2017.

5.8 Model #1 Groundwater Flow Direction and Gradient

Hydraulic gradients and direction were evaluated at both the local scale at Red Hill and the regional scale surrounding Red Hill. The local scale considerations are detailed in Section 3.4 and will be evaluated further with an alternative model that includes local-scale conceptualization details. The regional scale considerations are detailed in Section 3.5 and further evaluated against the model in Section 5.8.1.

5.8.1 Evaluation of Modeled Regional Flow Gradients and Direction

TEC evaluated the regional flow gradient and direction in both their studies in 2006 and 2010. Although the 2006 TEC study showed varying water level gradients, the 2010 evaluation, performed after re-surveying of the wells, showed water level gradients to the west; the results are reproduced in Table 5.8.1-1. The gradients from Model #1 are from east to west, which is the same as the TEC evaluation of 270 degrees from north. However, the Model #1 gradients are higher than conditions reported by TEC (2010). Recent data collection efforts and corrections to available information have also indicated flatter water level gradients along Red Hill than were simulated by Model #1. Alternate models were also evaluated in this regard that better capture the very flat gradients that are noted in this region, and will be discussed later.

Table 5.8.1-1: Comparison of Regional Groundwater Flow Gradients and Direction

	TEC (2007)		TEC (2010)		Model #1			Simulated Gradients
Date	Direction	Gradient	Direction	Gradient	Modeled Date	Direction	Modeled Gradient	Modeled Gradient
18-May-06	180	0.00051	270	0.000089	2006	270	3.79×10^{-4}	5.82×10^{-4}
25-May-06	306	0.0024	270	0.00015	2015	270	1.41×10^{-3}	6.32×10^{-4}
30-May-06	184	0.00051	270	0.000093	2017	270	4.48×10^{-4}	6.07×10^{-4}

Notes: Direction is degrees clockwise from North.
Gradient is in feet/feet water level drop to run.

5.8.2 Contouring using November 2016 Synoptic Data, and Average 2006, 2015, and 2017, and Associated Steady-State Simulated Water Levels using a Consistent Methodology

TEC (2010) also used a contouring approach to evaluate regional water level gradients at Red Hill. This approach was also applied to Model #1 to evaluate if consistent contouring was obtained with data from the model. Therefore, water levels from the model at the same seven wells (RHS, OWDFMW01, RHMW02, RHMW03, RHMW04, TAMC MW2, and Manaiki T45) were extracted from Model #1 and contoured as per the approach discussed in Section 3.4.2. The observed and simulated water levels in these wells, for each of the modeled years, are shown in Table 5.8.2-1. The observed and simulated water levels at RHS represented asynchronous measurements and are therefore different from each other. The pumping represented in the different years of the model is different from pumping conditions of May 2006 when the TEC data was collected.

Table 5.8.2-1: Comparison of Observed and Simulated Water Levels for the Interim Model Steady-State Calibration – Select Basalt Wells

	2006		2015		2017	
Well Name	Observed	Simulated	Observed	Simulated	Observed	Simulated
2153-13	19.28	20.614	19.82	19.379	19.94	19.992
Red Hill Shaft	16.63	16.936	16.87	14.419	18.76	15.474
OWDFMW01	20.27	18.929	17.36	17.843	19.28	18.45
RHMW02	20.17	20.428	17.74	19.15	19.4	19.773
RHMW03	20.56	20.743	17.74	19.459	19.4	20.077
RHMW04	21.13	21.054	17.77	19.744	19.42	20.361
2153-09	20.83	21.69	18.86	20.2	20.03	20.94

Figures 5.8.2-1, 5.8.2-2, and 5.8.2-3 show the water level contours for 2006, 2015, and 2017 annual average conditions, respectively, from Model #1, using the same set of wells and the same TEC (2010) Method 2 contouring methodology as was used for the May 2006 synoptic data. As shown on the figures, the simulated contours and gradient representations compare reasonably well to those of Figures 3.4.2-1 and 3.4.2-2, with regional northwest pointing contoured gradients. Thus, the simulated conditions are consistent with observed conditions when analyzed in an identical manner. Alternate models were largely recalibrated to the key focus area wells (which are used for this contouring approach) and therefore also show this trend.

5.8.3 Key Model #1 Head Differences with Hālawa Shaft

A key objective of the modeling effort is to evaluate the potential for groundwater migration toward Hālawa Shaft from the Facility and to be protective of Hālawa Shaft. In that regard, the apparent hydraulic head differences between the Red Hill area and Hālawa Shaft are considerable but do not necessarily indicate the hydraulic gradient or flow direction. The apparent hydraulic head difference was noted also for alternate models that had larger hydraulic conductivities between Red Hill and Hālawa Shaft.

A comparison of the target values with simulated head differences between the Red Hill monitoring wells and Hālawa Shaft is shown in Table 5.8.3-1. In general, there is a positive simulated head difference from the focus area wells toward Hālawa Shaft. Also, the simulated differences are larger than target values at most wells. RHS was a notable exception, for the 2015 and 2017 simulations, most likely due to the lack of correlation between simulated annual average pumping and water level measurement calibration targets at these pumping locations as noted in Sections 3.3.2 and 3.3.3.

Table 5.8.3-1: Comparison of Observed and Model #1 Simulated Head Differences Between Hālawa Shaft and Red Hill Wells

	Measured Differences with Hālawa Shaft			Simulated Differences with Hālawa Shaft			Simulated Minus Measured Difference		
Well Name	2006	2015	2017	2006	2015	2017	2006	2015	2017
OWDFMW01	6.57	3.12	4.92	6.42	2.93	4.1	-0.15	-0.19	-0.82
RHMW01	5.1	3.62	5.11	7.59	3.89	5.1	2.49	0.27	-0.01
RHMW02	6.47	3.5	5.04	7.92	4.23	5.43	1.45	0.73	0.39
RHMW03	6.86	3.5	5.04	8.23	4.54	5.73	1.37	1.04	0.69
RHMW04	7.43	3.53	5.06	8.54	4.83	6.02	1.11	1.3	0.95
RHMW05	5.03	3.57	5.17	5.82	1.57	2.97	0.79	-2	-2.2
RHMW06	4.76	3.1	4.94	8.18	4.49	5.68	3.42	1.39	0.74
RHMW07	9.16	7.78	9.23	11.84	7.24	8.48	2.68	-0.54	-0.75
RHMW08	4.58	4.58	4.74	7.21	3.45	4.68	2.63	-1.14	-0.07
RHMW09	4.21	4.21	4.58	7.74	4.05	5.25	3.53	-0.16	0.67
Red Hill Shaft	2.93	2.63	4.4	4.42	-0.5	1.13	1.49	-3.13	-3.27

5.9 OTHER MODELS

To evaluate the potential effect of approximations in the conceptual and numerical models and of uncertainty in observed water levels, model parameterization, and boundary stresses, a multi-model analysis was conducted. The approach to developing the multiple models is as follows:

- A traditional sensitivity analysis was first conducted by selecting a particular conceptual model, material parameter, or boundary stress, and setting its value as required at the minimum or maximum of the range for that parameter or stress. Sensitivity analyses were also conducted on sets of parameters and stresses instead of varying just one single parameter or stress. Steady-state 2006, 2015, and 2017 conditions were simulated for each sensitivity analysis. Calibration statistics for the focus area wells, drain fluxes, and observed versus simulated water level scatterplots were evaluated. The sensitivity of a parameter or a set of parameters or stresses to model calibration was therefore determined relative to Model #1. Comparisons with other models were also conducted as appropriate. Changes in the calibration were classified as Insensitive (Insignificant), Slightly Sensitive (Insignificant), Moderately Sensitive (Significant), or Very Sensitive (Significant) as shown in Table 5.9-1.
- If required, a minor model recalibration was performed by varying other model parameters.
- The recalibrated model was then examined in a similar manner to Model #1 to note calibration statistics, simulated water level gradients, spatial bias in the residuals, and whether the simulation was conservative/protective of the various modeling objectives.
- The recalibrated model was further evaluated in terms of whether it generally captured field behavior and whether it was consistent with the conceptualization of flow at the site.

Not all of the calibration details for these alternate models are reported because a lot of their behavior is similar to that of Model #1. Therefore, only the significant similarities of these models with Model #1 are discussed and relevant differences are highlighted.

Table 5.9-1: Categorization of Sensitivity to Model Calibration

Category	Mean Error Change from Model #1 (ft)	PH Flux change from Model #1 (mgd)
Insensitive (Insignificant)	ME change ≤ 0.5	Flux change ≤ 2
Slightly sensitive (Insignificant)	0.5 < ME change ≤ 1.5	2 < Flux change ≤ 4
Moderately sensitive (Significant)	1.5 < ME change ≤ 2.5	4 < Flux change ≤ 6
Highly sensitive (Significant)	ME change > 2.5	Flux change > 6

5.9.1 Parameters and Boundaries Evaluated for Sensitivity Analyses

Overall, 43 different sensitivity analyses were conducted and alternate models were created to capture the range of errors in modeling assumptions and uncertainty in input parameters. The realizations included analysis of:

- Heterogeneity due to a high-K zone (e.g., clinker)
- Lateral GHB boundary flows
- Basalt hydraulic properties
- Saprolite hydraulic properties
- Caprock hydraulic properties
- Offshore GHB conductance
- Northeast boundary inflow
- Recharge
- Transient flow properties for various models of interest

Parameter values and a summary of the results are shown in Table 5.9.1-1. Analysis of each parameter is detailed below.

Table 5.9.1-1: Categorization of Sensitivity Analyses and Models

Model Number	Parameter	Sensitivity to Calibration
Model #2	Heterogeneity due to Presence of Clinker	Slightly Sensitive
Model #3	GHB 1: 2017 Interpolated Stages	Slightly Sensitive
Model #4	GHB 2: Lower NW and SE Stage	Insensitive
Model #5	GHB 3: Lower NW and Higher SE Stage	Moderately Sensitive
Model #6	GHB 4: NW and SE Stages Lowered 3-ft	Highly Sensitive
Model #7	GHB 5: 2017 Interpolated Stages with Higher NW Stage for GHB in Basalt	Moderately/Highly Sensitive
Model #8	Saprolite Assuming Basalt Properties	Moderately/Slightly Sensitive
Model #9 - Low Value Model #10 - High Value	Basalt Kv	Moderately/Slightly Sensitive Insensitive
Model #11	Basalt Kh (higher value)	Highly Sensitive
Model #12 - Low Value Model #13 - High Value	Saprolite Hydraulic Conductivity	Insensitive Slightly Sensitive
Model #14	Lower Basalt Kv and higher Saprolite Kh	Moderately/Slightly Sensitive
Model #15 - Low Value Model #16 - High Value	Offshore GHB Boundary Conductance	Insensitive Highly Sensitive
Model #17 - Low Value Model #18 - High Value	Recharge	Slightly Sensitive Highly Sensitive
Model #19 - Low Value Model #20 - High Value	Basalt Horizontal Anisotropy	Insensitive Moderately/Highly Sensitive
Model #21 - Low Value Model #22 - High Value	NE Boundary Inflow	Moderate/Slightly Sensitive
Model #23 - Lowest Value Model #24 - Low Value Model #25 - High Value	Caprock Horizontal Hydraulic Conductivity	Highly Sensitive Slightly/Moderately Sensitive Insensitive
Model #26 Model #27	Zonation of Caprock into alluvial and marine sediments (with saprolite properties same as basalt for Model #27)	Highly Sensitive
Model #28	Model Bottom Elevation	Insensitive
Model #29 - Low Value Model #30 - High Value	Combined changes in Recharge and NE Boundary Inflow	Highly Sensitive
Model #31	Elevation of Hālawa Shaft and Red Hill Shaft	Insensitive
Model #32	Transient 2006 Synoptic Study using Model #1	n/a
Model #33	Transient 20156 Synoptic Study using Model #1	n/a
Model #34 - Low Value Model #35 - High Value	2006 Transient Synoptic Study - Specific Yield	n/a
Model #36 - Low Value Model #37 - High Value	2006 Transient Synoptic Study - Specific Storage	n/a
Model #38 - Low Value Model #39 - High Value	2006 Transient Synoptic Study - HANI	n/a
Model #40	2006 Transient Synoptic Study - No Saprolite	n/a
Model #41 - Low Value Model #42 - High Value	2006 Transient Synoptic Study - Clinker Porosity	n/a
Model #43	2006 Transient Synoptic Study - Basalt Kh	n/a

n/a not available

5.9.2 Sensitivity to Heterogeneity Due to Presence of Clinker (Model #2)

Model #2 was designed to provide a model to evaluate local scale heterogeneities along Red Hill. Specifically, the CSM indicated that there were high conductivity clinker materials and bridges present along or near to the water table at RHMW08, RHMW06, and RHS, which were likely connected. Therefore, a high-K zone was included in Model #2 to represent this material as an unlikely extreme case. Figure 5.9.2-1 shows a conceptual high-K clinker zone (assumed K = 5.0×10^6 ft/d) that was assigned in model layer 2 of the model underneath Red Hill for this modeling case.

Calibration statistics of the focus area wells for Model #2 are shown in Table 5.9.2-1. Model #1 statistics are also shown for comparison. Calibration statistics are slightly sensitive, while drain fluxes are insensitive to addition of the clinker zone. However, presence of the clinker zone decreased the RMS error of the focus area wells as compared to Model #1, indicating a slightly better local fit. Scatterplots are shown on Figure 5.9.2-2 for the 3 years that are very similar to those of Model #1 (as are the average statistics in Table 5.9.2-1), indicating that the regional flow field had not generally changed. The WLEs in Layer 2 and Layer 3 are shown on Figures 5.9.2-3 and 5.9.2-4, respectively, with focus on the local scale. A localized northwest gradient is noted toward the clinker material, and a significantly flatter gradient is noted between the tank farm and RHS.

Table 5.9.2-1: Sensitivity to Heterogeneity – Presence of Clinker: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #2:	0.27	0.93	9.2	9.7	11.3	0.10	0.11	0.12

The high-K clinker material likely causes very rapid flow between the tank farm and RHS. Therefore, Model #2 was flagged for further evaluation critical to RHS to provide an extremely conservative (i.e., protective) analysis. By similar reasoning, Model #2 would not be as protective as Model #1 for considerations of migration toward Hālawa Shaft and the Moanalua Wells, which are located in a transverse direction to the orientation of the high-K clinker material.

5.9.3 Sensitivity to GHB Stage: 1 – 2017 Interpolated Stages (Model #3)

The conceptual model considered no flow across the valleys bounding the model to the northwest and southeast. Therefore, no-flow conditions were implemented in Model #1 by supplying a very low GHB conductance value (10^{-7} ft^2/d) along the lateral northwest and southeast model boundaries. To evaluate the impact of uncertainty in this boundary flow, models were developed using the other extreme of GHB conductance (10^7 ft^2/d) to allow water to freely flow in or out of these boundaries under the prescribed GHB head conditions. Water level processing that was detailed in Section 3 provided the GHB head values along the lateral boundaries. However, due to uncertainty in these head values, various alternate head configurations were also evaluated.

Five alternate models were developed to evaluate various boundary head configurations along the northwest and southeast lateral model boundaries:

- *Model #3:* 2017 interpolated GHB heads (discussed in this section)
- *Model #4:* lower GHB stage along northwest and southeast boundaries (Section 5.9.4)
- *Model #5:* lower northwest and higher southeast stage (Section 5.9.5)

- *Model #6:* lowering both the northwest and southeast boundary stages by 3 feet (Section 5.9.6)
- *Model #7:* 2017 interpolated northwest and southeast boundary stages as in Model #3 but with a higher northwest basalt stage near Pearl Harbor (Section 5.9.8)

Sensitivity to 2017 interpolated GHB heads (Model #3) was evaluated by providing boundary GHB heads as shown on Figure 5.9.3-1 with linear interpolation between values shown. Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.3-1. Scatterplots are shown on Figure 5.9.3-2. Water level contours for Layer 2 and Layer 3 are shown on Figures 5.9.3-3 and 5.9.3.4, respectively. Water budgets for this model are shown in Table 5.9.3-2.

Table 5.9.3-1: Sensitivity to 2017 GHB Stage: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #3:	-1.05	1.8	10.6	10.8	11.1	0.14	0.14	0.15

Table 5.9.3-2: Sensitivity to 2017 GHB Stage: Groundwater Volumetric Budget (mgd)

Year	2006	2015	2017
IN (mgd)			
NE Flux	22.4	22.4	22.4
Recharge	48	35.8	36.8
GHB Pearl Harbor Bay	0.0	0.0	0.0
Pearl Harbor Spring	0.0	0.0	0.0
Kalauao Spring	0.0	0.0	0.0
GHB Offshore (south)	0.0	0.0	0.0
GHB NW Boundary	195.1	195	193.4
GHB SE Boundary	85.3	85.9	85.8
Total IN	**350.8**	**339**	**338.3**
OUT (mgd)			
Well Discharge	37.3	28.9	27.1
GHB Pearl Harbor Bay	18.5	18	18.1
Pearl Harbor Spring	10.6	10.8	11.1
Kalauao Spring	0.14	0.14	0.15
GHB Offshore (south)	43.2	42.7	42.7
GHB NW Boundary	183.5	183.4	183.9
GHB SE Boundary	57.5	55	55.2
Total OUT	**350.7**	**339**	**338.3**

As shown in Table 5.9.3-1, calibration statistics were slightly sensitive to GHB stage influence along the northwest and southeast boundaries. Pearl Harbor drain fluxes were insensitive to the interpolated GHB. Compared to Model #1, increasing the GHB conductance resulted in higher simulated water levels as shown by the lowering of the ME in Table 5.9.3-1 and the scatterplots of Figure 5.9.3-2. However, the overall hydraulic gradient remained from east to west with a similar slope as in Model #1.

Localized inflow and outflow along the northwest and southeast lateral boundaries are noted on Figures 5.9.3-3 and 5.9.3.4. Specifically, high inflow and outflow conditions occur along the northwest boundary near Pearl Harbor as noted from the hydraulic gradients. Local anomalies in water levels are also noted along the southeast boundary. The water budget terms for Model #3 are shown in Table 5.9.3-2. Large inflow occurred across the lateral northwest GHB boundary, which was compensated by a large outflow along the lateral northwest boundary and some extra flow into Pearl Harbor Bay. Large inflow also occurred across the lateral southwest GHB boundary, which was compensated by a large outflow along the lateral southeast GHB boundary and some extra flow to the offshore GHB boundary to the south. Thus, these boundary effects are noted to be local and do not have significant effect in the area of interest along Red Hill and across its adjacent valleys.

Model #3 generally showed larger flow toward Hālawa Shaft from the northwest boundary with associated less potential for flow from Facility and is therefore generally less protective for analysis of Hālawa Shaft than Model #1. Outflow at the southeast boundary in Model #3 causes regionally lower water levels near the Moanalua Wells, making it a more conservative (protective) analysis for Moanalua wells. Also, these wells are deep and not likely to withdraw water from near the water table at Facility. Opening up the northwest and southeast boundaries to flow may therefore not be as protective for analyses of migration from the Facility toward Hālawa Shaft or Moanalua wells as compared to Model #1. Application of the models will ultimately determine its impact to the relevant objectives and this is detailed further in Section 6.

5.9.4 Sensitivity to GHB Stage: 2 – Lower Northwest and Southeast Stage (Model #4)

Sensitivity to GHB stages was also modeled by decreasing the stages on the northwest and southeast (Model #4) as shown on Figure 5.9.4-1. The impact of this was to have steeper ambient regional gradients in upstream portions of the domain toward the northeast, and flatter hydraulic gradients at Red Hill and further downstream as compared to Model #3.

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.4-1. Scatterplots are shown on Figure 5.9.4-2. The water level contours for Layer 3 are shown on Figure 5.9.4-3.

Table 5.9.4-1: Sensitivity to Lower NW and SE GHB Stage: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #4:	-0.04	1.19	10.8	11.0	11.2	0.13	0.13	0.14

Water enters the domain from the northwest boundary and leaves from portions of the southeast boundary causing a change in the simulated flow direction from Model #3, but with little change in the calibration statistics for the focus wells as shown by the ME in Table 5.9.4-1 or in the scatterplots of Figure 5.9.4-2 (when compared to the scatterplots of Model #1 shown on Figure 5.4-1). Also, the flow field across Red Hill shows similar hydraulic gradients to Model #1 and Model #3 even though the regional flow field has changed. As shown in Table 5.9.4-1, both the calibration statistics and drain fluxes were insensitive to GHB stage influence along the northwest and southeast boundaries.

5.9.5 Sensitivity to GHB Stage: 3 – Lower Northwest and Higher Southeast Stage (Model #5)

Another GHB stage model (Model #5) considered decreasing northwest and increasing southeast stages from those of Model #3 as shown on Figure 5.9.5-1. Compared to Model #3, this model allowed for the study of more northwestwardly regional boundary gradients than conceptualized through water level interpolations.

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.5-1. Water level contours for Layer 3 are shown on Figure 5.9.5-2. Similar to Model #3 (Section 5.9.3), the hydraulic gradient is from the east to the west. However, groundwater elevations are higher in the southeast portions of the domain, which removes the anomalous flow along the southeast boundary that was noted in Model #3 and Model #4. Simulated water levels are on average, more than a foot higher in the focus area than Model #1 as shown by the lowering of the ME in Table 5.9.5-1. Calibration statistics were moderately sensitive and drain fluxes were insensitive to GHB stage influence along the northwest and southeast boundaries.

Table 5.9.5-1: Sensitivity to Lower NW and Higher SE GHB Stage: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #5:	-1.81	2.19	11.2	11.4	11.7	0.14	0.14	0.14

5.9.6 Sensitivity to GHB Stage: 4 – Northwest and Southeast Stages Lowered 3-ft (Model #6)

Another GHB stage model (Model #6) considered decreasing northwest and southeast stages from those of Model #3, by 3 feet as shown on Figure 5.9.6-1. Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.6-1. Water level contours for Layer 2 and Layer 3 are shown on Figures 5.9.6-2 and 5.9.6-3, respectively. Similar to Model #3 (Section 5.9.3), groundwater flow is from the east to the west. However, in Model #6, groundwater elevations are approximately 3 ft lower (Figures 5.9.6-2 and 5.9.6-3) as also noted in Table 5.9.6-1.

Table 5.9.6-1: Sensitivity to Lowering NW and SE GHB Stage by 3-ft: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #6:	1.3	1.8	4.4	4.6	4.8	0.08	0.08	0.08

5.9.7 Sensitivity to GHB Stage: 5 – 2017 Interpolated Northwest and Southeast Stages with Higher Northwest Basalt Stage (Model #7)

The northwest boundary heads gradually reduced to zero in the southwest direction toward Pearl Harbor in Model #3. This condition was maintained for all model layers. A more refined conceptualization of the northwest boundary heads was to allow caprock head values to go to zero as the location approaches the coast, however, water levels in the basalt would remain high under confinement even beneath Pearl Harbor. To accommodate this conceptualization, Model #7 used boundary values from Model #3, but altered the GHB heads along the northwest in the basalt (model layers 2-5) to remain high beneath Pearl Harbor as indicated on Figure 5.9.7-1.

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.7-1. Statistics are included for Model #1 as well as Model #3 for comparison. Water level contours for Layer 3 are shown on Figure 5.9.7-2. Similar to Model #3 (Section 5.9.3), groundwater flow is from the east to the west and no significant change in groundwater elevations was observed. Compared to Model #1, simulated water levels are higher as shown by the lowering of the ME in Table 5.9.7-1. Calibration statistics are moderately sensitive and drain fluxes are highly sensitive to GHB stage influence along the northwest and southeast boundaries.

Table 5.9.7-1: Sensitivity to 2017 Interpolated NW and SE GHB Stage with Higher NW Basalt Stage: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #3:	-1.05	1.8	10.6	10.8	11.1	0.14	0.14	0.15
Model #7 (Sensitivity Analysis):	-1.75	2.12	21.2	21.4	21.7	0.2	0.2	0.21
Model #7 (Recalibrated):	-1.82	2.18	11.2	11.3	11.4	0.23	0.24	0.24

This sensitivity simulation threw the model off calibration to a substantial degree, especially the drain fluxes at Pearl Harbor Spring. Therefore, a recalibration of the drain fluxes was performed by lowering the drain conductance, which had only a slight additional impact on the other residual statistics that are also shown in Table 5.9.7-1. Water levels for the recalibrated model are also shown on Figure 5.9.7-2. Water levels in layer 3 of the model are similar for the sensitivity simulation and the recalibrated model except around the Pearl Harbor Spring drain. Thus, this boundary condition (specifically flow in from the northwest boundary within the basalt can control Pearl Harbor Spring flux without having much impact on water levels or gradients in the focus area of the study.

The water budget terms for Model #7 (the recalibrated model) are shown in Table 5.9.7-2. The northeast GHB boundary inflows and outflows are the only terms that are significantly different (about 125 mgd less) from those of Model #3 (Table 5.9.3-2). Therefore, the change in boundary condition between Model #3 and Model #7 did not significantly impact flows or water levels beyond the local region along which the boundary values were changed and did not affect flow conditions simulated in the area of interest along Red Hill and across its adjacent valleys.

Table 5.9.7-2: Sensitivity to 2017 Interpolated NW and SE GHB Stage with Higher NW Basalt Stage: Volumetric Budget (mgd)

Year	2006	2015	2017
IN (mgd)			
NE Flux	22.4	22.4	22.4
Recharge	48	35.8	36.8
GHB Pearl Harbor Bay	0.2	0.2	0.2
Pearl Harbor Spring	0.0	0.0	0.0
Kalauao Spring	0.0	0.0	0.0
GHB Offshore (south)	0.0	0.0	0.0
GHB NW Boundary	69.3	69	67.2
GHB SE Boundary	85	85.5	85.5

Year	2006	2015	2017
Total IN	**225**	**213**	**212.1**
OUT (mgd)			
Well Discharge	37.3	28.9	27.1
GHB Pearl Harbor Bay	19.9	19.4	19.5
Pearl Harbor Spring	11.2	11.3	11.4
Kalauao Spring	0.23	0.24	0.24
GHB Offshore (south)	43.4	42.9	42.9
GHB NW Boundary	54.5	54.3	54.7
GHB SE Boundary	58.5	55.9	56.1
Total OUT	**224.9**	**212.9**	**212**

5.9.8 Sensitivity to Saprolite with Hydraulic Properties same as Basalt (Model #8)

There is some uncertainty regarding the depth and extent of saprolite beneath the water table under the valleys. An extreme model was developed in this regard, to note the impact of having no saprolite underneath the valleys. Therefore, the sensitivity to presence of saprolite was modeled by assigning the saprolite the same hydrogeologic properties as basalt (Model #8).

Calibration statistics of focus area wells are shown in Table 5.9.8-1. WLEs for Layer 2 and Layer 3 are shown on Figures 5.9.8-1 and 5.9.8-2, respectively. Water levels for Model #1 are also shown on these figures for comparison.

Table 5.9.8-1: Sensitivity to Saprolite with Basalt Properties: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #8 (Sensitivity Analysis):	1.61	2.15	7.6	6.3	8.1	0.09	0.07	0.09
Model #8 (Recalibrated):	0.66	1.56	10.2	8.8	10.7	0.21	0.19	0.22

As shown in Table 5.9.8-1, calibration statistics are moderately sensitive and drain fluxes slightly sensitive to the presence of saprolite. As shown on Figures 5.9.8-1 and 5.9.8-2, simulated water levels are lower from those of Model #1 by approximately 2 feet. However, unlike Model #1, no mounding in the location of the saprolite is observed in Layer 2.

5.9.9 Sensitivity to Basalt Kv (Model #9 and Model #10)

Sensitivity to basalt Kv was evaluated by decreasing (Model #9) and increasing (Model #10) the Kv of basalt by a factor of 10. Thus, Model #9 had a basalt Kv of 2 ft/d and Model #10 had a basalt Kv of 200 ft/d. Calibration statistics for both models are shown in Table 5.9.9-1. Lowering the Kv of basalt raises water levels in the focus area wells by about 2 feet, while raising the Kv of basalt lowers water levels by about a foot. Therefore, both models were approximately recalibrated for further evaluations and model application.

Table 5.9.9-1: Sensitivity to Saprolite with Basalt Kv: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #9 (Sensitivity Analysis):	-2.23	3.14	8.40	7.32	8.76	0.17	0.15	0.17
Model #9 (Recalibrated):	1.26	2.67	7.38	6.12	7.82	0.07	0.06	0.07
Model #10 (Sensitivity Analysis):	0.92	1.37	12.60	10.87	13.09	0.07	0.06	0.07
Model #10 (Recalibrated):	0.21	1.02	14.70	12.95	15.19	0.09	0.08	0.09

Calibration statistics of focus area wells are moderately sensitive and drain fluxes slightly sensitive to lower basalt Kv (Model #9) as shown in Table 5.9.9-1. Comparatively, increasing the basalt Kv (Model #10) resulted in slightly sensitive calibration statistics and insensitive drain fluxes.

5.9.10 Sensitivity to Basalt Kh (Model #11)

Sensitivity to basalt Kh was evaluated by increasing Model #1 Kh of basalt by a factor of 3 for a value of 6,000 ft/d. Sensitivity to the lowering Kh of basalt was not evaluated because the values in Model #1 was considered to be at the lower end since it results in gradients along Red Hill that are at the upper end of more recently measured water levels at Red Hill monitoring wells.

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.10-1. Water level contours are shown on Figure 5.9.10-1. Compared to Model #1, lowering the basalt Kh decreased the simulated water levels (Table 5.9.10-1) and flattened the hydraulic gradient (Figure 5.9.10-1). Calibration statistics were highly sensitive and drain fluxes slightly sensitive/insensitive to increasing the basalt Kh as shown in Table 5.9.10-1.

Table 5.9.10-1: Sensitivity to Saprolite with Basalt Kv: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #11 (Sensitivity Analysis):	4.55	4.68	13.7	11.8	14.0	0.07	0.06	0.07
Model #11 (Recalibrated):	0.001	1.02	14.9	13.3	15.2	0.05	0.04	0.05

Figure 5.9.10-1 also shows water levels in layer 3 in the model focus area indicating that gradients are about a foot per mile and a half. These gradients are similar to those conceptualized for the area.

5.9.11 Sensitivity to Saprolite Hydraulic Conductivity (Model #12 and #13)

Sensitivity to saprolite hydraulic conductivity was evaluated by decreasing (Model #12) and increasing (Model #13) both Kh and Kv of the saprolite in layers 2 and 3 by a factor of 10. Parameter input values for the saprolite are shown in Table 5.9.11-1.

Table 5.9.11-1: Sensitivity to Saprolite K: Saprolite Parameter Values

	Saprolite Layer 2		Saprolite Layer 3	
	Kh	Kv	Kh	Kv
Model #1:	0.1	0.01	10	1
Model #12:	0.01	0.001	1	0.1
Model #13:	1	0.1	100	10

Calibration statistics of focus area wells are shown in Table 5.9.11-2. Scatterplots are shown on Figure 5.9.11-1. As shown in Table 5.9.11-2, calibration statistics are insensitive to lowering the saprolite conductivity and slightly sensitive to increasing the conductivity. Drain fluxes are insensitive to changes in the saprolite hydraulic conductivity.

Table 5.9.11-2: Sensitivity to Saprolite K: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #12:	-0.59	3.05	11.06	9.64	11.55	0.12	0.11	0.12
Model #13:	0.72	1.59	9.50	8.06	9.93	0.10	0.09	0.11

Compared to Model #1, decreasing the conductivity increased the simulated water levels, while increasing the conductivity had the opposite effect as reflected in changes in the ME (Table 5.9.11-2). The biggest impact of lowering the conductivity was observed at well RHMW07 (Figure 5.9.11-1). Since RHMW07 was conceptualized to lie within the saprolite, a lowering of the saprolite hydraulic conductivity raises the simulated water level RHMW07.

5.9.12 Sensitivity to Lower Basalt Kv with Higher Saprolite Kh (Model #14)

Participants in the GWMWG expressed interest to investigate the model sensitivity for the combination of lowering the Kv of basalt by a factor of 10 and simultaneously raising the Kh values for saprolite by a factor of 10. Model #14 was therefore a combined sensitivity of Model #9 and Model #12. Note that Model #9 was a recalibrated model since lowering the Kv of basalt had a large impact on the water levels. Therefore, the recalibrated Model #9 was used along with Model #12 for this analysis.

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.12-1. Model #14 was very similar to Model #9 with a slight decrease in water levels from Model #9 resulting from increasing the saprolite hydraulic conductivity (Table 5.9.12-1). Calibration statistics are moderately sensitive and drain fluxes slightly sensitive as shown on the table.

Table 5.9.12-1: Sensitivity to Lower Basalt Kv with Higher Saprolite Kh: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #9 (Recalibrated):	1.26	2.67	7.4	6.1	7.8	0.07	0.06	0.07
Model #14:	1.48	2.80	7.4	6.1	7.8	0.07	0.06	0.07

5.9.13 Sensitivity to Offshore GHB Conductance (Model #15 and Model #16)

Sensitivity to offshore GHB conductance was evaluated by decreasing (Model #15) and increasing (Model #16) values for the Pearl Harbor and offshore GHB conductance by a factor of 10. Thus, the connectivity of the bay and ocean to the caprock was varied by a factor of 10.

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.13-2. Scatterplots for the entire model domain are shown on Figures 5.9.13-1. As shown in Table 5.9.13-2, calibration statistics were moderately sensitive to lowering the offshore GHB conductance and slightly sensitive to raising the conductance. Drain fluxes were highly to moderately sensitive to decreasing the offshore GHB conductance, but were insensitive to increasing the conductance.

Table 5.9.13-1: Sensitivity to Offshore GHB Conductance: Parameter Values

GHB Conductance	Pearl Harbor (1/d)	Offshore (1/d)
Model #1:	0.005	0.014
Model #15 (×0.1):	0.0005	0.0014
Model #16 (×0.1):	0.05	0.14

Table 5.9.13-2: Sensitivity to Offshore GHB Conductance: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #15:	-2.62	2.88	17.4	15.3	17.4	0.18	0.16	0.18
Model #16:	0.32	1.25	9.5	8.1	10.0	0.10	0.09	0.11

Compared to Model #1, decreasing the GHB conductance raised the simulated water levels, while increasing the conductance had the opposite effect (Figure 5.9.13-1). In both cases, water levels in the caprock were out of calibration, either being simulated very high (Model #15), or very low (Model #16). These models could not be recalibrated to the caprock water levels and were therefore used in their sensitivity form, for further analyses. As a result, these models are unlikely and thus should have a reduced weighting when evaluating migration of water from beneath Red Hill or when analyzing source zones for public supply wells.

5.9.14 Sensitivity to Recharge (Model #17 and Model #18)

Sensitivity to recharge was evaluated by decreasing (Model #17) and increasing (Model #18) the recharge assigned to Model #1 by 20 percent. Parameter input values are shown in Table 5.9.14-1.

Table 5.9.14-1: Sensitivity to Recharge: Parameter Values

Recharge (mgd)	2006	2015	2017
Model #1:	48.04	35.81	36.77
Model #17 (×0.8):	10.03	29.84	30.64
Model #18 (×1.2):	57.65	42.97	44.12

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.14-2. As shown in Table 5.9.14-2, calibration statistics were highly sensitive to a 20 percent change in recharge. Drain fluxes were highly to moderately sensitive to decreasing the recharge and moderately to slightly sensitive to increasing the recharge.

Table 5.9.14-2: Sensitivity to Recharge: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #17 (Sensitivity Analysis):	2.53	2.79	5.2	5.1	7	0.06	0.06	0.08
Model #17 (Recalibrated):	0.79	1.4	9.5	9.5	11.4	0.1	0.1	0.12
Model #18 (Sensitivity Analysis):	-2.98	3.27	16.6	13.7	15.7	0.17	0.15	0.17
Model #18 (Recalibrated):	-0.8	1.57	11	8.4	10.2	0.12	0.1	0.11

Compared to Model #1, decreasing the recharge lowered the simulated water levels, while increasing the recharge had the opposite effect as reflected in changes in the ME (Table 5.9.14-2). This sensitivity simulation threw the model off calibration to a substantial degree; therefore, both models were approximately recalibrated for further evaluations and model application.

5.9.15 Sensitivity to Basalt Horizontal Anisotropy (Model #19 and Model #20)

Sensitivity to basalt horizontal anisotropy (HANI) was evaluated by decreasing (Model #19) and increasing (Model #20) the anisotropy value of Model #1 as shown in Table 5.9.15-1.

Table 5.9.15-1: Sensitivity to Basalt Horizontal Anisotropy: Parameter Values

	Horizontal Anisotropy Ratio
Model #1:	0.33
Model #19:	0.2
Model #20:	0.5

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.15-2. As shown in Table 5.9.15-2, calibration statistics were highly to moderately sensitive to a change in basalt HANI. Drain fluxes were insensitive to the changes.

Table 5.9.15-2: Sensitivity to Basalt Horizontal Anisotropy: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #19 (Sensitivity Analysis):	-2.9	3.25	9.3	8	9.8	0.1	0.1	0.1
Model #19 (Recalibrated):	0.13	0.99	18.18	16.4	18.62	0.14	0.12	0.14
Model #20 (Sensitivity Analysis):	1.41	1.78	11.95	10.3	12.3	0.11	0.1	0.11
Model #20 (Recalibrated):	-0.13	0.99	22.46	20.51	22.84	0.17	0.15	0.17

Compared to Model #1, decreasing the anisotropy increased the simulated water levels, while increasing the anisotropy had the opposite effect as reflected in changes in the ME (Table 5.9.15-2). This sensitivity simulation threw the model off calibration to a substantial degree; therefore, both models were approximately recalibrated for further evaluations and model application.

5.9.16 Sensitivity to Northeast Flux (Model #21 and Model #22)

Sensitivity to the northeast boundary inflow was evaluated by decreasing (Model #21) and increasing (Model #22) the northeast flux value of Model #1 by 20 percent. Parameter input values are shown in Table 5.9.16-1.

Table 5.9.16-1: Sensitivity to NE Flux: Parameter Values

	Horizontal Anisotropy Ratio
Model #1:	22.4
Model #21 (×0.8):	17.9
Model #22 (×1.2):	26.88

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.16-2. As shown in Table 5.9.16-2, calibration statistics are moderately sensitive and drain fluxes slightly sensitive to a 20 percent change in the northeast flux.

Table 5.9.16-2: Sensitivity to Basalt Horizontal Anisotropy: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #21 (Sensitivity Analysis):	1.5	1.92	7.9	6.4	8.4	0.09	0.07	0.09
Model #21 (Recalibrated):	0.45	1.27	10.6	9	11	0.11	0.1	0.12
Model #22 (Sensitivity Analysis):	-1.98	2.32	13.8	12.4	14.3	0.15	0.13	0.15
Model #22 (Recalibrated):	-0.81	1.46	10.9	9.5	11.3	0.12	0.11	0.12

Compared to Model #1, decreasing the northeast flux decreased the simulated water levels, while increasing the northeast flux had the opposite effect as reflected in changes in the ME (Table 5.9.16-2). This sensitivity simulation threw the model off calibration to a substantial degree; therefore, both models were approximately recalibrated for further evaluations and model application.

5.9.17 Sensitivity to Caprock Kh (Model #23, Model #24 and Model #25)

Sensitivity to caprock Kh was evaluated by decreasing (Model #23 and Model #24) and increasing (Model #25) the Kh of the caprock Model #1 value as shown in Table 5.9.17-1. Two low caprock Kh values were considered: an extremely low value (Model #23) and a reasonable low value (Model #24). The extremely low value of Model #23 was simulated after comments from the GWMWG indicating that caprock hydraulic conductivity should be much lower – probably lower than even 0.1 ft/d.

Table 5.9.17-1: Sensitivity to Caprock Kh: Parameter Values

	Caprock Kh (ft/d)
Model #1:	1,208
Model #23 (Lowest Kh):	1
Model #24 (Low Kh):	100
Model #25 (High Kh):	2,400

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.17-2. Scatterplots and water level contours are shown on Figures 5.9.17-1 and 5.9.17-2, respectively.

Table 5.9.17-2: Sensitivity to Caprock Kh: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #23 (Sensitivity Analysis):	-2.12	2.47	8.0	6.1	7.9	0.1	0.09	0.1
Model #23 (Recalibrated):	-1.75	2.12	0.5	0.0	0.4	0.03	0.0	0.03
Model #24 (Sensitivity Analysis):	-2.67	2.93	15.7	13.8	15.8	0.17	0.15	0.17
Model #24 (Recalibrated):	-1.23	1.74	11.1	9.3	11.2	0.12	0.11	0.13
Model #25 (Sensitivity Analysis):	0.06	1.2	10.3	8.9	10.8	0.11	0.1	0.12
Model #25 (Recalibrated):	-0.17	1.21	10.9	9.4	11.3	0.12	0.1	0.12

As shown in Table 5.9.17-2, calibration statistics for the focus area wells are moderately sensitive to decreasing caprock Kh, but insensitive to increasing the Kh. Drain fluxes are slightly to moderately sensitive to decreasing the caprock Kh, but insensitive to increasing the Kh. Compared to Model #1, decreasing the caprock Kh to 100 ft/d (Model #24) raised the simulated water levels, especially in wells screened in the caprock (Table 5.9.17-2). Increasing the caprock Kh to 2400 ft/d had little effect on the simulated water levels and only a slight decline in spring flow.

This sensitivity simulation threw the models off calibration to a sufficient degree; therefore, all models (#23, #24 and #25) were roughly recalibrated for further evaluations. However, as shown on Figure 5.9.17-2, Model #23 did not calibrate within the caprock and significant mounding of groundwater was observed in the caprock (Figure 5.9.17-2), which reflected in the significantly increased simulated water levels (Figure 5.9.17-1).

5.9.18 Sensitivity to Zonation of Caprock (Model #26 and Model #27)

The TEC (2007, 2010) models of the site had used a single material property representing the caprock. That approach was followed for the models discussed so far. However, the caprock can be segregated into two zones as done in the USGS saltwater intrusion modeling study (Oki 2005). Figure 1.2-2 shows the material property distribution of the USGS model, in model layer 1. The first zone represents the alluvial deposits just below the valleys in the upper reaches of the caprock formation, which have a low hydraulic conductivity (the USGS study used a value of 0.6 ft/d). The second zone represents the marine deposits nearer to the coast, which have a significantly higher hydraulic conductivity (the USGS study used a value of 2,500 ft/d). A model was therefore developed (Model #26) to evaluate the impact of this caprock configuration.

The USGS caprock configuration was implemented into Model #26. Preliminary simulations with this configuration produced unreasonably high water levels in the alluvial low hydraulic conductivity zone of the caprock similar to Model #23 that used a single caprock zone with a low hydraulic conductivity. Upon closer examination of the model, the saltwater interface as determined by the Ghyben Herzberg Principle (which was used in the previous models) caused the freshwater in the basalt to exit only within this low hydraulic conductivity zone causing these higher water levels. A closer examination of the USGS model saltwater interface (Figure 1.2-5) showed that it was significantly deeper beneath the caprock such that the freshwater would exit into the caprock in the higher conductivity marine sediments. Therefore, further adjustments were made to the bottom of the model domain using the saltwater interface simulated by the USGS model. This would be more representative of the saltwater interface because Ghyben Herzberg assumes vertical equilibrium, while there are actually high vertical gradients through the caprock.

An additional model was developed with two zones in the caprock. In addition to the two zones, this model (Model #27) considered that the saprolite was not present and thus prescribed properties of basalt to the saprolite zones. This model was developed at the request of the GWMWG.

With these changes, Model #26 and Model #27 were calibrated as shown in Table 5.9.18-1. Calibration statistics for the focus area wells are shown in Table 5.9.18-2. Model #1 calibration statistics are also shown for comparison. Both models are well calibrated and the parameters are within range of expected values for the caprock zones. Properties for saprolite (for Model #26), basalt, and valley fill were the same as for Model #1.

Table 5.9.18-1: Sensitivity to Zonation of Caprock: Parameter Values for Caprock Zones

	Kh (ft/d)	Kv (ft/d)
Model #1:	1,208	0.08
Model #26 (zone of marine sediments):	2,500	7
Model #26 (zone of alluvium):	1	1

Table 5.9.18-2: Sensitivity to Zonation of Caprock: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #26:	0.18	1.31	11.9	12.1	12.3	0.19	0.2	0.2
Model #27:	0.12	1.57	12.7	12.9	13	0.21	0.21	0.22

Figure 5.9.18-1 shows the scatterplots for Model #26. The caprock water levels are better simulated for this case than for Model #1. Water levels in the basalt are well calibrated to observed conditions. Figure 5.9.18-2 shows the water levels in model layers 1 and 2. Water levels in layer 1 have very steep gradients in low conductivity alluvium zone within the caprock. Water levels in layer 2 are similar to previous models with a generally east to west hydraulic gradient across the model domain.

Figure 5.9.18-3 shows the scatterplots for Model #27. This model shows similar behavior to Model #26.

5.9.19 Sensitivity to Elevation of Model Bottom (Model #28)

The bottom of the freshwater model domain was evaluated using the Ghyben Herzberg Principle in prior models (Model #1 through Model #25). This representation was noted to be fairly accurate in unconfined portions of the basalt, but was noted to under-predict the bottom elevation beneath the caprock as noted from the USGS saltwater intrusion model (Oki 2005).

To note the impact of uncertainty in the bottom elevation, Model #28 was constructed with a model bottom elevation that was 164 feet (50 meters) deeper than for Model #1. Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.19-1. As shown in Table 5.9.19-1, calibration statistics are insensitive and drain fluxes insensitive sensitive to a lower model bottom elevation.

Table 5.9.19-1: Sensitivity to Model Bottom Elevation: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #28:	0.32	1.23	10.7	9.3	11.2	0.11	0.10	0.12

5.9.20 Sensitivity to Combined changes in Recharge and Northeast Lateral Boundary Inflow (Model #29 and Model #30)

Participants in the GWMWG expressed interest to investigate a combined sensitivity to changing the recharge value and the northeast lateral boundary inflow value. Thus, both recharge and northeast lateral boundary inflow were changed simultaneously from Model #1 by decreasing the Model #1 values by 20 percent (Model #29) and increasing Model #1 values by 20 percent (Model #30). Model #29 was therefore a combined sensitivity of Model #17 and Model #21, while Model #30 was a combined sensitivity of Model #18 and Model #22. The recharge and northeast flux values for these simulations are shown in Table 5.9.20-1.

Table 5.9.20-1: Sensitivity to Combined Recharge and NE Inflow: Flux Values

Parameters (mgd)	2006	2015	2017
Model #1 – Recharge (NE Flux):	48.04 (22.4)	35.81 (22.4)	36.77 (22.4)
Model #29 – Recharge (NE Flux):	57.65 (26.88)	42.97 (26.88)	44.12 (26.88)
Model #30 – Recharge (NE Flux):	40.03 (17.9)	29.84 (17.9)	30.64 (17.9)

Calibration statistics of focus area wells to assess changes in model calibration are shown in Table 5.9.20-2. Calibration statistics and drain fluxes are highly sensitive for both models. Therefore, an attempt was made to recalibrate both models. Model #29 could be recalibrated to water levels, but drain fluxes could not be recalibrated and were too low resulting from lowered inflows into the model from recharge as well as from the northeast inflow boundary indicating that the inflows to the model are probably too low. Model #30 was recalibrated to the water level statistics as well as drain fluxes at the springs in the model domain.

Table 5.9.20-2: Sensitivity to Combined Recharge and NE Inflow: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #29 (Recalibrated):	-4.03	4.19	19.3	16.4	18.4	0.2	0.17	0.19
Model #29 (Sensitivity Analysis):	0.51	1.35	7.8	5.5	7.2	0.09	0.07	0.09
Model #30 (Recalibrated):	4.01	4.2	3	2.7	4.6	0.04	0.04	0.05
Model #30 (Sensitivity Analysis):	0.04	1.15	12.8	12.5	14.7	0.13	0.13	0.15

5.9.21 Sensitivity to Elevation of Hālawa Shaft and Red Hill Shaft (Model #31)

Model #1 through Model #30 used elevations for Hālawa Shaft and RHS as presented in the TEC (2007) study because the as-built details of these shafts were not otherwise available. During the course of developing these models, however, the shaft details were made available due to the efforts of the GWMWG. Model #31 was therefore constructed from Model #1 but with using the as-built elevations of the shafts as shown in Table 5.9.21-1.

Table 5.9.21-1: Sensitivity to Shaft Elevation: Parameter Values

	Hālawa Shaft Elevation (ft)	Red Hill Shaft Elevation (ft)
Model #1:	-18	-2
Model #31:	-10	+3

Calibration statistics at focus area wells to assess changes in model calibration are shown in Table 5.9.21-2. As shown in Table 5.9.21-2, both calibration statistics and drain fluxes are insensitive to raising the elevations for both shafts.

Table 5.9.21-2: Sensitivity to Shaft Elevation: Simulation Statistics Summary

			Pearl Harbor Spring at Kalauao Flux (mgd)			Kalauao Spring Flux (mgd)		
	ME (ft)	RMS (ft)	2006	2015	2017	2006	2015	2017
Model #1:	-0.25	1.20	10.9	10.0	11.6	0.12	0.11	0.12
Model #31:	-0.17	1.21	10.8	9.3	11.2	0.12	0.10	0.12

5.10 Transient Simulations of Synoptic Studies of 2006, 2015, and 2017

Synoptic water level and pumping rate measurements were made at several wells during a short time span in 2006, 2015, and 2017/2018. These synoptic studies provide valuable information on the impact of well pumping at one location, and to water levels at several locations regionally. From this impact, the connectivity between a pumping well and the water level observation can be established. Specifically, the modeled impact of pumping changes as compared to observed impacts was evaluated to note the simulated connectivity in relation to observations for various parts of the model domain. This analysis was conducted for Model #1 as well as several key models to note the simulated behavior of the models. In general, the simulations bracket the observed transient pumping signals.

5.10.1 Transient Model Parameters

Storage parameters used for the transient synoptic study simulations are shown in Table 5.10.1-1. The specific yield and specific storage of caprock and basalt used in the current model were obtained from TEC (2007). Similar to the TEC (2007) study, specific storage of saprolite was assumed to be the same as valley fill. To evaluate the impact of uncertainties of these parameters, a sensitivity study was implemented that developed models with a range of transient model parameters.

Table 5.10.1-1: Interim Model Transient Synoptic Study Storage Parameters

	Caprock	Valley Fill	Saprolite	Basalt
Specific yield [-]	0.1	0.15	0.15	0.031
Specific storage [ft^{-1}]	3.05×10^{-5}	1.52×10^{-5}	1.52×10^{-5}	1.07×10^{-5}

5.10.2 Simulation of the 2006 Synoptic Study Using Model #1 (Model #32)

The synoptic study of 2006 was detailed in Section 3.2.3 and depicted on Figure 3.2.3-1. In summary, pumping at Hālawa Shaft oscillated daily between 8 and 15 mgd from April 1 through May 14 (averaging 13 mgd), was constant at about 8 mgd through May 21, and then varied (generally between 12 and 15 mgd) through May 31. Pumping at RHS oscillated daily between [redacted] and [redacted] mgd from April 1 through May 12 (averaging about [redacted] mgd), was zero through May 19, oscillated daily between [redacted] and [redacted] mgd through May 26, and was largely zero through May 31. These primary pumping regimes were implemented into a transient model developed from Model #1 to evaluate the simulated transient impact at the various monitoring wells. The pumping variations implemented into the model were the same as those of the TEC (2007) study.

Simulation of the 2006 synoptic study was initiated with 2006 steady-state conditions of Model #1. A comparison of simulated and observed water levels for the five 2006 synoptic study wells (RHMW02, RHMW03, RHMW04, OWDFMW01, and Well Number 2253-33) is shown on Figures 5.10.2-1 through 5.10.2-5. In addition to the observed and simulated water level changes over time, the figures include the simulated pumping rate at the RHS and Hālawa Shaft during that time period.

The observed and simulated water levels respond mainly to pumping changes at RHS. Changes in Hālawa Shaft pumping did not cause noticeable water level changes in these monitoring wells. Water levels in observation wells increased when RHS was turned off on May 12. When pumping resumed on May 19, the water levels in observation wells dropped through May 26, when pumping is again reduced. A slight time lag in the water level response was also noted in wells further away from RHS. The simulated changes in water levels at all wells are similar to observed changes; however, the daily fluctuations due to pumping fluctuations at RHS were muted compared to observed conditions. In general, however, Model #1 reproduces the water level changes of the 2006 synoptic study wells reasonably well.

5.10.3 Simulation of the 2015 Synoptic Study (Model #33)

The synoptic study of 2015 is depicted on Figure 3.2.3-2. For this study, pumping at Hālawa Shaft was generally constant at 6 mgd between May 1 and May 7, was zero through May 15, then oscillated around 14 mgd through May 22, and was constant at around 6 mgd through May 31, with pumping spikes for a day or less in between. Pumping at RHS turned on and off throughout this period on a sub-daily basis, with peak pumping varying from [redacted] to [redacted] mgd. The primary pumping regime of Hālawa Shaft discussed here was implemented into the base case model to evaluate the simulated impact at the various monitoring wells. The pumping regime of RHS was averaged to daily values and the sub-daily fluctuations were not simulated.

Simulation of the 2015 synoptic study was initiated with 2006 steady-state conditions of Model #1. A comparison of simulated and observed water levels for the nine 2015 synoptic study wells is shown on Figures 5.10.3-1 through 5.10.3-9. In addition to the observed and simulated water level changes over time, the figures include the simulated pumping rates at the RHS and Hālawa Shaft.

The observed and simulated water levels appear to respond to pumping changes at both Hālawa Shaft and RHS. Water levels in observation wells increase when Hālawa Shaft is turned off on May 8, then decrease when pumping resumes on May 14. Water levels then increase again as pumping at Hālawa Shaft reduces. This response was simulated in wells RHMW05, OWDFMW01, HALAWA T45, Navy ʻAiea, Moanalua DH43, Kaʻamilo Deep, Moanalua T24, and Moanalua Deep. However, simulated water levels in well RHMW07 were flat because of the low conductivity saprolite at RHMW07. Observed response at RHMW07 was also fairly flat and the small fluctuations did not seem to correlate with pumping at either RHS or Hālawa Shaft. In general, the simulated changes in water levels at all wells were similar to observed changes and the Model #33, with hydraulic conductivity properties of Model #1 reproduced the water level changes of the 2015 synoptic study wells reasonably well.

5.10.4 Sensitivity to 2006 Transient Synoptic Studies (Model #34 through Model #43)

Sensitivity analyses were conducted to evaluate the impact of transient input parameters on the transient synoptic studies of 2006. The sensitivity studies were conducted using Model #1, by varying the following: specific yield (low value: Model #34; high value: Model #35), and specific storage (low value: Model #36; high value: Model #37). Table 5.10.1-2 shows the transient parameter values for these models.

Table 5.10.1-2: Sensitivity to 2006 Transient Synoptic Studies: Transient Model Parameters

	Caprock	Valley Fill	Saprolite	Basalt
Model #1 -Specific yield [-]	0.1	0.15	0.15	0.031
Model #1 - Specific storage [ft^{-1}]	$3.05{\times}10^{-5}$	$1.52{\times}10^{-5}$	$1.52{\times}10^{-5}$	$1.07{\times}10^{-5}$
Model #34 -Specific yield [-]	0.1	0.15	0.15	0.0031
Model #35 - Specific yield [-]	0.1	0.15	0.15	0.31
Model #36 -Specific yield [-]	$3.05{\times}10^{-5}$	$1.52{\times}10^{-5}$	$1.52{\times}10^{-5}$	$1.07{\times}10^{-6}$
Model #37 -Specific yield [-]	$3.05{\times}10^{-5}$	$1.52{\times}10^{-5}$	$1.52{\times}10^{-5}$	$1.07{\times}10^{-4}$

Sensitivity analyses were also conducted to evaluate the transient impact of some of the other models. These models are as follows:

- Models that evaluated low and high values for the HANI of basalt (low value: Model #38; high value: Model #39). These transient models were developed form their steady-state counterparts, Model #19, Model #20, respectively.
- A model that evaluated presence of saprolite (Model #40). This transient model was developed from its steady-state counterpart, Model #8.

- A model that evaluated presence of clinker (with a low porosity value of 0.04: Model #41; with a high porosity value of 0.5: Model #42). This transient model was developed from its steady-state counterpart, Model #2.
- A model that evaluated high hydraulic conductivity for basalt (Model #43). This transient model was developed from its steady-state counterpart, Model #11.

For these models, the storage parameter values of Table 5.10.1-1 were used.

Water level changes for all of these simulations in wells RHMW02, RHMW03, RHMW04, OWDFMW01, Hālawa shallow observation well 2255-33, Hālawa deep observation well 2255-40, south Hālawa deep observation well HDMW2253-03, and RHS are shown on Figures 5.10.4-1 through 5.10.4-16.

Decreasing the specific yield increased the smaller fluctuation amplitude, but resulted in larger long-term changes in wells RHMW02, RHMW03, RHMW04, OWDFMW01, and HDMW2253-03 (Figures 5.10.4-1 to 5.10.4-4, and 5.10.4-7). In these wells, the higher specific yield muted water level fluctuations. In well 2255-40, simulated water levels are higher than observed values (Figure 5.10.4-6). Well 2255-33 was sensitive to changes in the specific yield (Figure 5.10.4-5). Water levels within the RHS were insensitive to changes in specific yield (Figure 5.10.4-8).

Increasing specific storage caused smaller long-term changes in wells RHMW02, RHMW03, RHMW04, OWDFMW01, and HDMW2253-03 (Figures 5.10.4-1 to 5.10.4-4, and 5.10.4-7). Well 2255-33 was sensitive to the higher specific storage, but insensitive to the lower specific storage (Figure 5.10.4-5). At this well, simulated water level changes were higher than observed even with higher storage terms. Higher simulated water level changes than observed conditions were also observed in well 2255-40 (Figure 5.10.4-6).

Wells RHMW02, RHMW03, RHMW04, OWDFMW01, HDMW2253-03 (Figures 5.10.4-1 to 5.10.4-4, and 5.10.4-7), and water levels within the RHS (Figure 5.10.4-8) were insensitive to changes in the Kh of basalt. In well 2255-40 (Figure 5.10.4-6), simulated water level changes are higher than observed (comparing with TEC [2007] reported observed maximum changes of about 0.2 foot for the synoptic study).

Increasing basalt Kh slightly increased the amplitude of smaller fluctuations and resulted in slightly smaller long-term changes in well RHMW02, RHMW03, RHMW04, OWDFMW01, and HDMW2253-03 (Figures 5.10.4-9 to 5.10.4-12, and 5.10.4-15). Water levels in these wells were very sensitive to the presence of the clinker, but insensitive to the removal of the saprolite. Although a sensitivity to the high porosity clinker was observed in well 2255-33 (Figure 5.10.4-13), the well was insensitive to changes in increasing basalt Kh, removing the saprolite, and lowering the clinker porosity. In Well 2255-40 (Figure 5.10.4-14), simulated water level changes were higher than observed values (comparing with TEC [2007] reported maximum observed changes of about 0.5 foot for the synoptic study). At the RHS (Figure 5.10.4-16), increasing basalt Kh or including the clinker reduced drawdown at the shaft by simulating a larger groundwater flow toward pumping at the shaft. A better match to the water level signature at the shaft was obtained with the higher basalt Kh.

Overall, the sensitivity analysis models bracketed observed conditions within the modeling domain. With RHS pumping, the model is insensitive to HANI of basalt, slightly sensitive to specific storage parameters, sensitive to larger basalt Kh, and highly sensitive to specific yield parameters. Additionally, based on the response of wells, the modeled connectivity from the Facility toward the Hālawa and Kalihi Valleys was larger than was observed.

5.11 CONCLUDING REMARKS ON MODEL DEVELOPMENT AND CALIBRATION

Several insights were gained in developing and calibrating the models. Certain parameters sets or conceptualizations resulted in models that had better or worse calibration and water budget terms, providing insights on advantages and limitations of parameter ranges and conceptualizations. For instance, zoning of the caprock into alluvial and marine sediments (Model #26) created better modeling statistics, while a very low hydraulic conductivity of the caprock (Model #23) resulted in a model that did not calibrate. This will help inform development of the final flow model as discussed in Section 8.

Conservative models were developed and calibrated for the interim study evaluation for the various simulation objectives. General points in that regard include:

- Regionally, the calibrated water levels were generally lower than measured in the northwest of the domain, causing higher apparent gradients toward the northwest than measured conditions. Therefore, the models were conservative (protective) with respect to potential migration toward Hālawa Shaft.
- Parameters for the models were evaluated with transient calibration runs against synoptic study data from 2006 and 2015. Observed behavior was bracketed by simulated results from the models, indicating that the models included the range of extreme conditions.
- Various models were examined as sensitivities from Model #1 to analyze the impact of parameter uncertainty on calibration. The various models were also evaluated as separate calibration-constrained models when possible to assess if the recalibrated model is feasible, and to estimate particle migration using the various recalibrated models (discussed in Section 6).
- In most models, water levels at Hālawa Shaft were conservatively simulated lower than measured relative to observed water levels beneath the Facility, causing larger draw toward Hālawa Shaft as compared to the calibration dataset value.
- Conservative models were used to evaluate various critical objectives:
  - The conceptual model that is most conservative (protective) with respect to evaluating potential migration toward RHS included a high-K clinker zone between the Facility and the RHS.
  - The conceptual models that are most conservative (protective) with respect to evaluating potential migration toward Hālawa Shaft do not include a clinker zone and evaluate high hydraulic conductivity of the saprolite barrier. A “what-if” condition of no saprolite barrier was also simulated that was protective of Hālawa Shaft.

Finally, multiple models were developed to bracket the range of parameter values, stresses, or conceptualizations at various scales. The model development effort was guided by comments from the GWMWG, and several of the models were developed as a result of their input. A deliberate approach toward constructing and calibrating these models provided a valuable understanding of the significant controlling mechanisms that drive the hydrogeologic system at Red Hill. A focused approach of developing multiple models for the interim modeling study also provides guidance for developing the final groundwater flow model.

6. Model Application

The interim model was developed to help evaluate migration of water from beneath the Facility and estimate the zones of source water for key nearby water supply wells and shafts; specifically, the RHS, the Hālawa Shaft, and Moanalua wells. A particle tracking approach was used to evaluate this migration and source zone evaluation. A traditional sensitivity analysis was conducted on parameter ranges and to evaluate the impact of various conceptual representations and numerical approximations on the calibration as discussed in Section 5. The sensitivity analysis was extended to evaluate the impact on the conclusions and is discussed further in this section. Uncertainty in the evaluation was estimated using the multiple models that were developed. This section summarizes the approach and results of model runs created to meet the modeling objectives.

6.1 Objectives

The objectives of this interim modeling study were to:

1. Evaluate the zones of source water for key pumping wells/shafts within the modeling domain, including the timing and trajectory of backward particle tracking from each well.
2. Evaluate the forward migration timing and trajectory of groundwater underlying the Facility.
3. Evaluate the impact of uncertainty and model approximations on the source water zones for key wells and on forward migration from underneath the Facility.
4. Develop an understanding of the hydrogeologic system behavior and prepare for development of a comprehensive final groundwater flow and transport model.

6.2 Modeling Approach

The various models that were developed and discussed in Section 5 were used to evaluate migration and source water zones. The steady-state 2017 model was used in the analysis. The evaluations were conducted under extreme conditions for pumping at key locations to provide conservative evaluations. Two primary scenarios were considered in this regard:

1. Maximum pumping at Hālawa Shaft (16 mgd), RHS [redacted] mgd), and Moanalua Well (3.7 mgd)
2. Maximum pumping at Hālawa Shaft and Moanalua Well with no pumping at RHS

The first scenario is referred to as the "RHS Pumping Scenario", while the second scenario is referred to as the "RHS Not Pumping Scenario". The groundwater flow models were run for each of these two scenarios, with all other conditions of a model being unchanged from the 2017 steady-state simulation input. Use of steady-state flow conditions for the evaluations provides additional conservatism to the analysis because in practice, these large pumping rates cannot be sustained indefinitely as simulated (per BWS discussions at the June GWMWG meeting). Also, the buffering that occurs due to storage effects of transient conditions is neglected with steady-state flow conditions.

Particle tracking was then conducted on the flow field generated by each model for each of the above two scenarios. Mod-PATH3DU, a particle-tracking model developed for unstructured grids and applicable to MODFLOW-USG, is available from within GMS and was therefore used for this analysis. Preliminary simulations for the interim modeling effort used Version 1 of Mod-PATH3DU (SSPA 2014), while later particle tracking simulations used the updated Version 2 of Mod-PATH3DU (SSPA 2018). Besides differences in input structure and inclusion of routines to limit oscillation of particles and improve convergence around pumping wells or shafts, Version 2 of the code includes enhancements to the particle tracking routine itself. Specifically, a particle's movement in Version 1 was limited to a cell face if the time integration step would take it past the cell face. Version 2 no longer limits the cell movement, and this difference can have slight differences in the results (SSPA, personal communication). Due to more restrictions on particle movement in Version 1, its results may be more accurate than those of Version 2 unless time stepping is also restricted. Version 1 of Mod-PATH3DU was run in Version 10.3 of GMS, while Version 2 of Mod-PATH3DU was run in Version 10.4 of GMS.

These issues were noticed in simulations conducted for the interim model. Specifically for forward particle tracking, some models exhibited oscillations and did not converge with Version 1 of Mod-PATH3DU. Forward particle tracking using Version 2 of the code converged for all models but there were slight differences in the results, which lead to one particle from the Facility migrating to Hālawa Shaft when none had, with Version 1 in several of the models. Differences also occurred due to GMS issues in vertical placement of the particles. Thus, the forward particle tracking plots for the individual models and their associated discussions in Sections 6.4.3 through 6.4.22 were developed for some of the models using Version 1 and others using Version 2. Reverse particle tracking simulations were all conducted in Version 1 of Mod-PATH3DU as there were no associated issues. All particle tracking simulations could not be redone in Version 2 due to scheduling considerations. However, the conclusions of the interim study regarding migration from the Facility to Hālawa Shaft are not altered by either version of the code.

Reverse particle tracking was conducted from RHS, Hālawa Shaft, and the Moanalua Wells to achieve Objective 1 mentioned above. Forward particle tracking from a trapezoidal area encompassing the Facility tanks was conducted to achieve Objective 2 mentioned above. Objective 3 was achieved by performing a multi-model analysis. Results from all models were synthesized to provide a comprehensive picture of the evaluations. The individual model results were also evaluated to identify parameters or models that may be critical to particular objectives.

To meet modeling objectives, sets of particles were released at four locations (Figure 6.2-1): forward tracking particles were released beneath the Facility tanks; backward tracking particles were released along the RHS; backward tracking particles were released along the Hālawa Shaft; and backward tracking particles were released at the Moanalua wells. In addition to visualizing groundwater travel trajectories, particle tracking also provided an estimation of travel times.

Reverse particle tracks were generated by GMS for Hālawa Shaft and Red Hill Shaft, only at the center elevation of the shaft. This was a limitation of GMS for the interim modeling effort, and a request has been made to the GMS developers to add flexibility and resolve other related issues for future modeling including for final flow model development as needed.

6.3 RESULTS FROM MODEL #1 FOR RHS PUMPING AND RHS NOT PUMPING

Results from Model #1 are examined in detail in this section to understand simulated behavior. For the other models, the similarities and differences with Model #1 are noted in the next section such that impacts of the range of parameter values and specific conceptual representations can be comprehensively evaluated without detailing each and every model. Particle tracking results are displayed for each model, however, to note if specific conditions warrant further attention. The particle tracking results are also synthesized for all models to comprehensively address uncertainty.

6.3.1 Water Levels

The simulated steady-state water level elevations for the RHS Pumping Scenario and the RHS Not Pumping Scenario with Model #1 are shown on Figures 6.3.1-1 and 6.3.1-2, respectively. There was a deep cone of depression in water levels at RHS and Hālawa Shaft for the first case, with very flat gradients past RHS for the second case. Furthermore, this pumping regime depresses the regional water table by about 5 feet for the RHS Pumping Scenario and about 3 feet for the RHS Not Pumping Scenario, as compared to simulated 2017 conditions (Figures 5.6-2 and 5.6-3).

Water levels at key wells for the RHS Pumping and RHS Not Pumping Scenarios with Model #1, and a comparison of head differences between key wells and Hālawa Shaft is shown in Table 6.3.1-1. The water levels are noted to be fairly flat down to RHS when it is not pumping. When comparing with Table 5.8.3-1 for the calibration simulations, the apparent water level gradients from the Facility toward Hālawa Shaft are significantly larger under the application scenarios than were calibrated or observed, thereby providing conditions that are extremely conservative in evaluating migration toward Hālawa Shaft. This is especially true of the RHS Not Pumping Scenario, the setup of which itself is extreme (i.e., that RHS does not pump indefinitely, while Hālawa Shaft pumps at 16 mgd indefinitely).

Table 6.3.1-1: Model Application – Key Head Differences Between Hālawa Shaft and Red Hill Wells

	Water Levels		Water Level Difference with Hālawa Shaft	
Well Name	Red Hill Shaft On	Red Hill Shaft Off	Red Hill Shaft On	Red Hill Shaft Off
OWDFMW01	14.14	16.32	8.29	8.72
RHMW01	15.05	17.36	9.22	9.76
RHMW02	15.43	17.55	9.58	9.93
RHMW03	15.75	17.75	9.90	10.14
RHMW04	16.05	17.98	10.20	10.38
RHMW05	12.38	16.97	6.53	9.37
RHMW06	15.69	17.71	9.85	10.10
RHMW07	18.37	20.44	12.52	12.83
RHMW08	14.52	17.21	8.73	9.61
RHMW09	15.25	17.44	9.39	9.82
Red Hill Shaft	9.75	16.87	3.90	9.26

6.3.2 Migration from the Water Table beneath Facility when Red Hill Shaft is Pumping

Forward migration timing and trajectory of groundwater underlying the Facility was evaluated by placing 16 particles in and around the Storage Tanks and tracking forward travel as shown on Figure 6.3.2-1, for the RHS Pumping Scenario with Model #1. With each yellow arrow on Figure 6.3.2-1 representing a travel time of 30 days, groundwater underlying the Facility reaches the RHS between 30 and 360 days depending on the starting location. All pathlines under the Facility remain in Layer 2 of the model. All of the particles that originated from beneath the Facility were captured by the pumping at RHS.

6.3.3 Source Water Zones of Red Hill Shaft, Hālawa Shaft, and Moanalua Well

Source water zones of the RHS, Hālawa Shaft, and the Moanalua well were also evaluated for the RHS Pumping and RHS Not Pumping Scenarios.

For the RHS Not Pumping Scenario, backward tracking particles were traced from the Hālawa Shaft and the Moanalua Well, while forward tracking particles were traced from the Facility for Model #1. The source water zones are delineated by the pathlines shown on Figures 6.3.3-1 and 6.3.3-2. The Moanalua well draws groundwater only from deeper in the basalt, in model Layer 5. For the Hālawa Shaft, groundwater originated in the basalt at the simulated upstream model boundary in model layers 2 and 3, from locations northeast of Hālawa Shaft and was drawn into the deeper layers of the basalt (Layers 4 and 5) before being pulled up into Hālawa Shaft located in Layer 3 of the model. Groundwater originating from beneath the Facility migrates in the basalt past RHS in a southwesterly direction, then curves to the west at the bottom of the valley. The water then travels upwards into the caprock (model Layer 1) and in a southwesterly, then westerly direction toward Pearl Harbor where it discharges into the bay.

For the RHS Pumping Scenario, backward tracking particles were traced from the Hālawa Shaft, the Moanalua wells, and the RHS. Source water zones are delineated by the pathlines shown on Figures 6.3.3-3, 6.3.3-4, and 6.3.3-5. As shown on Figure 6.3.3-3, the pumping at RHS does not appear to impact the source water zone of the Moanalua well or of Hālawa Shaft (compared to Figure 6.3.3-1). Groundwater that is pumped at RHS originated from locations to the northeast of the shaft and migrates beneath the Facility. Some water extracted at RHS also originated from across South Hālawa Valley by traveling beneath the saprolite.

6.4 Evaluation of the Impact of Model Sensitivity and Uncertainty

A multi-model approach was used in this study to evaluate the impact of parameter uncertainty, different conceptual representations, and numerical approximations, on modeling flow and migration of groundwater from beneath Facility, and on the source water zones for key wells.

The multiple models were calibrated as detailed in Section 5. Each of these models was further used with the particle tracking approach applied to Model #1 detailed above to evaluate the response of these various representations. Parameter sensitivity to calibration was evaluated, where applicable, as detailed in Section 5. Sensitivity of these parameters was further noted toward the simulation objectives for each of the application scenarios (RHS Pumping and RHS Not Pumping), and for each of the objectives (specifically the source water zones of each of the water supply shafts/wells and the migration behavior of water from beneath Facility). The sensitivity analyses were categorized based on ASTM International (ASTM) classifications to identify data significance. Finally, the results of multiple models were synthesized to provide a comprehensive evaluation of uncertainty as depicted by each of the models.

6.4.1 Approach

A peer-review published approach toward evaluating the uncertainty in capture zones is to couple particle tracking with a Monte Carlo framework (i.e., PT-MC) (Frind and Molson 2018; Anderson, Woessner, and Hunt 2015). Under PT-MC, hundreds of equally probable values of a single input parameter are obtained based on the parameter's underlying statistical distribution, and a groundwater model is created for each probable value. Multiple parameters are varied and combined in a random manner in this approach. Each of the models could further be calibration-constrained. The models may further be parsed to be conceptually reasonable by inclusion of expert information and via a post-audit of each of the models to establish reasonableness in conceptual representation and water budgets. Particle tracking is then performed for each selected model and particle-tracking results from all models are combined to create a capture frequency or capture probability map. Evaluation of forward migration of particles can be done in a similar manner.

Our approach is similar to the PT-MC approach. However, instead of creating hundreds of models with random combinations of material parameters as in the MC method, the current study deliberately selected models with focused sets of parameters to provide an understanding of the impact of the ranges of individual model parameters as well as of various conceptualizations and numerical or boundary approximations. The current approach further provides a traditional sensitivity analysis and each model is examined separately to provide focused information on the significance of specific data or model conceptualization, as related to the migration of water from the Facility or the source water zones of key public supply locations.

6.4.2 Sensitivity Analysis and Categorization

The impact of the sensitivity analysis on the recalibrated (if performed) model was determined based on calibration statistics. Changes in calibration statistics from those of Model #1 were judged as per Table 5.9-1. ASTM (2002) guidelines on sensitivity analyses suggest that the changes in modeling objectives be paired with changes in calibration statistics to provide additional information on the significance of a parameter value's relevance to the modeling objectives.

Specific modeling objectives that were determined as significant for this analysis included qualitative evaluations of:

- The source water zones (including an evaluation of direction and width, and difference between time markers on the backward particle tracking trajectories) of the Moanalua wells, Hālawa Shaft, and RHS.
- The migration of groundwater from beneath the Facility, including an evaluation of direction and width, and difference between time markers on the forward particle tracking trajectories.

Changes in the modeling objectives were classified as Insensitive (Insignificant), Slightly Sensitive (Insignificant), or Highly Sensitive (Significant) as shown in Table 6.4.2-1. The evaluations were performed for both the RHS Pumping Scenario and RHS Not Pumping Scenario.

Table 6.4.2-1: Categorization of Sensitivity to Modeling Objectives

Category	Remarks
Insensitivity (Insignificant)	No visible change in capture width or direction from Model 0
Slightly Sensitive (Insignificant)	Visually noticeable change in capture width or direction
Highly Sensitive (Significant)	Visually significant change in capture width or direction; Also evaluated estimates of change in width of capture at Hālawa Shaft is greater than 1,000 feet

The overall impact of a parameter was evaluated by categorizing the sensitivity analysis into Type 1, Type II, Type III, or Type IV Sensitivities, in accordance with ASTM guidelines, as detailed in Table 6.4.2-2. Of these, only Type IV Sensitivities are of concern in a traditional sensitivity analysis because this type of error requires additional data collection or evaluations to narrow data ranges and impacts. The alternative, as applied in the current study, is to use the more conservative model to provide a more protective estimation of the possible impact.

Table 6.4.2-2: ASTM Guidelines for Categorization of Sensitivity Simulations

ASTM Category	Change in Calibration	Change in Conclusion	Remarks
Type I	Insignificant	Insignificant	Not of concern because regardless of input because conclusion remains the same
Type II	Significant	Insignificant	Not of concern because regardless of input because conclusion remains the same
Type II	Significant	Significant	Not of concern in traditional sensitivity analysis because calibration eliminates unreasonable values
Type IV	Insignificant	Significant	Requires additional data collection or evaluations to narrow data range or evaluate impact

Table 5.9.1-1 summarizes the calibration sensitivity analyses. These models were further evaluated for sensitivity to the objectives as summarized and categorized in Table 6.4.2-3 for critical objectives of concern.

Table 6.4.2-3: Summary of Sensitivity Analyses and Models

Model Number	Parameter	Sensitivity to Calibration	Sensitivity to Conclusions	ASTM Sensitivity Type
Model #2	Heterogeneity due to Presence of Clinker	Slightly Sensitive	Insensitive/ Highly Sensitive	I or IV
Model #3	GHB 1: 2017 Interpolated Stages	Slightly Sensitive	Highly Sensitive	IV
Model #4	GHB 2: Lower NW and SE Stage	Insensitive	Highly Sensitive	IV
Model #5	GHB 3: Lower NW and Higher SE Stage	Moderately Sensitive	Highly Sensitive	III or IV
Model #6	GHB 4: NW and SE Stages Lowered 3-ft	Highly Sensitive	Highly Sensitive	III
Model #7	GHB 5: 2017 Interpolated Stages with Higher NW Stage for GHB in Basalt	Moderately/Highly Sensitive	Highly Sensitive	III
Model #8	Saprolite Assuming Basalt Properties	Moderately/Slightly Sensitive	Insensitive/ Highly Sensitive	I, II, or IV
Model #9 - Low Value Model #10 - High Value	Basalt Kv	Moderately/Slightly Sensitive Insensitive	Highly Sensitive	III or IV
Model #11	Basalt Kh (higher value)	Highly Sensitive	Insensitive	II
Model #12 - Low Value Model #13 - High Value	Saprolite Hydraulic Conductivity	Insensitive Slightly Sensitive	Insensitive	I
Model #14	Lower Basalt Kv and higher Saprolite K	Moderately/Slightly Sensitive	Highly Sensitive	III or IV
Model #15 - Low Value Model #16 - High Value	Offshore GHB Boundary Conductance	Highly Sensitive Insensitive	Insensitive	I or II
Model #17 - Low Value Model #18 - High Value	Recharge	Slightly Sensitive Highly Sensitive	Insensitive/ Slightly Sensitive	I or II
Model #19 - Low Value Model #20 - High Value	Basalt Horizontal Anisotropy	Insensitive Moderately/Highly Sensitive	Slightly Sensitive	I or II
Model #21 - Low Value Model #22 - High Value	NE Boundary Inflow	Moderate/Slightly Sensitive	Insensitive	I or II
Model #23 - Lowest Value Model #24 - Low Value Model #25 - High Value	Caprock Horizontal Hydraulic Conductivity	Highly Sensitive Slightly Moderately Sensitive Insensitive	Insensitive	I or II

Model Number	Parameter	Sensitivity to Calibration	Sensitivity to Conclusions	ASTM Sensitivity Type
Model #26 Model #27 – with saprolite properties same as basalt	Zonation of Caprock into alluvial and marine sediments	Highly Sensitive	Highly Sensitive	III
Model #28	Model Bottom Elevation	Insensitive	Insensitive	I
Model #29 - Low Value Model #30 - High Value	Combined changes in Recharge and NE Boundary Inflow	Highly Sensitive	Insensitive/ Highly Sensitive	II or III
Model #31	Elevation of Hālawa Shaft and Red Hill Shaft	Insensitive	Insensitive	I
Model #32	Transient 2006 Synoptic Study using Model #1	n/a	n/a	n/a
Model #33	Transient 20156 Synoptic Study using Model #1	n/a	n/a	n/a
Model #34 - Low Value Model #35 - High Value	2006 Transient Synoptic Study - Specific Yield	n/a	n/a	n/a
Model #36 - Low Value Model #37 - High Value	2006 Transient Synoptic Study - Specific Storage	n/a	n/a	n/a
Model #38 - Low Value Model #39 - High Value	2006 Transient Synoptic Study - HANI	n/a	n/a	n/a
Model #40	2006 Transient Synoptic Study - No Saprolite	n/a	n/a	n/a
Model #41 - Low Value Model #42 - High Value	2006 Transient Synoptic Study - Clinker Porosity	n/a	n/a	n/a
Model #43	2006 Transient Synoptic Study - Basalt Kh	n/a	n/a	n/a

n/a not applicable for particle tracking

6.4.3 Sensitivity to Heterogeneity Due to Presence of Clinker (Model #2)

Source water zones represented by particle tracks to assess the impact of Model #2 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.3-1 and 6.4.3-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping Scenario in Model #2, the Hālawa Shaft and Moanalua well source water zones were insensitive to the presence of the high-K clinker as shown on Figure 6.4.3-1. However, the RHS source water zone was highly sensitive to this heterogeneity, with the simulated clinker attracting water from a wider reach within the basalt than in Model #1. The RHS source water zone area was also sensitive to this heterogeneity in terms of travel times between the Facility and RHS. For instance, the travel time between RHMW02 and the RHS decreased from 64 days in Model #1 to 45 days in Model #2.

Model #2 only slightly affected the calibration statistics compared to Model #1 as noted in Section 5. Thus, upon evaluating both the changes in model calibration and changes in the modeling objectives, the presence of the clinker had a Type IV sensitivity for the RHS Pumping Scenario for migration from the Facility to RHS. Type IV sensitivity warrants closer examination and as a result, to be conservative of this uncertainty, Model #2 was used in evaluations where fast travel times were protective of RHS.

For the RHS Not Pumping Scenario, the presence of the clinker had no impact on the capture zones as noted on Figure 6.4.3-2. Thus, Model #2 had a Type I sensitivity for the RHS Not Pumping Scenario and at Hālawa Shaft and Moanalua well for both scenarios.

Finally, the source water zone of Hālawa Shaft does not originate from the water table beneath the Facility. The source water zone of the Moanalua wells also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.4 Sensitivity to GHB Stage: 1 – 2017 Interpolated Stages (Model #3)

Source water zones represented by particle tracks (the term "pathlines" is used interchangeably with particle tracks) to assess the impact of Model #3 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.4-1 and 6.4.4-2, respectively, along with the pathlines from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were highly sensitive to conditions of Model #3. In both Scenarios, as shown on Figures 6.4.4-1 and 6.4.4-2, the source water zone direction for all relevant water supply wells/shafts moved northward compared to Model #1.

Upon evaluating both the changes in model calibration (slightly sensitive) and changes in the modeling objectives, Model #3 had a Type IV sensitivity to all modeling objectives. However, the source water zone for Hālawa Shaft moved further away from the Facility from that of Model #1 and therefore it does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.5 Sensitivity to GHB Stage: 2 – Lower Northwest and Southeast Stage (Model #4)

Source water zones represented by particle tracks to assess the impact of Model #4 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.5-1 and 6.4.5-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were highly sensitive to conditions of Model #4. In both Scenarios, as shown on Figures 6.4.5-1 and 6.4.5-2, the source water zone direction for all relevant water supply wells/shafts moved northward compared to Model #1. For the RHS Pumping Scenario, RHS captures the water originating from beneath the tanks at the Facility for Model #4, as indicated on Figure 6.4.5-1 (third panel).

Upon evaluating both the changes in model calibration (insensitive) and changes in the modeling objectives, Model #4 had a Type IV sensitivity to all modeling objectives. However, the source water zone for Hālawa Shaft moved further away from the Facility from that of Model #1 and therefore it does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.6 Sensitivity to GHB Stage: 3 – Lower Northwest and Higher Southeast Stage (Model #5)

Source water zones represented by particle tracks to assess the impact of Model #5 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.6-1 and 6.4.6-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were moderately sensitive to conditions of Model #5. In both Scenarios, as shown on Figures 6.4.4-1 and 6.4.4-2, the source water zone direction for all relevant water supply wells/shafts moved slightly northward compared to Model #1.

Upon evaluating both the changes in model calibration (moderately sensitive) and changes in the modeling objectives, Model #5 had a Type III or IV sensitivity to all modeling objectives. However, the source water zone for Hālawa Shaft does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.7 Sensitivity to GHB Stage: 4 – Northwest and Southeast Stages Lowered 3-ft (Model #6)

Source water zones represented by particle tracks to assess the impact of Model #6 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.7-1 and 6.4.7-2, respectively, along with the particle tracks from Model #1 and Model #3 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were highly sensitive to conditions of Model #6 and looked very similar to Model #3. In both Scenarios, as shown on Figures 6.4.7-1 and 6.4.7-2, the source water zone for all relevant water supply wells/shafts moved slightly northward compared to Model #1.

Upon evaluating both the changes in model calibration (highly sensitive) and changes in the modeling objectives, Model #6 had a Type III sensitivity to all modeling objectives. Also, the source water zone for Hālawa Shaft had moved further away from the Facility compared to that of Model #1 and therefore it does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.8 Sensitivity to GHB Stage: 5 – 2017 Interpolated Northwest and Southeast Stages with Higher Northwest Basalt Stage (Model #7)

Source water zones represented by particle tracks to assess the impact of Model #7 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.8-1 and 6.4.8-2, respectively, along with the particle tracks from Model #1 and Model #3 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were highly sensitive to conditions of Model #7 and looked very similar to Model #3. In both Scenarios, as shown on Figures 6.4.8-1 and 6.4.8-2, the source water zone direction for all relevant water supply wells/shafts moved slightly northward compared to Model #1.

Upon evaluating both the changes in model calibration (moderate to highly sensitive) and changes in the modeling objectives, Model #7 had a Type III sensitivity to all modeling objectives. Also, the source water zone for Hālawa Shaft had moved further away from the Facility from that of Model #1 and therefore it does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.9 Sensitivity to Presence of Saprolite (Model #8)

Source water zones represented by particle tracks to assess the impact of Model #8 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.9-1 and 6.4.9-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping Scenario, the source water zone of Hālawa Shaft is slightly sensitive, while the Moanalua well is insensitive to Model #8 as shown on Figure 6.4.9-1. RHS source water zone covers the tanks at the Facility.

For the RHS Not Pumping Scenario, water from beneath the Facility flows in a southwest direction toward RHS then turns toward Hālawa Shaft. However, the Hālawa Shaft does not capture this water; rather, the water enters the caprock and flows toward Pearl Harbor. Figure 6.4.9-3 shows the water level contours that indicate the hydraulic gradients and hence flow directions. For the RHS Not Pumping Scenario, predictions are highly sensitive to the absence of saprolite.

Upon evaluating both the changes in model calibration (moderate to highly sensitive) and changes in the modeling objectives, Model #8 had a Type I or Type II sensitivity for the RHS Pumping Scenario and a Type II or Type IV sensitivity with the RHS Not Pumping Scenario. However, the source water zone for Hālawa Shaft does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath Facility and furthermore, lies deep in Layer 5 of the models. Therefore, even this extreme condition (for pumping and for presence of saprolite in the numerical model) does not translate to particle travel from the Facility to the Hālawa Shaft or the Moanalua well.

6.4.10 Sensitivity to Basalt Kv (Model #9 and Model #10)

Source water zones represented by particle tracks to assess the impact of Model #9 and Model #10 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.10-1 and 6.4.10-2, respectively, along with the particle tracks from Model #1 for comparison.

Predictions are highly sensitive to basalt Kv for both RHS Pumping and RHS Not Pumping Scenarios. The source water zone for the Hālawa Shaft is more northward for Model #9 (lower Kv) and more eastward for Model #10 (higher Kv) as compared to Model #1. Additionally, compared to Model #1, the Hālawa Shaft source water zone width is larger for Model #9 and smaller for Model #10. Lower Kv also resulted in larger tracking distances of the particles. Although the Moanalua well source water zone is highly sensitive to lower basalt Kv, it is insensitive to higher Kv.

Source water zone widths for the RHS, however, are insensitive to Kv for the RHS Pumping Scenario. RHS intercepts groundwater from beneath the Facility.

Upon evaluating both the changes in model calibration (moderate or insensitive) and changes in the modeling objectives, Model #9 and Model #10 had a Type III or Type IV sensitivity. However, the source water zone for Hālawa Shaft moved further away from the Facility relative to that of Model #1 and therefore it does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.11 Sensitivity to Basalt Kh (Model #11)

Source water zones represented by particle tracks to assess the impact of Model #11 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.11-1 and 6.4.11-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were generally insensitive to conditions of Model #11. However, travel times are quicker with longer distances traveled between the 1-year time markers than for Model #1.

Upon evaluating both the changes in model calibration (highly sensitive) and changes in the modeling objectives, Model #11 had a Type II sensitivity. For the RHS Pumping Scenario, RHS intercepts groundwater from beneath the Facility. Even with RHS off, the source water zone of Hālawa Shaft does not underlie the tanks at the Facility.

6.4.12 Sensitivity to Saprolite Hydraulic Conductivity (Model #12 and #13)

Source water zones represented by particle tracks to assess the impact of Model #12 and Model #13 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.12-1 and 6.4.12-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were insensitive to conditions of Model #12 and Model #13. Upon evaluating both the changes in model calibration (insensitive) and changes in the modeling objectives, Model #12 and Model #13 had a Type I sensitivity.

6.4.13 Sensitivity to Lower Basalt Kv with Higher Saprolite K (Model #14)

Source water zones represented by particle tracks to assess the impact of Model #14 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.13-1 and 6.4.13-2, respectively, along with the particle tracks from Model #1 and Model #9 for comparison. Note that Model #9 incorporates a lower Kv for basalt and exhibited a larger capture radius for Hālawa Shaft than Model #1 so the GWMWG requested this simulation to evaluate if higher hydraulic conductivity of saprolite (as in Model #13) would further impact the source water zone for Hālawa Shaft.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones of Model #14 were similar to those of Model #9, with a wider and slightly northward source water zone direction for Hālawa Shaft as compared to Model #1. Therefore, Model #14 also exhibits a Type III or Type IV sensitivity and does not impact the conclusions regarding migration from the Facility or source water zones of the key water supply locations.

6.4.14 Sensitivity to Offshore GHB Conductance (Model #15 and Model #16)

Source water zones represented by particle tracks to assess the impact of Model #15 and Model #16 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.14-1 and 6.4.14-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were insensitive to conditions of Model #15 and Model #16. Upon evaluating both the changes in model calibration (highly sensitive to Model #15 but insensitive to Model #16) and changes in the modeling objectives, Model #15 had a Type II sensitivity and Model #16 had a Type I sensitivity.

6.4.15 Sensitivity to Recharge (Model #17 and Model #18)

Source water zones represented by particle tracks to assess the impact of recharge rates (Model #17 and Model #18) on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.15-1 and 6.4.15-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping Scenario, source water zones were insensitive to conditions of Model #17 and Model #18 (Figure 6.4.15-1). For the RHS Not Pumping Scenario, the source water zone of Hālawa Shaft was slightly sensitive to conditions of Model #17 and Model #18 (Figure 6.4.15-2), with slightly narrower source water zones resulting from the higher recharge of Model #18.

Upon evaluating both the changes in model calibration (slightly sensitive to Model #17 but highly sensitive to Model #18) and changes in the modeling objectives, Model #17 had a Type I sensitivity and Model #18 had a Type I or Type II sensitivity.

6.4.16 Sensitivity to Basalt Horizontal Anisotropy (Model #19 and Model #20)

Source water zones represented by particle tracks to assess the impact of Model #17 and Model #18 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.16-1 and 6.4.16-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were insensitive to conditions of Model #19 and Model #20. Decreasing the anisotropy shifted the capture zones slightly to the west and marginally increased the Hālawa Shaft capture zone widths. Increasing the anisotropy shifted the capture zones slightly to the east and marginally decreased the Hālawa Shaft capture zone widths.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones are slightly sensitive to changes in the basalt HANI as shown on Figures 6.4.16-1 and 6.4.16-2, respectively.

With the RHS on, source water originating from the water table beneath the Facility footprint was intercepted by the RHS. Turning the RHS off also resulted in a slightly larger Hālawa Shaft source water zone width for the lower anisotropy analysis and a slight increase in the width under higher anisotropy conditions. With the RHS off, Hālawa Shaft did not intercept water originating from underneath the Facility.

Upon evaluating both the changes in model calibration (insensitive to Model #19 but moderate/highly sensitive to Model #20) and changes in the modeling objectives, Model #19 had a Type I sensitivity and Model #20 had a Type I or Type II.

6.4.17 Sensitivity to Northeast Boundary Inflow (Model #21 and Model #22)

Source water zones represented by particle tracks to assess the impact of Model #21 and Model #22 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.17-1 and 6.4.17-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were insensitive to conditions of Model #21 and Model #22.

Upon evaluating both the changes in model calibration (slight/moderate sensitive) and changes in the modeling objectives, Model #19 and Model #20 had a Type I or Type II sensitivity.

6.4.18 Sensitivity to Caprock Kh (Model #23, Model #24 and Model #25)

Source water zones represented by particle tracks to assess the impact of Model #23 Model #24 and Model #25 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.18-1 and 6.4.18-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were insensitive to conditions of Model #24 and Model #25. Model #23 was slightly sensitive, especially for particle tracks to Moanalua wells, however, it was noted (Section 5.9.17) that this model could not be calibrated and that a uniform caprock Kh value as low as 1 ft/d was not appropriate.

Upon evaluating both the changes in model calibration (slight/moderate sensitive) and changes in the modeling objectives, Model #23 Model #24 and Model #24 had a Type I or Type II sensitivity.

6.4.19 Sensitivity to zonation of Caprock (Model #26 and Model #27)

Source water zones represented by particle tracks to assess the impact of Model #26 and Model #27 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.19-1 and 6.4.19-2, respectively, along with the particle tracks from Model #1 for comparison. Recall that Model #26 had a lower hydraulic conductivity zone in upland regions of the caprock representing alluvial deposits and a higher hydraulic conductivity zone toward the coast representing marine sediments. Model #27, in addition, simulated saprolite properties the same as unweathered basalt, in effect considering that there was no saprolite.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were highly sensitive to conditions of Model #26 and Model #27 with a narrower source water zone for Hālawa Shaft than for Model #1. For Model #26, the source water zones for all wells and shafts shifted considerably to the northward from that of Model #1. The shift was even more for Model #27 with no saprolite in any of the valleys.

Upon evaluating both the changes in model calibration (highly sensitive) and changes in the modeling objectives, Model #26 and Model #27 had a Type III sensitivity to all modeling objectives. Also, the source water zone for Hālawa Shaft moved further away from the Facility from that of Model #1 and therefore it does not intercept groundwater originating from underneath the Facility. The source water zone of Moanalua well also does not originate from the water table beneath the Facility and furthermore, lies deep in Layer 5 of the models.

6.4.20 Sensitivity to Elevation of Model Bottom (Model #28)

Source water zones represented by particle tracks to assess the impact of Model #28 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.20-1 and 6.4.20-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were insensitive to conditions of Model #28. Upon evaluating both the changes in model calibration (insensitive) and changes in the modeling objectives, Model #28 had a Type I sensitivity to all modeling objectives.

6.4.21 Sensitivity to Combined changes in Recharge and Northeast Lateral Boundary Inflow (Model #29 and Model #30)

Source water zones represented by particle tracks to assess the impact of Model #29 and Model #30 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.21-1 and 6.4.21-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping Scenario, source water zones were slightly sensitive to conditions of Model #29 and Model #30. The source water zone width increased for Model #29 (reduced recharge and northeast boundary flux), and increased for Model #30, especially at Moanalua well.

For the RHS Not Pumping Scenario, source water zones were highly sensitive to conditions of Model #29. In this extremely conservative (and highly unlikely) scenario (Model #29), unlike all the other modeling scenarios, several of the pathlines extend southwestward beneath the Facility going further westward past RHS because it is not pumping, and eventually is traced northeastward to Hālawa Shaft. Figure 6.4.21-3 zooms in at Red Hill to show the pathlines from particles released beneath and around the Facility. The travel times from the Facility to Hālawa Shaft are noted to be between about 3 to 10 years. Thus, even this conservative model indicates a minimum of 3 years for groundwater to move from the Facility to Hālawa Shaft, if there were no pumping at RHS and the low recharge regime was sustained for that long.

The model scenario of Model #29 considers extreme conditions that do not actually occur at the Facility. This model assumes unreasonably low recharge coupled with unreasonably high pumping at Hālawa Shaft for an excessively extended period. During the June GWMWG meeting, BWS indicated that Hālawa Shaft could not pump at this rate for an extended period of time as is modeled in this scenario. As noted in Section 3.6.1, the recharge maps produced by the USGS that were used in this study already considered a dry period of precipitation. Net recharge was further reduced in the models for calibration of 2017 conditions (a multiplying factor of 0.97) as noted in Table 5.3-1. In addition, this sensitivity study reduced both net recharge and inflow from the northeast boundary by an additional 20 percent (multiplying factor of 0.8). Coupling such extreme recharge conditions with the extreme pumping of 16 mgd at Hālawa Shaft for extended periods of years would probably have other effects such as excessive regional drawdowns as indicated by the water level maps for this scenario (Figure 6.4.21-4) or saltwater intrusion, which would adversely impact groundwater resources. Finally, as noted in Section 5.9.20, the Model #29 could not be well recalibrated to the drain fluxes that were about 64 percent of conceptualized flow at Pearl Harbor Spring at Kalauao (Table 5.9.20-2).

Upon evaluating both the changes in model calibration (highly sensitive) and changes in the modeling objectives, Model #29 had a Type III sensitivity and Model #30 had a Type II sensitivity to all modeling objectives. As detailed by ASTM (2002), the Type III sensitivity of Model #29 is *"of no concern because, even though the model's conclusions change as a result of variation of the input, the parameters used in those simulations cause the model to become uncalibrated. Therefore, the calibration process eliminates those values from being considered to be realistic."* For Model #29, this was true even for the recalibration attempt and fluxes at the springs could not be accurately simulated.

6.4.22 Sensitivity to Elevation of Hālawa Shaft and Red Hill Shaft (Model #31)

Model #31 was developed at the request of the GWMWG. This model was not expected to be much different from its counterpart; however, it allowed for evaluation of impact of as-built details for RHS and Hālawa Shaft.

Source water zones represented by particle tracks to assess the impact of Model #31 on modeling objectives for the RHS Pumping and RHS Not Pumping Scenarios are shown on Figures 6.4.22-1 and 6.4.22-2, respectively, along with the particle tracks from Model #1 for comparison.

For the RHS Pumping and RHS Not Pumping Scenarios, source water zones were insensitive to conditions of Model #31. Upon evaluating both the changes in model calibration (insensitive) and changes in the modeling objectives, Model #28 had a Type I sensitivity to all modeling objectives.

6.5 CATEGORIZATION OF SENSITIVITY SIMULATIONS

A summary of the sensitivity analysis is provided in Table 6.4.2-3. The sensitivity simulations were categorized as per ASTM Guidelines to evaluate the significance of various parameters. Type IV sensitive parameters are significant because they show small impact to calibration (which means that the model remains largely calibrated), but can have a large impact on the conclusions.

Sensitivity Type IV parameters were further evaluated in terms of the objectives related to migration and source water zones for key water supply locations. Most Sensitivity Type IV models indicated that they were less conservative in terms of these objectives with source water zones for Hālawa Shaft being further away from the Facility.

For the different objectives, Model #2 was noted to be most conservative in terms of having the quickest travel times to RHS and therefore it was also used in further evaluations protective of that condition. Model #1, Model #8, Model #11, and Model #29 were most conservative in terms of travel toward Hālawa Shaft; however, Model #8 and Model #29 were conceptually inconsistent or represent severe hydrogeologic conditions with poor calibration statistics or spring fluxes. The source water zone of Moanalua wells did not originate from the water table beneath the Facility for any of the models and furthermore, it lies deep in Layer 5 in all models.

6.6 EVALUATION OF RISK AND IMPACT OF MODEL UNCERTAINTY ON THE GROUNDWATER MODELING PATHWAY

Uncertainty and approximations in representation of the hydrogeologic system were evaluated by utilizing a multi-model approach where several models were developed to test the impacts of various parameter ranges, boundary stresses, and conceptualizations. Each model was calibrated if possible, and examined to establish reasonableness in conceptual representation and water budgets. The models were then applied with extremely conservative pumping scenarios to establish migration of water from beneath the Facility and source water zones for key water supply locations. Conservative scenarios provided an additional factor of safety to the analyses.

The multiple models were examined individually to note their representativeness and evaluate migration and source water zones. Most of the models indicated that the source water zone for Hālawa Shaft did not underlie the Facility for even the most extreme scenario (where Hālawa Shaft pumps at 16 mgd and RHS is off). Two of the models indicated potential migration from Facility southwestward past RHS then northward toward Hālawa Shaft (Model #8 and Model #29. Model #8 is not conceptually realistic because it considered that saprolite properties were the same as unweathered basalt while it is known that the saprolite barrier exists underneath the valleys, and that in fact, saprolite extent is significantly deeper in the valleys in downstream reaches, than was modeled in any of the models. Particle tracking for Model #8 and Model #29 both indicated that migration from the Facility occurs in the southwest direction toward the downstream reaches of the valley, before turning northward from the lower valley toward Hālawa Shaft. In addition, Model #29 had such little net inflow, that the flux at Pearl Harbor springs could not be calibrated.

Results of the multiple models were also synthesized in a similar manner to the PT-MC approach introduced in Section 6.4.1. For each key public supply source water zone, the backward particle tracking results were collated into a probability distribution map for all of the models as follows. If particles from a model pass through any model cell, a particle counter is incremented within that cell. This is then done for all the models, in a weighted manner whereby the models are provided a weight depending on their plausibility. The total is then normalized to provide a capture probability distribution map – in this case, a probability distribution map for the source water zones of each of the key wells. A similar approach was used to evaluate the probability distribution of forward migration of particles from the Facility.

Weighting applied to most of the models was 1.0. This is because they are largely calibrated and represent the conceptual hydrogeologic system.

Exceptions include the following:

- Model #8 was given a weighting of 0.5. This is because lack of saprolite beneath the valleys is not a realistic scenario. This model was constructed to see what it would take to "break" the model. Even then, particles from beneath Facility were not intercepted by Hālawa Shaft.
- Model #23 was given a weighting of 0.2. This model had a uniform caprock hydraulic conductivity of 1 ft/d. This value was too low for caprock and resulted in unrealistic simulated water levels in the caprock of over 100 feet above msl.
- Model #26 was given a weighting of 1.5. This model uses separate zones to represent the alluvial sediments and marine sediments within the caprock. The higher weight is because this model provides a more realistic representation of the caprock.
- Model #27 is given a weighting of 0.75. This model uses the more realistic zonation of caprock as in Model #26 but also includes the less realistic situation of having no saprolite beneath the valleys.
- Model #29 was given a weighting of 0.2. Net inflow of this model was considerably smaller than conceptualized. Furthermore, the model resulted in low simulated fluxes at Pearl Harbor Springs, which could not be further calibrated.
- Model #31 was given a weighting of 0.5. This is because this model was just a minor adjustment from Model #1 and it was not expected that the results would be much different.

The probability distribution map for the source water zone of Hālawa Shaft is shown on Figure 6.6-1 for the RHS Pumping Scenario, and on Figure 6.6-2 for the RHS Not Pumping Scenario. The source water zone for Hālawa Shaft is likely wide extending underneath North Hālawa valley, and originates from northeast of the shaft.

The probability distribution map for the source water zone of RHS is shown on Figure 6.6-3 for the RHS Pumping Scenario. The models indicate that RHS is very likely a critical receptor of water from beneath the Facility tanks and their immediate vicinity.

The probability distribution map for migration of groundwater from beneath the Facility is shown on Figure 6.6-4 for the RHS Pumping Scenario, and on Figure 6.6-5 for the RHS Not Pumping Scenario. For the RHS Pumping Scenario, all water is intercepted by RHS. For the RHS Not Pumping Scenario, water discharges into Pearl Harbor. There is a small likelihood, however, that water from beneath the Facility could reach Hālawa Shaft. A closer examination of the models indicated that travel times between the Facility and Hālawa Shaft were longer than 3 years. As previously discussed, Hālawa Shaft would not be able to pump at 16 mgd for an extended time period. The backward particle tracking analyses for the source water zone evaluation of Hālawa Shaft did not show this condition because the vertical location of particles seeded around Hālawa Shaft were at the same elevation as the shaft itself. This was a result of the GMS preprocessing software and a request has been made to the GMS developers to rectify this limitation and add flexibility. The final modeling effort will further include starting particle locations that are above, below, and around the shaft location for such evaluations.

The probability distribution map for the source water zone of the Moanalua wells is shown on Figure 6.6-6 for the RHS Pumping Scenario, and on Figure 6.6-7 for the RHS Not Pumping Scenario. The source water zone for the Moanalua Wells extends in a northeast direction and does not include groundwater beneath the Facility. Furthermore, on comparing Figures 6.6-6 and 6.6-7, pumping at RHS had a very slight influence this source water zone, causing to move slightly northward when RHS was not pumping.

Several models had one particle that tracked from the Facility to Hālawa Shaft when Hālawa Shaft simulated pumping was a steady 16 mgd with RHS not pumping. This caused the probability distribution map of Figure 6.6-4 to show some probability of migration toward Hālawa Shaft. Therefore, an additional scenario was simulated using all the models to calculate the cut-off pumping rate at Hālawa Shaft where that does not happen. This Scenario included Hālawa Shaft pumping at a steady 10 mgd with RHS not pumping. Also, all forward tracking was performed for this scenario using Version 2 of the Mod-PATH3DU (SSPA 2018) software for consistency in this regard. The probability distribution map for migration of groundwater from beneath the Facility for this Scenario is shown on Figure 6.6-8.

Figure 6.6-8 is similar to Figure 6.6-4 when Hālawa Shaft was pumping 16 mgd except for the draw toward Hālawa Shaft that occurred, on closer examination of the models for this scenario, only for one particle from Model #29. Also, it took up to 6 years for that particle to migrate toward Hālawa Shaft from beneath the Facility instead of the minimum of 3 years for the scenario where Hālawa Shaft pumping was simulated at 16 mgd. Otherwise, most of the migration from underneath the Facility was in the southwest direction, then turning eastward and discharging into Pearl Harbor Bay.

Thus, the models that were constructed for the interim modeling evaluations indicated that it would require over 10 mgd pumping at Hālawa Shaft with RHS turned off for sustained periods of over 6 years for there to be any threat to Hālawa Shaft from beneath the Facility. The models themselves were developed in a conservative manner in terms of assumptions for saprolite extent and depth.

6.7 PRELIMINARY MONITORING AND CONTINGENCY STRATEGIES CONSIDERING MODEL UNCERTAINTY

All the groundwater flow models developed for this study indicate that groundwater from the Facility migrates in a southwest direction toward RHS, whether RHS is pumping or not. With RHS pumping at normal pumping rates, all the groundwater migrating from beneath the Facility is captured at RHS. The travel times between the Facility and RHS are between 45 and 90 days. This analysis should therefore be considered in providing for potential contingency or remedial strategies for capture at RHS.

When RHS is not pumping, groundwater from beneath the Facility travels in a southwest direction toward RHS, and then shifts to a northwesterly direction, discharging into Pearl Harbor for most models. Though some models did indicate a draw toward Hālawa Shaft, the travel times from the Facility were in excess of 3 years. Also, groundwater did not directly move from the Facility toward Hālawa Shaft. This analysis should therefore be considered in evaluating sentinel well locations and strategies for monitoring. This analysis will also be useful in evaluating potential vulnerable locations for groundwater migration from the Facility where additional data on saprolite depth and properties would be beneficial. As the final flow model and fate and transport models are developed, additional considerations related to sentinel wells and contingencies will be further evaluated.

7. Concluding Remarks on Model Application

Several insights were gained in application of the models. Section 6.7 illustrates how information from the interim modeling effort could help inform potential protection strategies and contingency plans. The interim model also provided a basis for developing a better final groundwater flow model. Further, it helped identify resolution issues, key parameters, and conceptual representations that are important for simulating migration of potential solutes in groundwater from beneath the Facility toward the multiple potential receptor locations. For instance, including a conceptual high-K clinker zone (Model #2) was an important feature for migration to RHS and this will be considered in the final model study (also proposed as a multi-model evaluation) for flow and solute transport.

The model application was conducted in an extremely conservative manner. Migration from the water table at the Facility area and the influence zones of RHS and Hālawa Shaft were simulated using two scenarios of extreme pumping conditions. The first scenario analyzed the impact of average pumping at RHS ([redacted] mgd) and maximum pumping at Hālawa Shaft (16 mgd) for an indefinite period. The focus of this scenario was to evaluate impacts at RHS. The scenario indicates that RHS captures all groundwater migrating from the water table beneath the facility for these conditions. The second scenario analyzed the impact of zero pumping at RHS (0 mgd) and extreme pumping at Hālawa Shaft (16 mgd and a subset of this scenario with pumping of 10 mgd) indefinitely. The focus of this scenario set was to evaluate impacts at Hālawa Shaft in the absence of pumping at RHS. Both scenarios are extreme and not feasible currently, but they demonstrate the potential impact of such extreme conditions.

The models have been applied using a steady-state flow field of these extreme pumping conditions to note source water zones, migration directions, and times. Steady-state flow fields also provide conservative estimates. The migration times were significantly larger than fluctuations in pumping at RHS or Hālawa Shaft thus indicating that the average conditions of a steady-state flow-field were applicable over the duration of migration from beneath the Facility toward these shafts. Migration times of concern for Hālawa Shaft were larger than 3 years, which is also larger than seasonal fluctuations in water levels indicating that average conditions were also applicable for critical simulations concerning Hālawa Shaft. Finally, multiple models were applied to evaluate the impact of plausible ranges of parameters, boundaries, or stresses.

8. Final Flow Model Considerations

Several lessons were learned in the preparation of the interim model. A detailed evaluation of available data was conducted, complexities of the local hydrogeologic system were highlighted, and shortcomings of the data and of conceptualizations and modeling assumptions were exposed. Additional data has also been collected since development of the interim flow model, which includes corrections to water level measurements, additional information on water levels and pumping, additional wells in the local area beneath the Facility, seismic studies conducted within the valleys, and the coordinated synoptic pumping/water level study conducted in 2017/2018. All of this information will be implemented in the final flow model that will be used to drive transport models that will finally evaluate potential groundwater protection strategies or contingency/monitoring plans.

Thus, the interim flow modeling effort served as a stepping stone toward development of the final flow model. Model calibration, and evaluation of source water zones and migration pathways for the multiple models also provided an understanding of the hydrogeologic behavior with conservative assumptions providing a bounding analysis in addressing uncertainty. An outline of the final flow model is being developed as even more data is forthcoming, additional wells are proposed, and the conceptual model is being enhanced. These additional data and conceptualizations will reduce this uncertainty in the final model development, providing a better definition of significant subsurface geology and stratigraphy and an improved understanding of the regional hydraulic connectivity between various significant locations. The final flow model development and calibration process will be similar to that of the interim model whereby all the information at the site will be considered and a multi-model approach is anticipated to address uncertainty. As currently envisioned, the proposed final flow model development steps are as provided below.

1. Evaluate water level data for long-term trends and seasonal fluctuations using all data and updated survey corrections.
2. Evaluate pumping drawdown characteristics at the shafts from synoptic water level and pumping information to establish the relationship for quasi-steady conditions to help establish long-term calibration targets.
3. Re-compute calibration targets for 2017 with the complete hydrologic dataset now available, the current understanding of local and regional flow gradients along and across Red Hill, and using the drawdown characteristics to provide the calibration targets at key pumping locations.
4. Evaluate latest geologic information to include saprolite depth at RHMW-11 and associated geologic model including extent and depth of saprolite through the valleys.
5. Include information on Honolulu Volcanics as another material zone in the numerical model in appropriate model layers as per current geologic interpretation.
6. Include two zones in caprock to delineate low conductivity alluvial sediments in upland areas and high conductivity marine sediments toward the coast. This is a more appropriate representation of the caprock, and the interim model indicated a better calibrated model for caprock wells than the single zone approximation.
7. Include saltwater interface (model bottom elevation) from SUTRA model results instead of using the Ghyben Herzberg Principle as was done in the interim models. The interface computed by Ghyben-Herzberg Principle was reasonably similar to the SUTRA results under Red Hill where the water is unconfined and the vertical equilibrium assumption is valid. However, the saltwater interface from the SUTRA model was significantly deeper under the caprock where the Ghyben-Herzberg vertical equilibrium assumption is poor. The interim models included one with interface elevation varied (Model #28) indicating minor sensitivity.
8. Revise vertical gridding to include 1 or 2 additional model layers near the water table for finer resolution of vertical gradients and transport concentrations. Saturated layer thickness of 20 feet for layers 2 and 3 under Red Hill, and Hālawa, with expanding thickness further down is anticipated.
9. Include corrected depths and geometries for water supply shafts. The interim models included one with corrected depths (Model #31) indicating minor sensitivity.
10. Update pumping rates and screen top and bottom elevations of pumping wells from the latest information.
11. Remove all wells that are outside of the domain from the conceptual model wells. This was confusing the water budgets of the interim model since some wells at the boundary were in the conceptual model but not there in the numerical model.

12. Develop groundwater flow Model #1 of the multi-model approach and simulate 2017 steady-state conditions.
13. Simulate transient flow conditions for the synoptic study of 2017/2018 with groundwater flow Model #1 and adjust all model parameters including hydraulic conductivity values and storage terms to match transient conditions. The 2017/2018 synoptic study is the most comprehensive evaluation of regional response of pumping changes in the vicinity, providing valuable information on the hydraulic connection between the pumping and monitoring locations.
14. Develop additional focused models by varying parameters or parameter sets to plausible ranges, or evaluating alternate conceptualizations on the simulated 2017 steady-state flow conditions, and recalibrate the models if possible. Evaluate calibration and water budgets for the reliability of the model.
15. Evaluate select additional models against transient synoptic 2017/2018 information. Evaluate calibration and water budgets to reduce uncertainty.
16. Simulate particle tracking from the Facility area, and reverse tracking from water supply shafts for various scenarios to evaluate source zones and migration pathways for select models as needed. Ensure that sufficient particles are seeded around, above, and below the required locations to provide adequate density of pathlines thus generated.
17. Select flow models that will be protective of the various solute transport modeling objectives.
18. Develop solute transport models using the various flow models and ranges of solute transport and reaction parameters. Use dual-porosity conceptualization to examine transport behavior and estimate preliminary mass transfer rate parameters.
19. Use solute transport models to narrow the range of uncertainty of the flow models.
20. Apply solute transport models to simulate potential scenarios in preparation for the solute transport modeling phase.
21. Report the findings of the final flow model.

Transport modeling will be conducted after the flow model has been reviewed and associated comments have been addressed.

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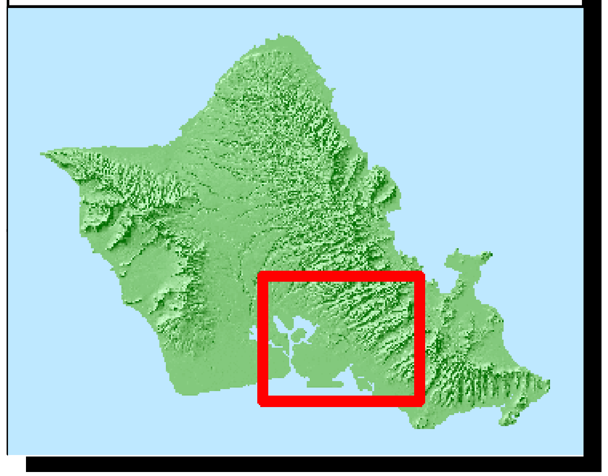
Figures

Location Map



Legend

- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Area
- Stream

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 1.1.1
Red Hill Bulk Fuel Storage Facility and Groundwater Model Area
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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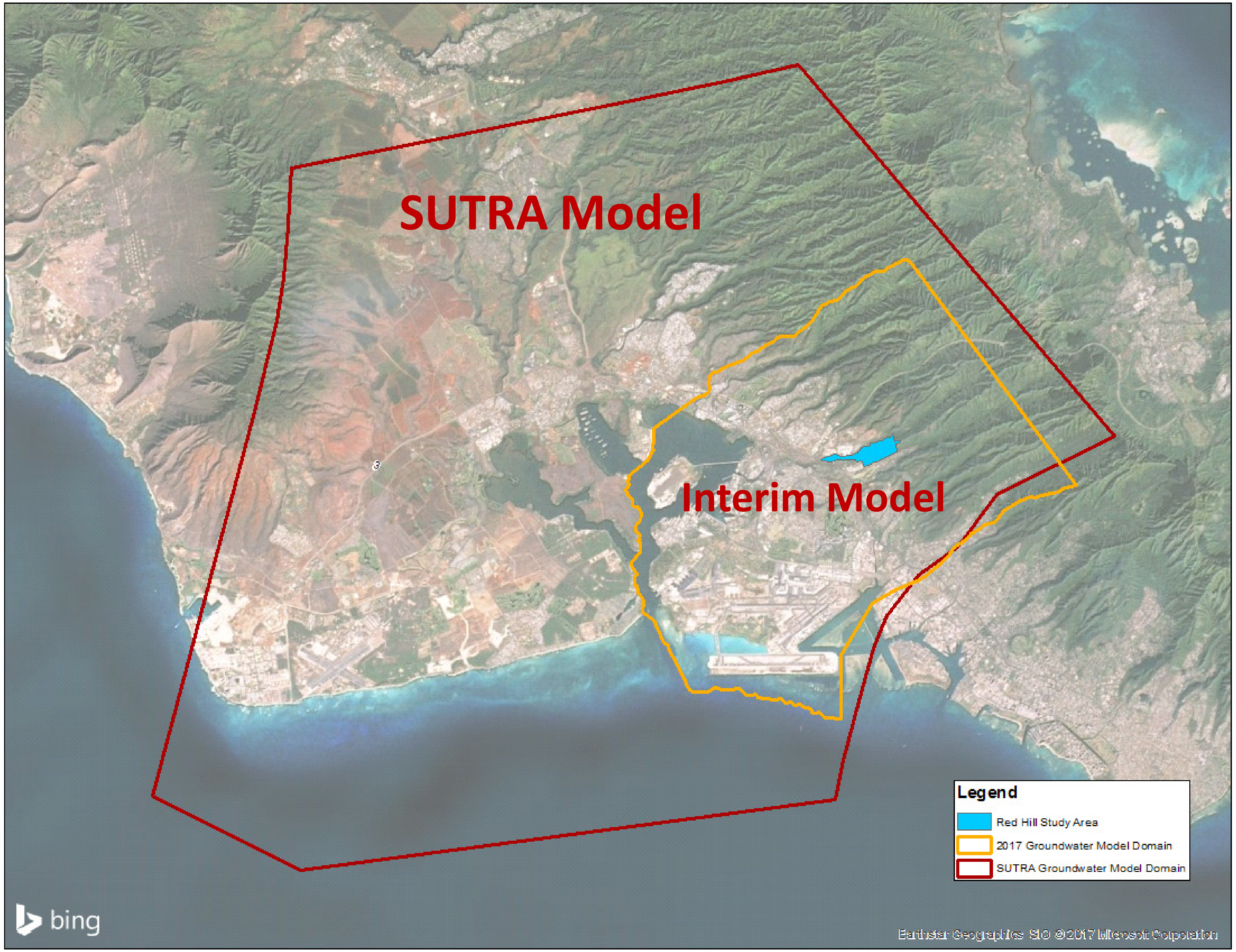

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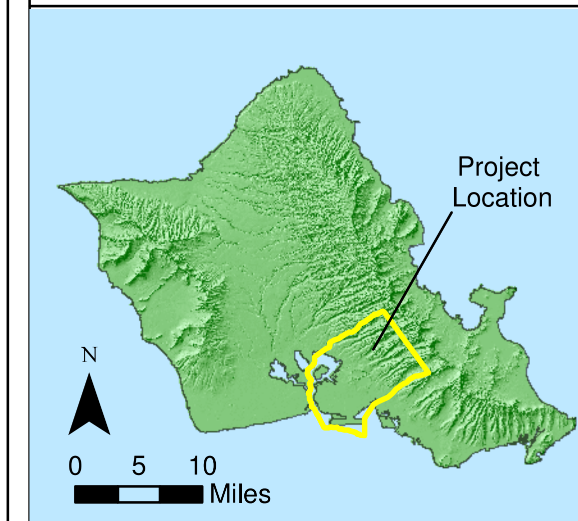


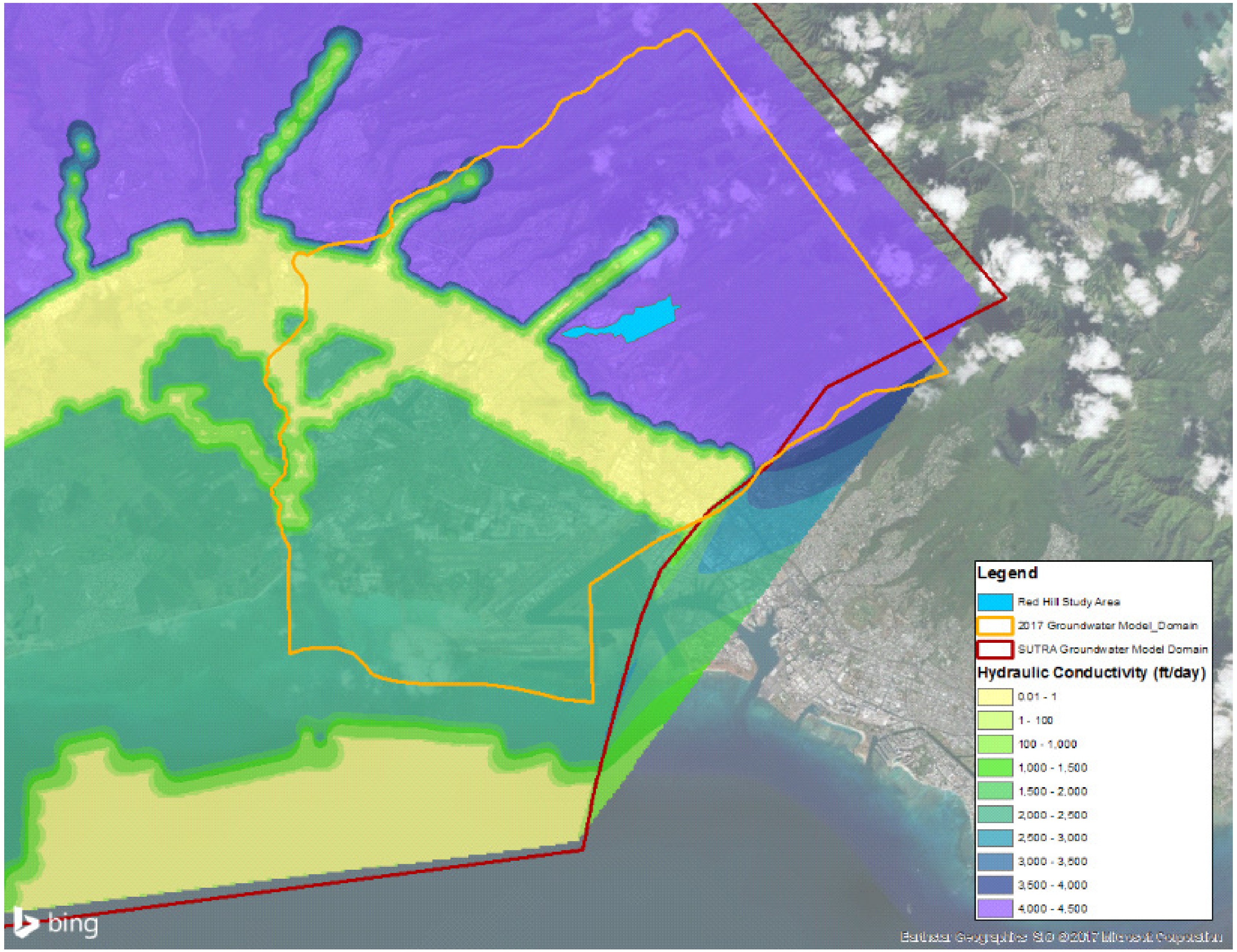
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet

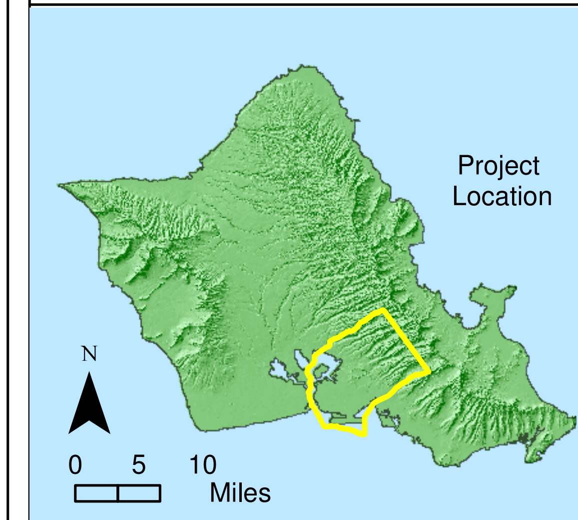
N

0 10,000 20,000 40,000 Feet

Figure 1.2.1
Location Map Indicating Model Domains for the SUTRA (Oki, 2005) Saltwater Intrusion Model and the Current Model
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet

N

0 5,000 10,000 20,000 Feet

Figure 1.2.2
SUTRA Model (USGS, 2005)
Layer 1 Hydraulic Conductivity (ft/day)
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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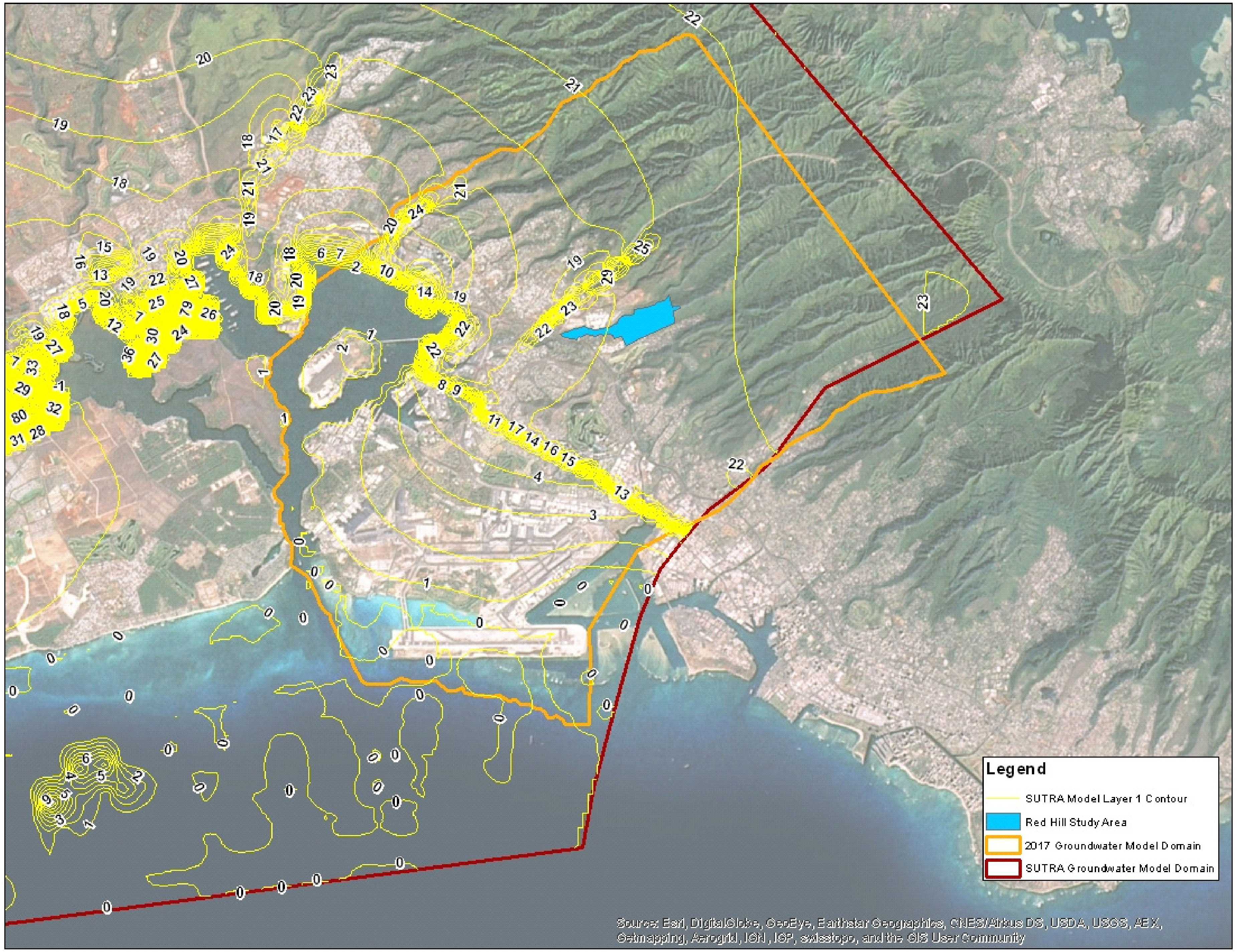
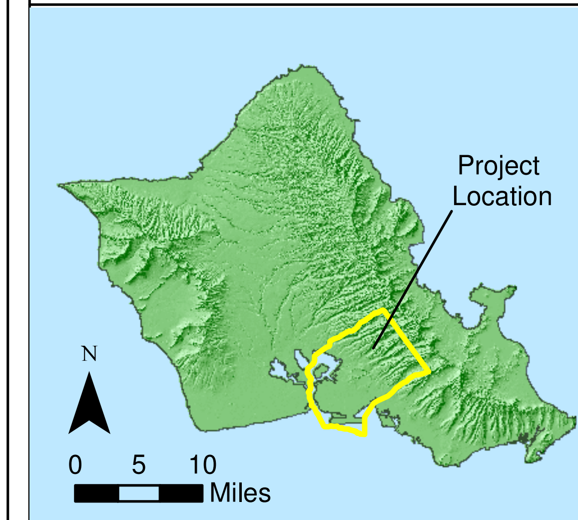


Location Map



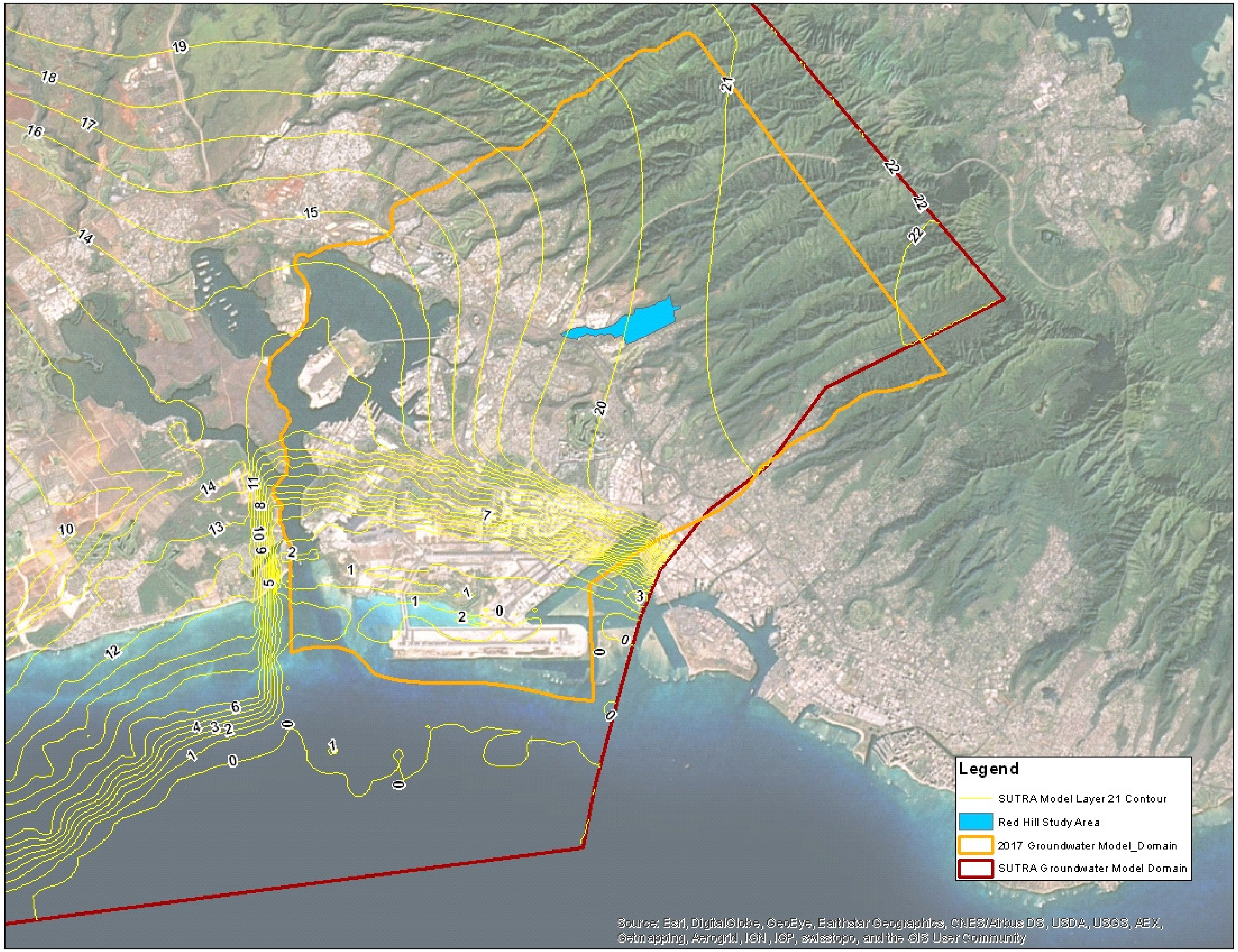
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet

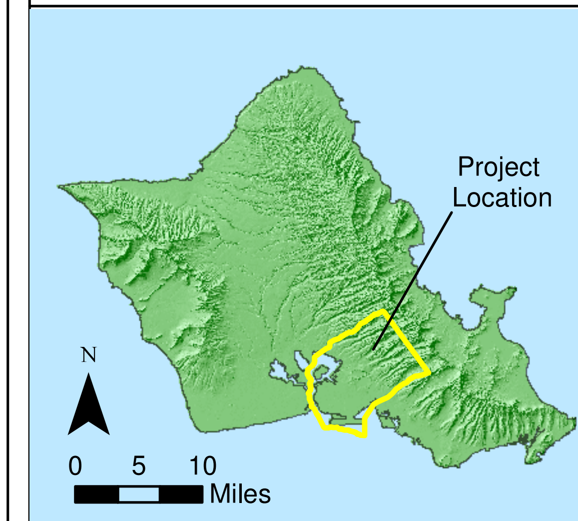
N

Feet
0 5,000 10,000 20,000

Figure 1.2.3
SUTRA Model (USGS, 2005)
Layer 1 Water Levels (ft msl)
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet

N

0 5,000 10,000 20,000 Feet

Figure 1.2.4
SUTRA Model (USGS, 2005)
Layer 21 Water Levels (ft msl)
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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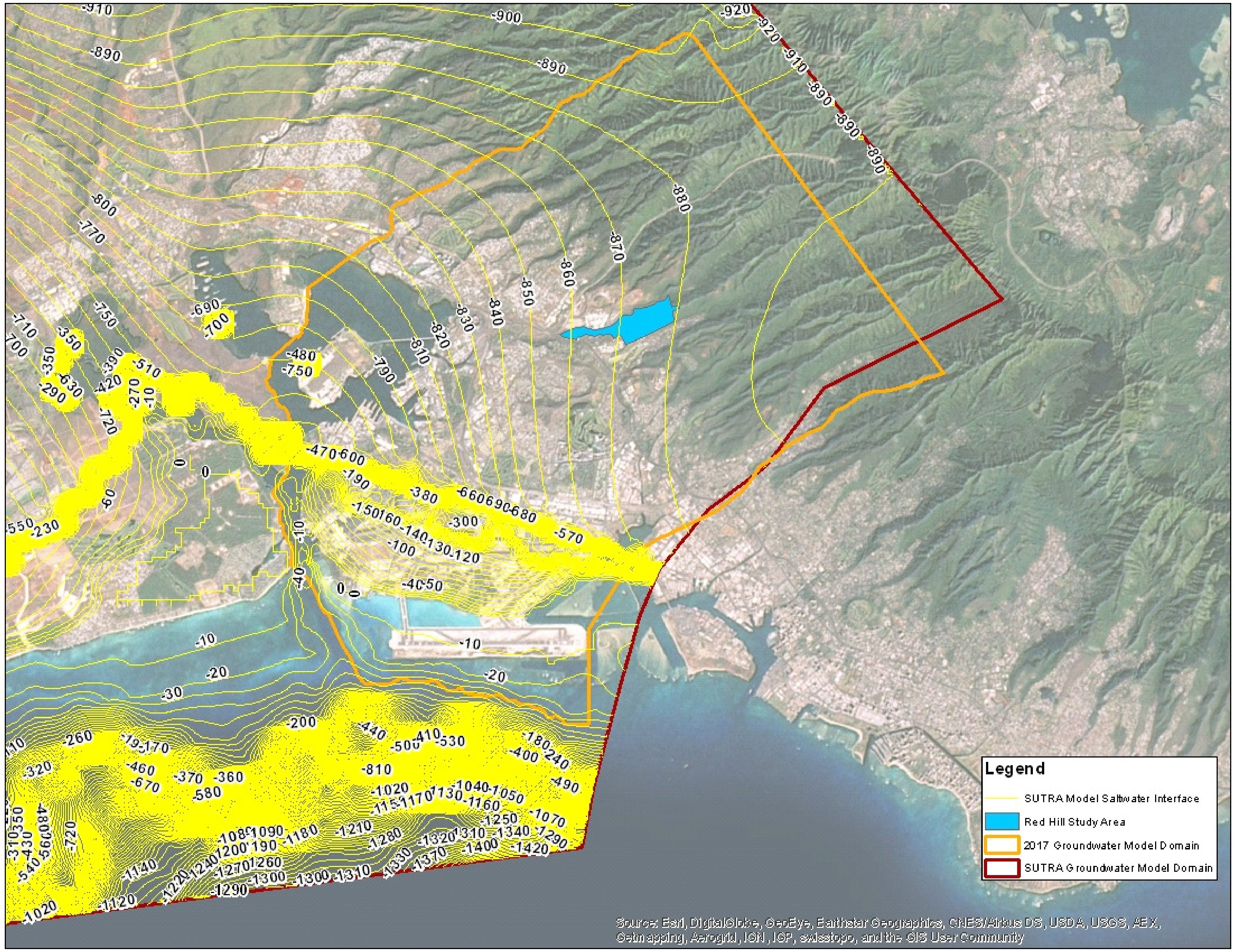
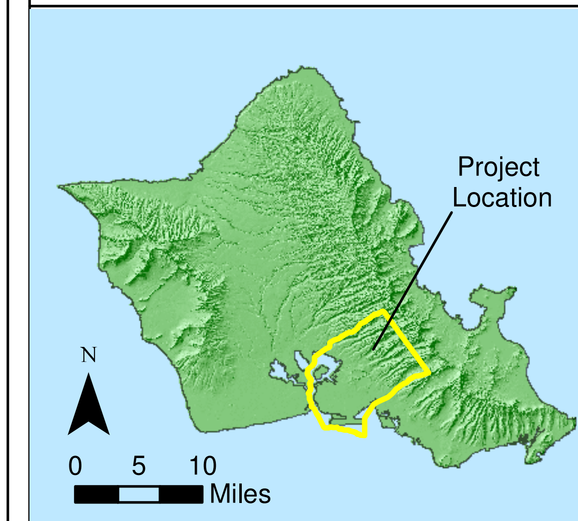


Location Map



Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet

N

Feet
0 5,000 10,000 20,000

Figure 1.2.5
SUTRA Model (USGS, 2005)
Saltwater/Freshwater Interface (ft msl)
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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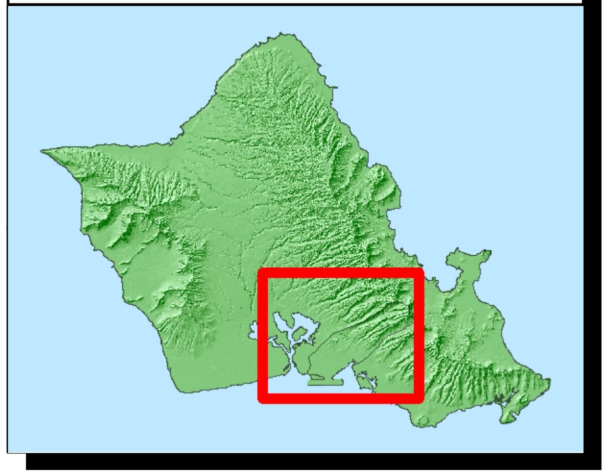
Location Map



Legend

- Current Groundwater Model Area
- 2007 Groundwater Model Area
- Red Hill Facility Boundary and Fuel Storage Tanks
- Stream

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 1.2.6
2007 and Current Model Domains
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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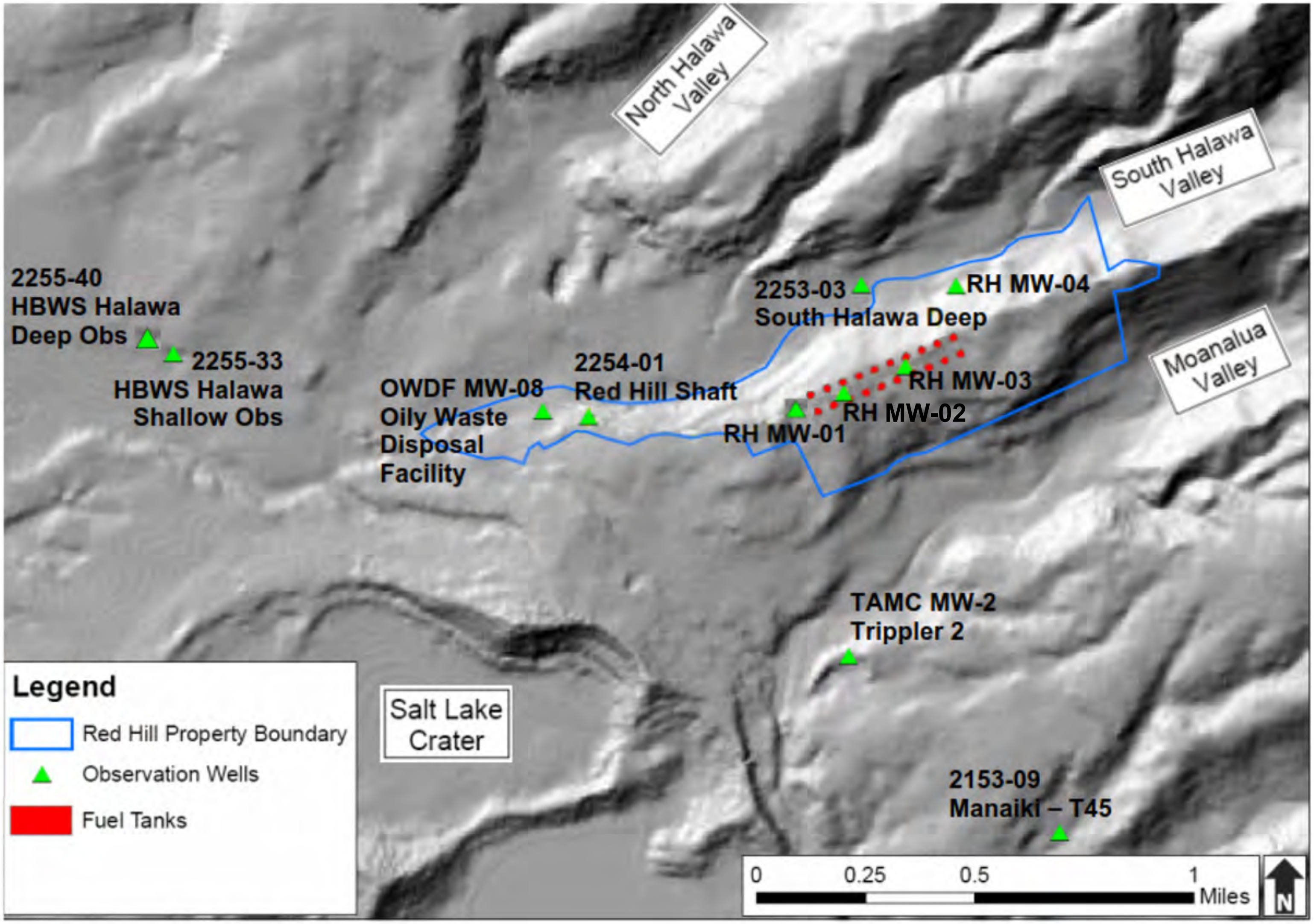
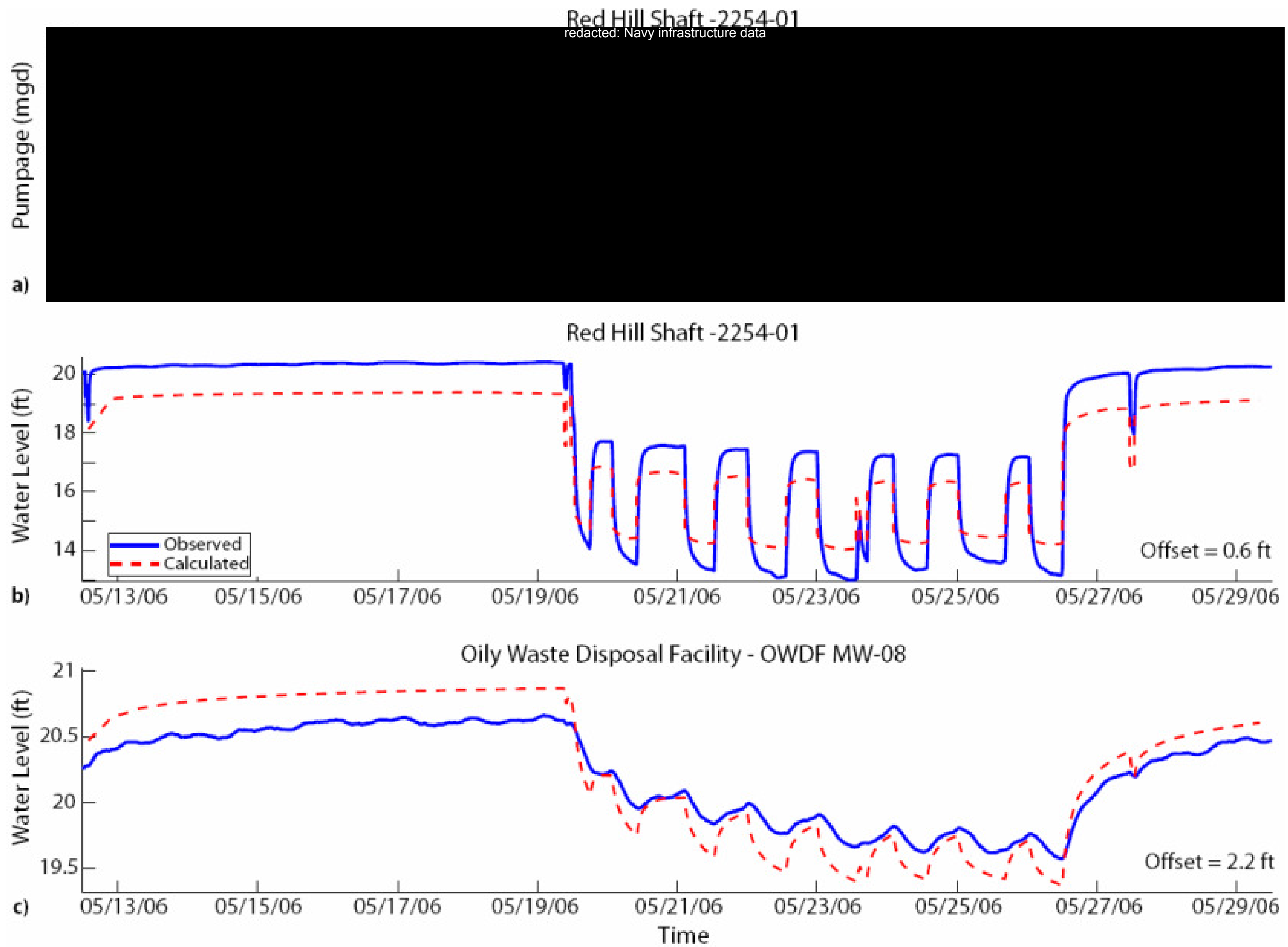


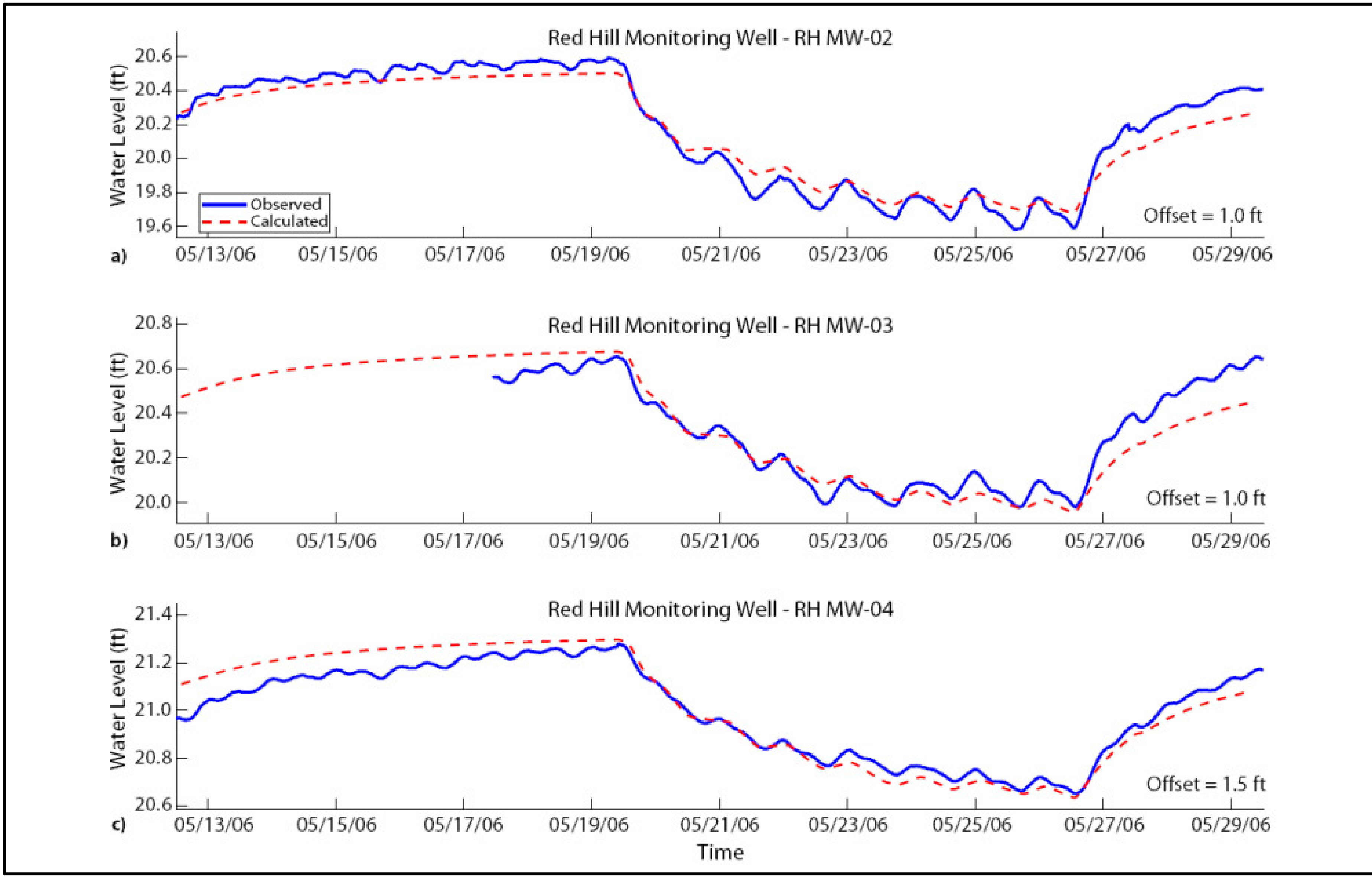
Source: U.S. Department of the Navy. 2007. *Red Hill Bulk Fuel Storage Facility, Final Technical Report*. Prepared by TEC, Inc. for Commander Naval Facilities Engineering Command, Pacific. August.

Figure 1.2.7
Location of Observation Wells for Synoptic Water Level Study Simulated by TEC 2007
Red Hill Bulk Fuel Storage Facility and Vicinity
Conceptual Site Model
Investigation and Remediation of Releases and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



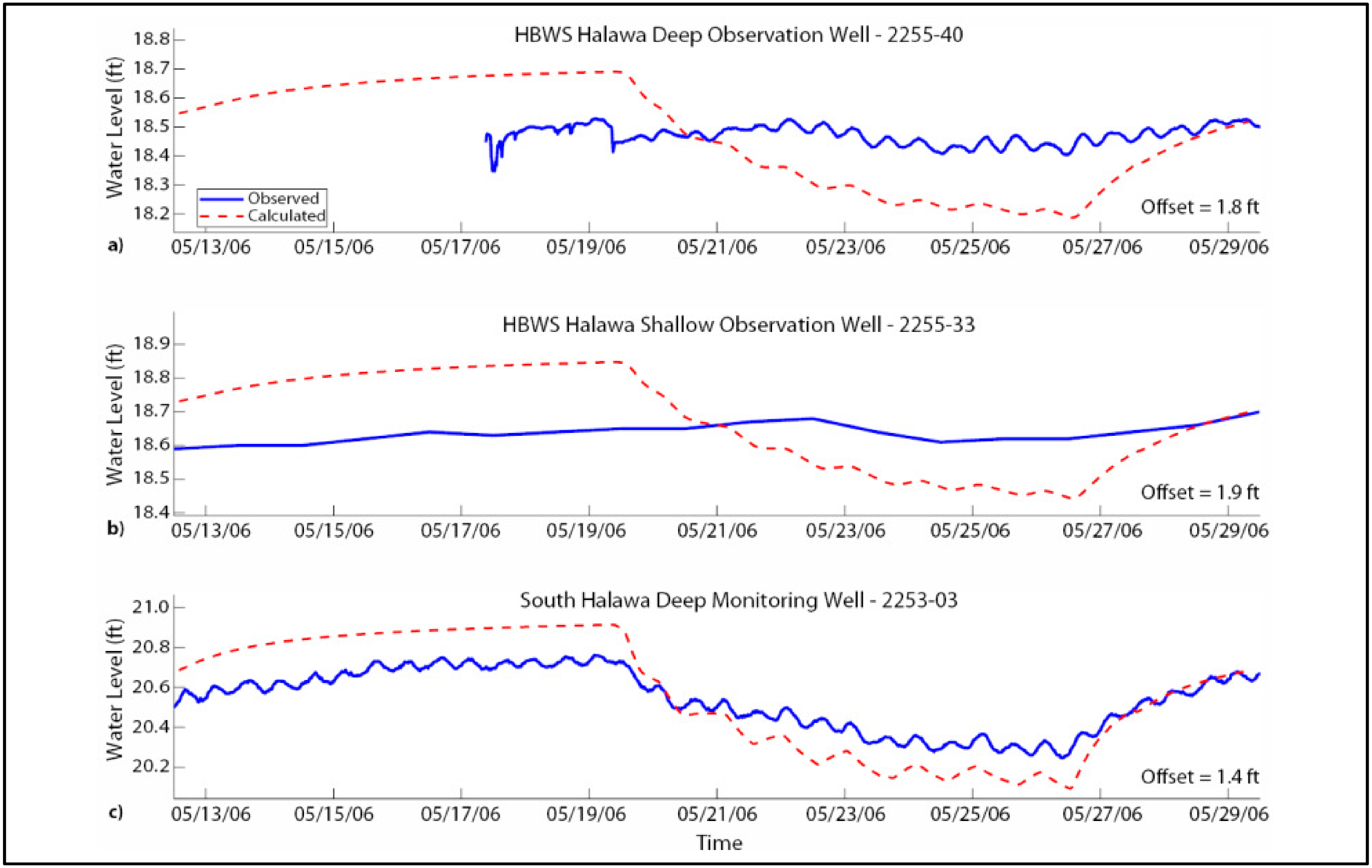
Source: U.S. Department of the Navy. 2007. *Red Hill Bulk Fuel Storage Facility, Final Technical Report*. Prepared by TEC, Inc. for Commander Naval Facilities Engineering Command, Pacific. August.

Figure 1.2.8
Pumping Rate at Red Hill Shaft, and Simulated and Observed Water Levels at Red Hill Shaft and OWDFMW-08
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



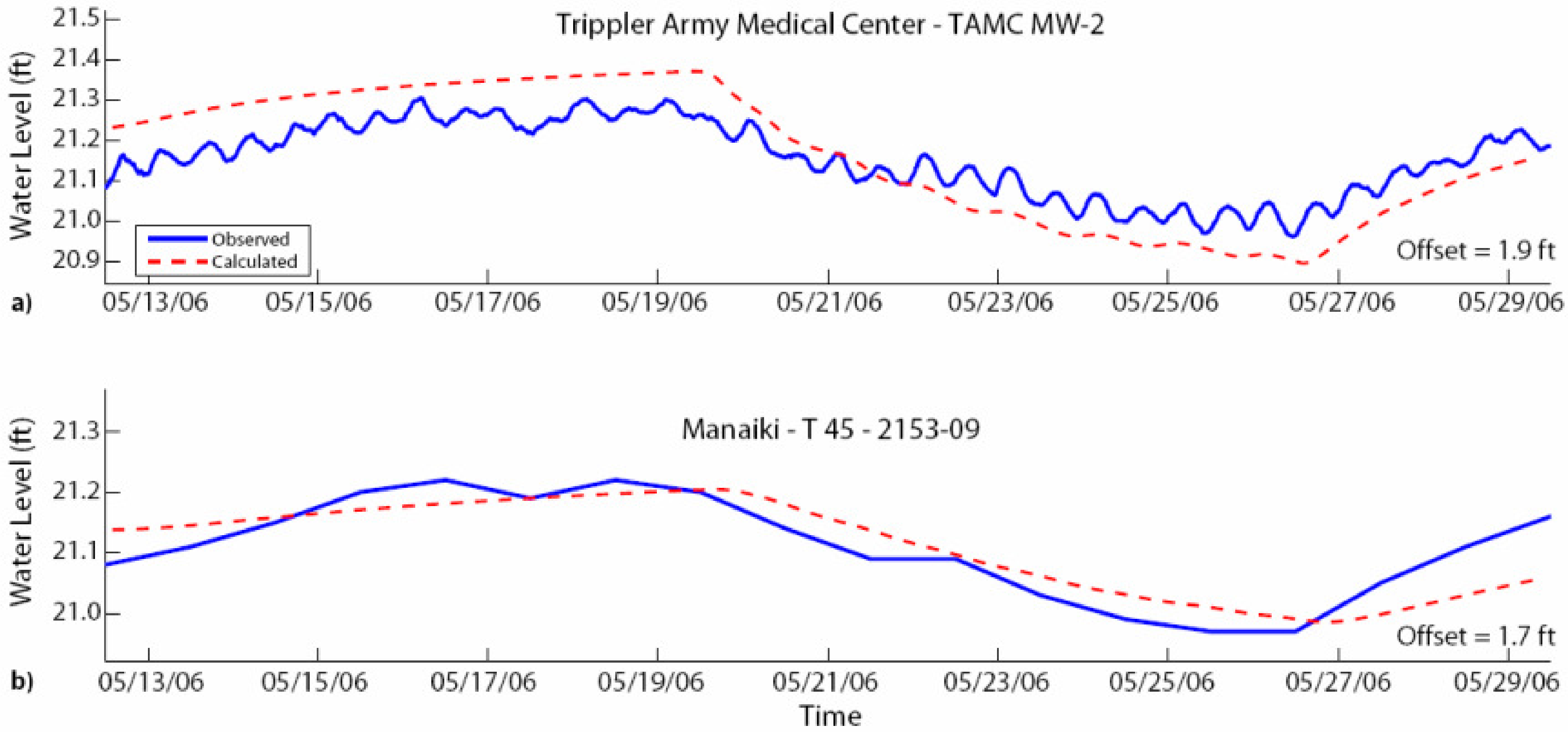
Source: U.S. Department of the Navy. 2007. *Red Hill Bulk Fuel Storage Facility, Final Technical Report*. Prepared by TEC, Inc. for Commander Naval Facilities Engineering Command, Pacific. August.

Figure 1.2.9
Simulated and Observed Groundwater Levels for RHMW02, RHMW03, and RHMW04
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



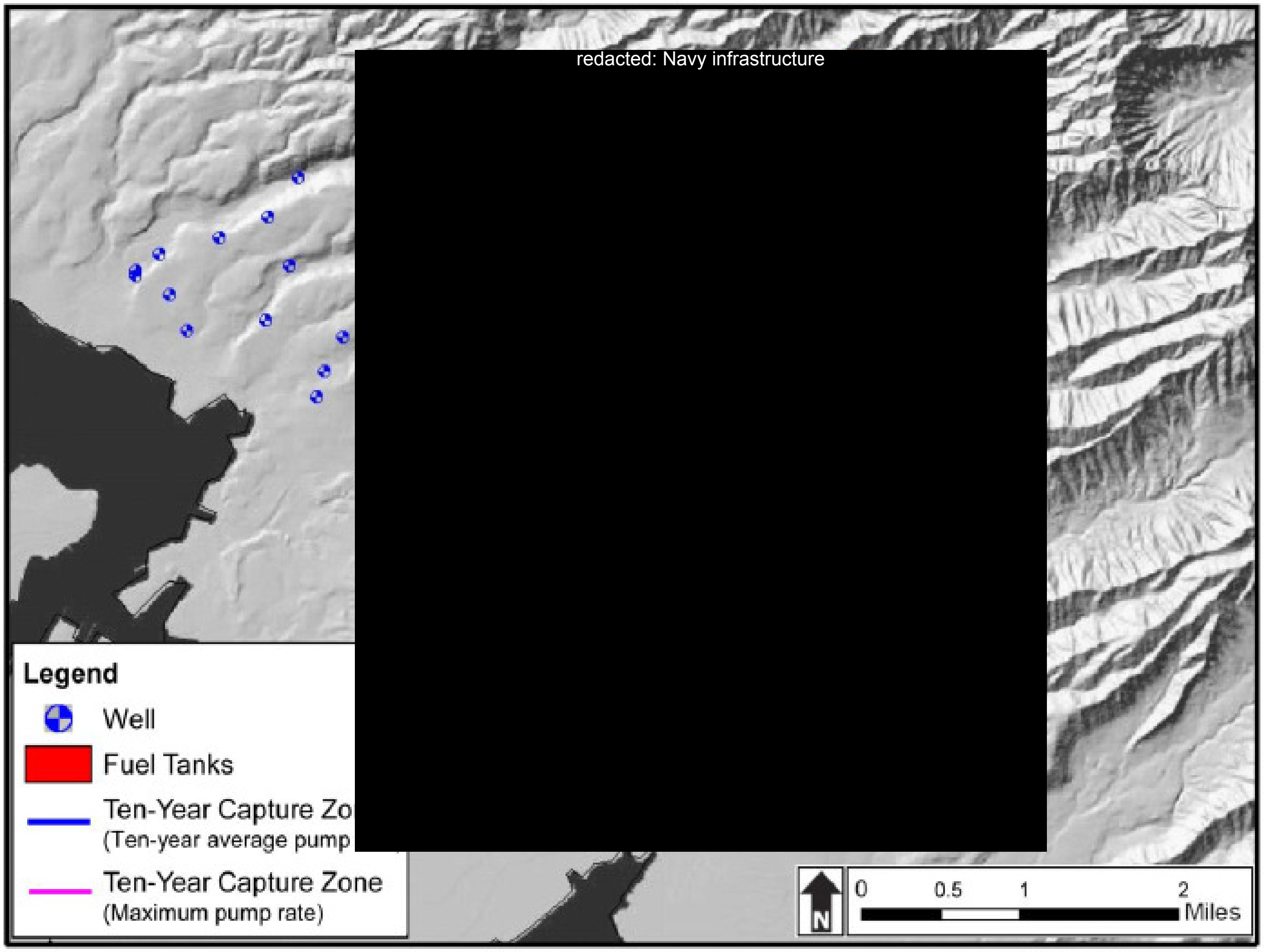
Source: U.S. Department of the Navy. 2007. *Red Hill Bulk Fuel Storage Facility, Final Technical Report*. Prepared by TEC, Inc. for Commander Naval Facilities Engineering Command, Pacific. August.

Figure 1.2.10
Simulated and Observed GW Levels for Hālawa Deep Observation, Hālawa Shallow Observation, and South Hālawa Deep Monitoring Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



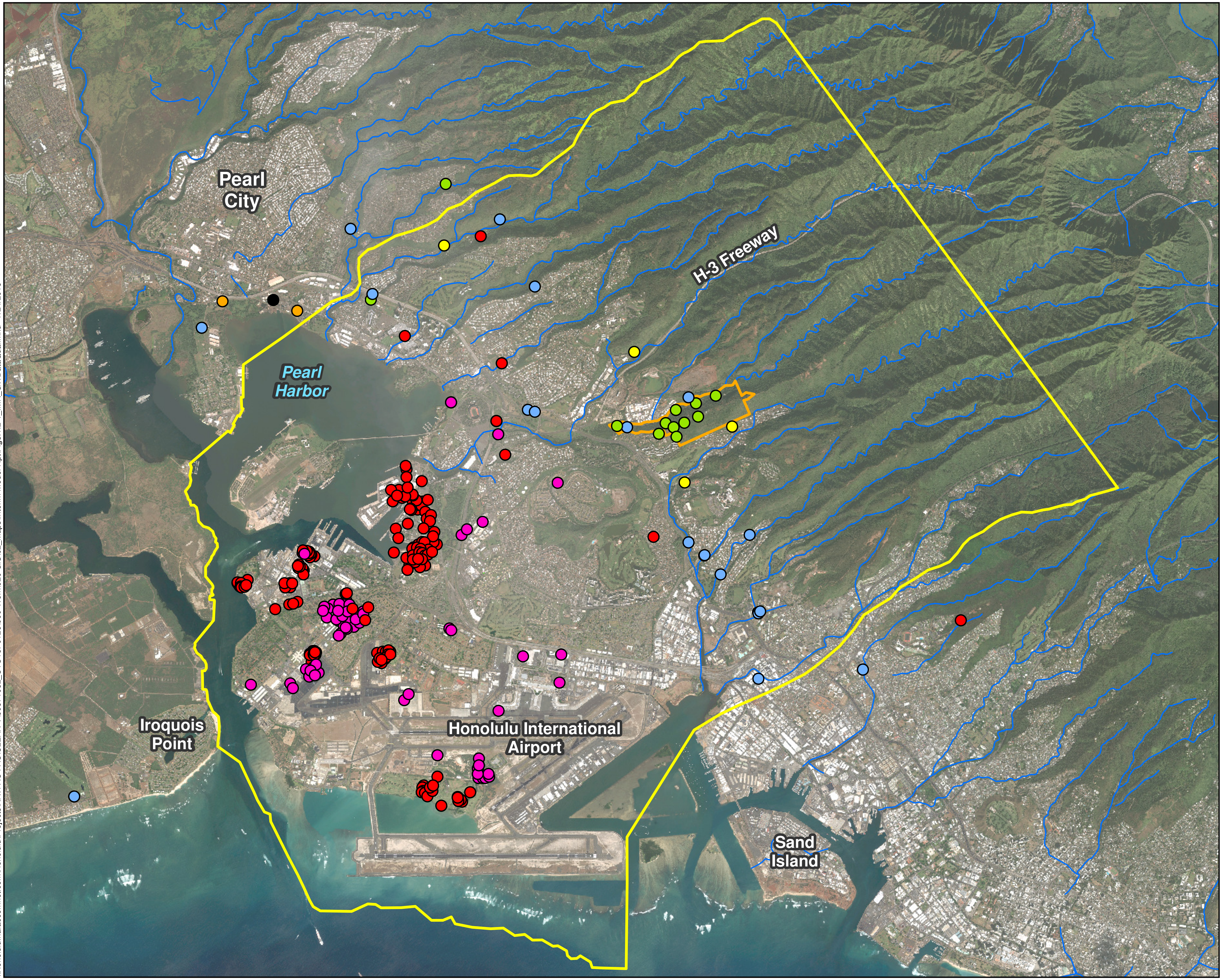
Source: U.S. Department of the Navy. 2007. *Red Hill Bulk Fuel Storage Facility, Final Technical Report*. Prepared by TEC, Inc. for Commander Naval Facilities Engineering Command, Pacific. August.

Figure 1.2.11
Simulated and Observed Groundwater Levels for Tripler Army Medical Center Monitor 2 and Manaiki T-45 Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

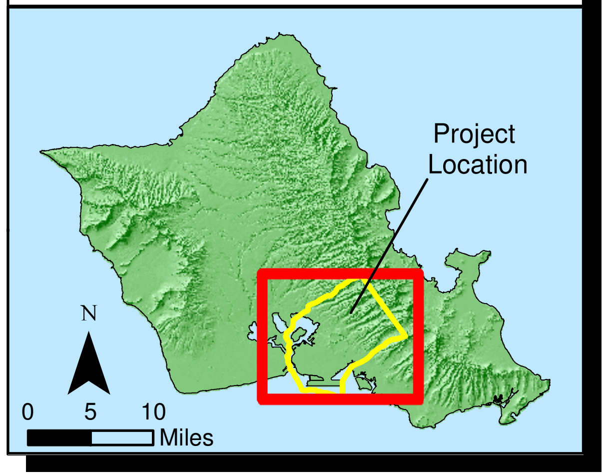


Source: Rotzoll, K. 2014. "Addendum to Rotzoll and El-Kadi (2007) Numerical Ground-Water Flow Simulation for Red Hill Fuel Storage Facilities, NAVFAC Pacific, Oahu, Hawaii." To: J. Shimabuku, NAVFAC HI; E. Lau, HBWS; cc: R. Whittier, HDOH; A. El-Kadi, University of Hawaii. January 29. Water Resources Research Center, University of Hawaii.

Figure 1.2.12
Simulated 10-Year Capture Zones by Rotzoll (2014) for Red Hill Shaft Not Pumping
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

- Well where both annual and monthly data are available
- Well where only annual data are sufficient to obtain a long-term regression
- Well with recent data, but insufficient for trend analyses
- Well with no data after 1999
- Well with insufficient data - after 1999
- Well with insufficient data - before 1999
- Well with no data/missing data
- Stream
- Groundwater Model
- Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 3.1.2-1
Groundwater Elevation Data Availability and Quality
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

Figure 3.1.3-1a
Water Level Hydrographs and Linear Trends – Blue Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

Figure 3.1.3-1b
Water Level Hydrographs and Linear Trends – Blue Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

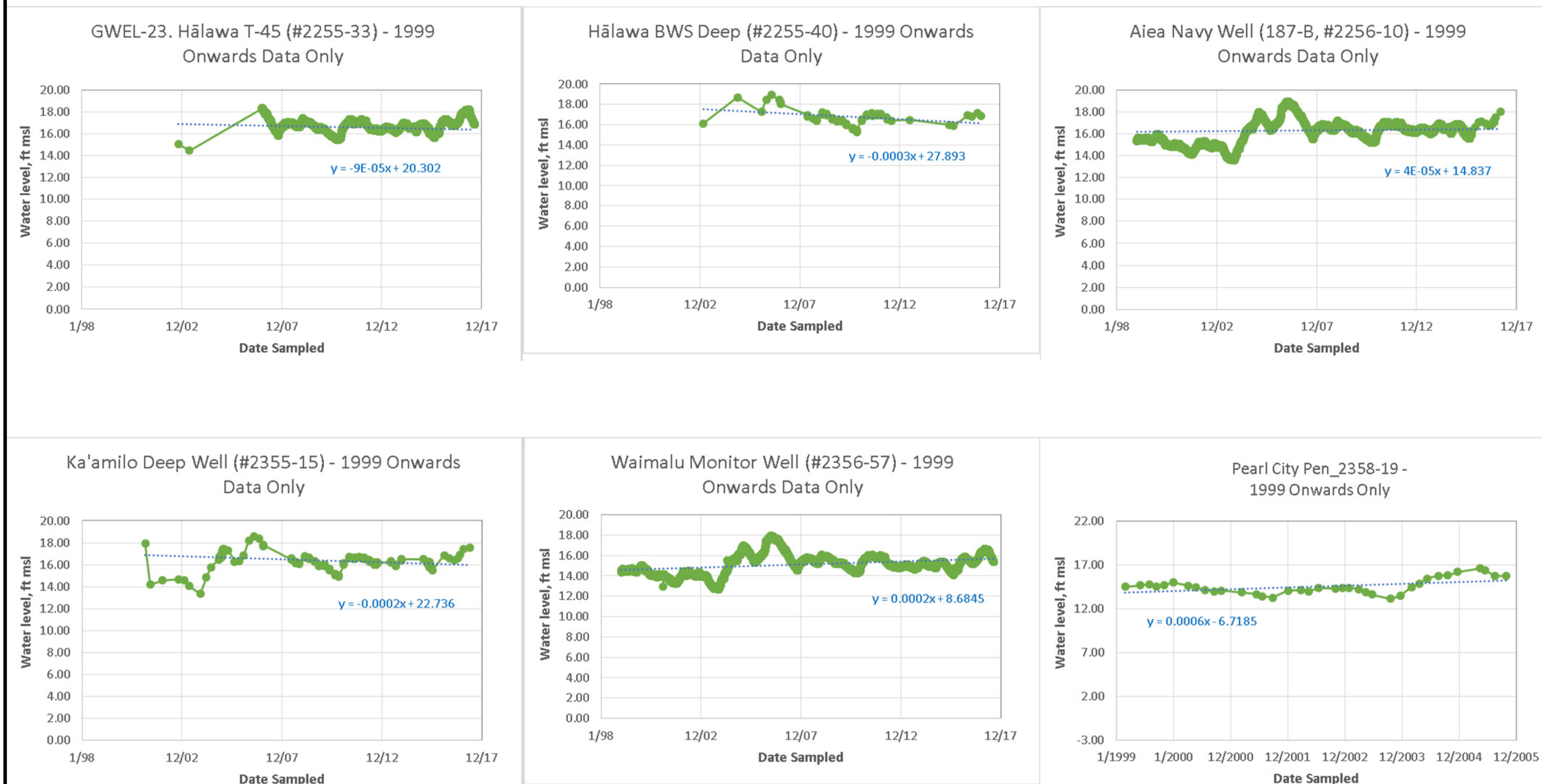
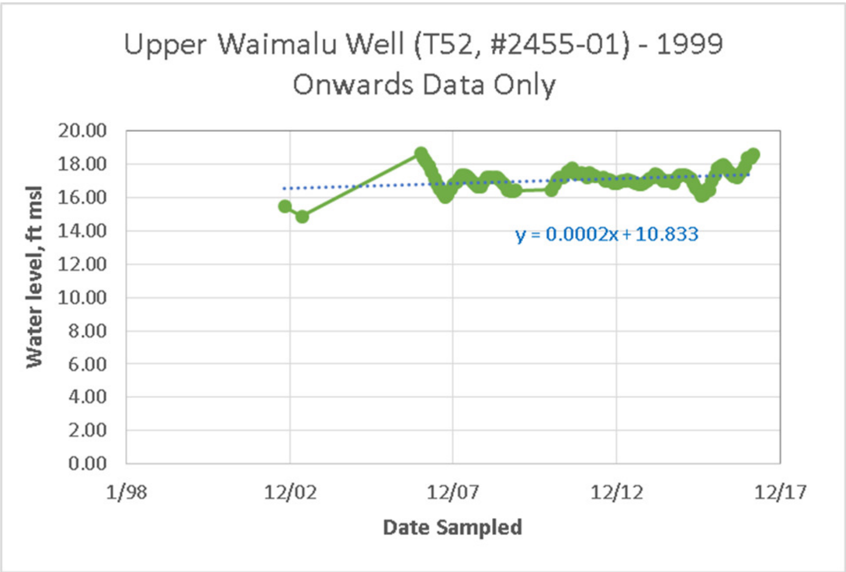


Figure 3.1.3-1c
Water Level Hydrographs and Linear Trends – Blue Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



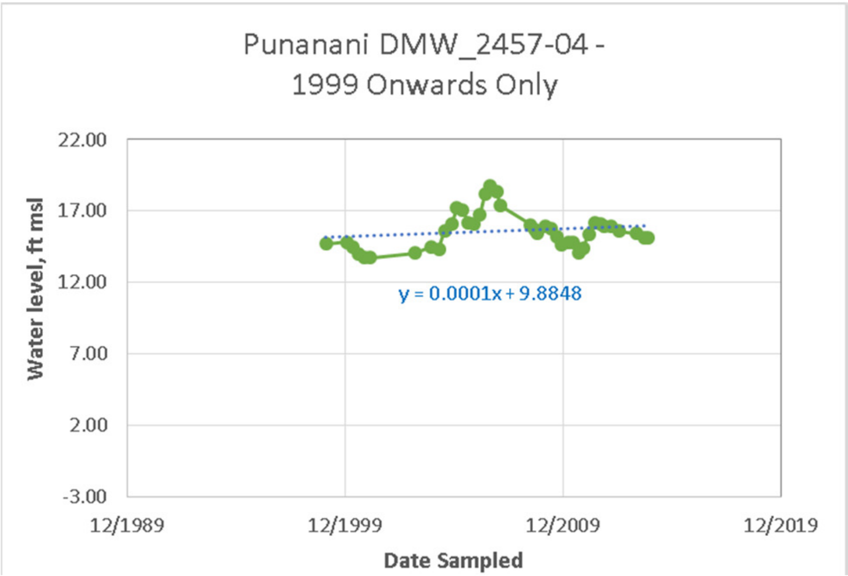


Figure 3.1.3-1d
Water Level Hydrographs and Linear Trends – Blue Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

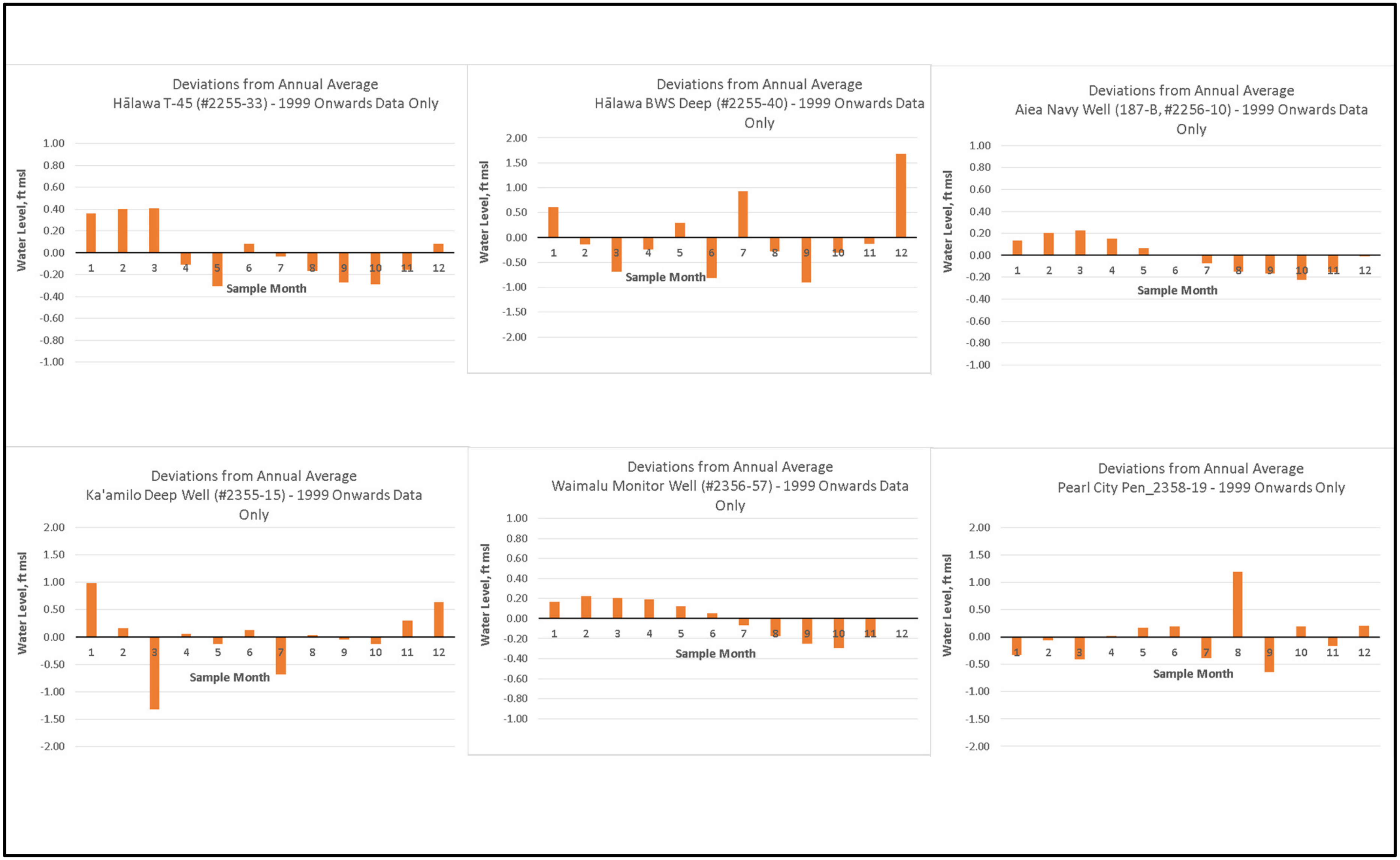
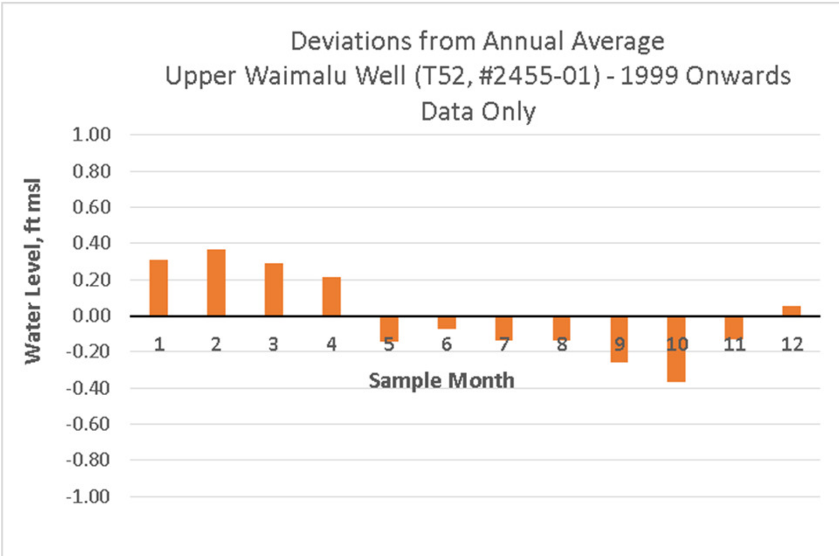
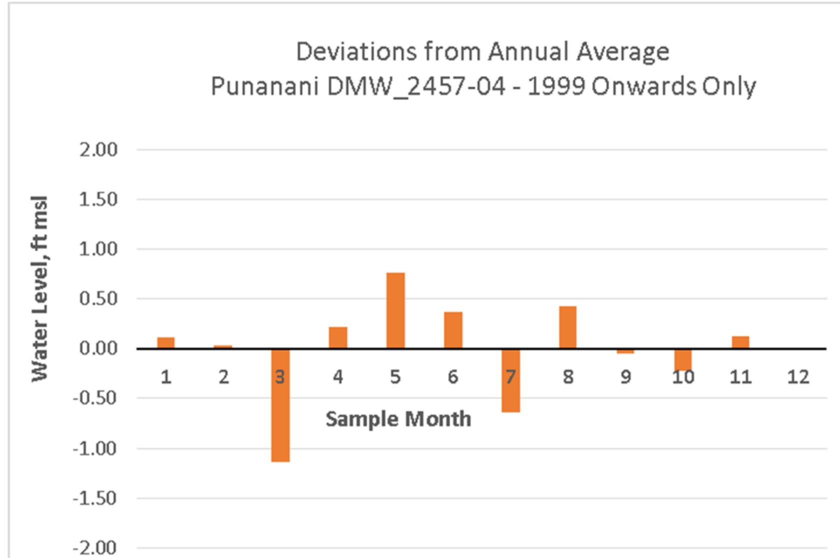


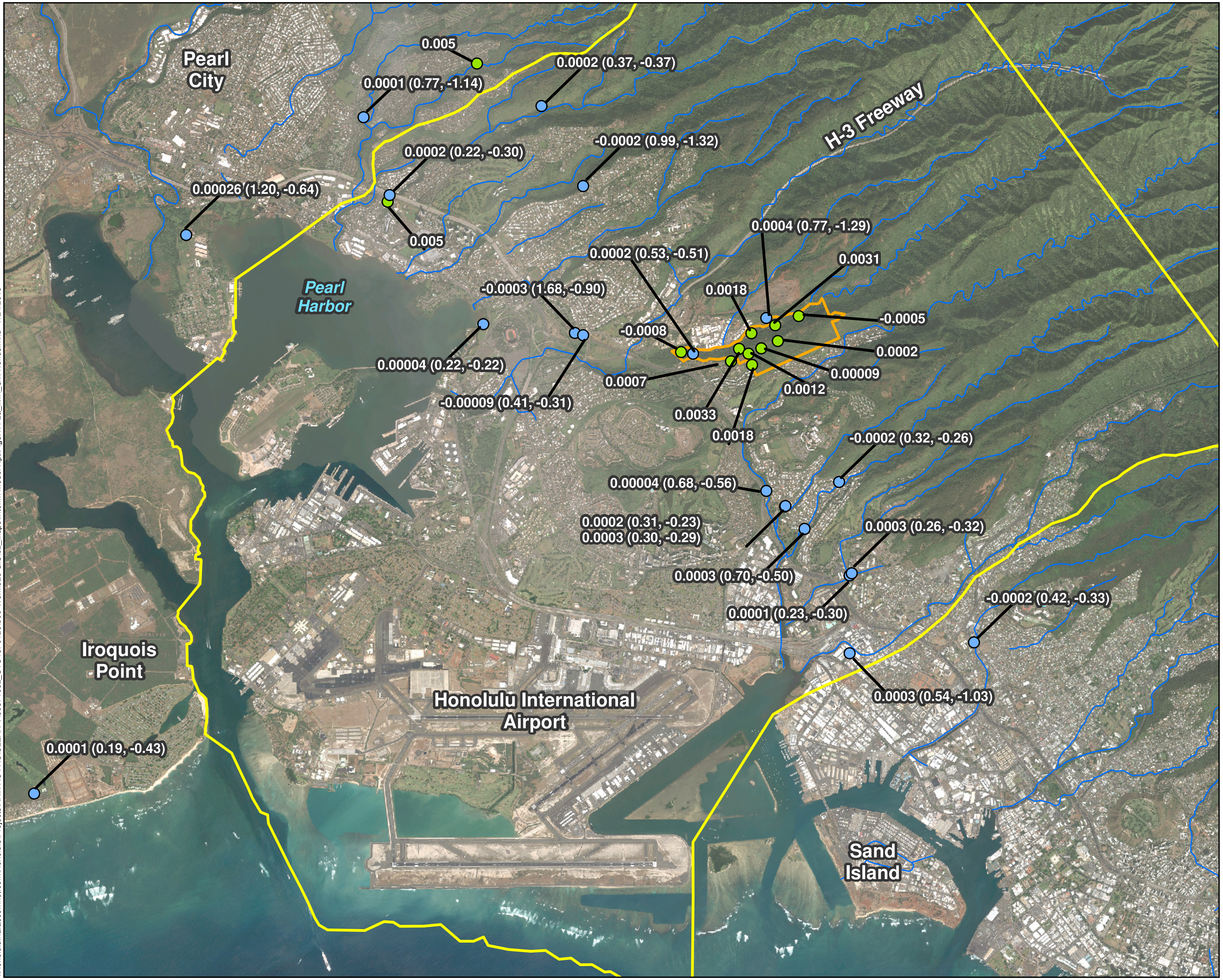
Figure 3.1.4-1a
Average Monthly Water Level Deviations – Blue Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



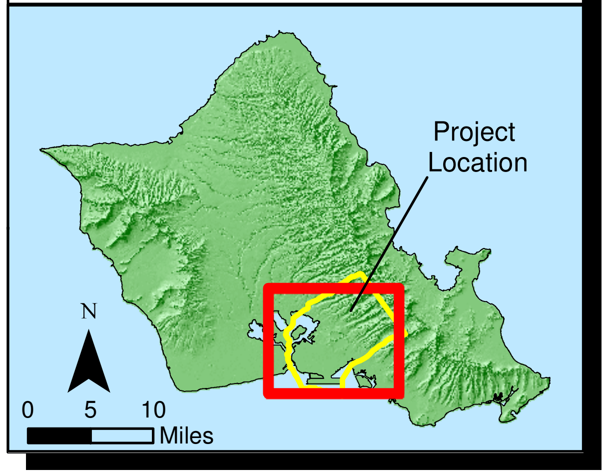


Month	1	2	3	4	5	6	7	8	9	10	11	12
Domain-Wide Average	0.19	0.23	-0.03	0.12	0.02	-0.11	-0.02	0.01	-0.29	-0.20	-0.09	0.17

Figure 3.1.4-1b
Average Monthly Water Level Deviations – Blue Wells
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

- Well where both annual and monthly data are available
- Well where only annual data are sufficient to obtain a long-term regression
- Stream
- Groundwater Model
- Red Hill Facility Boundary
- 0.0002 (0.22, -0.30) slope (max deviation, min deviation)

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 Feet

Figure 3.1.4-2a
Groundwater Elevation Trends and Monthly Deviations
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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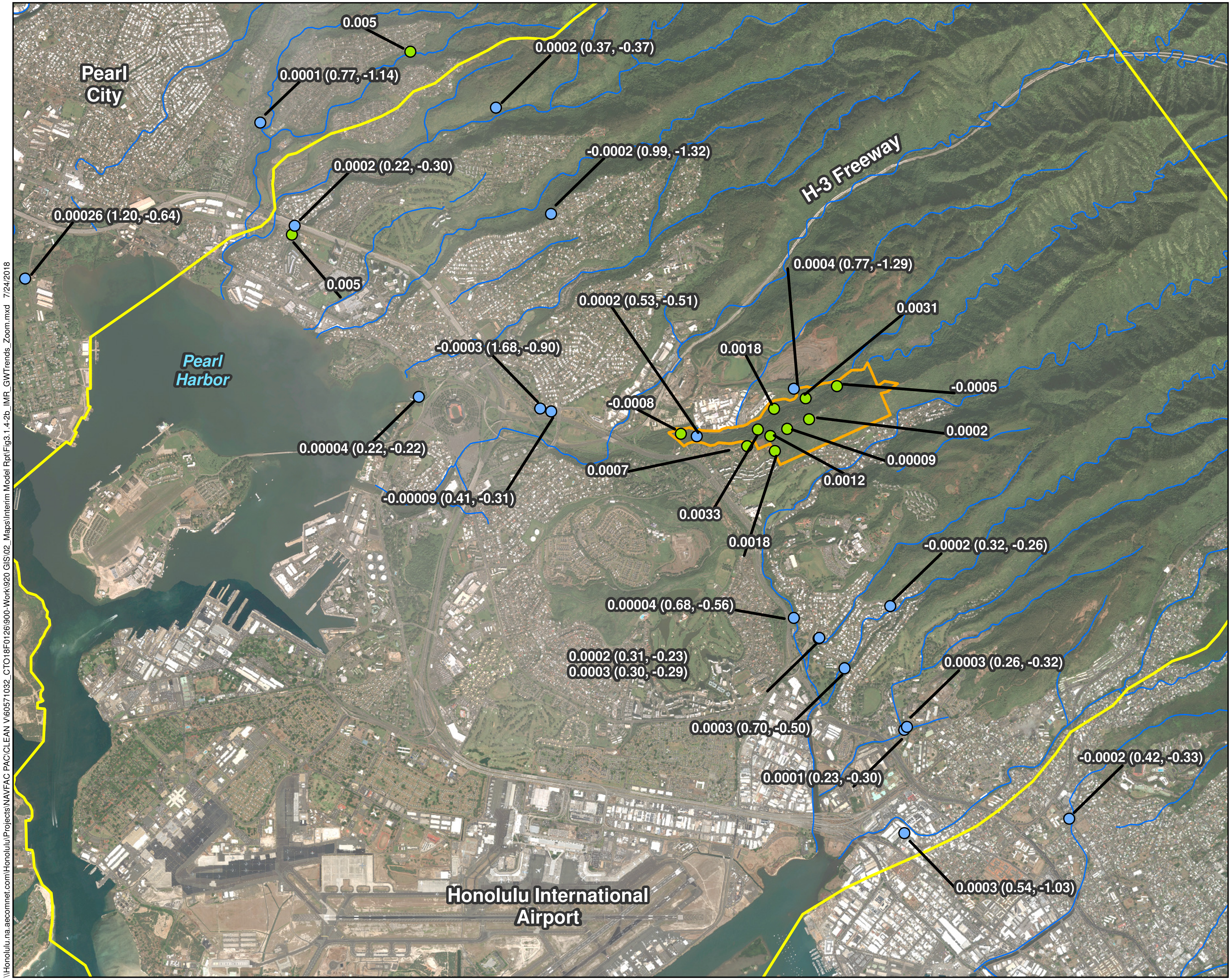

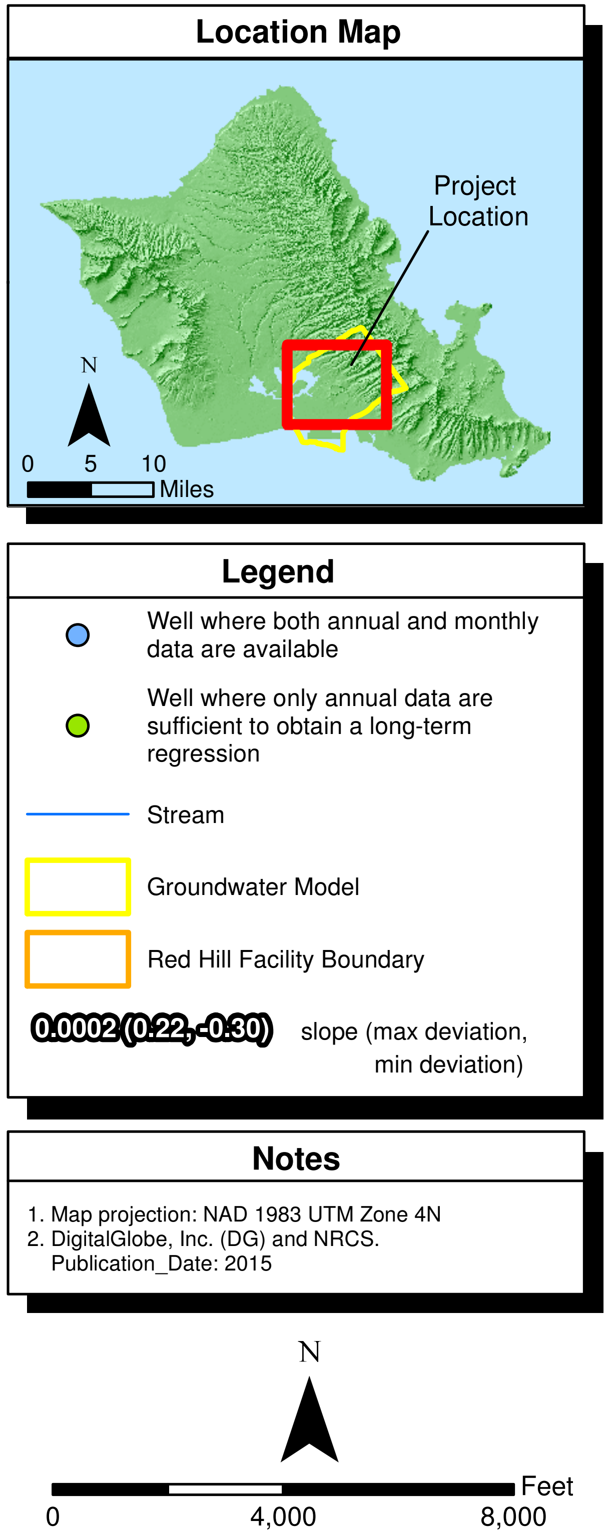

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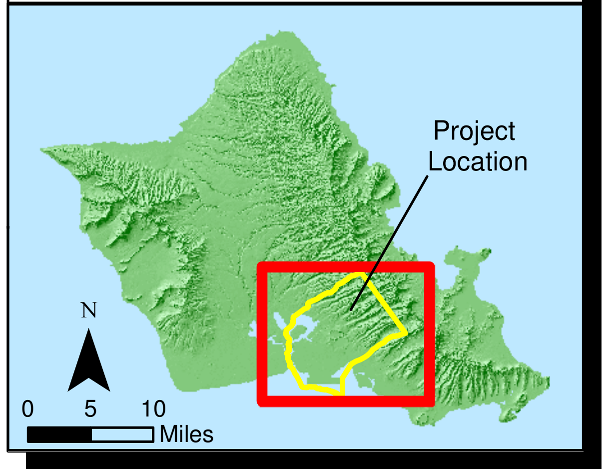
Figure 3.1.4-2b
Groundwater Elevation Trends and Monthly Deviations
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

Location Map



Legend

Projected Water Level Elevations (ft msl)

- 0 - 1.5
- 1.5 - 3.0
- 3.0 - 4.5
- 4.5 - 6.0
- 6.0 - 7.5
- 7.5 - 9.0
- 9.0 - 10.5
- 10.5 - 12.0
- 12.0 - 13.5
- 13.5 - 15.0
- 15.0 - 16.5
- 16.5 - 18.0
- 18.0 - 19.5
- 19.5 - 21.0
- 21.0 - 22.5
- 22.5 - 24.0

Stream

Groundwater Model

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Acronyms and Abbreviations:
   ft - feet
   msl - mean sea level

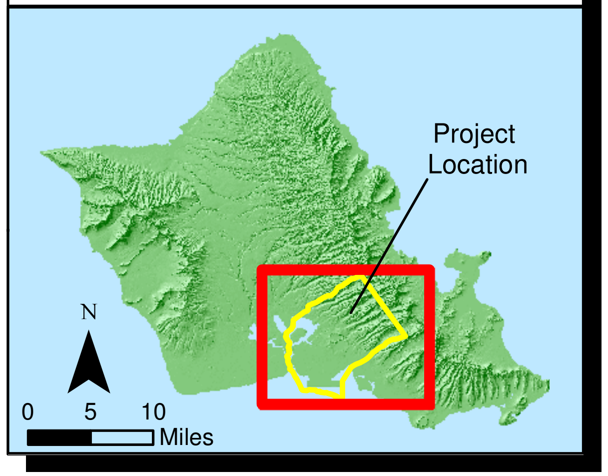
N

0 5,000 10,000 15,000 Feet

Figure 3.1.5-1
Projected Water Elevations for 2006
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig3.1.5-1_IMR_ProjectedGW2006.mxd 7/24/2018

Location Map



Legend

Projected Water Level Elevations (ft msl)

- 0 - 1.5
- 1.5 - 3.0
- 3.0 - 4.5
- 4.5 - 6.0
- 6.0 - 7.5
- 7.5 - 9.0
- 9.0 - 10.5
- 10.5 - 12.0
- 12.0 - 13.5
- 13.5 - 15.0
- 15.0 - 16.5
- 16.5 - 18.0
- 18.0 - 19.5
- 19.5 - 21.0
- 21.0 - 22.5
- 22.5 - 24.0

Stream

Groundwater Model Area

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Acronyms and Abbreviations:
   ft - feet
   msl - mean sea level

N

0 5,000 10,000 15,000 Feet

Figure 3.1.5-2
Projected Groundwater Elevations for 2015
Appendix A
Interim Groundwater Flow Model Report
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JBPHH, Oʻahu, HI

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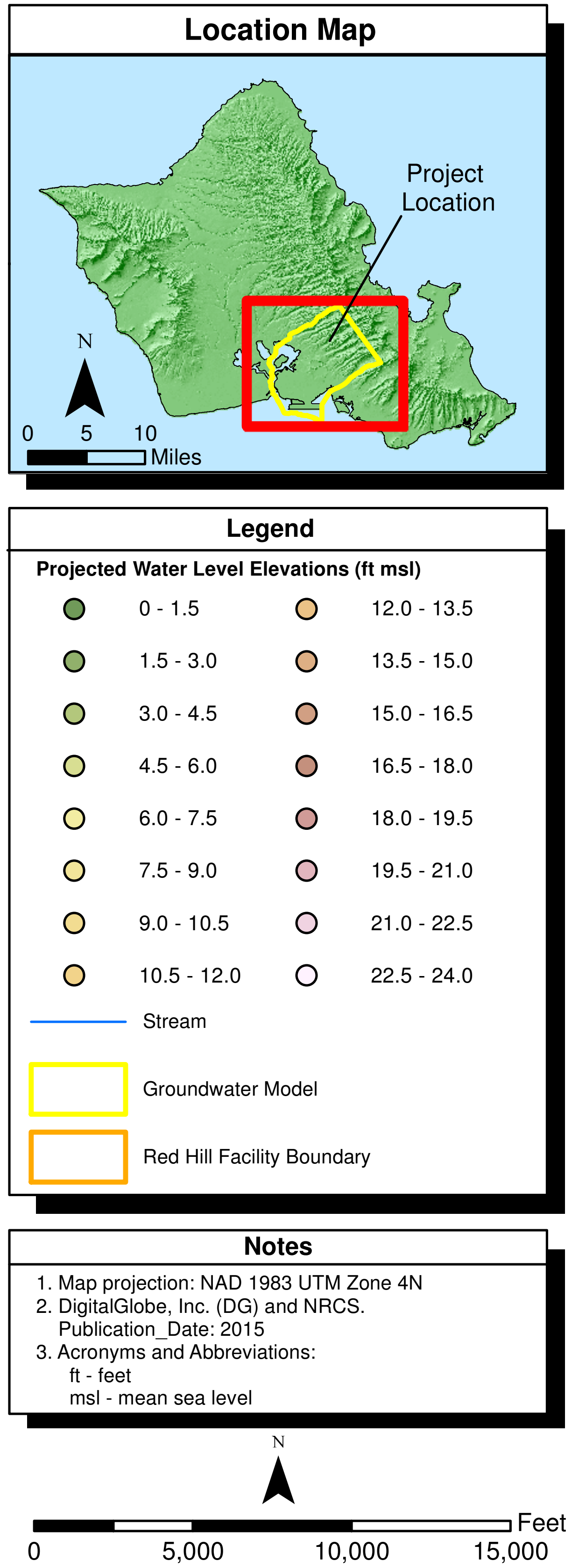

Figure 3.1.5-3
Projected Groundwater Elevations for 2017
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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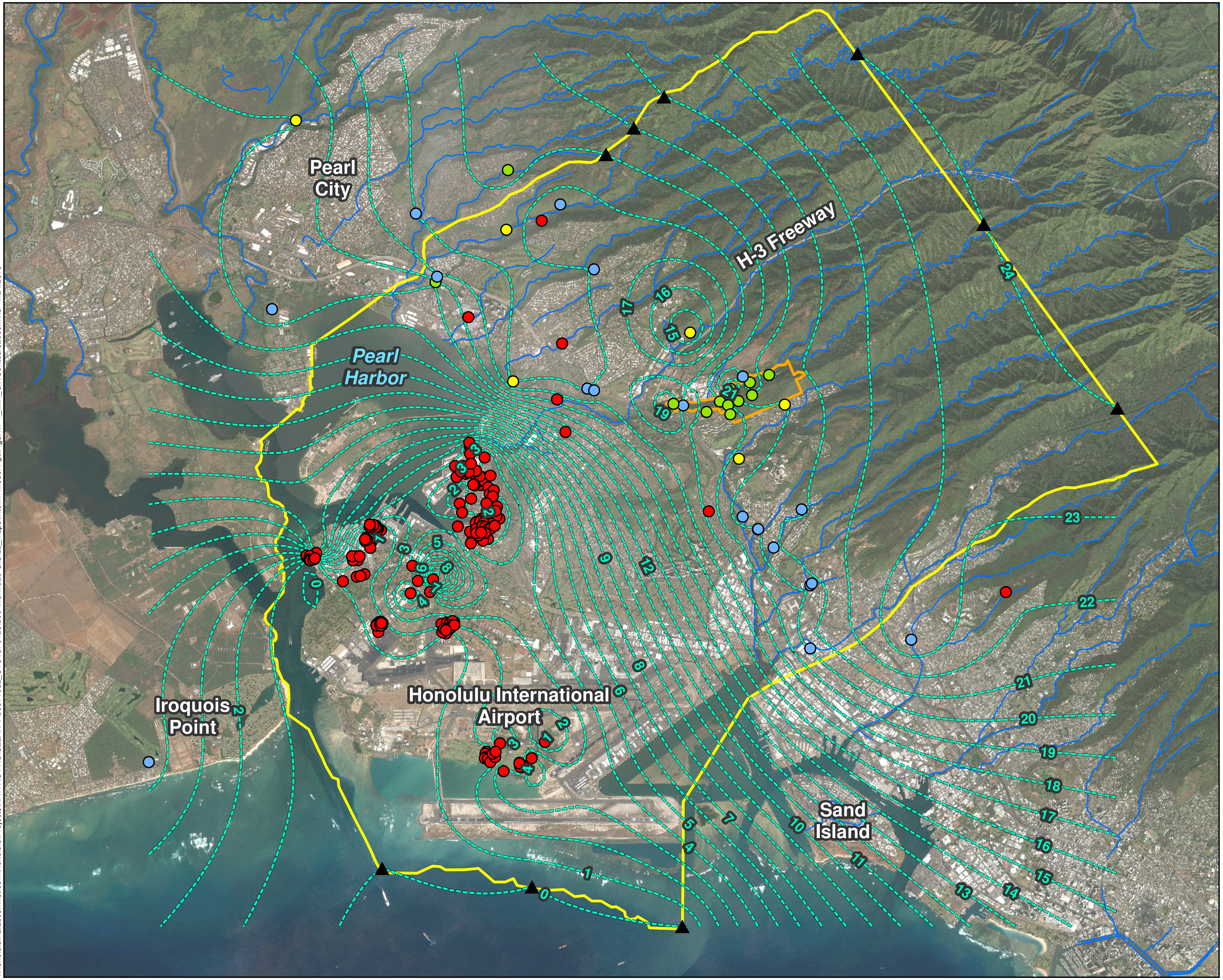
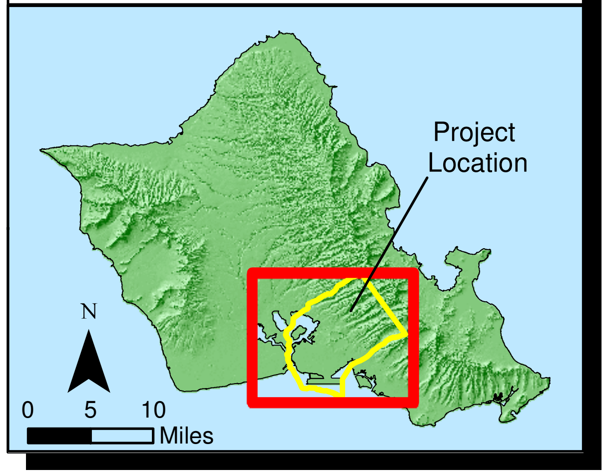


Location Map



Legend

- Well where both annual and monthly data are available
- Well where only annual data are sufficient to obtain a long-term regression
- Well with recent data, but insufficient for trend analyses
- Well with insufficient data - after 1999
- Control Point
- Approximate GW Elev (ft msl)
- Stream
- Groundwater Model Area
- Red Hill Facility Boundary

Notes

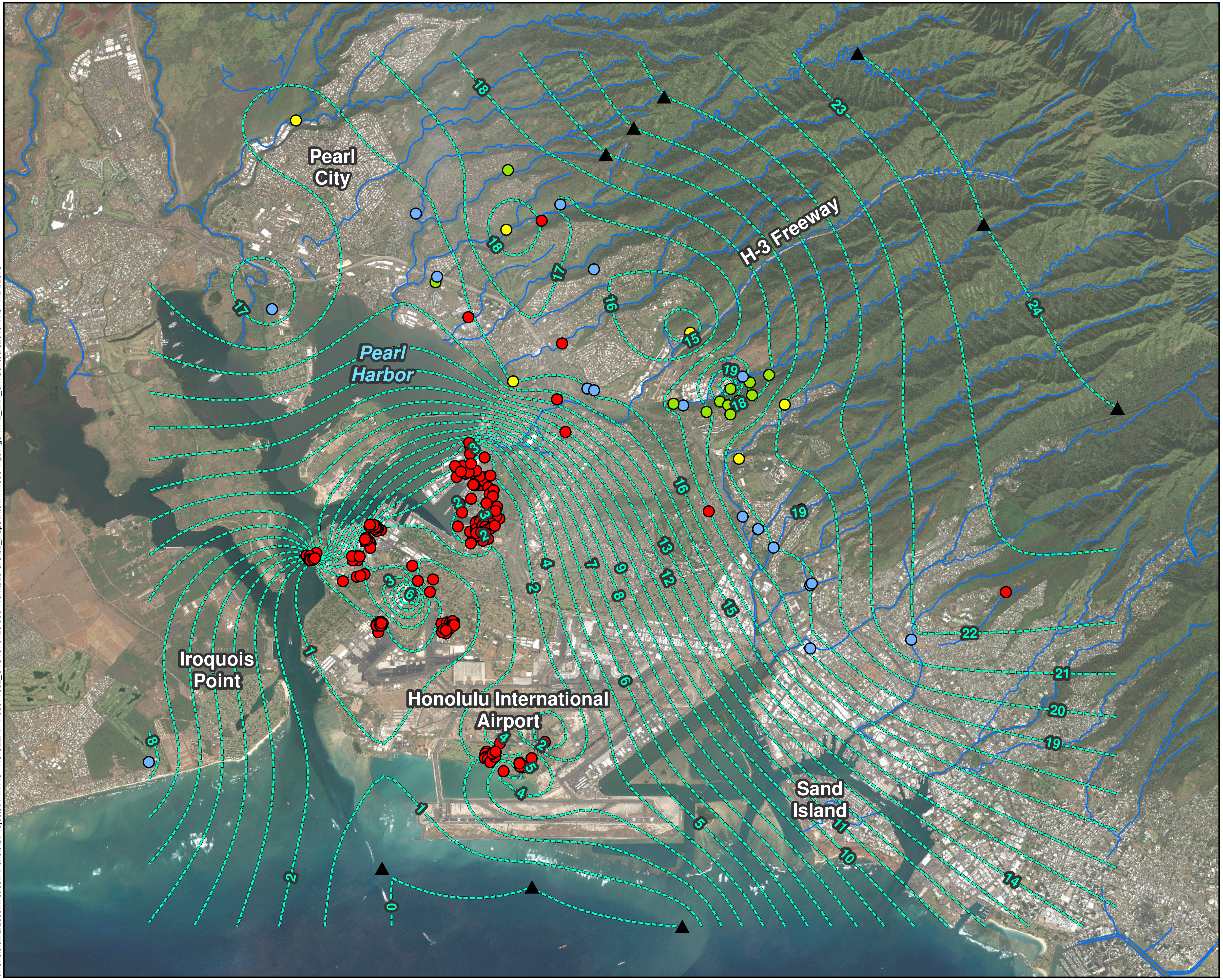
1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Acronyms and Abbreviations:

ft - feet	GW - groundwater
elev. - elevation	msl - mean sea level

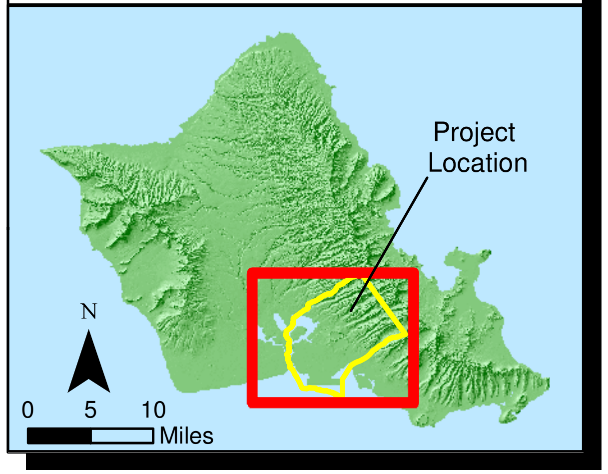
N

0 5,000 10,000 15,000 Feet

Figure 3.1.7-1
Groundwater Elevation Contours for 2006
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

- Well where both annual and monthly data are available
- Well where only annual data are sufficient to obtain a long-term regression
- Well with recent data, but insufficient for trend analyses
- Well with insufficient data - after 1999
- Control Point
- Approximate GW Elev (ft msl)
- Stream
- Groundwater Model
- Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Acronyms and Abbreviations:
   ft - feet GW - groundwater
   elev. - elevation msl - mean sea level

N

0 5,000 10,000 15,000 Feet

Figure 3.1.7-2
Groundwater Elevation Contours for 2015
Appendix A
Interim Groundwater Flow Model Report
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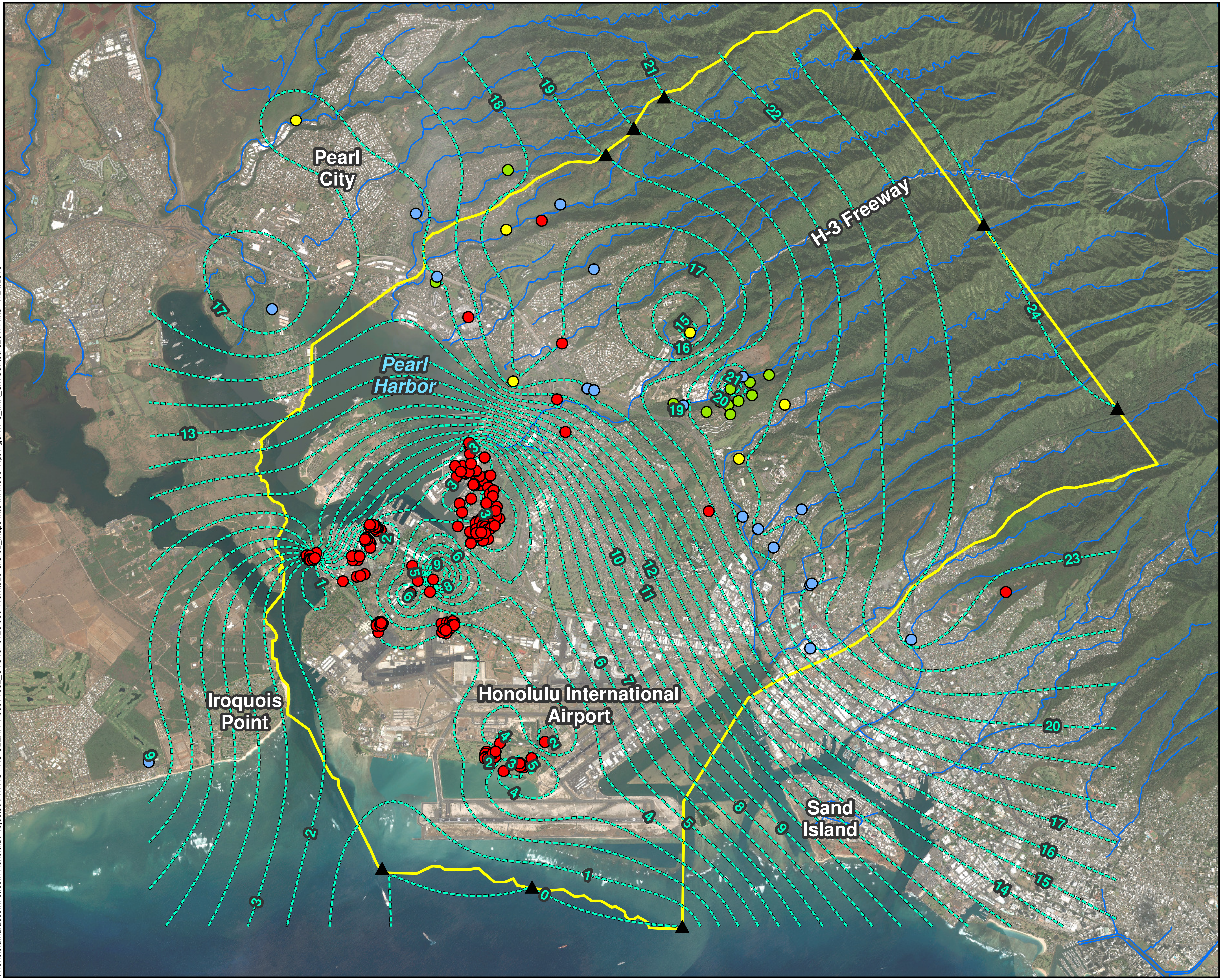
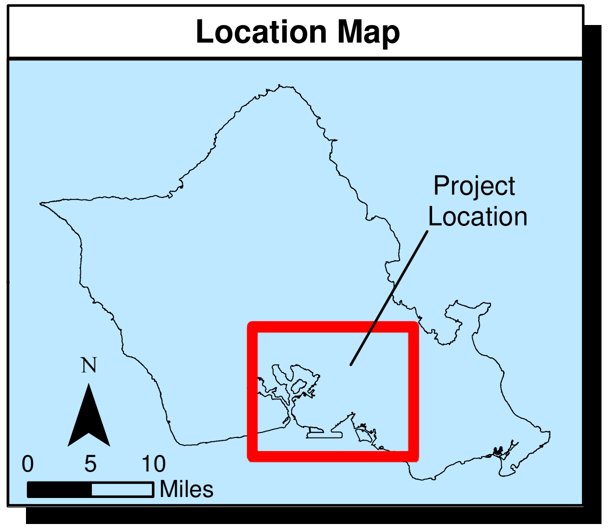




Legend

- Well where both annual and monthly data are available
- Well where only annual data are sufficient to obtain a long-term regression
- Well with recent data, but insufficient for trend analyses
- Well with insufficient data - after 1999
- Control Point
- Approximate GW Elev (ft msl)
- Stream
- Groundwater Model
- Red Hill Facility Boundary

Notes

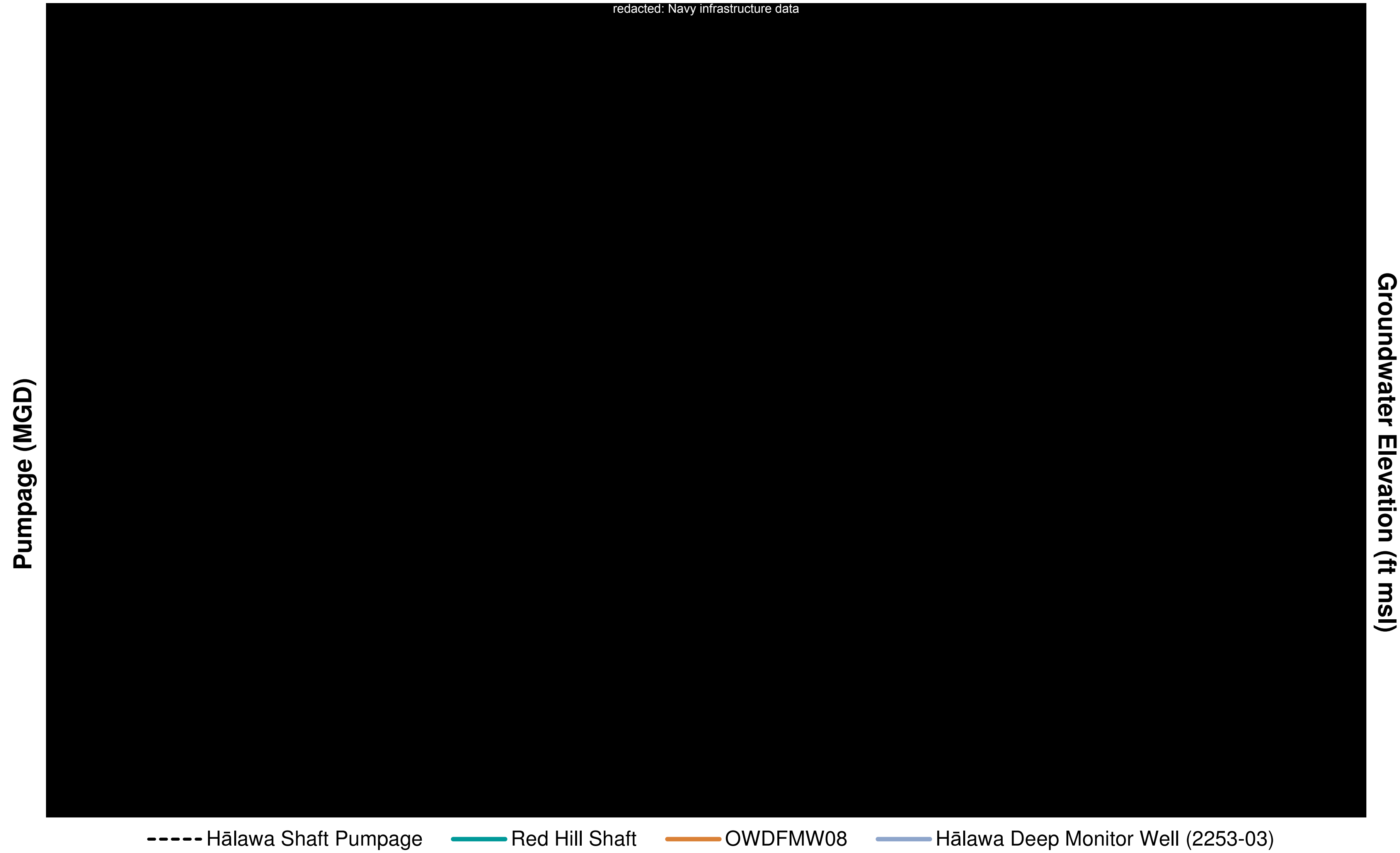
1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Acronyms and Abbreviations:
   ft - feet GW - groundwater
   elev. - elevation msl - mean sea level

N

0 5,000 10,000 15,000 Feet

Figure 3.1.7-3
Groundwater Elevation Contours for 2017
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig3.1.7-3_IMR_GWContours2017.mxd 7/24/2018



Note: OWDFMW08 is the former name of well OWDFMW01.

Figure 3.2.3-1a
Impact of Pumping on Groundwater Levels - Hālawa Shaft, 2006 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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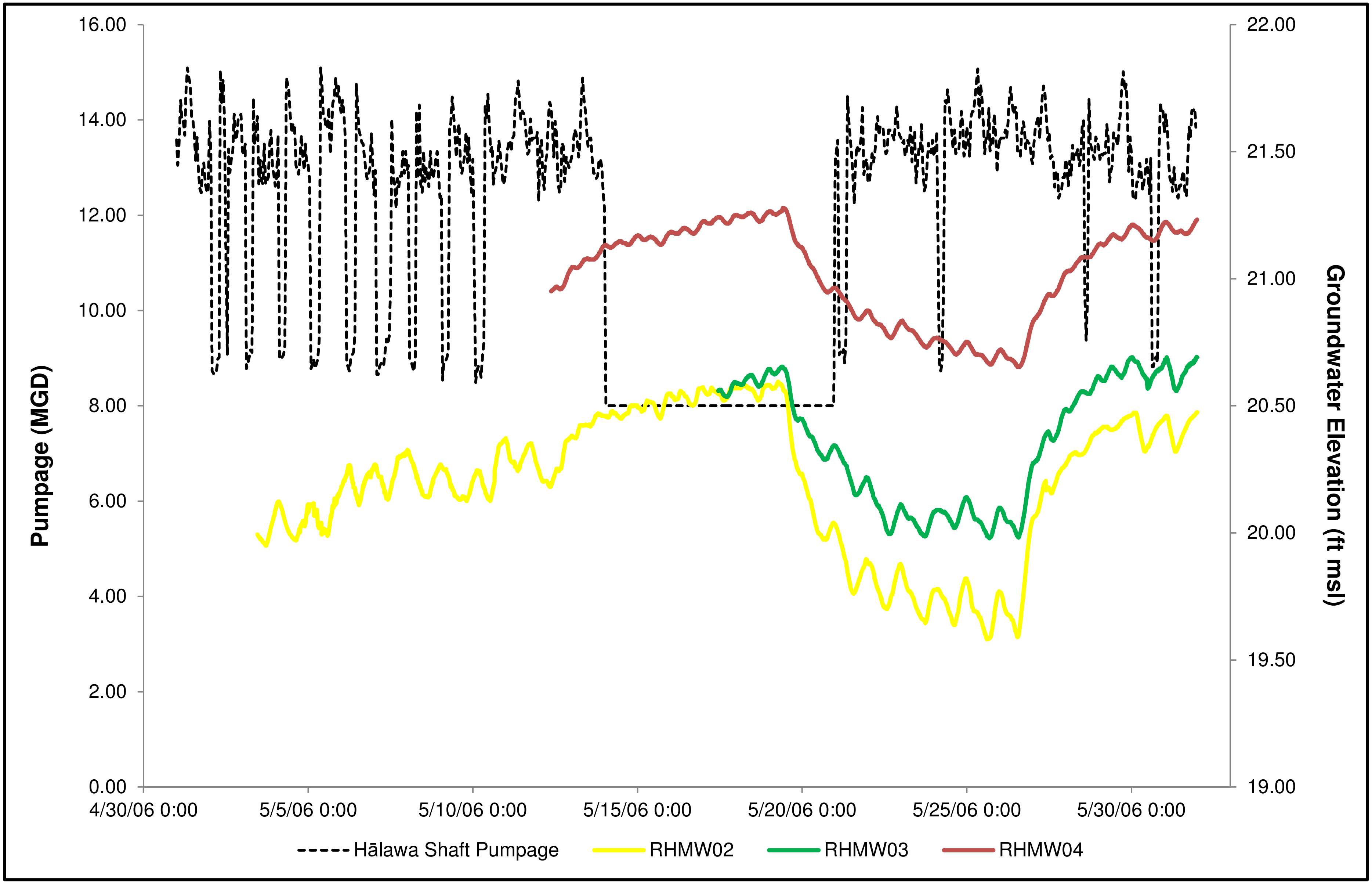

Figure 3.2.3-1b
Impact of Pumping on Groundwater Levels - Hālawa Shaft, 2006 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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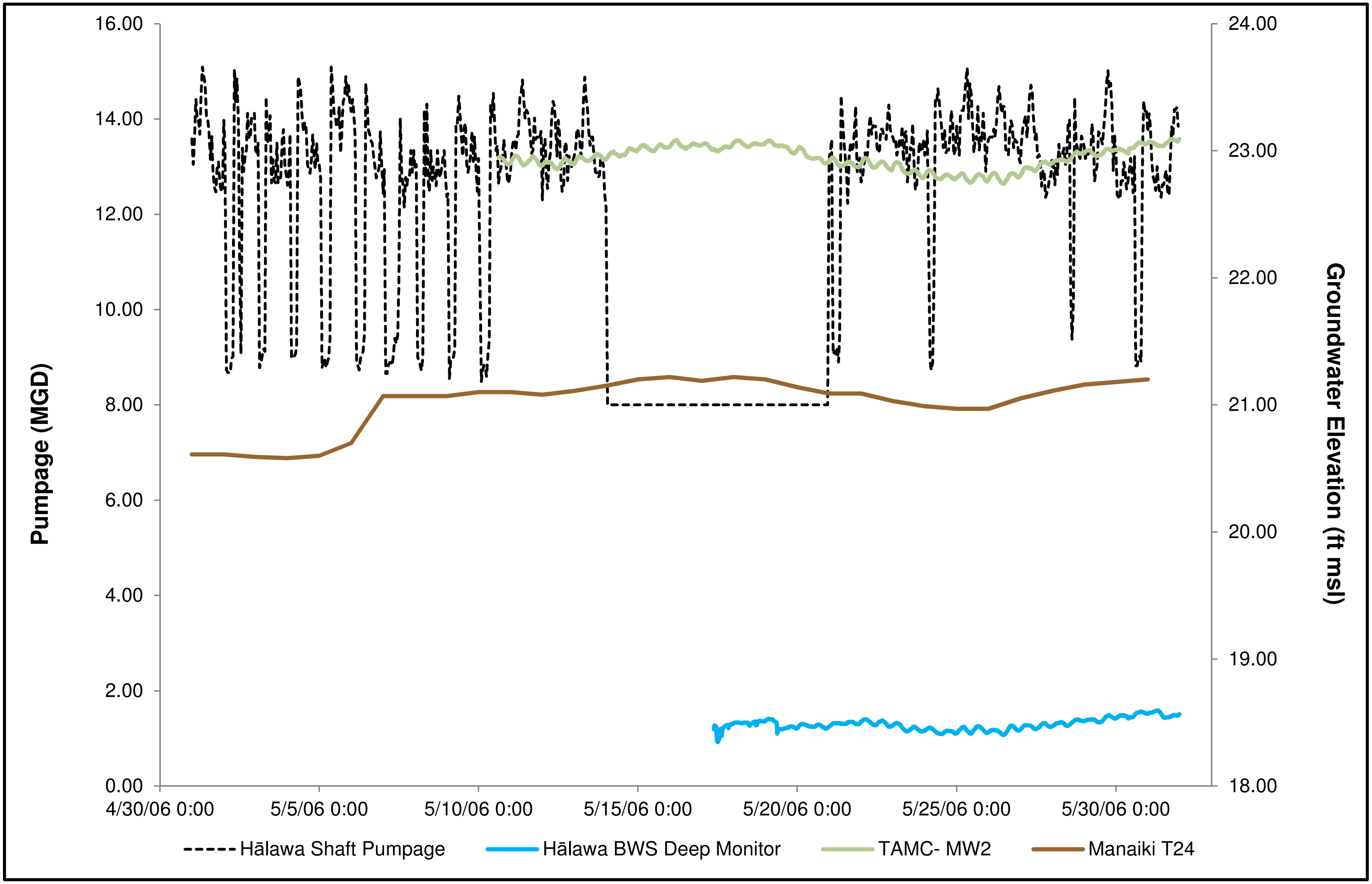

Figure 3.2.3-1c
Impact of Pumping on Groundwater Levels - Hālawa Shaft, 2006 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
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for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

redacted: Navy infrastructure data

[redacted]

Pumpage (MGD)

Groundwater Elevation (ft msl)

----- Red Hill Shaft Pumpage — Red Hill Shaft — OWDFMW08 — Hālawa Deep Monitor Well (2253-03)

Note: OWDFMW08 is the former name of well OWDFMW01.

Figure 3.2.3-1d
Impact of Pumping on Groundwater Levels - Red Hill Shaft, 2006 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
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JBPHH, Oʻahu, HI

Figure 3.2.3-1e
Impact of Pumping on Groundwater Levels - Red Hill Shaft, 2006 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
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for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

redacted: Navy infrastructure data

[redacted]

Pumpage (MGD)

Groundwater Elevation (ft msl)

Red Hill Shaft Pumpage — Hālawa BWS Deep Monitor — TAMC- MW2 — Manaiki T24

Figure 3.2.3-1f

Impact of Pumping on Groundwater Levels - Red Hill Shaft, 2006 Synoptic Study

Appendix A - Interim Groundwater Flow Model Report

Groundwater Protection and Evaluation Considerations

for the Red Hill Bulk Fuel Storage Facility

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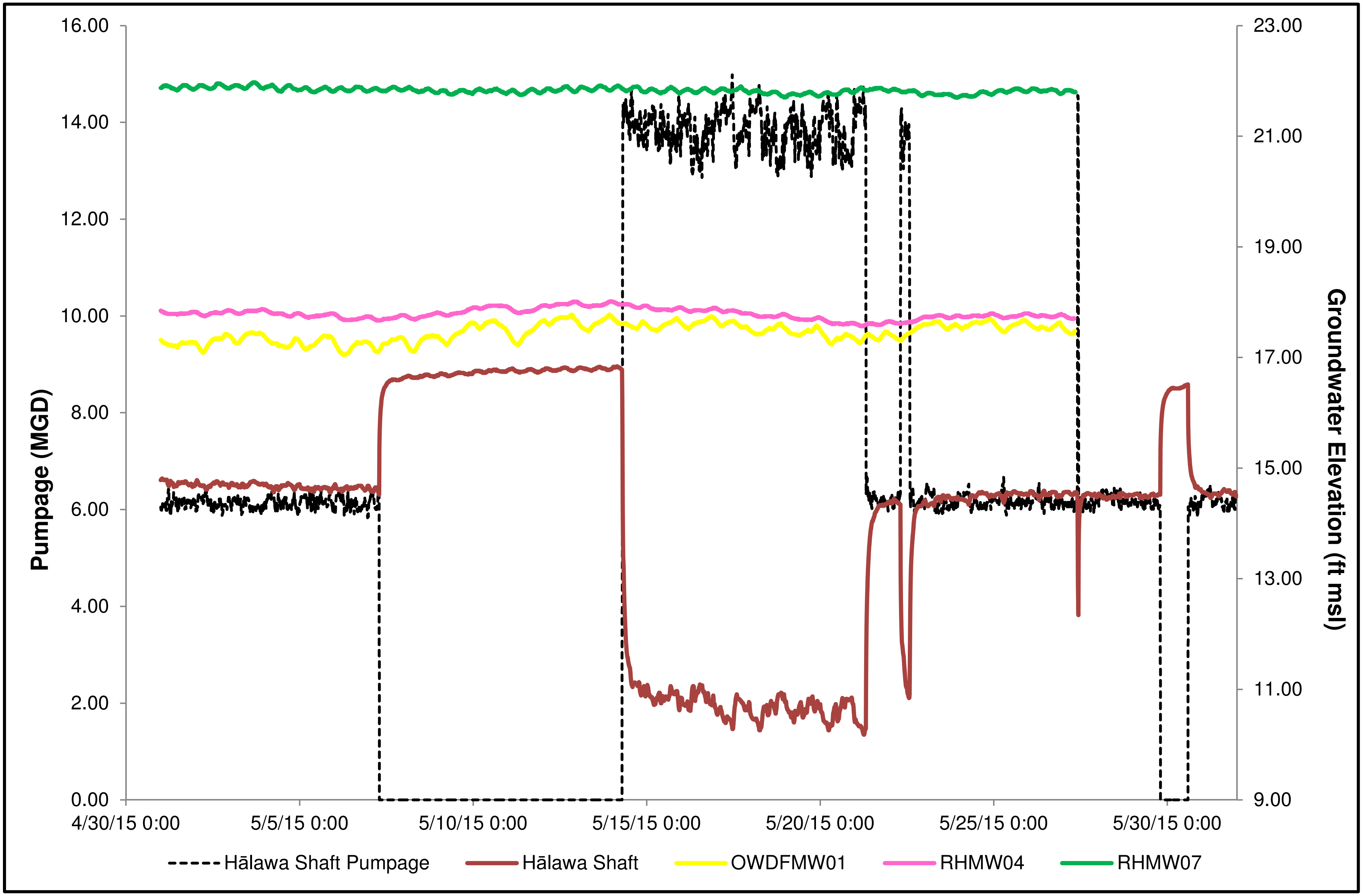
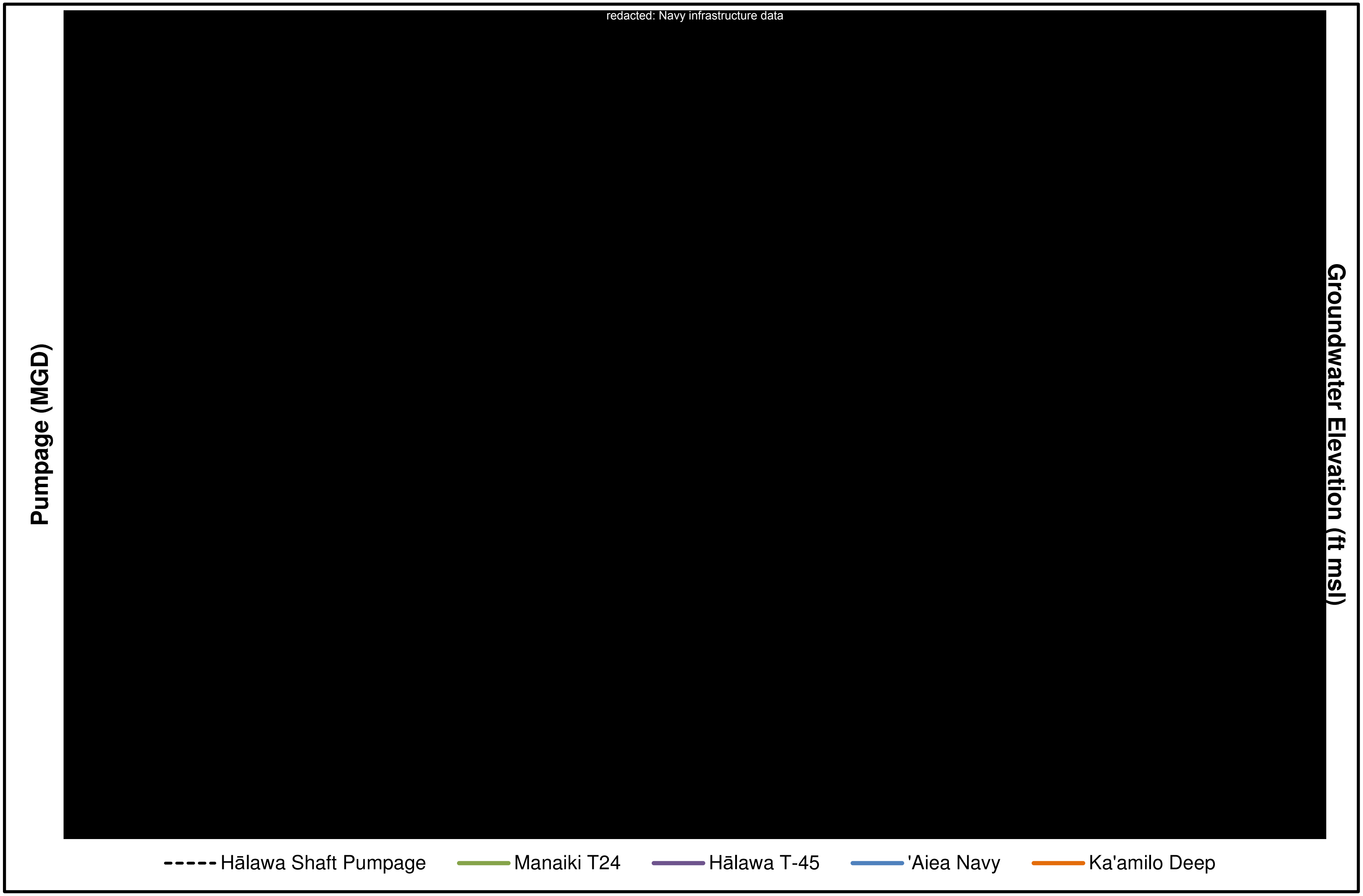


Figure 3.2.3-2a
Impact of Pumping on Groundwater Levels - Hālawa Shaft, 2015 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



[redacted]

Figure 3.2.3-2b
Impact of Pumping on Groundwater Levels - Hālawa Shaft, 2015 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

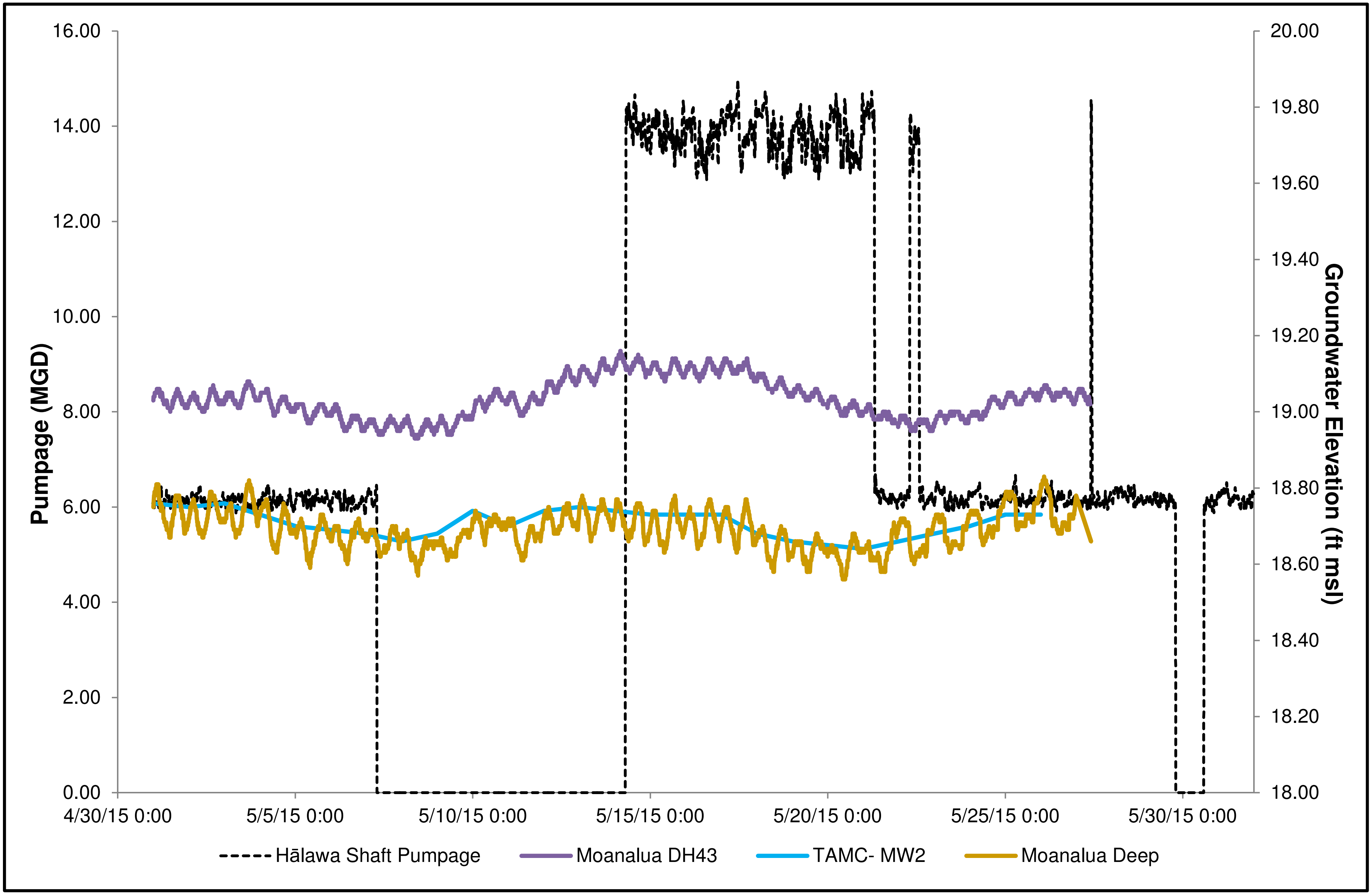


Figure 3.2.3-2c
Impact of Pumping on Groundwater Levels - Hālawa Shaft, 2015 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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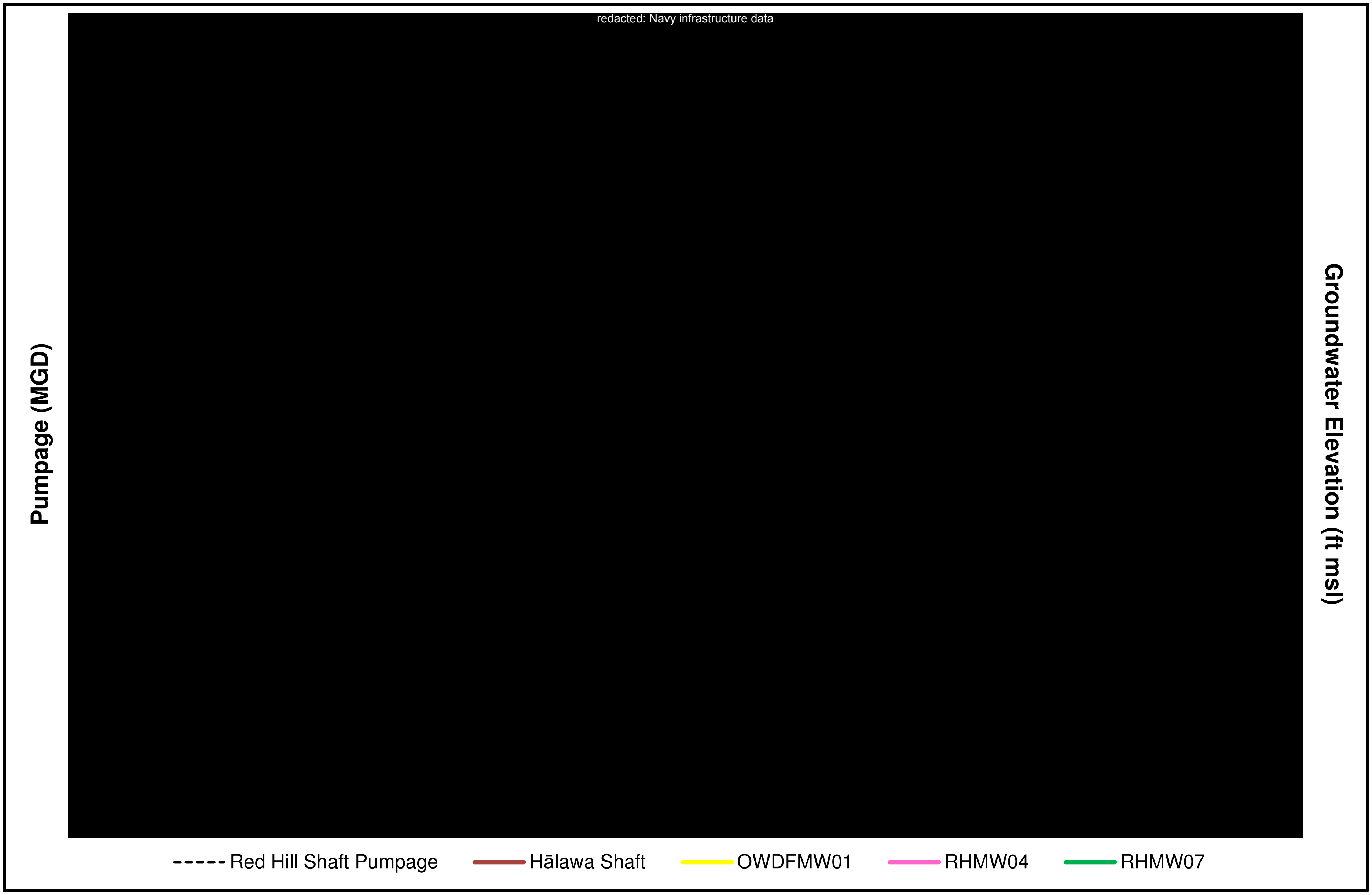

Figure 3.2.3-2d
Impact of Pumping on Groundwater Levels - Red Hill Shaft, 2015 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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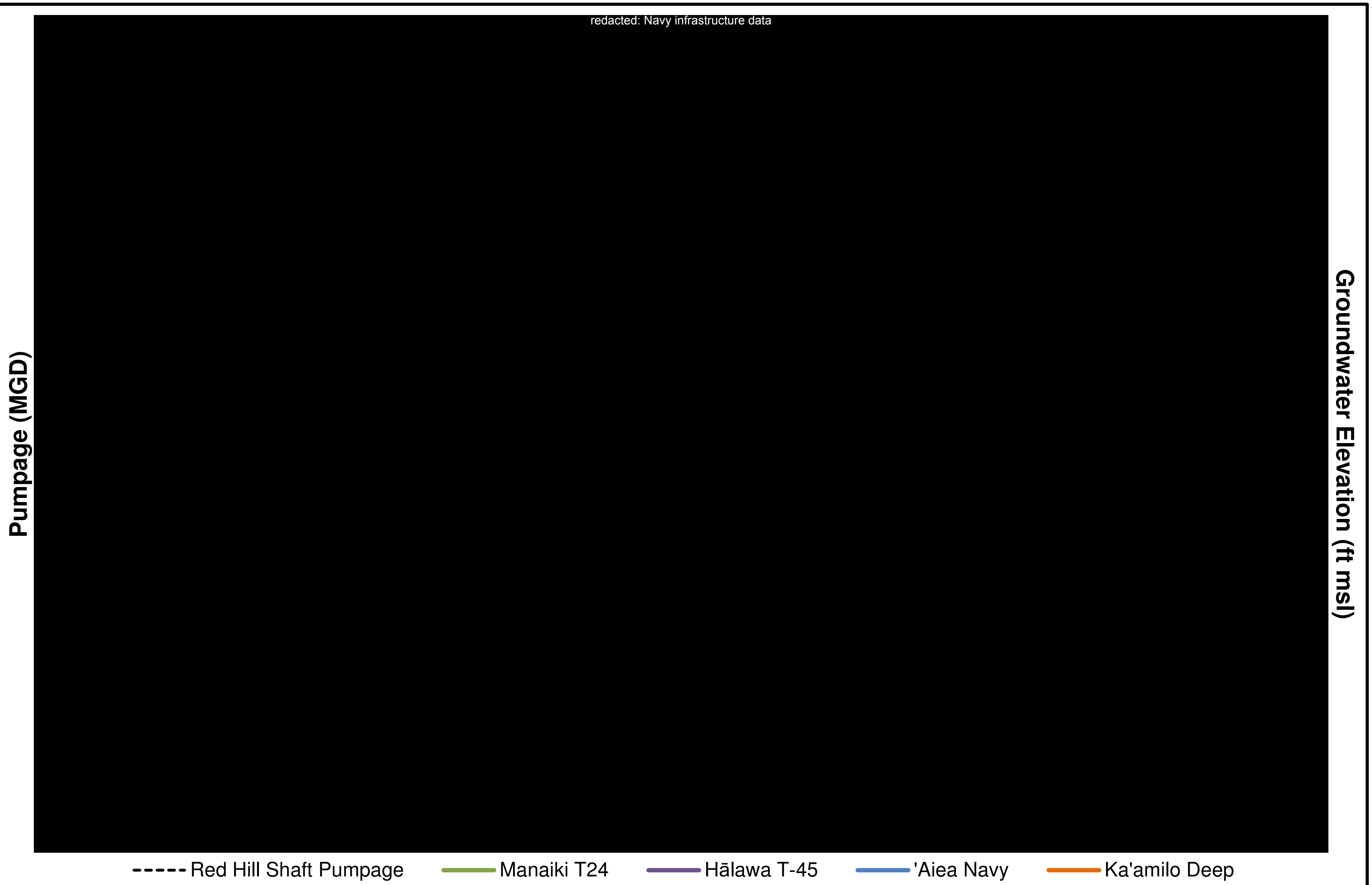


Figure 3.2.3-2e
Impact of Pumping on Groundwater Levels - Red Hill Shaft, 2015 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

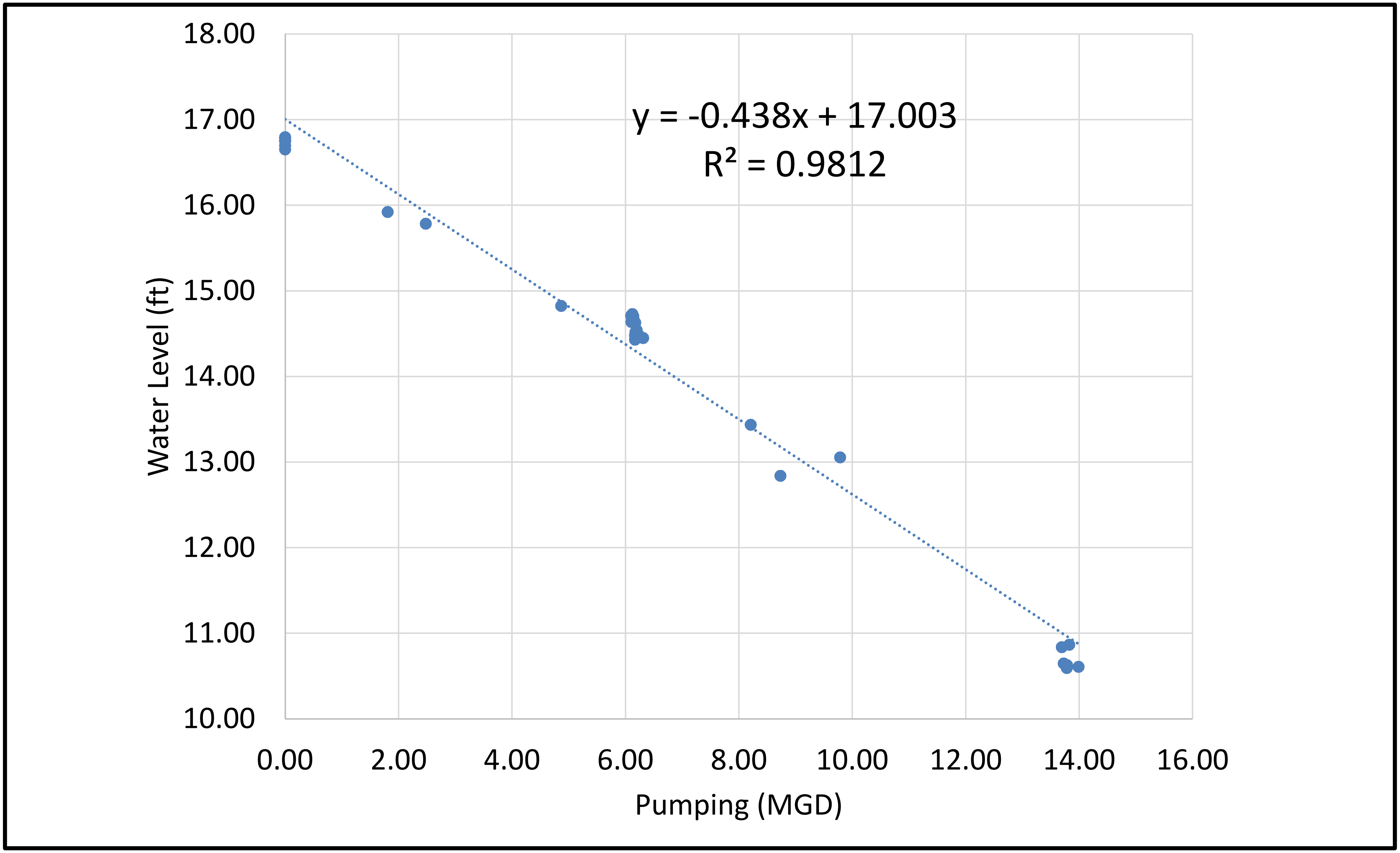


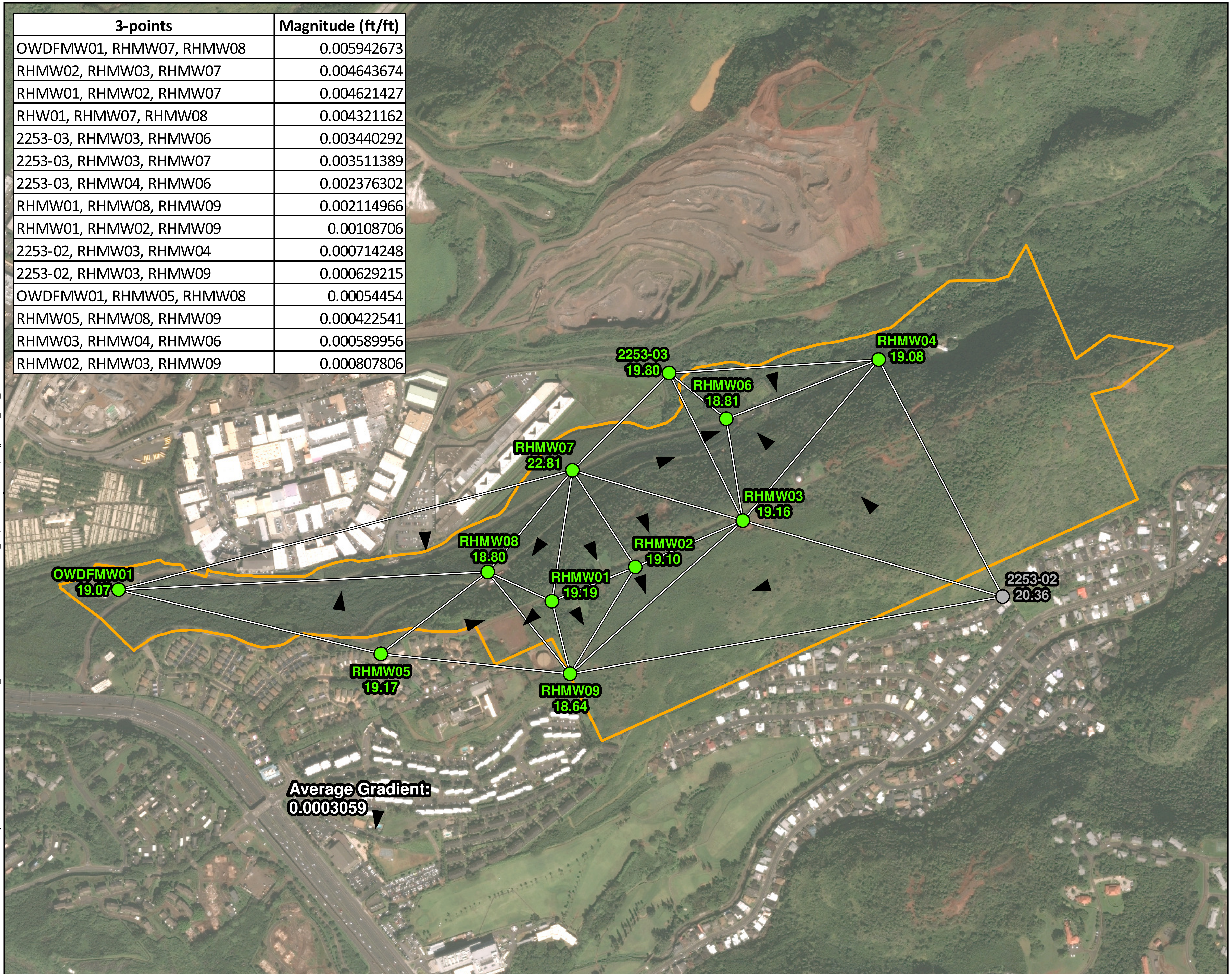
Figure 3.3.2-1
Impact of Withdrawals on Water Levels in Hālawa Shaft
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

redacted: Navy infrastructure data

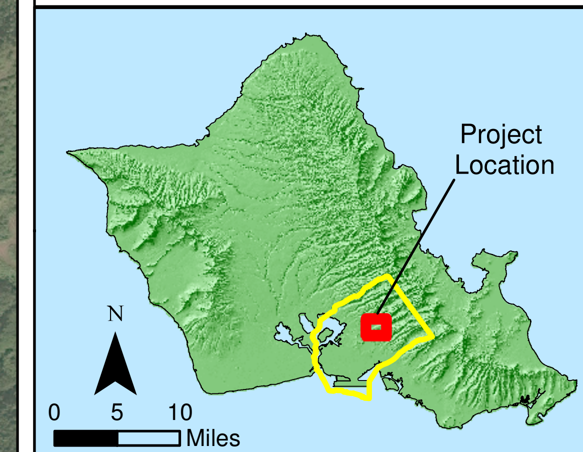
[redacted]

Figure 3.3.3-1
Impact of Withdrawals on Water Levels in Red Hill Shaft
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

3-points	Magnitude (ft/ft)
OWDFMW01, RHMW07, RHMW08	0.005942673
RHMW02, RHMW03, RHMW07	0.004643674
RHMW01, RHMW02, RHMW07	0.004621427
RHW01, RHMW07, RHMW08	0.004321162
2253-03, RHMW03, RHMW06	0.003440292
2253-03, RHMW03, RHMW07	0.003511389
2253-03, RHMW04, RHMW06	0.002376302
RHMW01, RHMW08, RHMW09	0.002114966
RHMW01, RHMW02, RHMW09	0.00108706
2253-02, RHMW03, RHMW04	0.000714248
2253-02, RHMW03, RHMW09	0.000629215
OWDFMW01, RHMW05, RHMW08	0.00054454
RHMW05, RHMW08, RHMW09	0.000422541
RHMW03, RHMW04, RHMW06	0.000589956
RHMW02, RHMW03, RHMW09	0.000807806



Location Map



Legend

- 20.00 Groundwater Monitoring Well - head value in feet above mean sea level
- 20.36 Use Unknown - head value in feet above mean sea level
- Three Point Grid
- Groundwater Gradient
- Groundwater Model Area
- Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Average groundwater gradient was calculated using EPA On-Line Tools for Site Assessment: https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/gradient4plus-ns.html
4. 3-point gradients were calculated using an adapted version of: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=287064

N

0 1,000 2,000 Feet

Figure 3.4.1-1
Local Groundwater Gradients for November 18, 2016 Synoptic Study
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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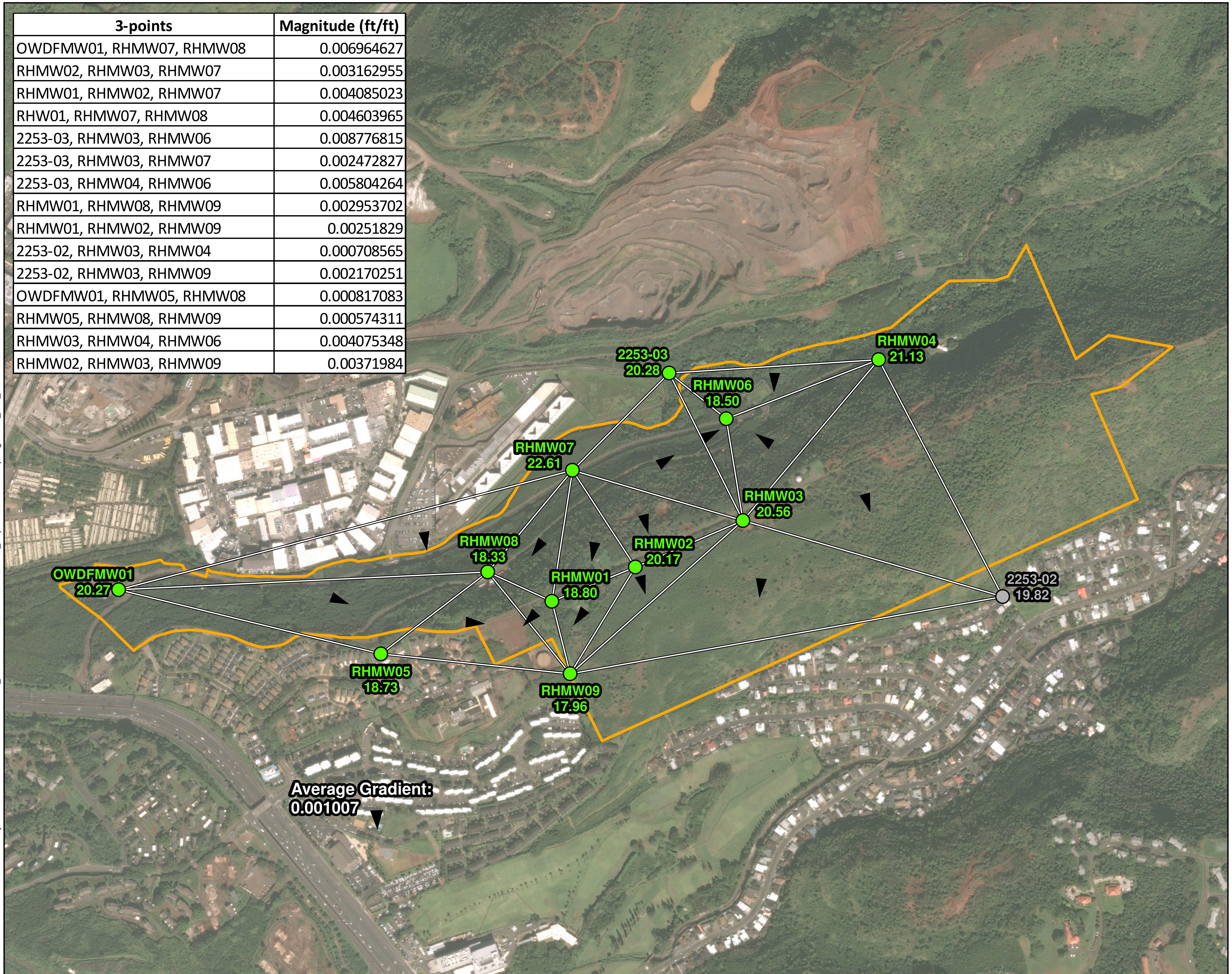
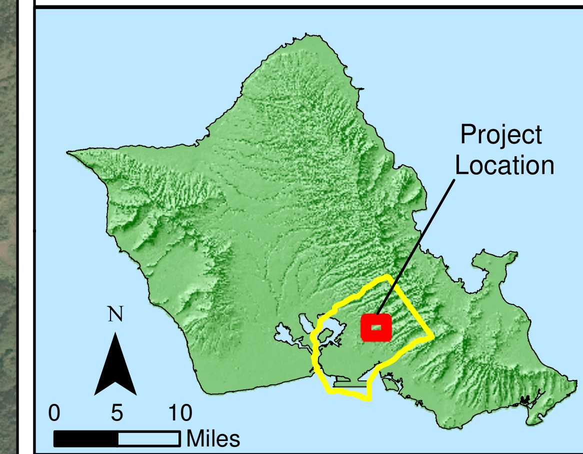
3-points	Magnitude (ft/ft)
OWDFMW01, RHMW07, RHMW08	0.006964627
RHMW02, RHMW03, RHMW07	0.003162955
RHMW01, RHMW02, RHMW07	0.004085023
RHW01, RHMW07, RHMW08	0.004603965
2253-03, RHMW03, RHMW06	0.008776815
2253-03, RHMW03, RHMW07	0.002472827
2253-03, RHMW04, RHMW06	0.005804264
RHMW01, RHMW08, RHMW09	0.002953702
RHMW01, RHMW02, RHMW09	0.00251829
2253-02, RHMW03, RHMW04	0.000708565
2253-02, RHMW03, RHMW09	0.002170251
OWDFMW01, RHMW05, RHMW08	0.000817083
RHMW05, RHMW08, RHMW09	0.000574311
RHMW03, RHMW04, RHMW06	0.004075348
RHMW02, RHMW03, RHMW09	0.00371984



Location Map



Legend

- 20.00 Groundwater Monitoring Well - head value in feet above mean sea level
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- Three Point Grid
- Groundwater Gradient
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- Red Hill Facility Boundary

Notes

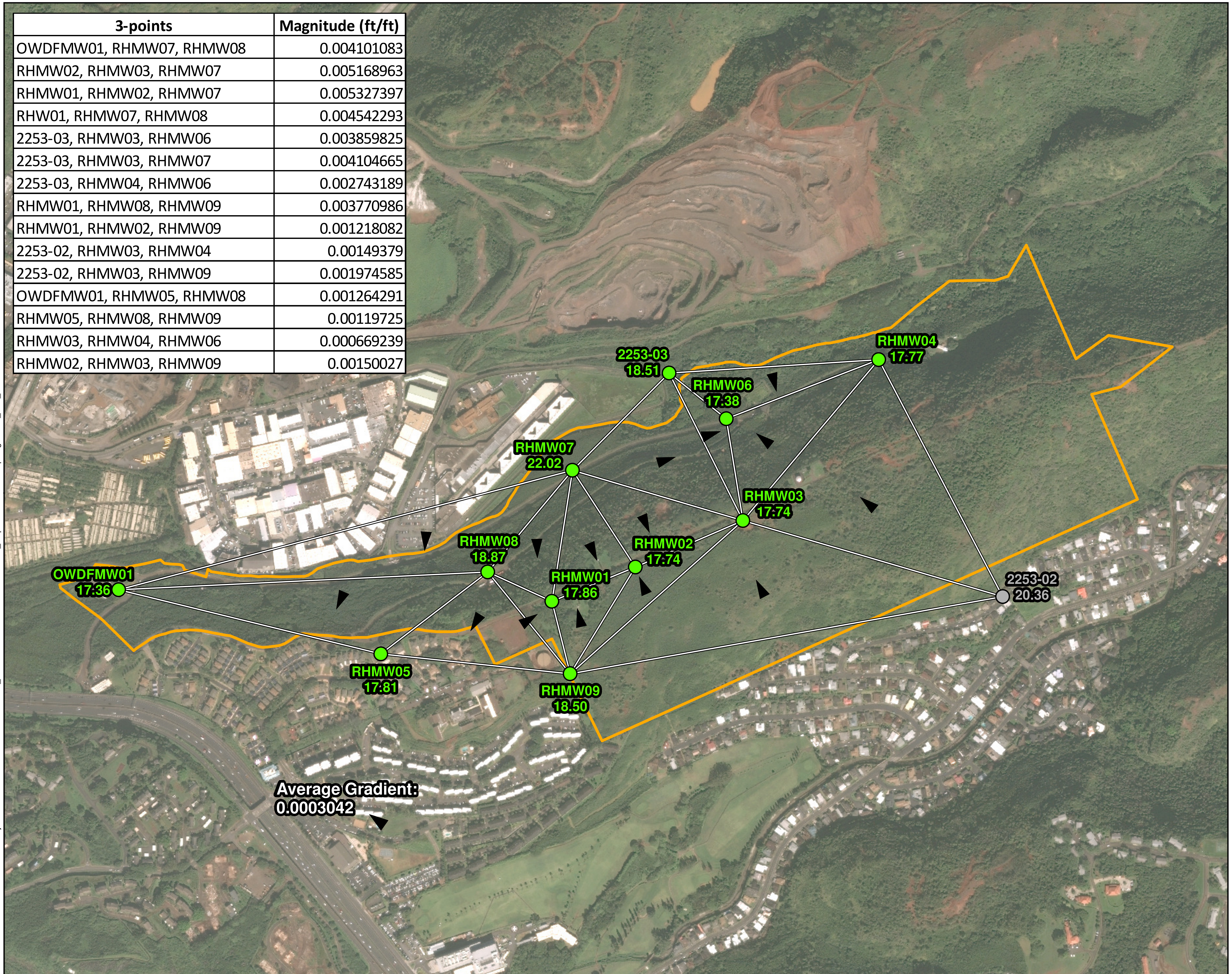
1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Average groundwater gradient was calculated using EPA On-Line Tools for Site Assessment: https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/gradient4plus-ns.html
4. 3-point gradients were calculated using an adapted version of: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=287064

N

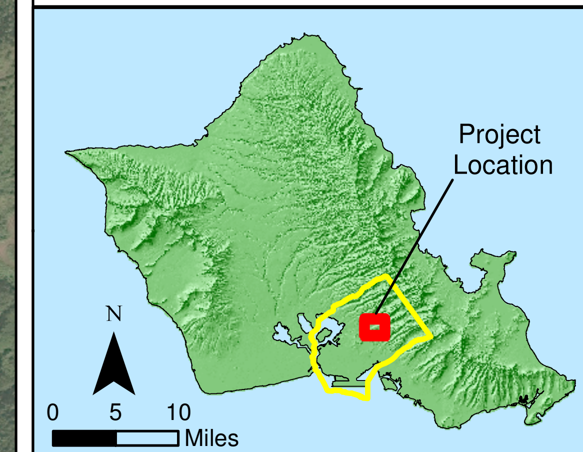
0 1,000 2,000 Feet

Figure 3.4.1-2
Projected Local Groundwater Gradients for Annual Average 2006 Conditions
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

3-points	Magnitude (ft/ft)
OWDFMW01, RHMW07, RHMW08	0.004101083
RHMW02, RHMW03, RHMW07	0.005168963
RHMW01, RHMW02, RHMW07	0.005327397
RHW01, RHMW07, RHMW08	0.004542293
2253-03, RHMW03, RHMW06	0.003859825
2253-03, RHMW03, RHMW07	0.004104665
2253-03, RHMW04, RHMW06	0.002743189
RHMW01, RHMW08, RHMW09	0.003770986
RHMW01, RHMW02, RHMW09	0.001218082
2253-02, RHMW03, RHMW04	0.00149379
2253-02, RHMW03, RHMW09	0.001974585
OWDFMW01, RHMW05, RHMW08	0.001264291
RHMW05, RHMW08, RHMW09	0.00119725
RHMW03, RHMW04, RHMW06	0.000669239
RHMW02, RHMW03, RHMW09	0.00150027



Location Map



Legend

- 20.00 Groundwater Monitoring Well - head value in feet above mean sea level
- 20.36 Use Unknown - head value in feet above mean sea level
- Three Point Grid
- Groundwater Gradient
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Notes

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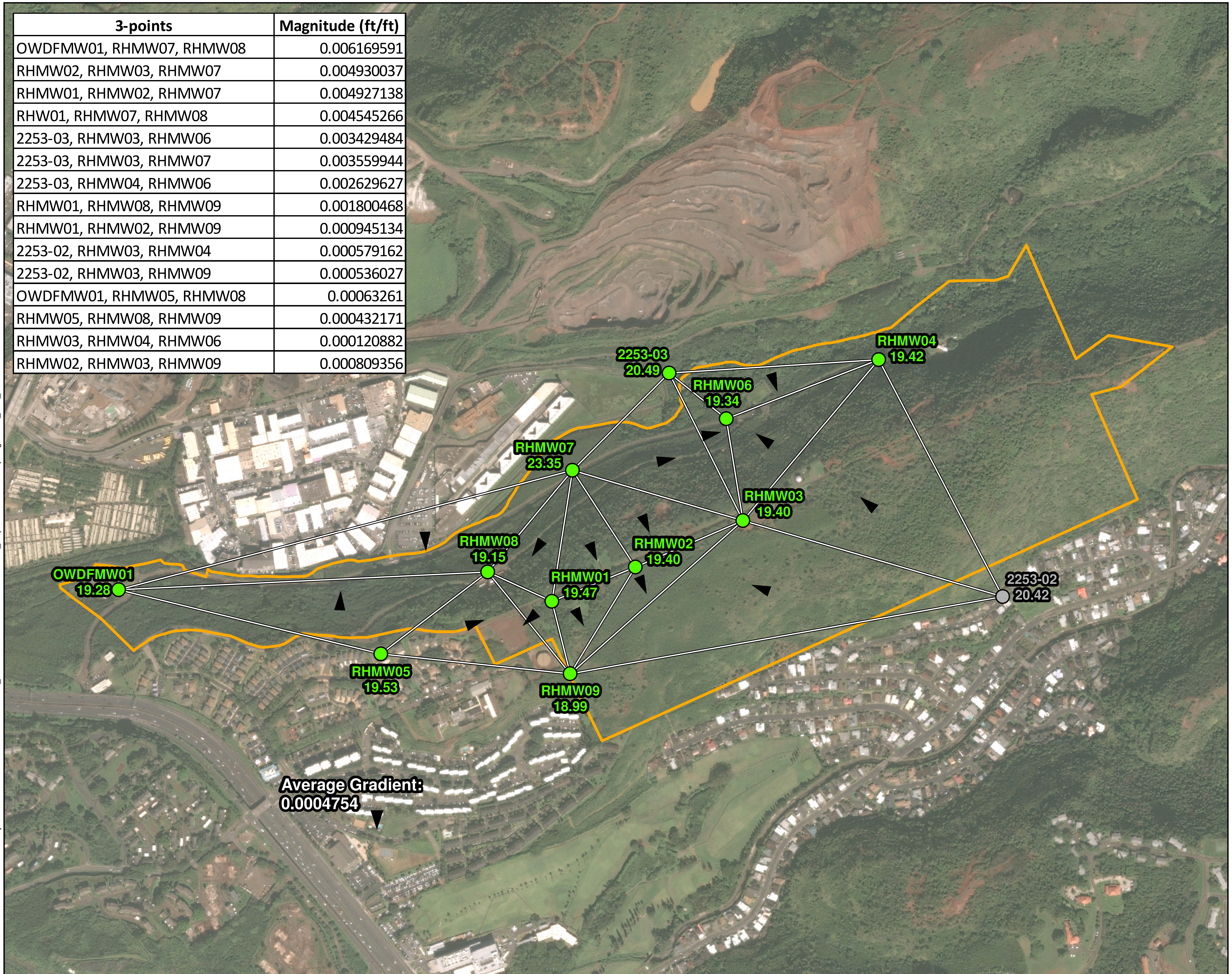
4. 3-point gradients were calculated using an adapted version of: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=287064

N

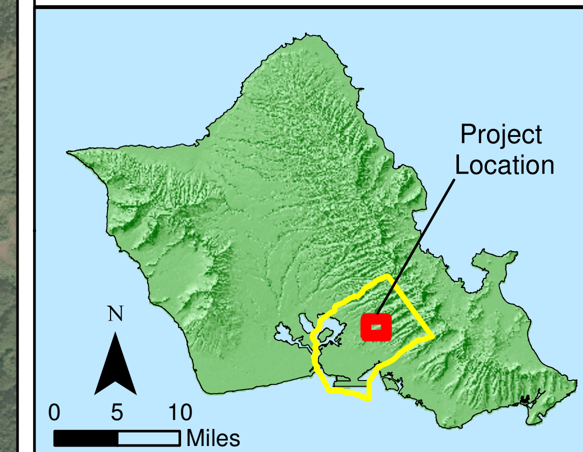
0 1,000 2,000 Feet

Figure 3.4.1-3
Projected Local Groundwater Gradients for Annual Average 2015 Conditions
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

3-points	Magnitude (ft/ft)
OWDFMW01, RHMW07, RHMW08	0.006169591
RHMW02, RHMW03, RHMW07	0.004930037
RHMW01, RHMW02, RHMW07	0.004927138
RHW01, RHMW07, RHMW08	0.004545266
2253-03, RHMW03, RHMW06	0.003429484
2253-03, RHMW03, RHMW07	0.003559944
2253-03, RHMW04, RHMW06	0.002629627
RHMW01, RHMW08, RHMW09	0.001800468
RHMW01, RHMW02, RHMW09	0.000945134
2253-02, RHMW03, RHMW04	0.000579162
2253-02, RHMW03, RHMW09	0.000536027
OWDFMW01, RHMW05, RHMW08	0.00063261
RHMW05, RHMW08, RHMW09	0.000432171
RHMW03, RHMW04, RHMW06	0.000120882
RHMW02, RHMW03, RHMW09	0.000809356



Location Map



Legend

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- 20.36 Use Unknown - head value in feet above mean sea level
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4. 3-point gradients were calculated using an adapted version of: https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=287064

N

0 1,000 2,000 Feet

Figure 3.4.1-4
Projected Local Groundwater Gradients for Annual Average 2017 Conditions
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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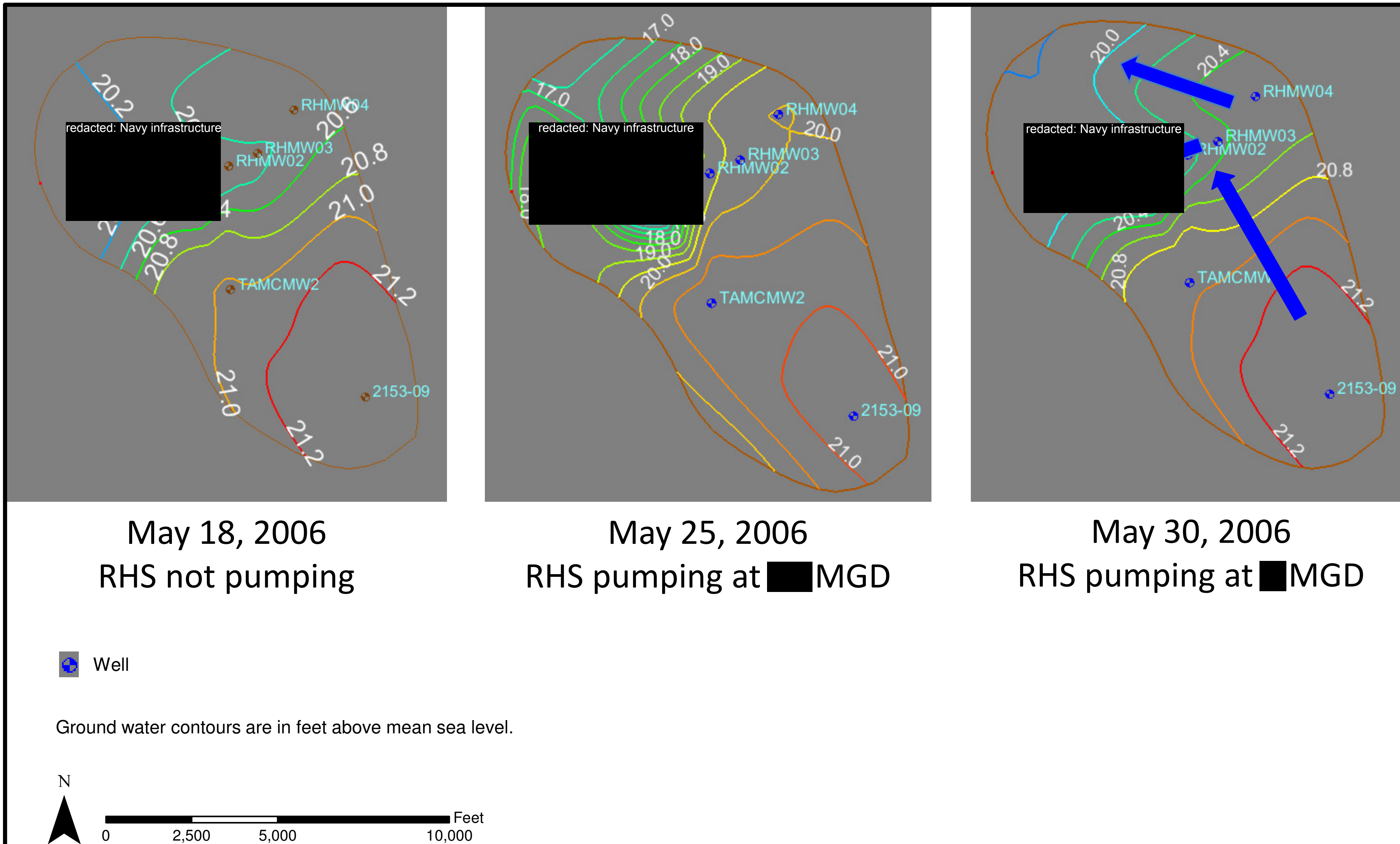


Figure 3.4.2-1
Regional Water Level Contouring at Red Hill for the 2006 Synoptic Study
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

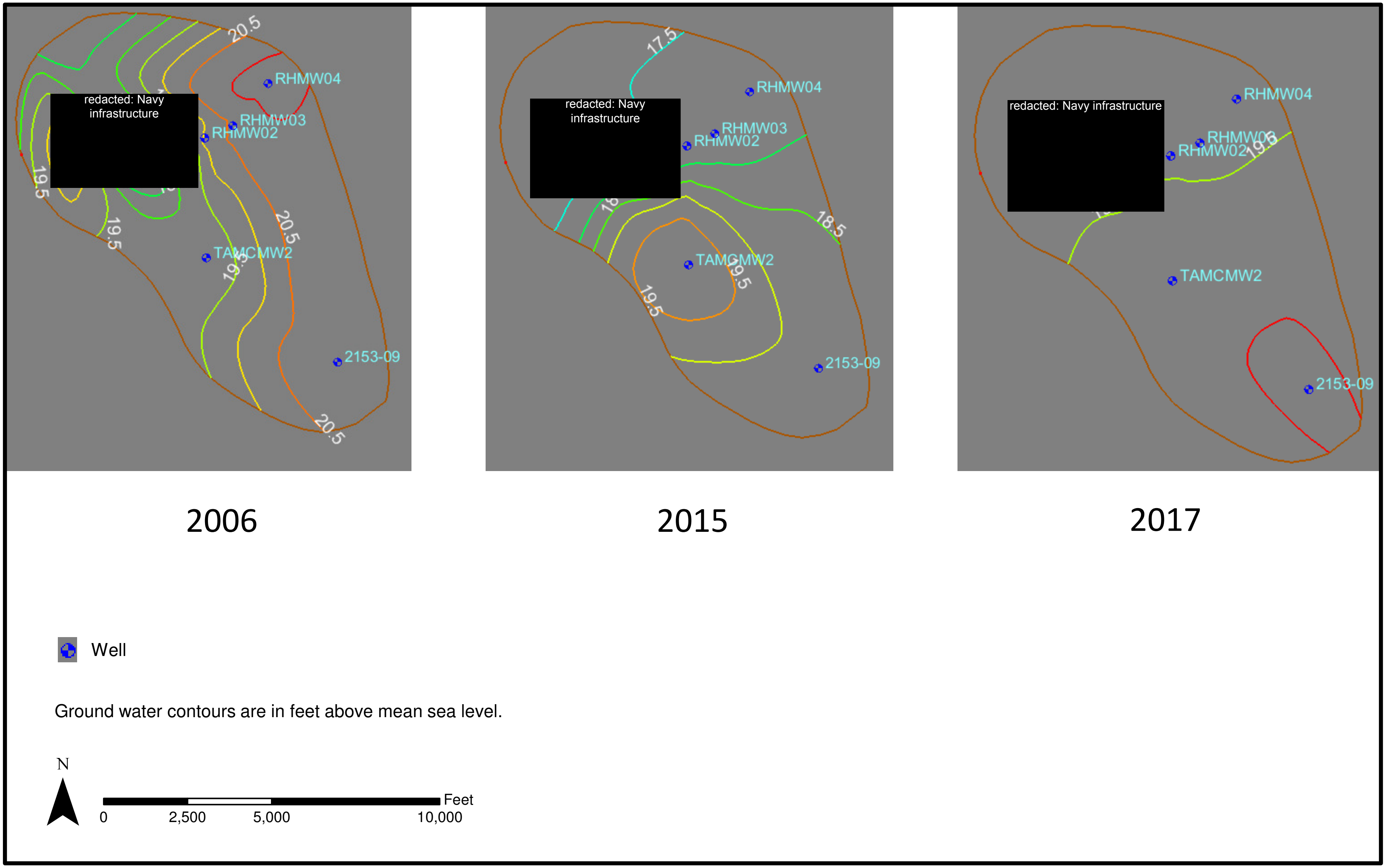
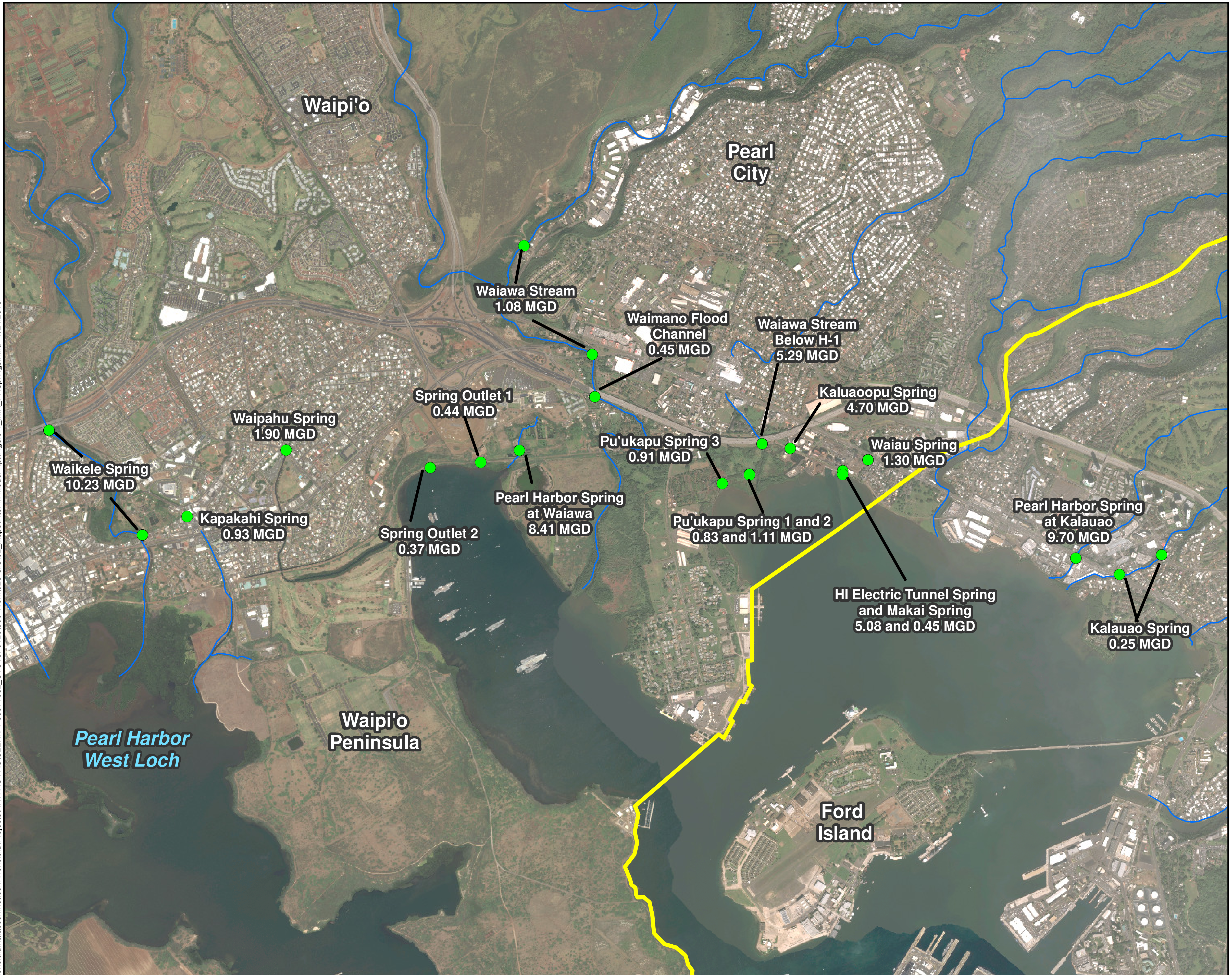
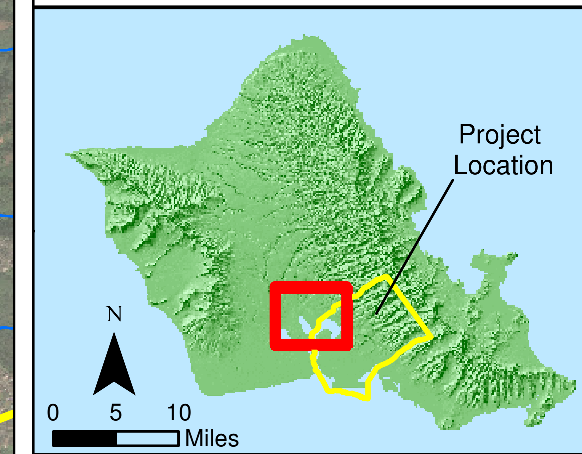


Figure 3.4.2-2
Regional Water Level Contouring at Red Hill for Average 2005, 2015, and 2017 Conditions
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

- USGS-Monitored Spring
- Stream
- Groundwater Model Area
- Regional Model (see Location Map)
- Waikele Spring 10.23 MGD — Spring Name, Average Spring Flow

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Waikele, Waiawa, and Kalauao Springs are submerged; discharge is measured by subtracting upstream stream flow from downstream flow.

N

0 2,500 5,000 Feet

Figure 3.5-1
Locations of Springs in Model Domain
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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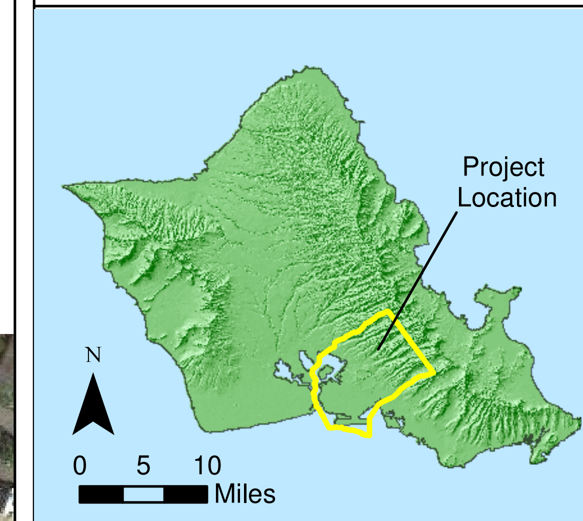
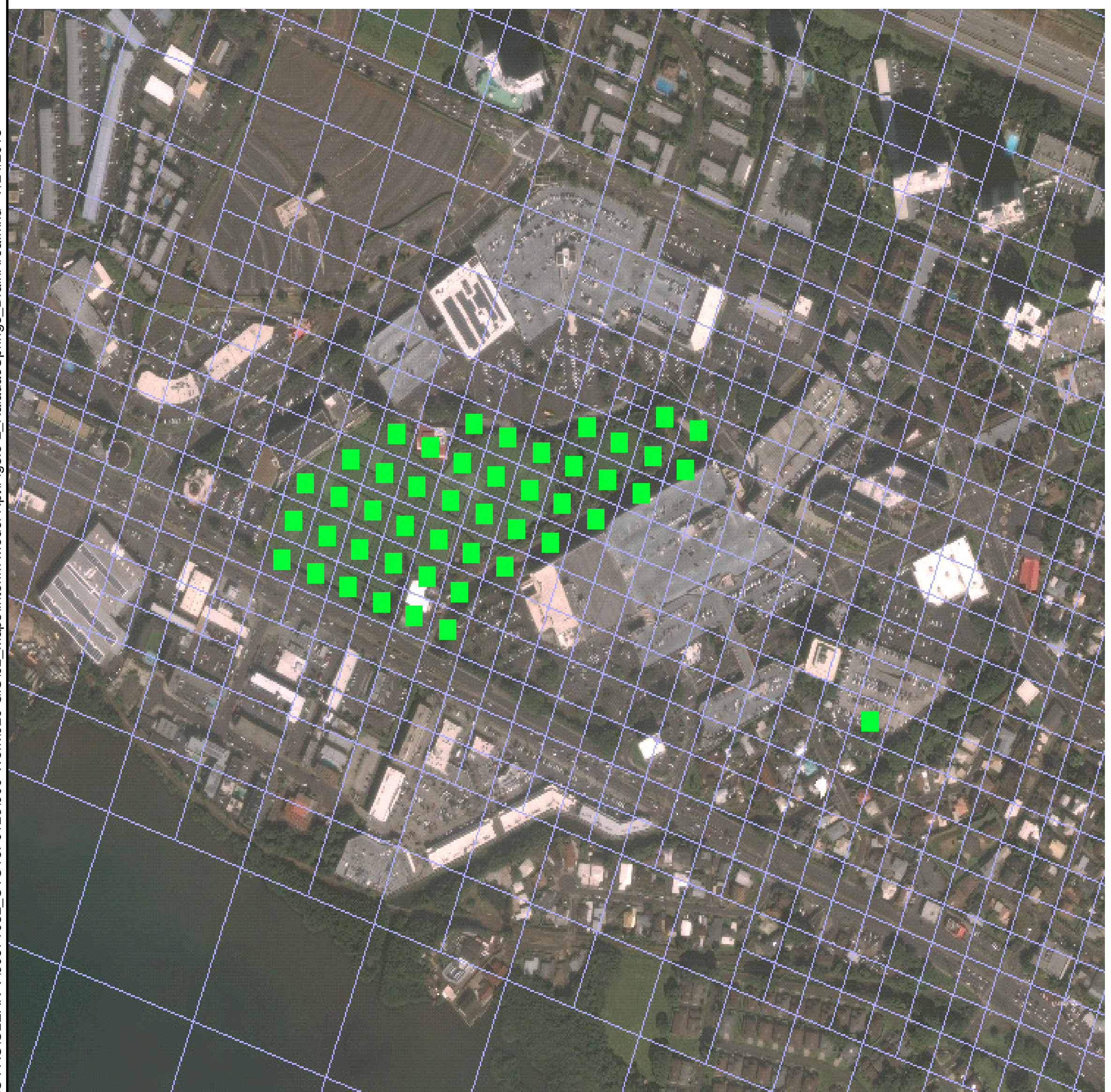
Location Map



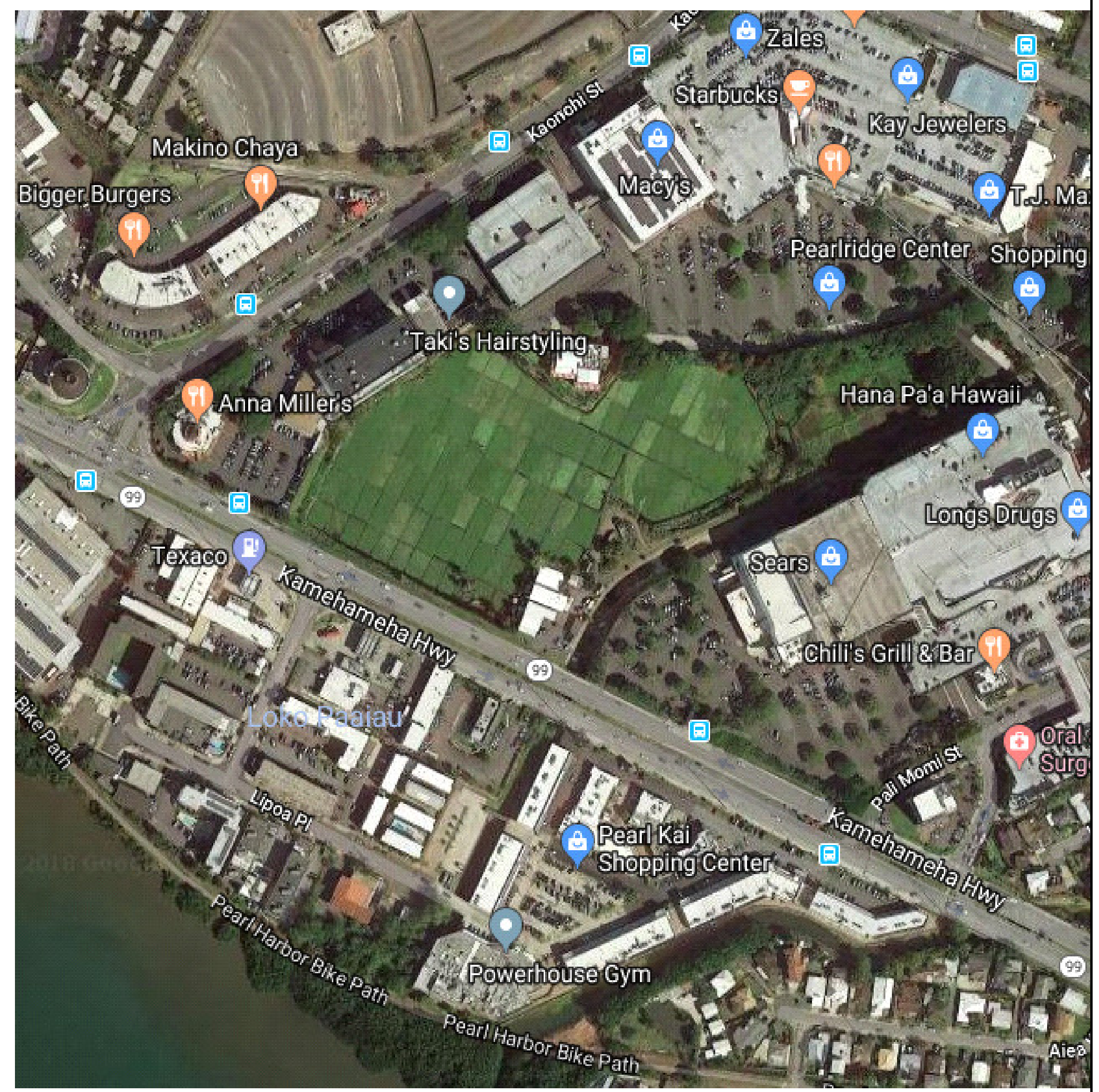
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet



N

Feet
0 250 500 1,000



N

Feet
0 250 500 1,000

Figure 3.5-2
Kalauao Springs (Watercress Farm) Drain Area
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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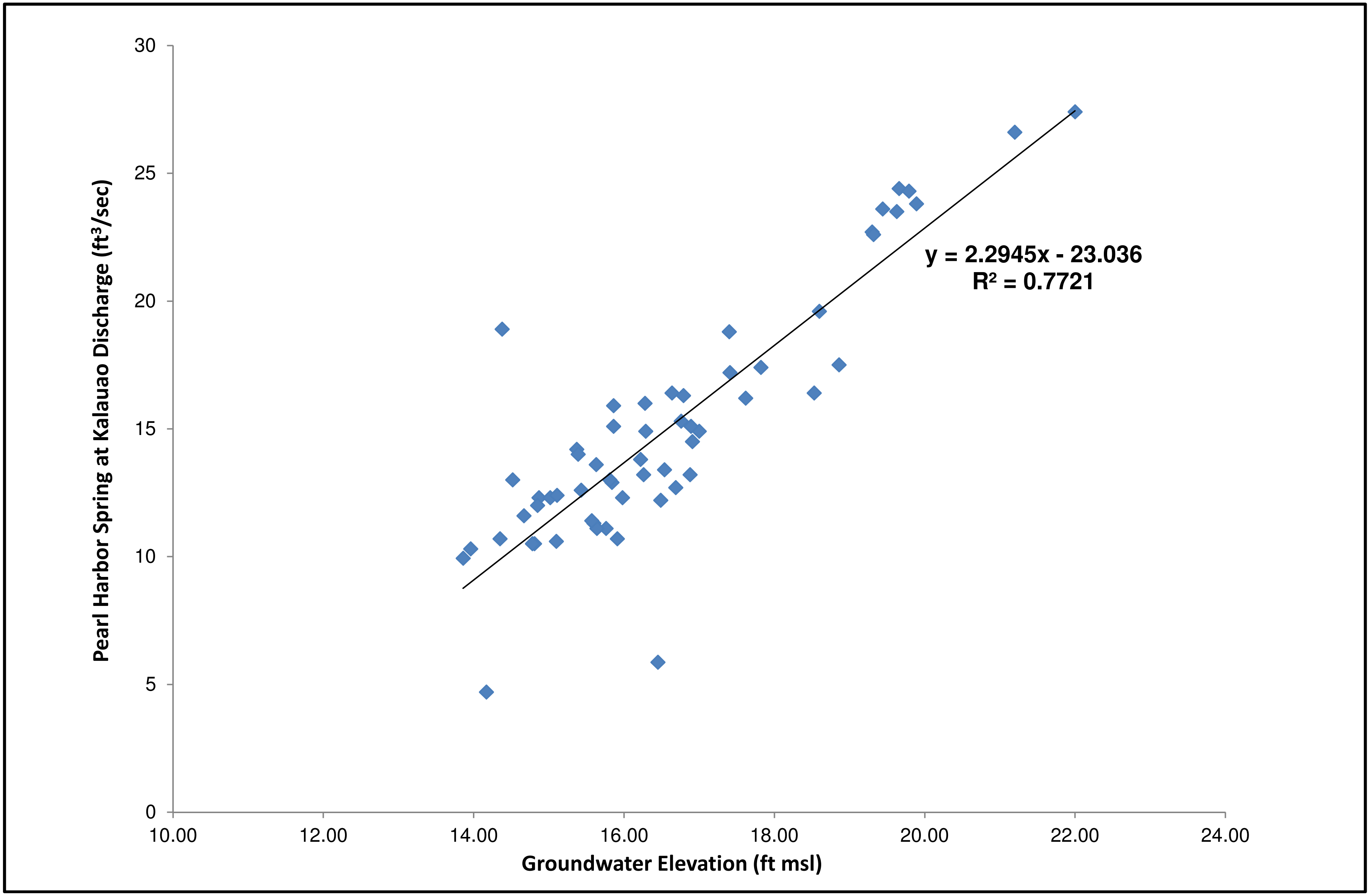

Figure 3.5-3
Relationship Between Flow at Pearl Harbor Spring at Kalauao and Water Level Elevations at Navy ʻAiea Well
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

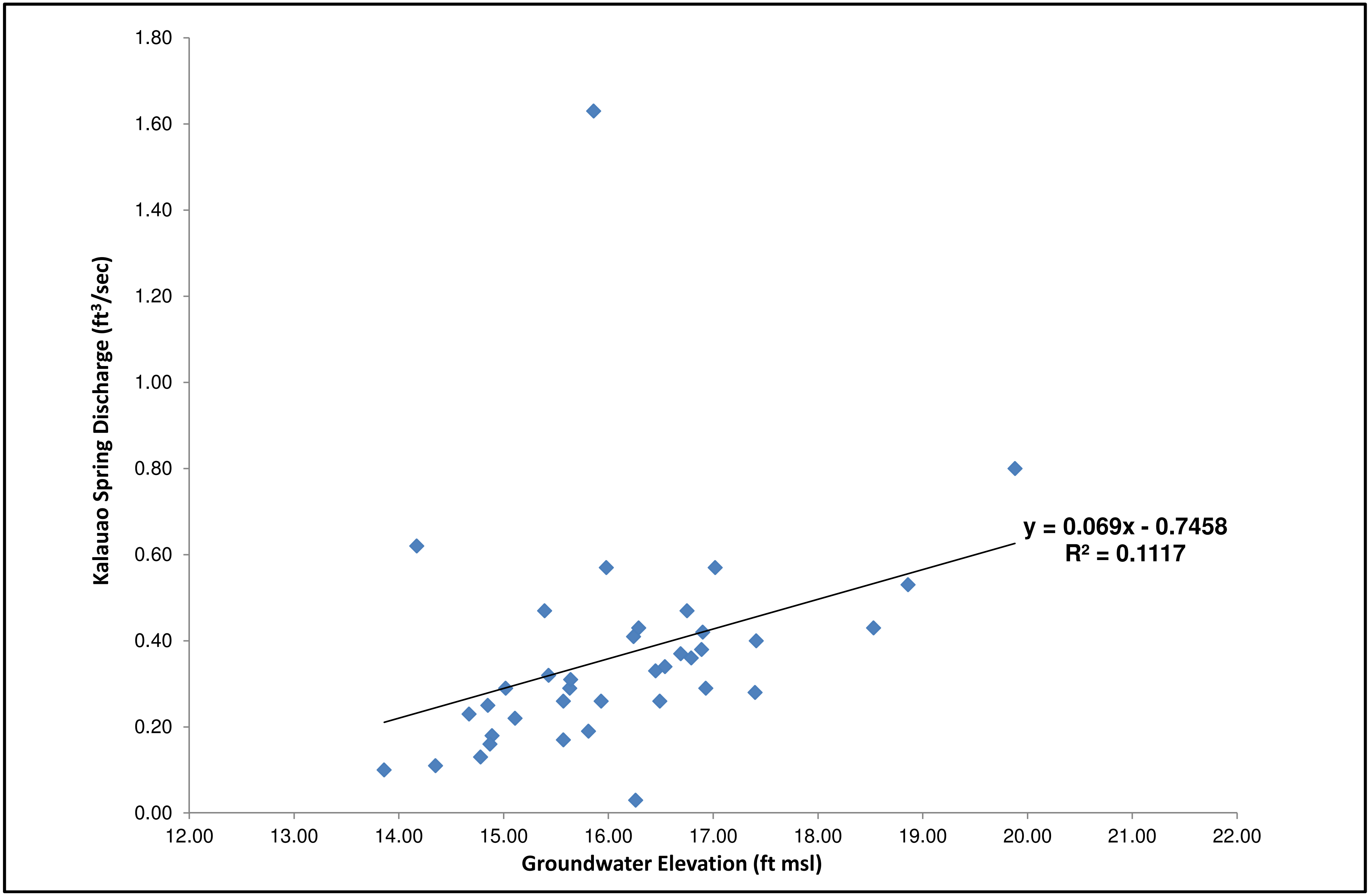

Figure 3.5-4
Relationship Between Flow at Kalauao and Water Level Elevations at Navy ‘Aiea Well
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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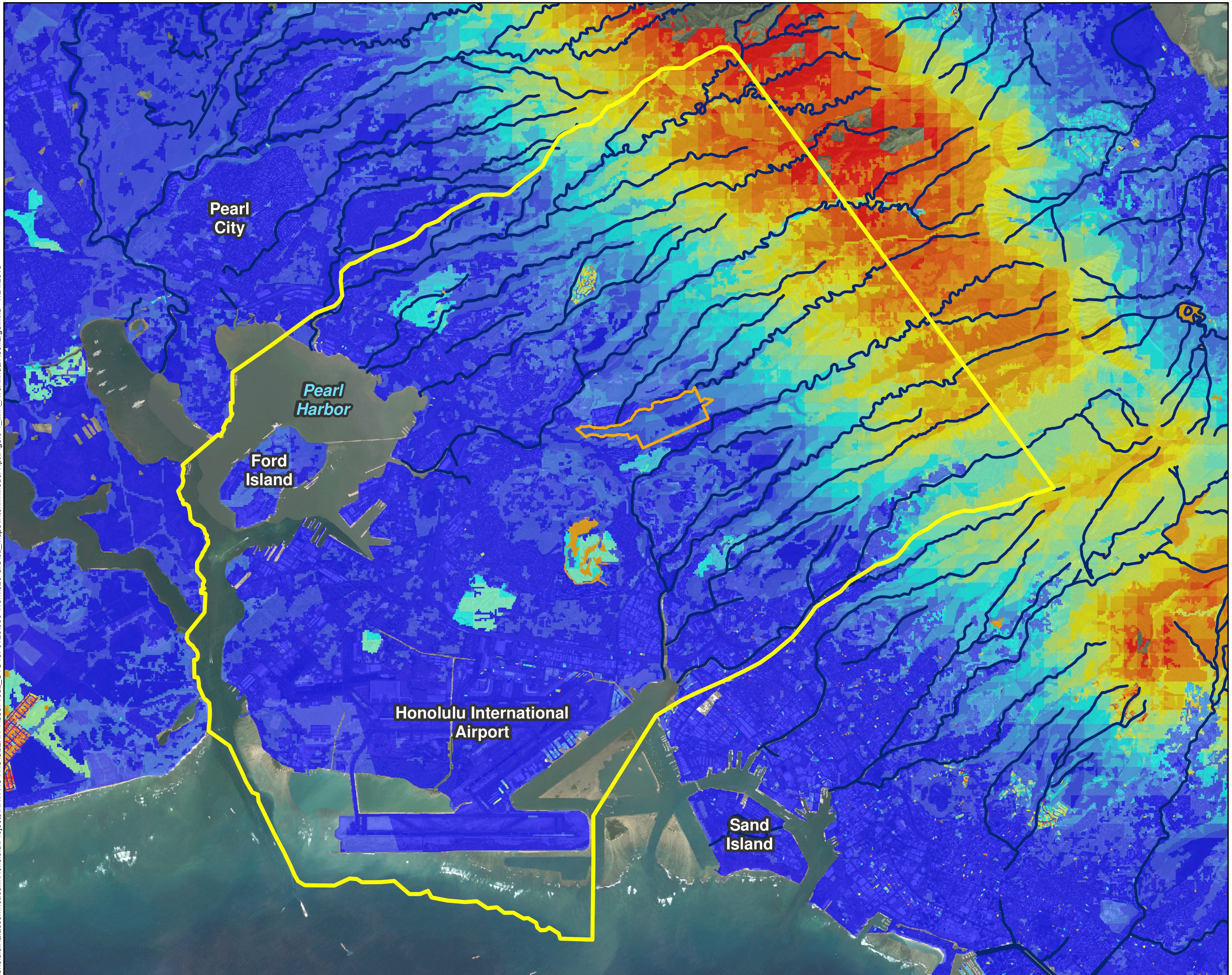
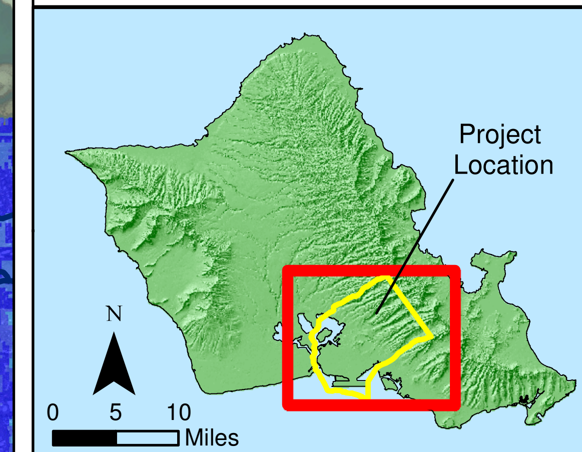


Location Map



Legend

Stream
Groundwater Model Area
Red Hill Facility Boundary

Recharge (inches/year)

0.0 - 5.0	40.0 - 45.0
5.0 - 10.0	45.0 - 50.0
10.0 - 15.0	50.0 - 55.0
15.0 - 20.0	55.0 - 60.0
20.0 - 25.0	60.0 - 65.0
25.0 - 30.0	65.0 - 70.0
30.0 - 35.0	70.0 - 75.0
35.0 - 40.0	75.0 - 80.0

Notes

1. Map projection: NAD83 State Plane Zone 3 Feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Recharge Data from Mean Annual Water-Budget Components for the Island of Oahu, Hawaii, for Average Climate Conditions, 1978-2007 Rainfall and 2010 Land Cover (Version 2.0). USGS

N

0 5,000 10,000 15,000 Feet

Figure 3.6-1
Average Annual Recharge Distribution
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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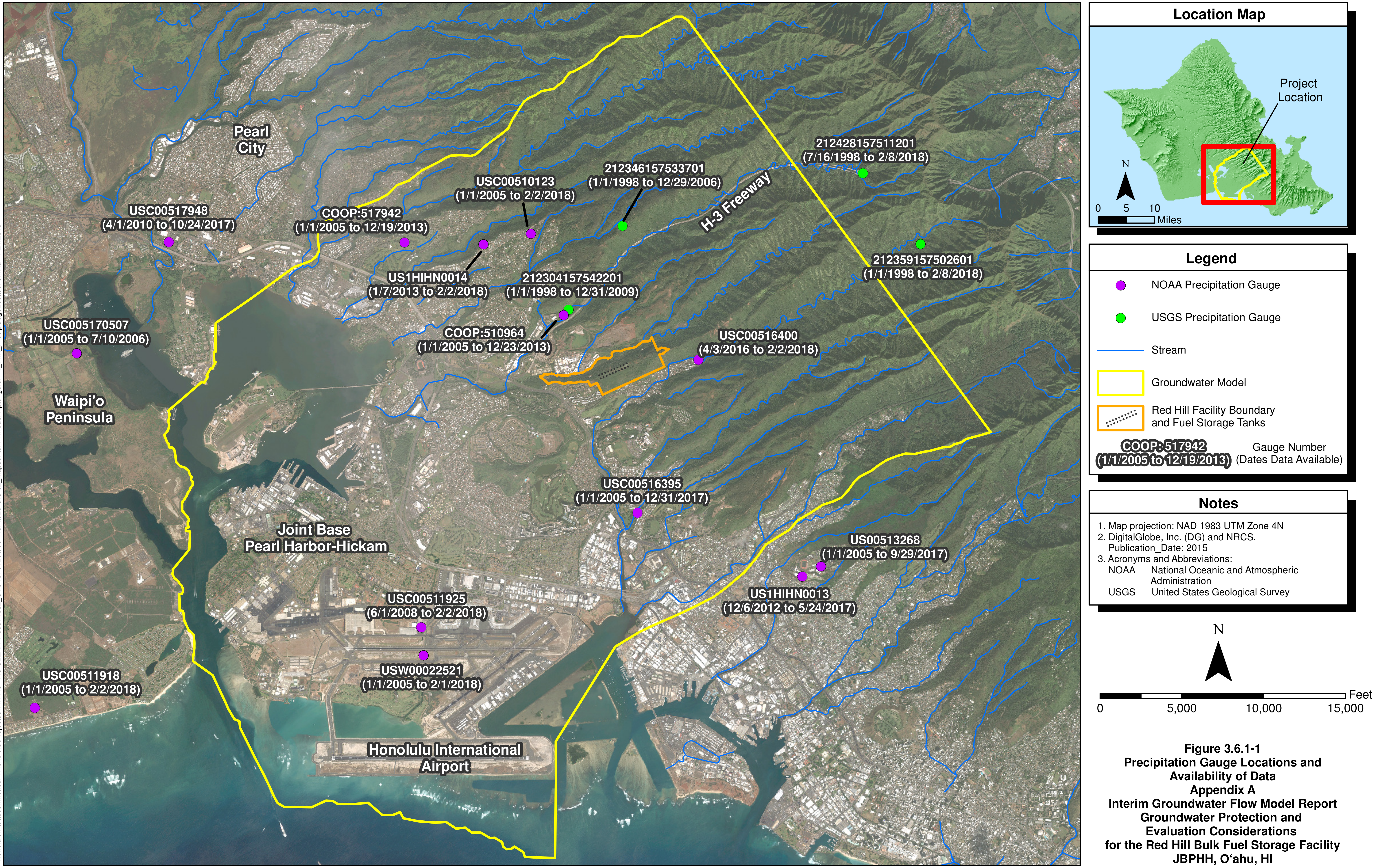
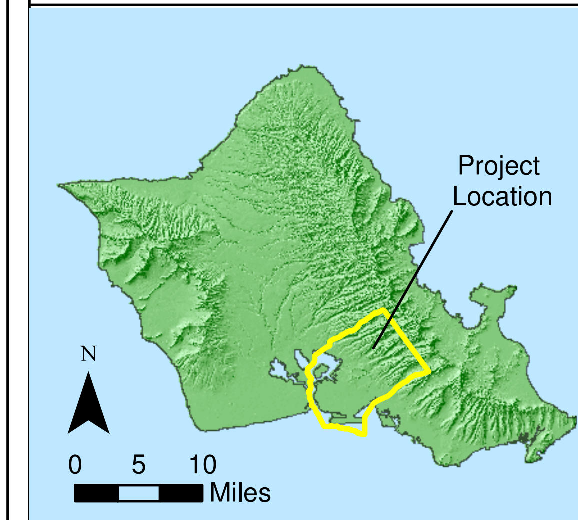


Figure 3.6.1-1
Precipitation Gauge Locations and Availability of Data
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

Location Map



Legend

Model Grids

Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 2,500 5,000 10,000 Feet

Figure 4.1-1
Model Domain and Grid
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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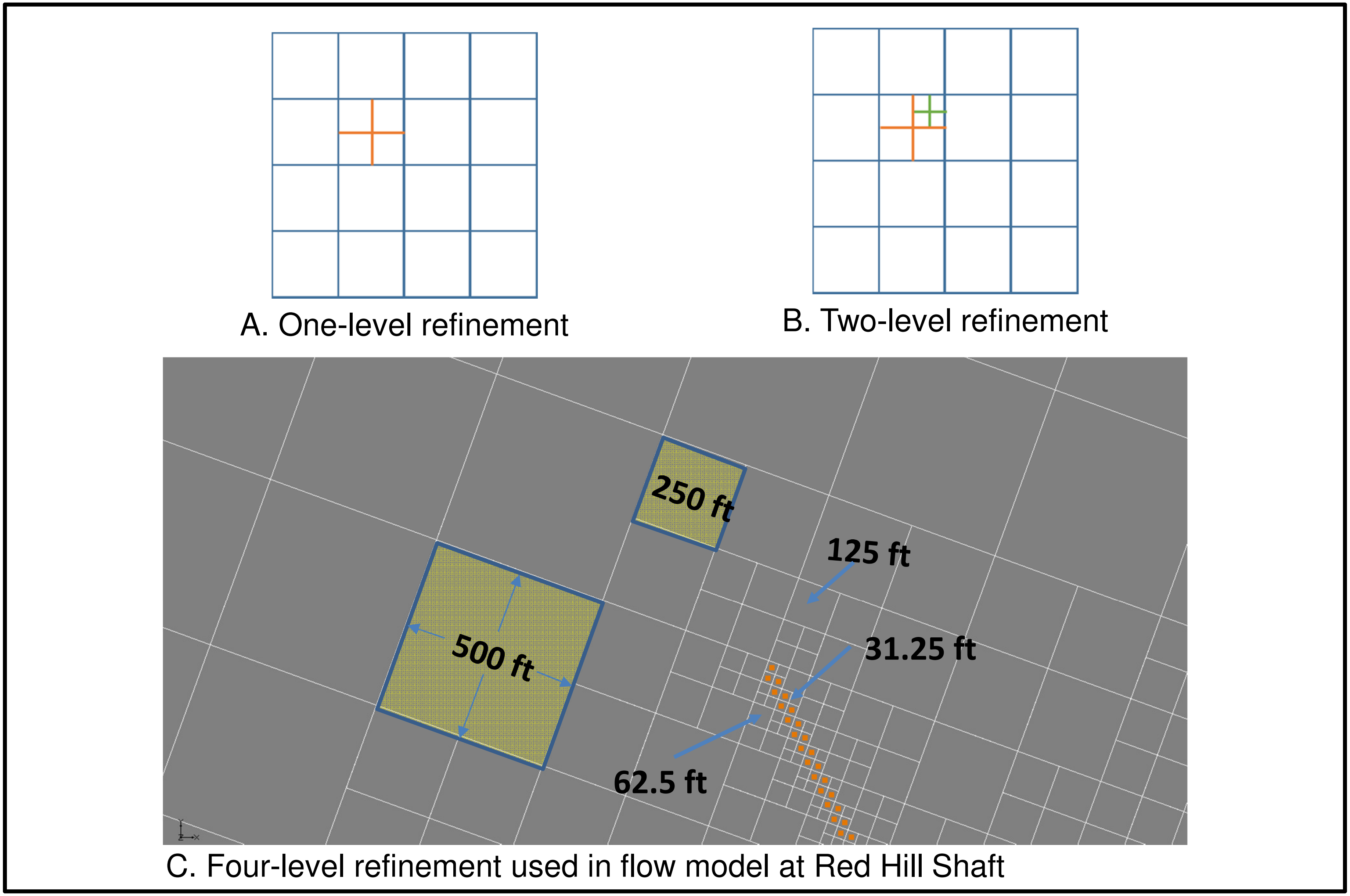

Figure 4.1-2
Unstructured (Quad) Grids and Refinement
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

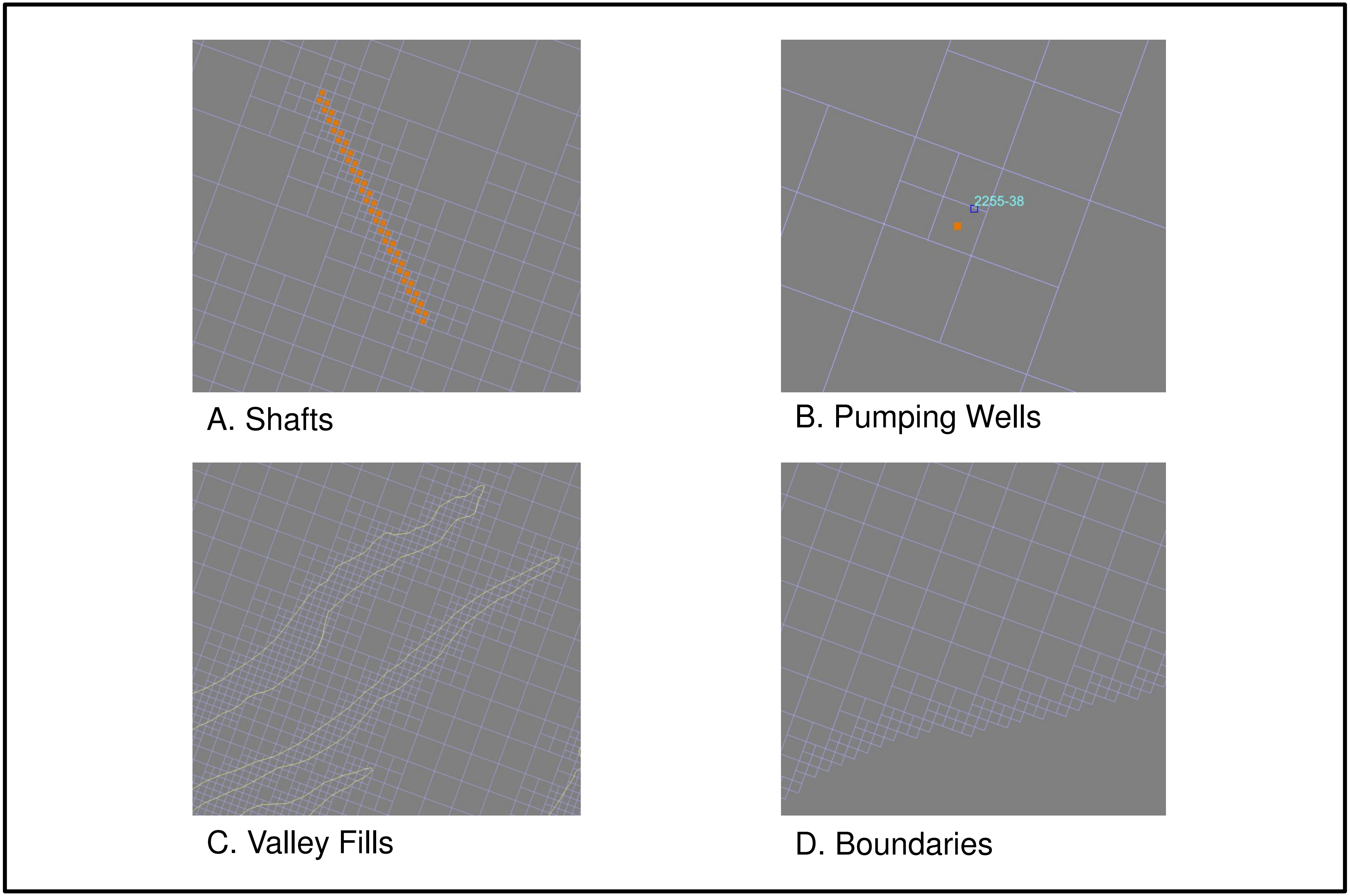

Figure 4.1-3
Modeled Quadtree Refinement Areas
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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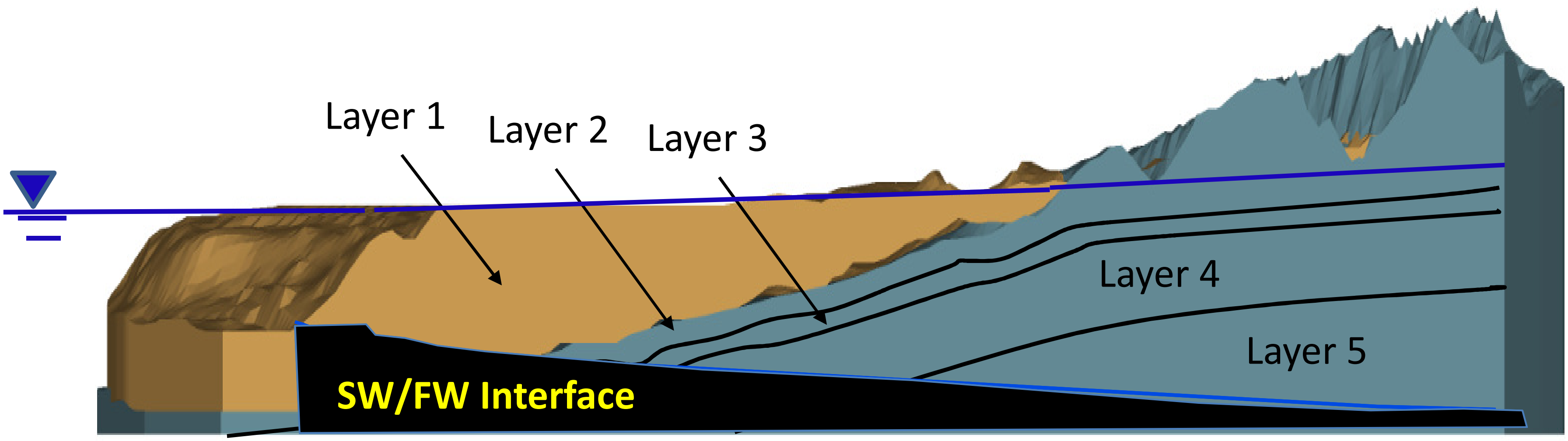
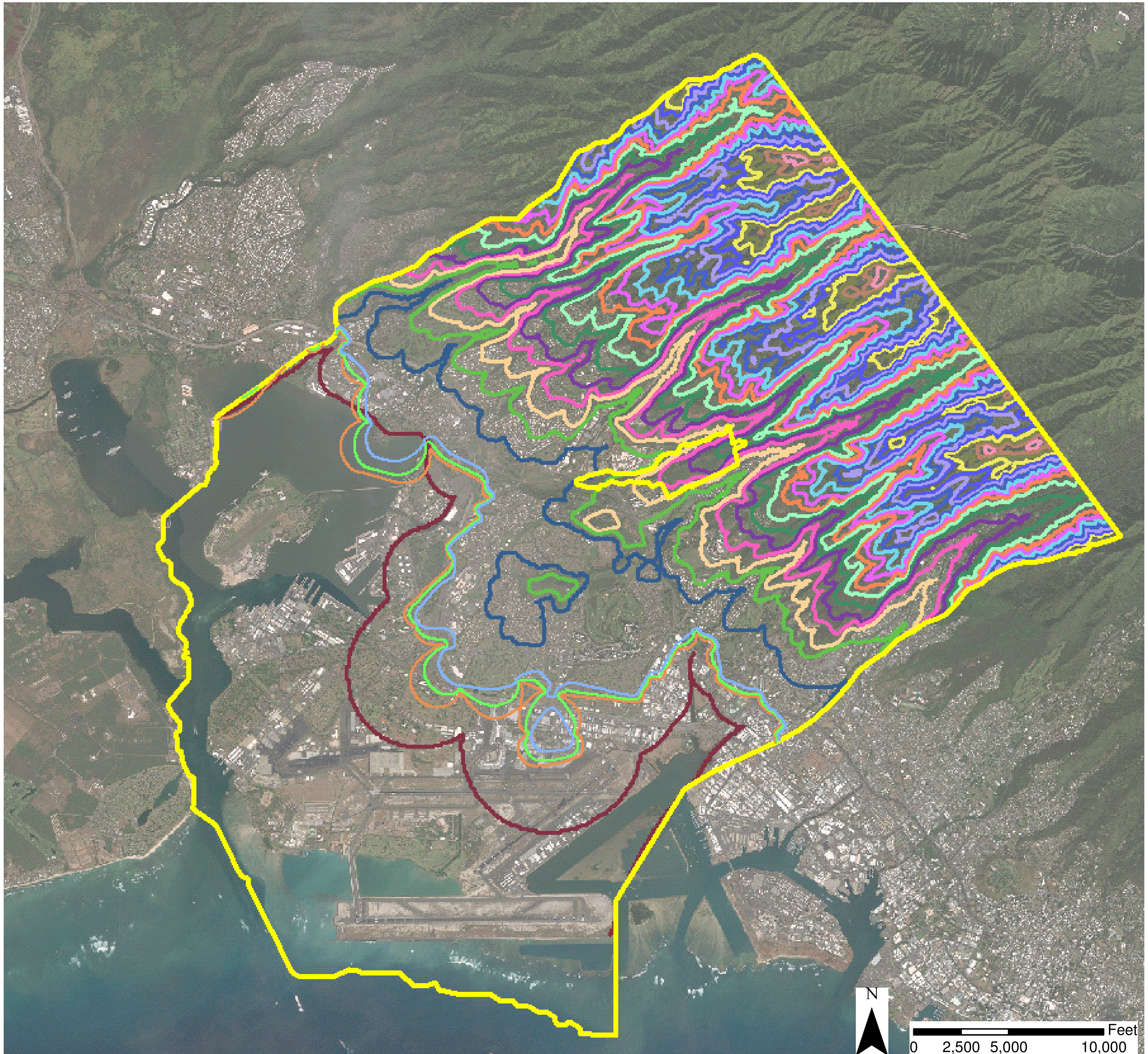
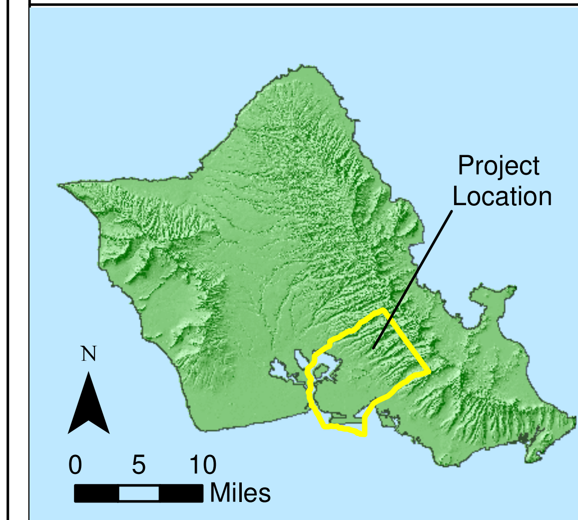


Figure 4.2-1
Schematic of Model Layering
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Surface Contours (feet above mean sea level)

- 0
- 5
- 20
- 50
- 100
- 200
- 300
- 400
- 500
- 600
- 700
- 800
- 900
- 1000
- 1100
- 1200
- 1300
- 1400
- 1500
- 1600
- 1700

Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 4.2-2
Topographic Surface Elevation
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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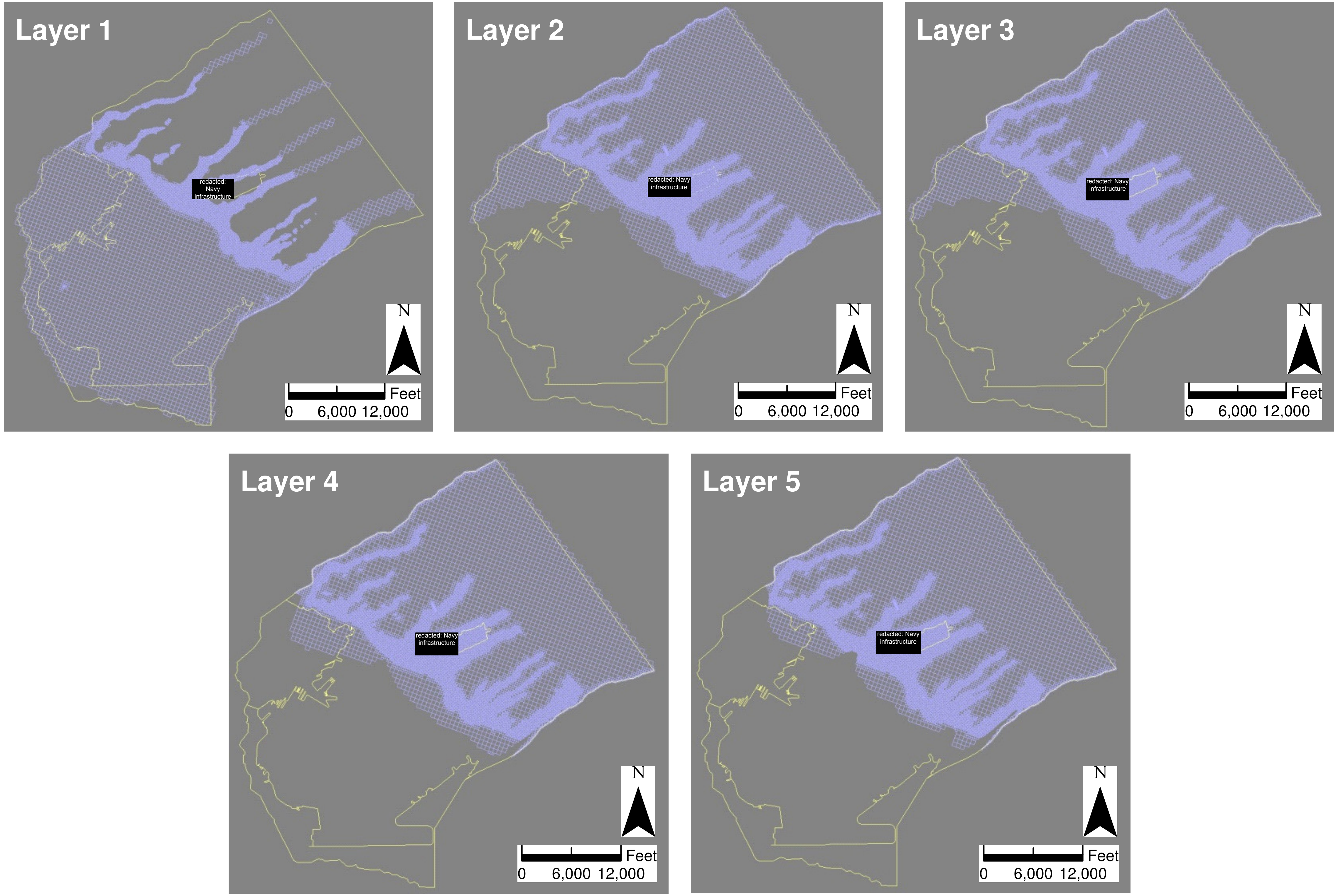
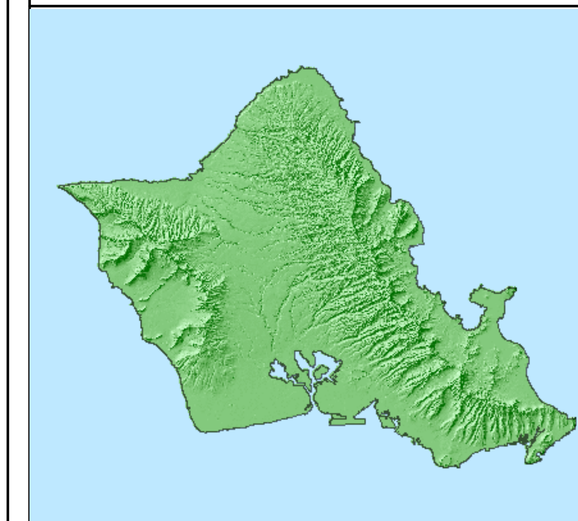


Location Map



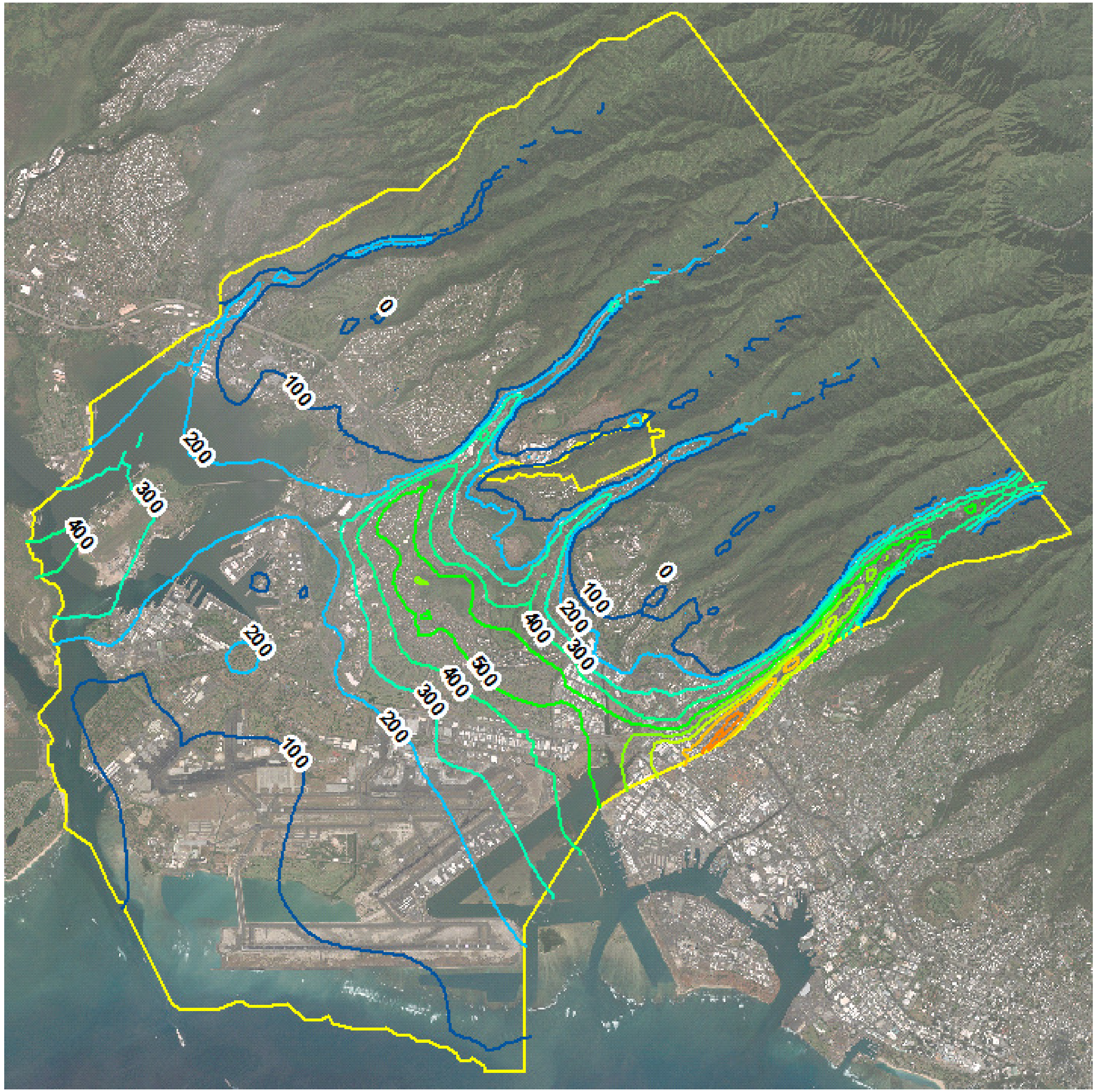
Legend

- Model Grids
- Model Boundary

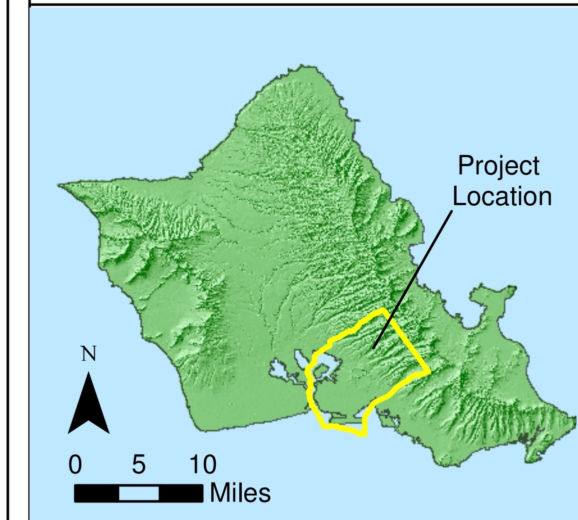
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 4.2-3
Active Areas of Model Domain
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Layer Thickness (feet)

- 1000
- 800
- 600
- 400
- 200
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 2,500 5,000 10,000 Feet

Figure 4.2-4
Thickness of Model Layer 1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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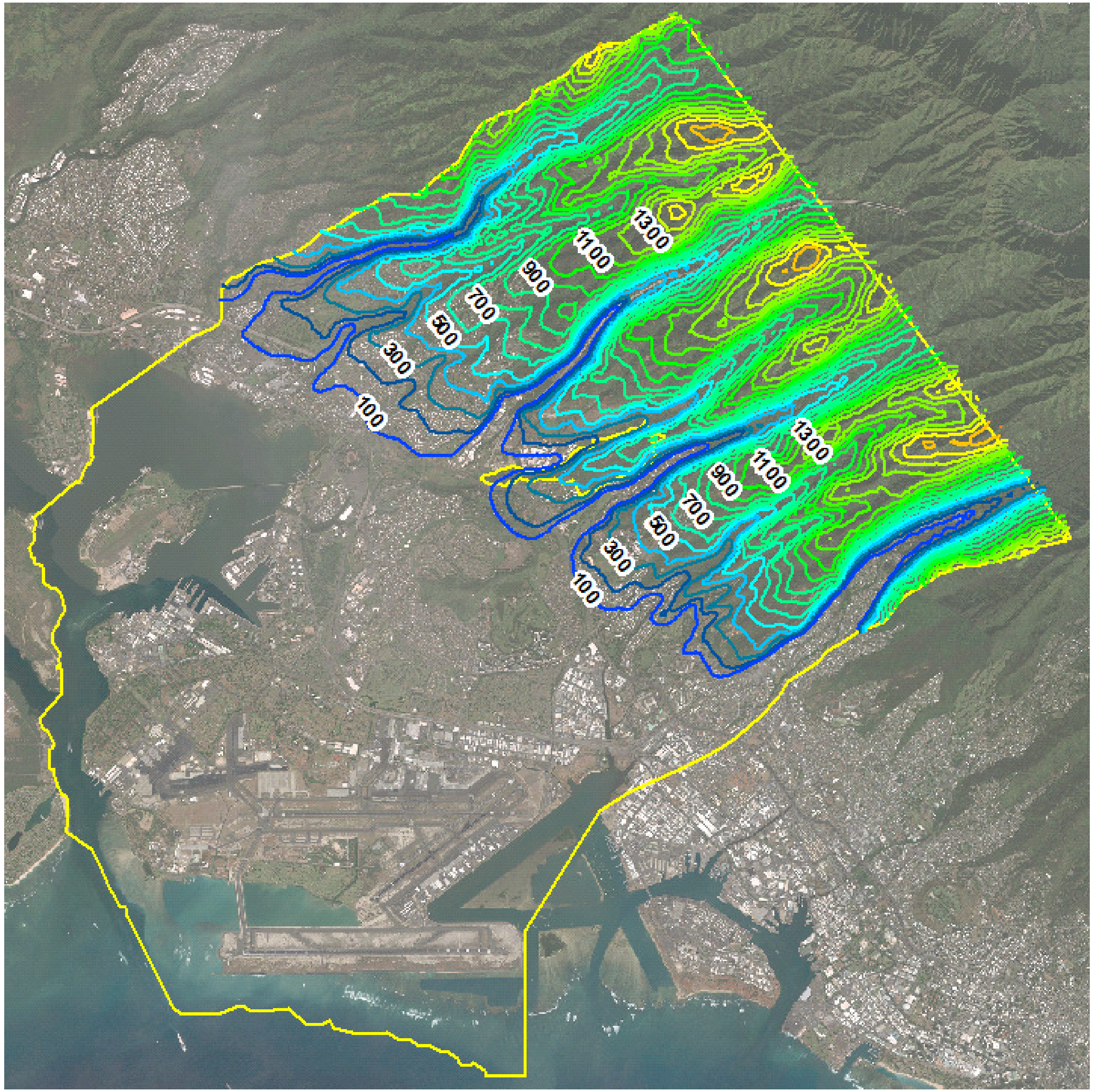
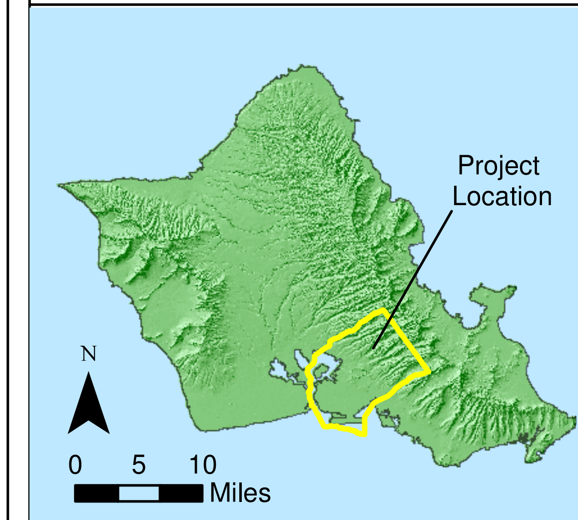


Location Map



Legend

Layer Thickness (feet)

- 2000
- 1600
- 1200
- 800
- 400
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 2,500 5,000 10,000 Feet

Figure 4.2-5
Thickness of Model Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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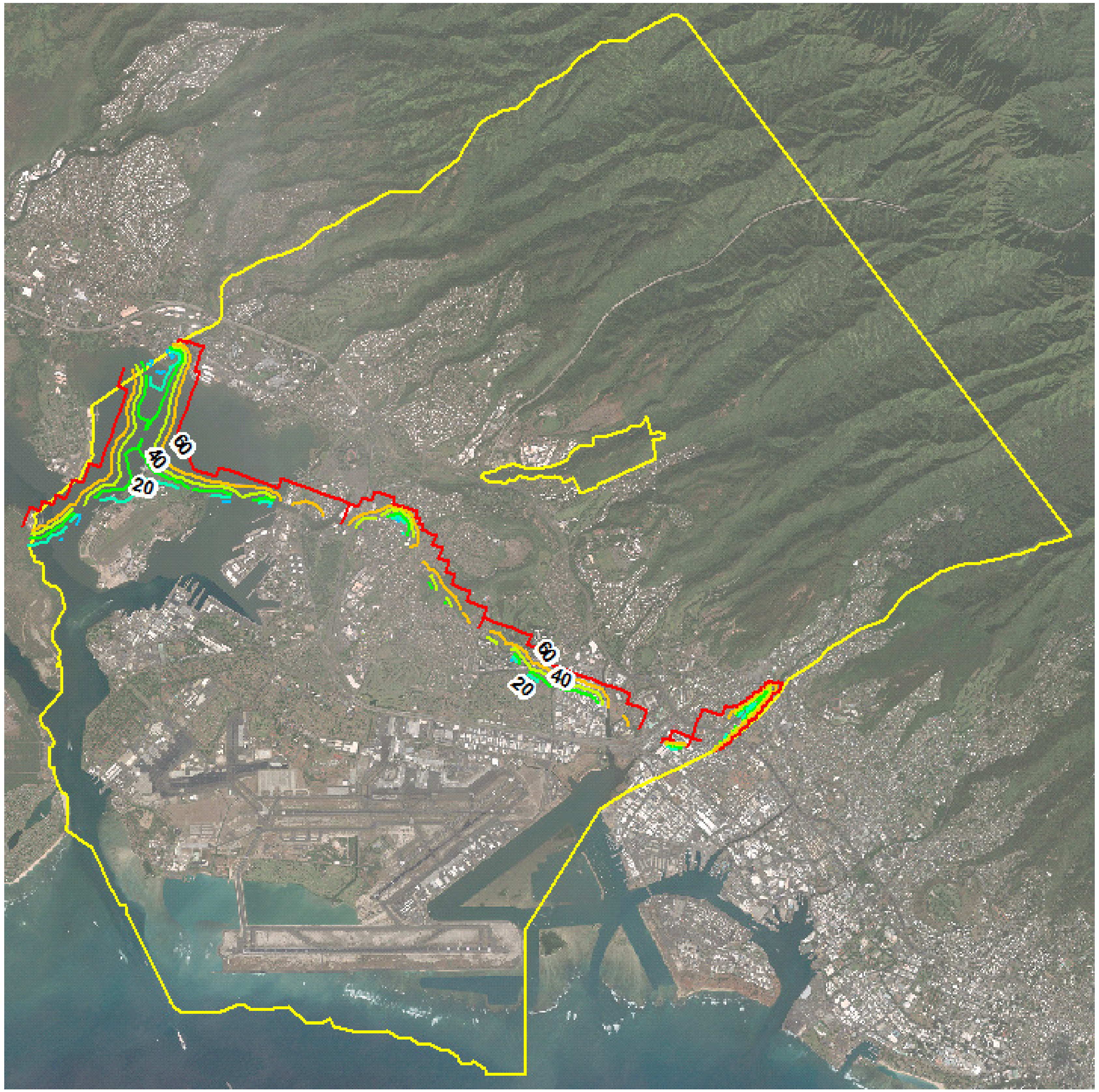
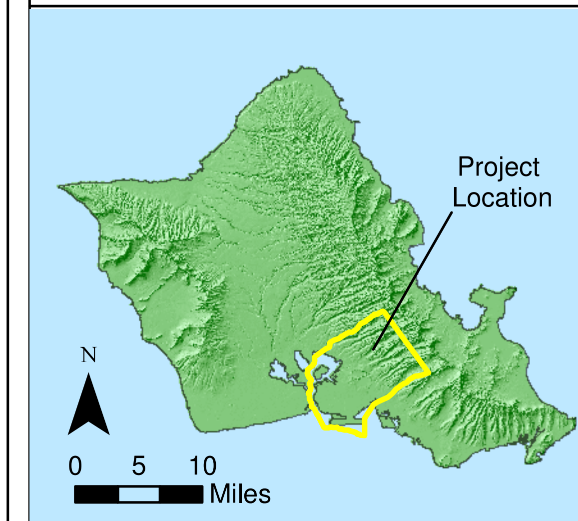


Location Map



Legend

Layer Thickness (feet)

- 60
- 50
- 40
- 30
- 20
- 10
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

Feet
0 2,500 5,000 10,000

Figure 4.2-6
Thickness of Model Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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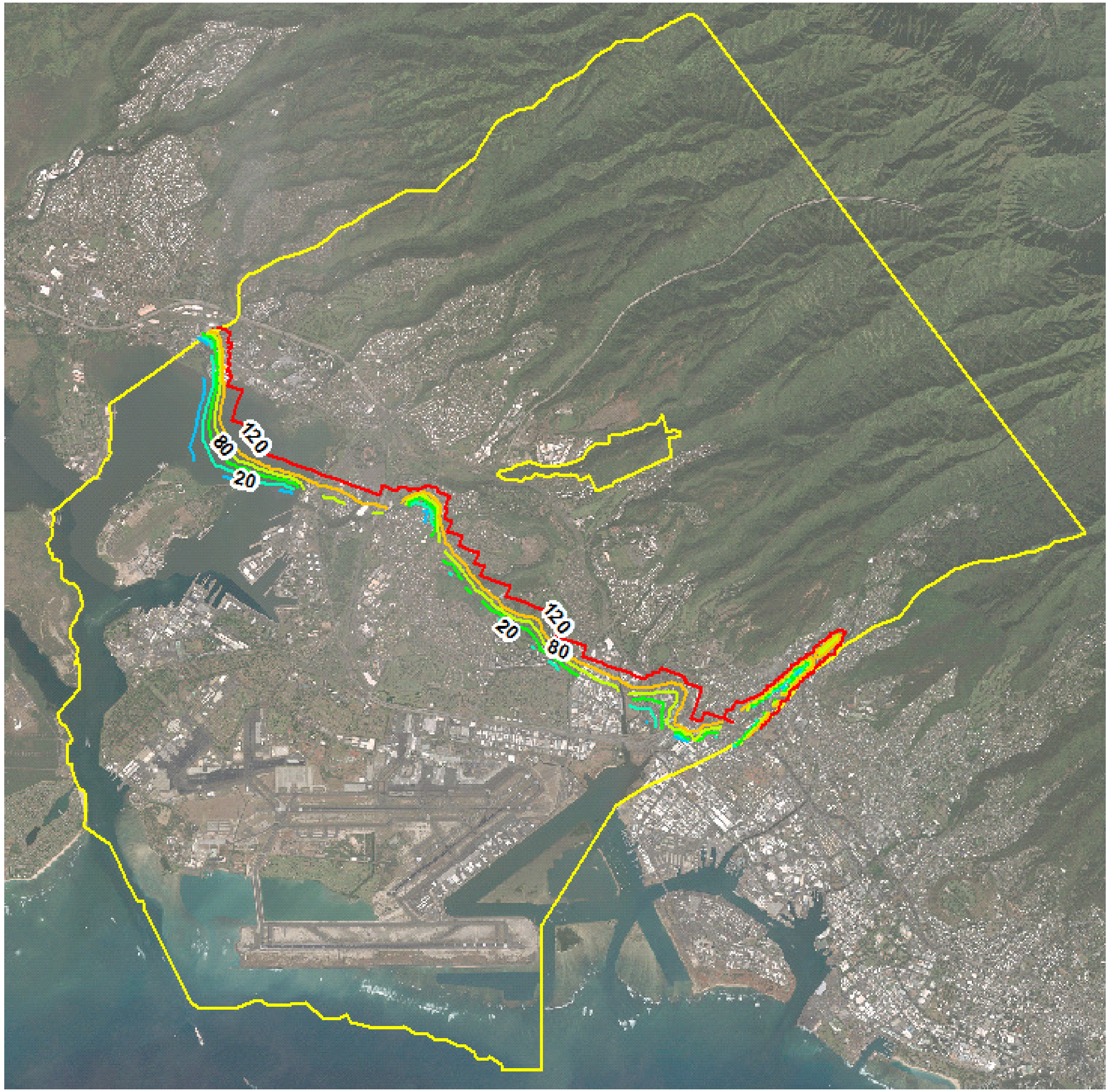
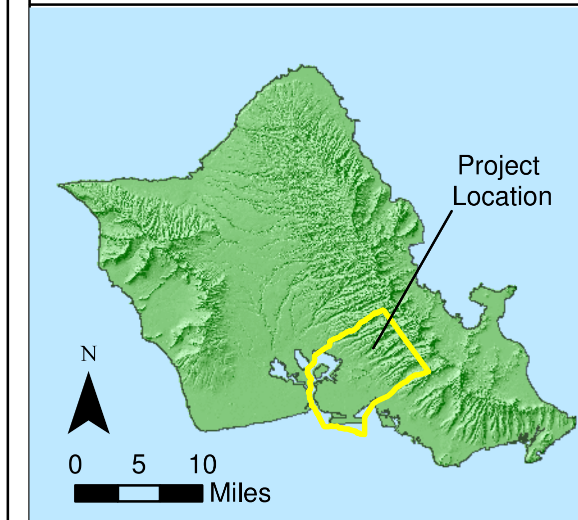


Location Map



Legend

Layer Thickness (feet)

- 120
- 100
- 80
- 60
- 40
- 20
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 2,500 5,000 10,000 Feet

Figure 4.2-7
Thickness of Model Layer 4
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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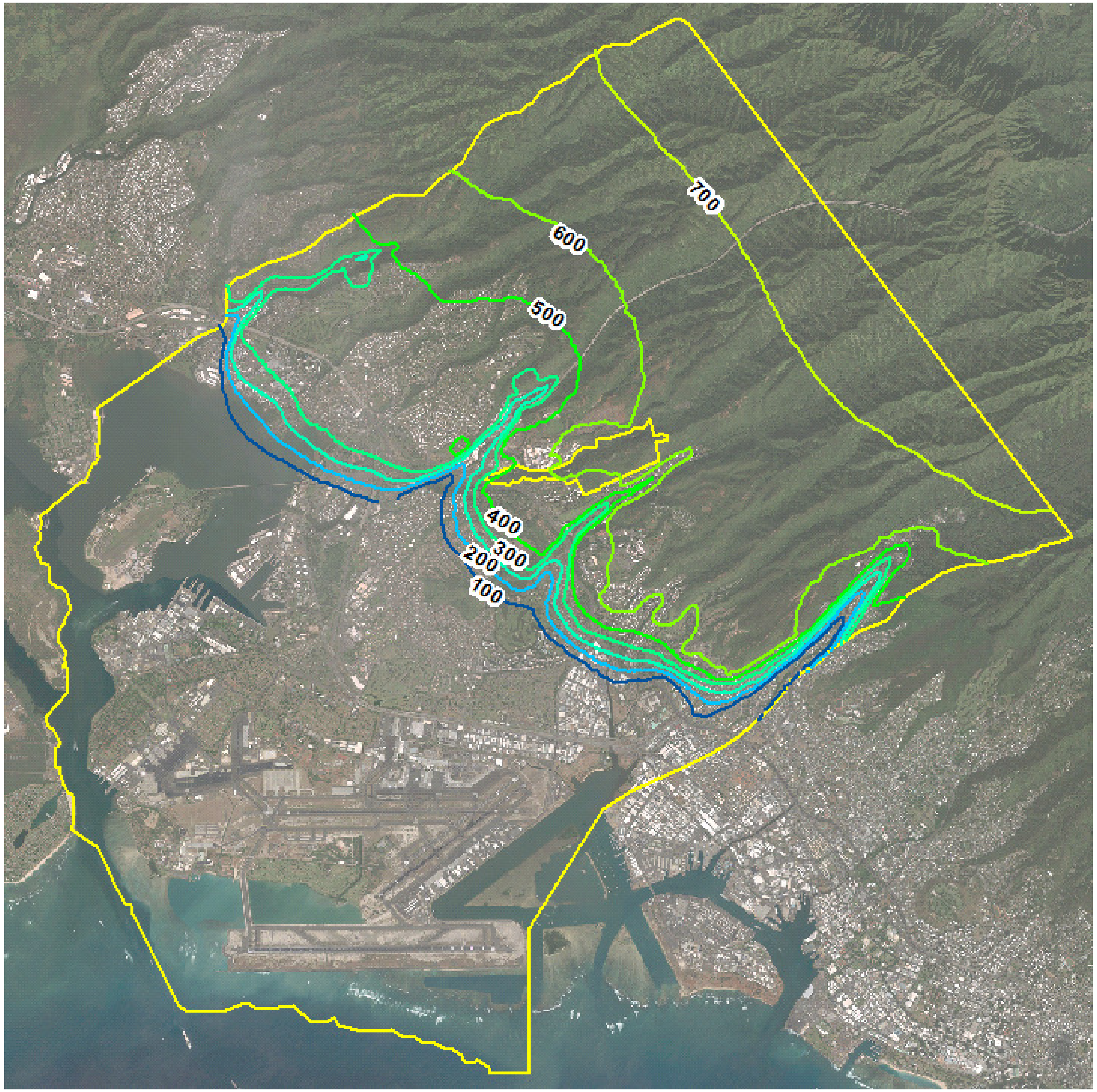
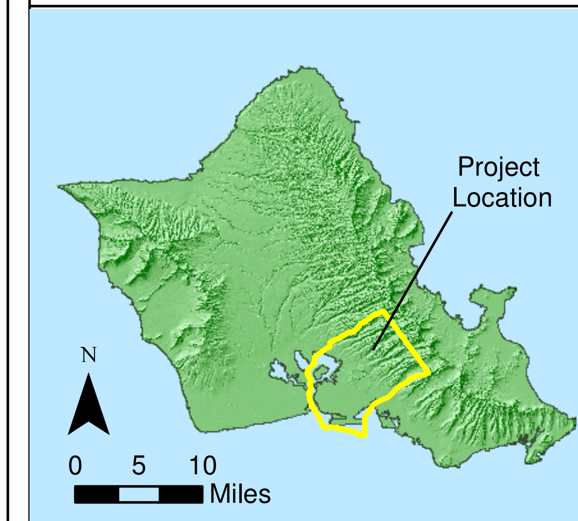


Location Map



Legend

Layer Thickness (feet)

- 1000
- 800
- 600
- 400
- 200
- 0
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 2,500 5,000 10,000 Feet

Figure 4.2-8
Thickness of Model Layer 5
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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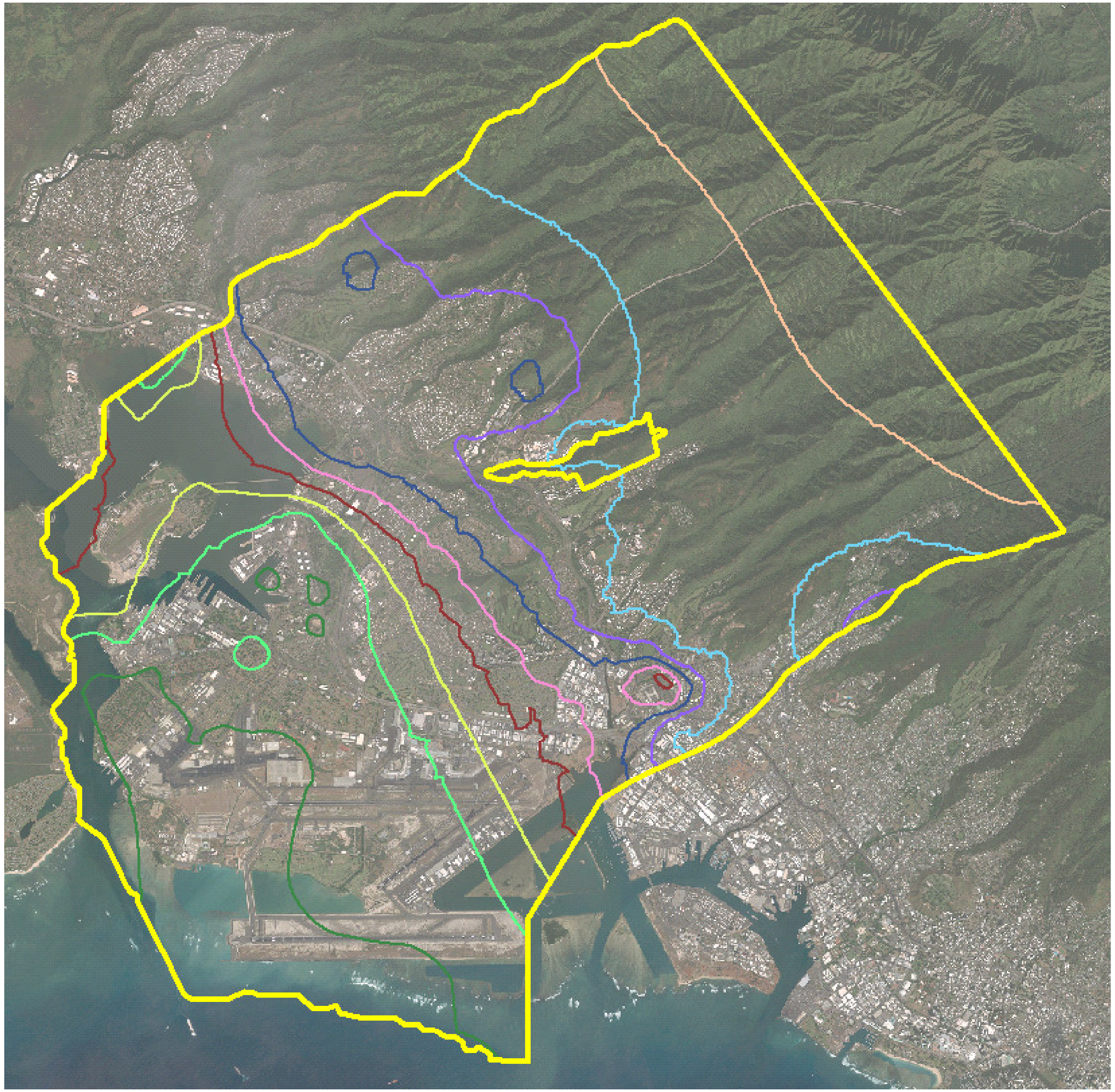
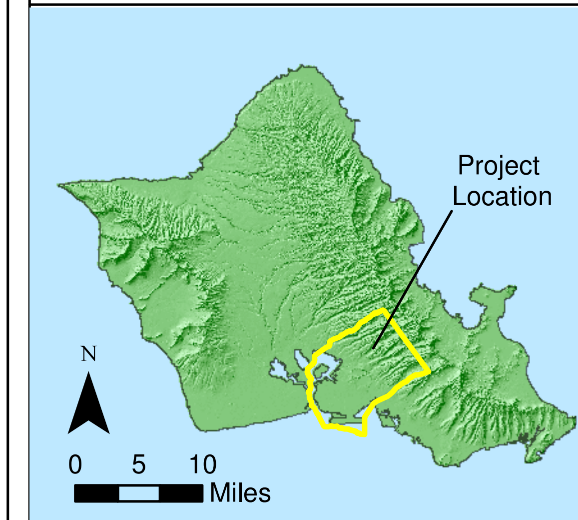


Location Map



Legend

Model Bottom Contours (feet above mean sea level)

- -900
- -800
- -700
- -600
- -500
- -400
- -300
- -200
- -100

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 2,500 5,000 10,000 Feet

Figure 4.2-9
Bottom of Model Domain Contours
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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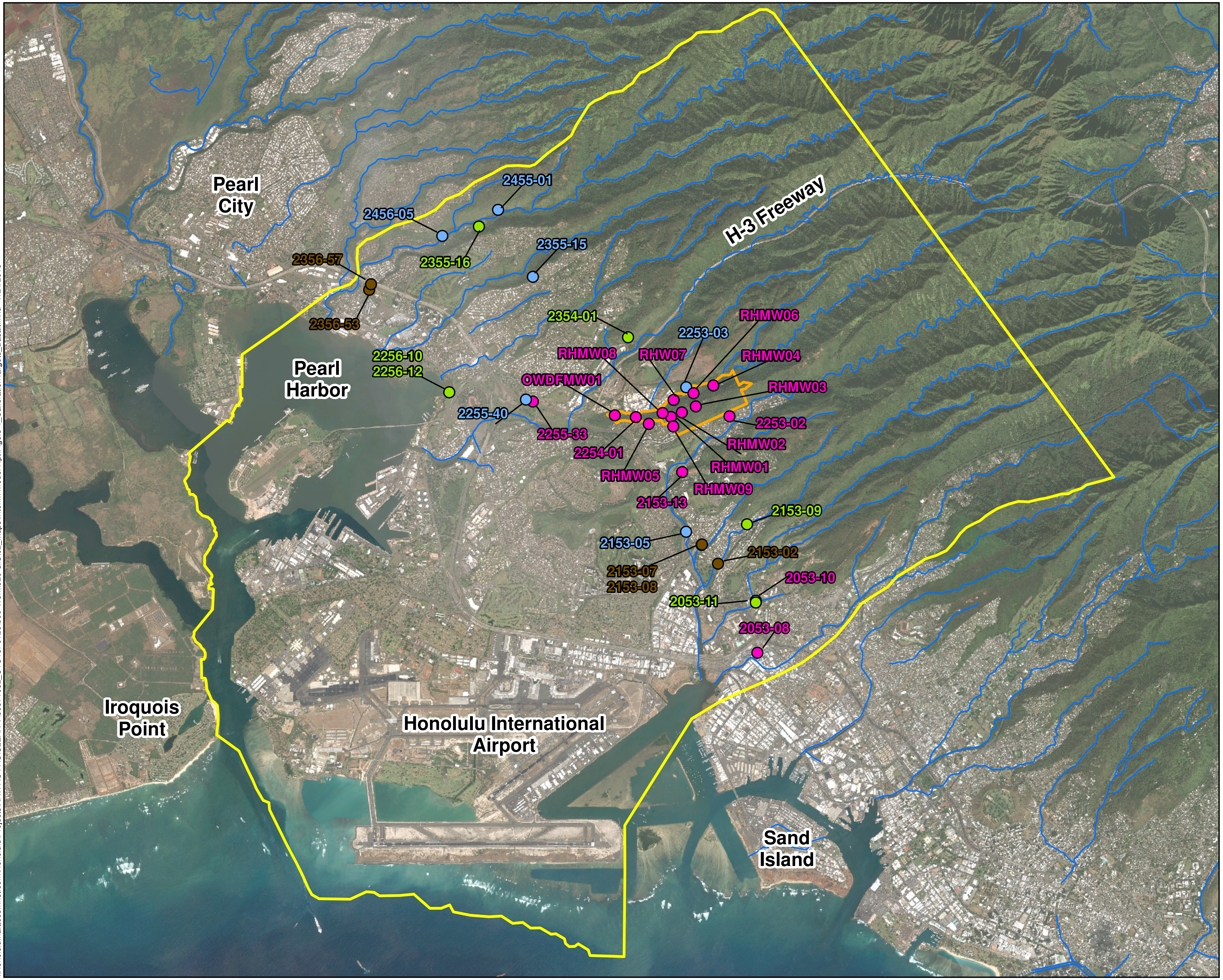

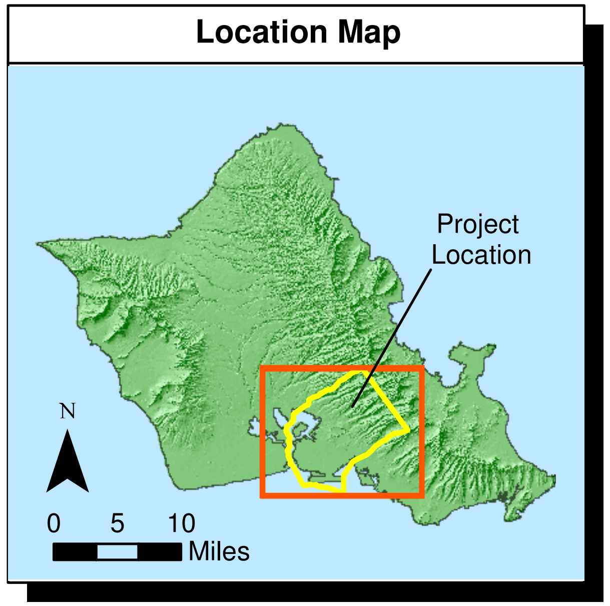

Legend

Model Layer Number

- 2
- 3
- 4
- 5
- Model
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

Feet
0 2,500 5,000 10,000

Figure 5.3-1
Layer Numbers for Model Calibration Target Wells in Basalt
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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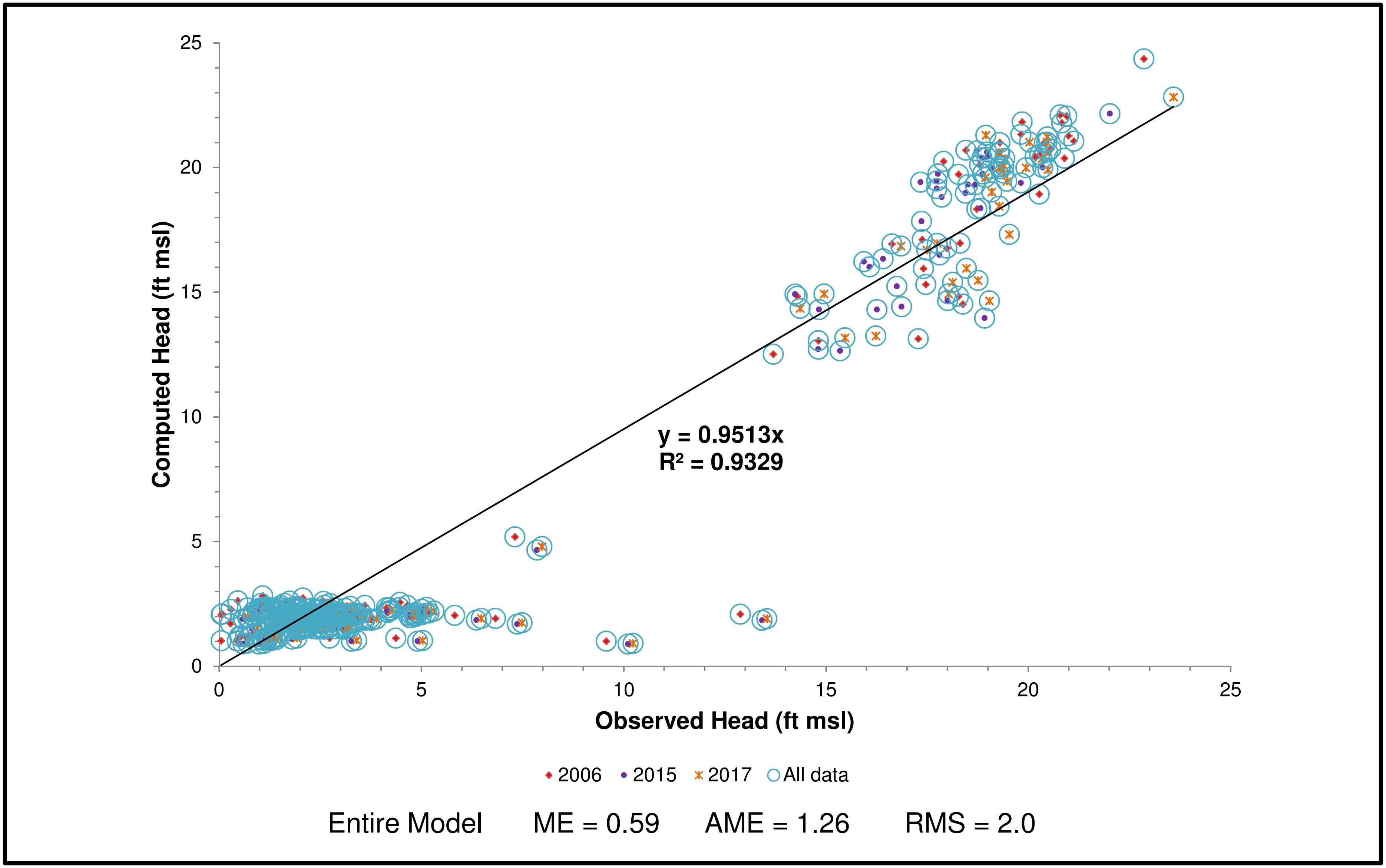

Figure 5.4-1
Model Calibration Results- Entire Model Domain
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

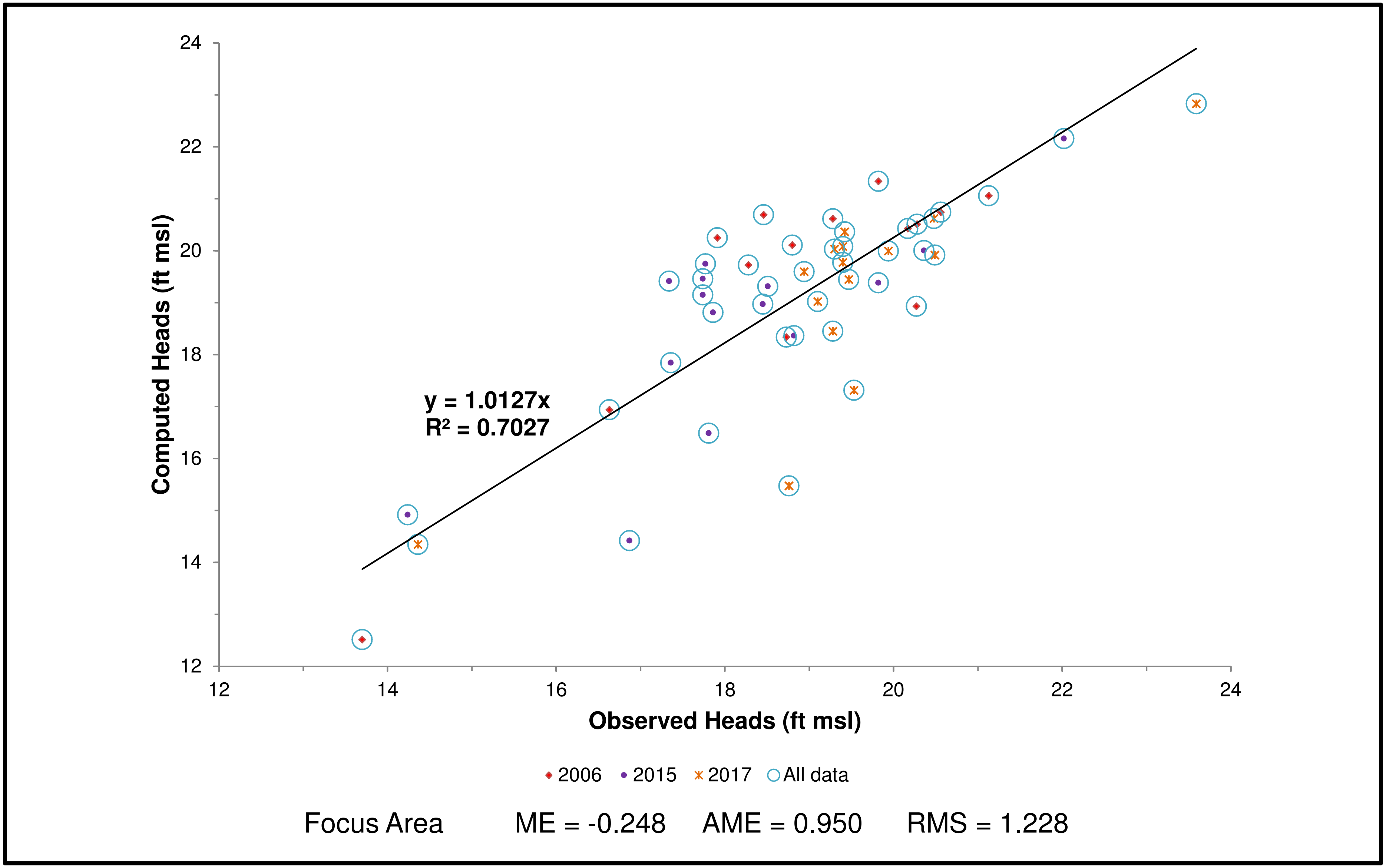

Figure 5.4-2
Model Calibration Results- Red Hill Focus Area
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

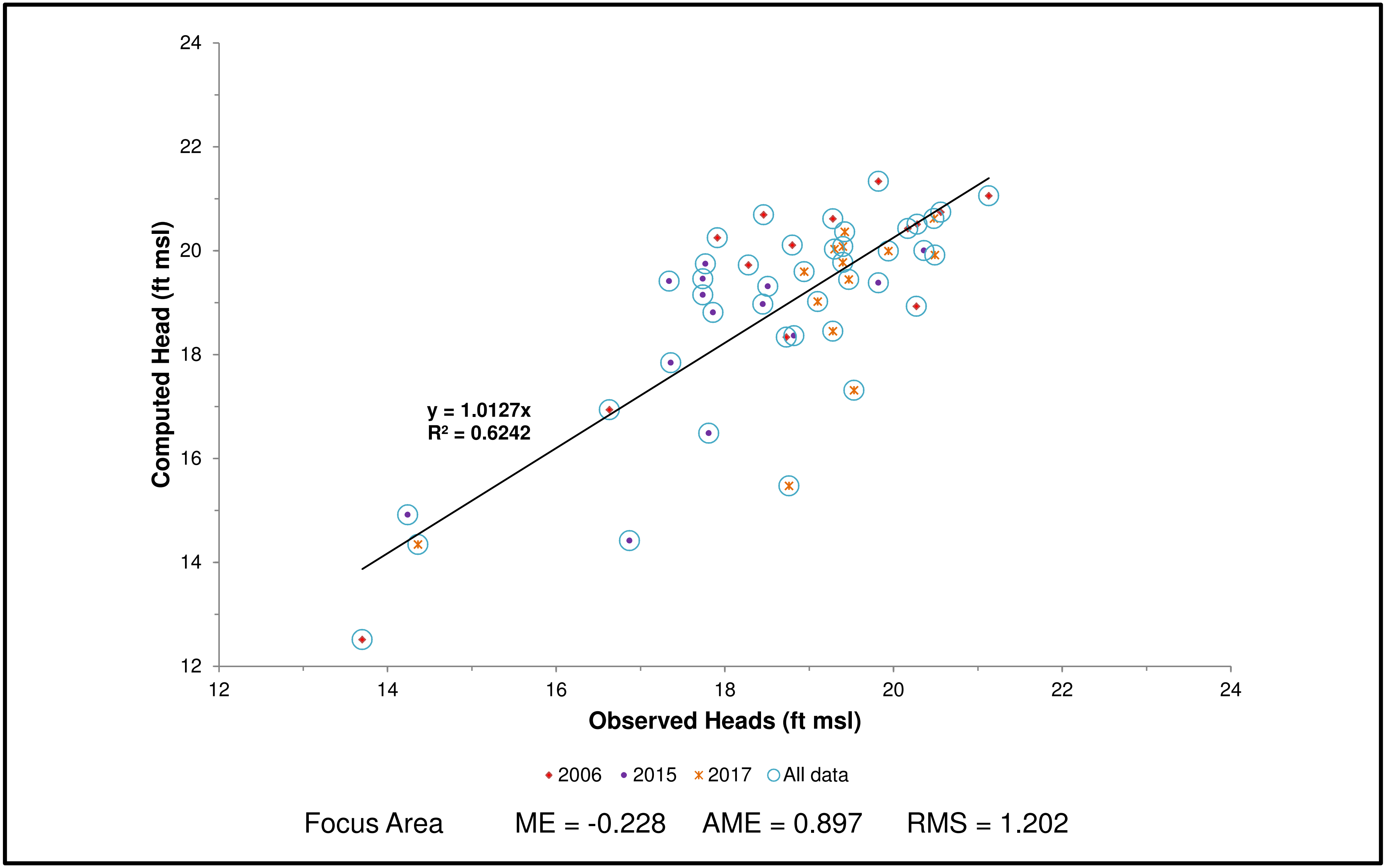

Figure 5.4-3
Model Calibration Results- Red Hill Focus Area Without RHMW07
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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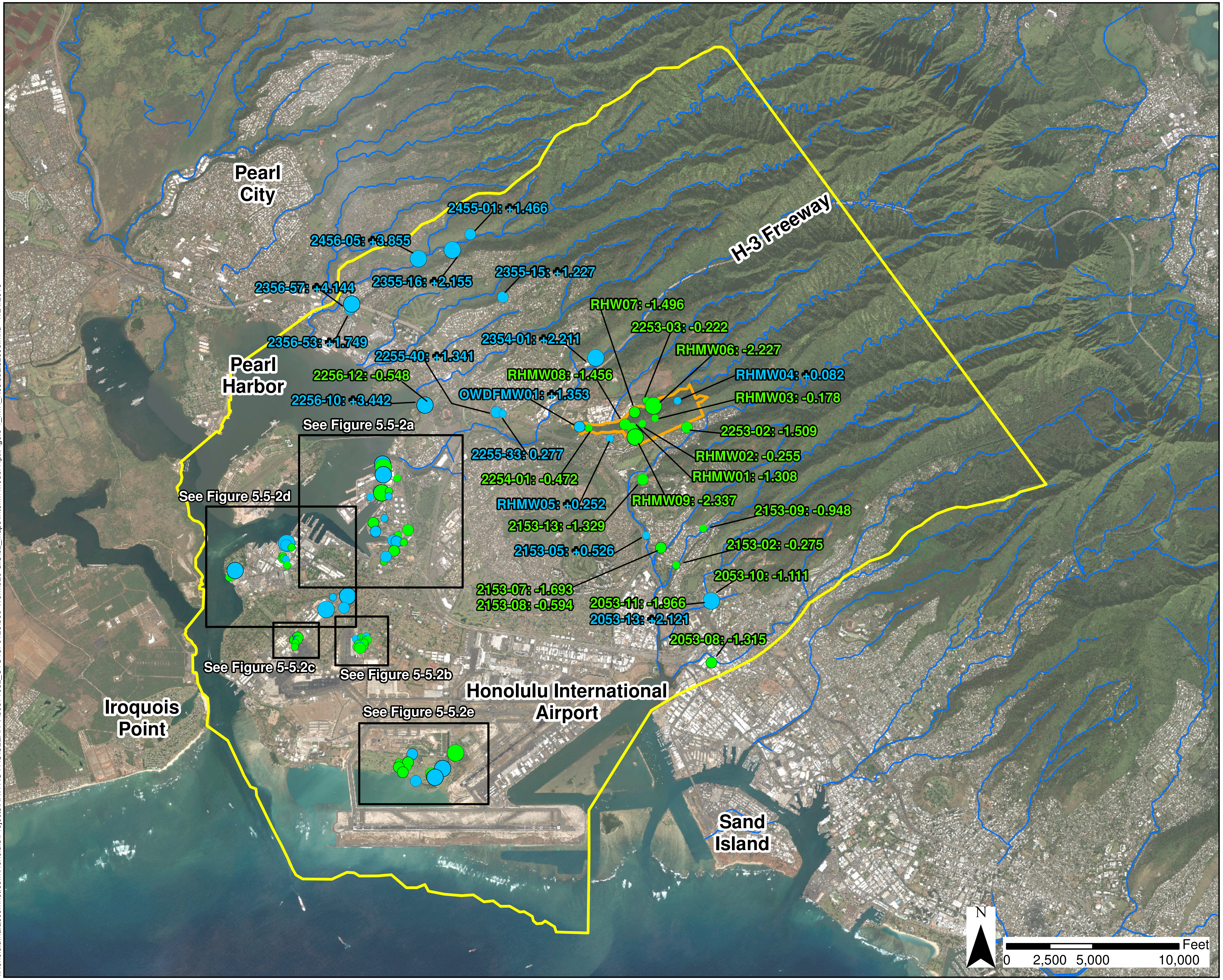
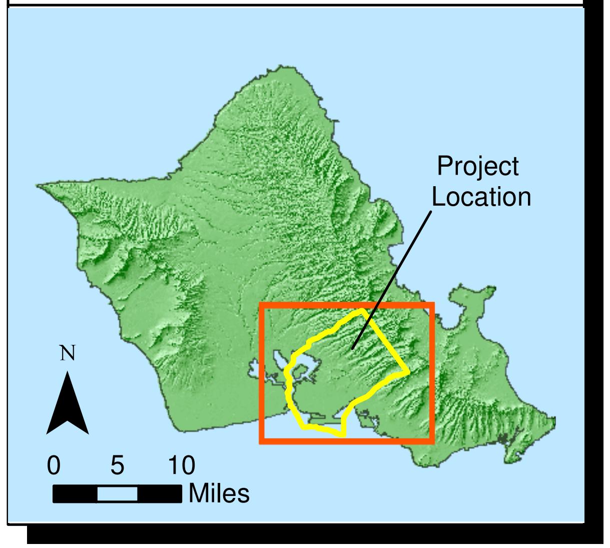


\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.5-1_IMR_Residuals2006.mxd 7/24/2018

Location Map



Legend

Distribution of Residuals

- ≤ -2.00
- ≤ 1.00 and < -2.00
- < 0.00 and < -1.00
- ≥ 0.00 and < 1.00
- ≥ 1.00 and < 2.00
- ≥ 2.00
- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Well Name: Head Residual Value

2153-05: +0.246

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.5-1
Distribution of Residuals 2006
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

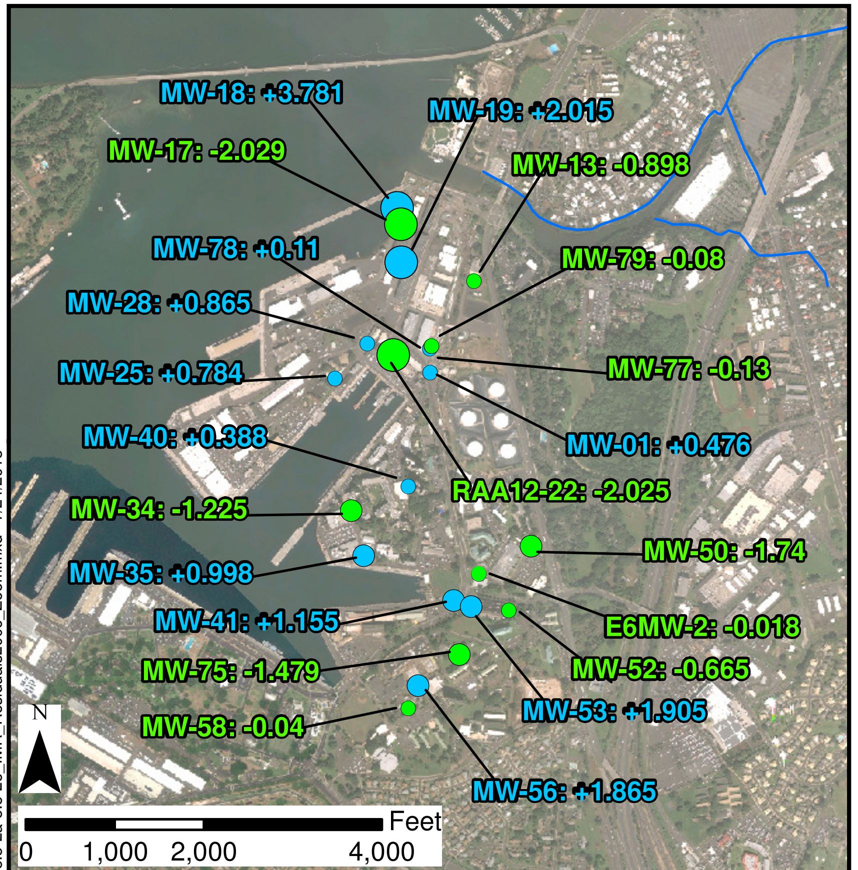


Figure 5-5.2a

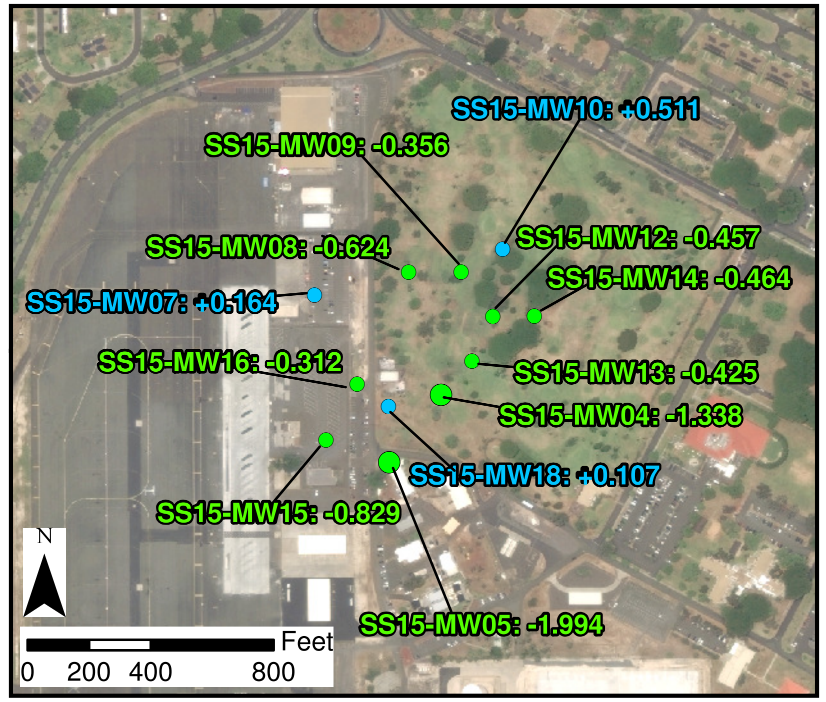


Figure 5-5.2b

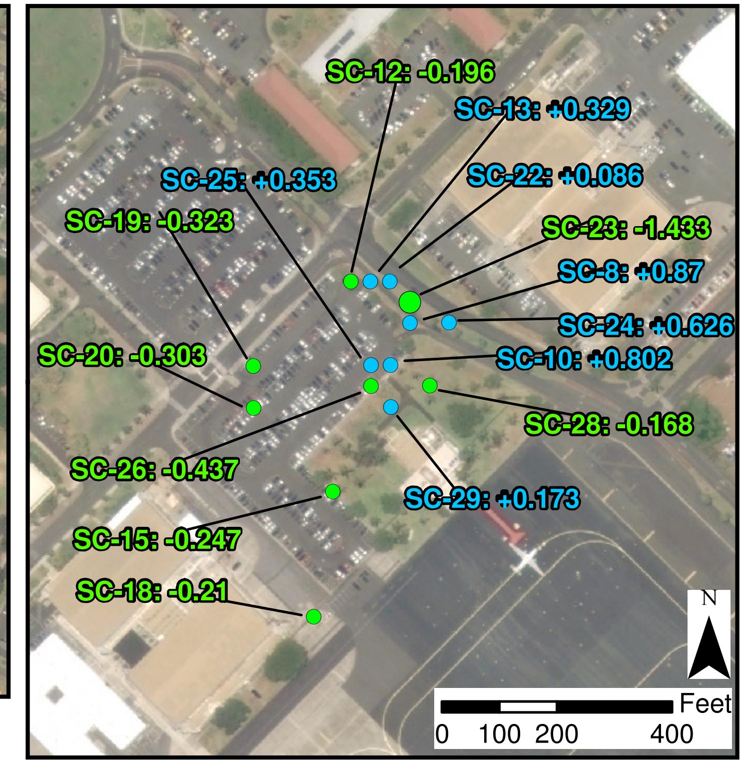


Figure 5-5.2c

Figure 5-5.2d

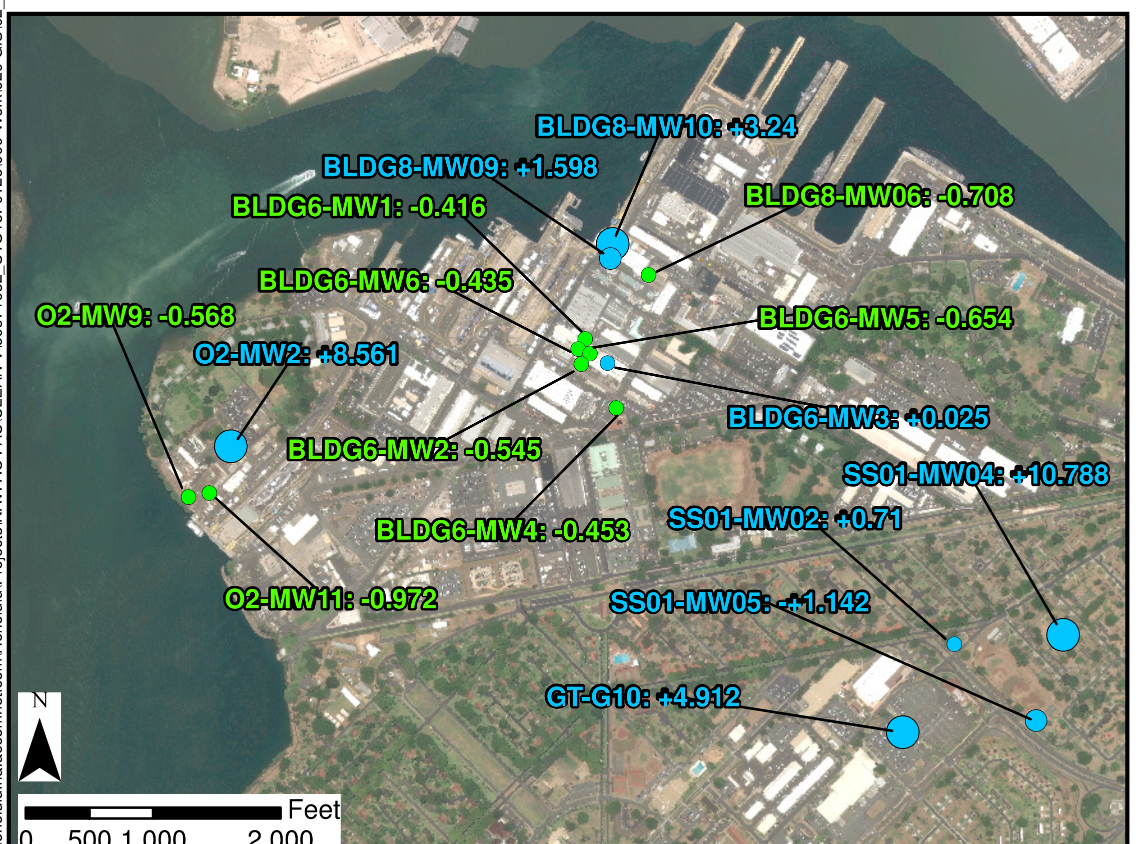
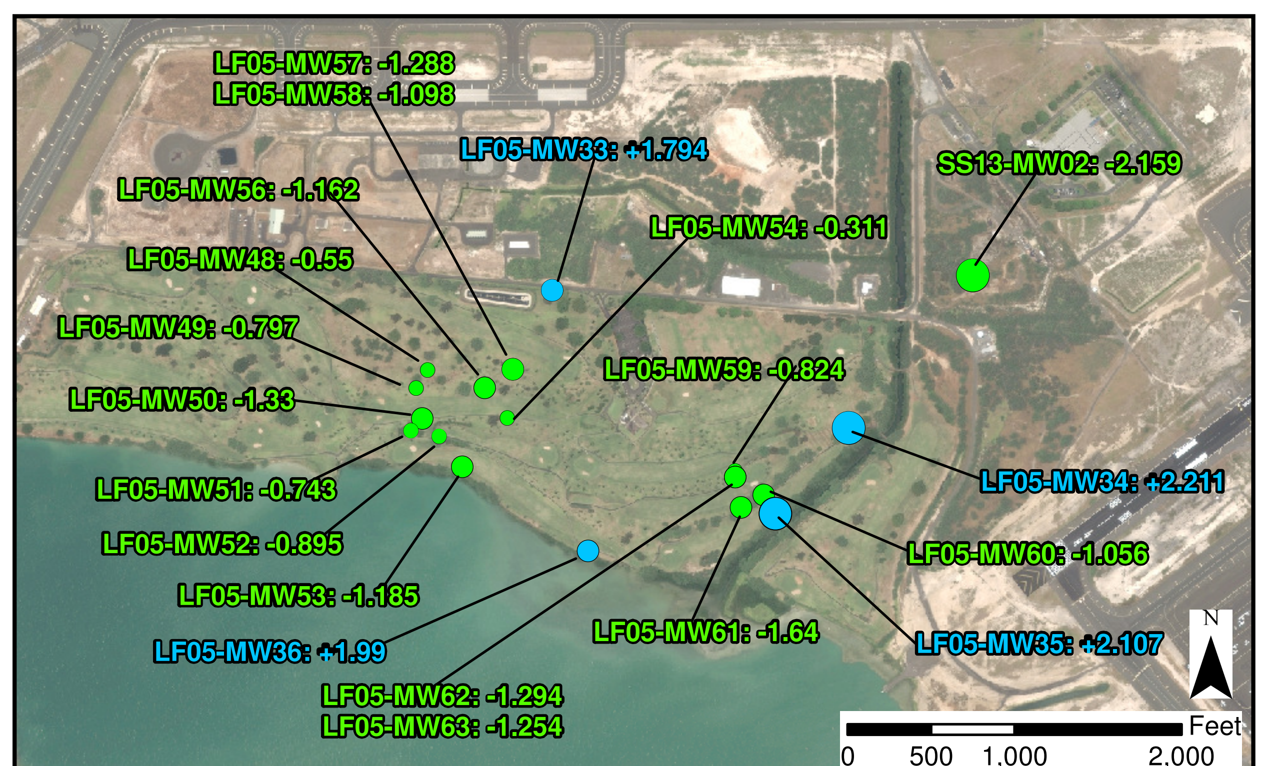
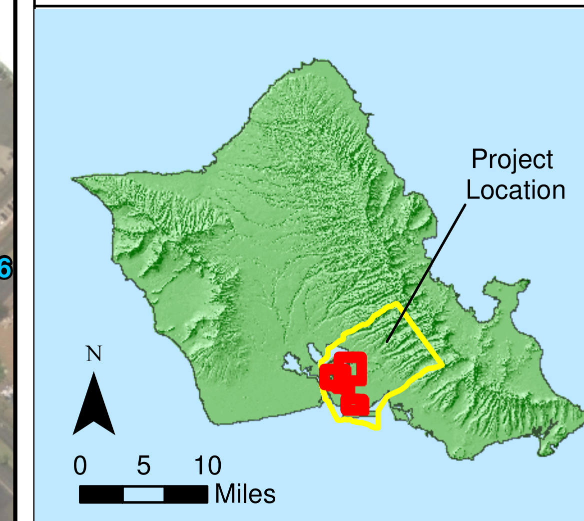


Figure 5-5.2e



Location Map



Legend

Distribution of Residuals

- ≤ -2.00
- ≤ 1.00 and < -2.00
- < 0.00 and < -1.00
- ≥ 0.00 and < 1.00
- ≥ 1.00 and < 2.00
- ≥ 2.00

Model Area

Stream

Well Name: Head Residual Value

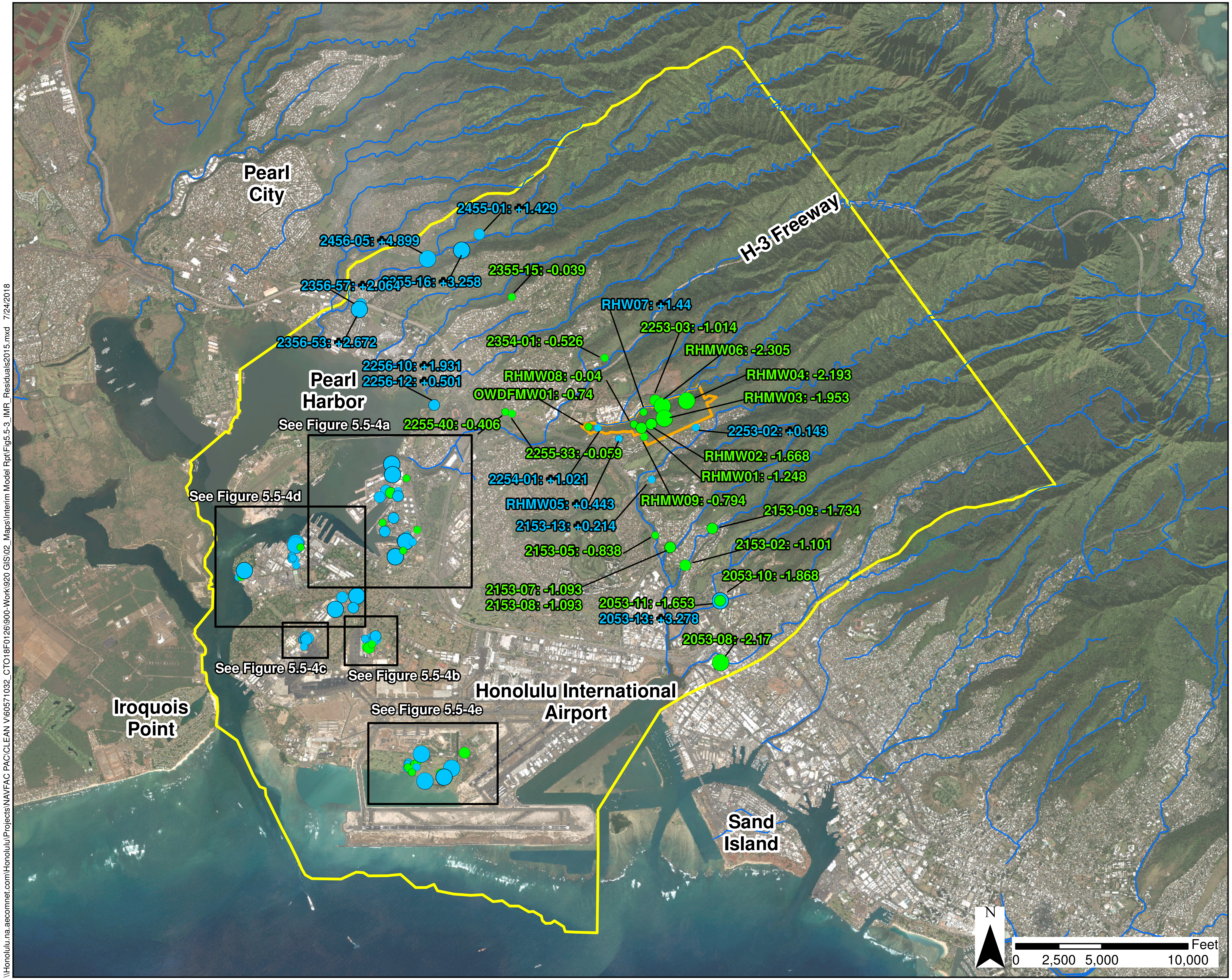
2153-05: +0.246

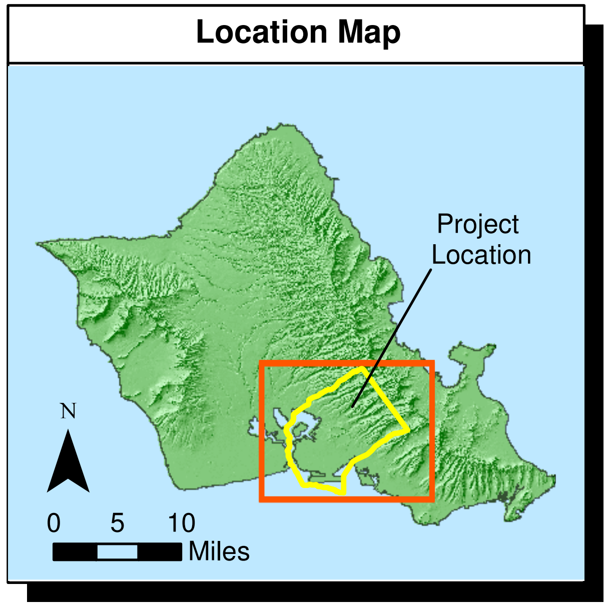
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.5-2a - 5.5-2e
Distribution of Residuals 2006
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.5-2a-5.5-2e_IMR_Residuals2006_Zoom.mxd 7/24/2018





Legend

Distribution of Residuals

- ≤ -2.00
- ≤ 1.00 and < -2.00
- < 0.00 and < -1.00
- ≥ 0.00 and < 1.00
- ≥ 1.00 and < 2.00
- ≥ 2.00
- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

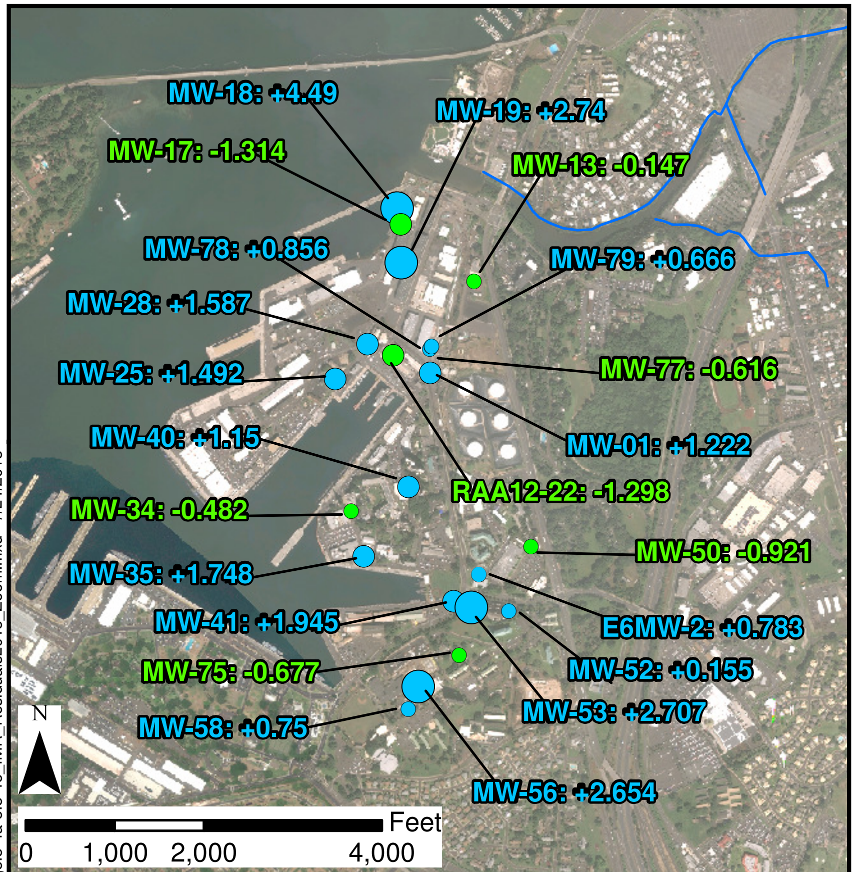
Well Name: Head Residual Value

2153-05: +0.246

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.5-3
Distribution of Residuals 2015
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



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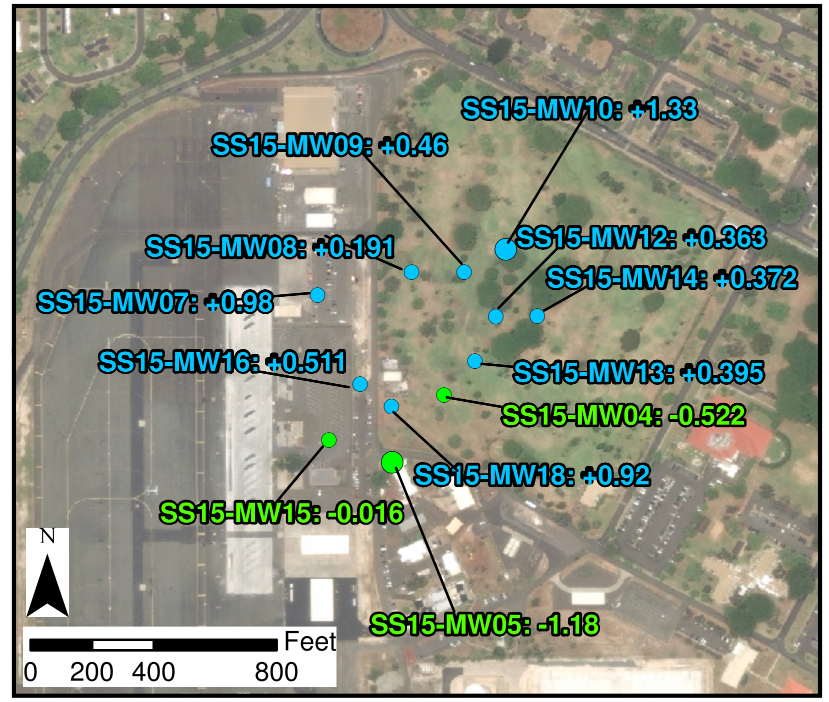


Figure 5-5.4b

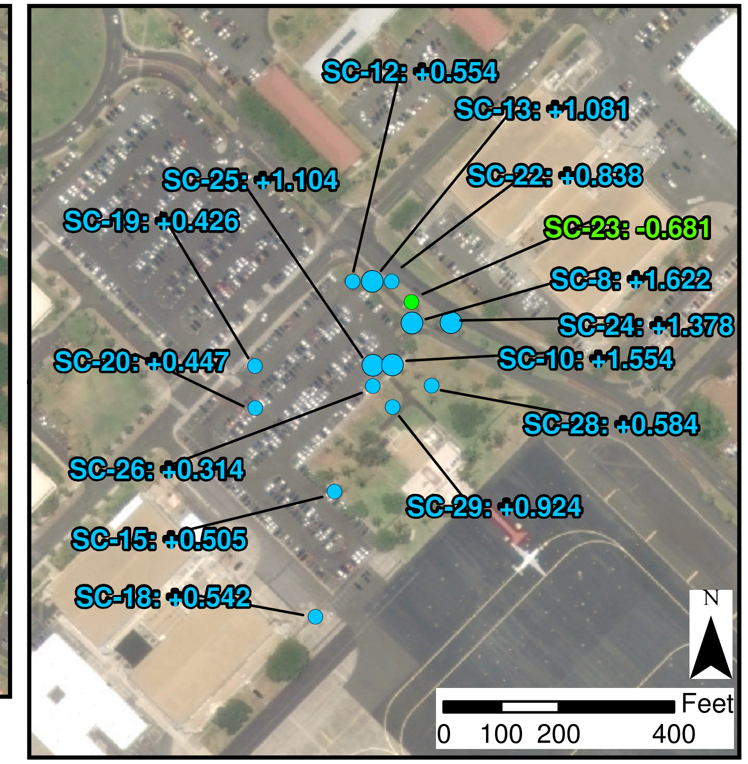
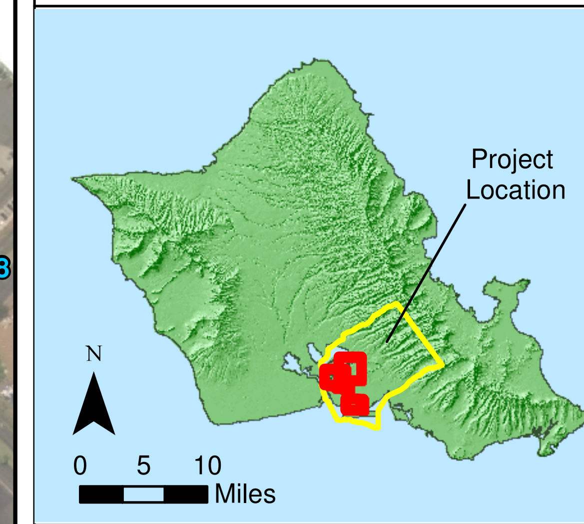


Figure 5-5.4c

Location Map



Legend

Distribution of Residuals

- ≤ -2.00
- ≤ 1.00 and < -2.00
- < 0.00 and < -1.00
- ≥ 0.00 and < 1.00
- ≥ 1.00 and < 2.00
- ≥ 2.00
- Model Area
- Stream

Well Name: Head Residual Value

2153-05: +0.246

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.5-4d

Figure 5-5.4e

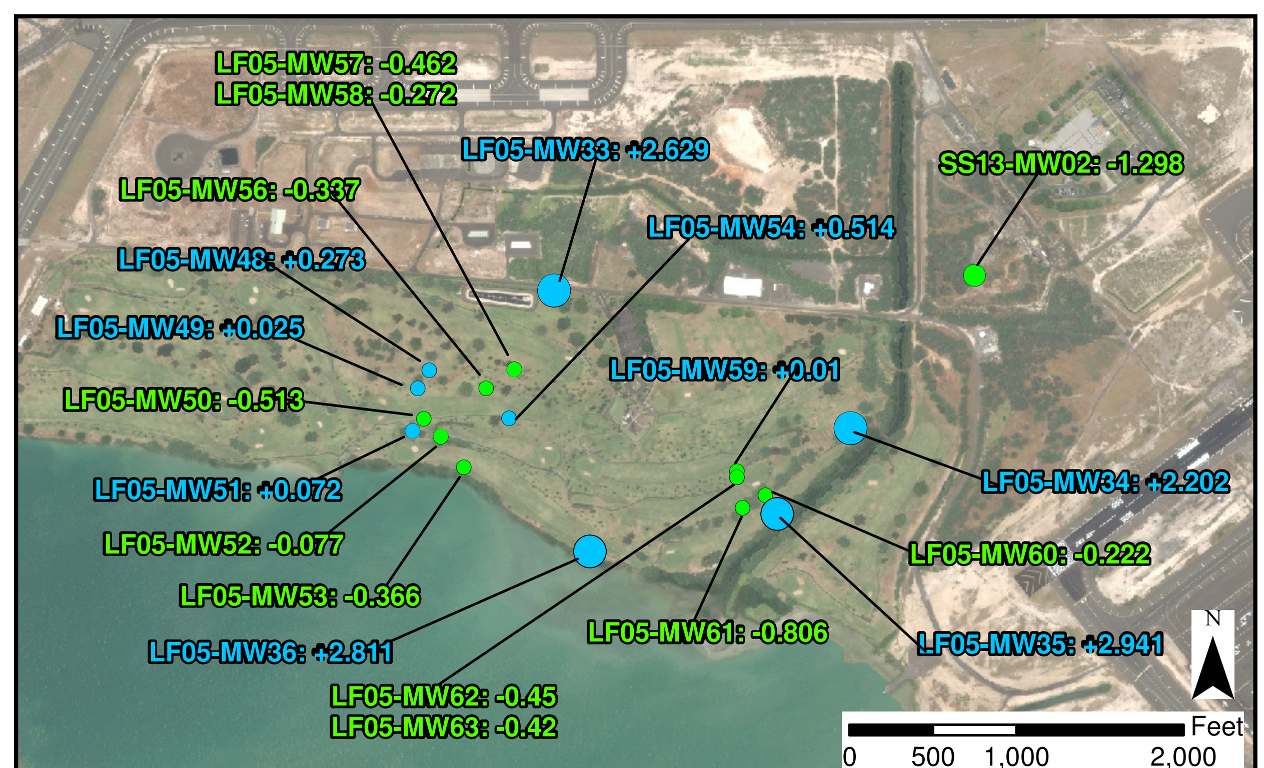


Figure 5.5-4a - 5.5-4e
Distribution of Residuals 2015
Appendix A
Interim Groundwater Flow Model Report
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Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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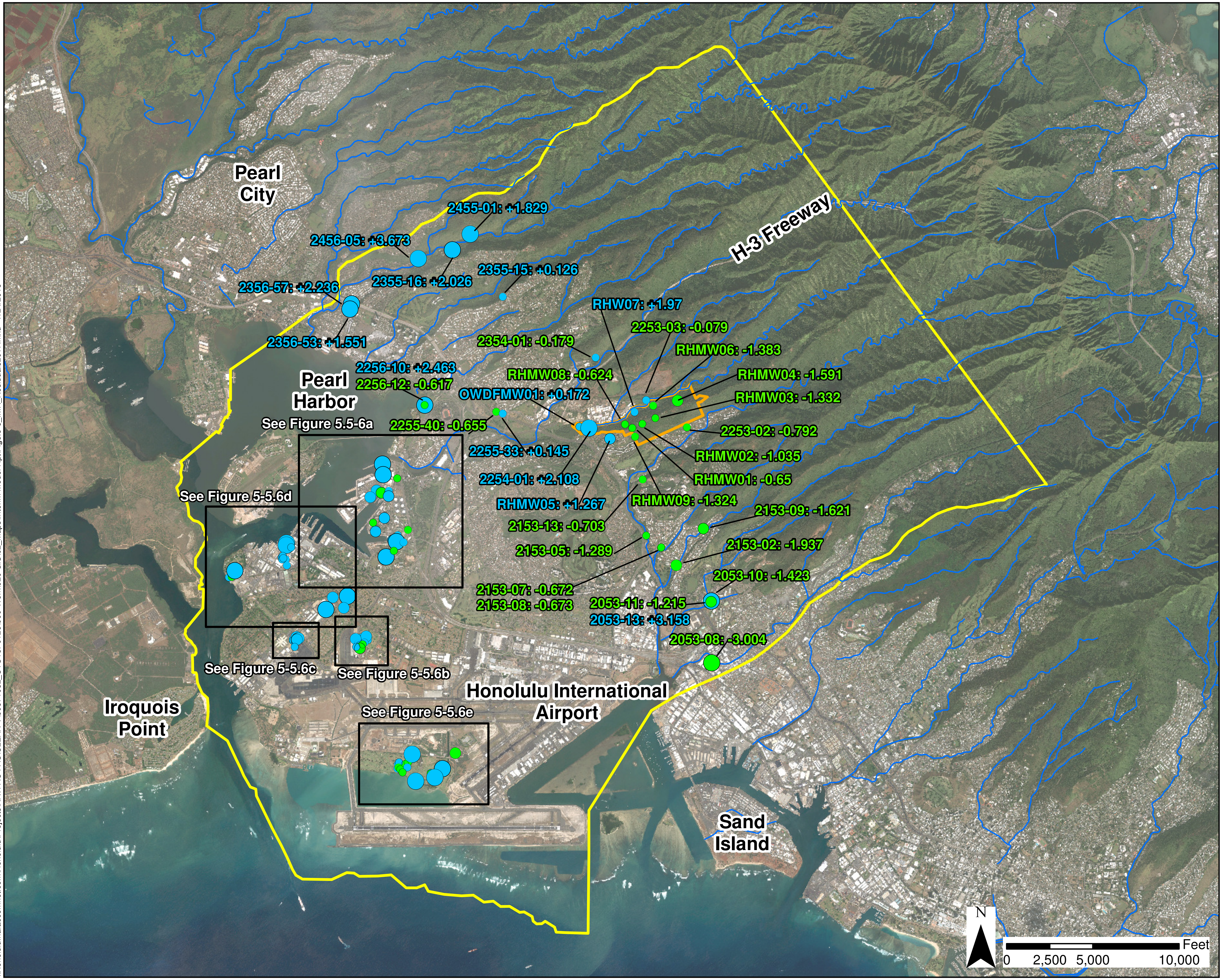
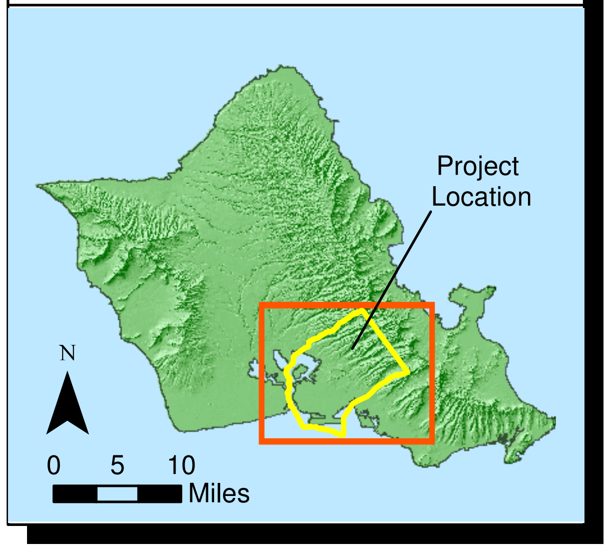


Location Map



Legend

Distribution of Residuals

- ≤ -2.00
- ≤ 1.00 and < -2.00
- < 0.00 and < -1.00
- ≥ 0.00 and < 1.00
- ≥ 1.00 and < 2.00
- ≥ 2.00
- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Well Name: Head Residual Value

2153-05: +0.246

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.5-5
Distribution of Residuals 2017
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.5-5_IMR_Residuals2017.mxd 7/24/2018

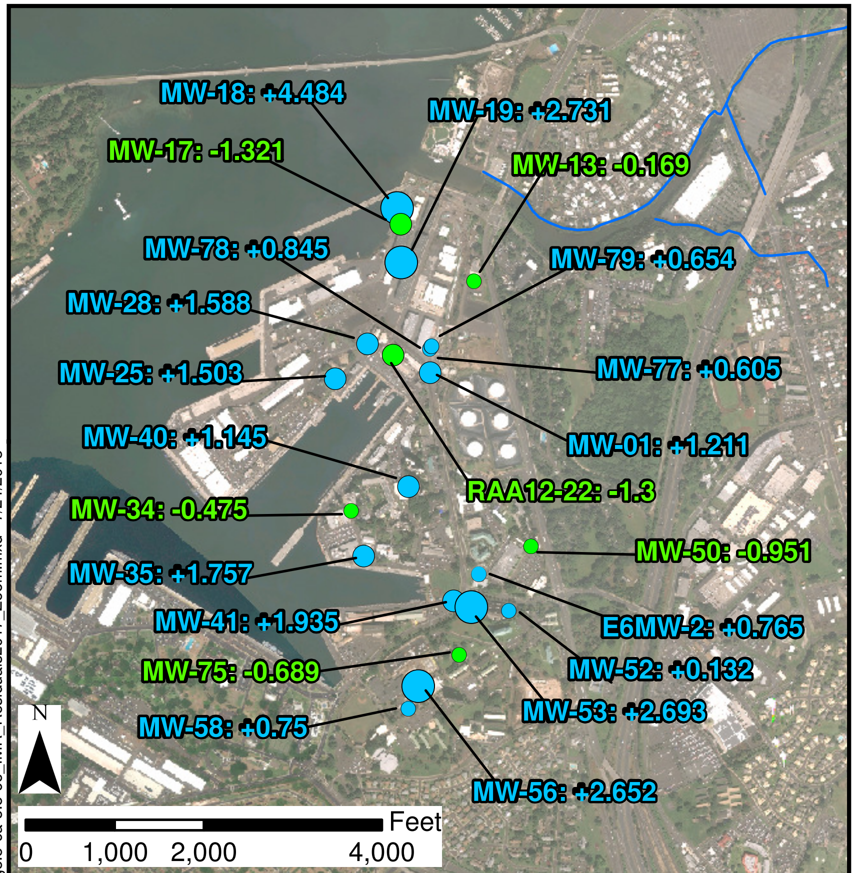


Figure 5.5-6a

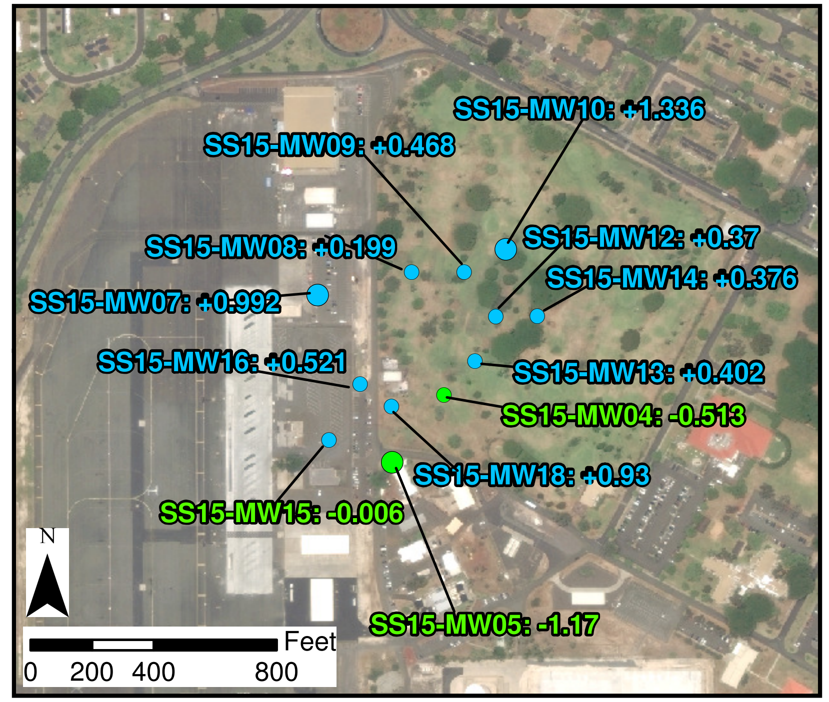


Figure 5-5.6b

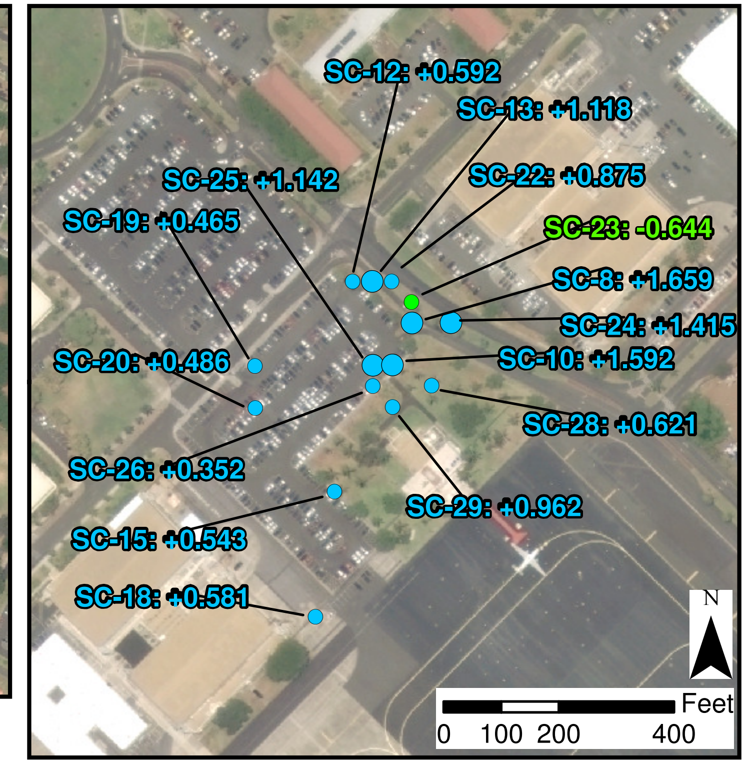
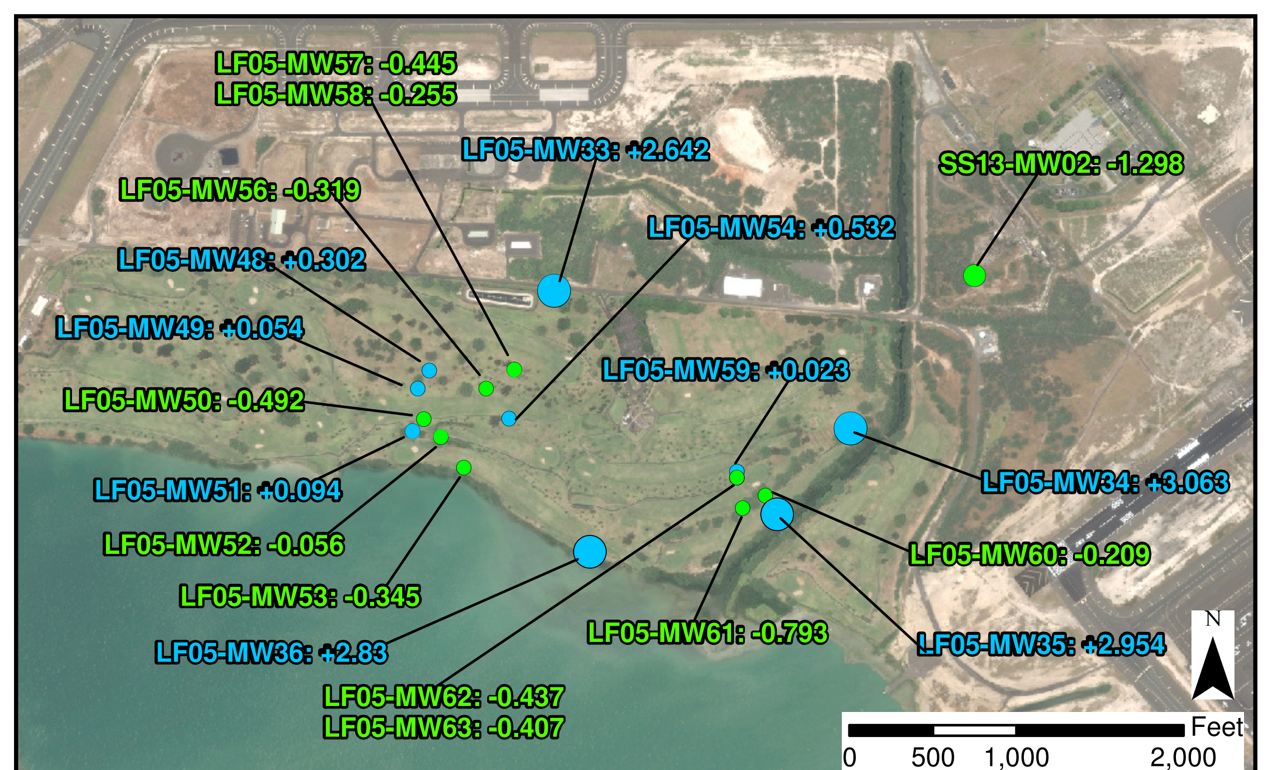


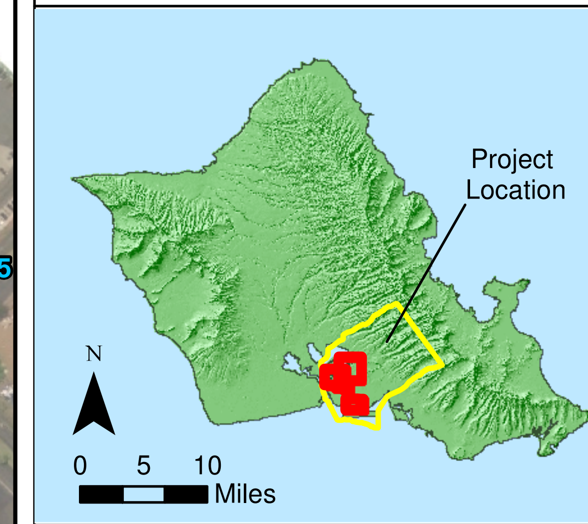
Figure 5-5.6c

Figure 5-5.6d

Figure 5-5.6e



Location Map



Legend

Distribution of Residuals

- ≤ -2.00
- ≤ 1.00 and < -2.00
- < 0.00 and < -1.00
- ≥ 0.00 and < 1.00
- ≥ 1.00 and < 2.00
- ≥ 2.00
- Model Area
- Stream

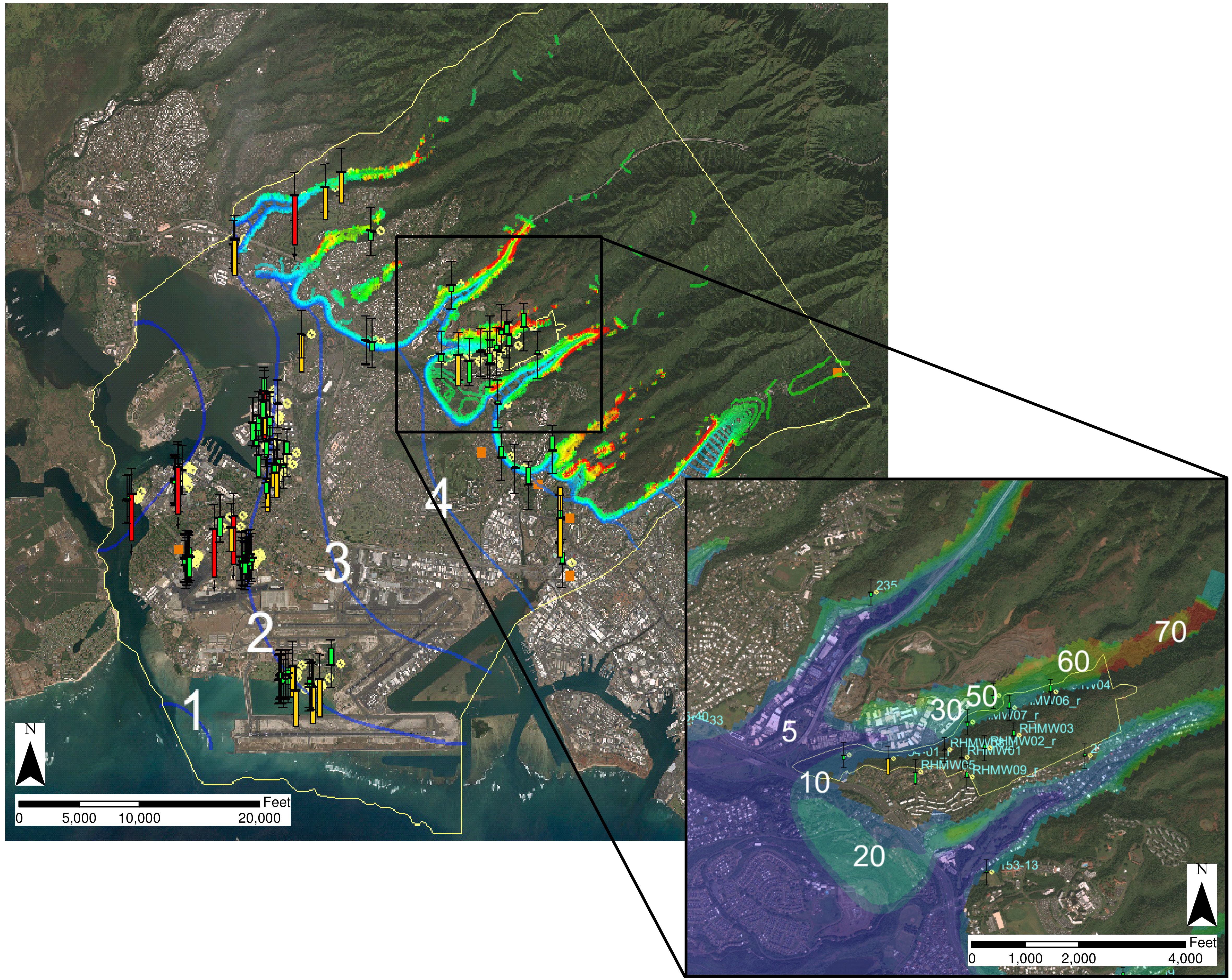
Well Name: Head Residual Value

2153-05: +0.246

Notes

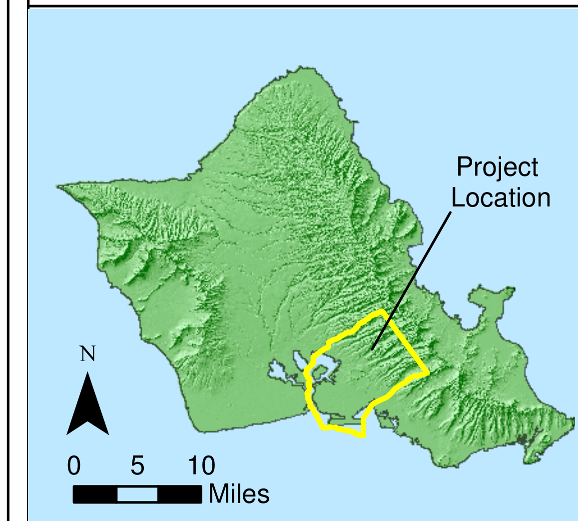
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.5-6a - 5.5-6e
Distribution of Residuals 2017
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.6-1_Simulated_2017_GW_Elev_Contours_ModelLayer1.mxd 7/24/2018

Location Map



Legend

Groundwater Contour (feet above mean sea level)

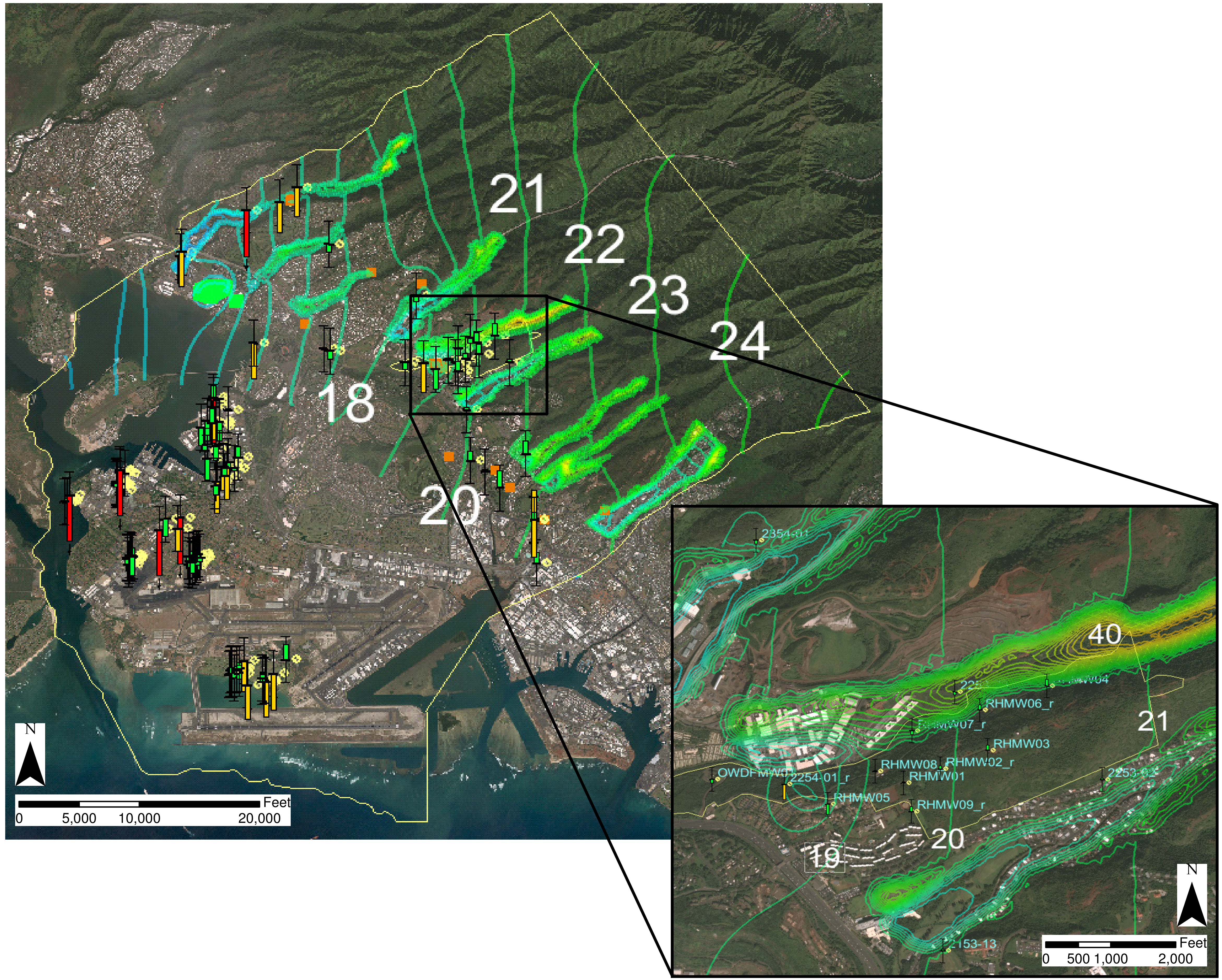
100
90
80
70
60
50
40
30
20
10
0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

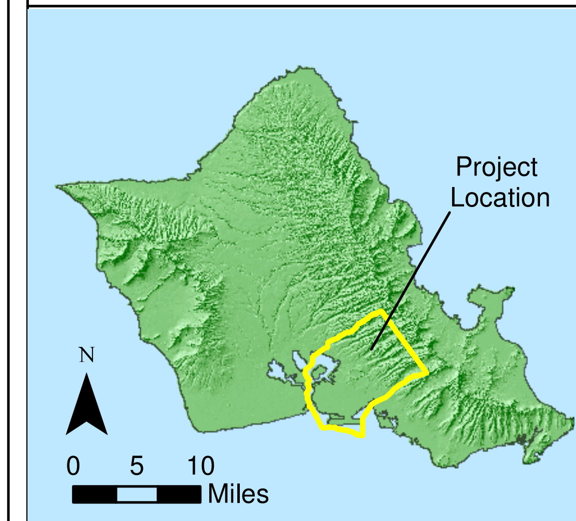
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.6-1
Simulated 2017 Groundwater Elevation Contours in Model Layer 1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

Groundwater Contour (feet above mean sea level)

- 50
- 45
- 40
- 35
- 30
- 25
- 20
- 15
- 10
- 5
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.6-2
Simulated 2017 Groundwater Elevation Contours in Model Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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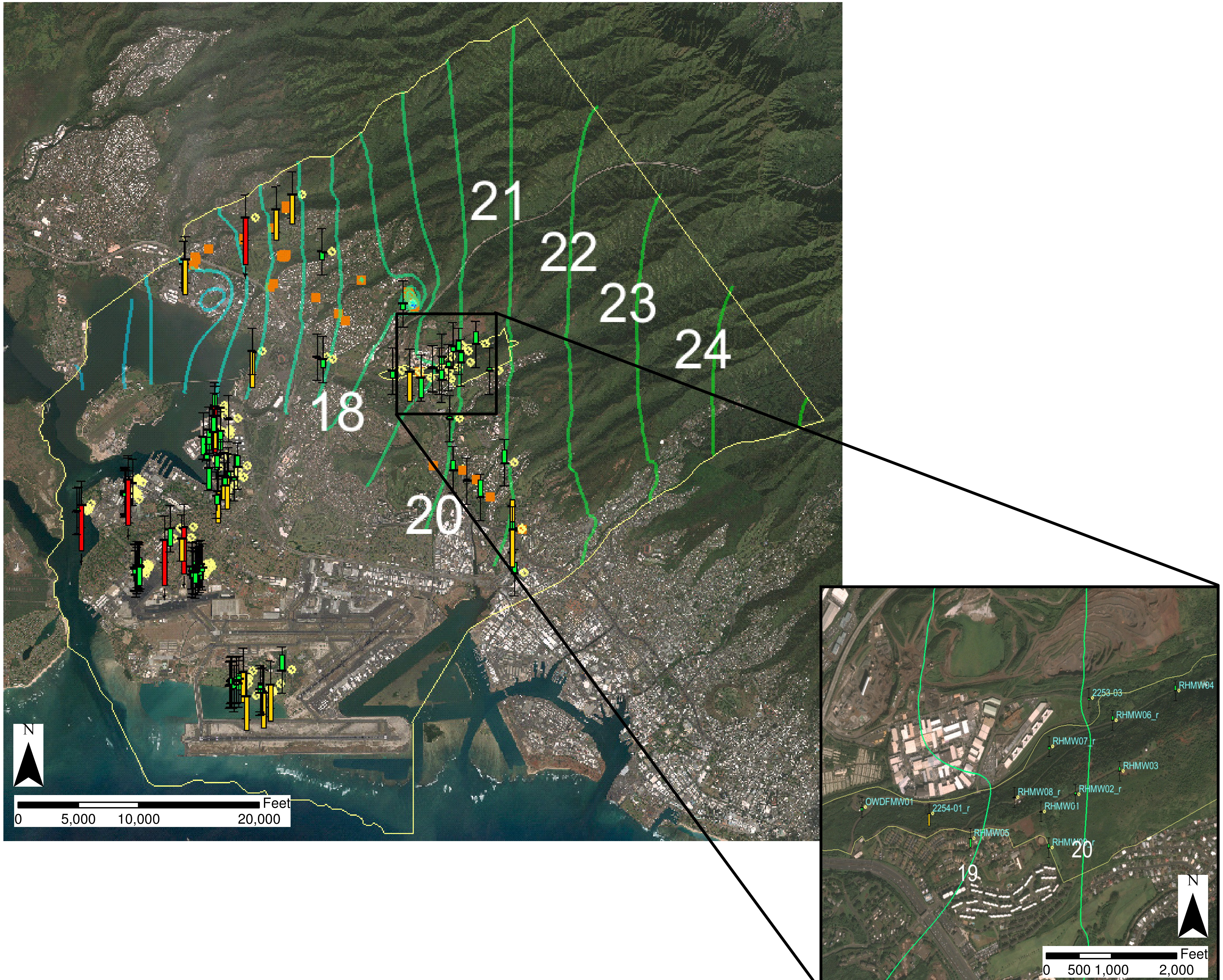
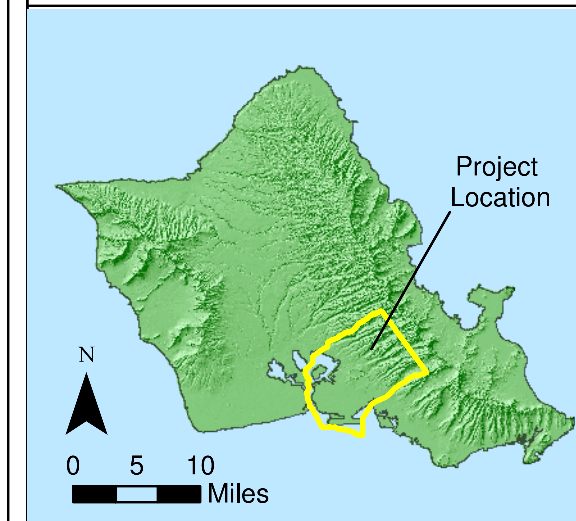


Location Map



Legend

Groundwater Contour (feet above mean sea level)

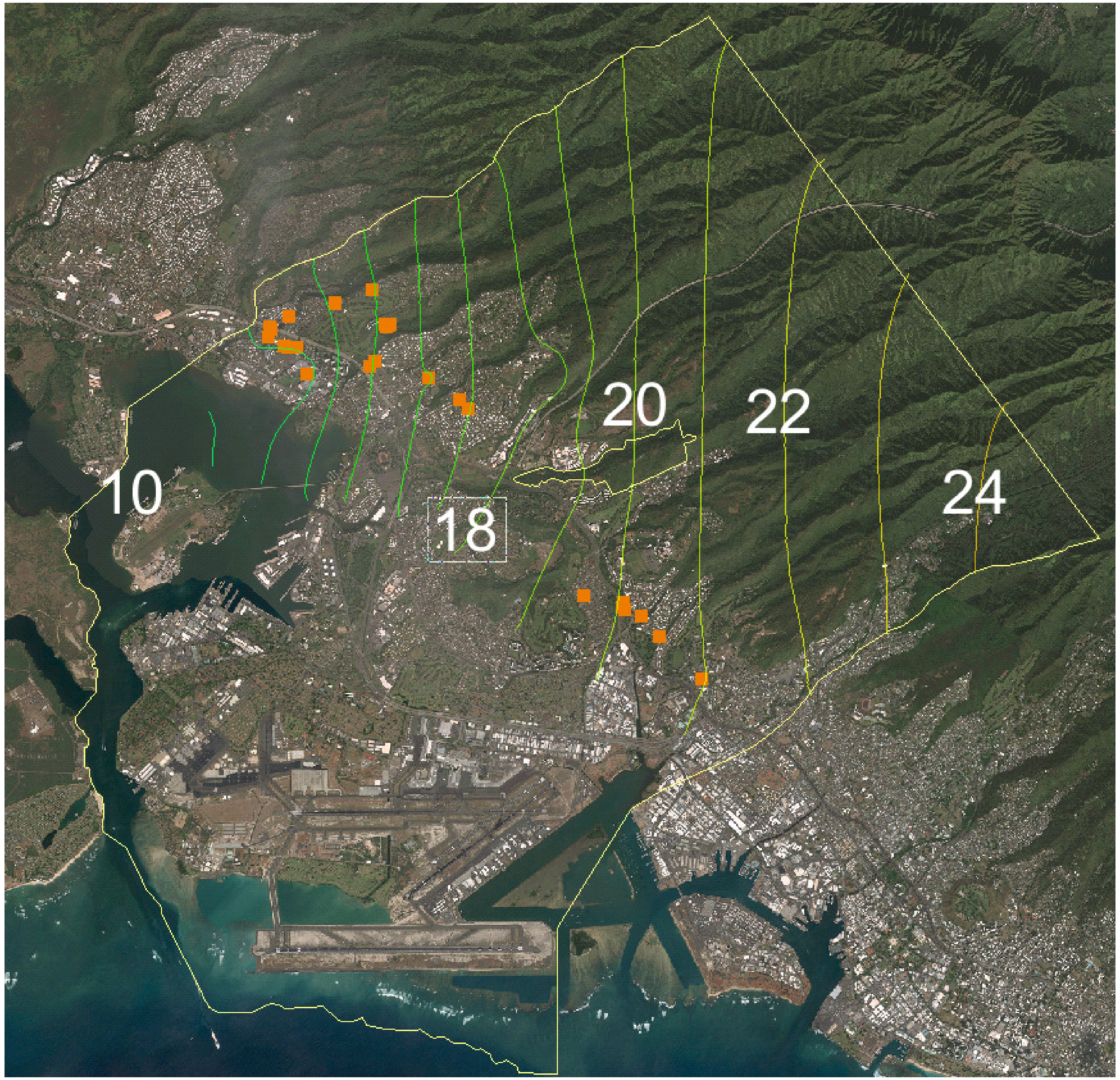
- 50
- 45
- 40
- 35
- 30
- 25
- 20
- 15
- 10
- 5
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

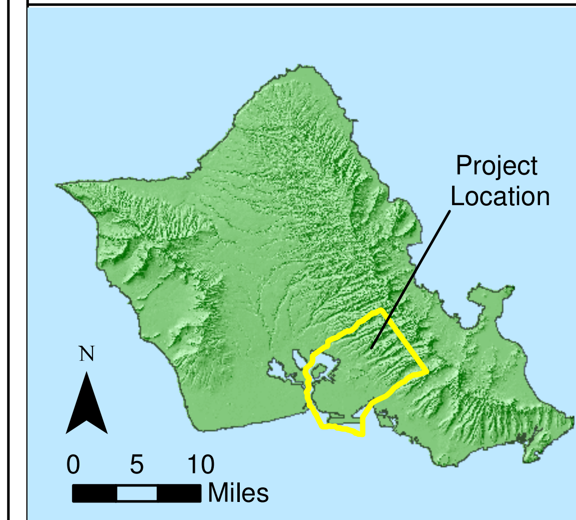
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Key Observation: No simulated water level mounding under saprolite.

Figure 5.6-3
Simulated 2017 Groundwater Elevation Contours in Model Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

Groundwater Contour (feet above mean sea level)

- 50
- 45
- 40
- 35
- 30
- 25
- 20
- 15
- 10
- 5
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Key Observation: No simulated water level mounding under saprolite.

N

0 5,000 10,000 20,000 Feet

Figure 5.6-4
Simulated 2017 Groundwater Elevation Contours in Model Layer 4
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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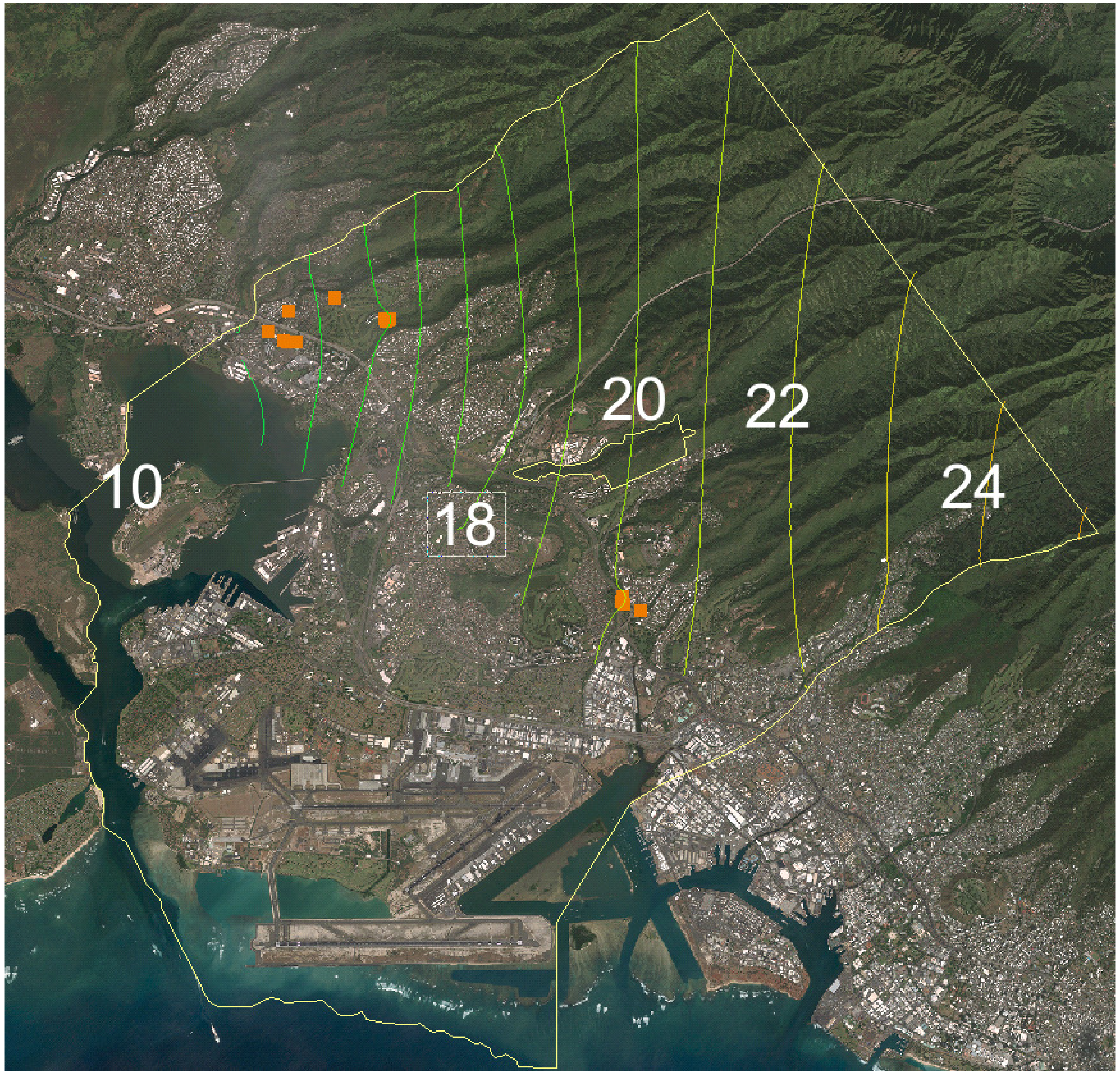
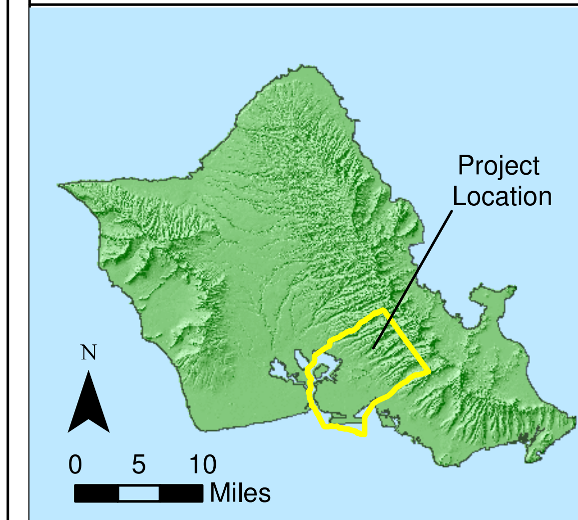


Location Map



Legend

Ground Water Contour (feet above mean sea level)

- 50
- 45
- 40
- 35
- 30
- 25
- 20
- 15
- 10
- 5
- 0

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

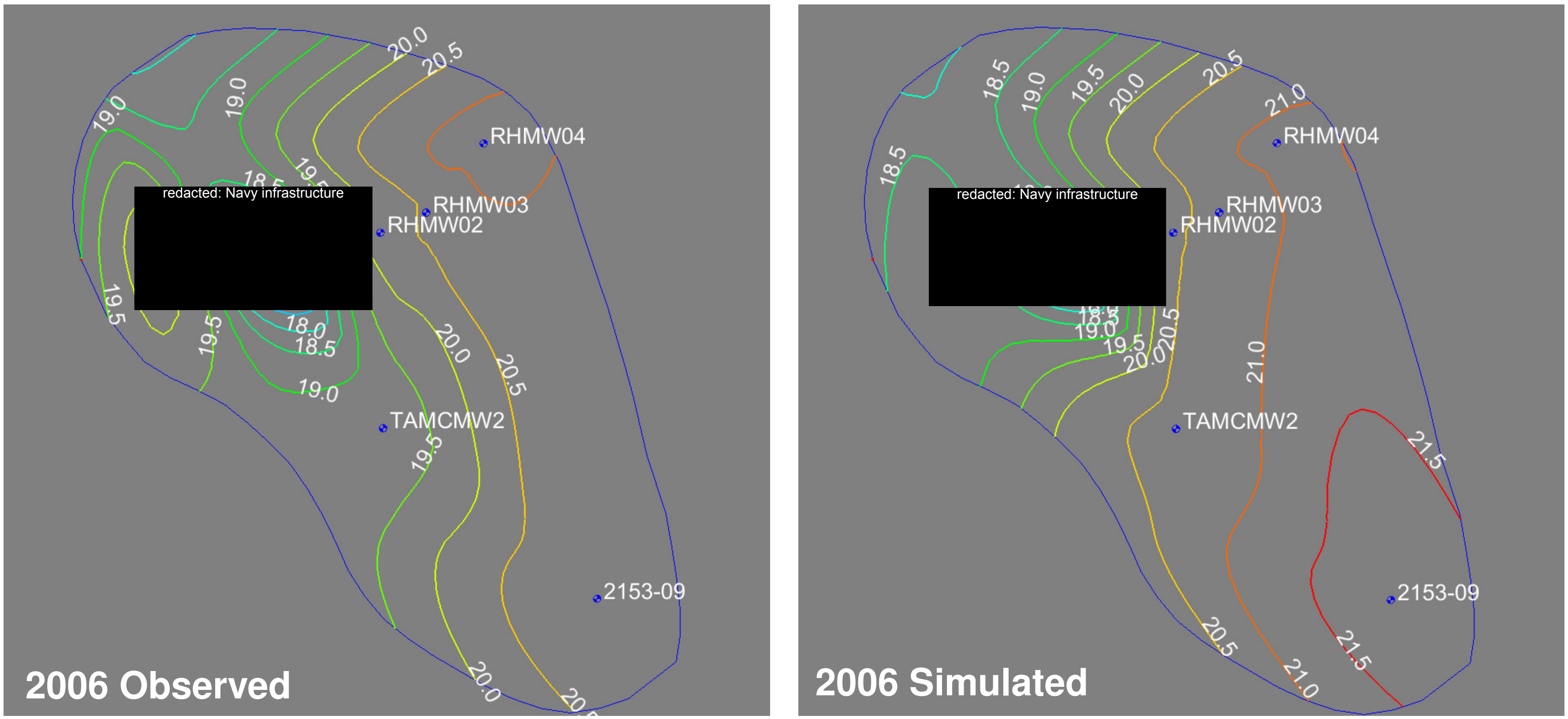
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Key Observation: No simulated water level mounding under saprolite.

N

0 5,000 10,000 20,000 Feet

Figure 5.6-5
Simulated 2017 Groundwater Elevation Contours in Model Layer 5
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Interpolation Methods:

1. TIN interpolation method- Natural neighbor
2. Nodal function- Constant
3. Bounding psuedo point- 10% beyond convex hull

Well

Groundwater contours are in feet above mean sea level.

N

0 1,000 2,000 4,000 Feet

Figure 5.8.2-1
Simulated Groundwater Elevation Contours for 2006 Using TEC 2010 Contouring Approach
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

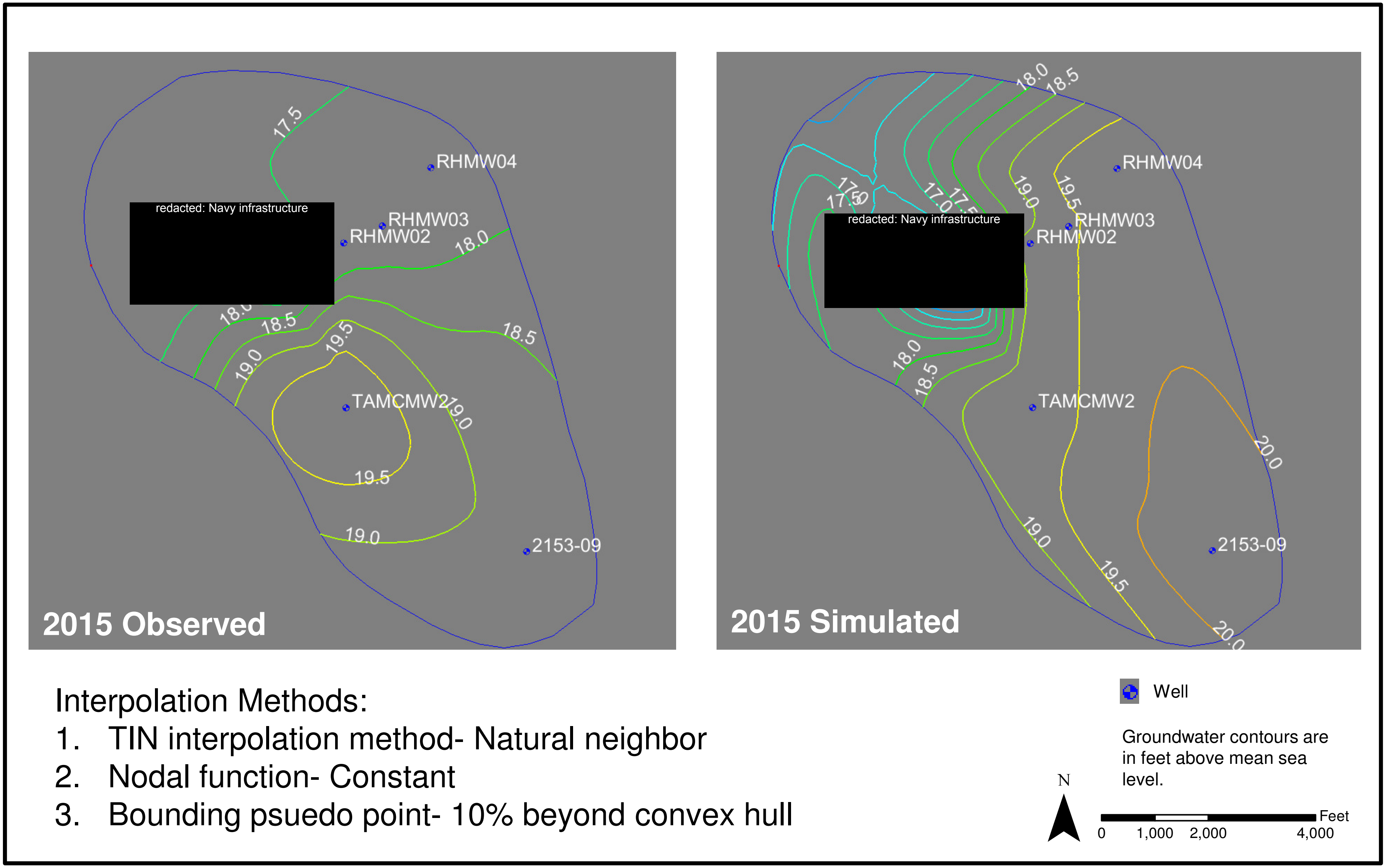
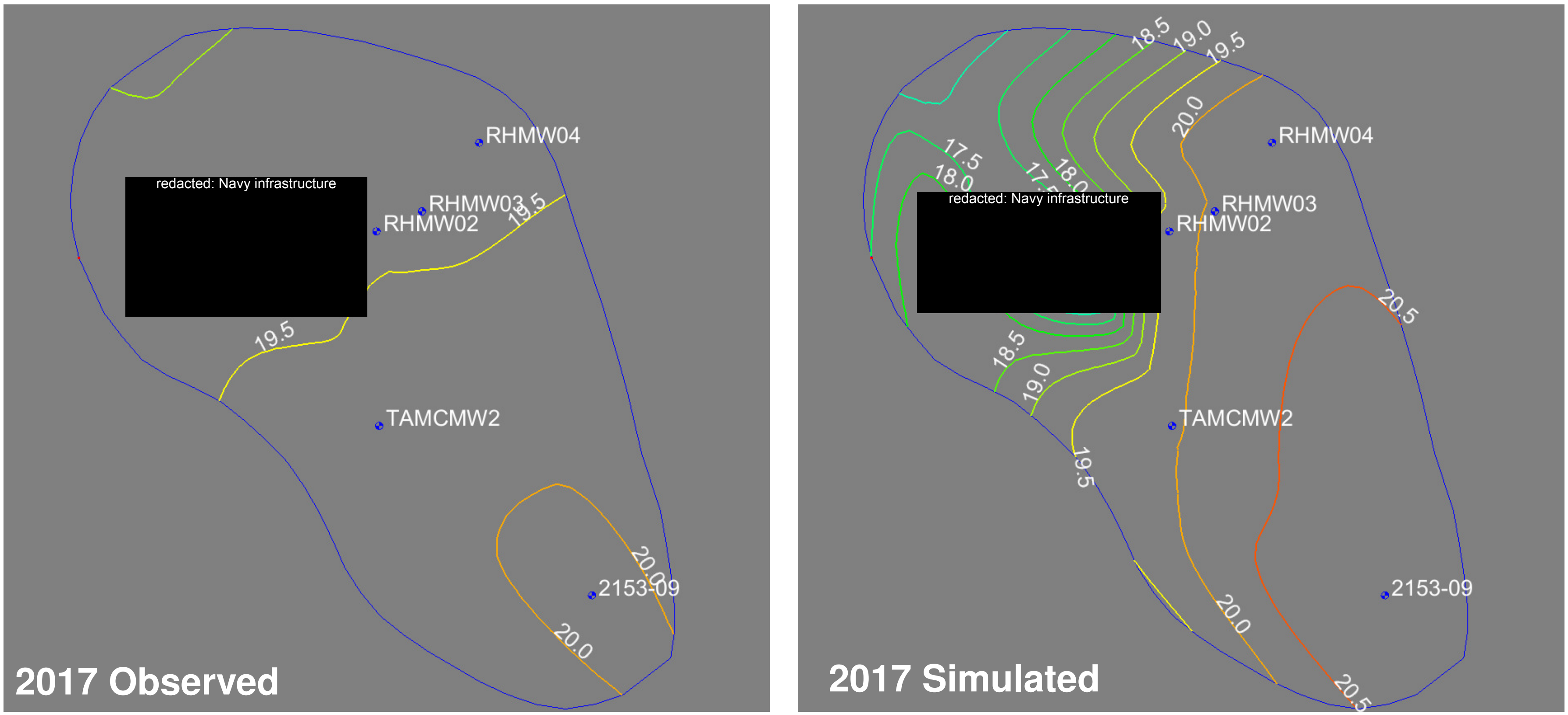


Figure 5.8.2-2
Simulated Groundwater Elevation Contours for 2015 Using TEC 2010 Contouring Approach
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Interpolation Methods:

1. TIN interpolation method- Natural neighbor
2. Nodal function- Constant
3. Bounding psuedo point- 10% beyond convex hull

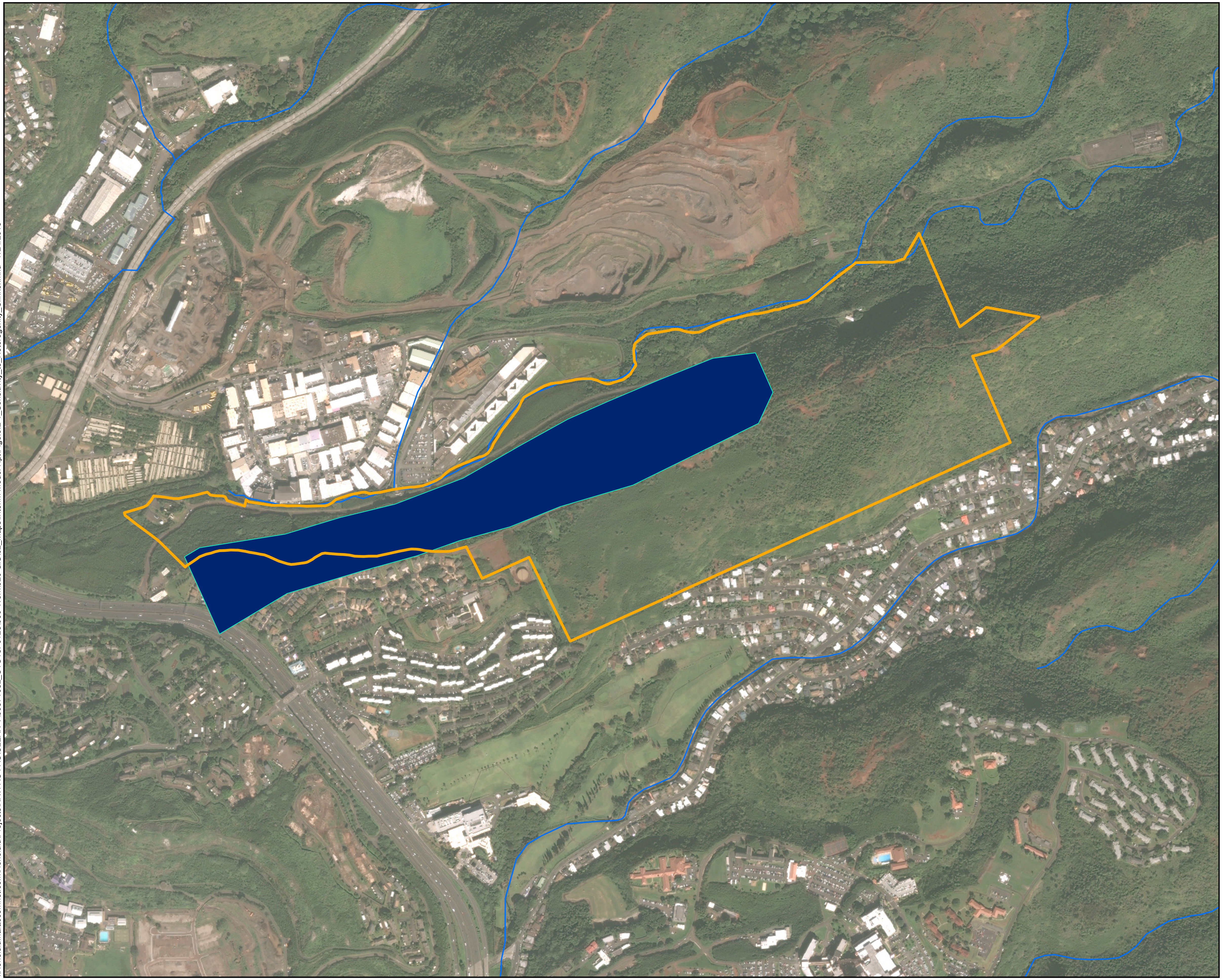
Well

Groundwater contours are in feet above mean sea level.

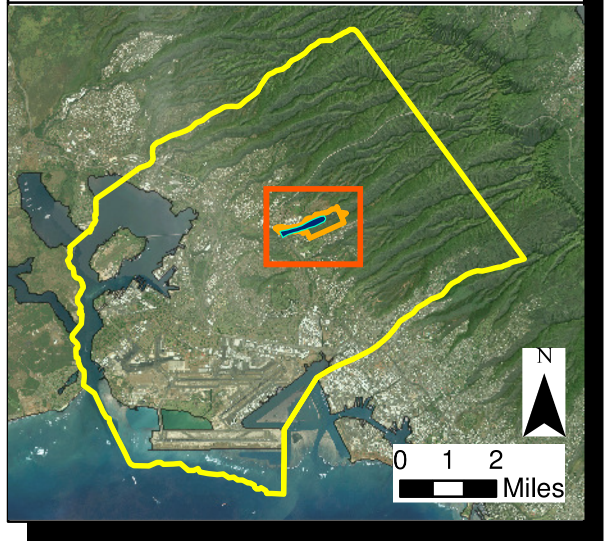
N

Feet
0 1,000 2,000 4,000

Figure 5.8.2-3
Simulated Groundwater Elevation Contours for 2017 Using TEC 2010 Contouring Approach
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



Location Map



Legend

- Clinker
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Area
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

Feet
0 500 1,000 2,000

Figure 5.9.2-1
Sensitivity to Heterogeneity: Location of Clinker
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.9.2-1_Sensitivity_to_Heterogenity_Clinker.mxd 7/24/2018

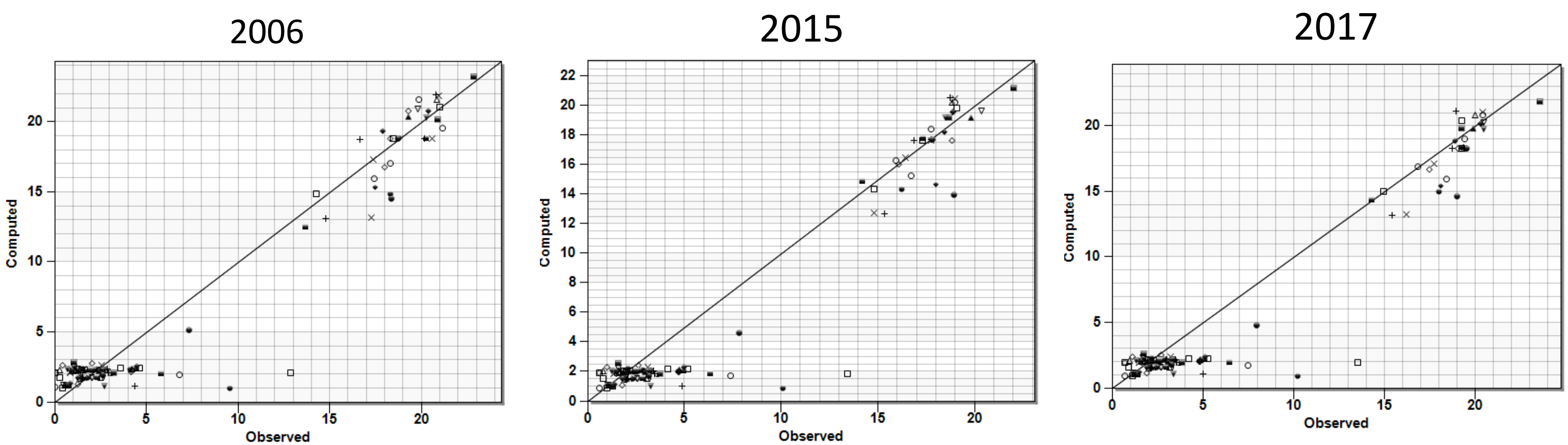
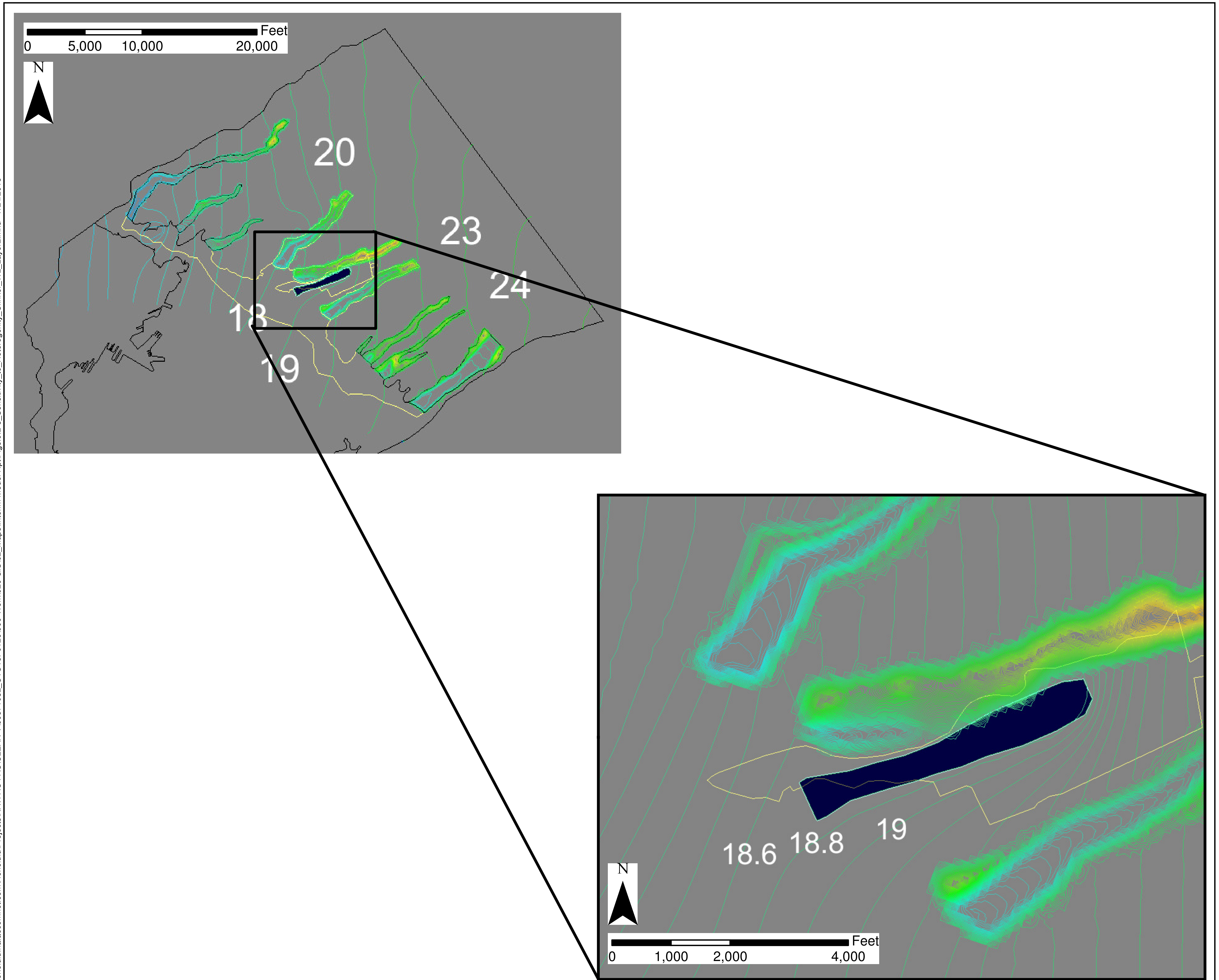
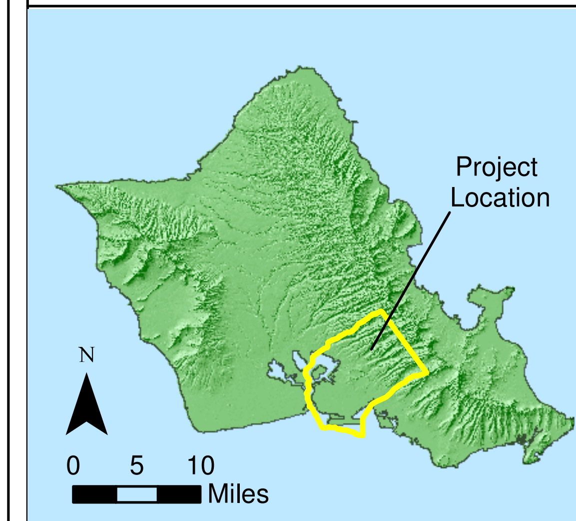


Figure 5.9.2-2
Sensitivity to Heterogeneity: Presence of Clinker – Scatter Plotts
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



Location Map



Legend

- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.2-3
Sensitivity to Heterogeneity: Presence of Clinker - Water Levels in Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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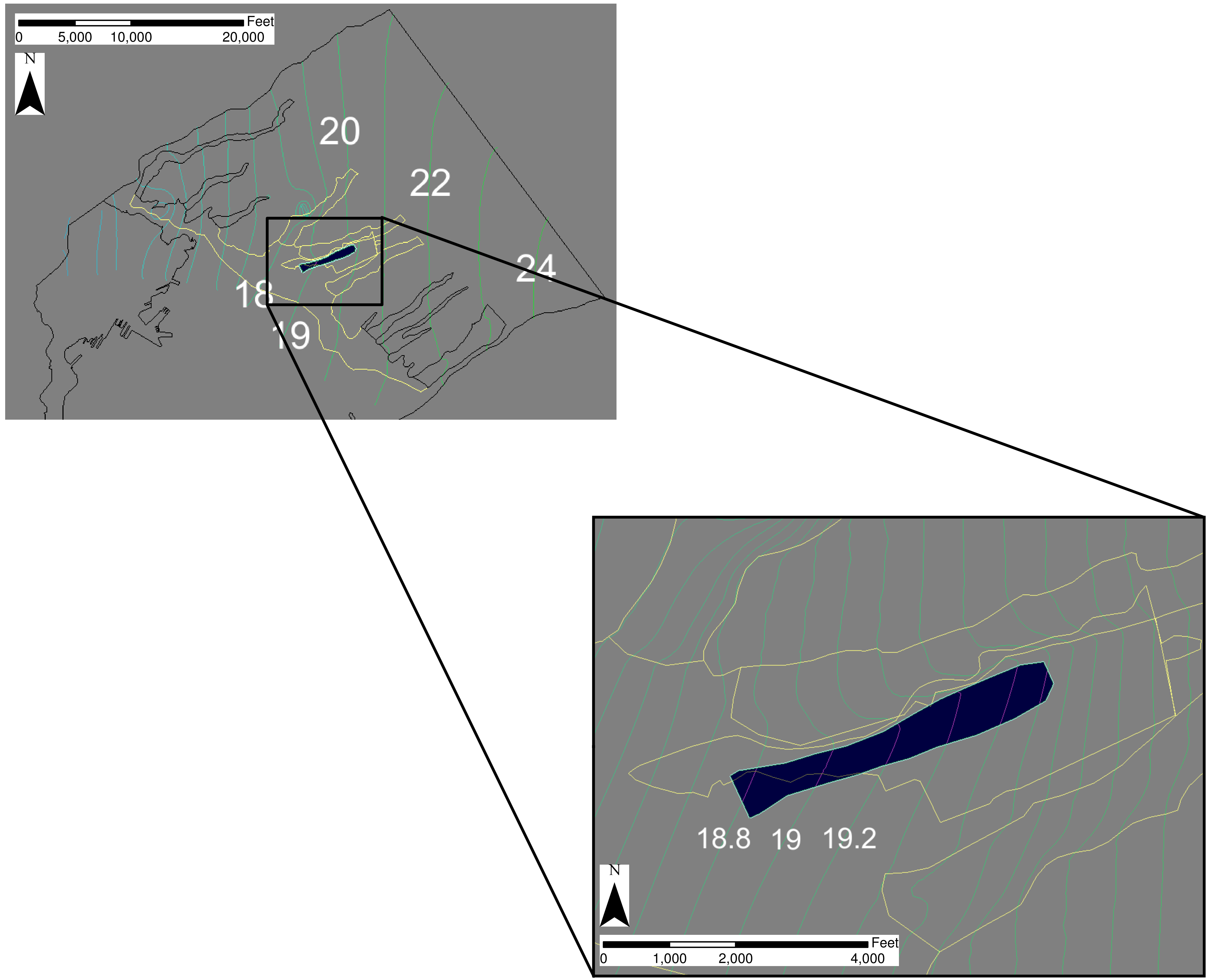
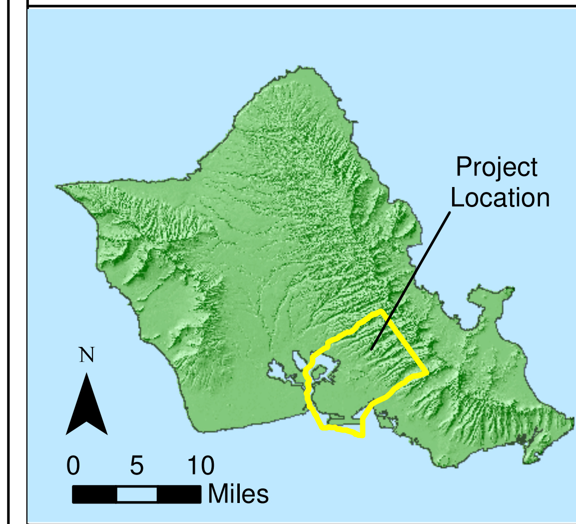


Location Map



Legend

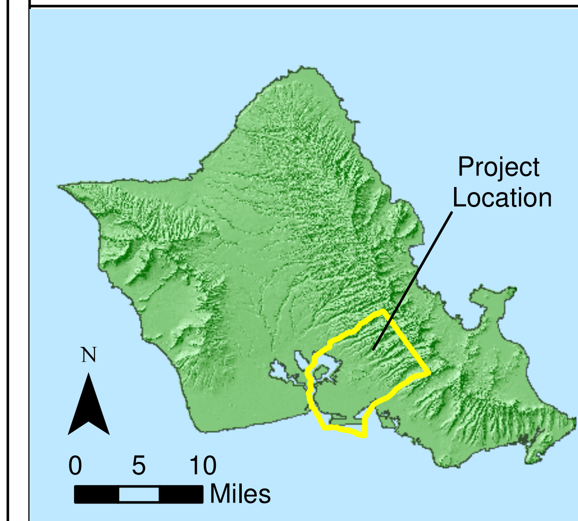
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.2-4
Sensitivity to Heterogeneity: Presence of Clinker - Water Levels in Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

Location Map



Legend

- NW and SE GHB
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

Feet
0 2,500 5,000 10,000

Figure 5.9.3-1
Sensitivity to 2017 GHB Stage (Model #3) - Parameter Values
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.9.3-1_Sensitivity_to_2017_GHB_Stage_Model3.mxd 7/24/2018

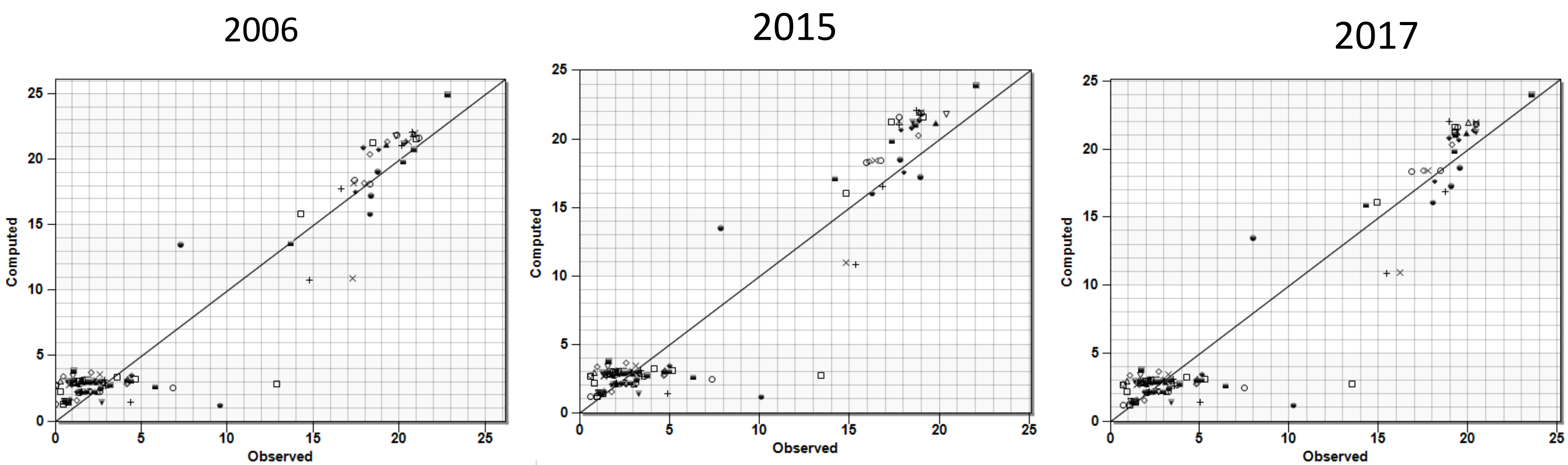
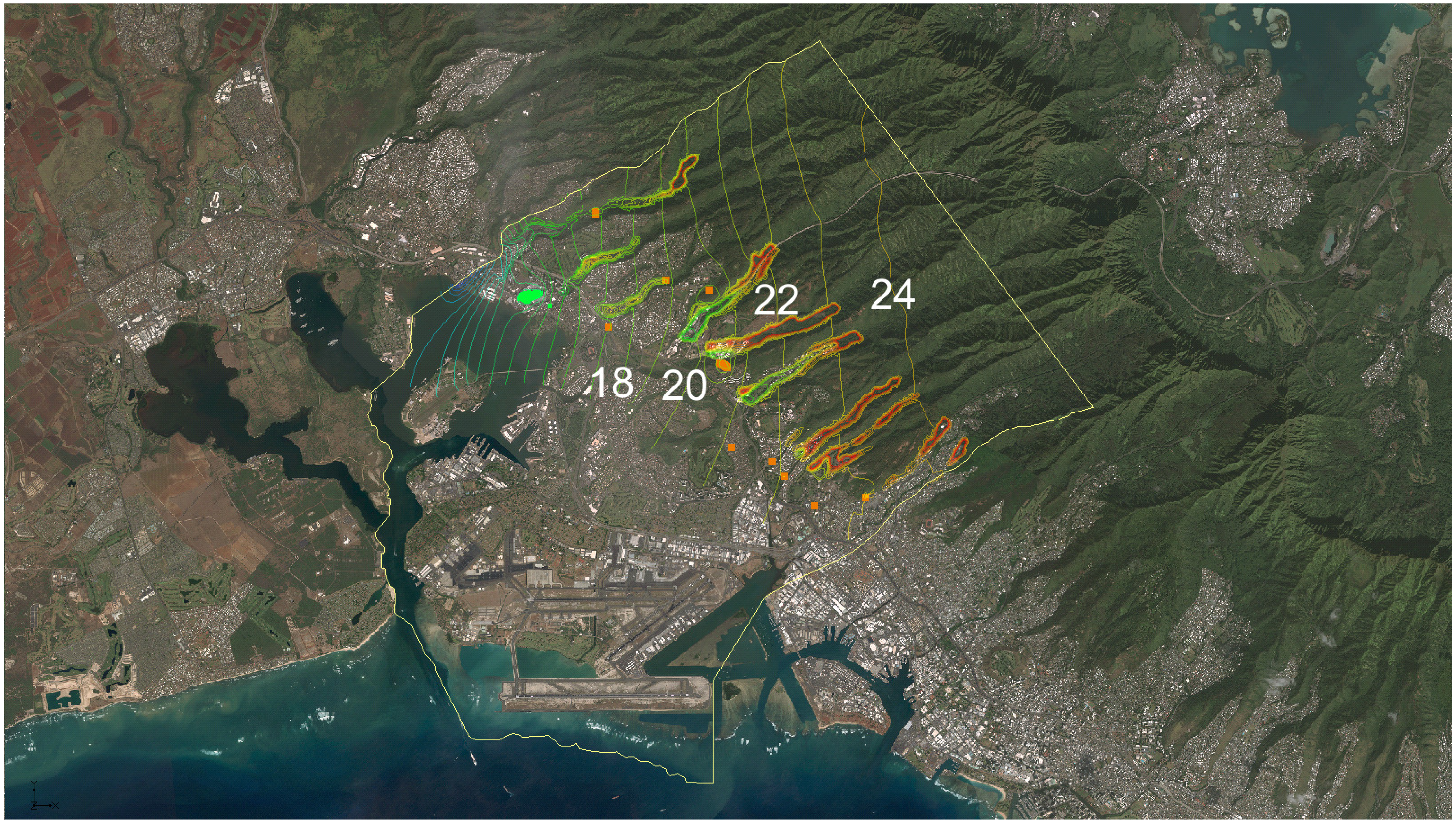
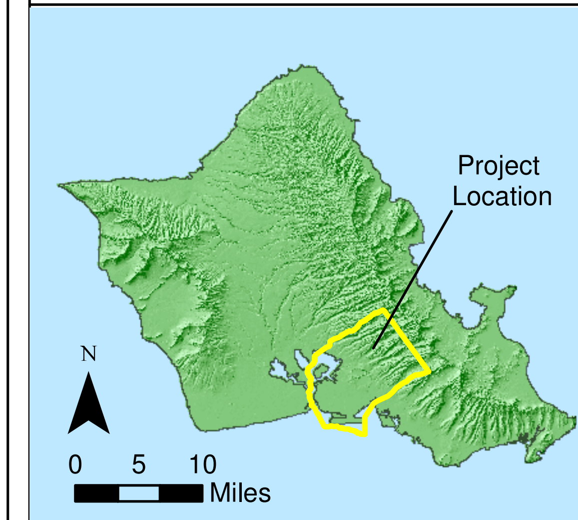


Figure 5.9.3-2
Sensitivity to 2017 GHB Stage (Model #3) – Scatter Plots
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

Model Boundary

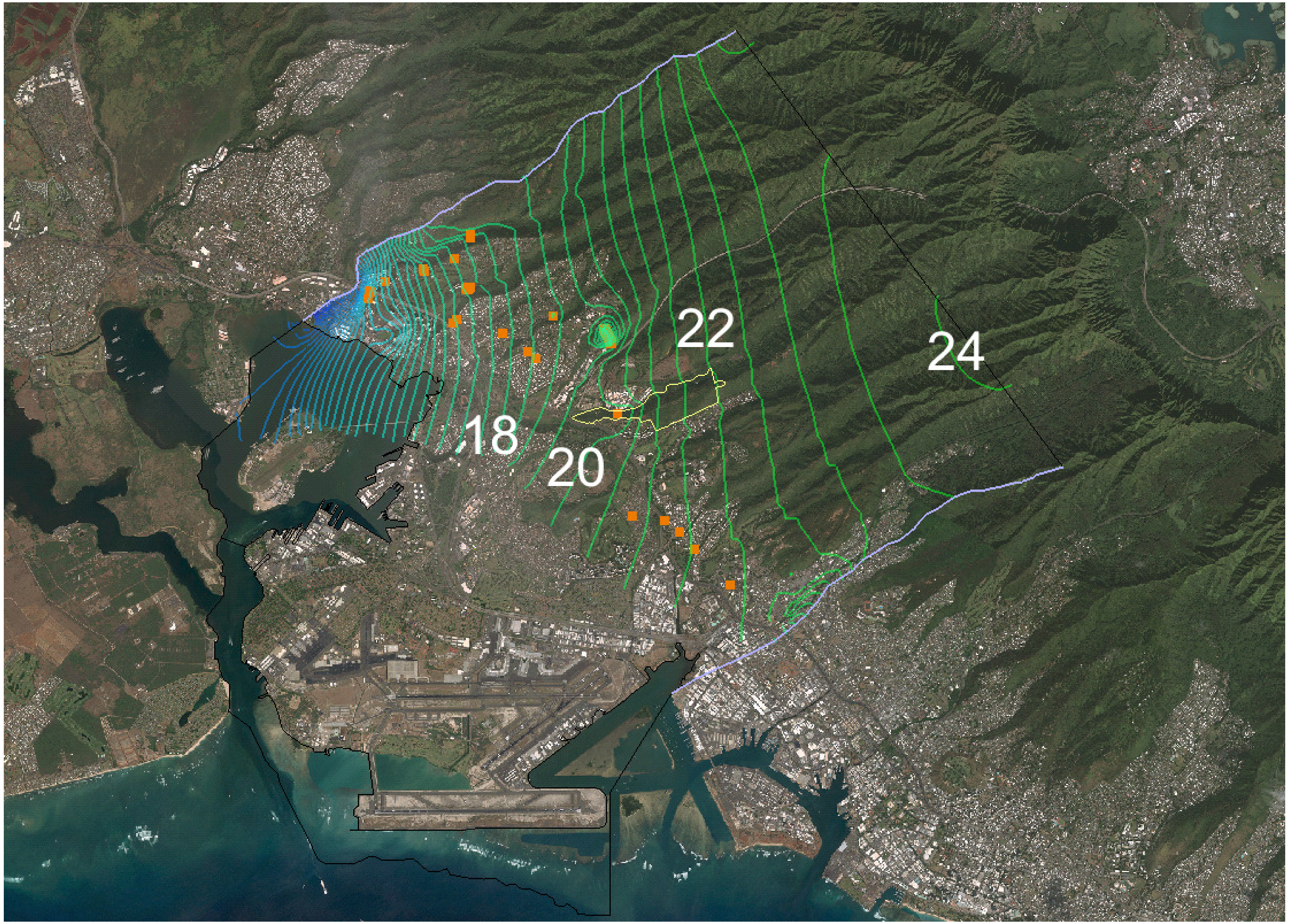
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

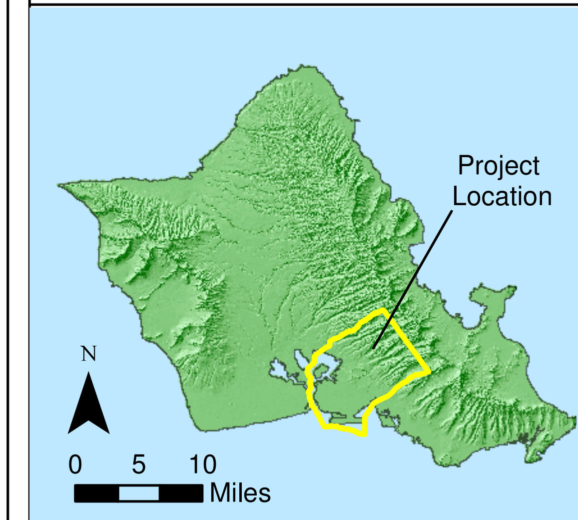
N

0 5,000 10,000 20,000 Feet

Figure 5.9.3-3
Sensitivity to 2017 GHB Stage (Model #3) - Water Level Contours in Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

NW and SE GHB
Red Hill Bulk Fuel Storage Facility Boundary
Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

Feet
0 2,500 5,000 10,000

Figure 5.9.3-4
Sensitivity to 2017 GHB Stage (Model #3) - Water Level Contours in Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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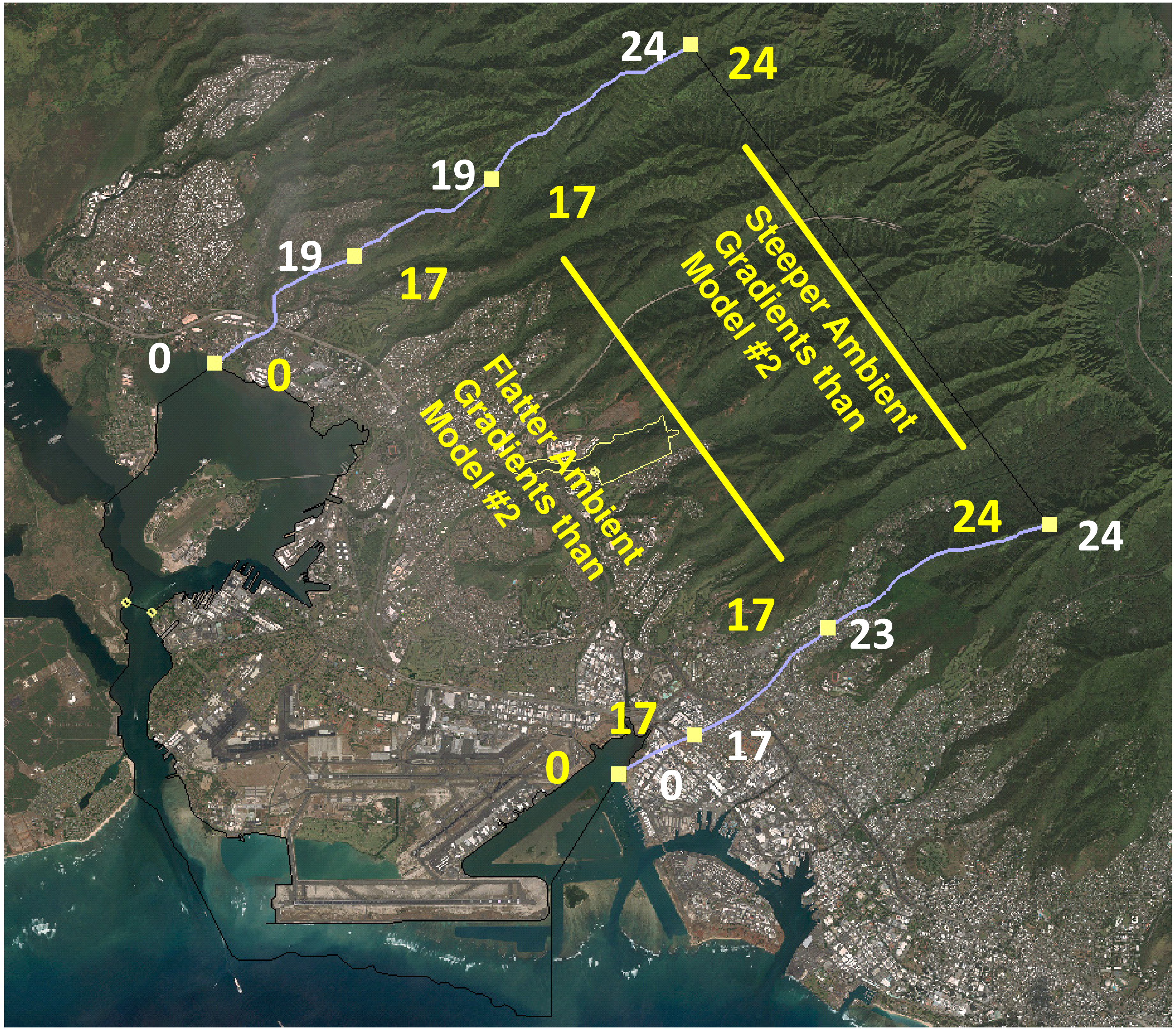
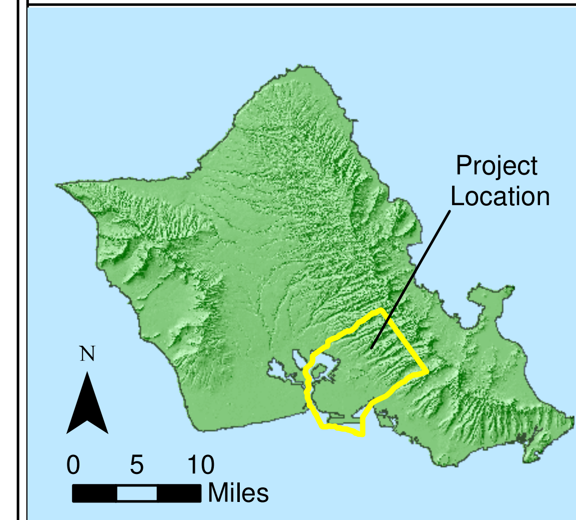


Location Map



Legend

- NW and SE GHB
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

Feet
0 2,500 5,000 10,000

Figure 5.9.4-1
Sensitivity to Lower NW and SE GHB Stage (Model #4) - Parameter Values
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.9.4-1_Sensitivity_to_GHBStage_Model4.mxd 7/24/2018

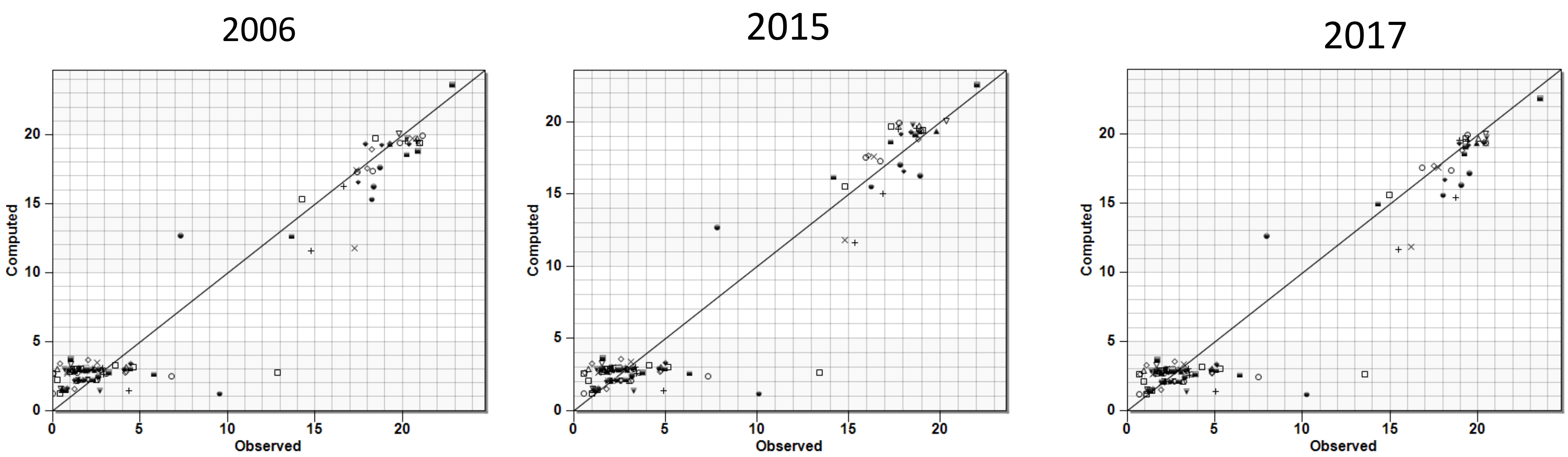
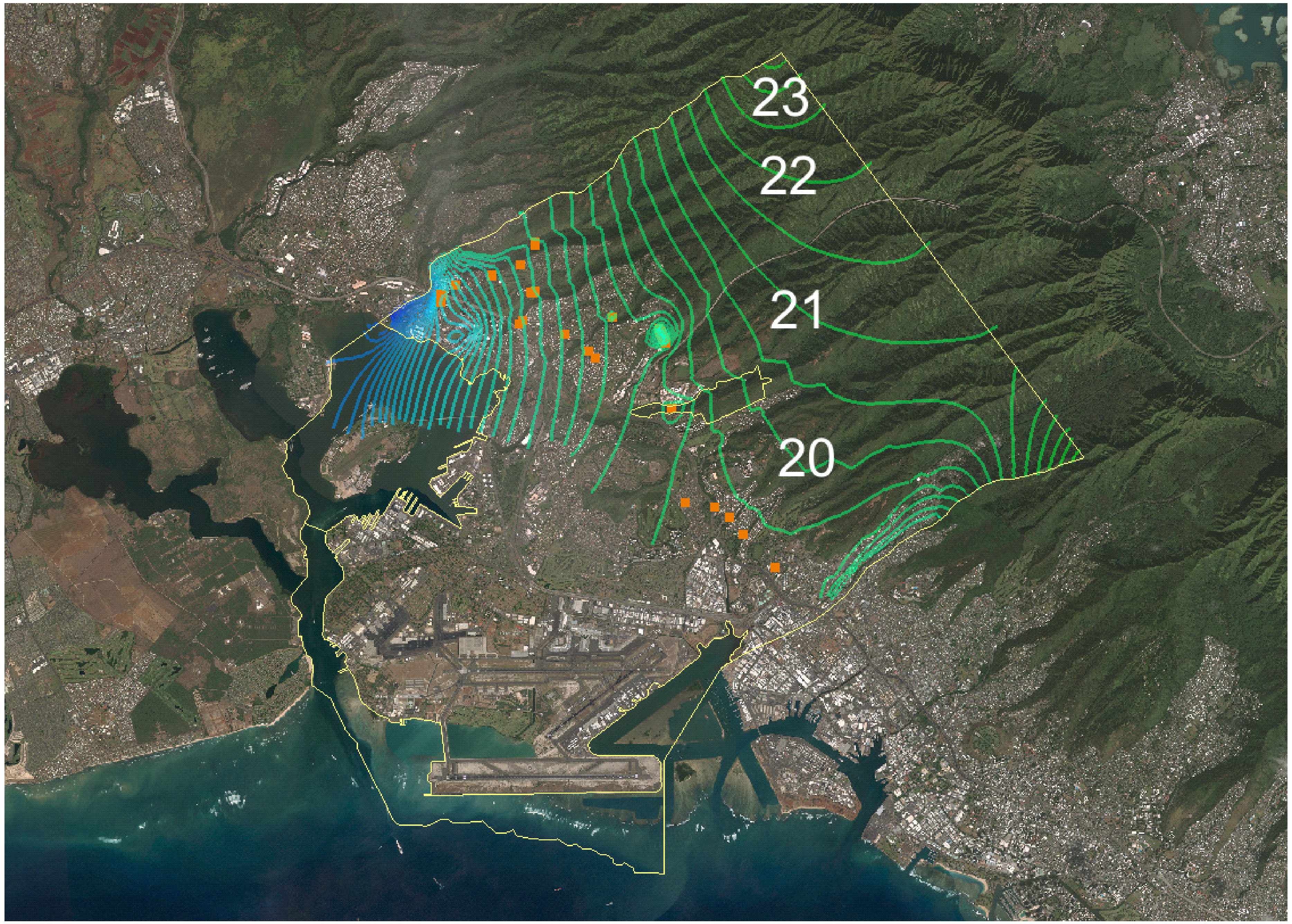
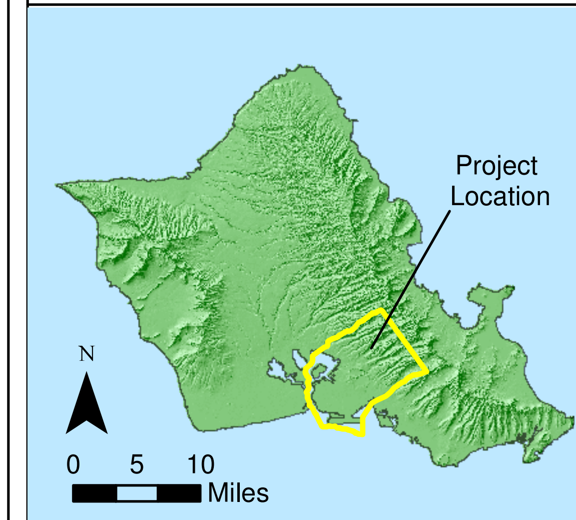


Figure 5.9.4-2
Sensitivity to Lower NW and SE GHB Stage with Higher Conductance (Model 3) – Scatter Plots
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Model Boundary

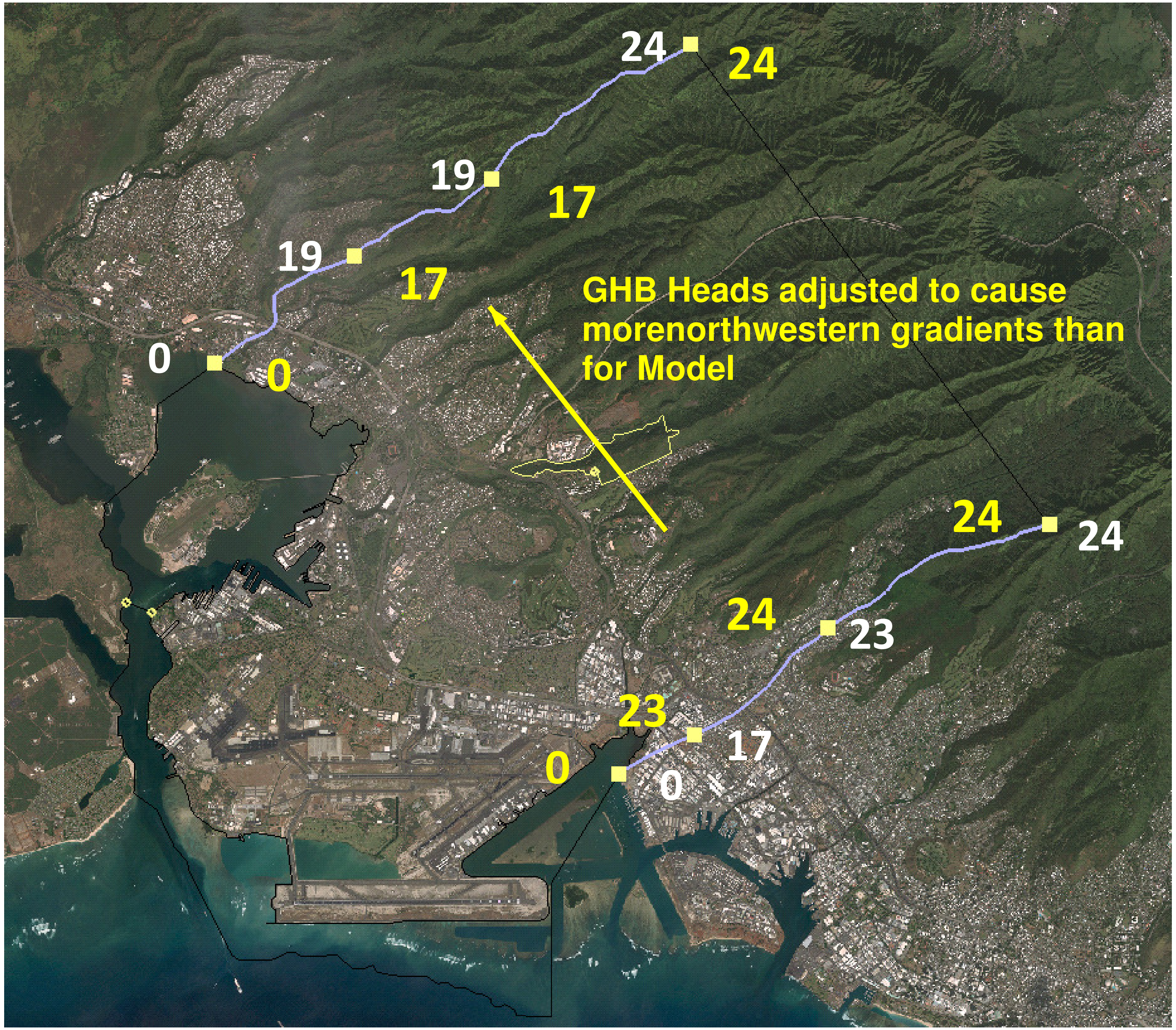
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

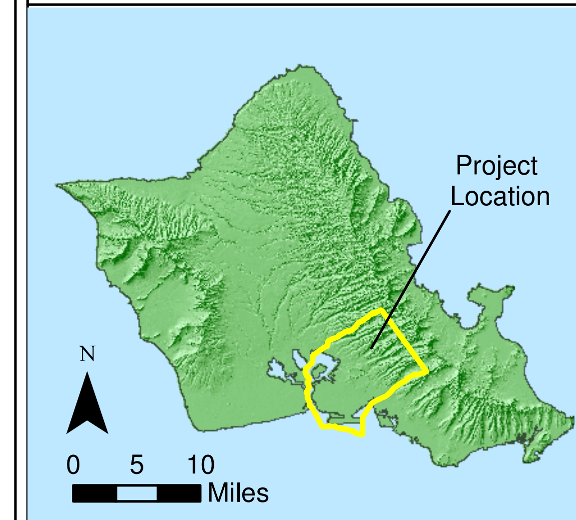
N

Feet
0 5,000 10,000 20,000

Figure 5.9.4-3
Sensitivity to 2017 GHB Stage (Model #4) - Water Level Contours in Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

- NW and SE GHB
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

0 2,500 5,000 10,000 Feet

Figure 5.9.5-1
Sensitivity to Lower NW and SE GHB Stage (Model #5) - Parameter Values
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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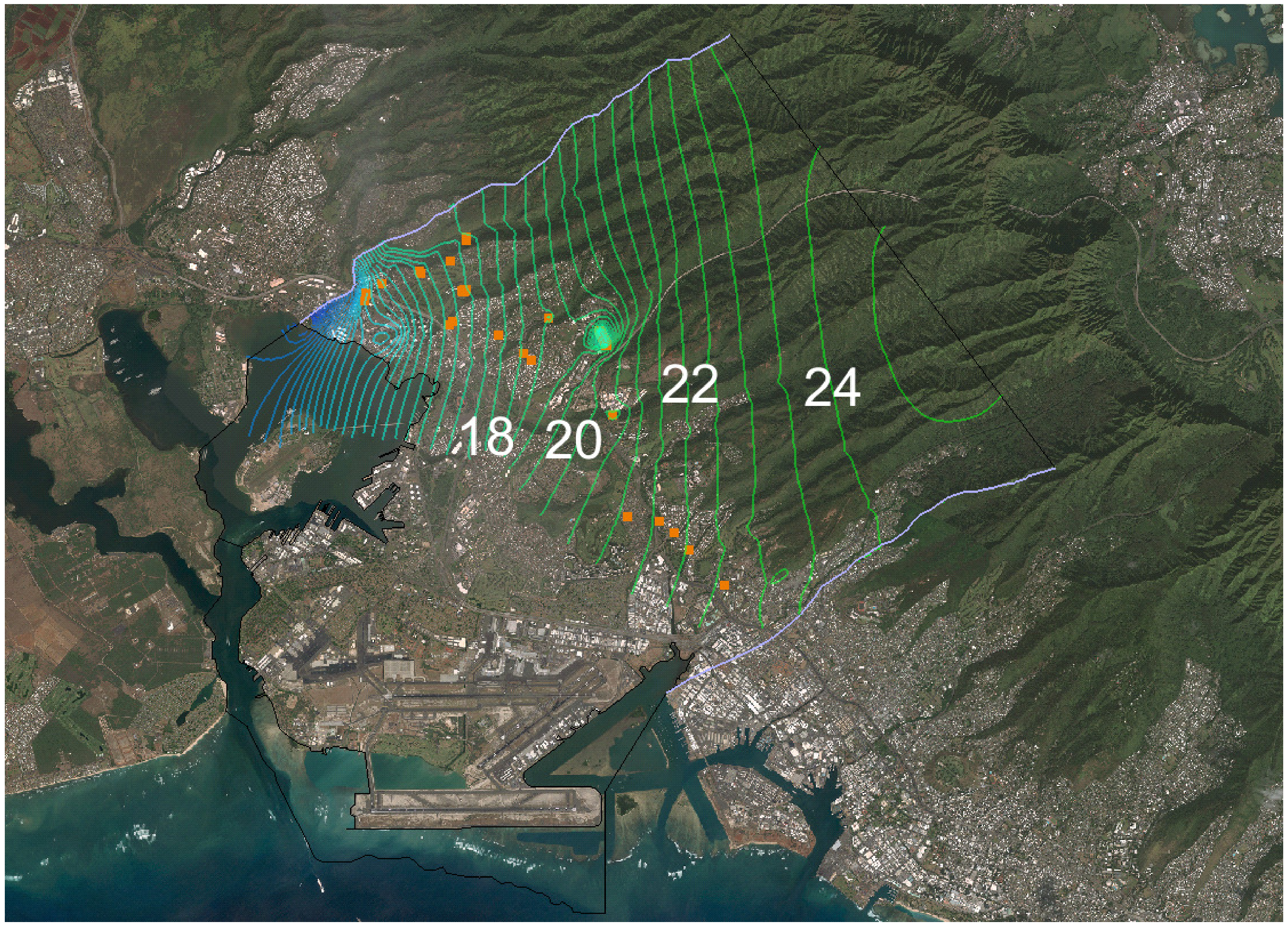
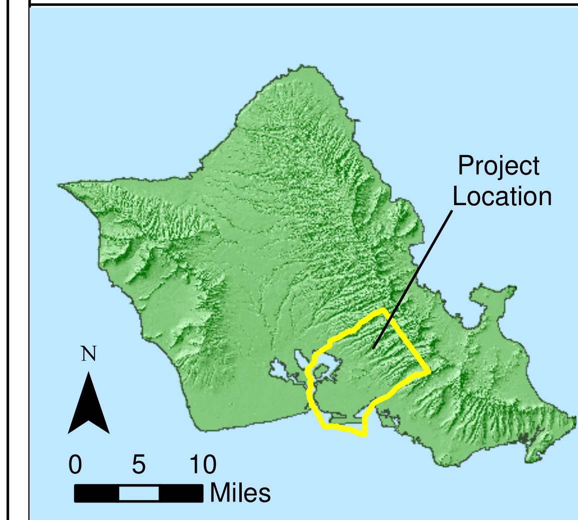


Location Map



Legend

- NW and SE GHB
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

0 5,000 10,000 20,000 Feet

Figure 5.9.5-2
Sensitivity to 2017 Lower NW and Higher SE GHB Stage (Model #5) -
Water Level Contours in Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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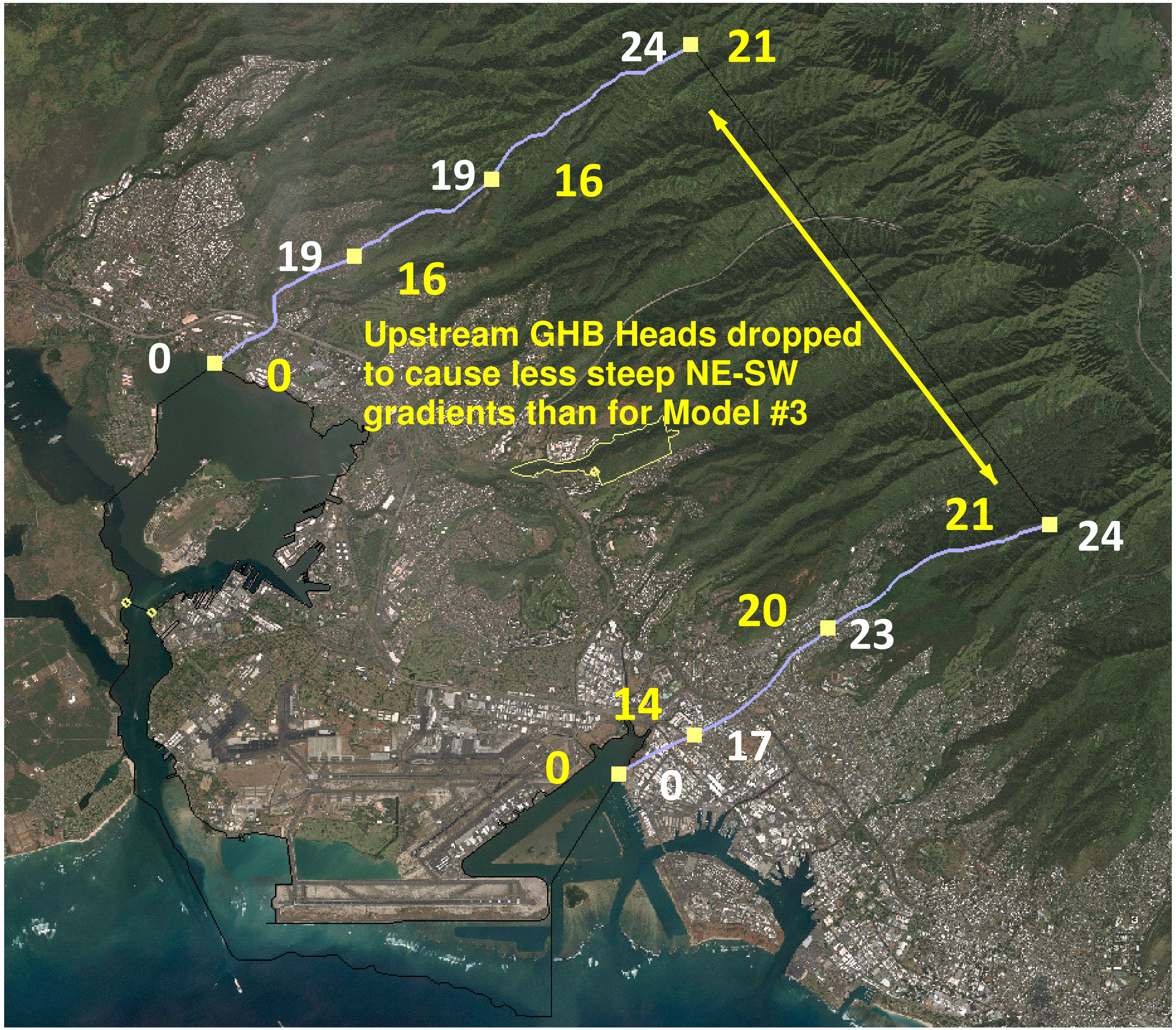
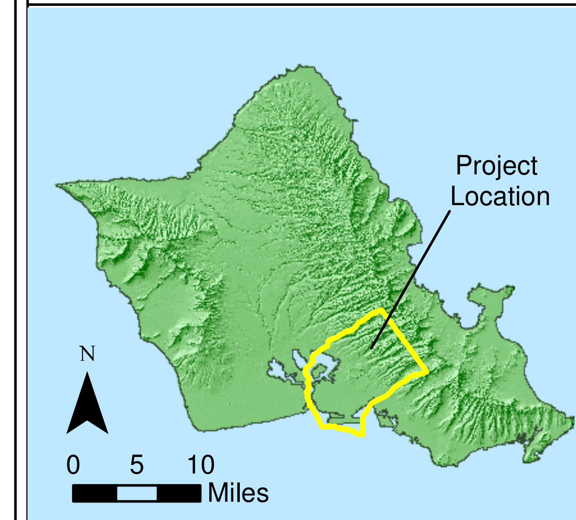


Location Map



Legend

- NW and SE GHB
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

0 2,500 5,000 10,000 Feet

Figure 5.9.6-1
Sensitivity to Lowering NW and SE GHB Stage by 3-Feet (Model #6) - Parameter Values
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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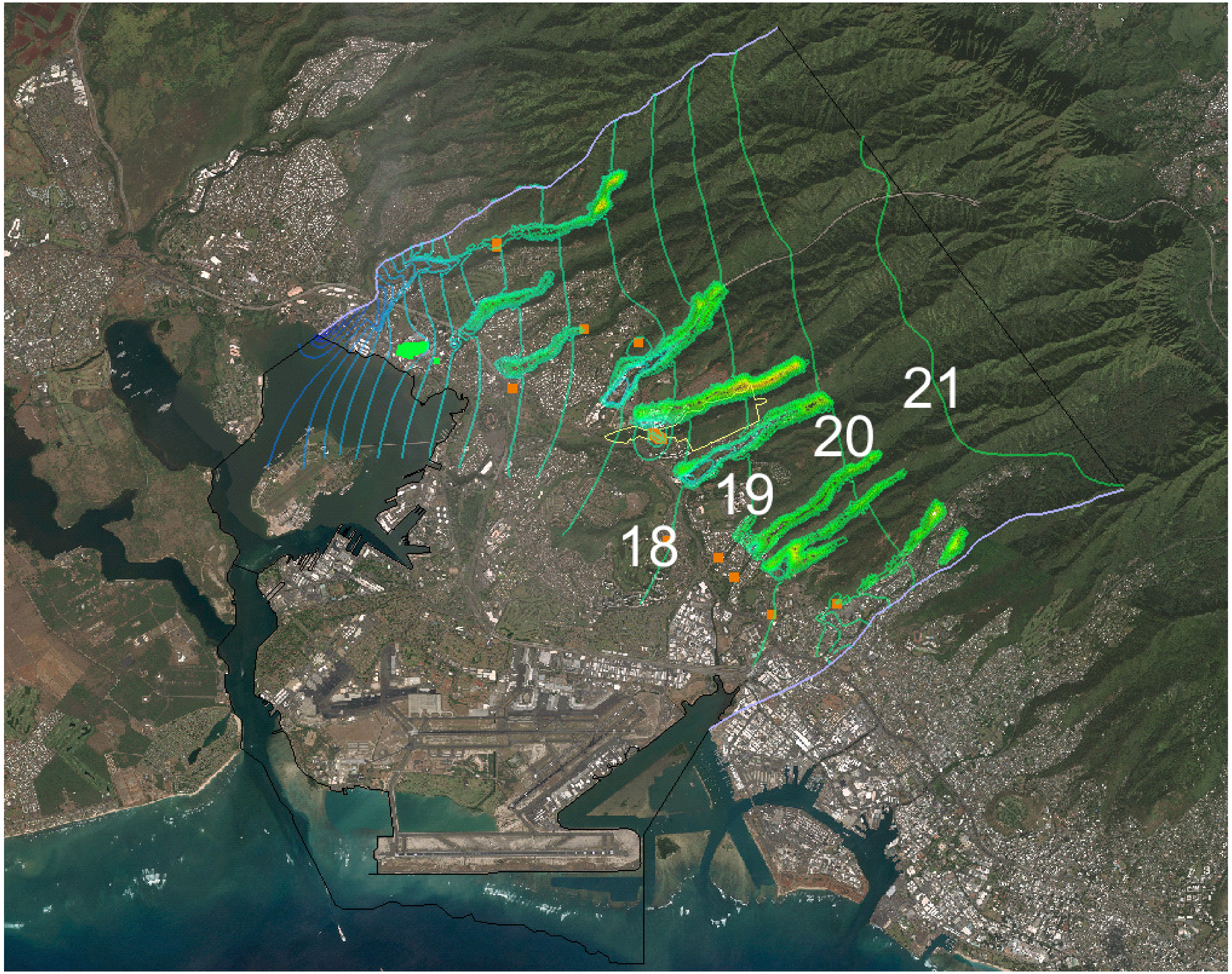
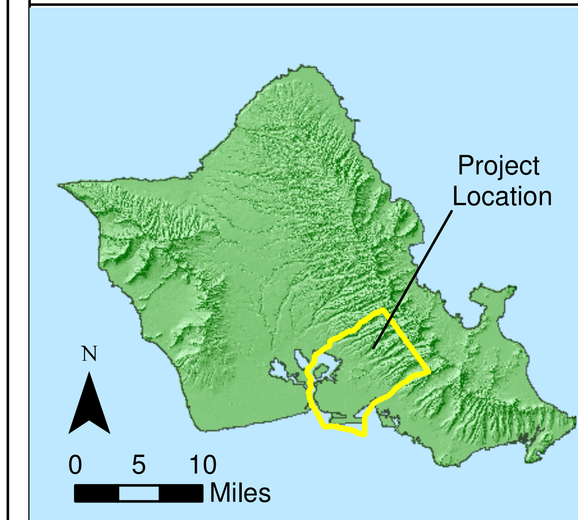


Location Map



Legend

- NW and SE GHB
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

0 2,500 5,000 10,000 Feet

Figure 5.9.6-2
Sensitivity to Lower NW and Higher SE GHB Stage (Model #6) - Water Level in Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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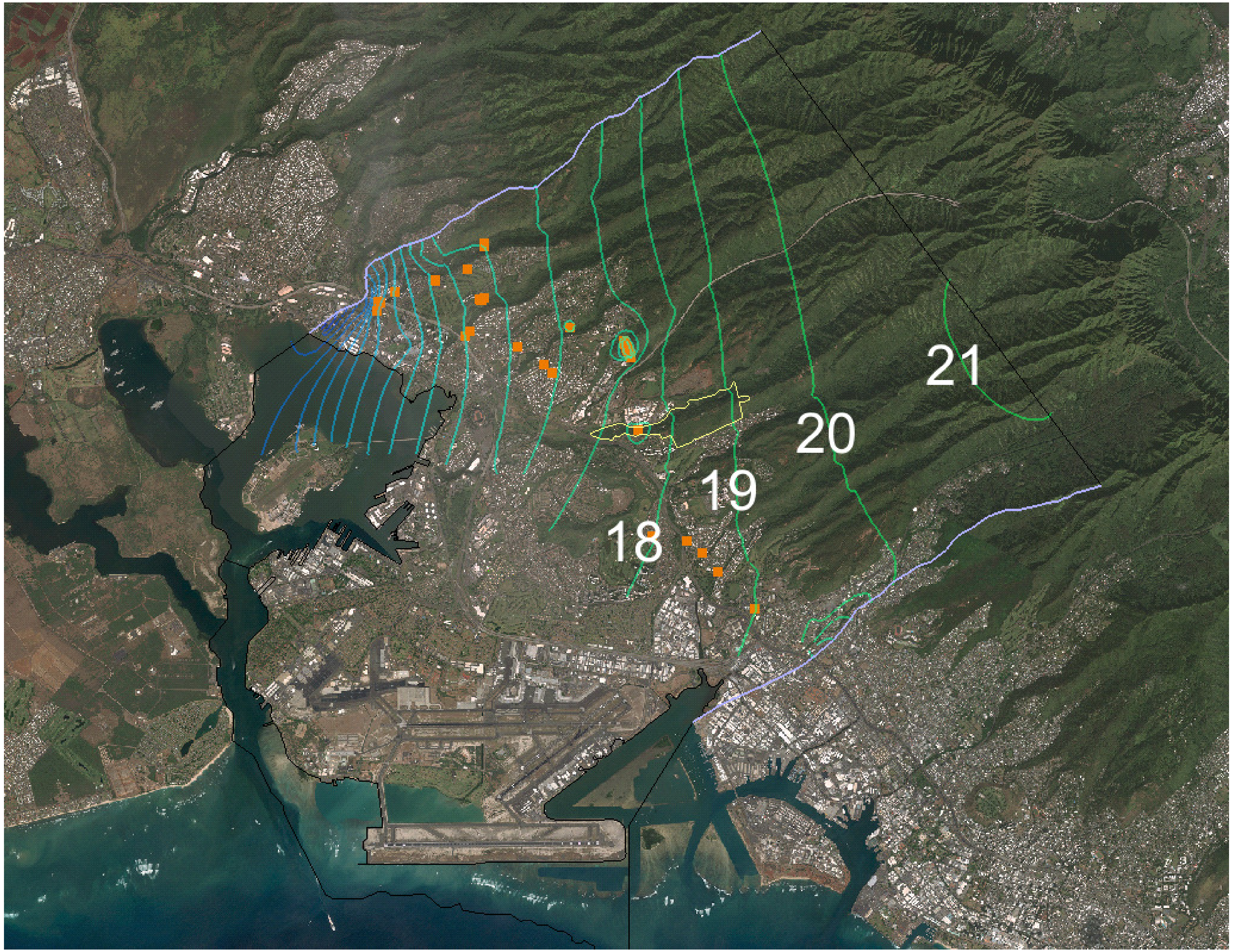
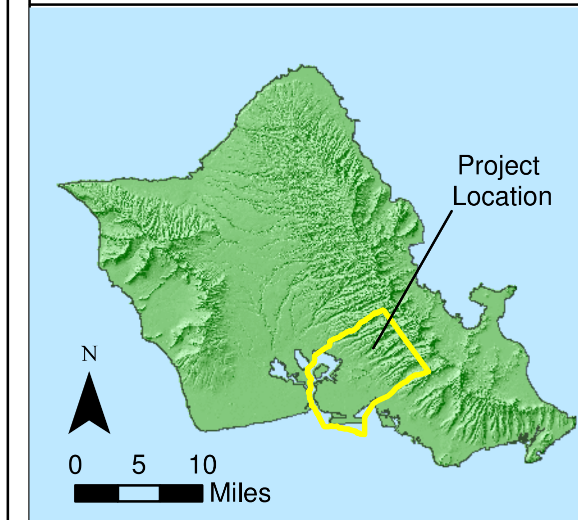


Location Map



Legend

- NW and SE GHB
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

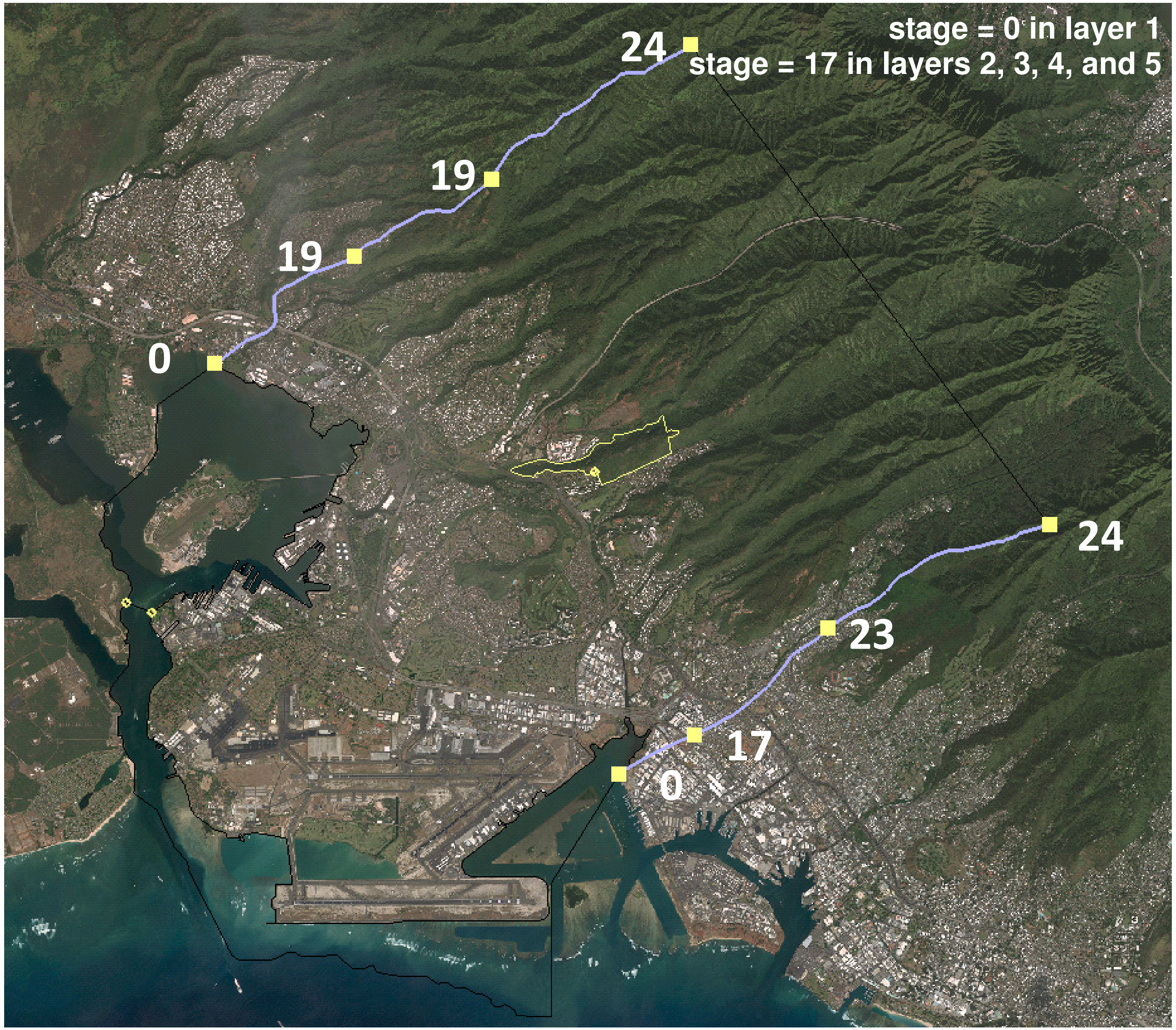
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

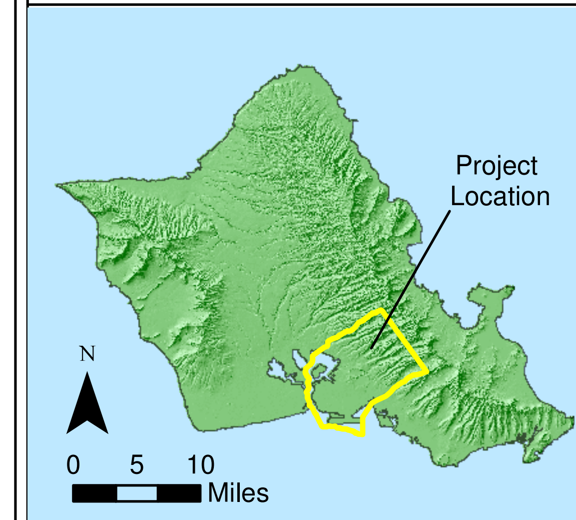
N

0 2,500 5,000 10,000 Feet

Figure 5.9.6-3
Sensitivity to Lower NW and Higher SE GHB Stage (Model #6) - Water Level in Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

- NW and SE GHB
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

N

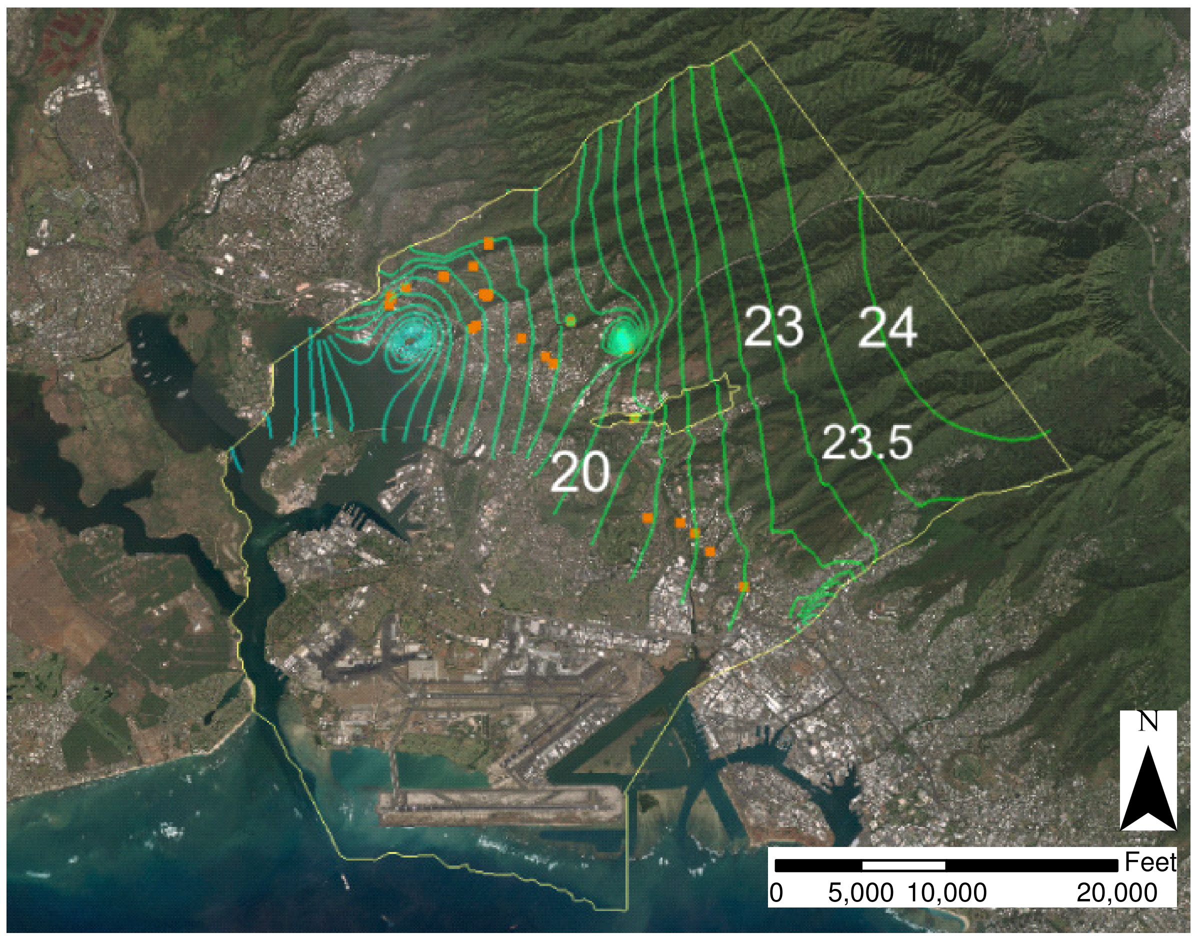
0 2,500 5,000 10,000 Feet

Figure 5.9.7-1
Sensitivity to 2017 Interpolated NW and SE GHB Stage with Higher NW Basalt Stage (Model #7) - Parameter Values
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

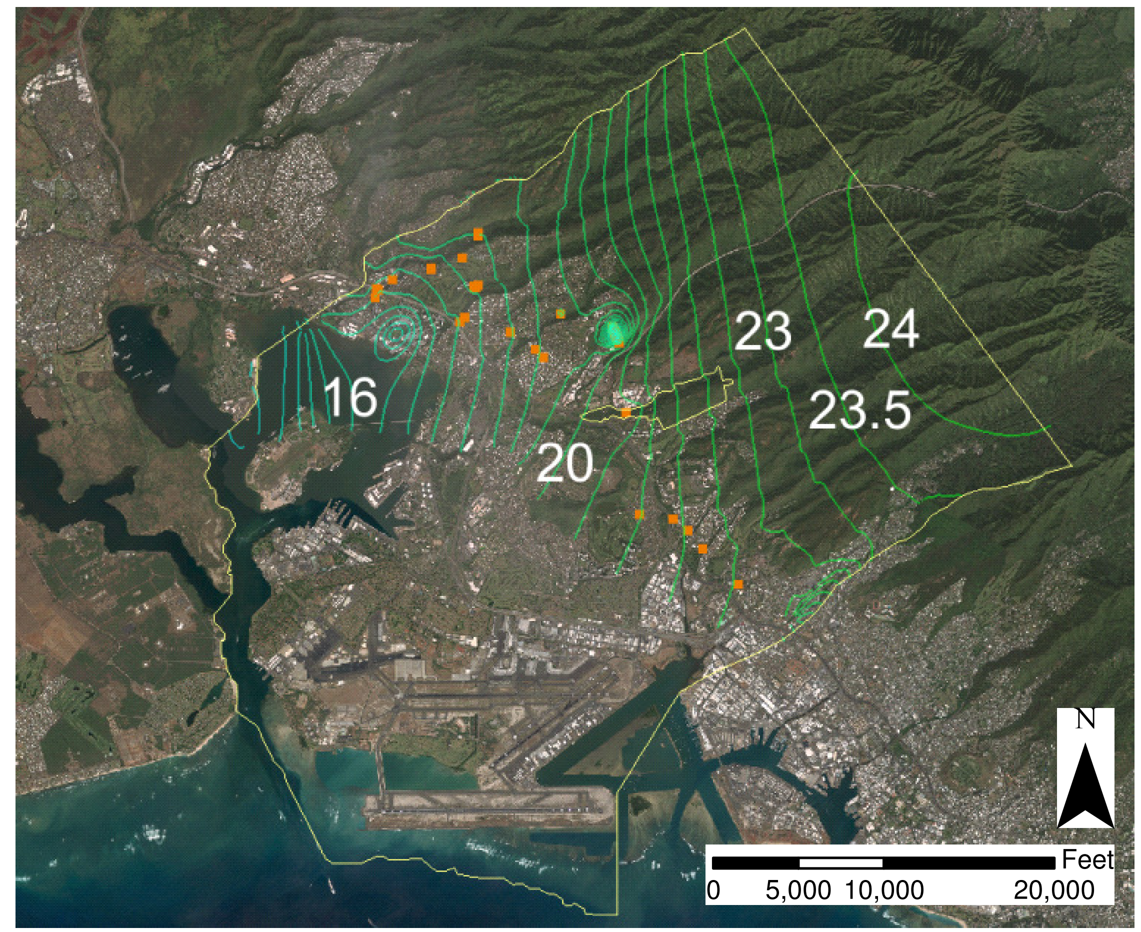
\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.9.7-1_Sensitivity_to_2017_Interp_GHB_HigherNW_Basalt_Model7.mxd 7/24/2018

\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig5.9.7-2_Sensitivity_to_Lower_NW_Higher_SE_Model7_Laye3.mxd 7/24/2018

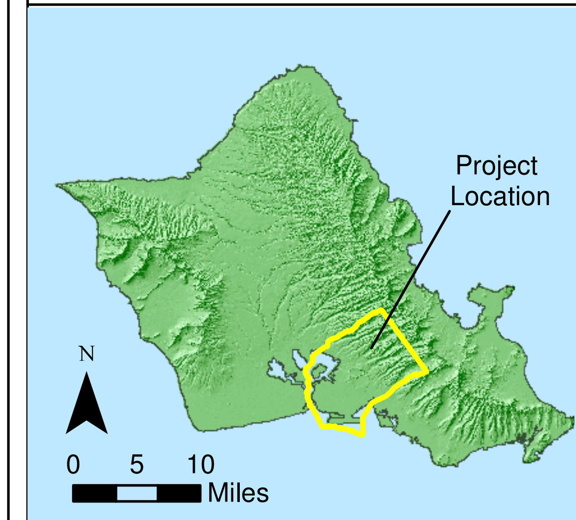
Sensitivity Model # 7



Recalibrated Model # 7



Location Map



Legend

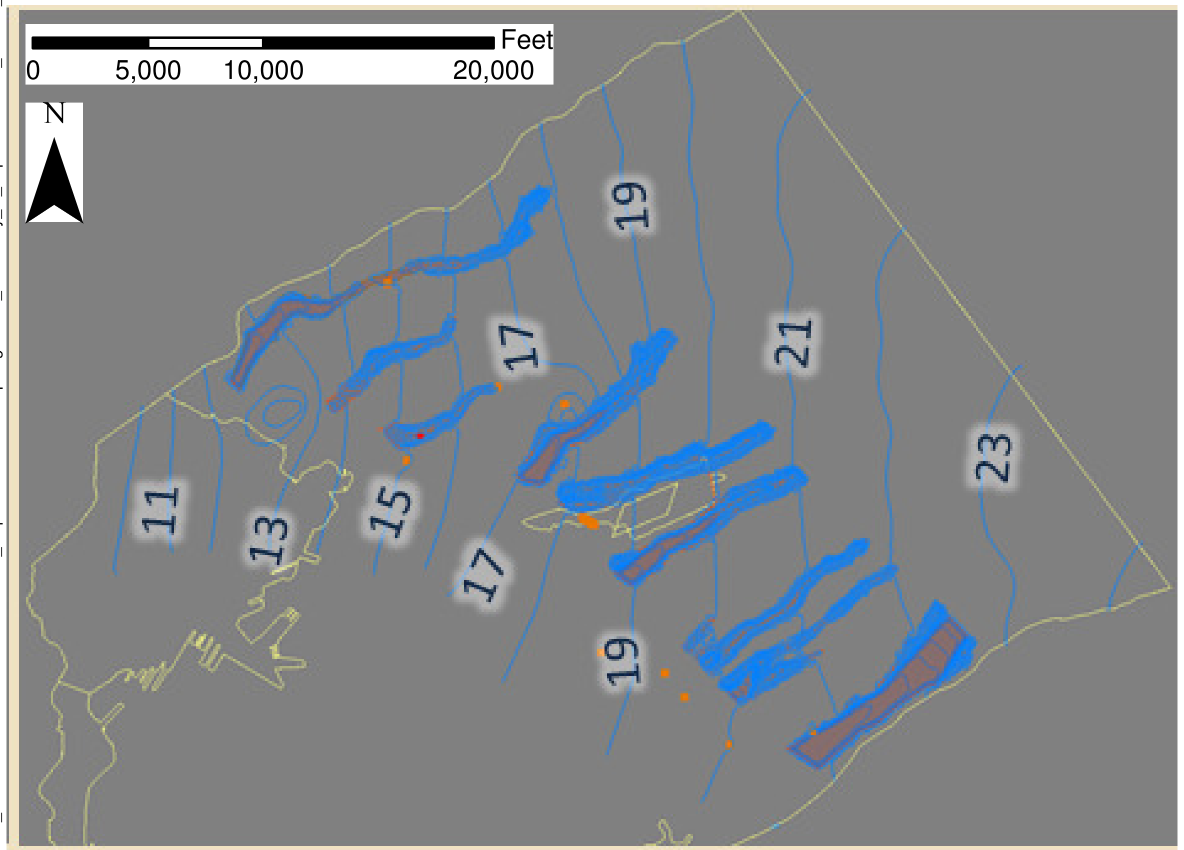
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

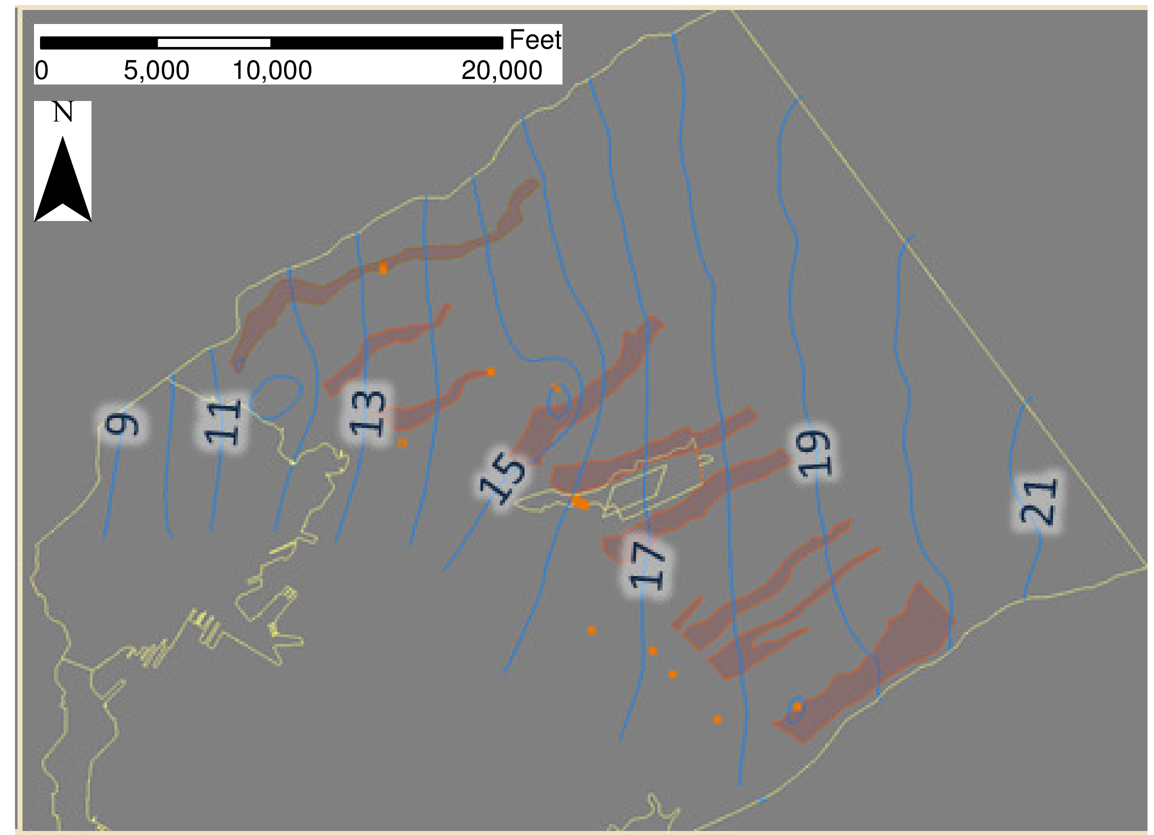
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.
4. Contours are in 0.5 ft intervals.

Figure 5.9.7-2
Sensitivity to Lower NW and Higher SE GHB Stage with Higher NW Basalt Stage (Model #7) - Water Levels in Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

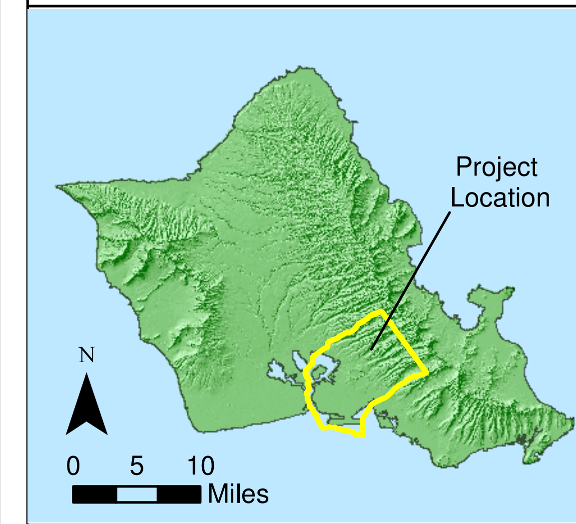
Model #1



Model #8



Location Map



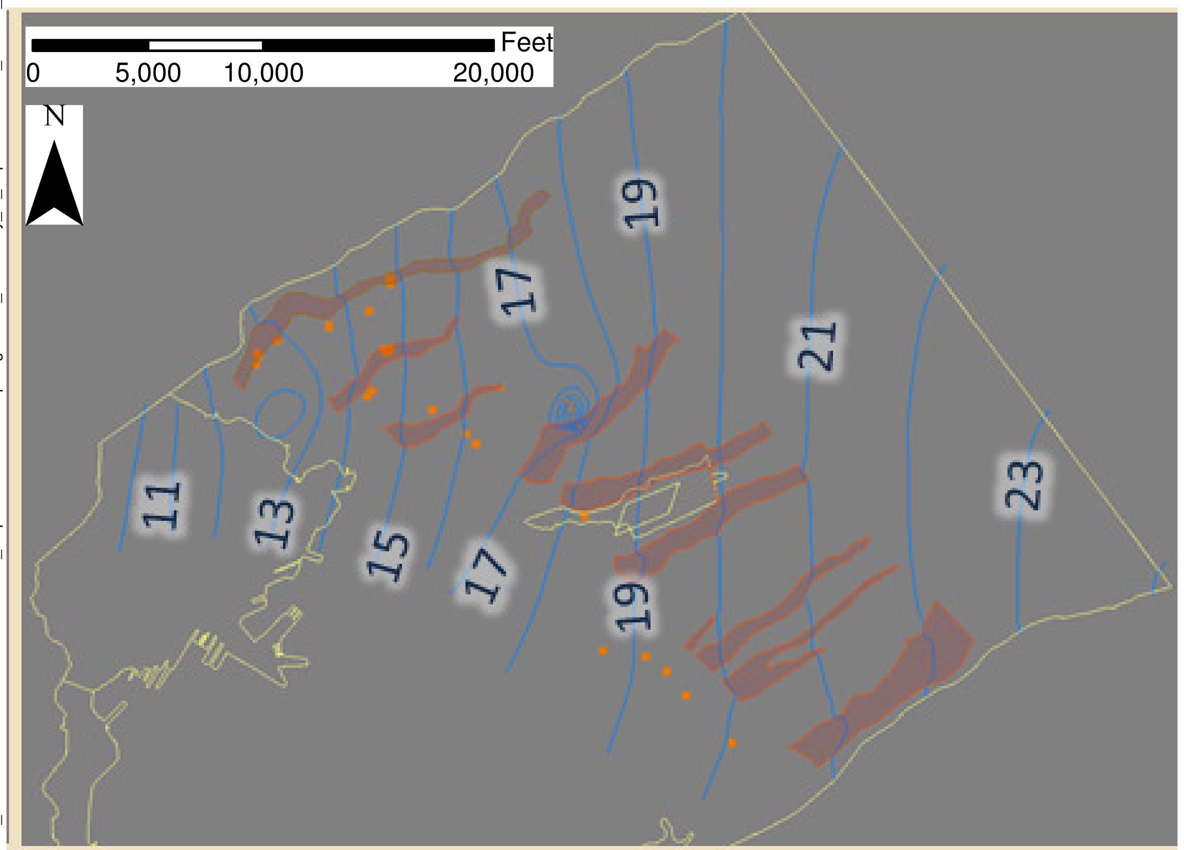
Legend

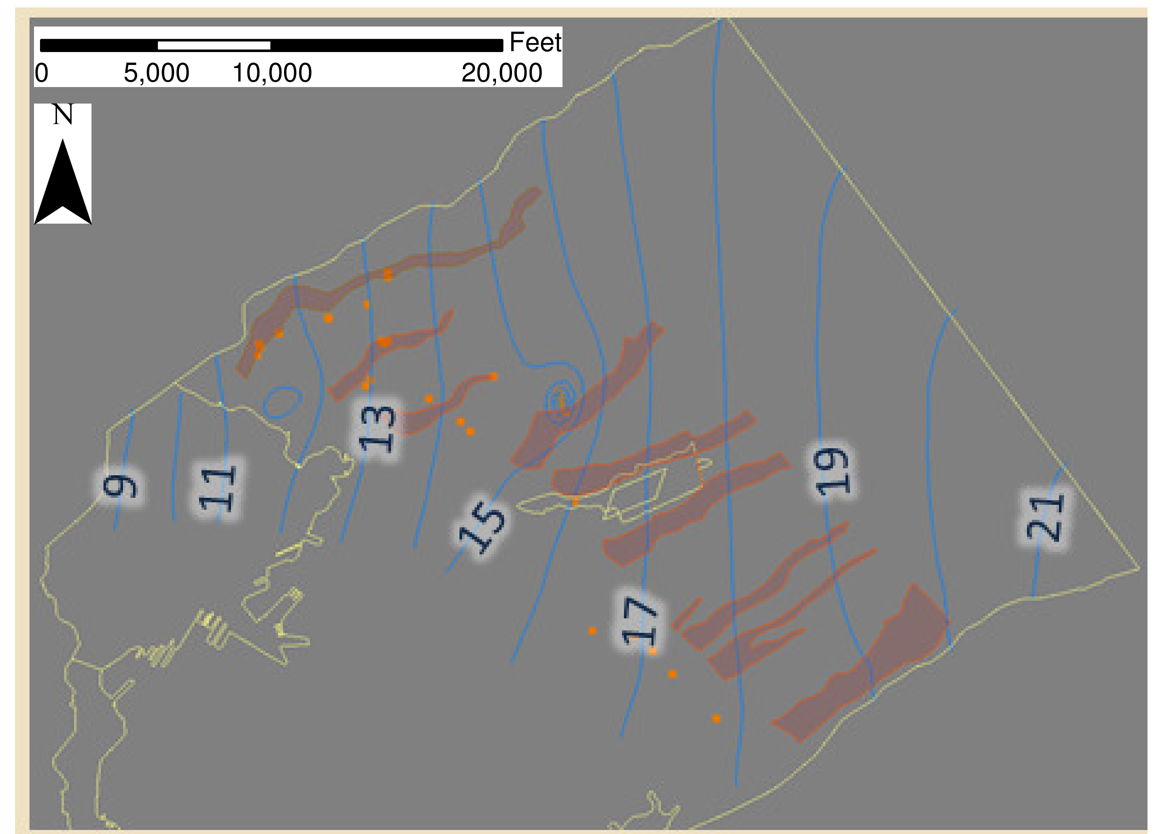
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

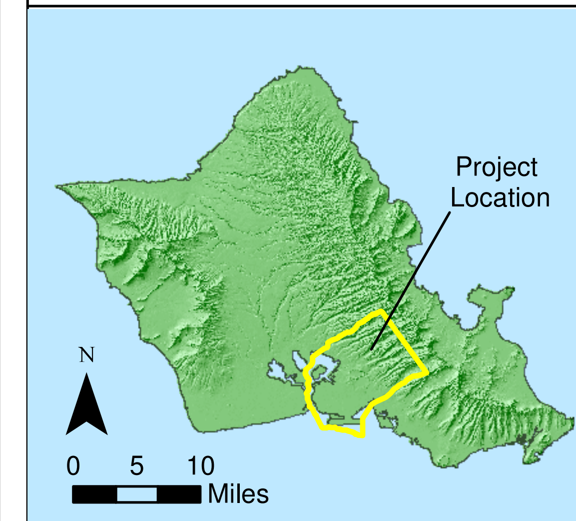
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.8-1
Sensitivity to Saprolite with Basalt Properties (Model #8) - 2017 Water Level Contours in Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI





Location Map



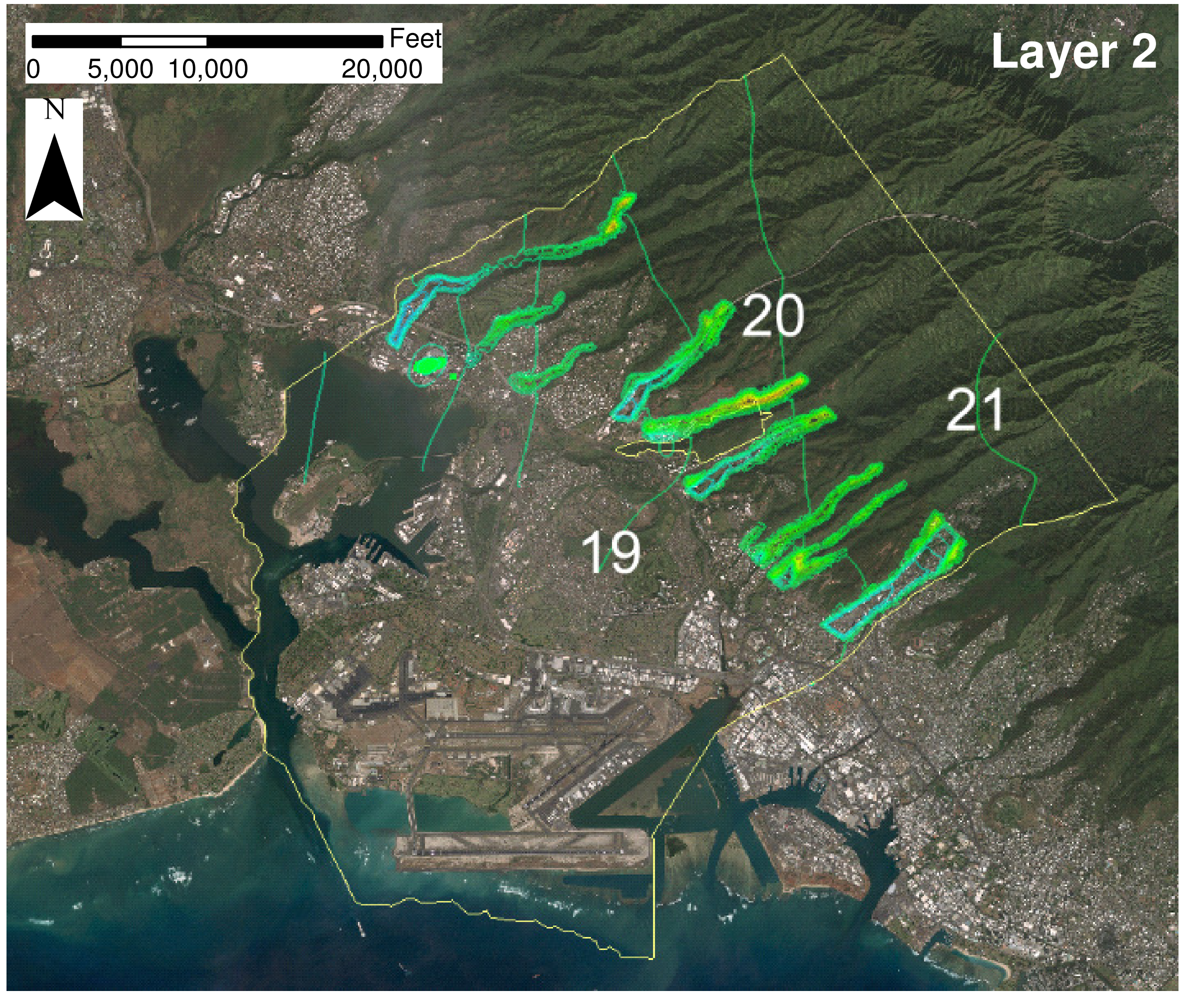
Legend

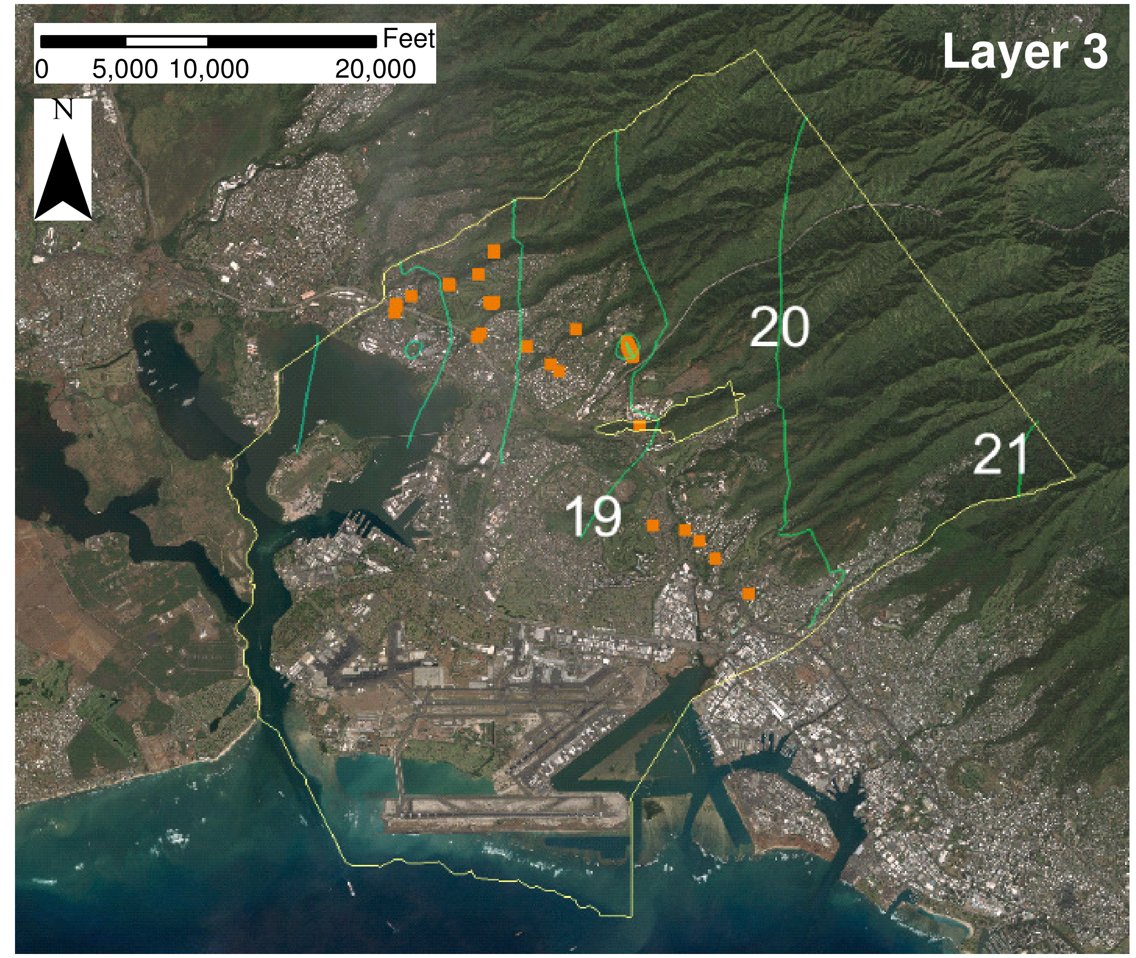
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

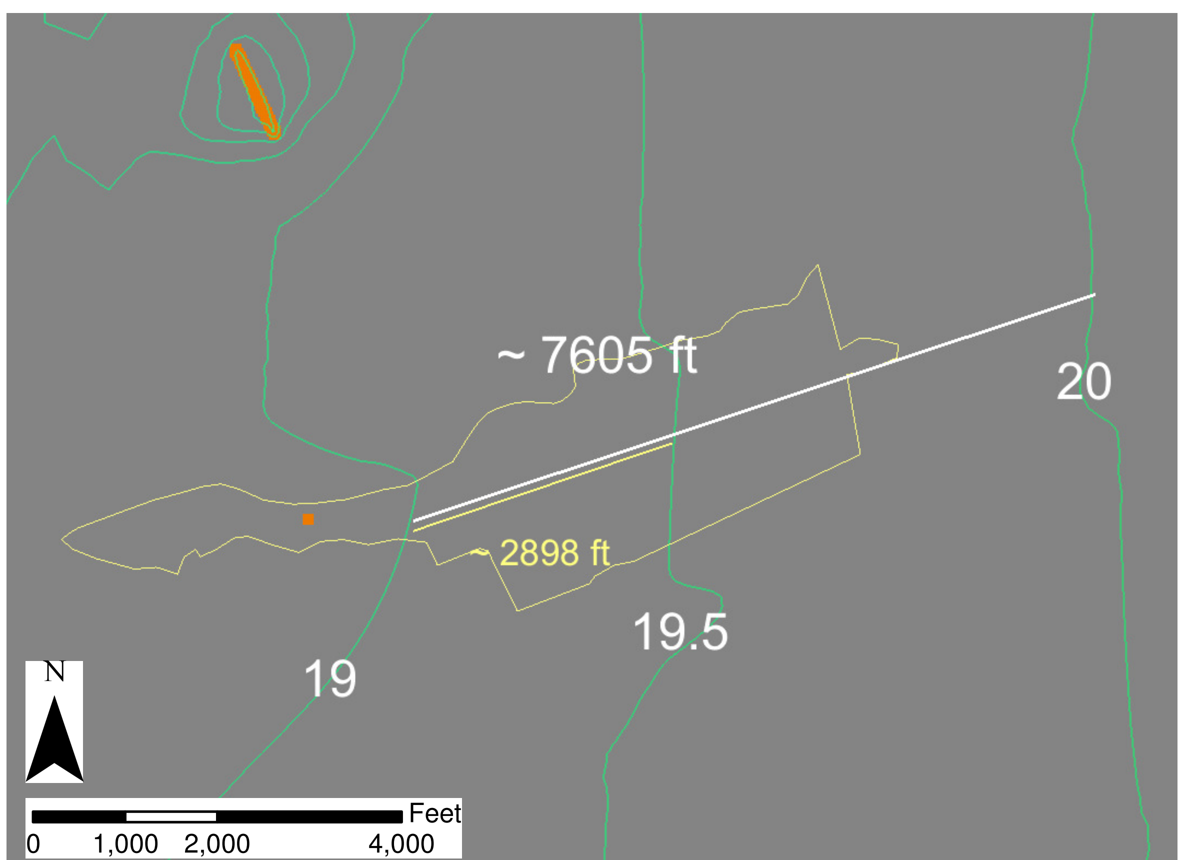
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.8-2
Sensitivity to Saprolite with Basalt Properties (Model #8) - 2017 Water Level Contours in Layer 3
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

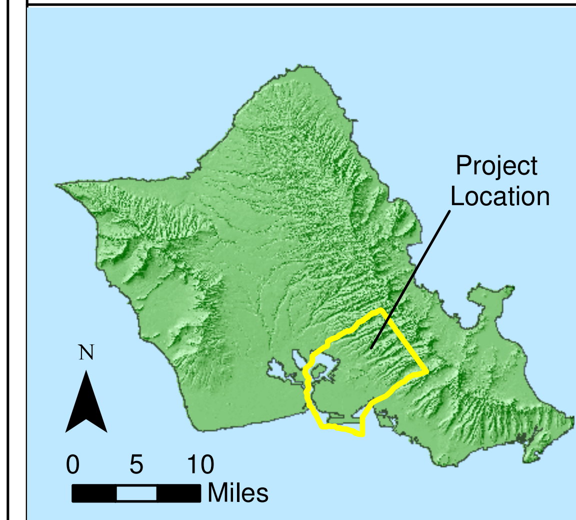






Simulated Water Level Gradients:
- 1 foot in 7,600 feet = 0.00013
- 0.5 feet in 3,000 feet = 0.00017

Location Map



Legend

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.10-1
Sensitivity to Basalt KH - Capture Zones with Red Hill Shaft (Model #11) - 2017 Water Levels
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

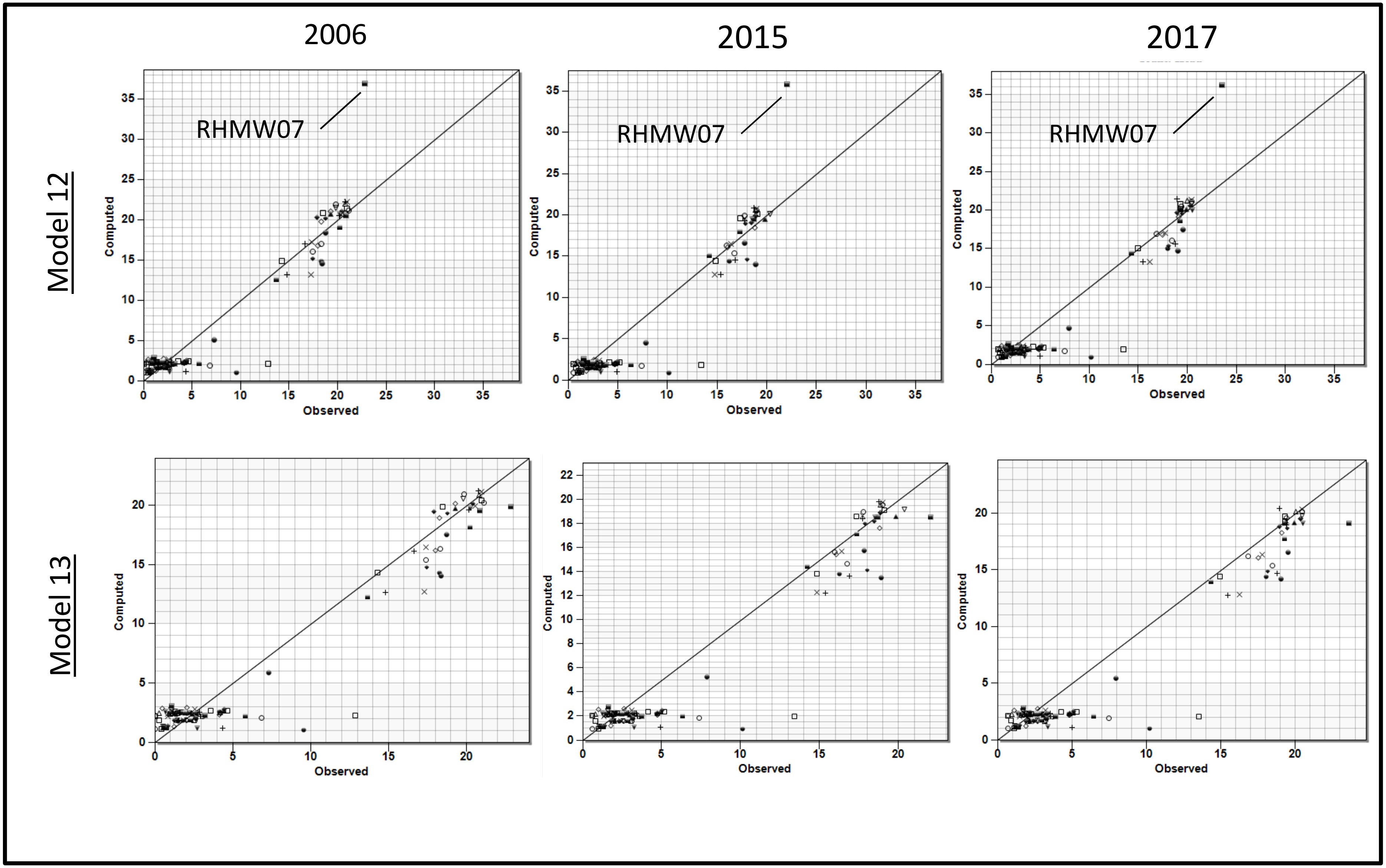
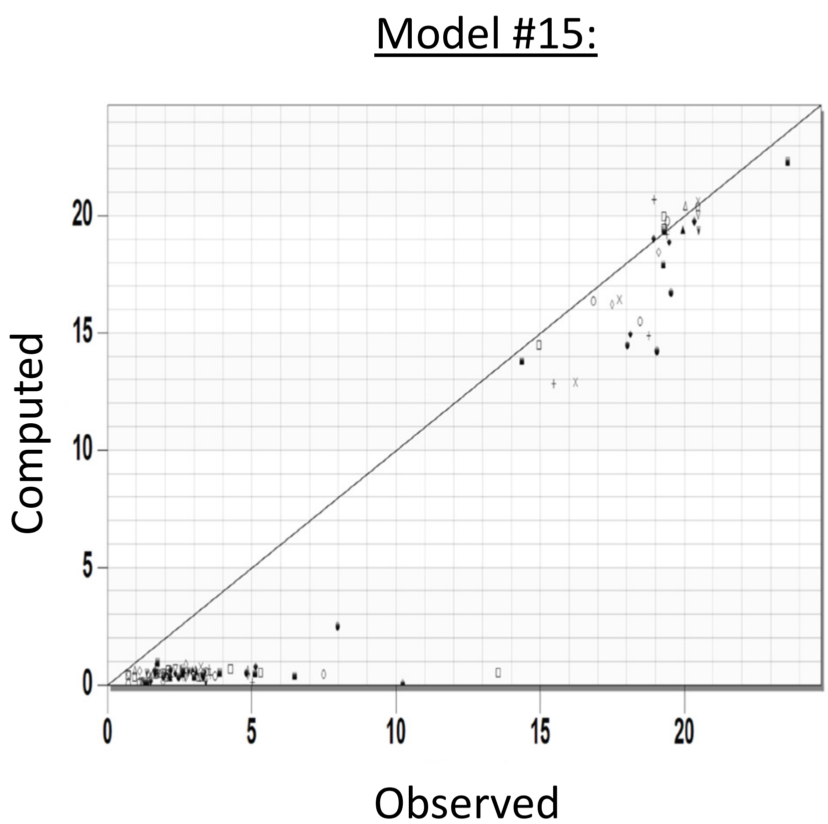


Figure 5.9.11-1
Sensitivity to Saprolite K (Model #12 & Model #13) – Scatter Plots
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



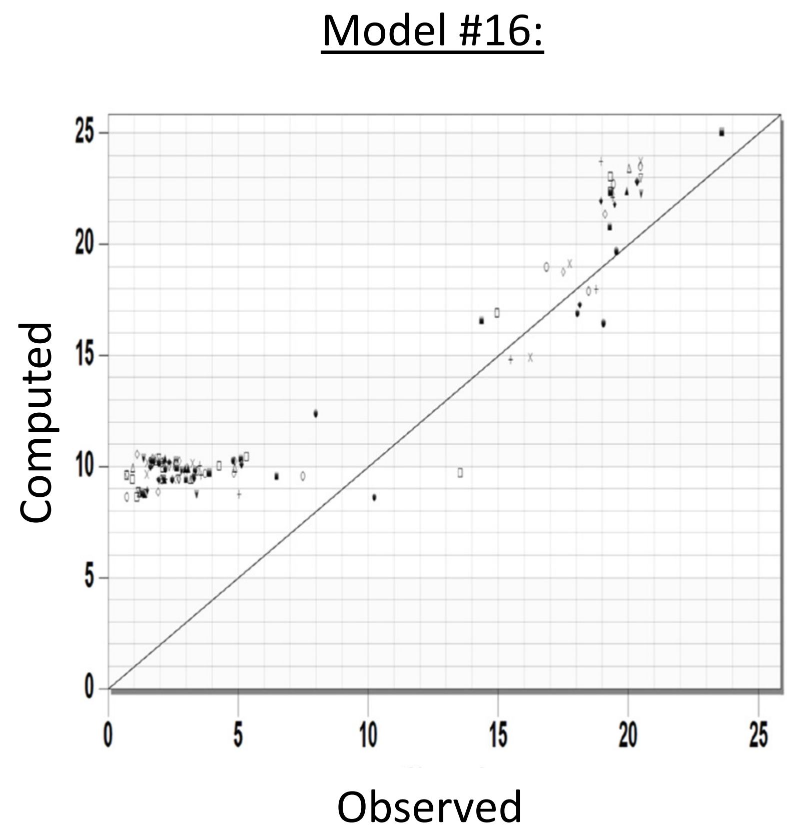


Figure 5.9.13-1
Sensitivity to Offshore GHB (Model #15 & Model #16) – 2017 Scatter Plots
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

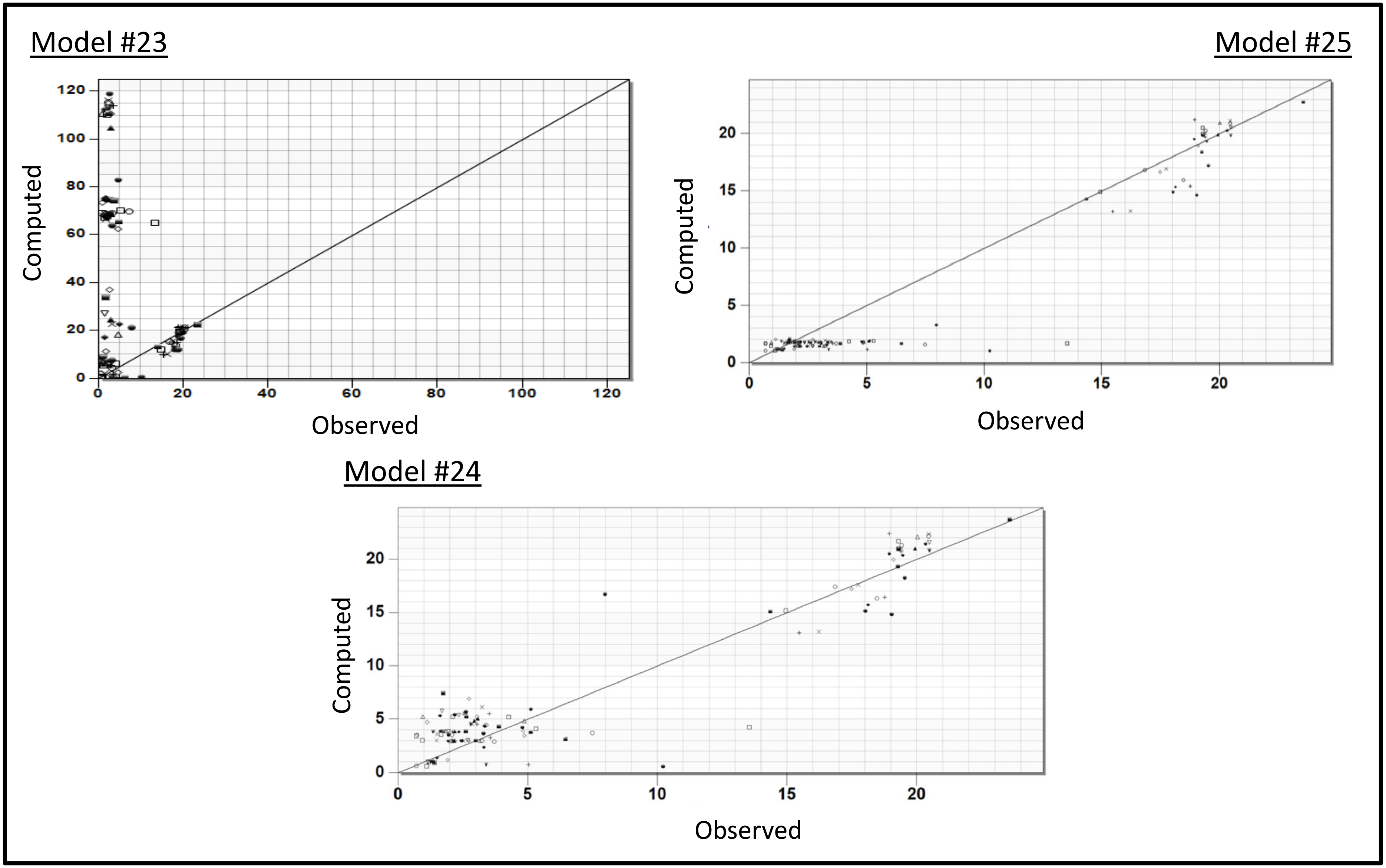
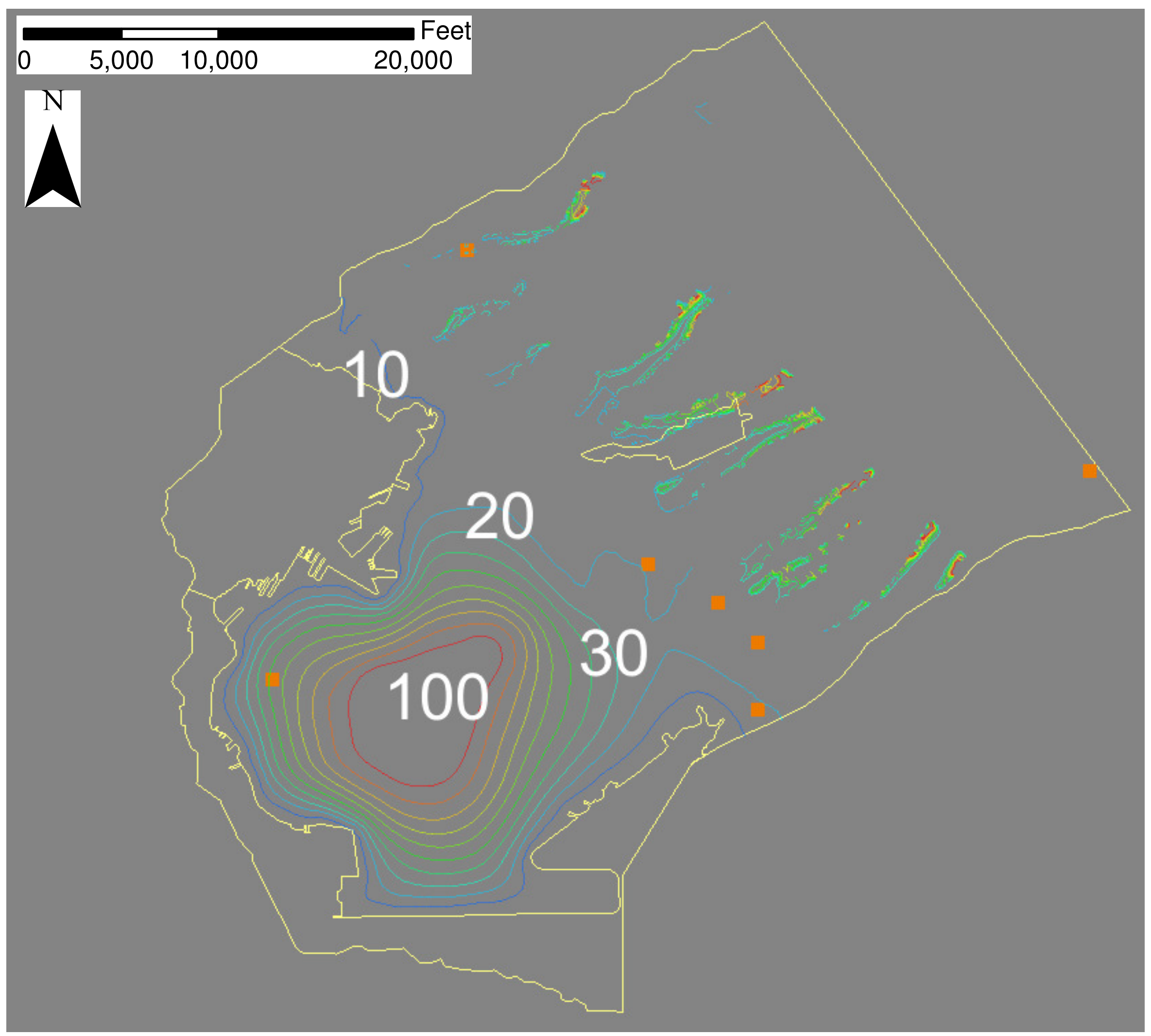
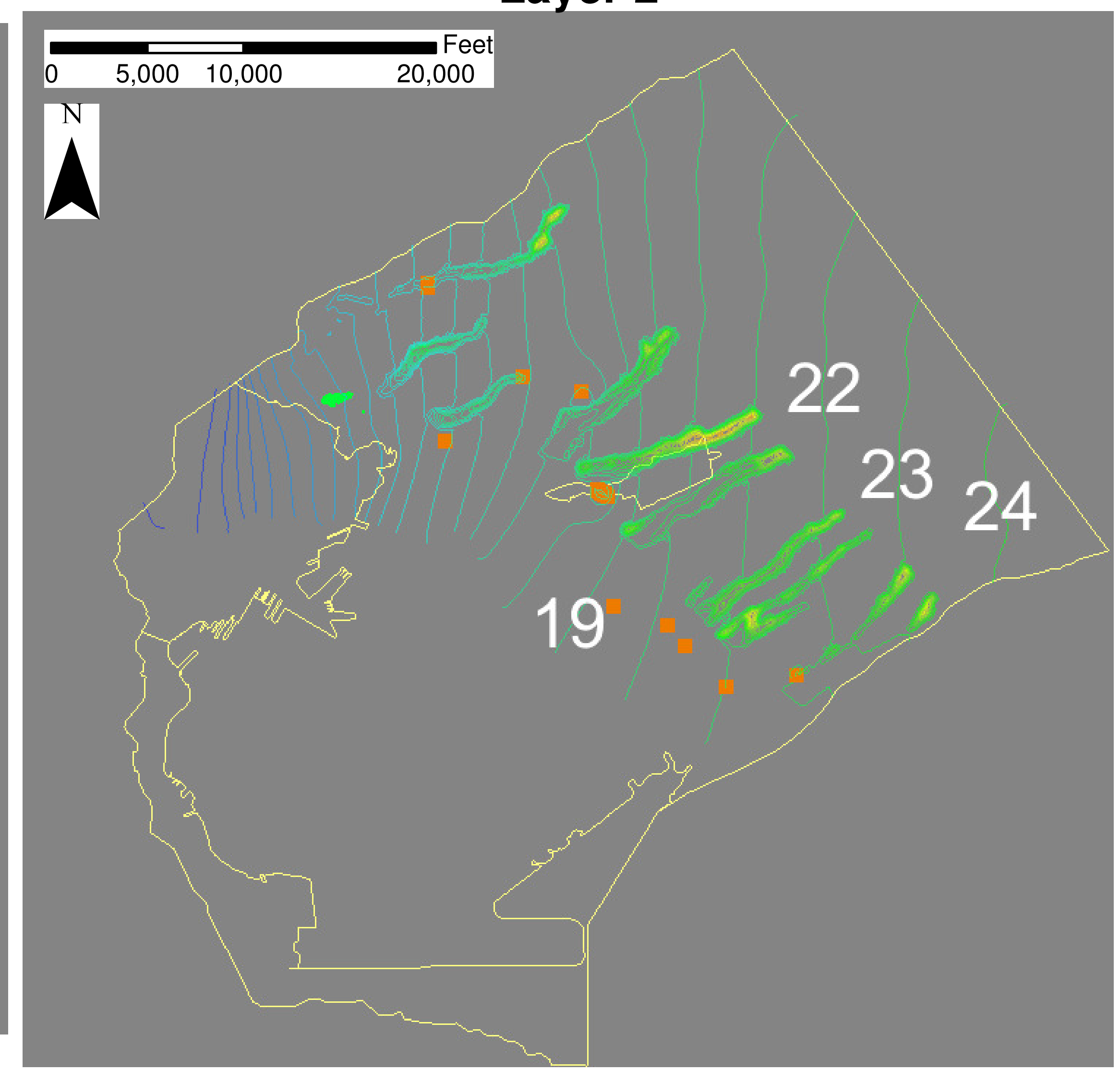


Figure 5.9.17-1
Sensitivity to Caprock KH (Model #23, Model #24, & Model #25) – 2017 Scatter Plots
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

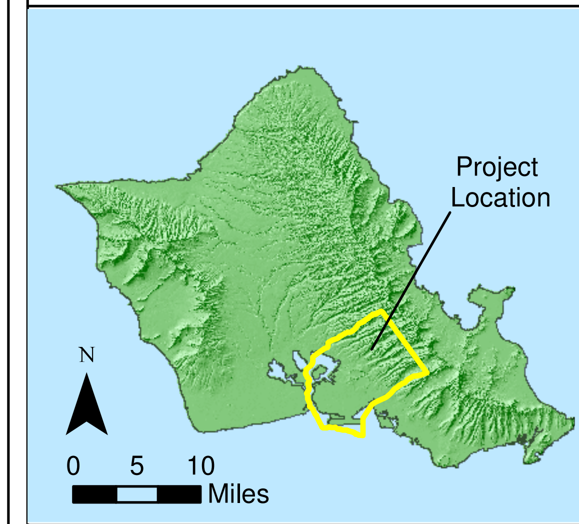
Layer 1



Layer 2



Location Map



Legend

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.17-2
Sensitivity to Caprok KH (Model #23) - Water Level Contours
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

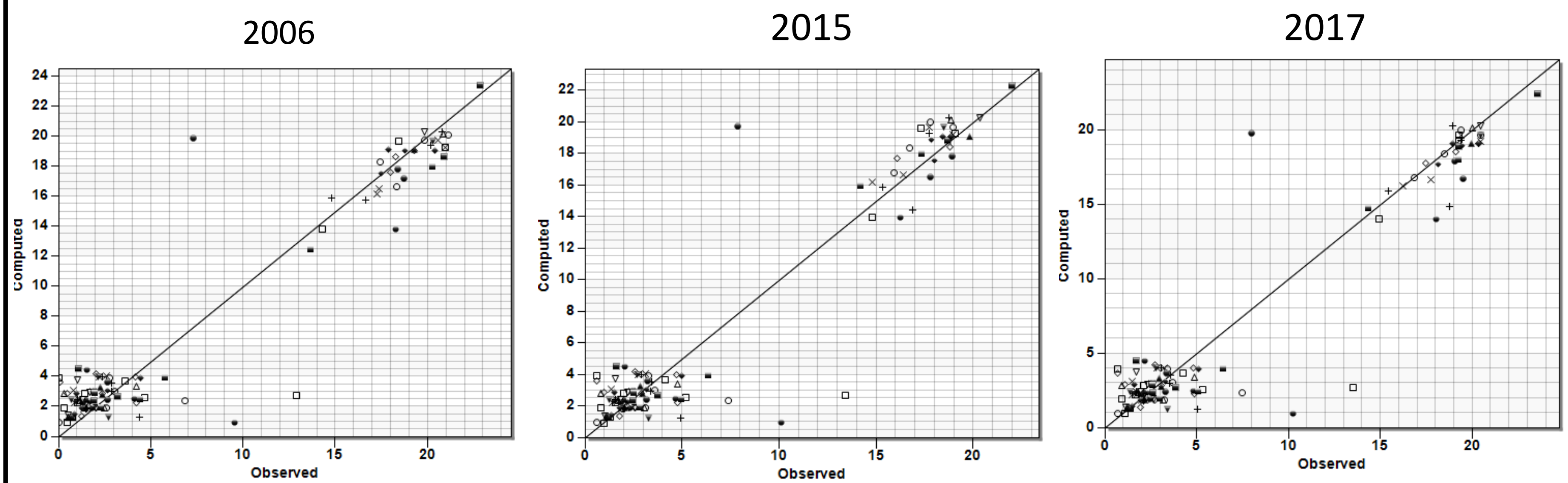
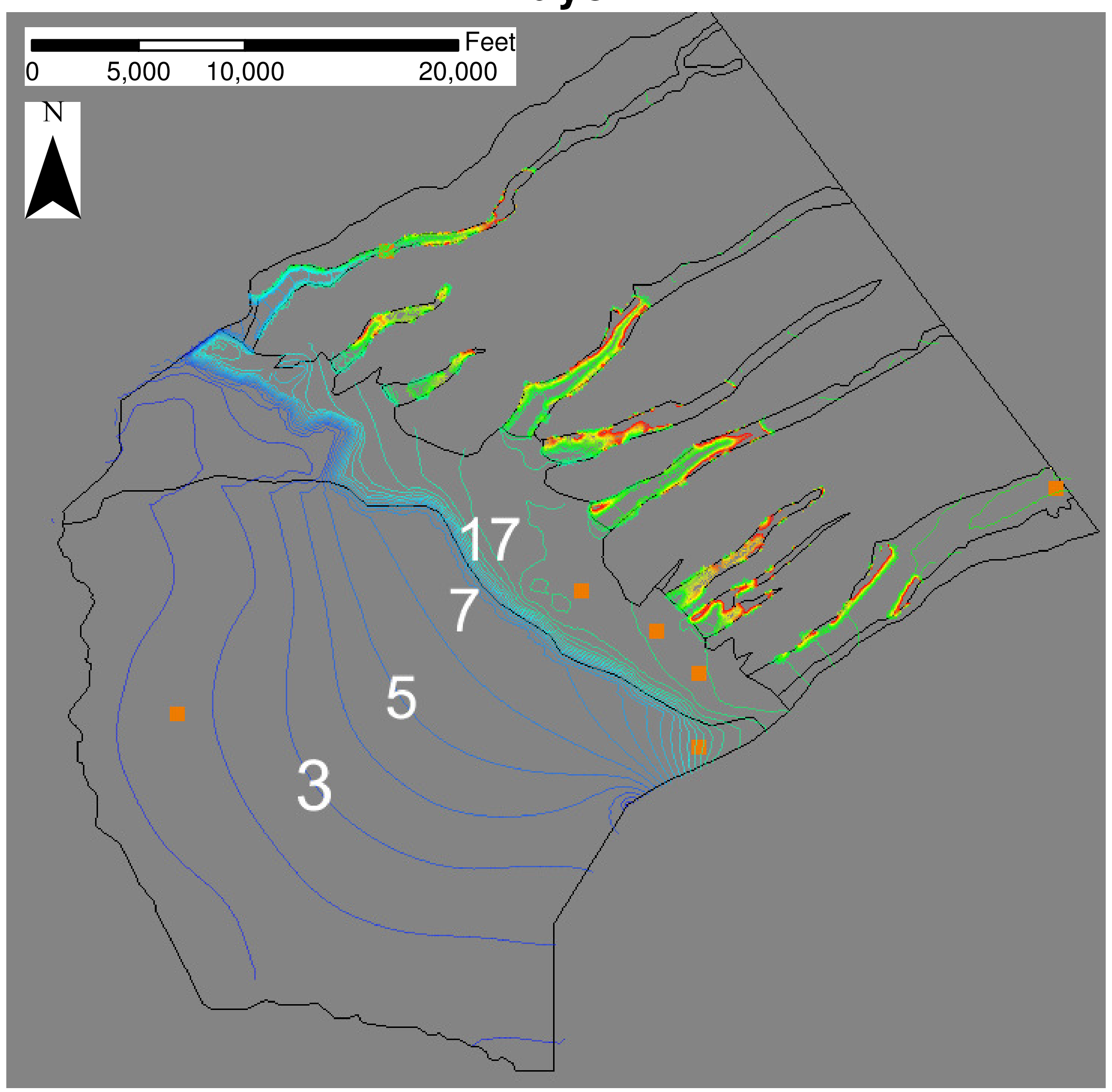
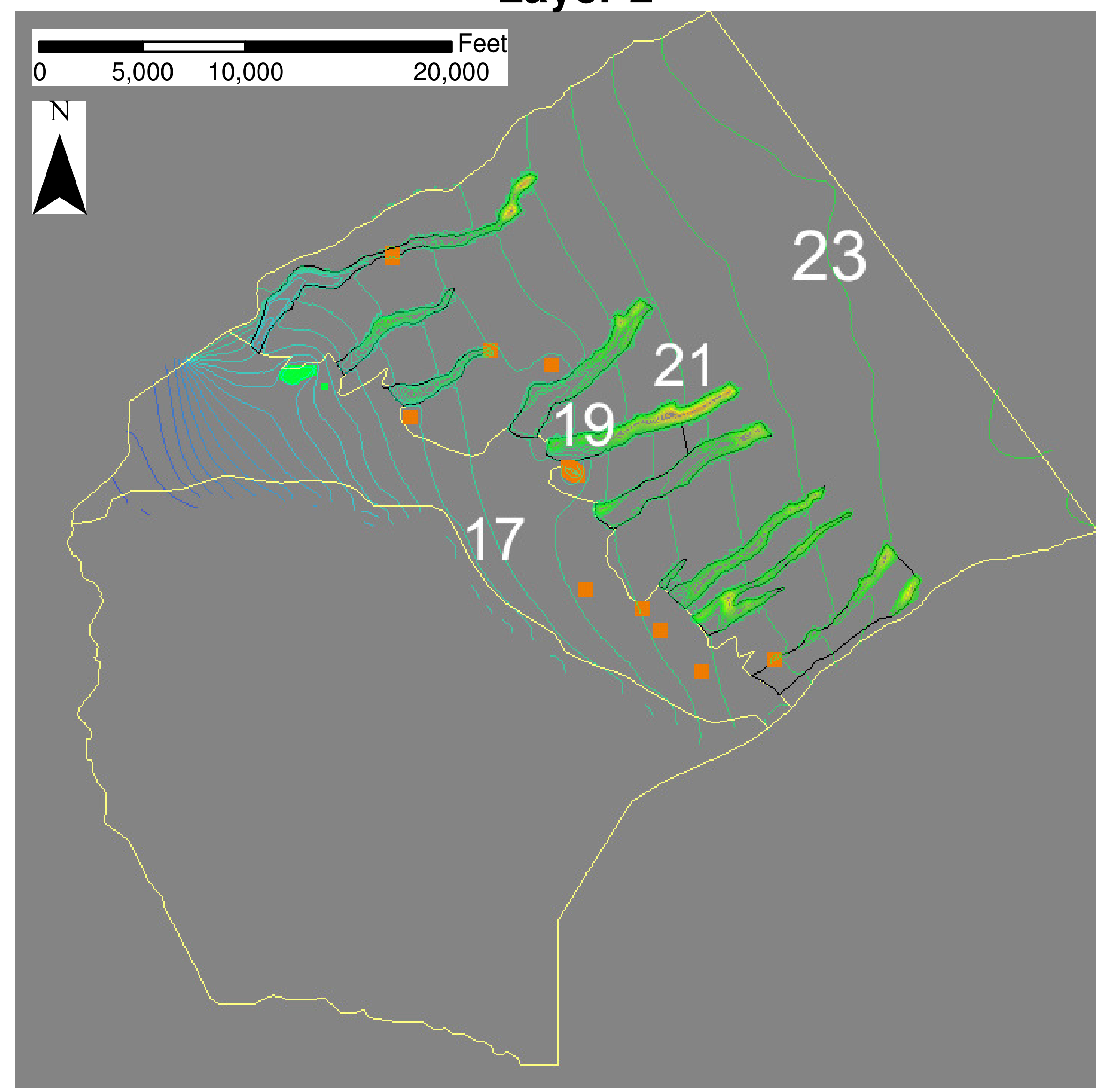


Figure 5.9.18-1
Sensitivity to Zonation of Caprock (Model #26) – Scatter Plots
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

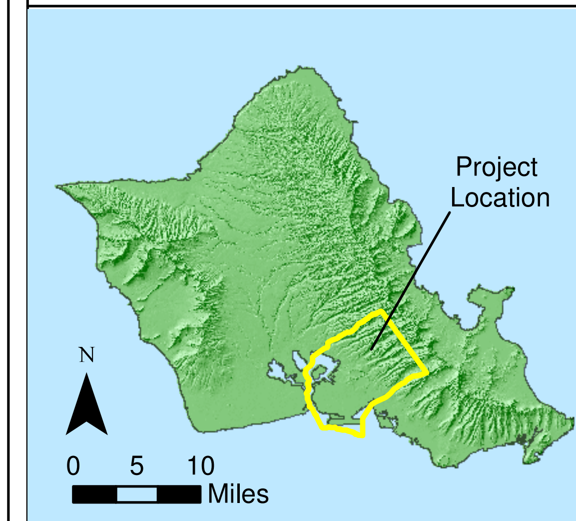
Layer 1



Layer 2



Location Map



Legend

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.18-2
Sensitivity to Zonation of Caprock (Model #26): 2017 Water Levels in Layer 1 and Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

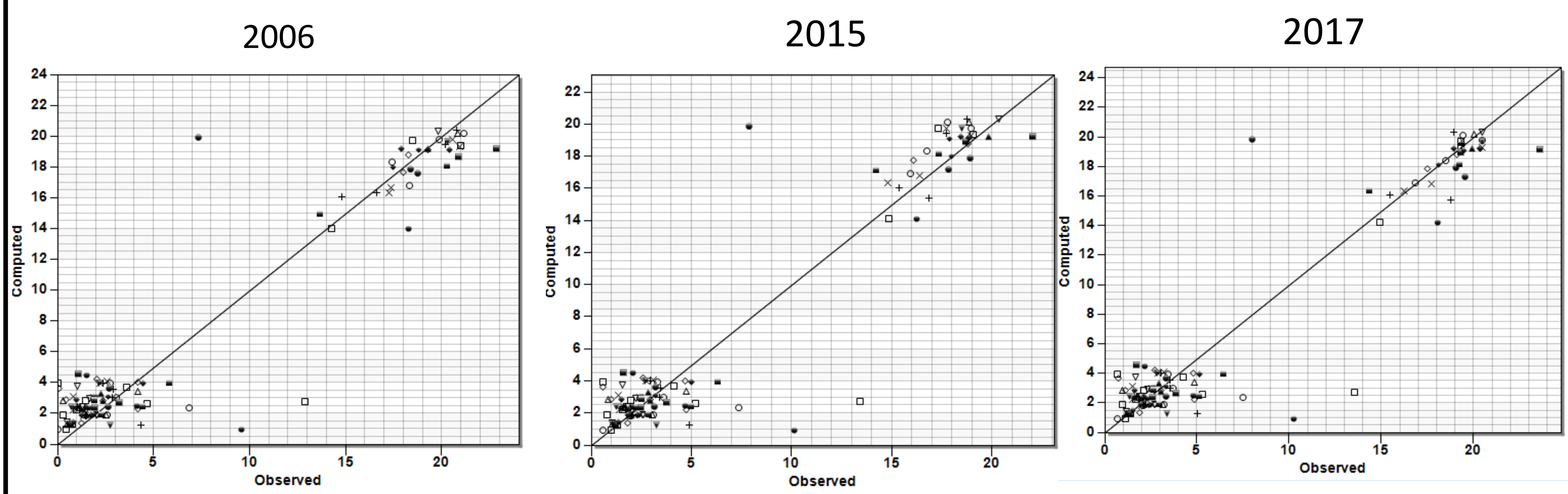
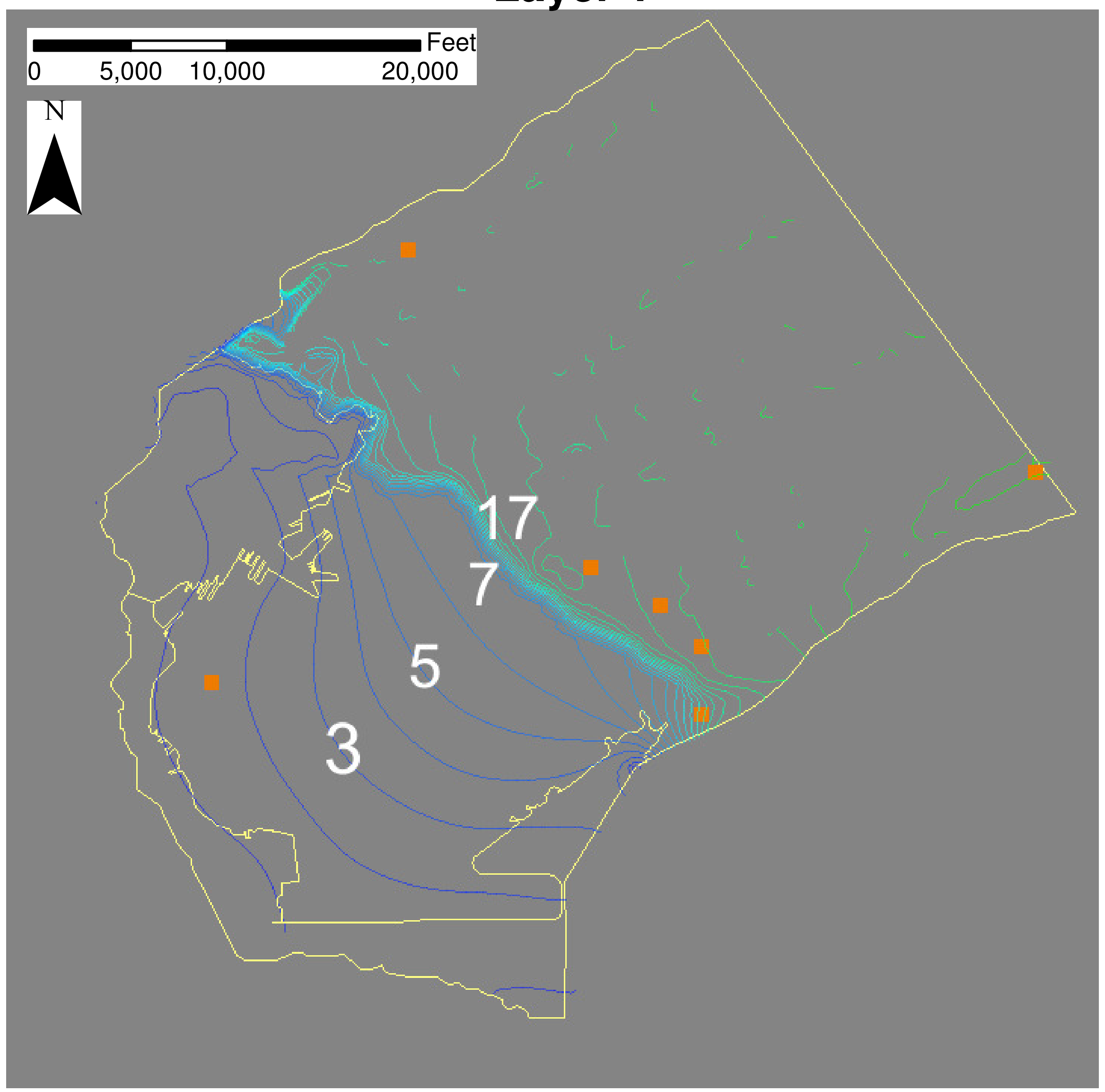
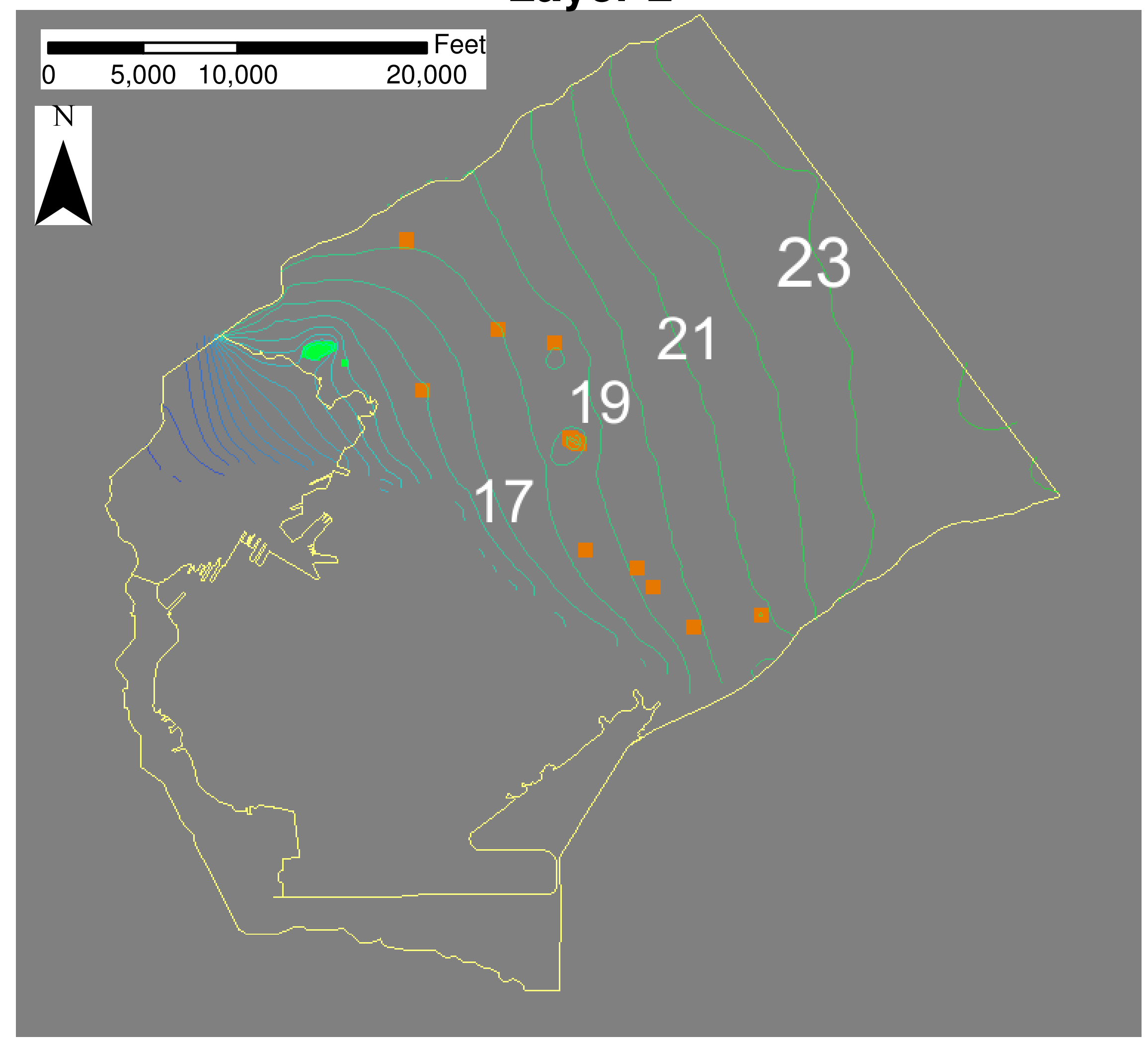


Figure 5.9.18-3
Sensitivity to Zonation of Caprock with Saprolite Properties Same as Basalt (Model #27) –Scatter Plots
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

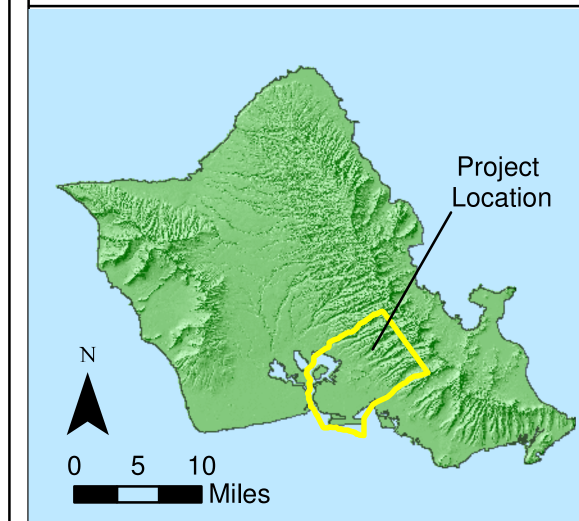
Layer 1



Layer 2



Location Map



Legend

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 5.9.18-4
Sensitivity to Zonation of Caprock with Saprolite Proprties Same as Basalt (Model #27): 2017 Water Levels in Layer 1 and Layer 2
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

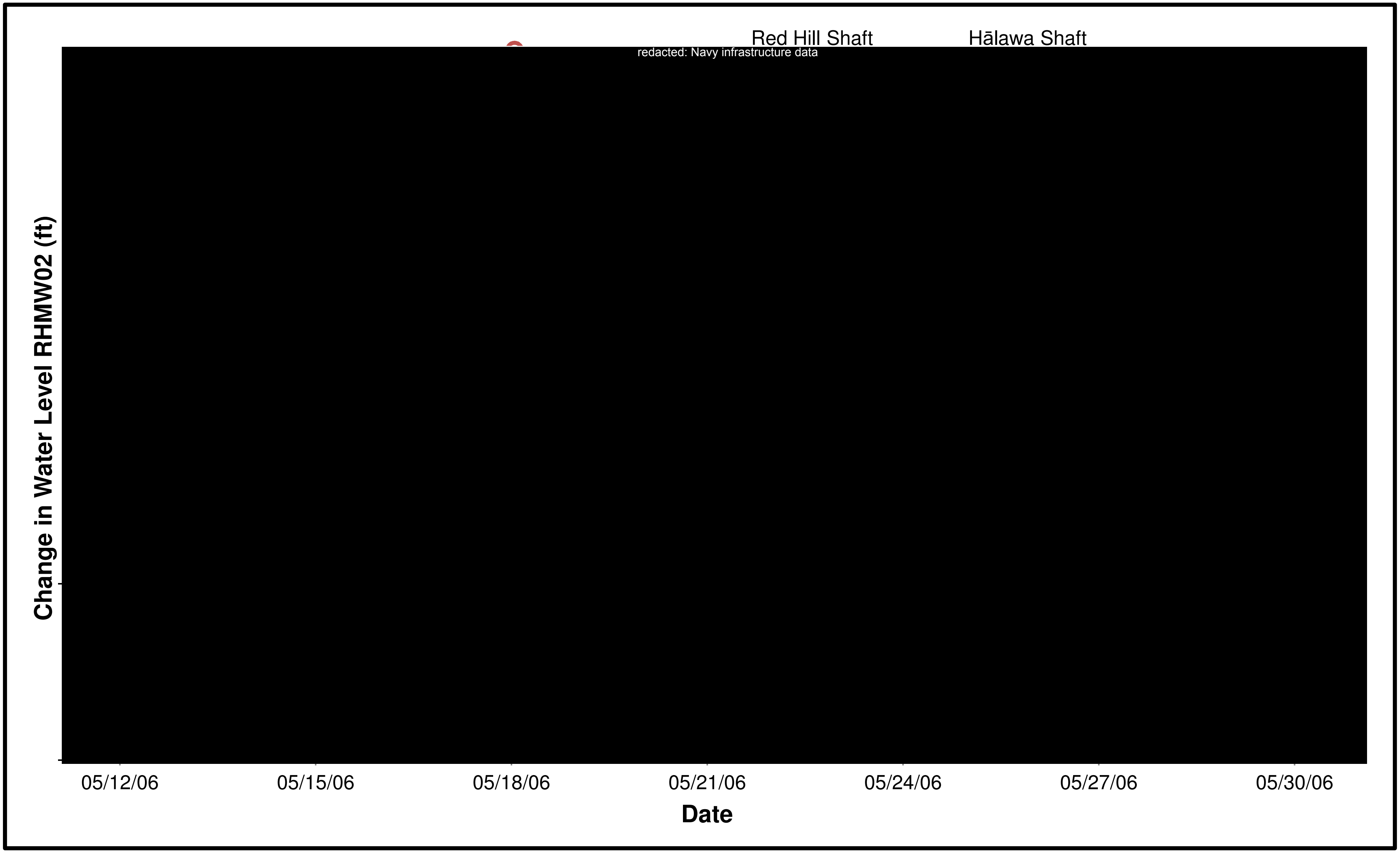


Figure 5.10.2-1
2006 Transient Synoptic Study Results at RHMW02
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

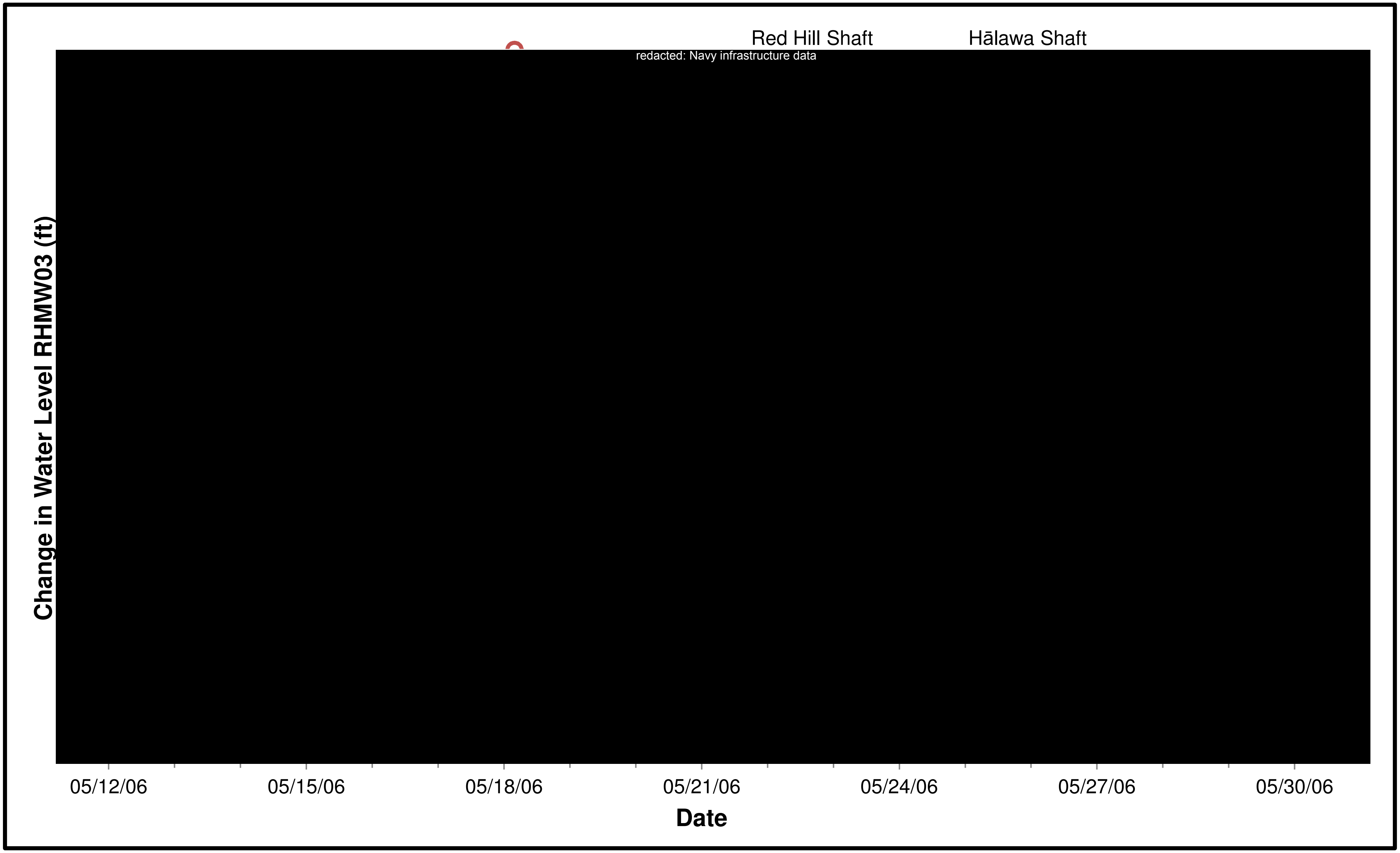


Figure 5.10.2-2
2006 Transient Synoptic Study Results at RHMW03
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

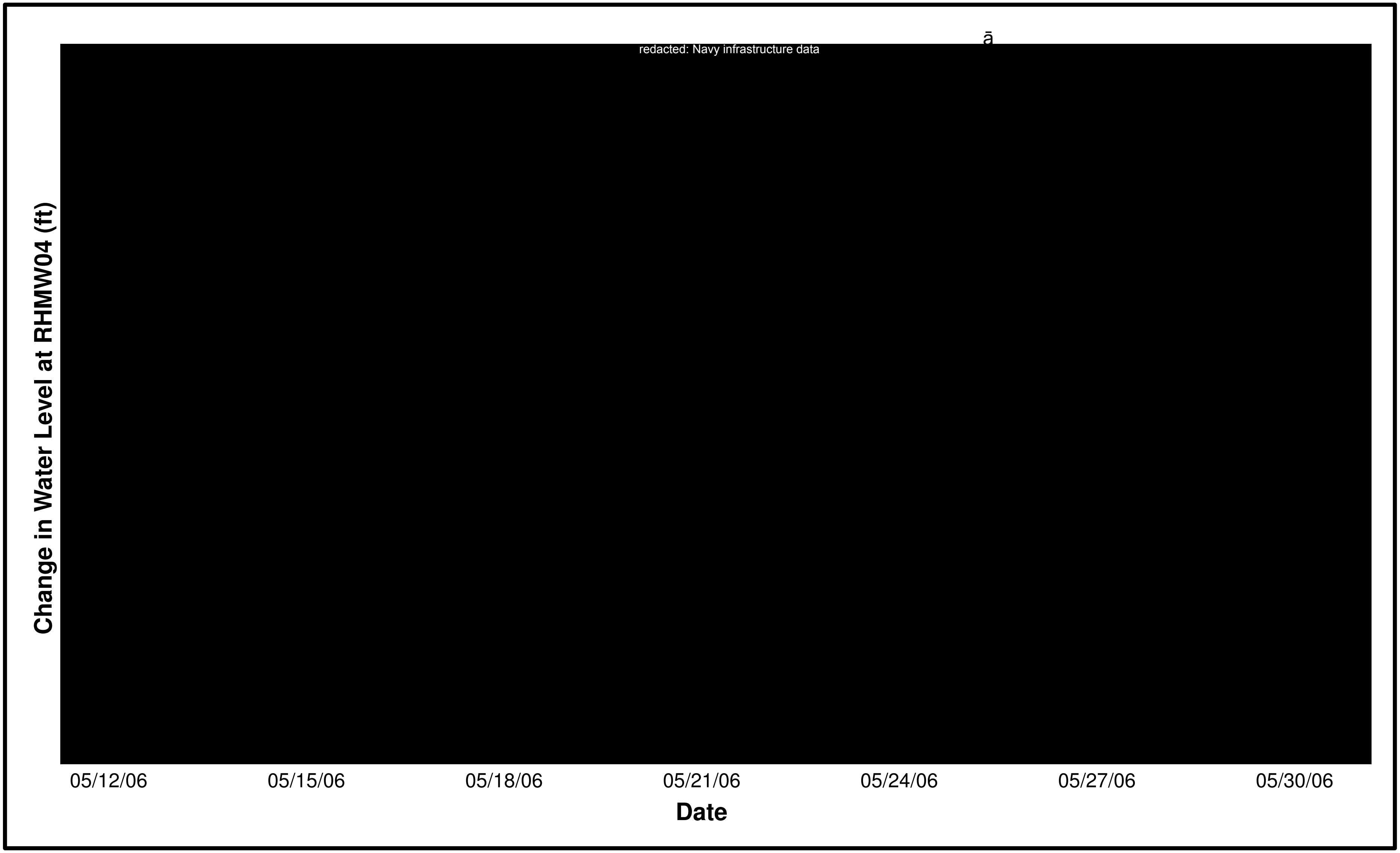


Figure 5.10.2-3
2006 Transient Synoptic Study Results at RHMW04
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

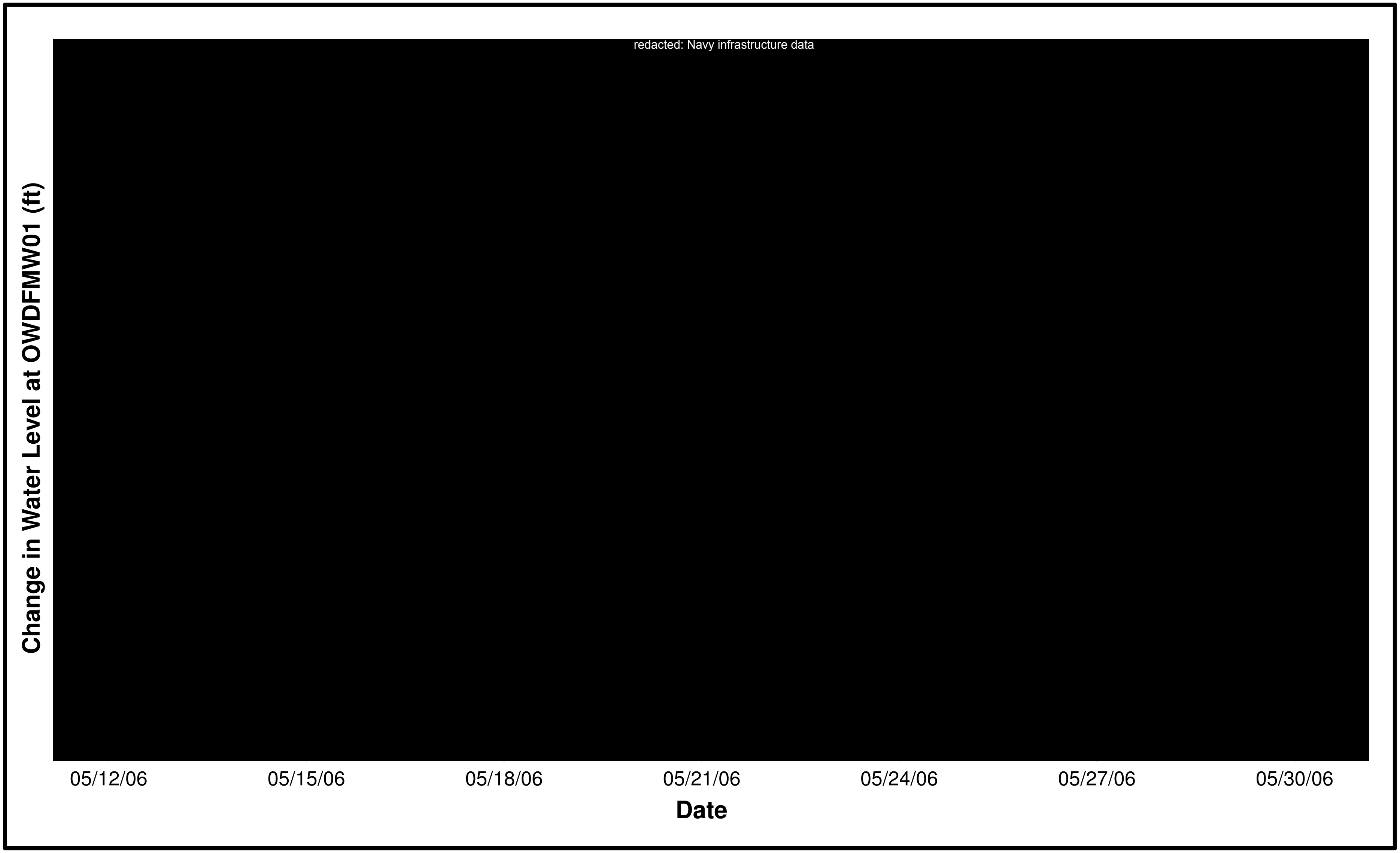


Figure 5.10.2-4
2006 Transient Synoptic Study Results at OWDFMW01
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

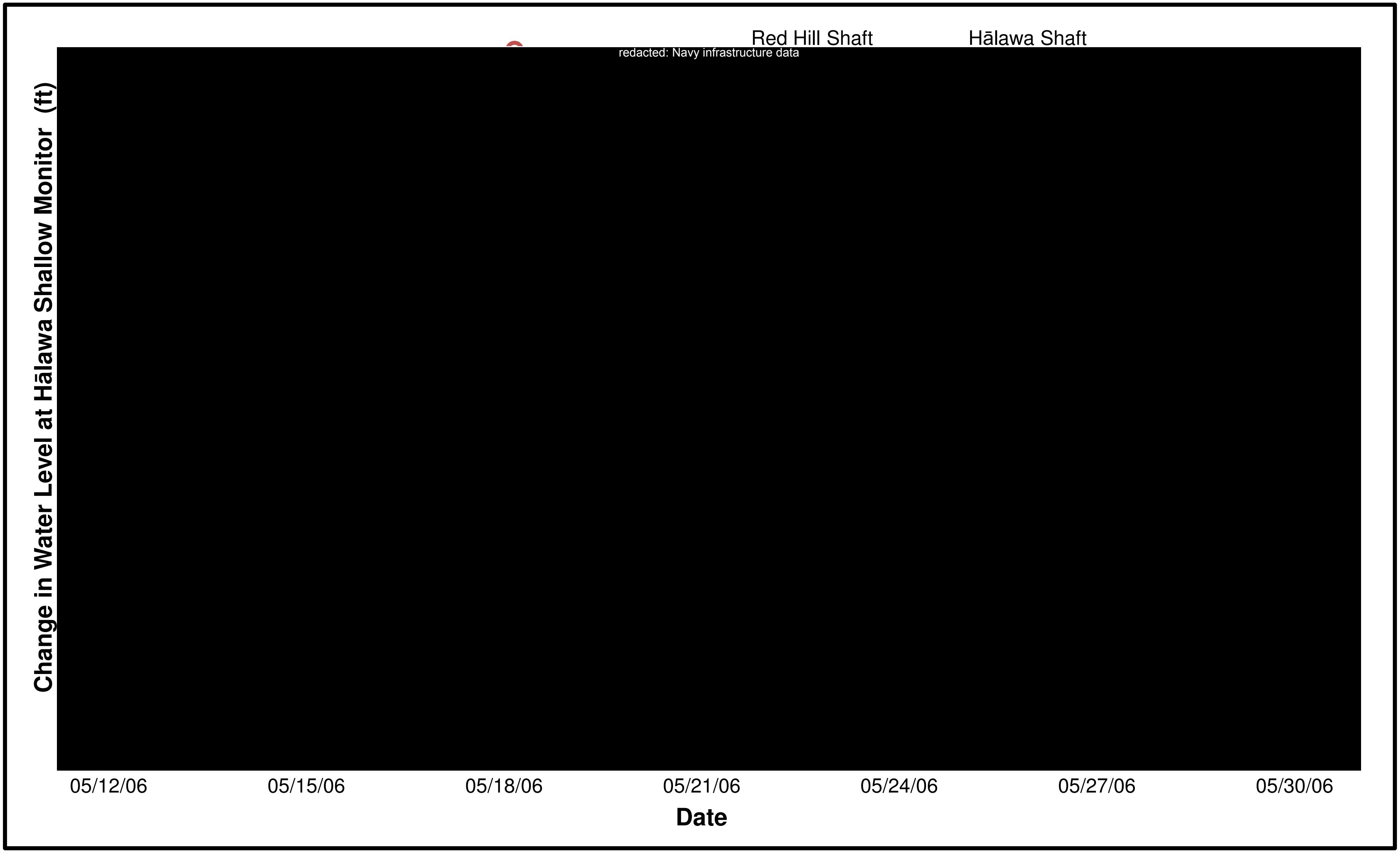


Figure 5.10.2-5
2006 Transient Synoptic Study Results at Hālawa Shallow Monitor (#2255-33)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

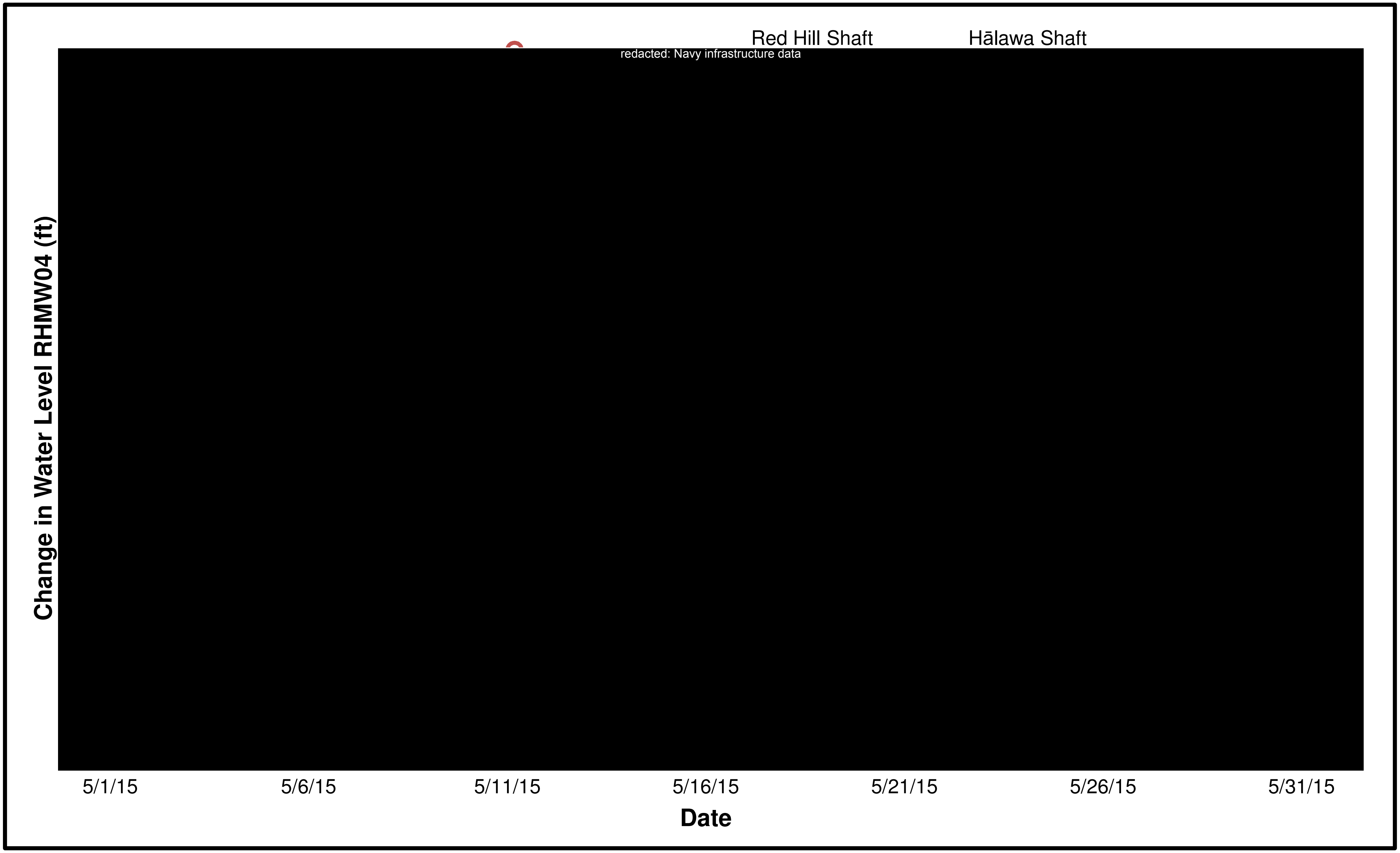


Figure 5.10.3-1
2015 Transient Synoptic Study Results at RHMW04
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

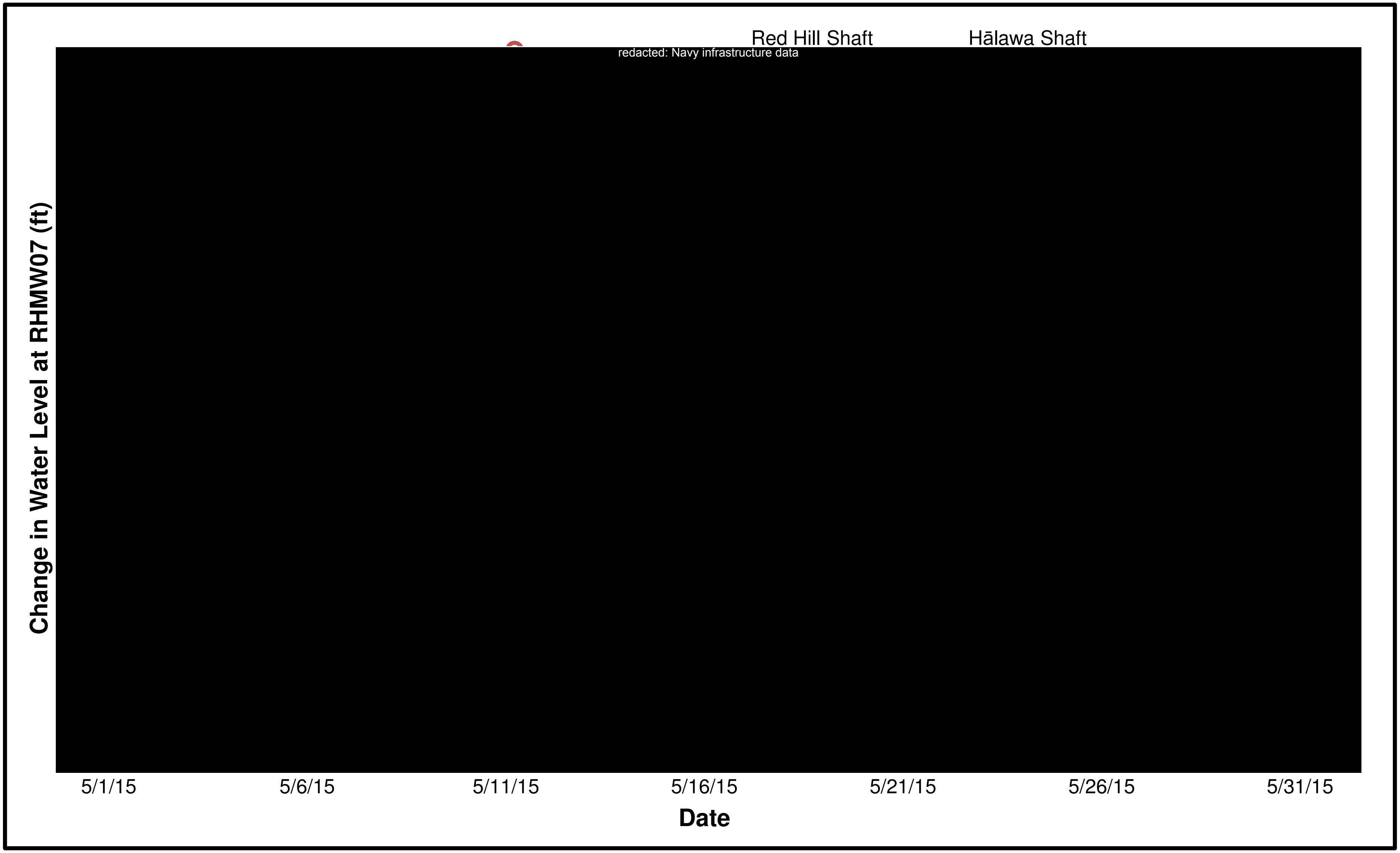


Figure 5.10.3-2
2015 Transient Synoptic Study Results at RHMW07
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

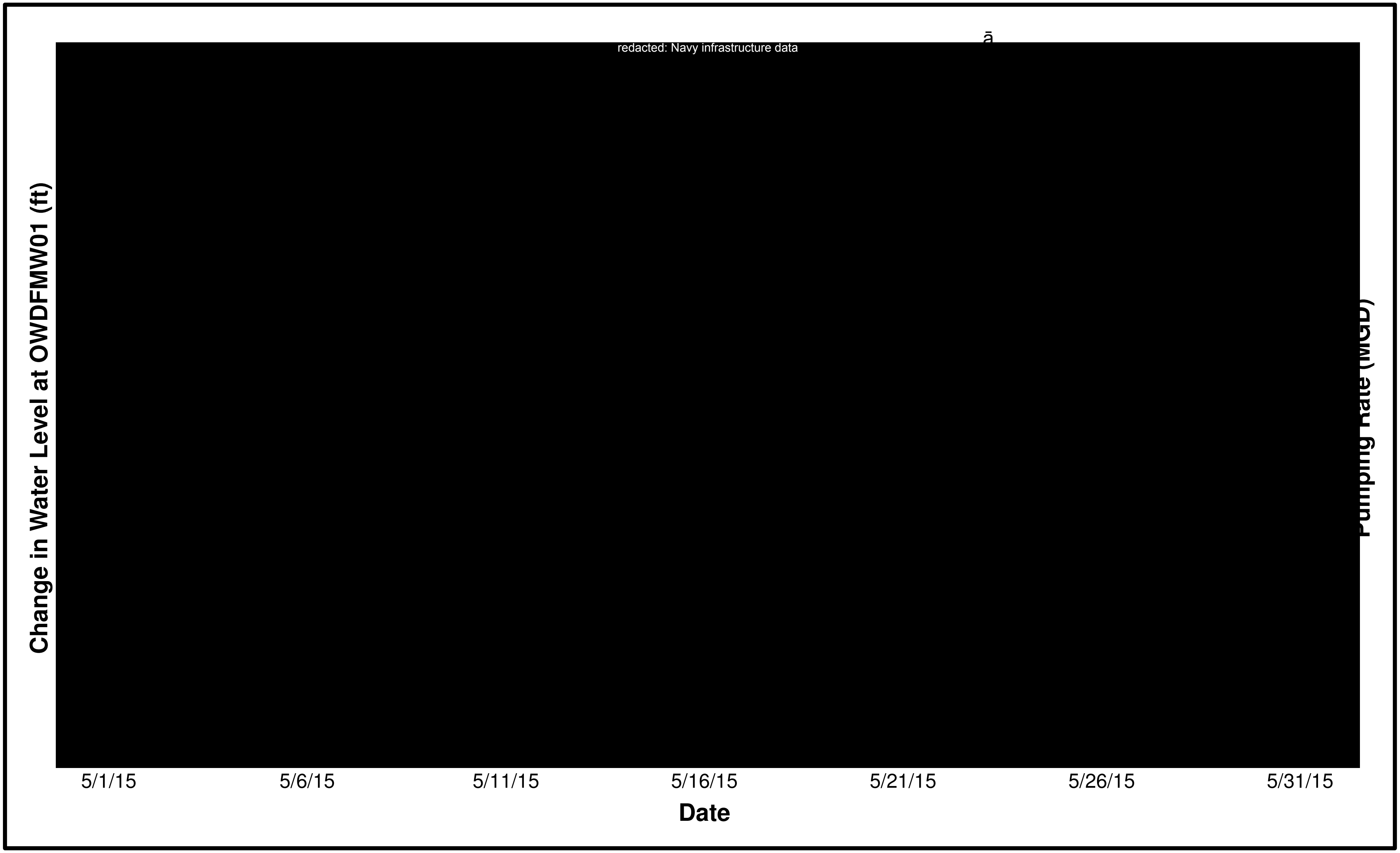


Figure 5.10.3-3
2015 Transient Synoptic Study Results at OWDFMW01
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

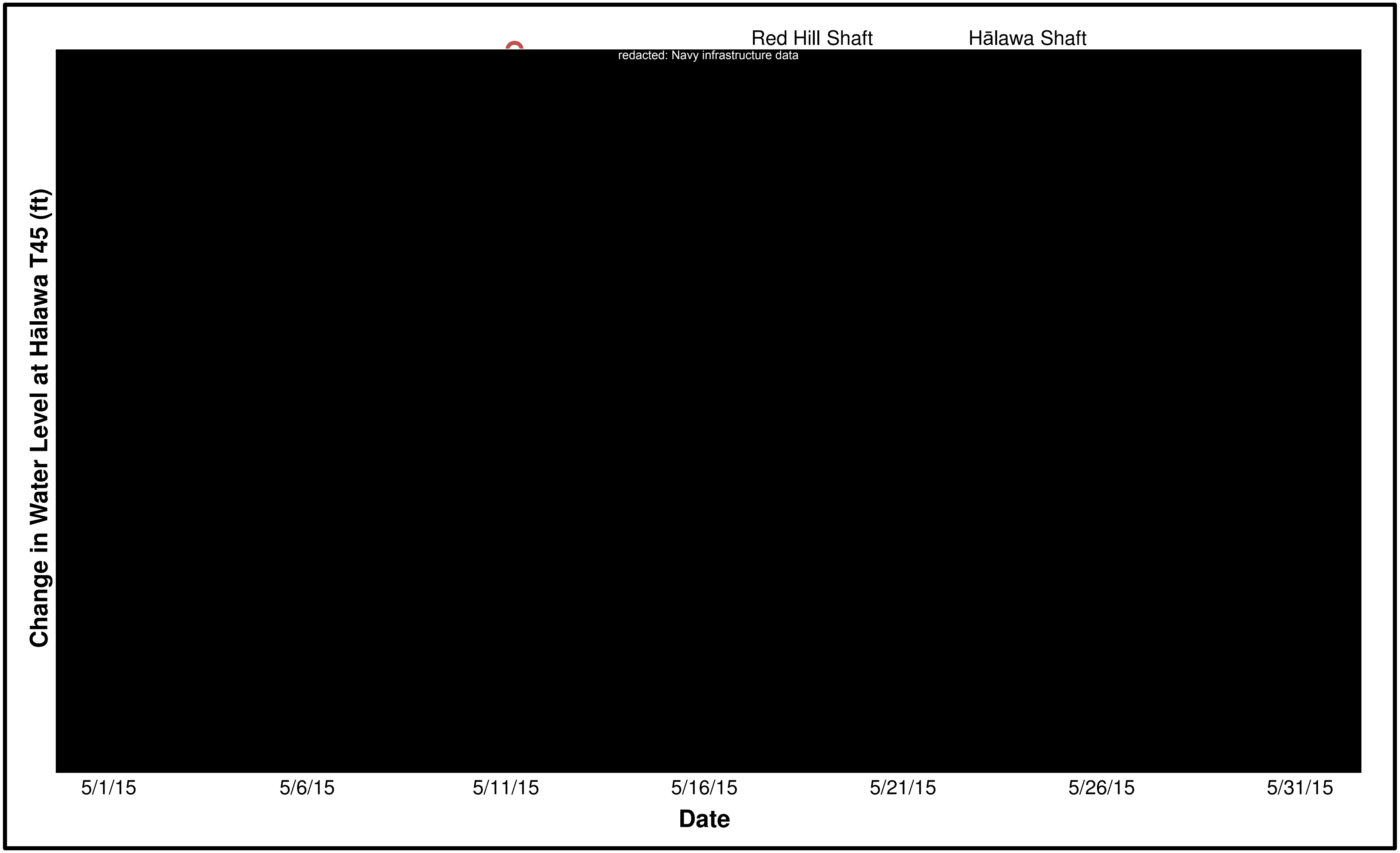


Figure 5.10.3-4
2015 Transient Synoptic Study Results at Hālawa T45 (2255-33)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

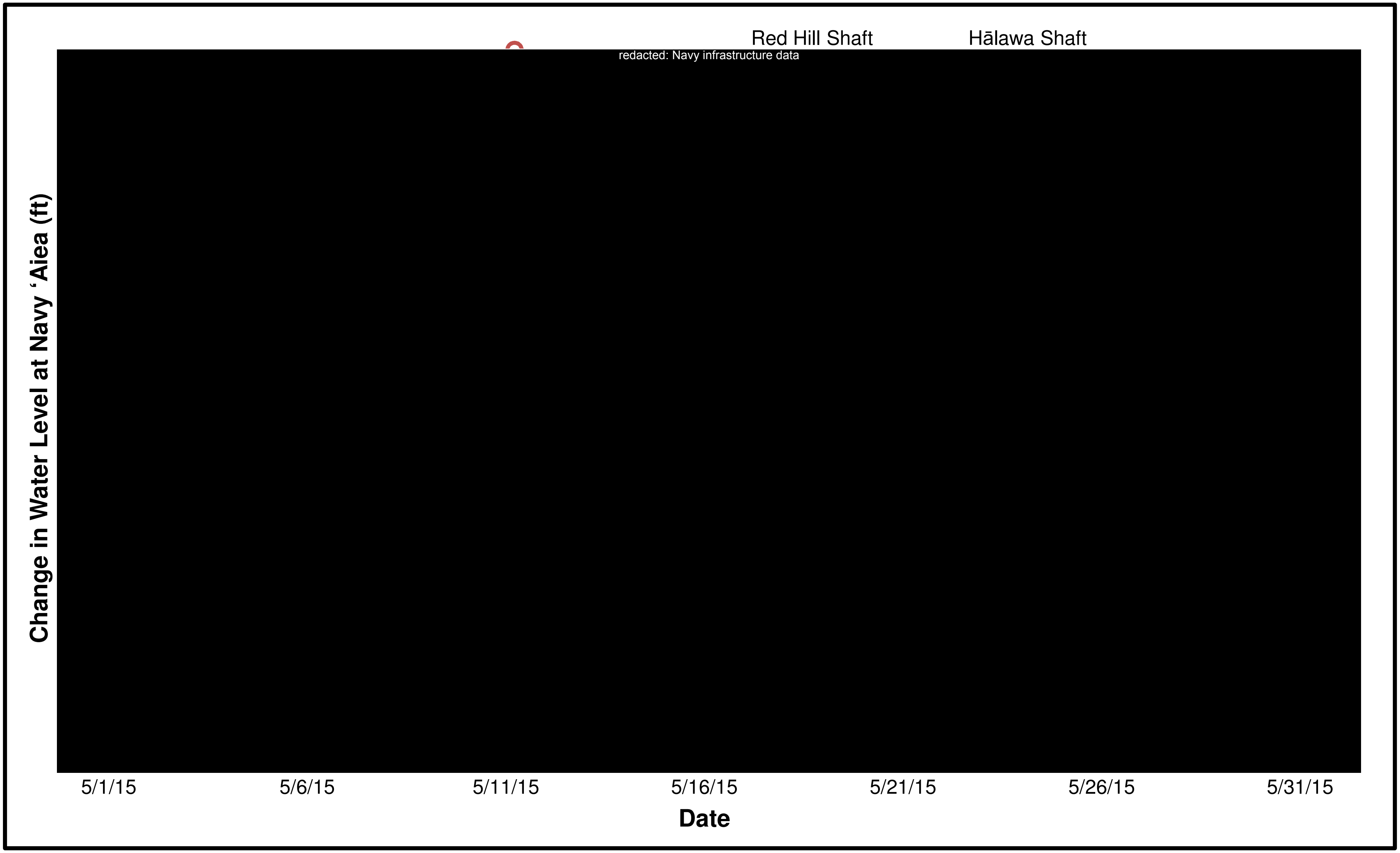


Figure 5.10.3-5
2015 Transient Synoptic Study Results at ‘Aiea Navy (2256-10)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

Figure 5.10.3-6
2015 Transient Synoptic Study Results at Kaʻamilo Deep (2355-15)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

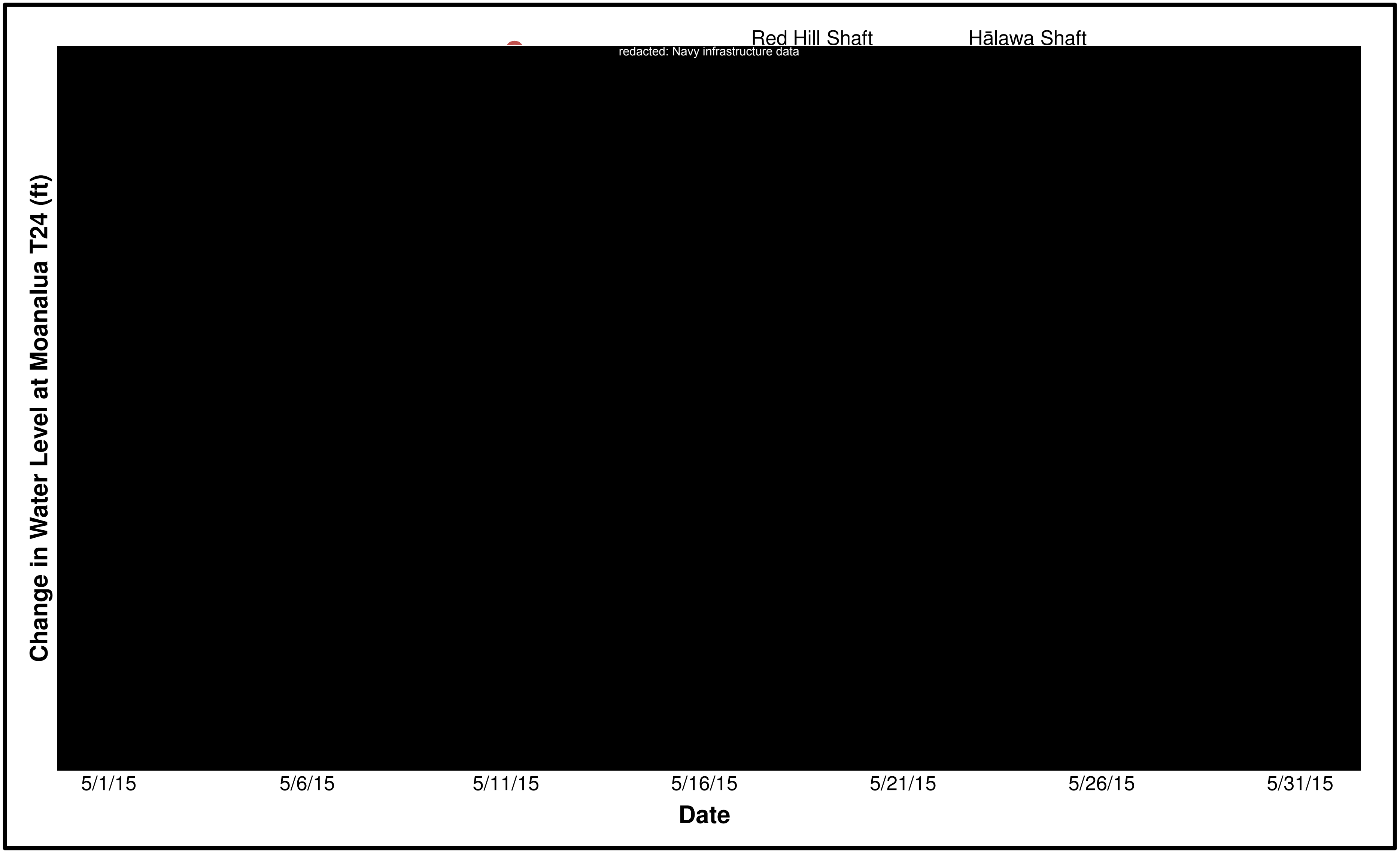


Figure 5.10.3-7
2015 Transient Synoptic Study Results at Manaiki T24 (2153-09)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

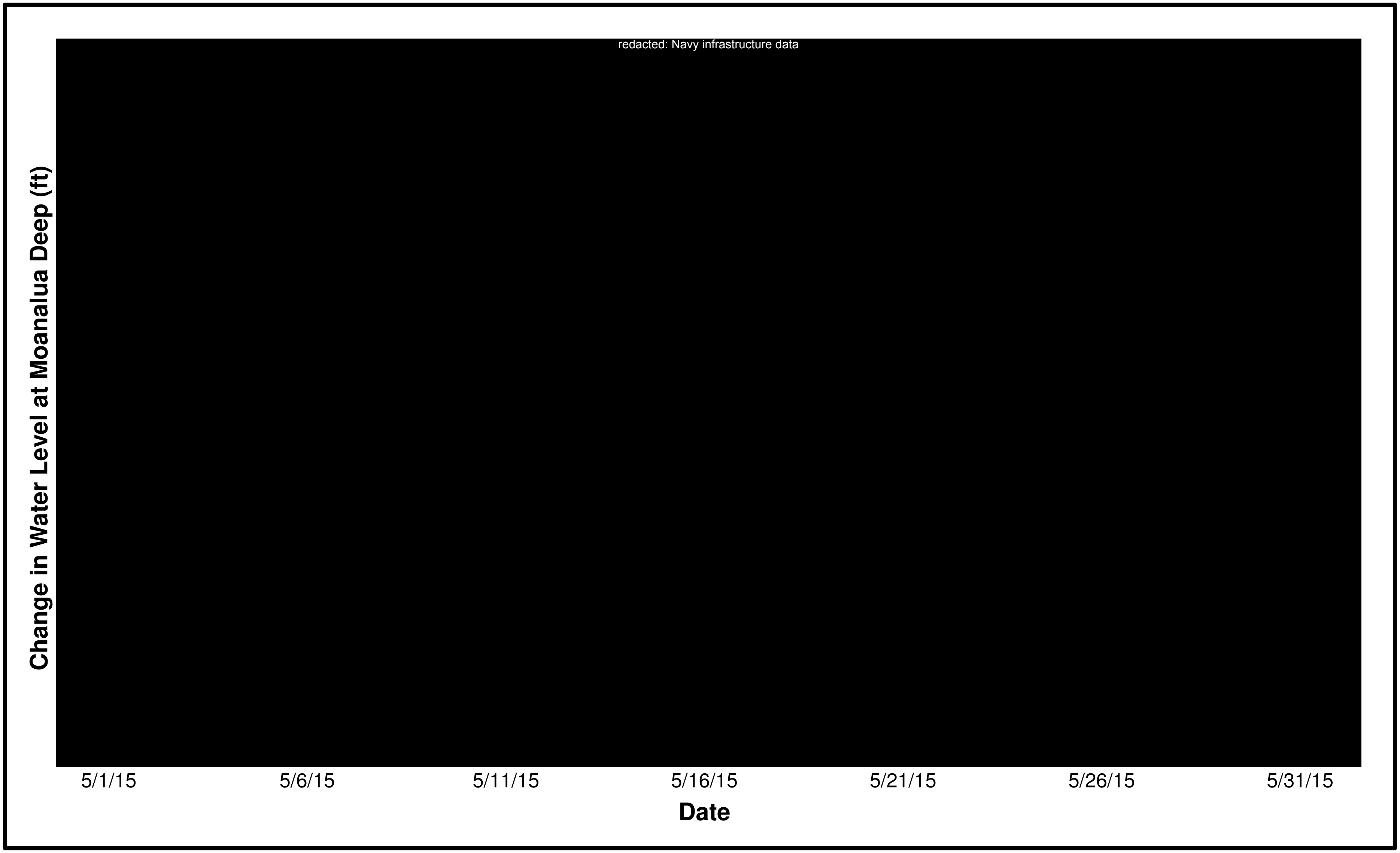


Figure 5.10.3-8
2015 Transient Synoptic Study Results at Moanalua Deep (2153-05)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

Figure 5.10.3-9
2015 Transient Synoptic Study Results at Moanalua DH43 (2253-02)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

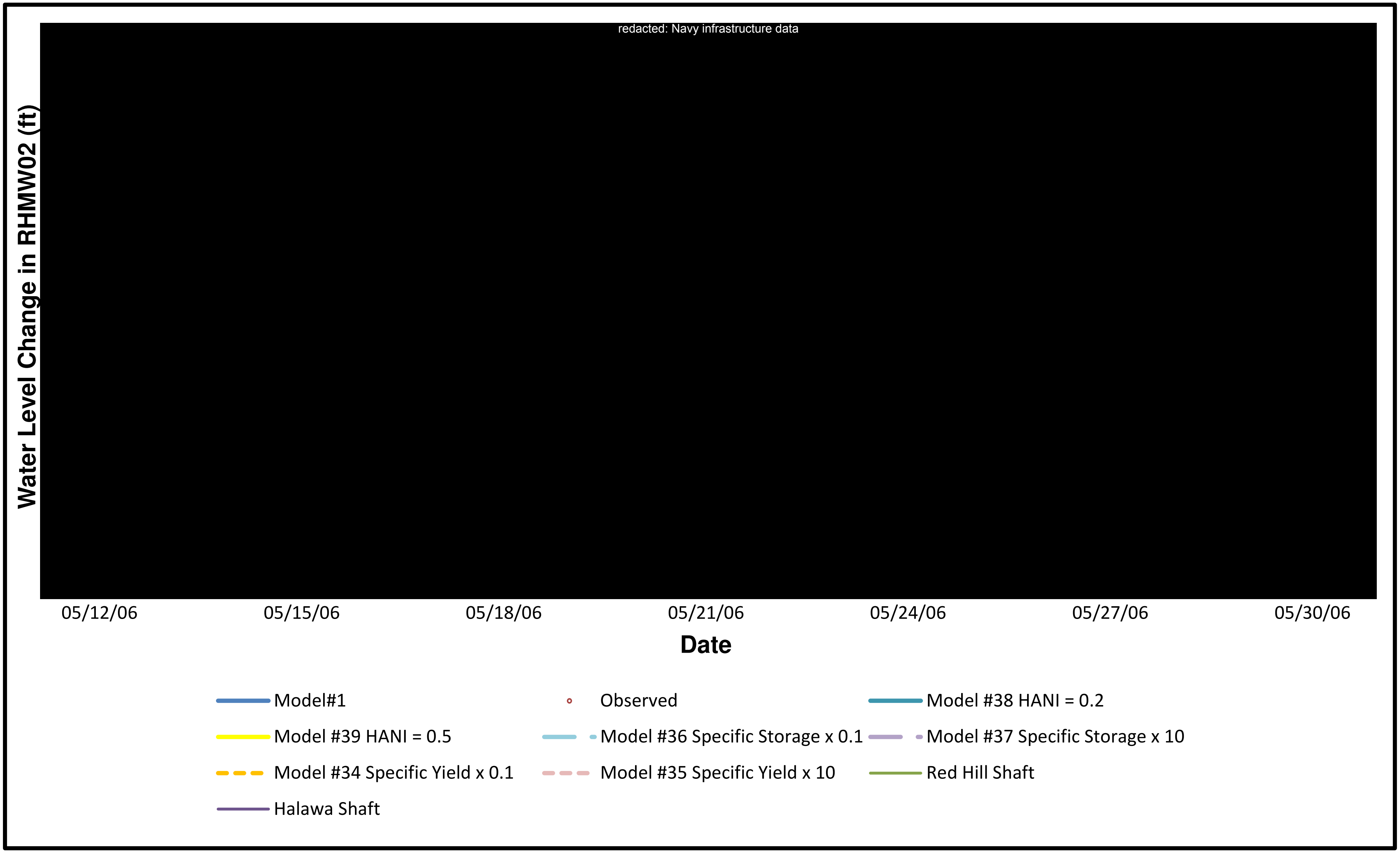


Figure 5.10.4-1
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) – Water Levels in RHMW02
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

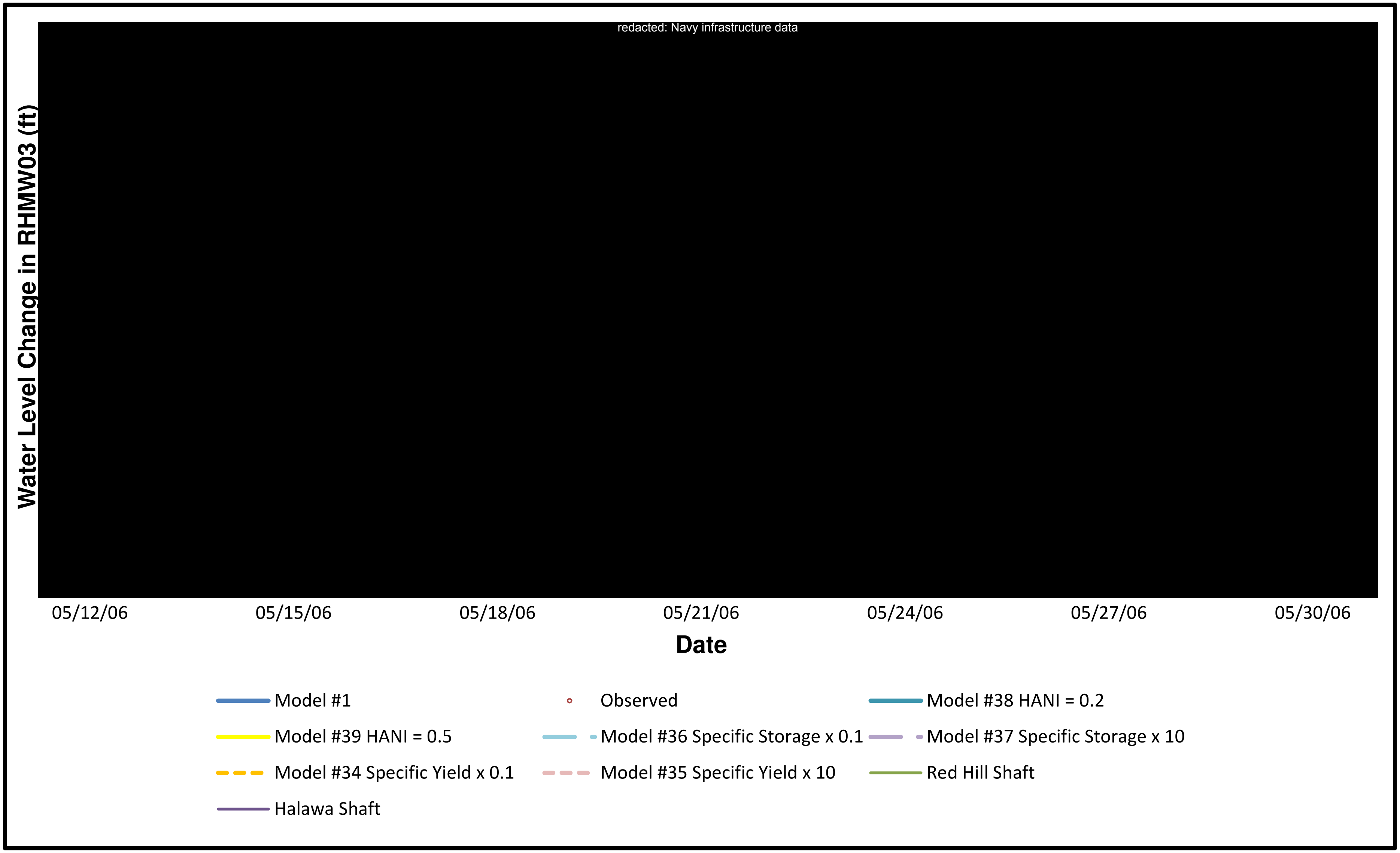


Figure 5.10.4-2
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) – Water Levels in RHMW03
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

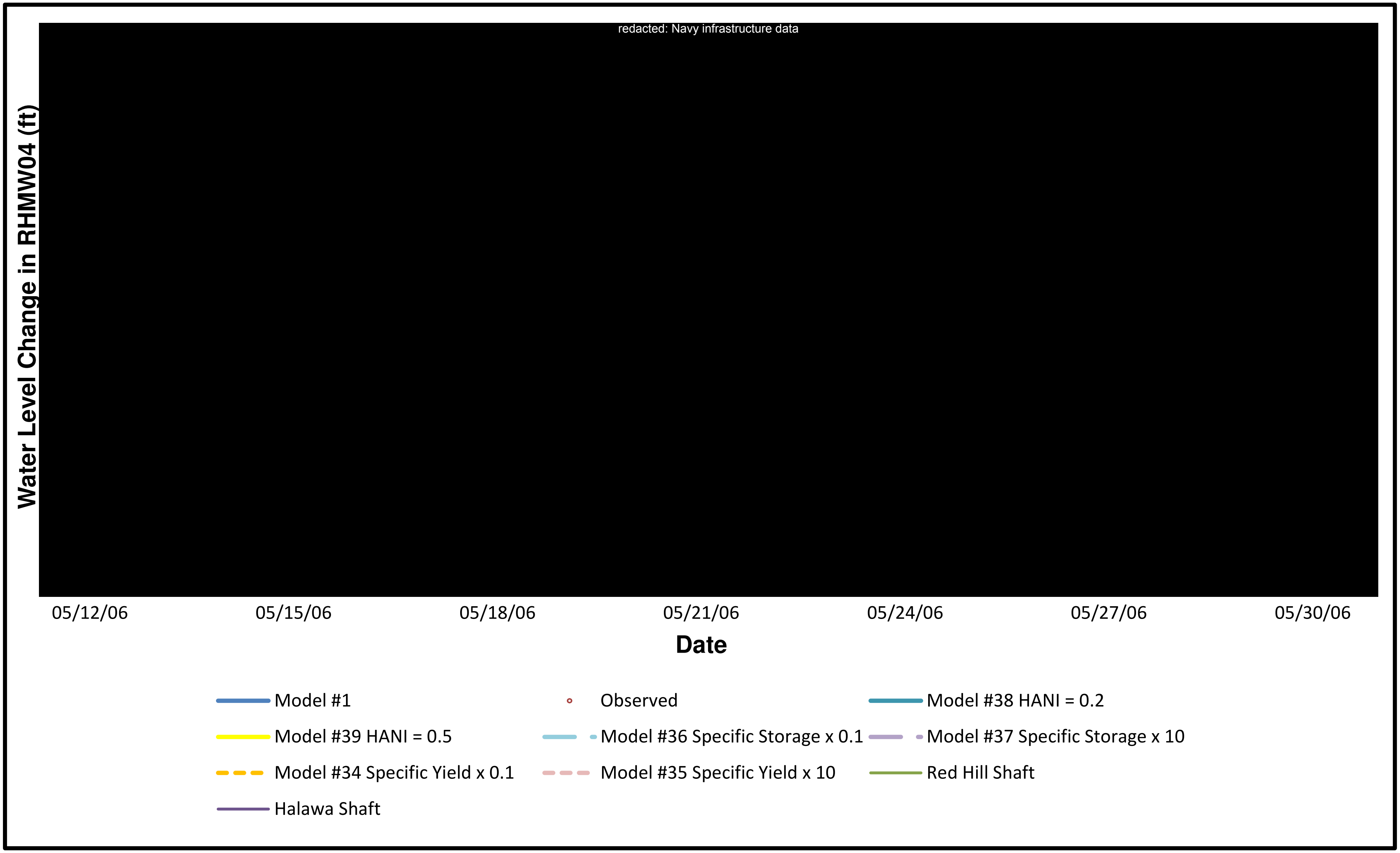


Figure 5.10.4-3
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) – Water Levels in RHMW04
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

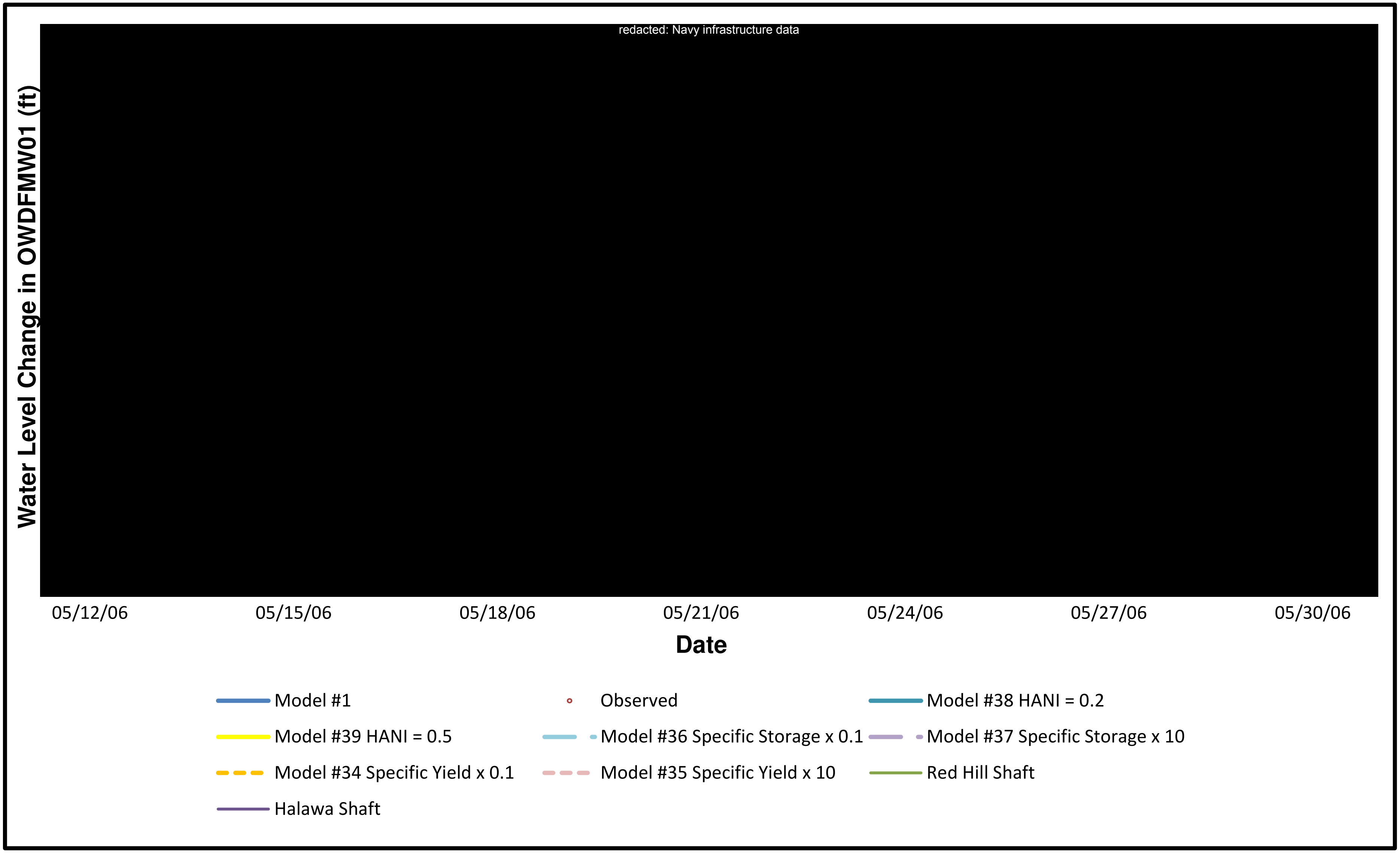


Figure 5.10.4-4
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) –
Water Levels in OWDFMW01
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

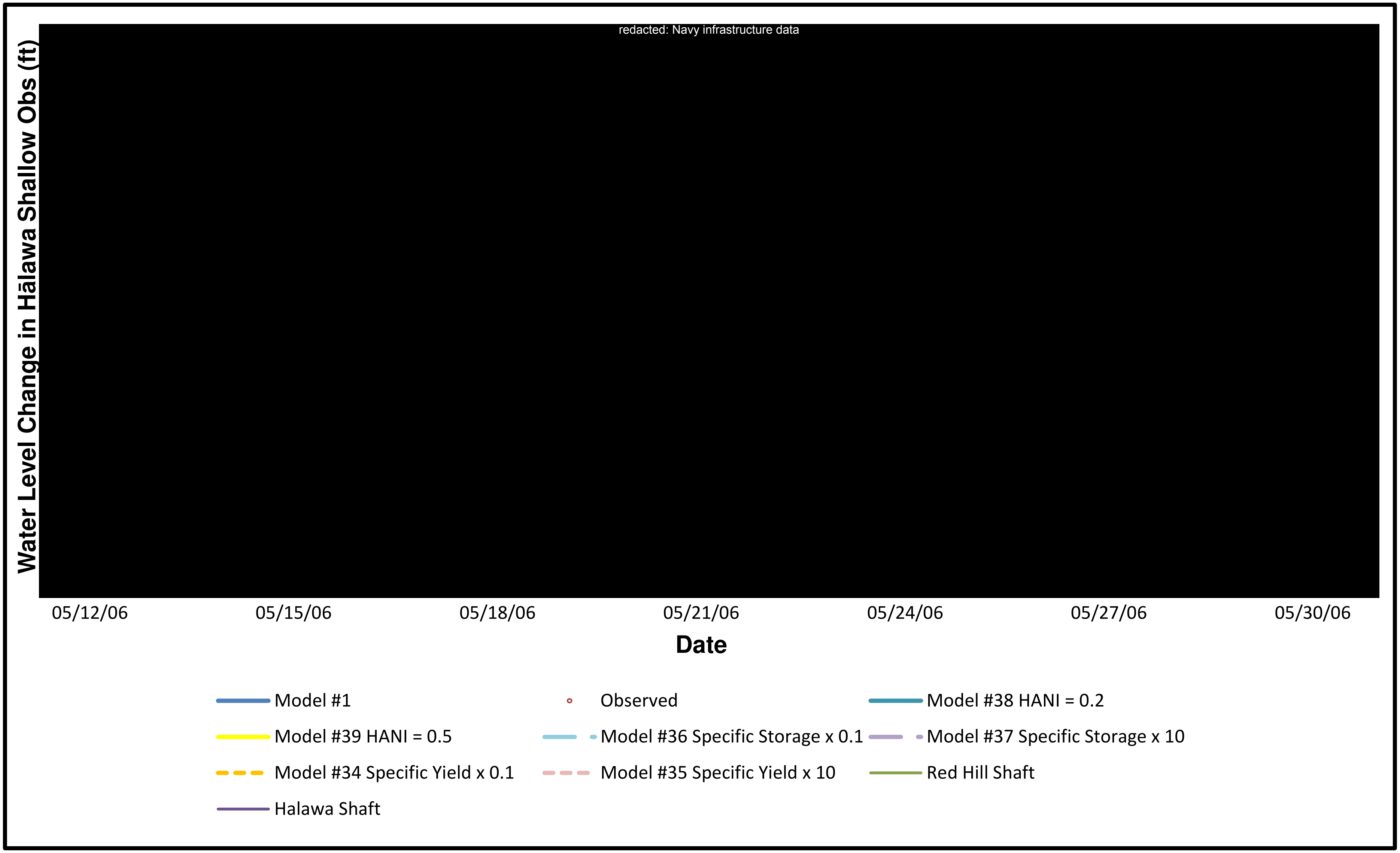


Figure 5.10.4-5
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) –
Water Levels in Hālawa Shallow Obs (2255-33)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

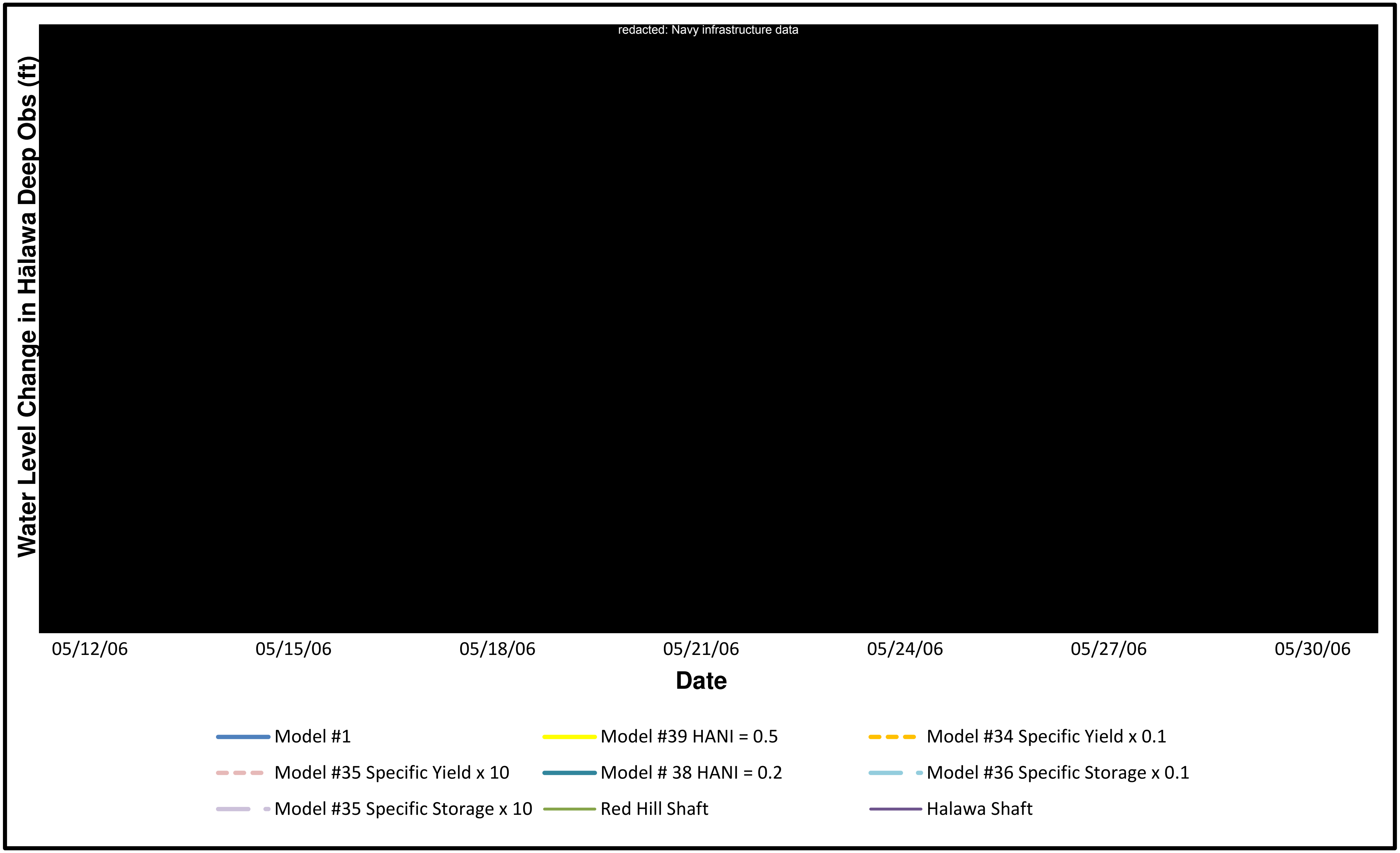


Figure 5.10.4-6
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) –
Water Levels in Hālawa Deep Obs (2255-40)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

Figure 5.10.4-7
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) –
Water Levels in South Hālawa Deep Obs (2253-03)
Appendix A- Interim Groundwater Flow Model Report Groundwater Protection
and Evaluation Considerations for Input to the TUA Decision Process
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

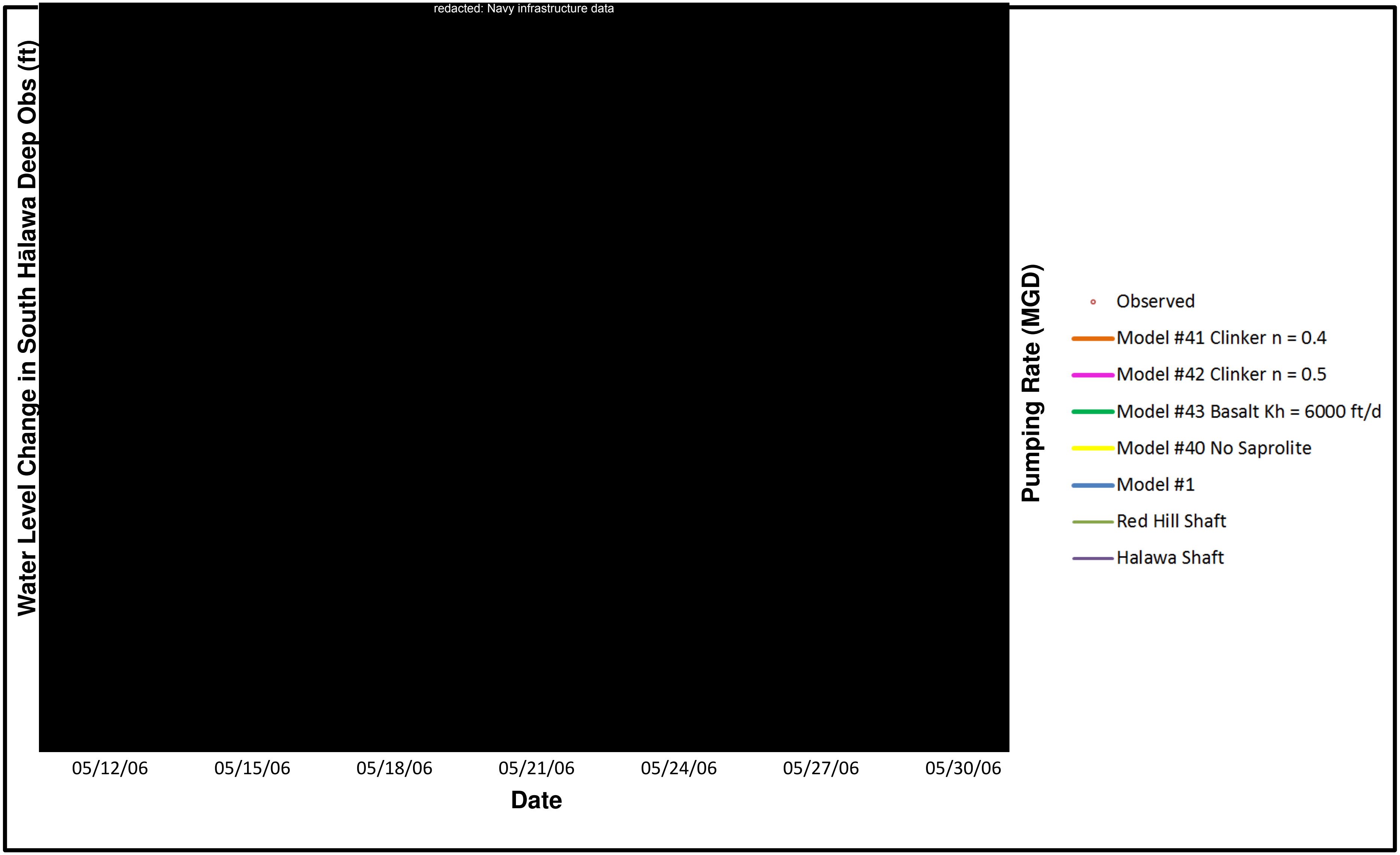


Figure 5.10.4-8
Sensitivity to 2006 Transient Synoptic Study (Models 26 to 31) –
Water Levels in Red Hill Shaft
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

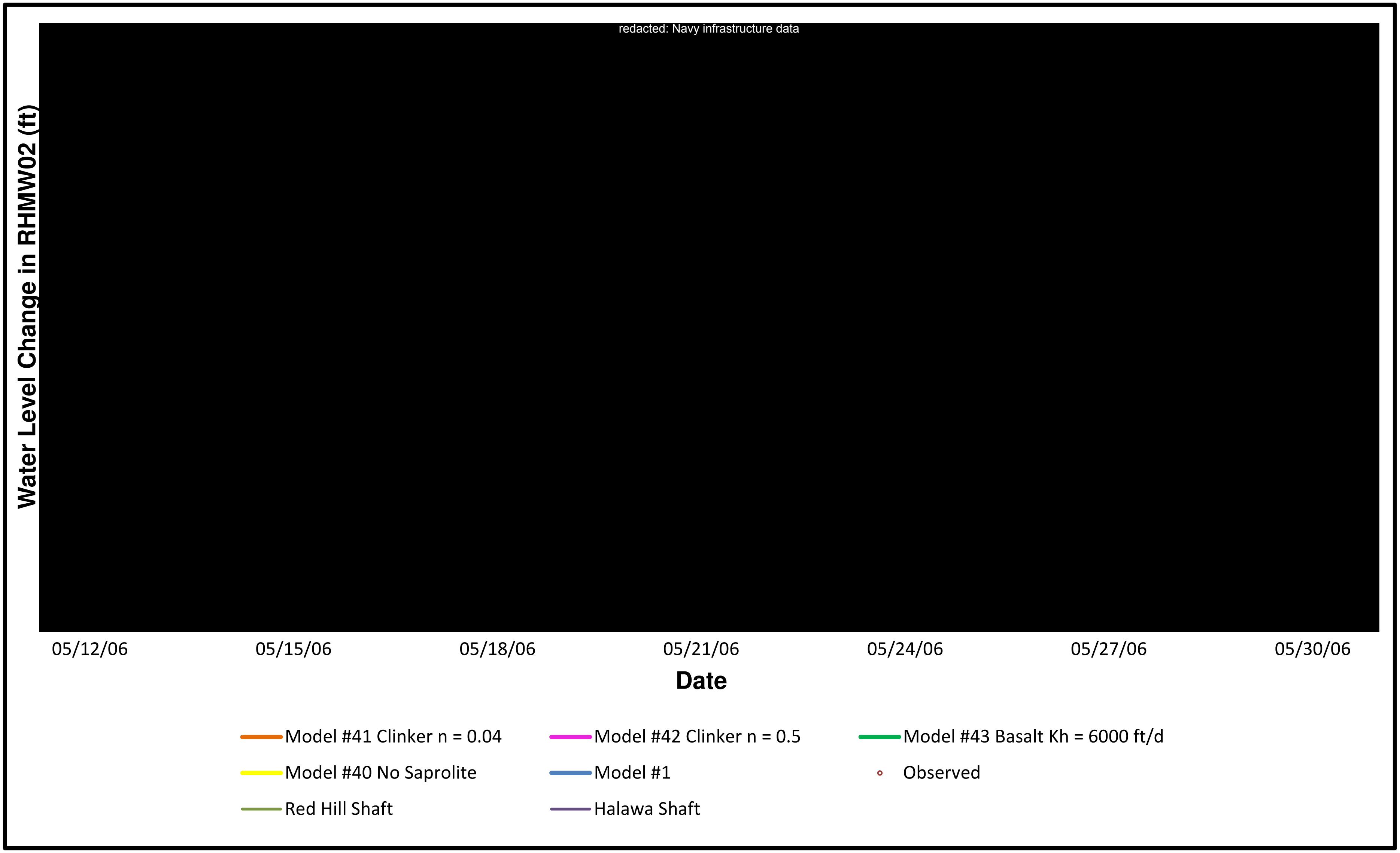


Figure 5.10.4-9
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) – Water Levels in RHMW02
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

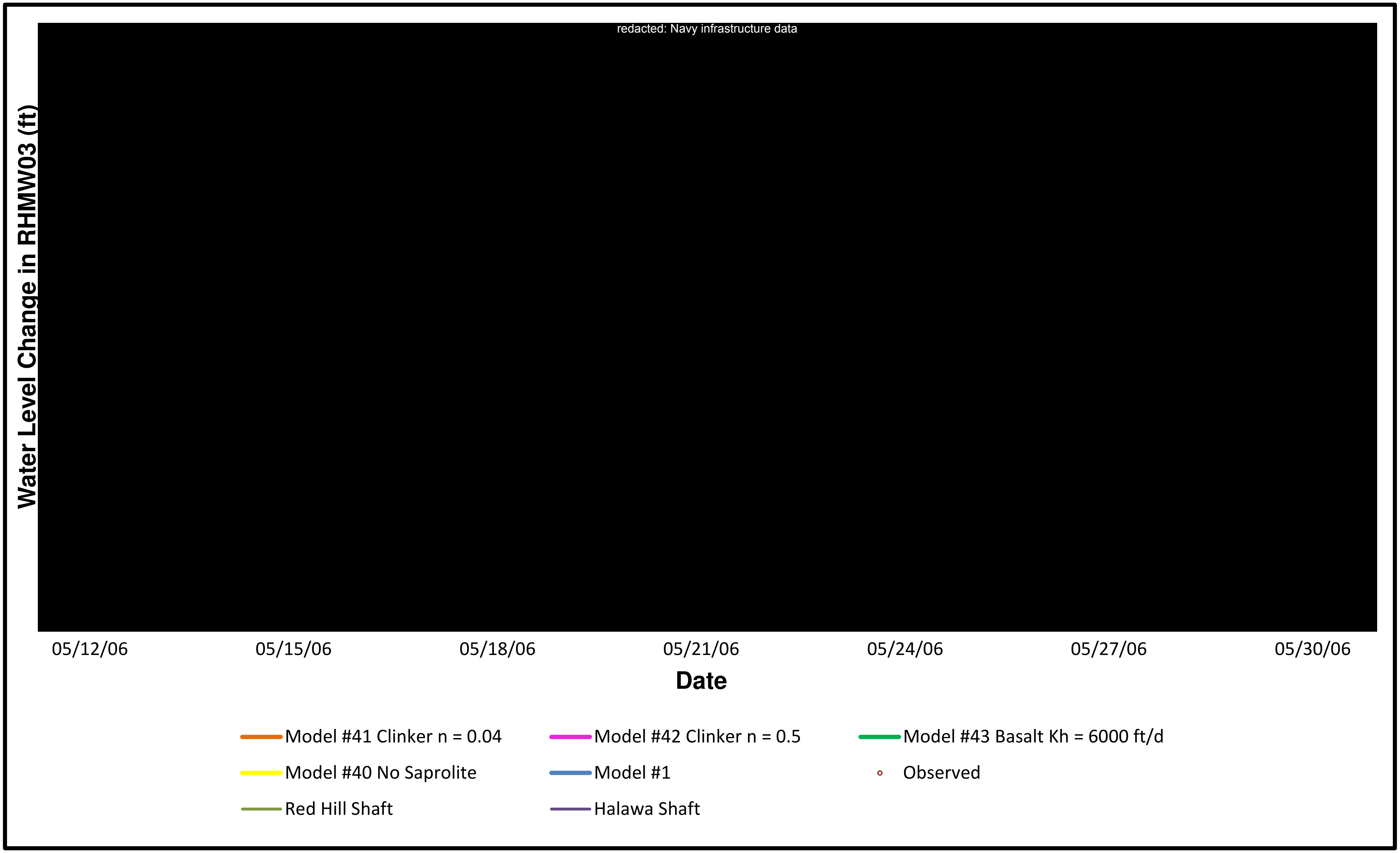


Figure 5.10.4-10
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) – Water Levels in RHMW03
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

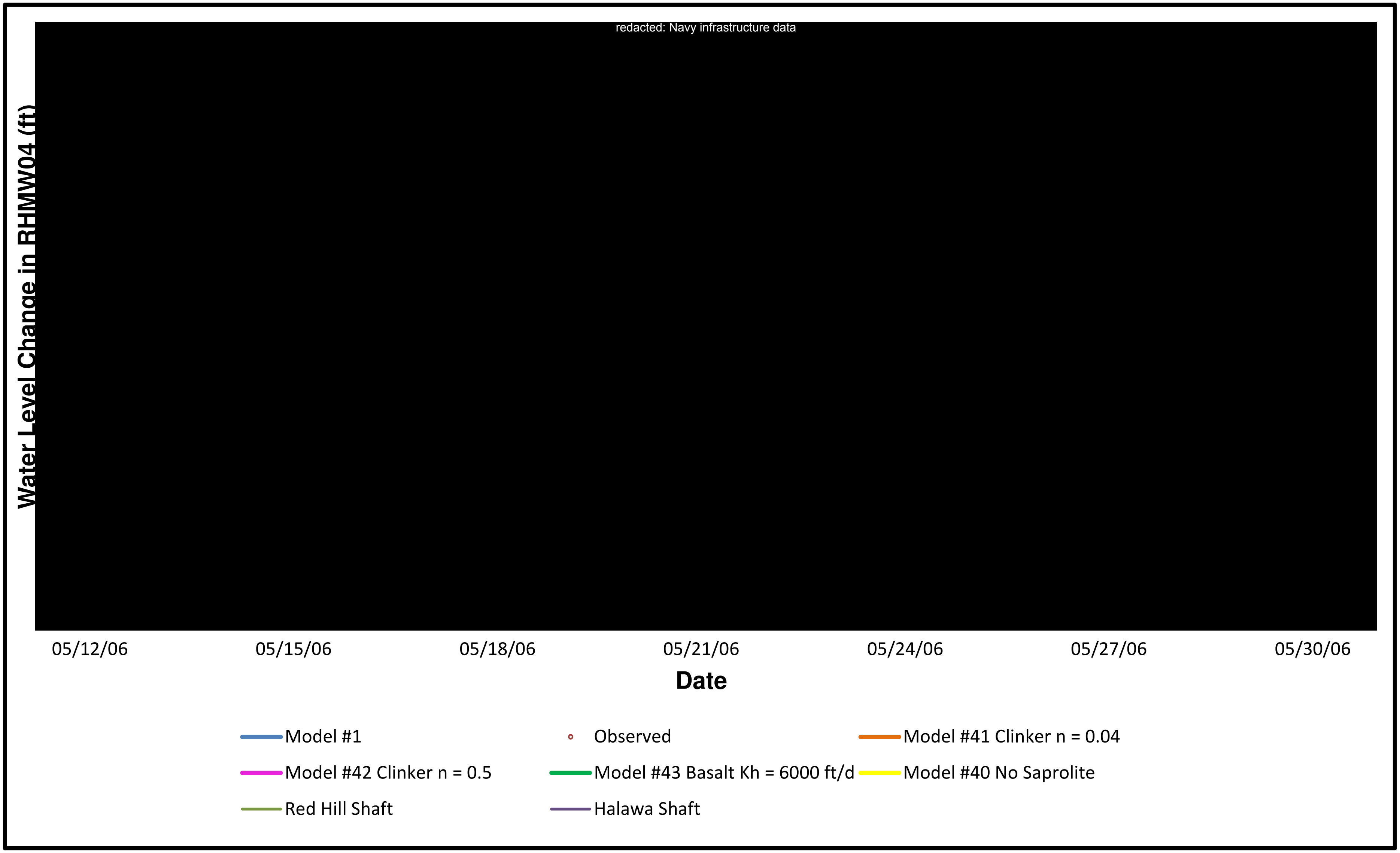


Figure 5.10.4-11
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) – Water Levels in RHMW04
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

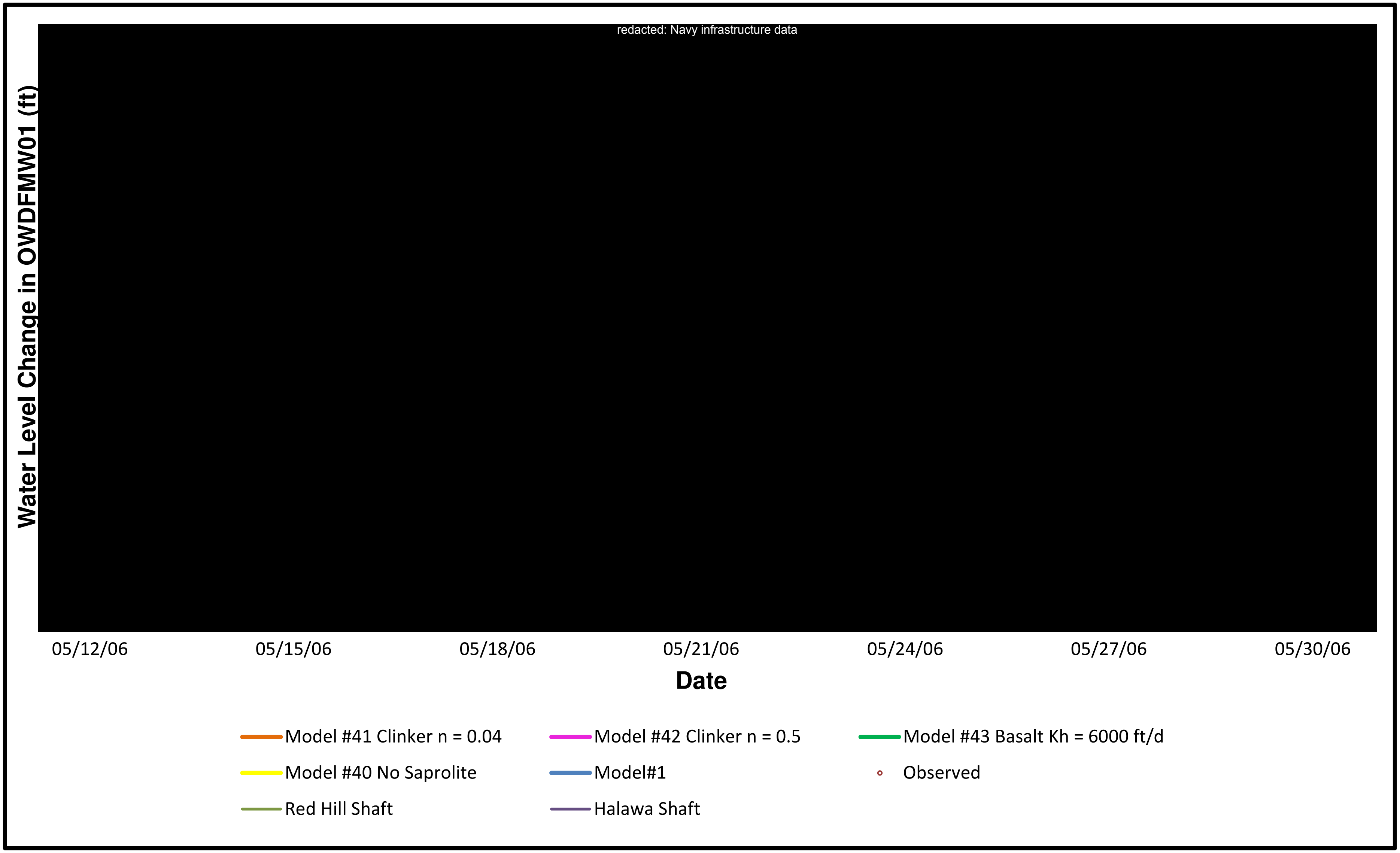


Figure 5.10.4-12
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) – Water Levels in OWDFMW01
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

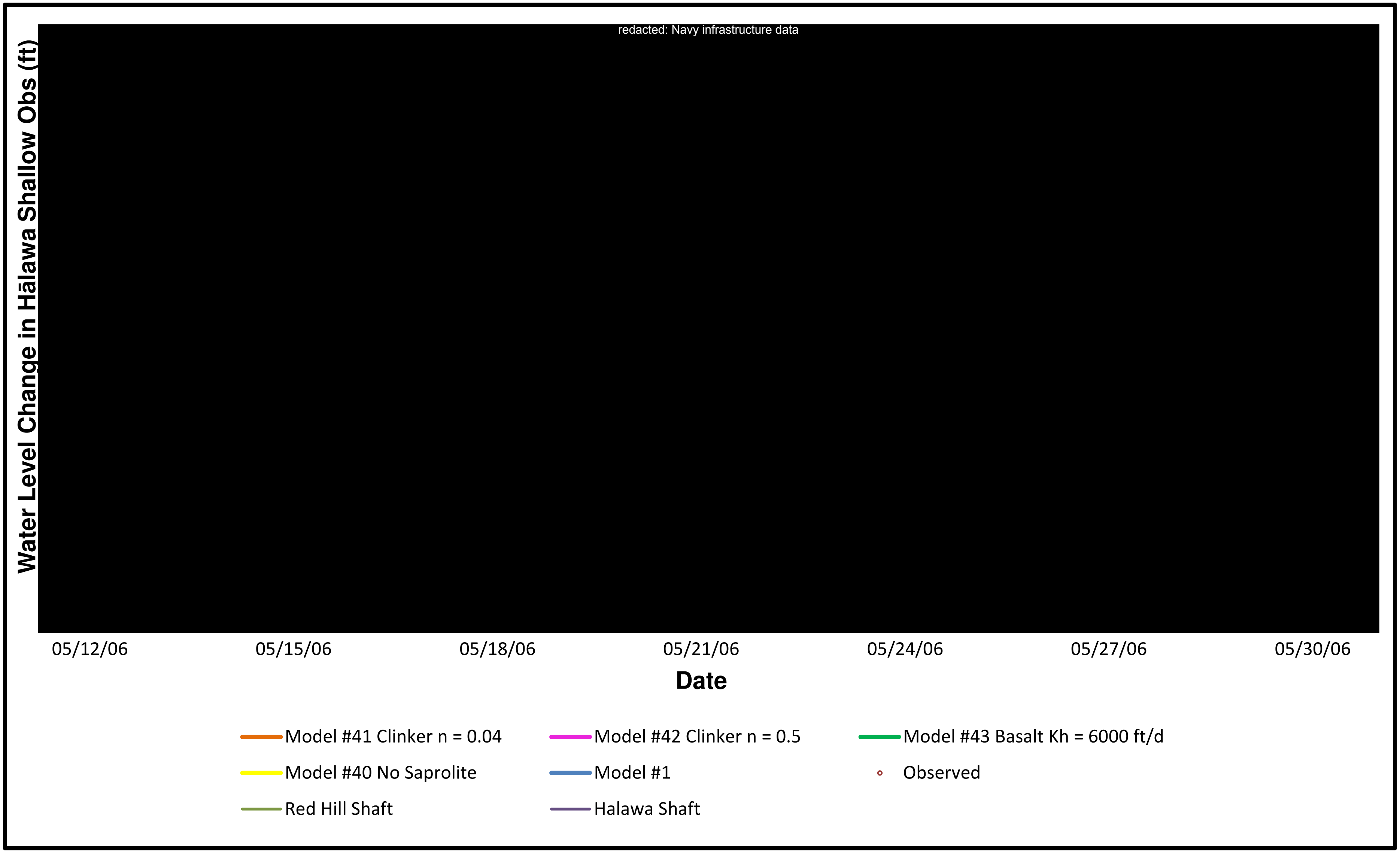


Figure 5.10.4-13
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) –
Water Levels in Hālawa Shallow Obs (2255-33)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

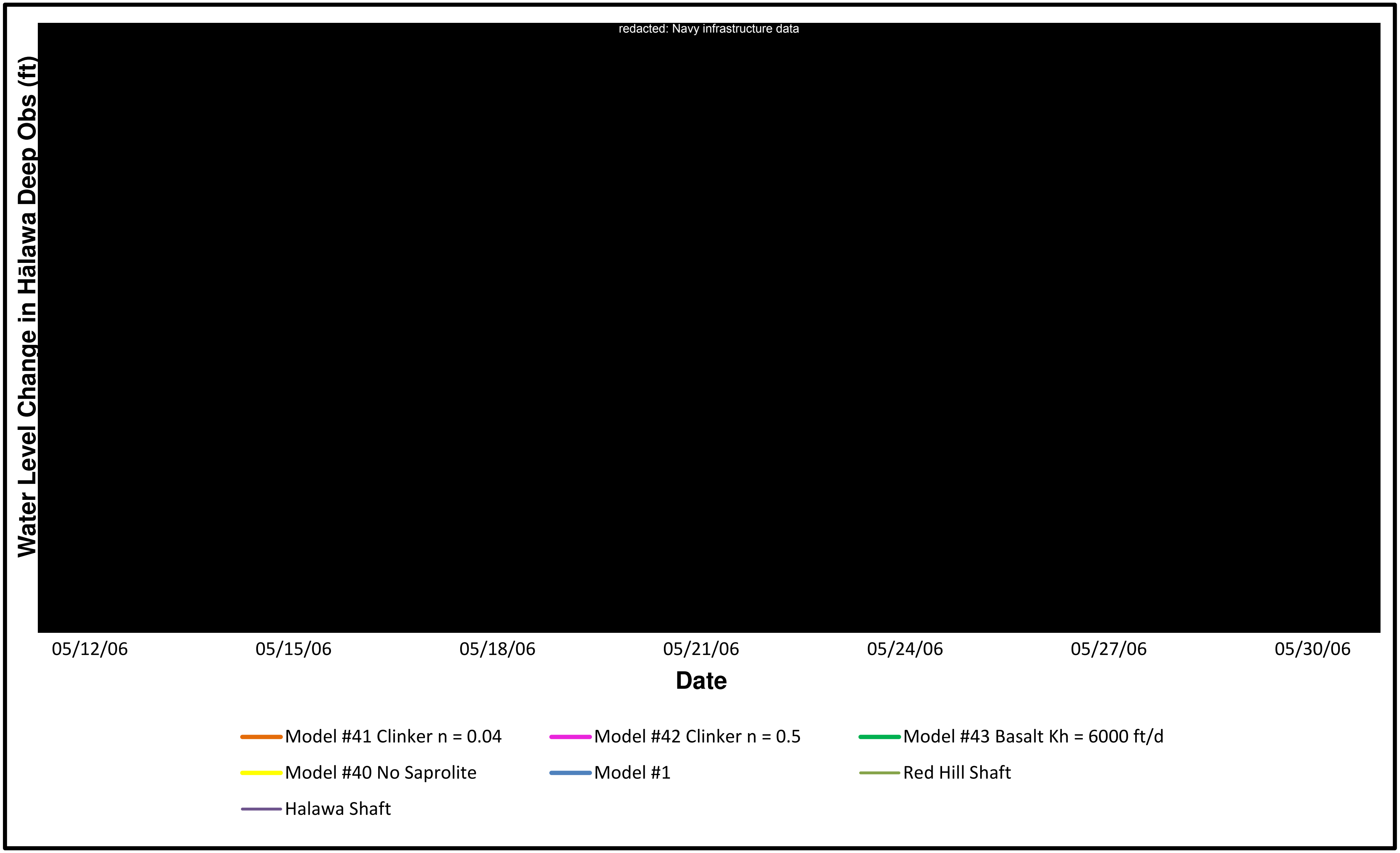


Figure 5.10.4-14
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) –
Water Levels in Hālawa Deep Obs (2255-33)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

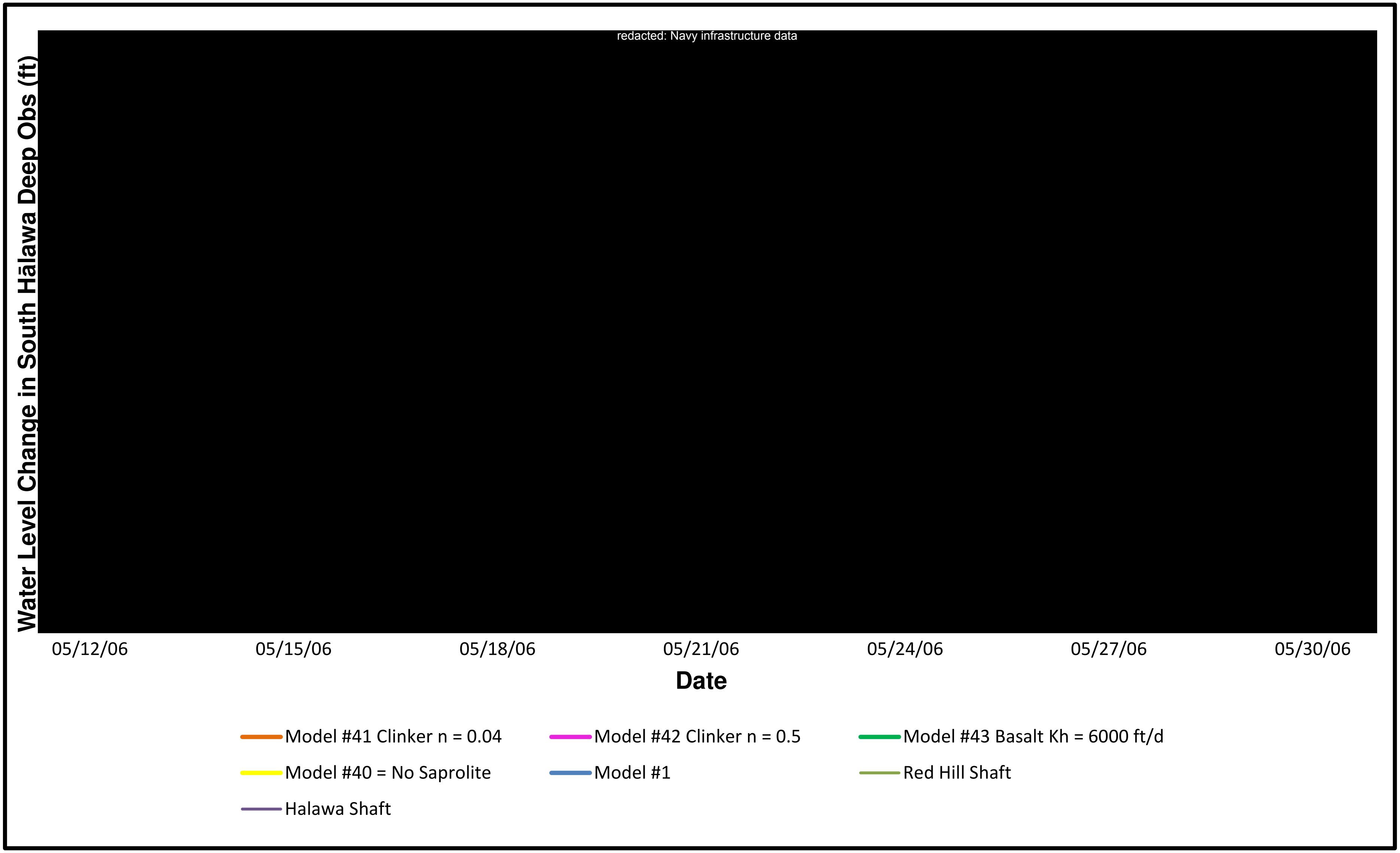


Figure 5.10.4-15
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) –
Water Levels in South Hālawa Deep Obs (2253-03)
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

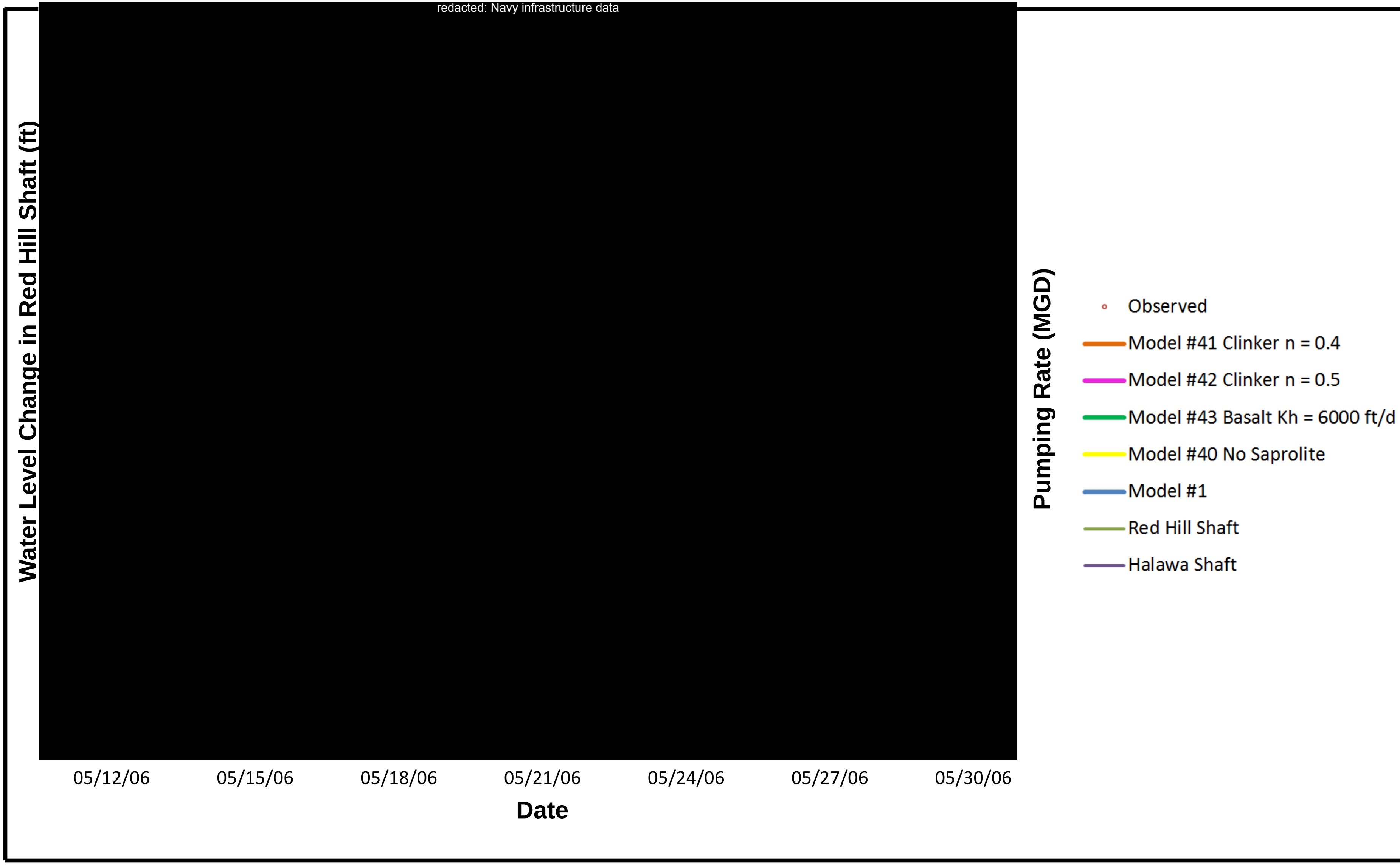
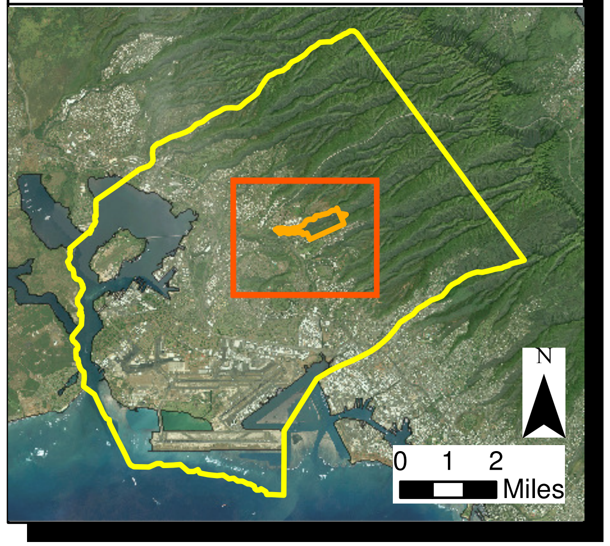


Figure 5.10.4-16
Sensitivity to 2006 Transient Synoptic Study (Models 32 to 35) – Water Levels in Red Hill Shaft
Appendix A - Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

Location Map



Legend

Particles are Released:

- Along the Hālawa Shaft in Layer 3
- From Moanalua Well in Layer 5
- Along Red Hill Shaft in Layer 2
- Within the Source Water Zone in Layer 2
- Source Water Zone
- Red Hill Bulk Fuel Storage Facility Boundary
- Model Area
- Stream

Notes

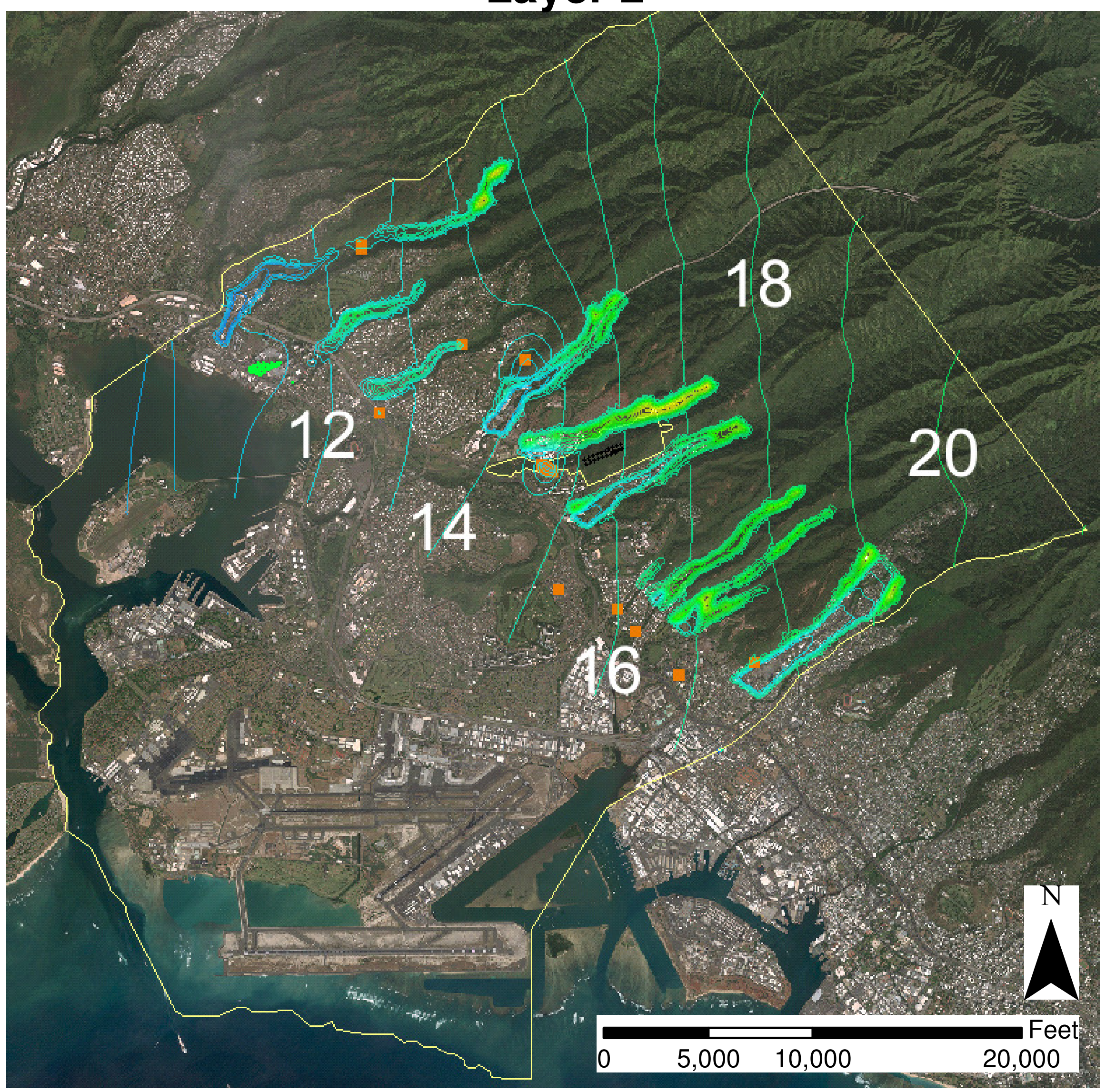
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

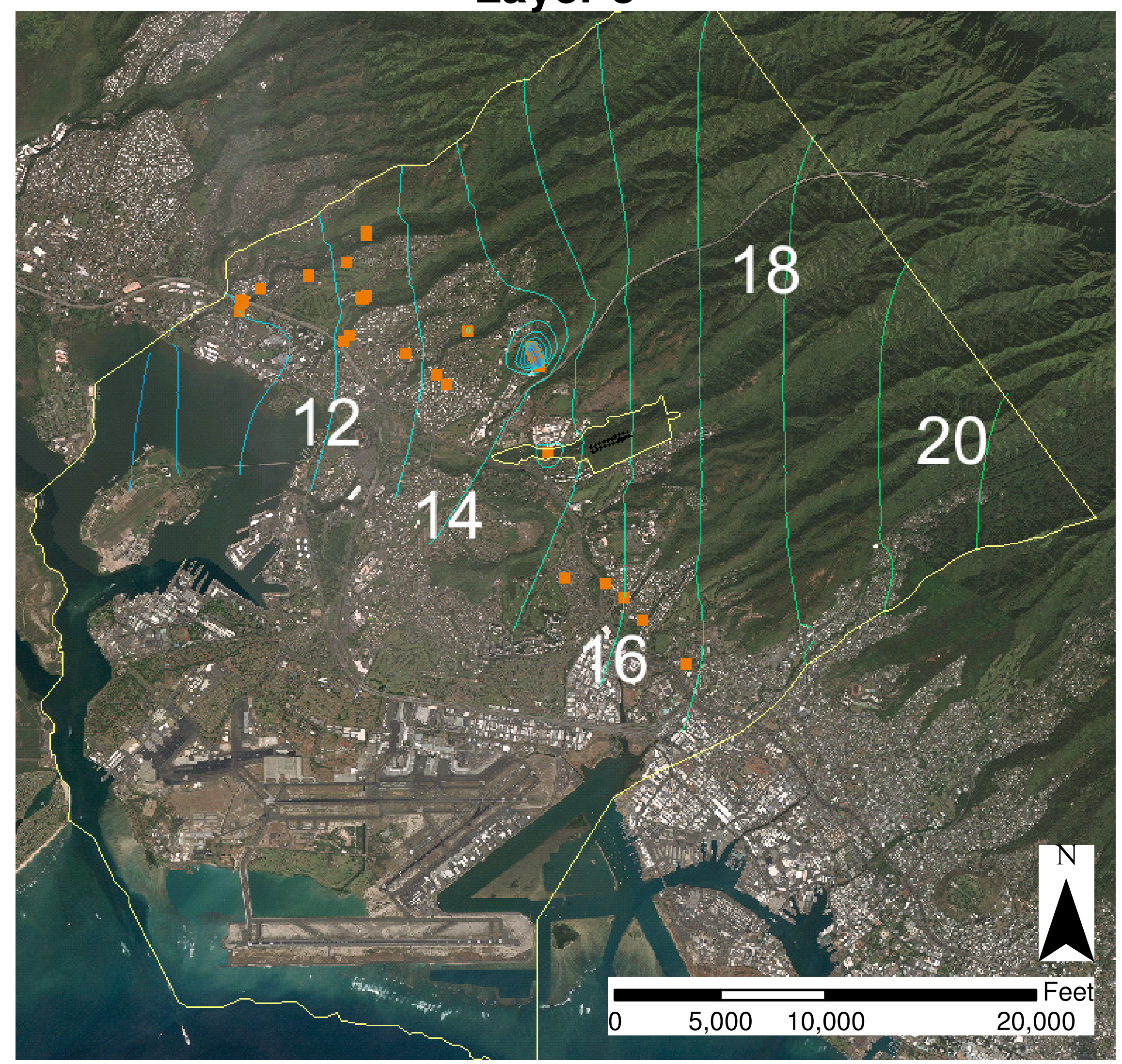
Feet
0 500 1,000 2,000

Figure 6.2-1
Particle Release Locations for Migration and Source Water Zone Evaluations
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

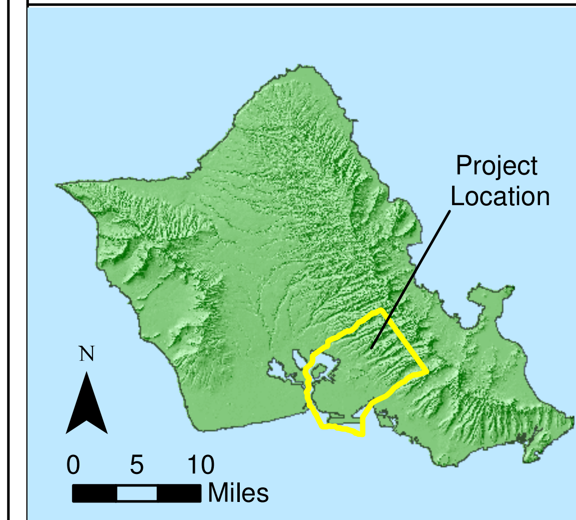
Layer 2



Layer 3



Location Map



Legend

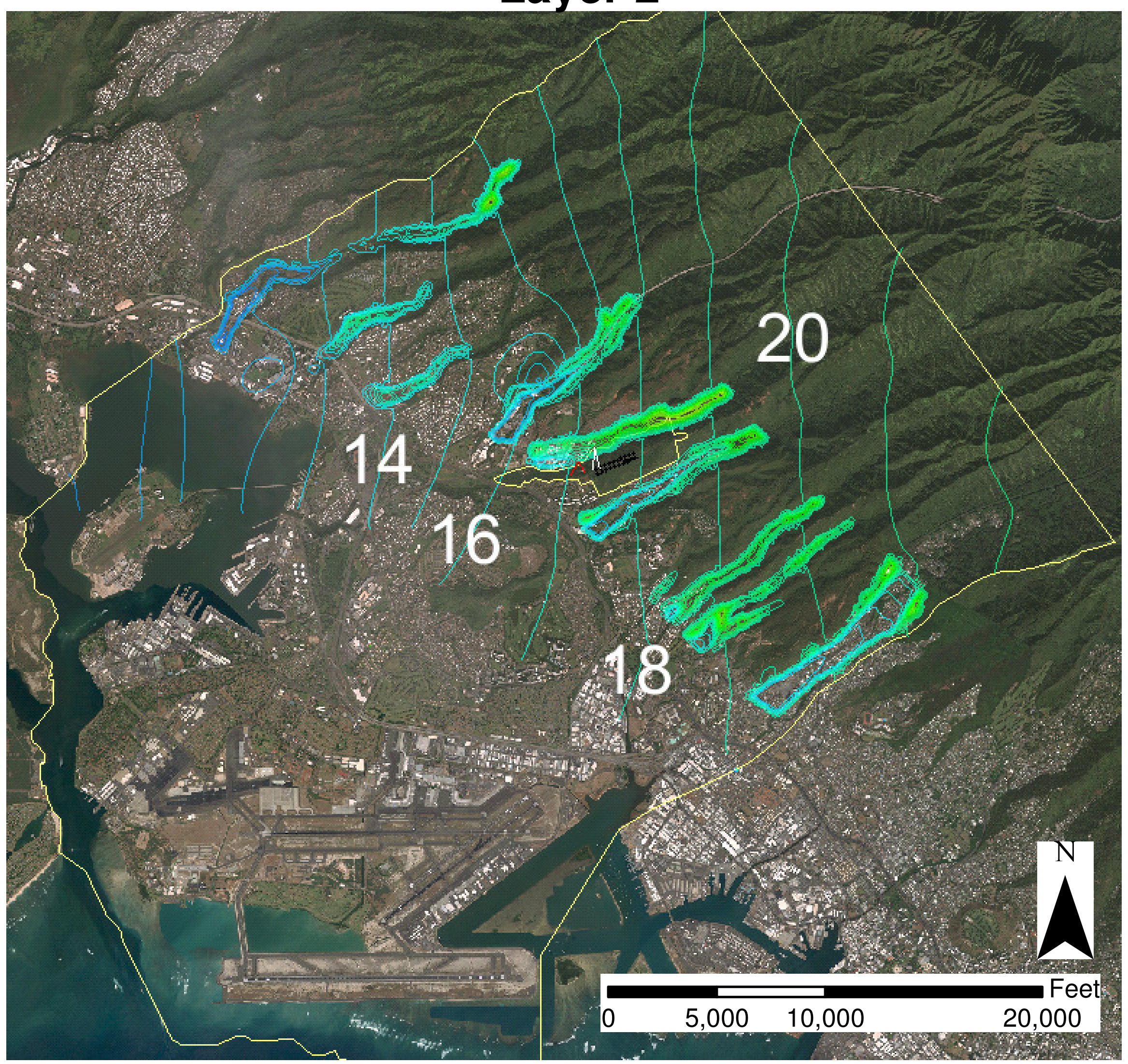
- Red Hill Fuel Storage Tank
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

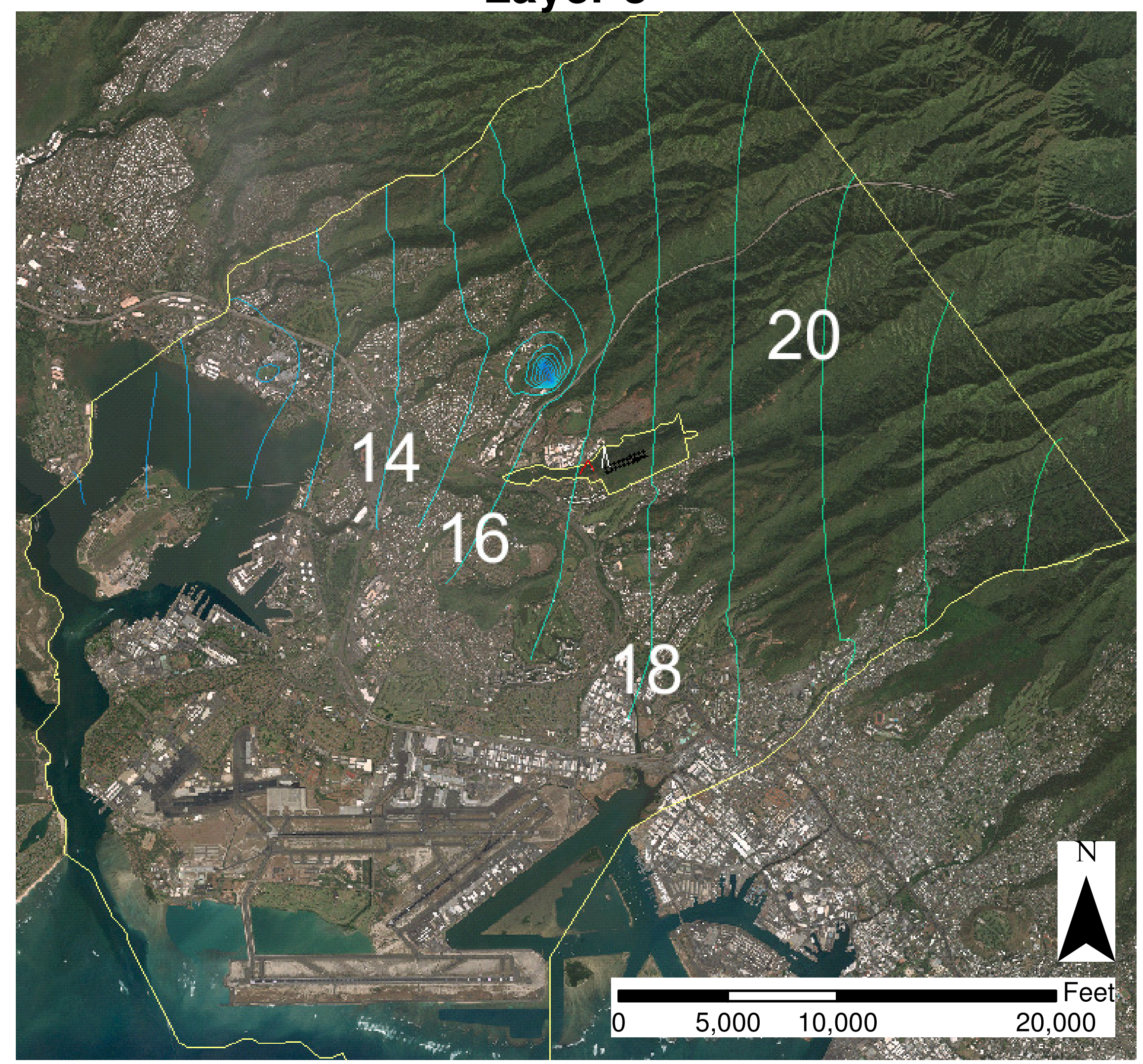
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 6.3.1-1
Steady-State Water Level Elevations for
Red Hill Shaft Pumping Scenario with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and
Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

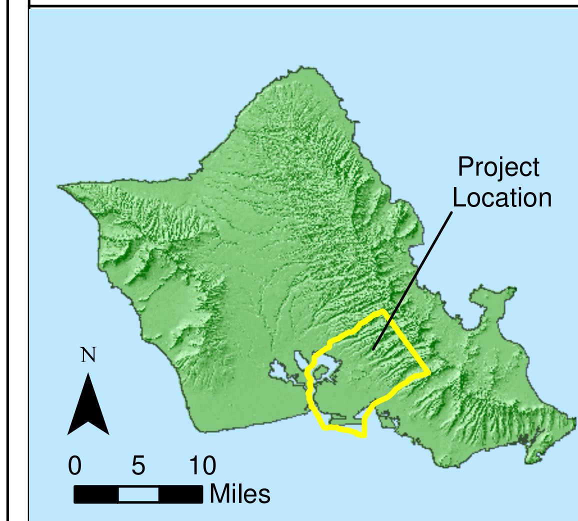
Layer 2



Layer 3



Location Map



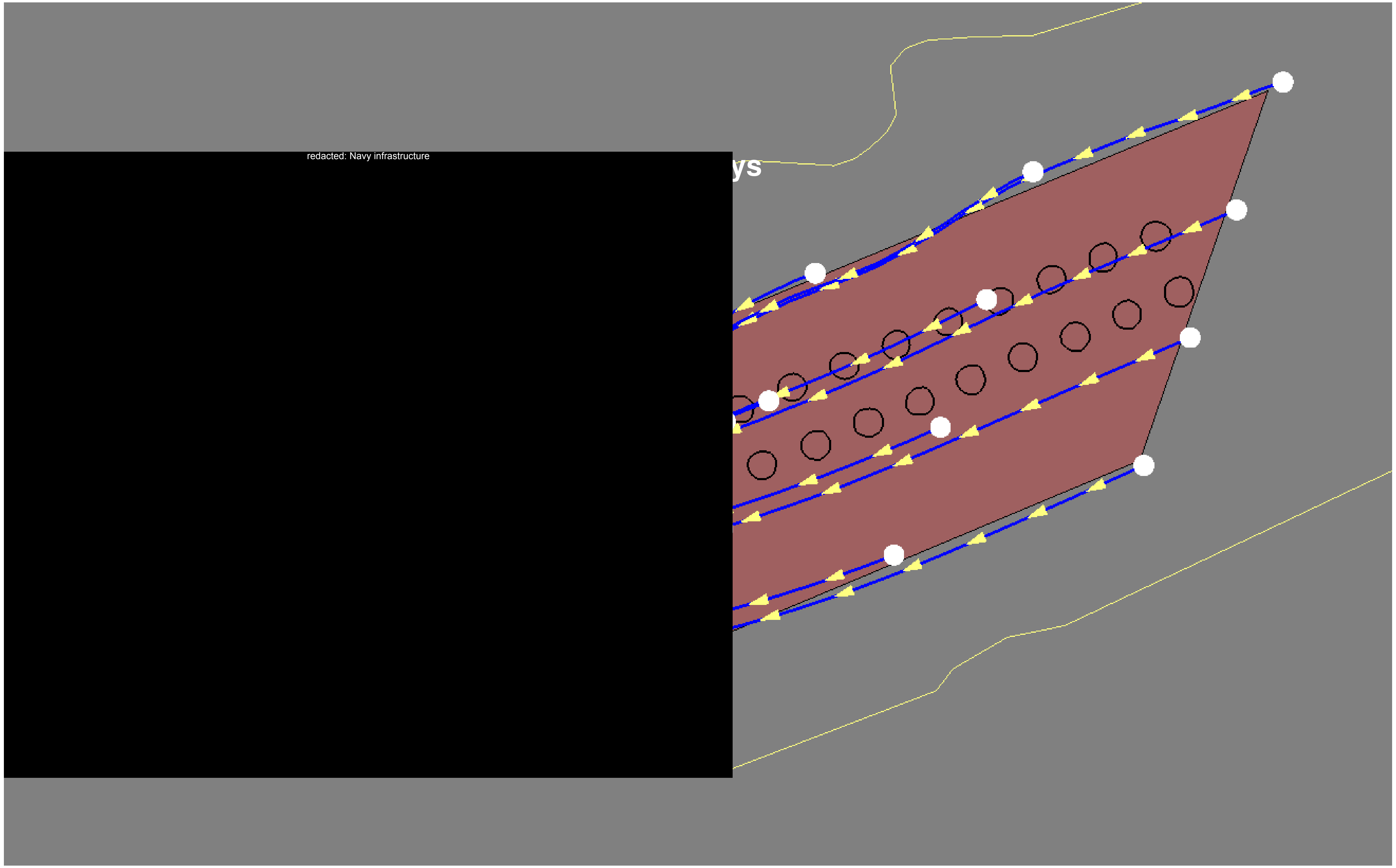
Legend

- Red Hill Fuel Storage Tank
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

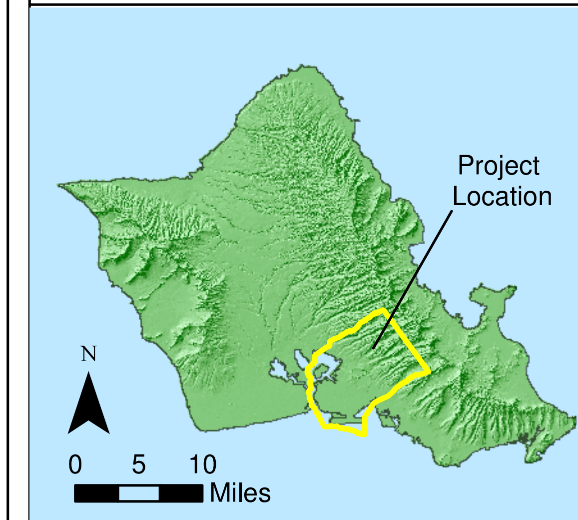
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Head values are in feet above mean sea level.

Figure 6.3.1-2
Steady-State Water Level Elevations for Red Hill Shaft Not Pumping Scenario with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

- Particles
- 30-day Time Intervals
- Layer 2 Pathlines
- Red Hill Fuel Storage Tank
- Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Particles may reach shaft approximately between 30 ad 360 days.
4. All particles remain in Layer 2.

N

Feet
0 250 500 1,000

Figure 6.3.2-1
Groundwater Trajectory and Travel Time Between the Facility and Red Hill Shaft with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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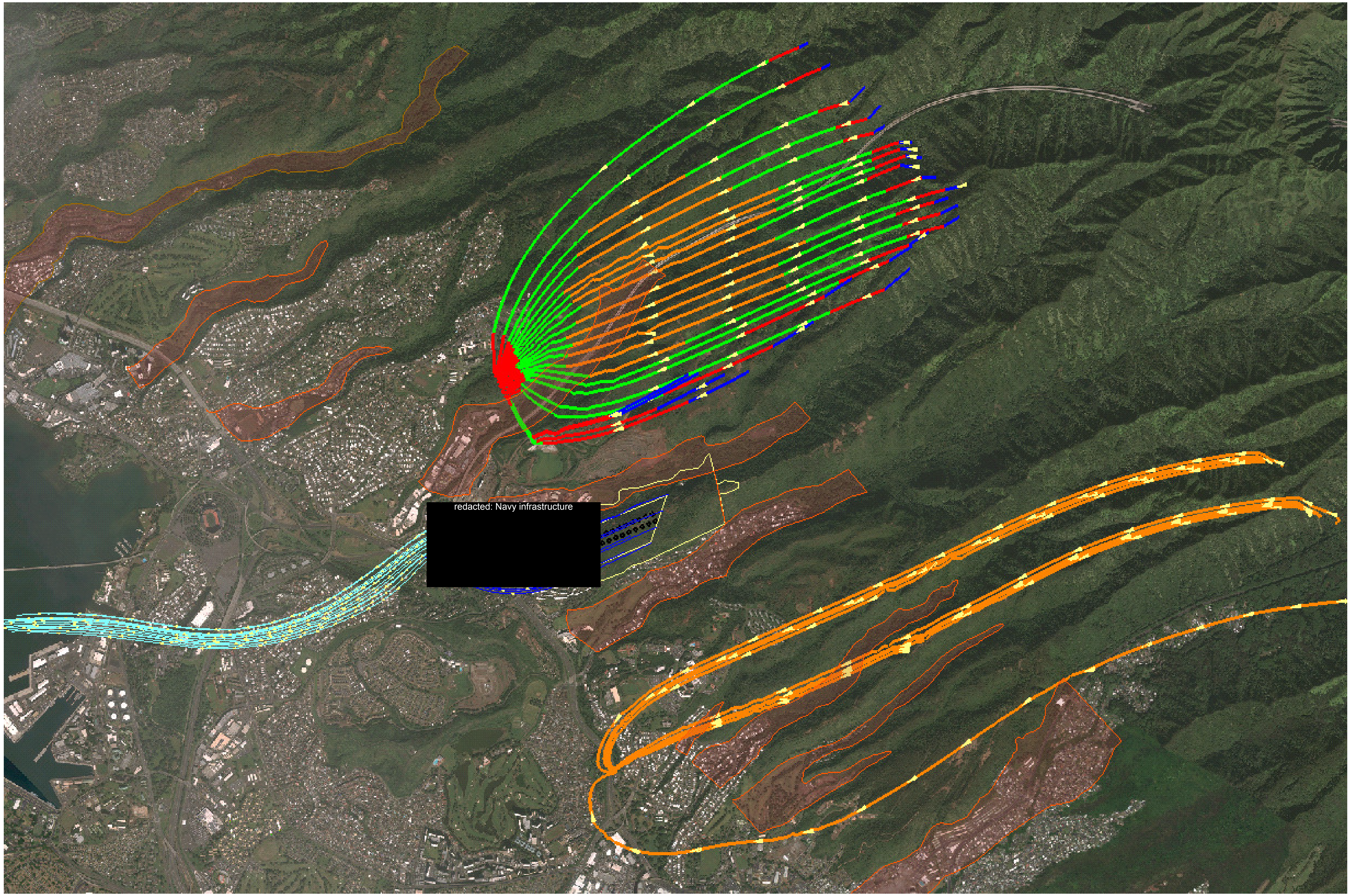

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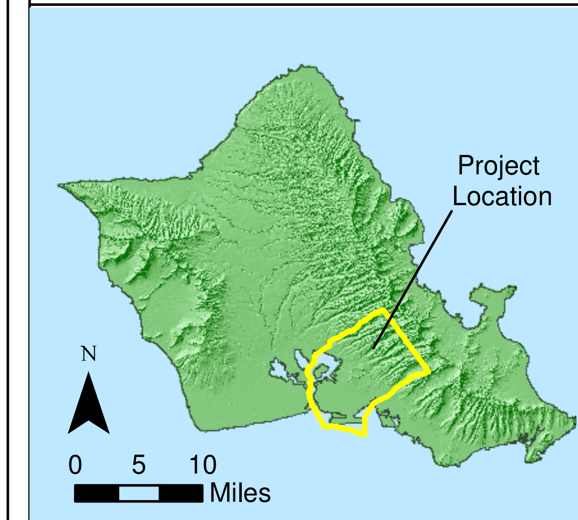


Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Red Hill Bulk Fuel Storage Facility Boundary

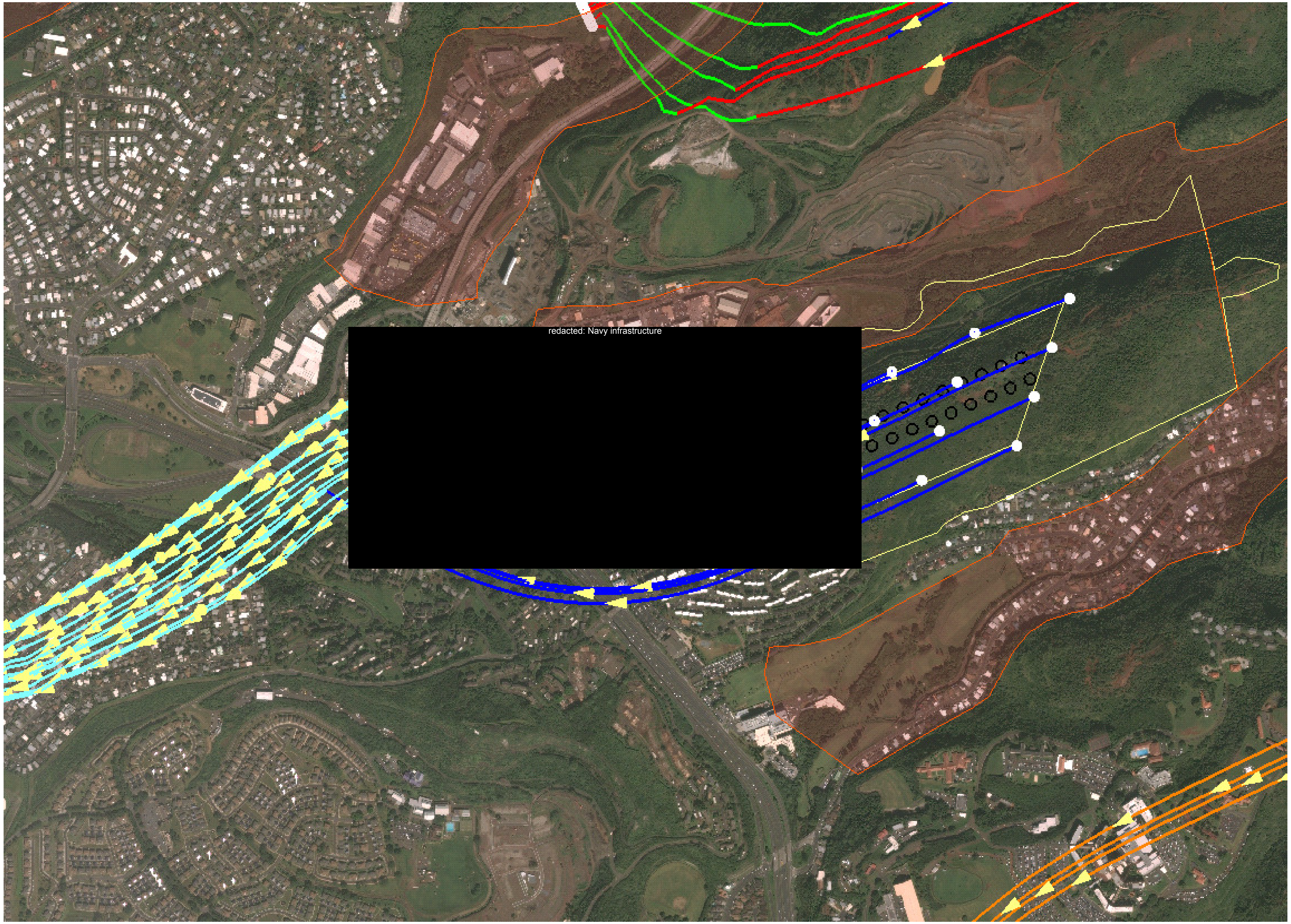
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Inverse praticle tracks to Moanalua wells and Hālawa Shaft.
4. Foward particle tracks from Red Hill Facility.
5. Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

N

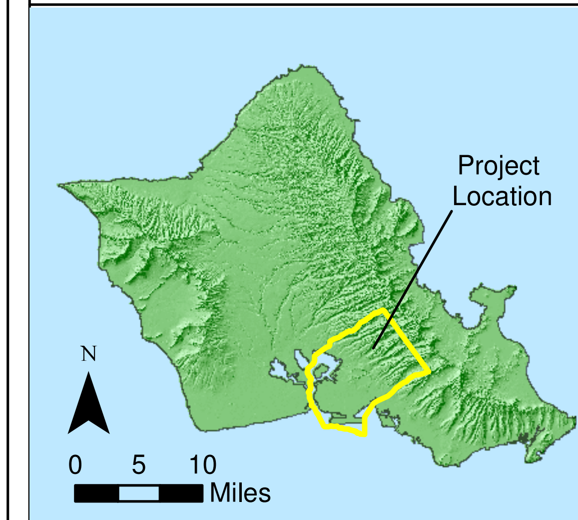
0 1,500 3,000 6,000 Feet

Figure 6.3.3-1
Migration from the Facility and Source Water Zones for Red Hill Shaft Not Pumping Scenario with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



[redacted]

Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

- Particles
- 1-year Time Intervals
- Red Hill Fuel Storage Tank
- Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

N

0 500 1,000 2,000 Feet

Figure 6.3.3-2
Zoom View of Migration from the Facility for Red Hill Shaft Not Pumping Scenario with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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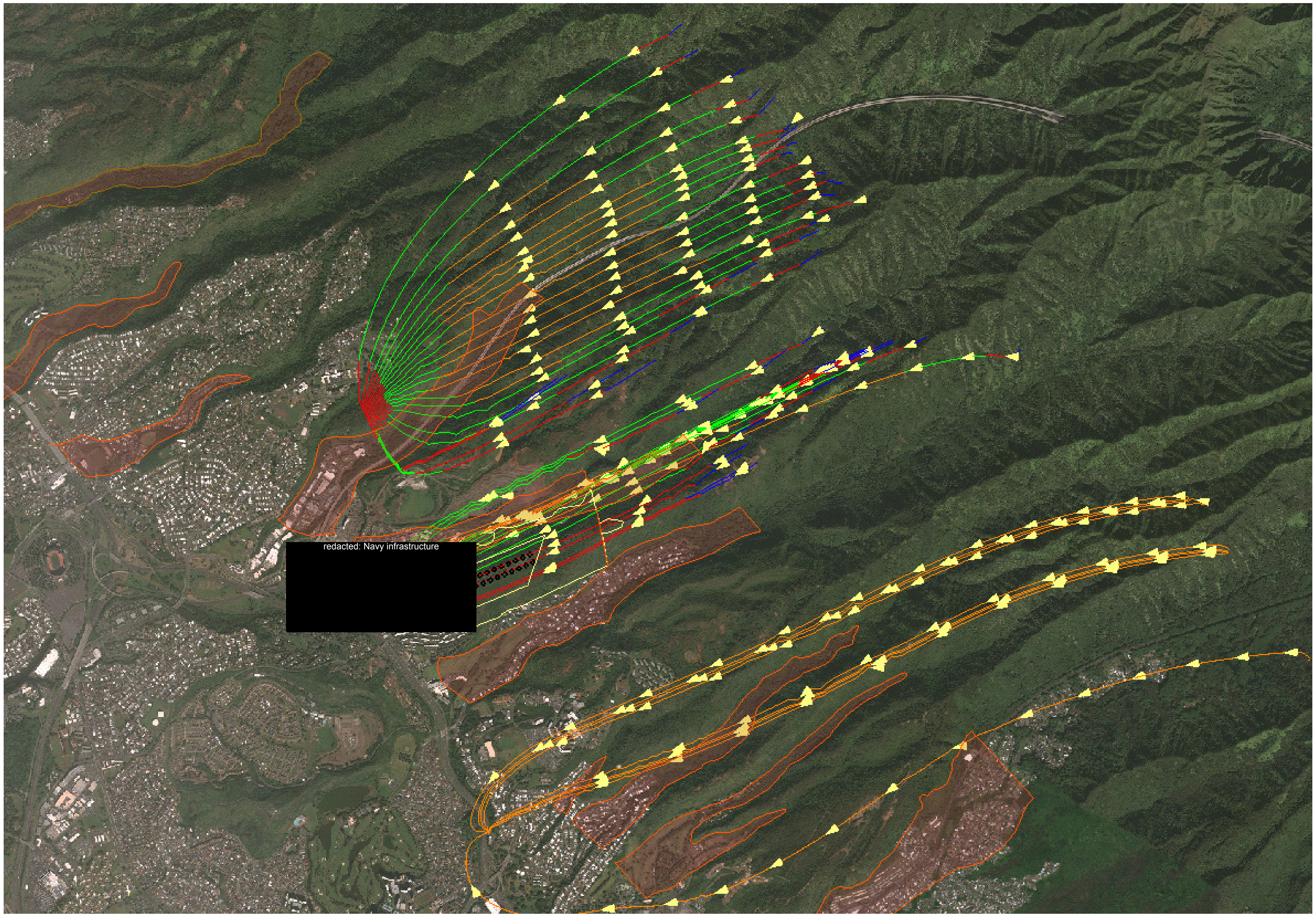
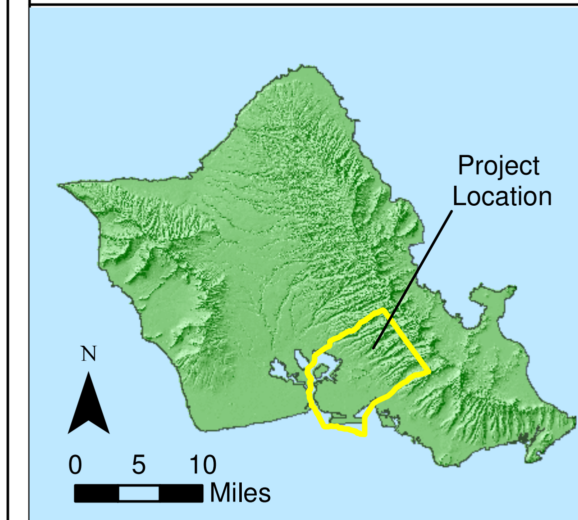


Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- 1-year Time Intervals
- Red Hill Fuel Storage Tank
- Red Hill Bulk Fuel Storage Facility Boundary

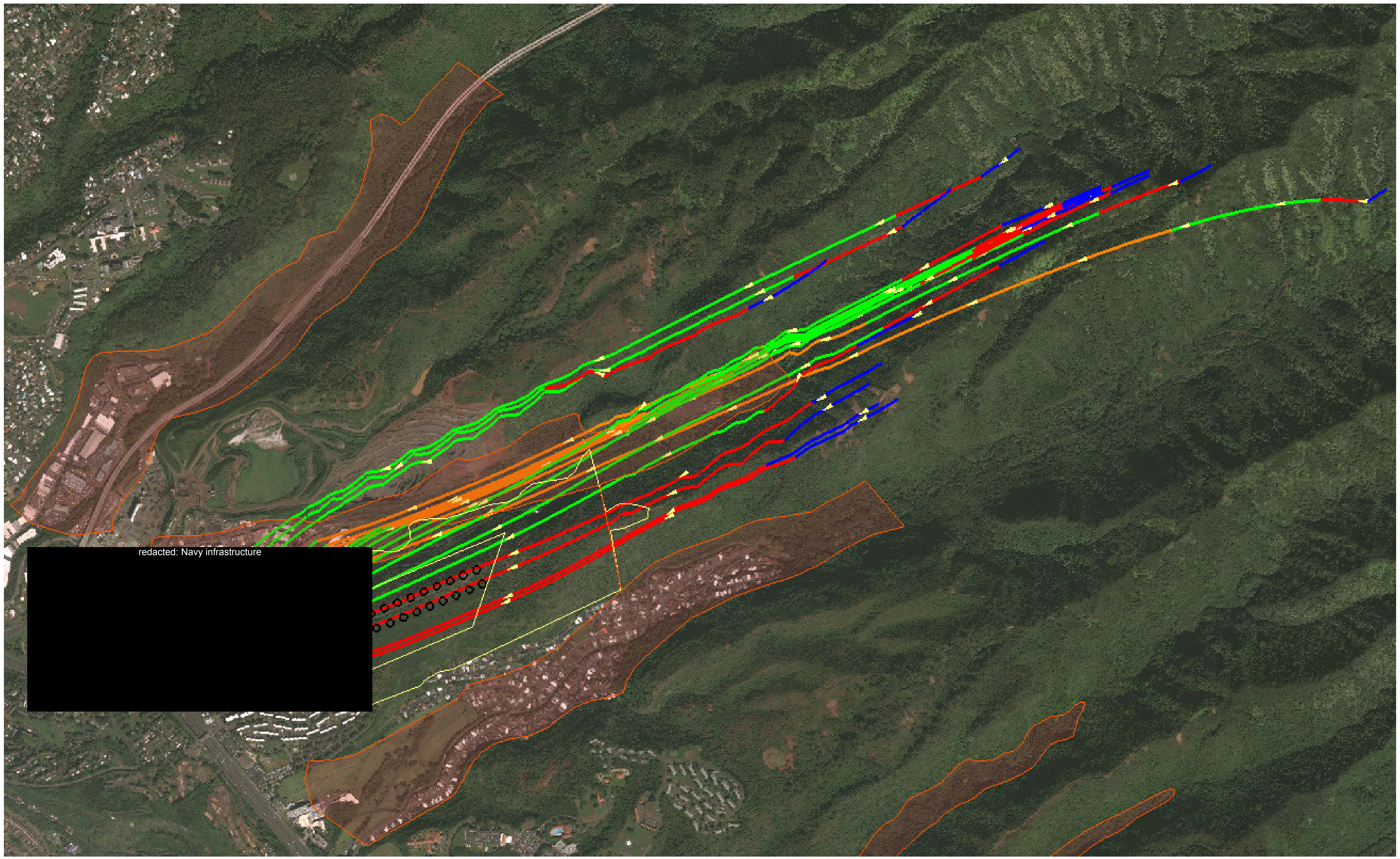
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

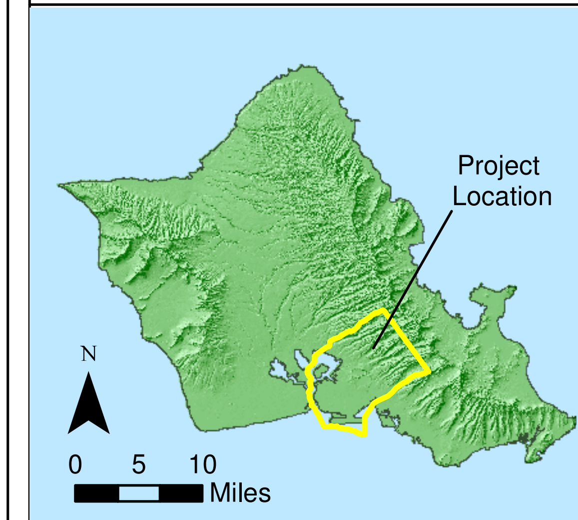
N

Feet
0 1,500 3,000 6,000

Figure 6.3.3-3
Migration from the Facility and Source Water Zones for Red Hill Shaft Pumping Scenario with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- 1-year Time Intervals
- Red Hill Fuel Storage Tank
- Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Inverse praticle tracks.
4. Partilces released immediately upgradient of Red Hill Shaft cells.
5. Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

N
0 1,000 2,000 4,000 Feet

Figure 6.3.3-4
Zoom View of Source Water Zones for Red Hill Shaft for Red Hill Shaft Pumping Scenario with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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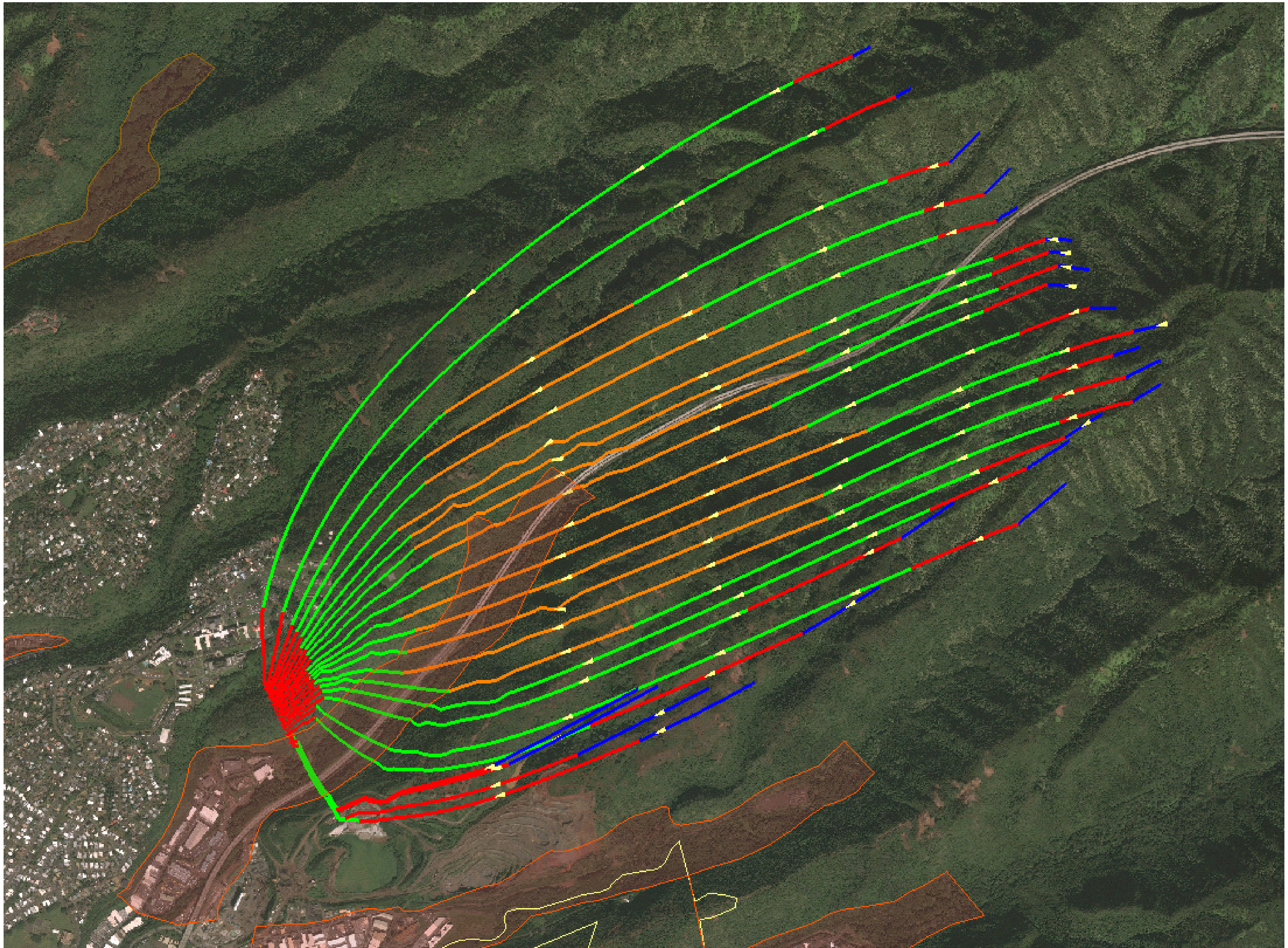
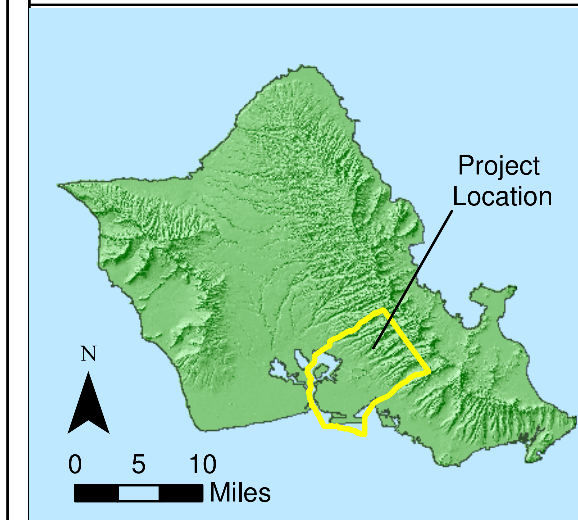
\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig6.3.3-5_Zoom_SourceWaterZone_HalawaShaft_RHS_pumping_Model1.mxd 7/24/2018



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- 1-year Time Intervals
- Red Hill Bulk Fuel Storage Facility Boundary

Notes

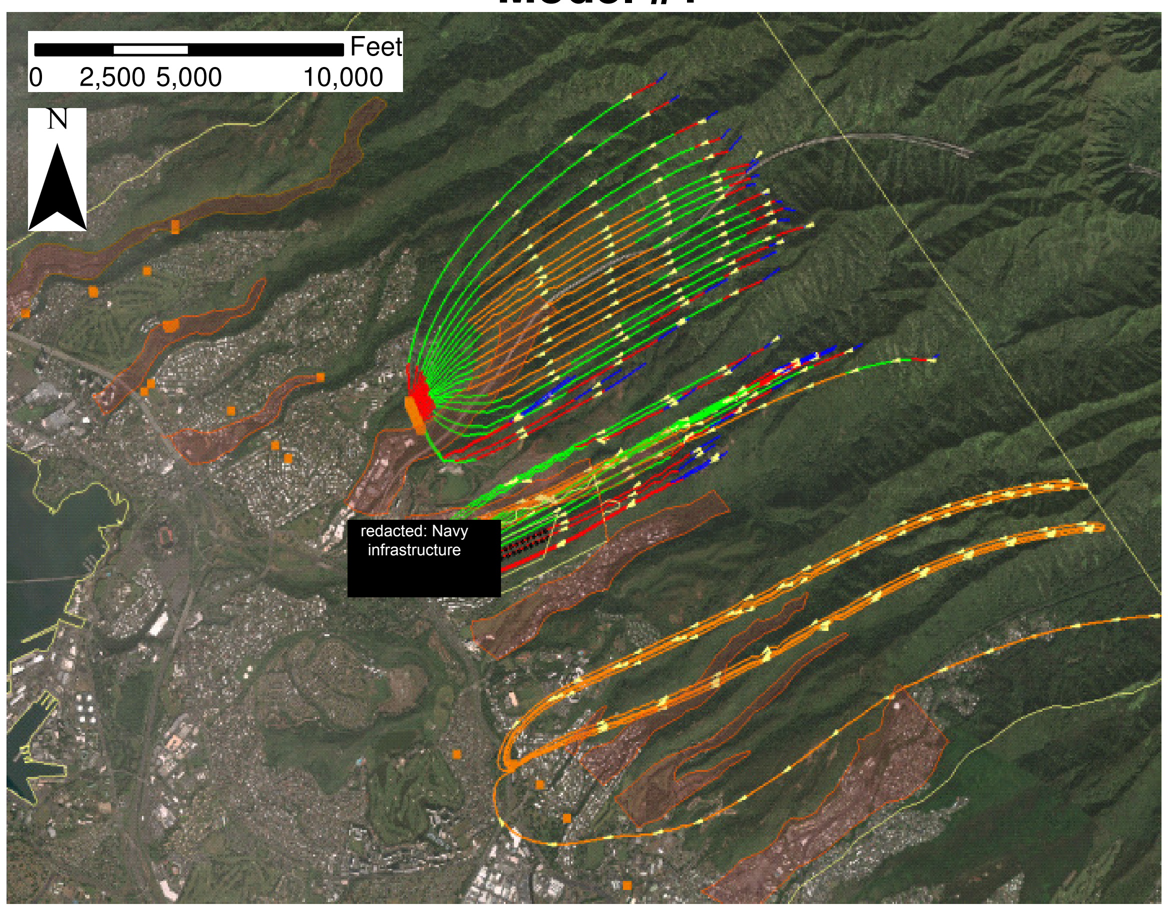
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Inverse praticle tracks.
4. Hālawa Shaft orientation will be revised in final model.
5. Colored pathlines are based on the beta version of GMS, which has not been officially released yet.

N

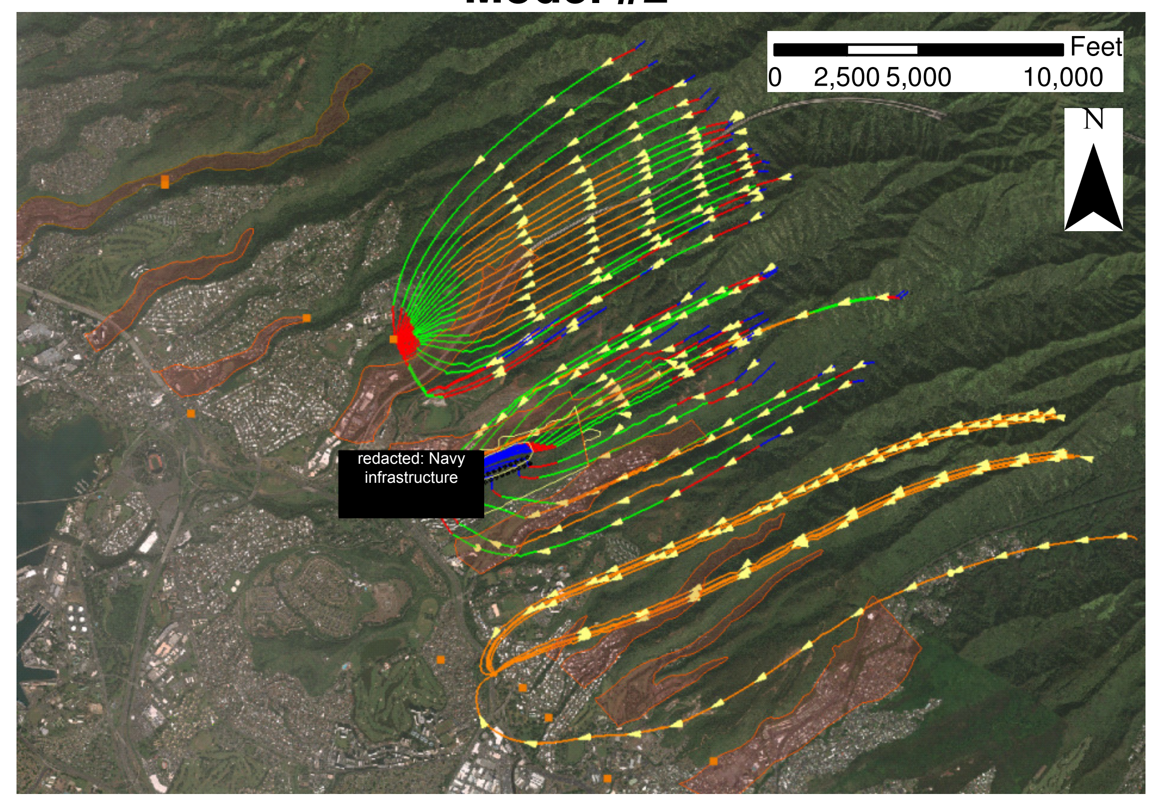
0 1,000 2,000 4,000 Feet

Figure 6.3.3-5
Zoom View of Source Water Zones for Hālawa Shaft for Red Hill Shaft Pumping Scenario with Model #1
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

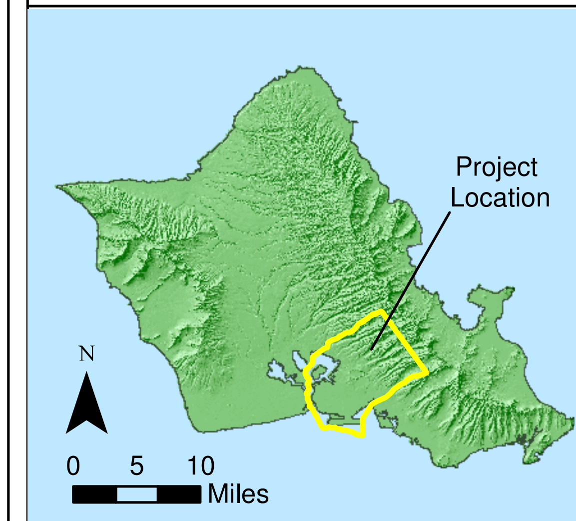
Model #1



Model #2



Location Map



Legend

Pathline Colors:

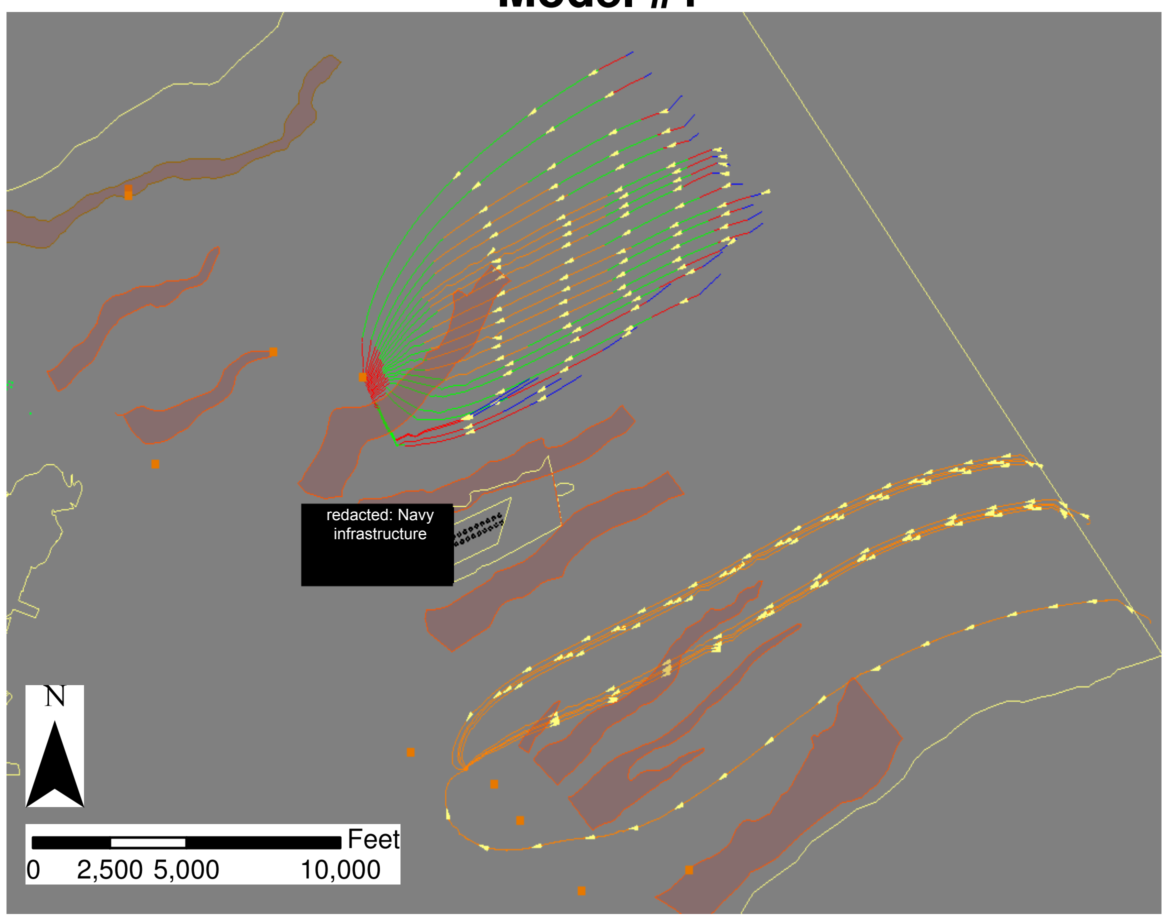
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- 1-year Time Intervals
- Red Hill Fuel Storage Tank
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

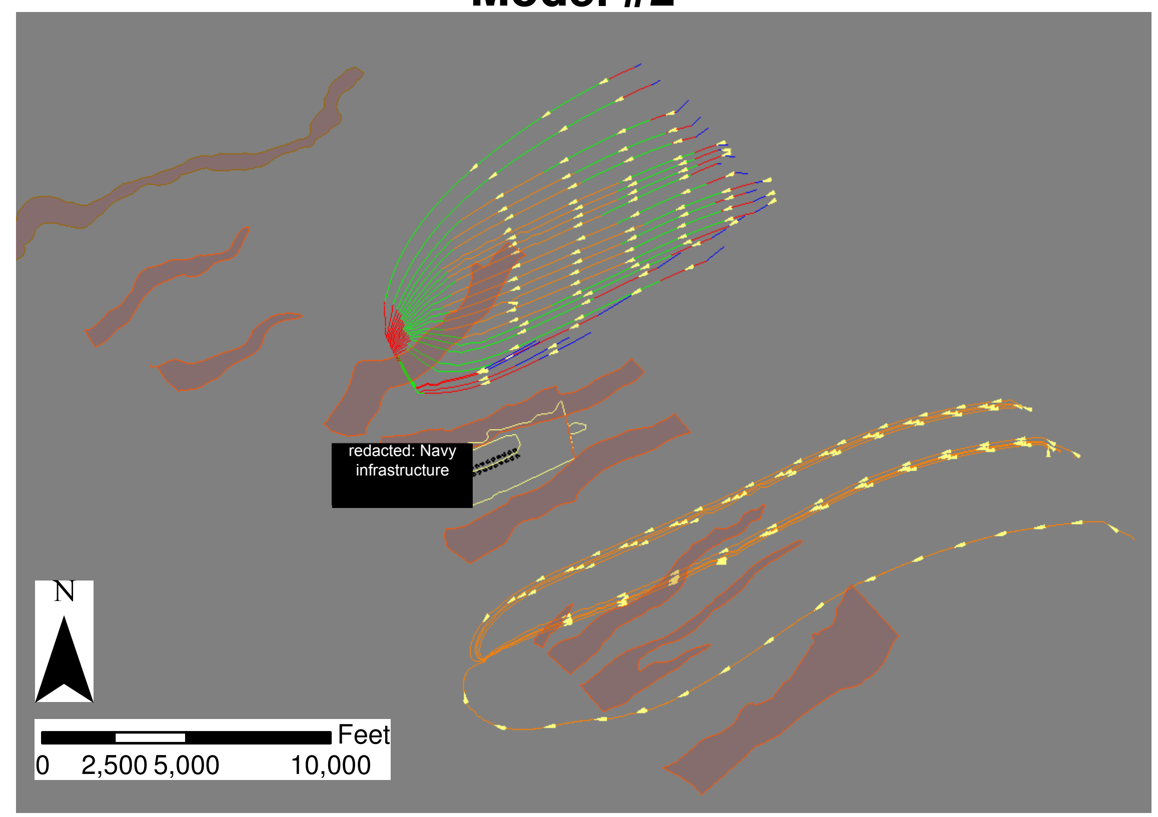
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.3-1
Model #2: Heterogeneity - Presence of Clinker - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

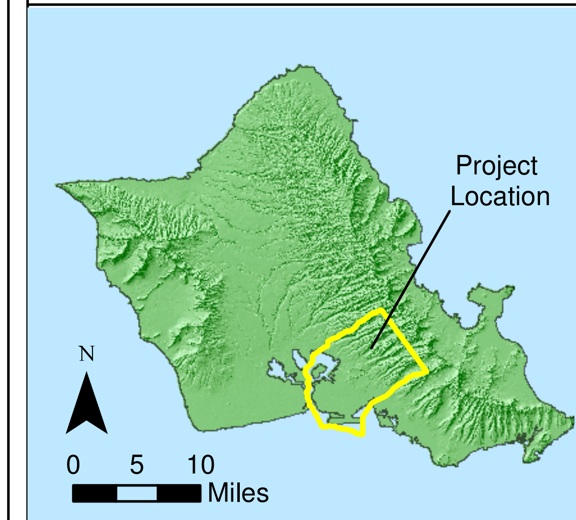
Model #1



Model #2



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.3-2
Model #2: Heterogeneity - Presence of Clinker - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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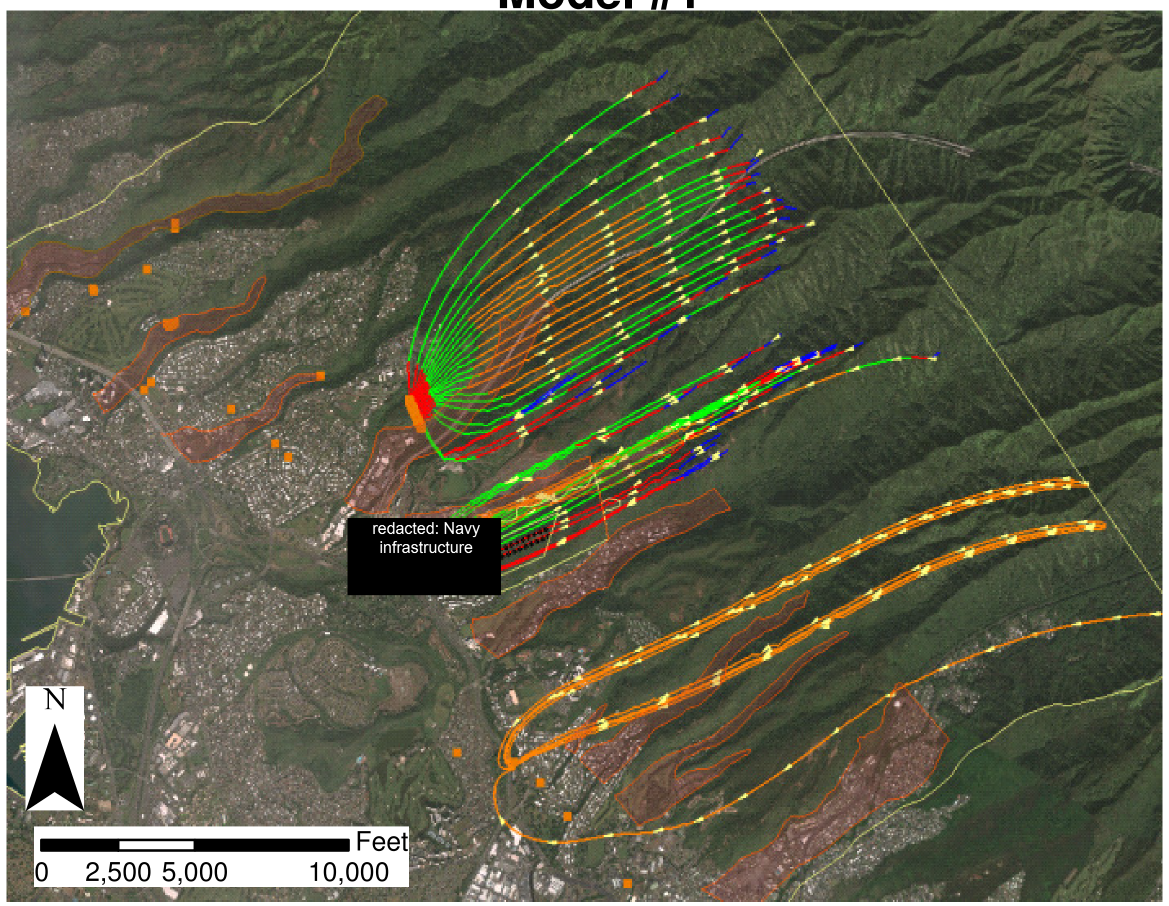
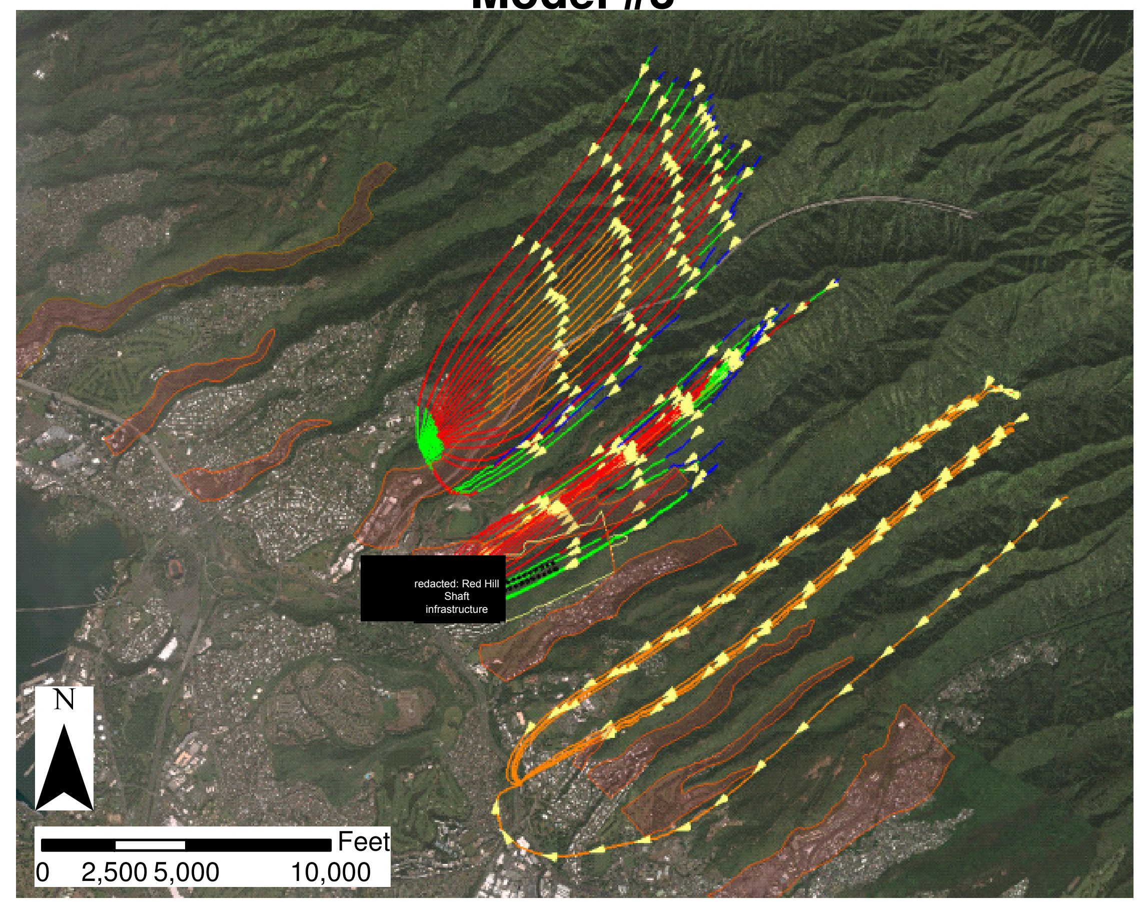
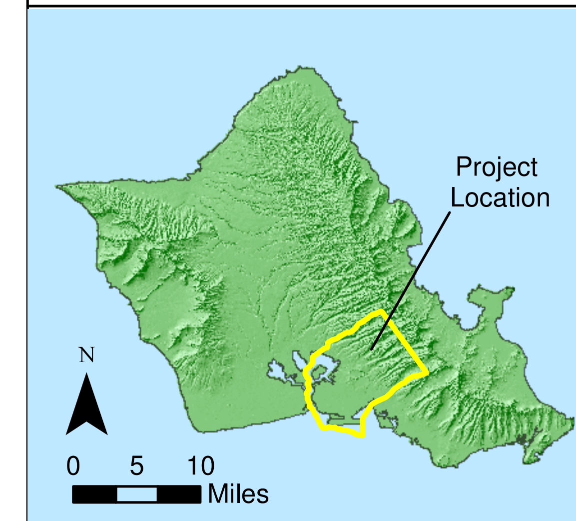
Model #1



Model #3



Location Map



Legend

Pathline Colors:

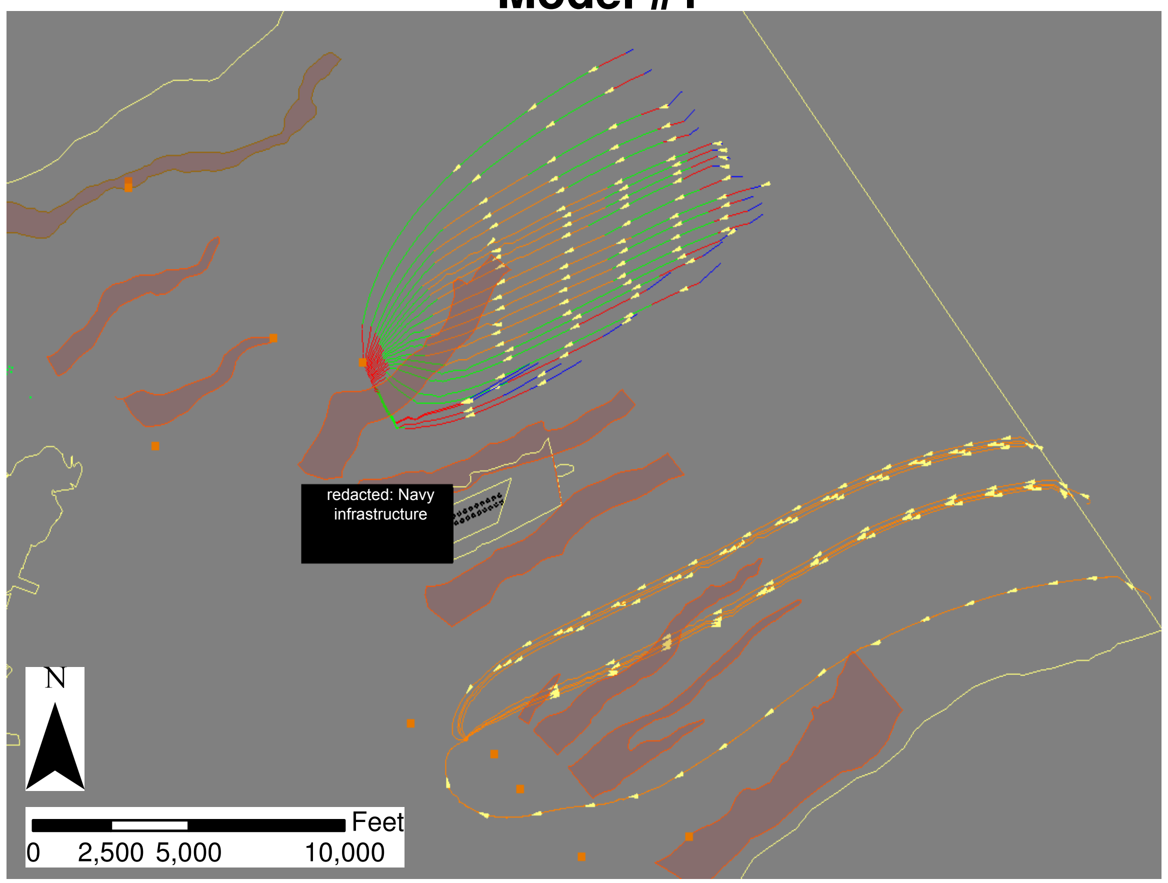
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- 1-year Time Intervals
- Red Hill Fuel Storage Tank
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

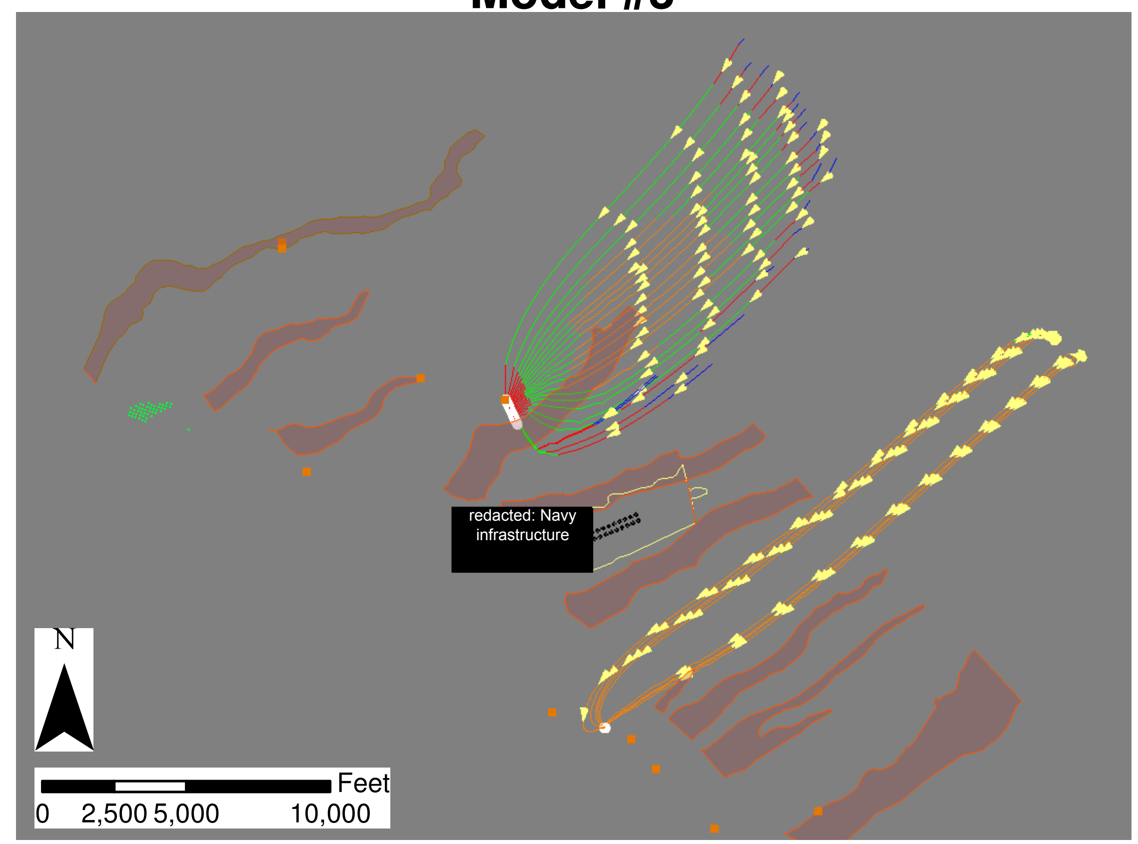
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.4-1
GHB Stage I: 2017 Interpolated Stages (Model #3) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

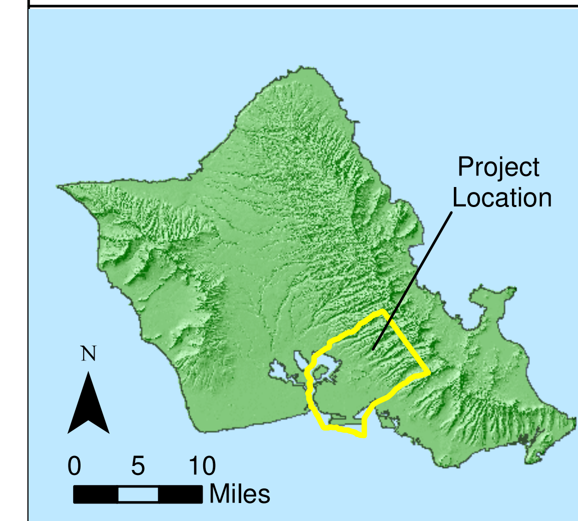
Model #1



Model #3



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

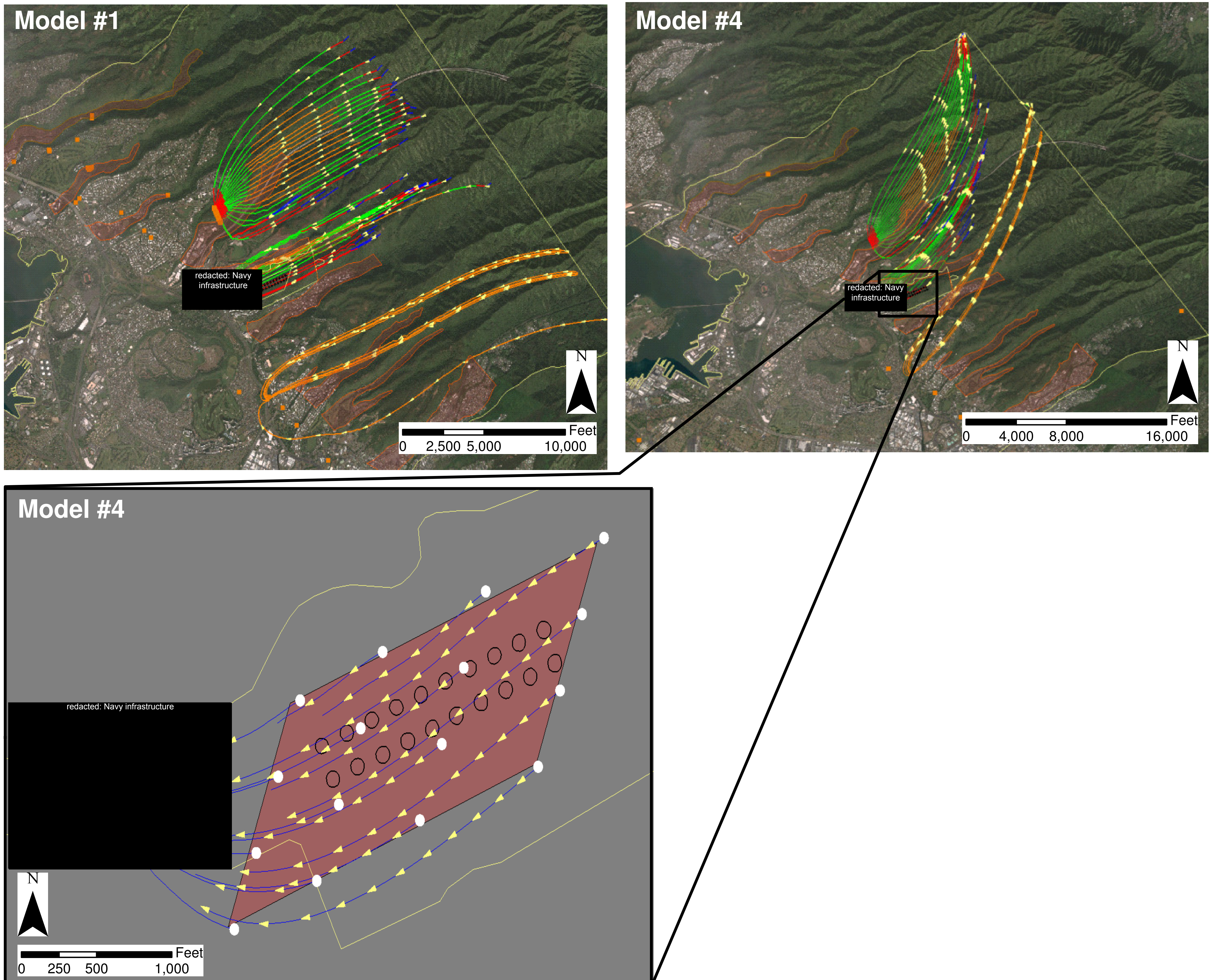
Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

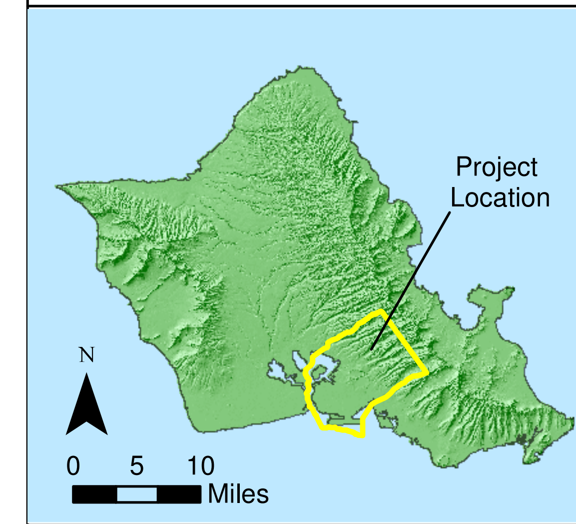
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.4-2
GHB Stage I: 2017 Interpolated Stages (Model #3) - Source Water Zones for Red Hill Shaft
Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- 1-year Time Intervals
- Particle
- Red Hill Fuel Storage Tank
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.5-1
GHB Stage II: Lower NW and SE GHB Stage (Model #4) - Source Water Zones for RHS Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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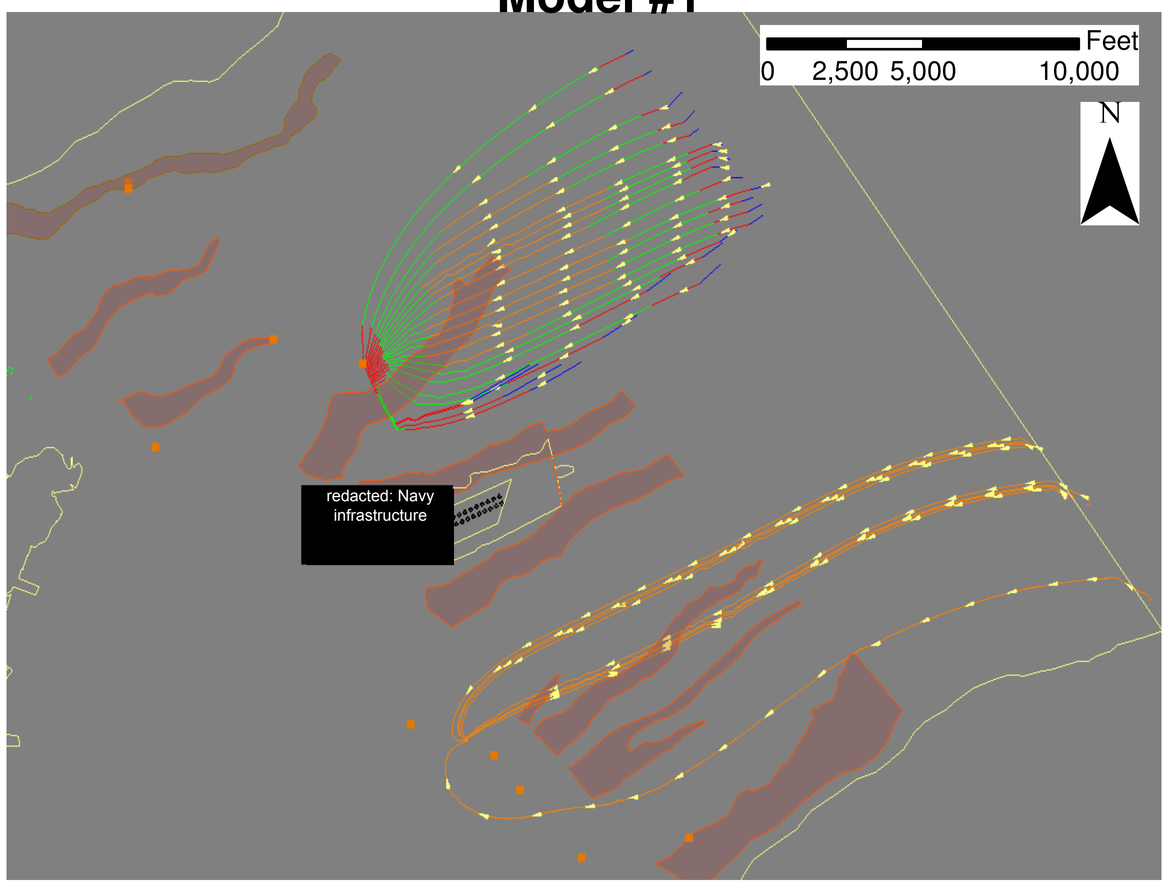
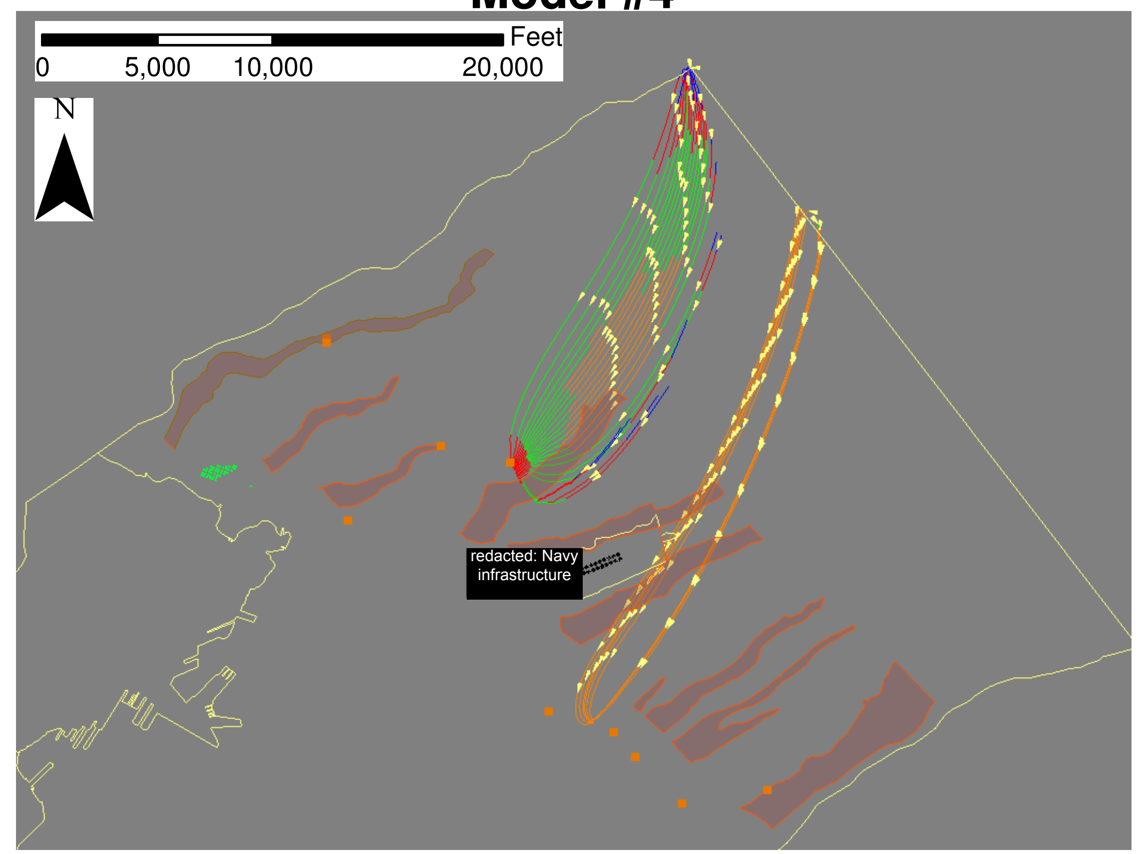
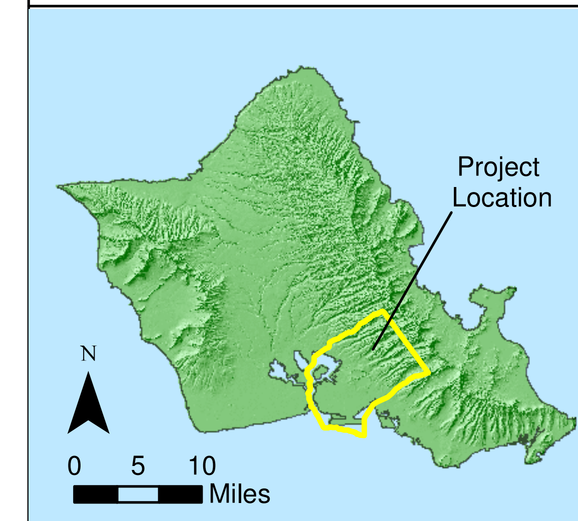
Model #1



Model #4



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

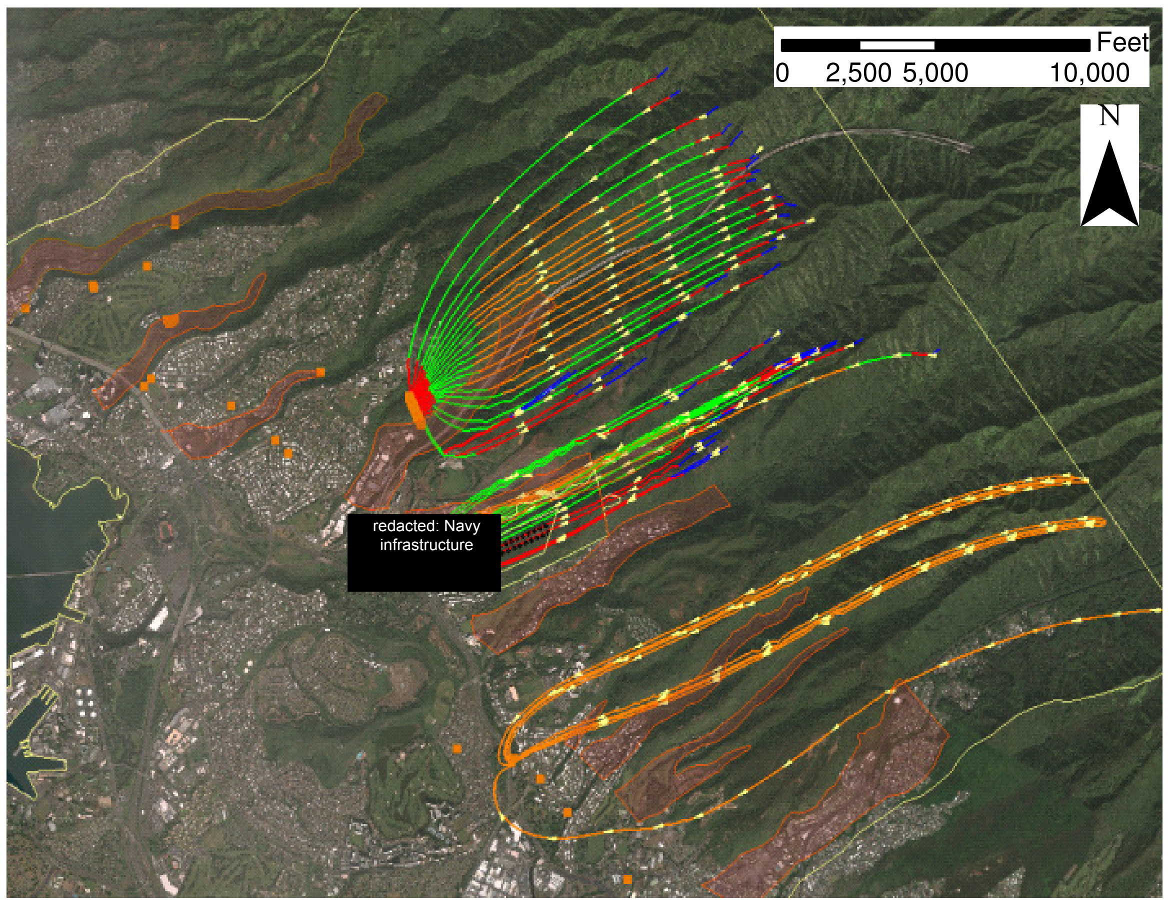
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

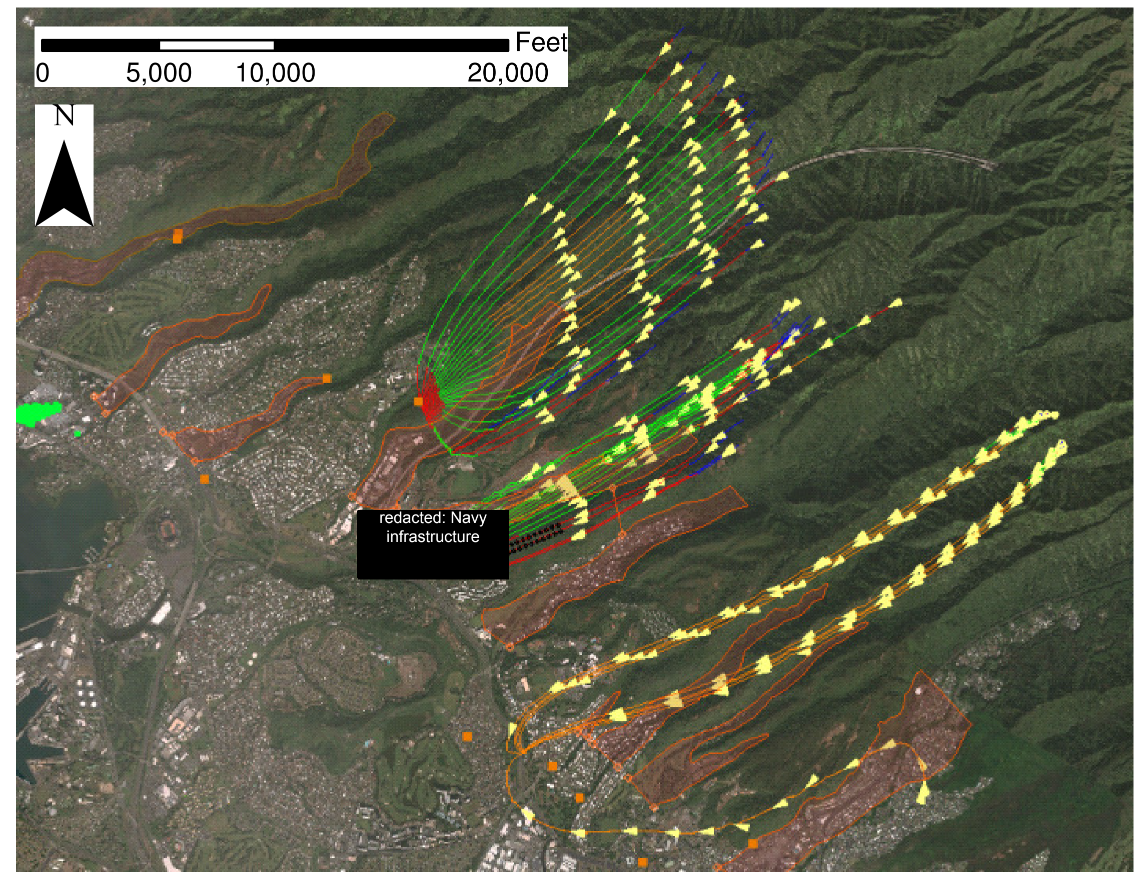
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.5-2
GHB Stage II: Lower NW and SE GHB Stage (Model #4) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

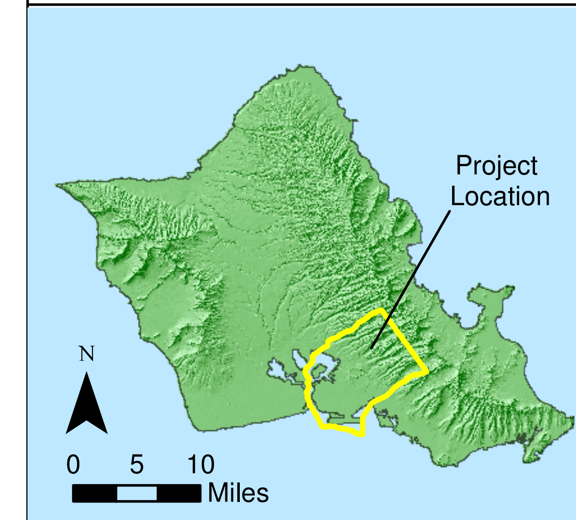
Model #1



Model #5



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

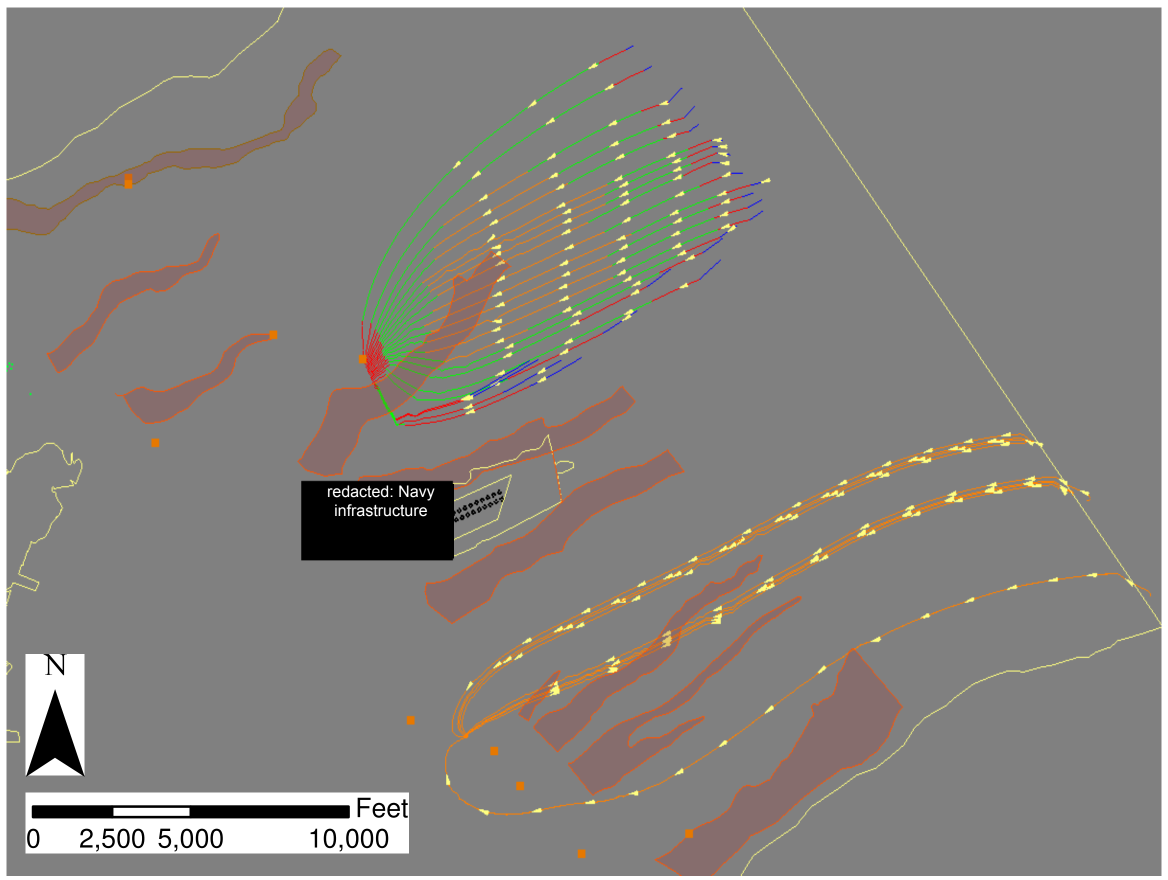
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

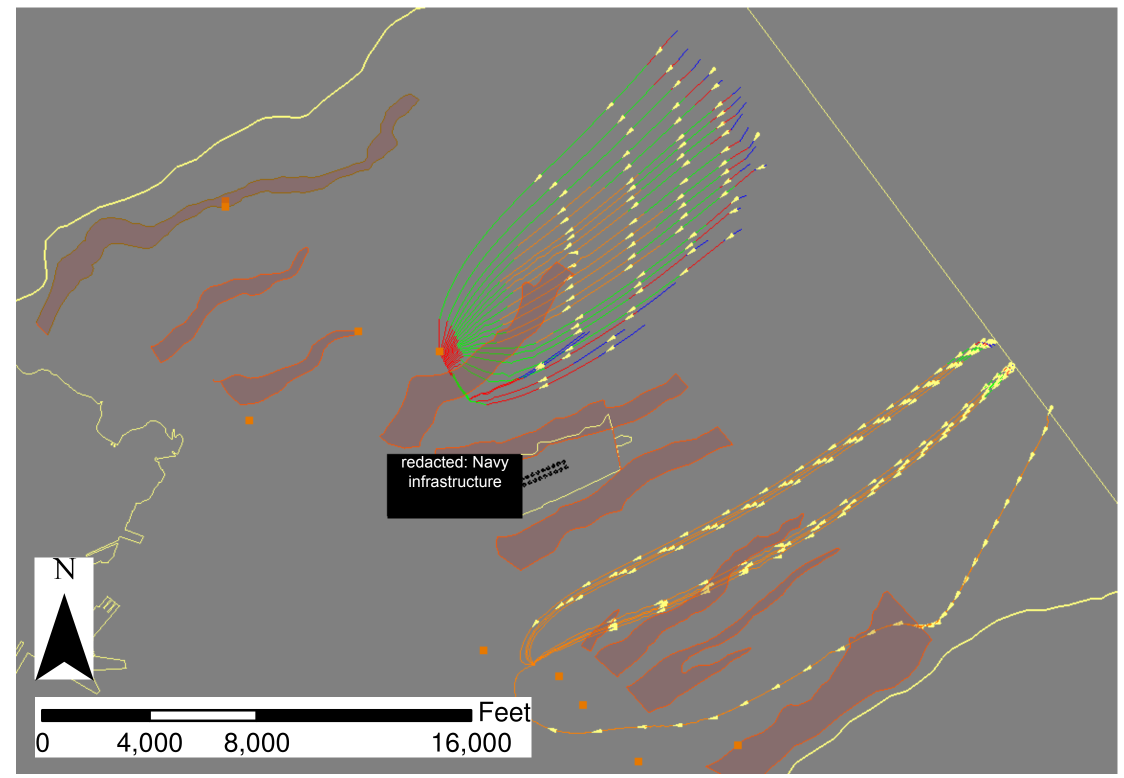
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.6-1
GHB Stage III: Lower NW and Higher SE Stage (Model #5) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

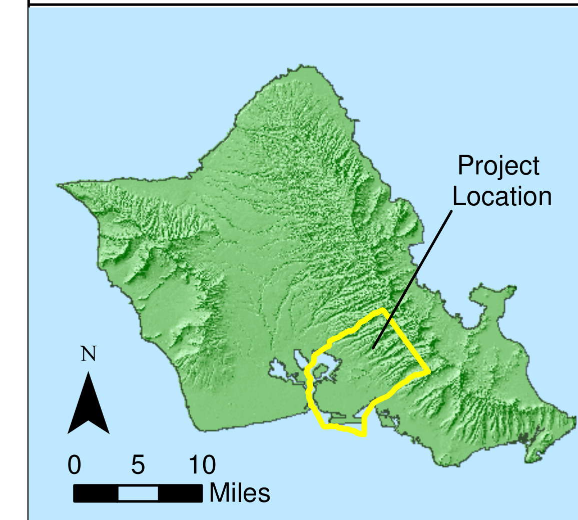
Model #1



Model #5



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.6-2
GHB Stage III: Lower NW and Higher SE Stage (Model #5) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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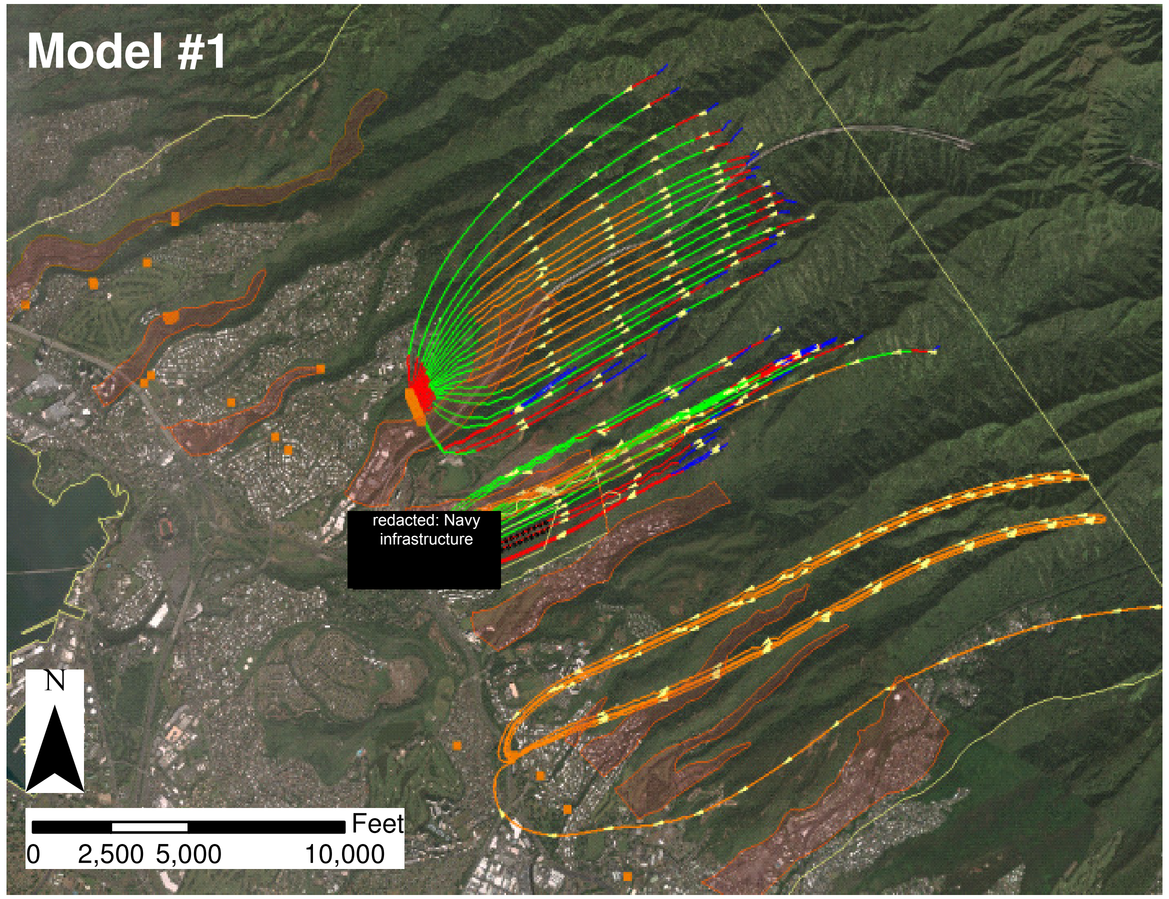
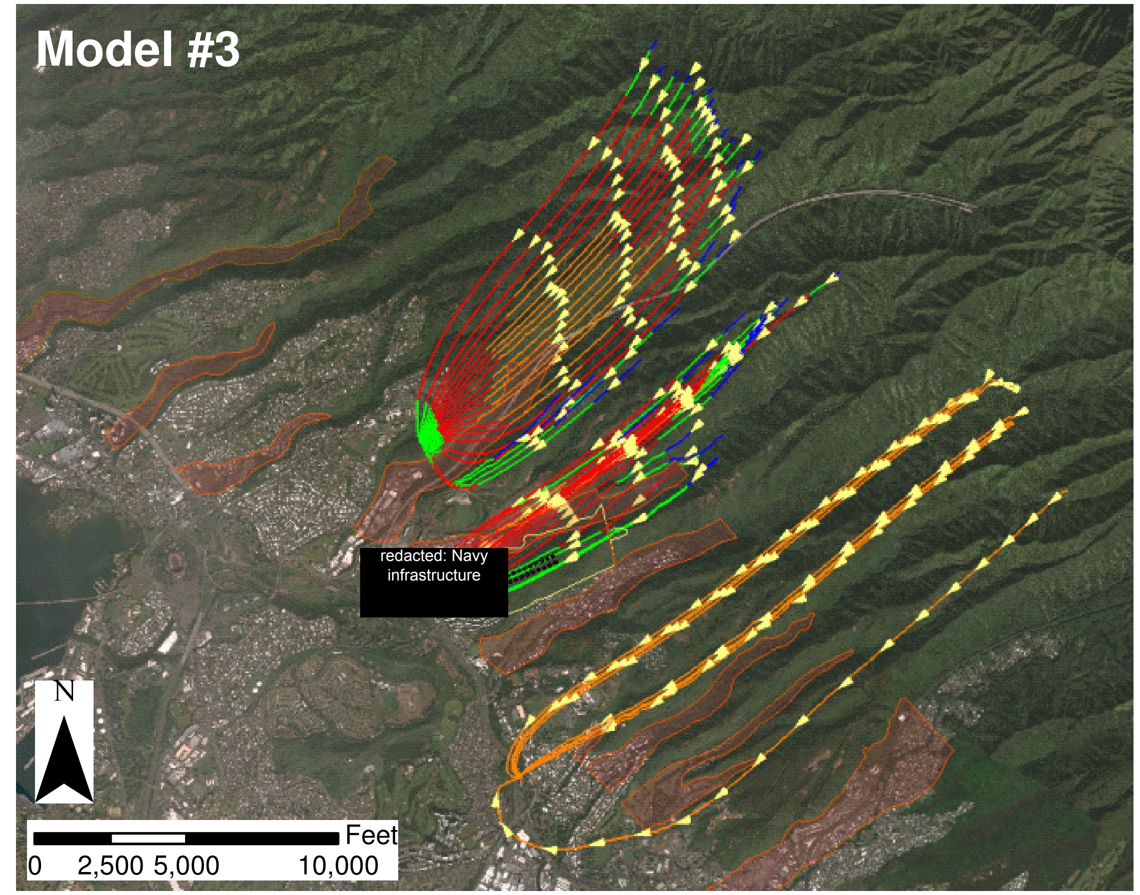
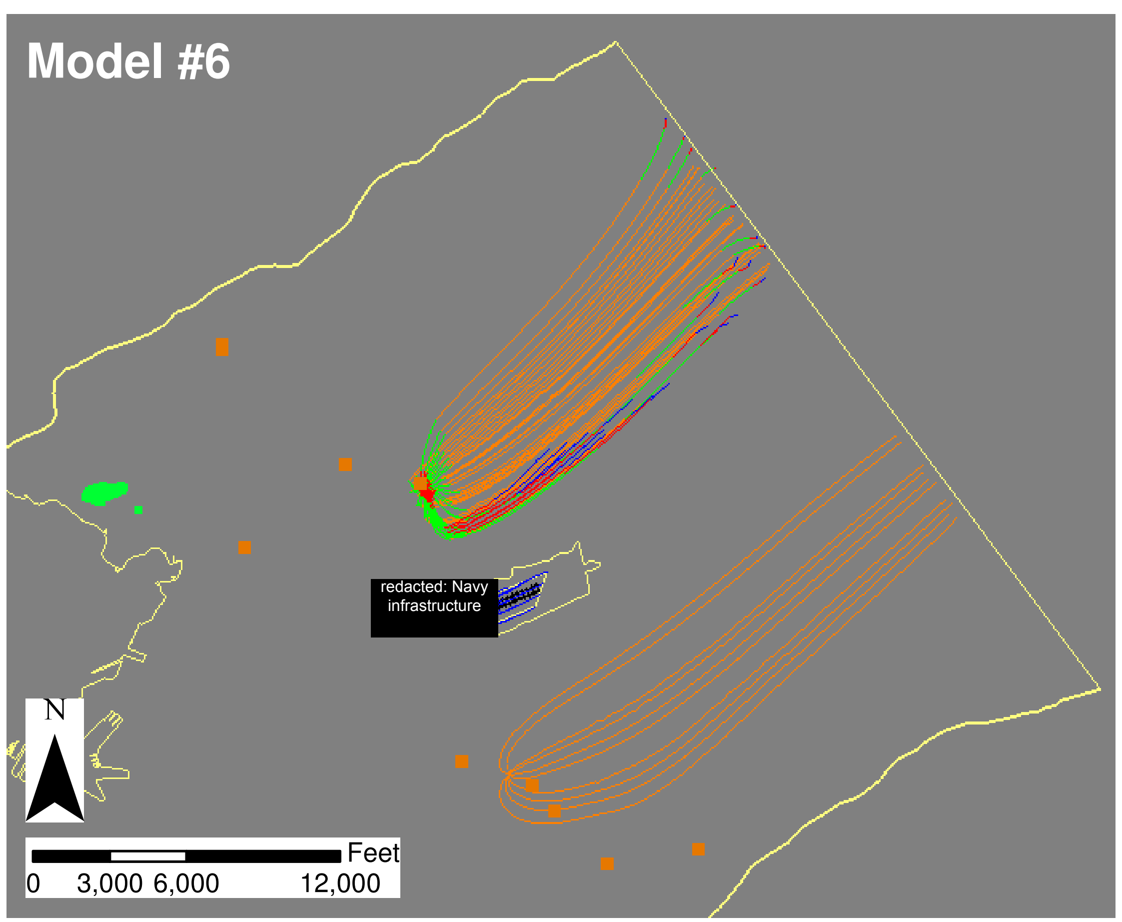
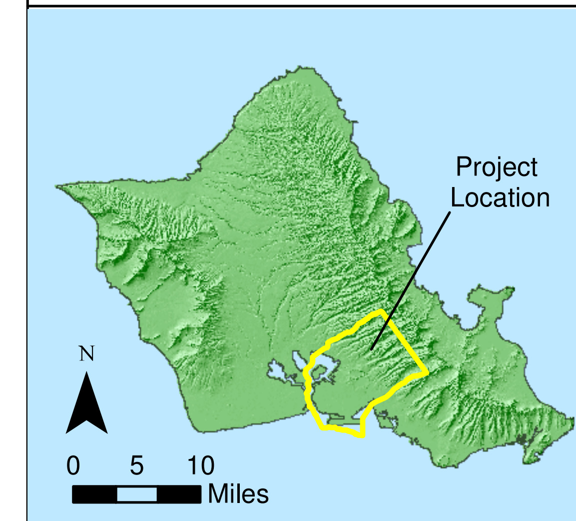






Location Map



Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.7-1
GHB Stage IV: Northwest and Southeast Stages Lowered 3-feet (Model #6) Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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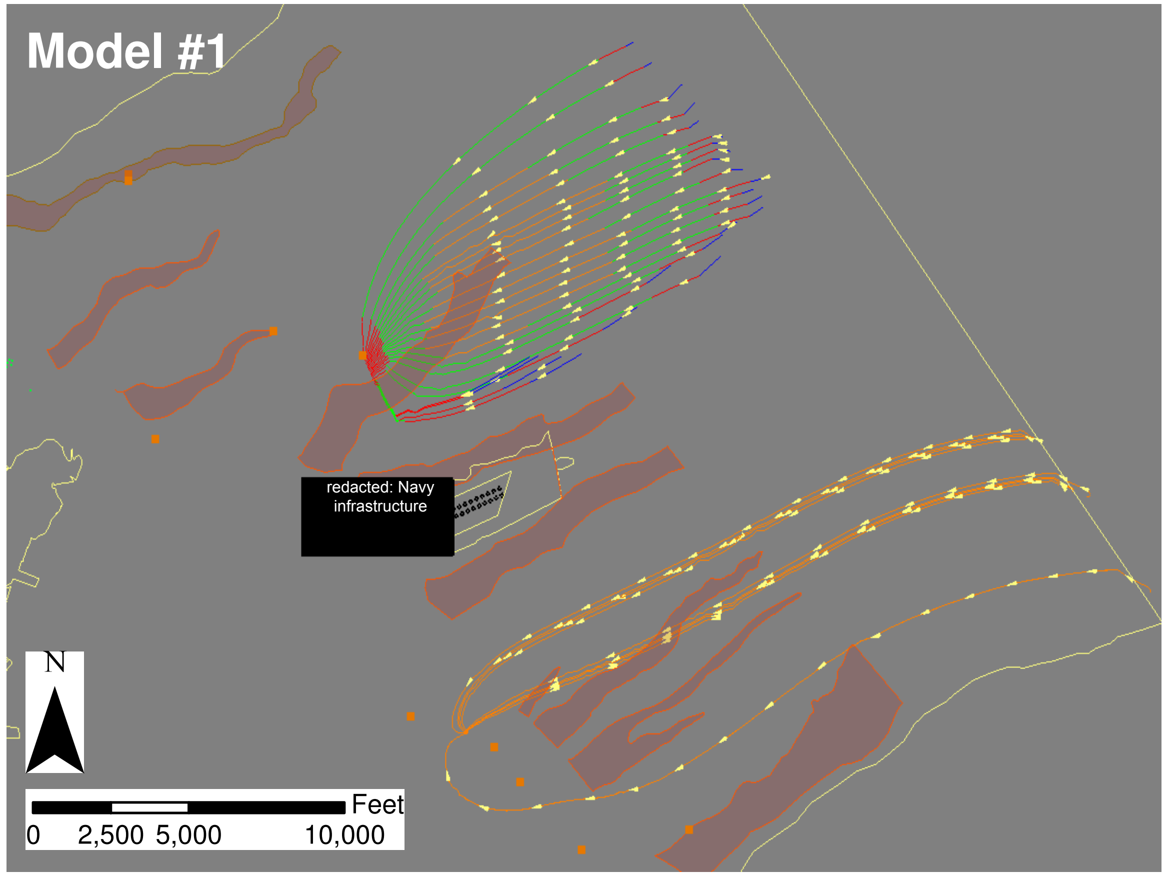

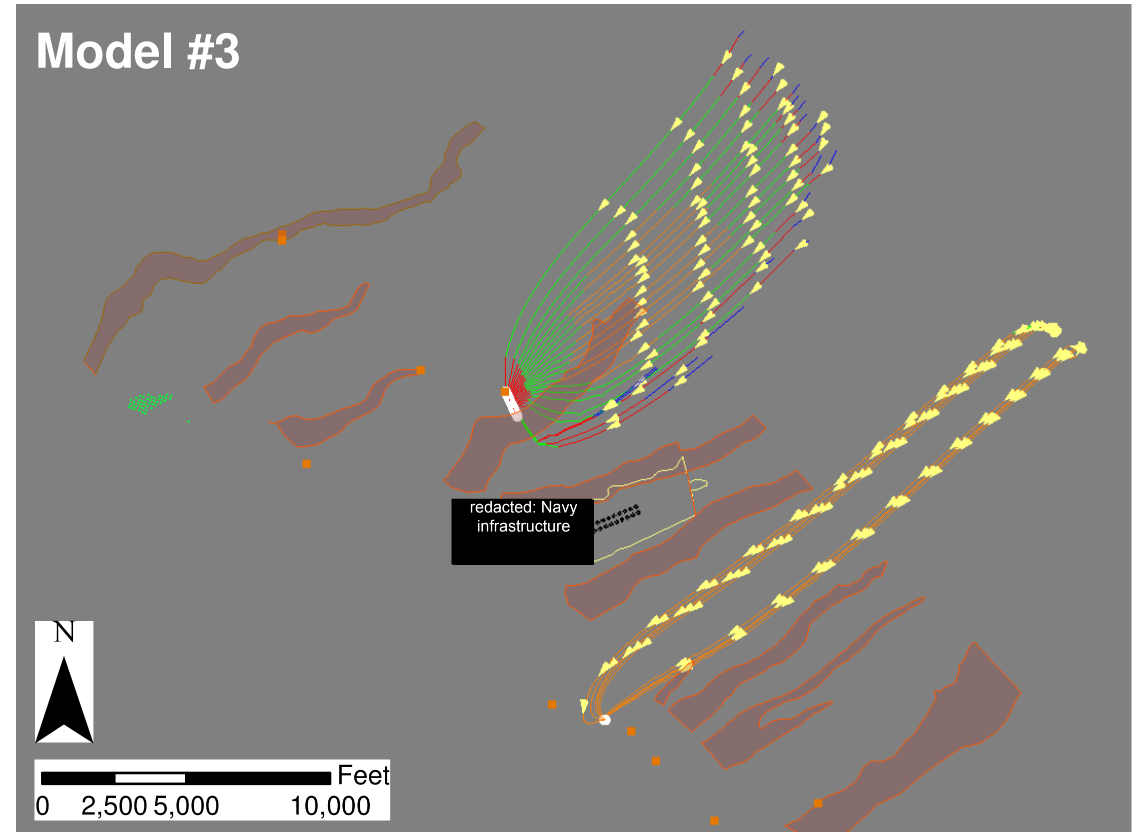

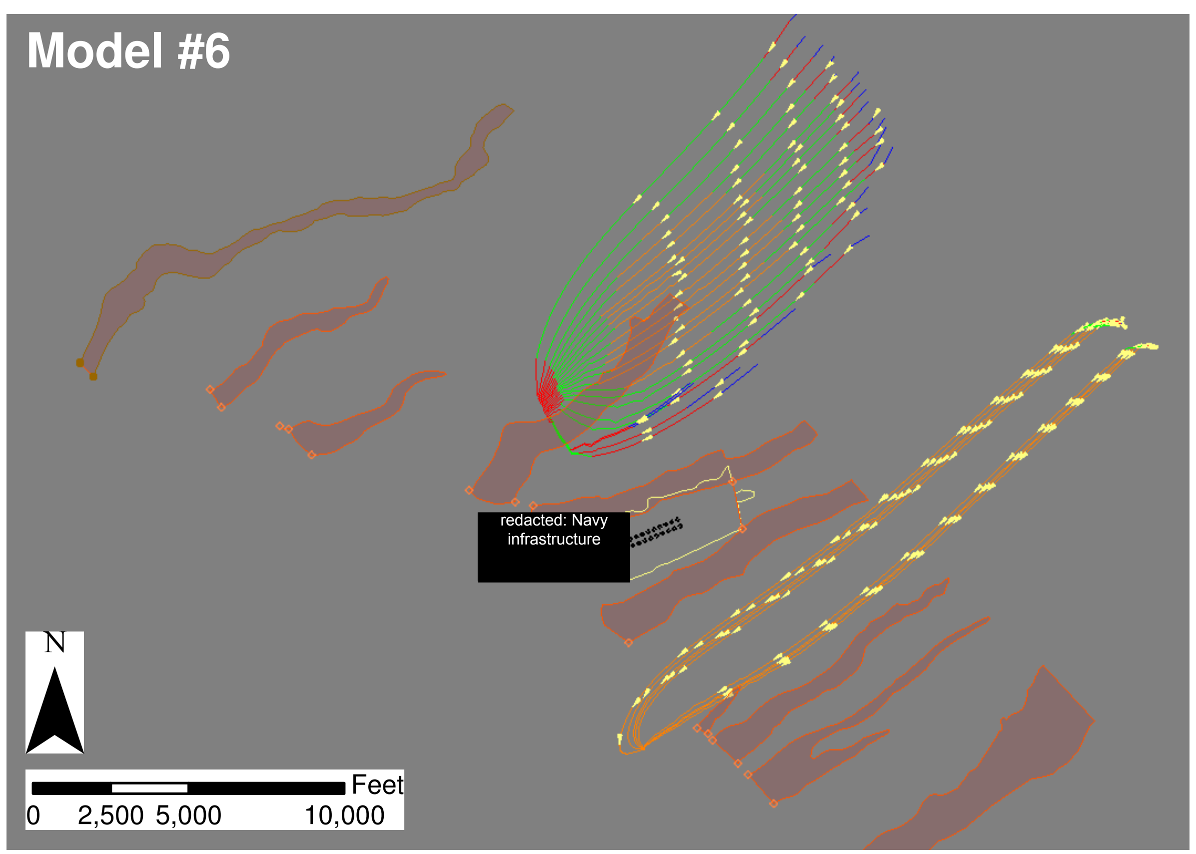

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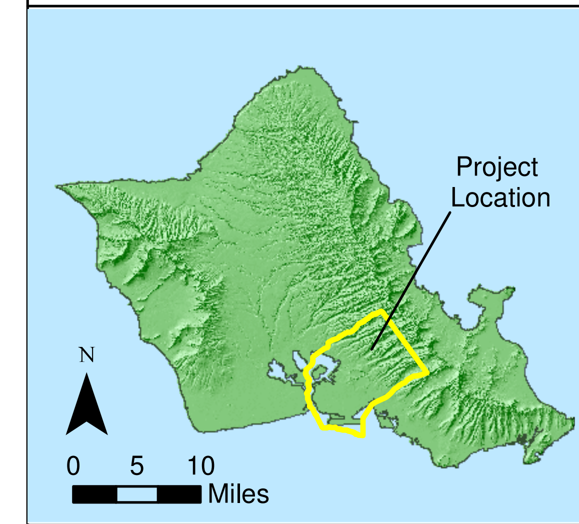

Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.7-2
GHB Stage IV: Northwest and Southeast Stages Lowered 3-feet (Model #6) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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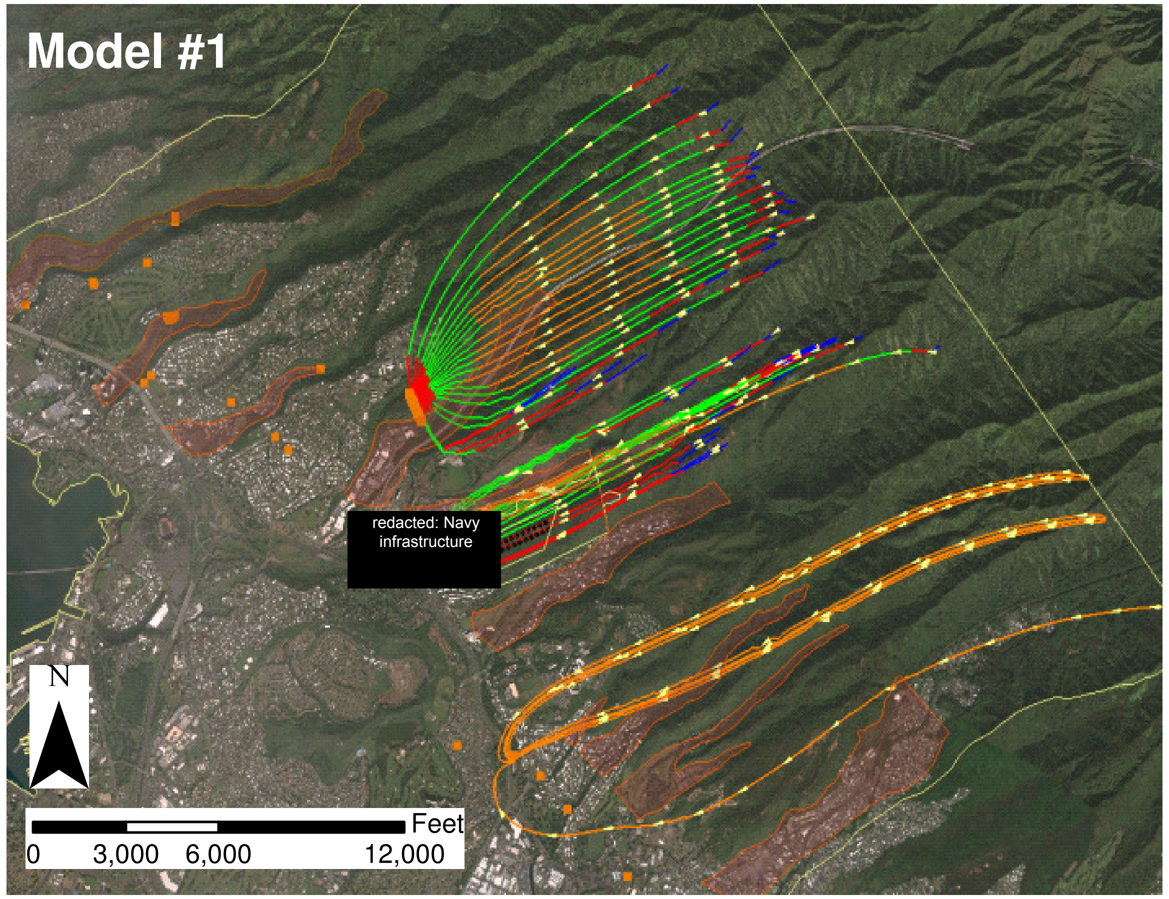

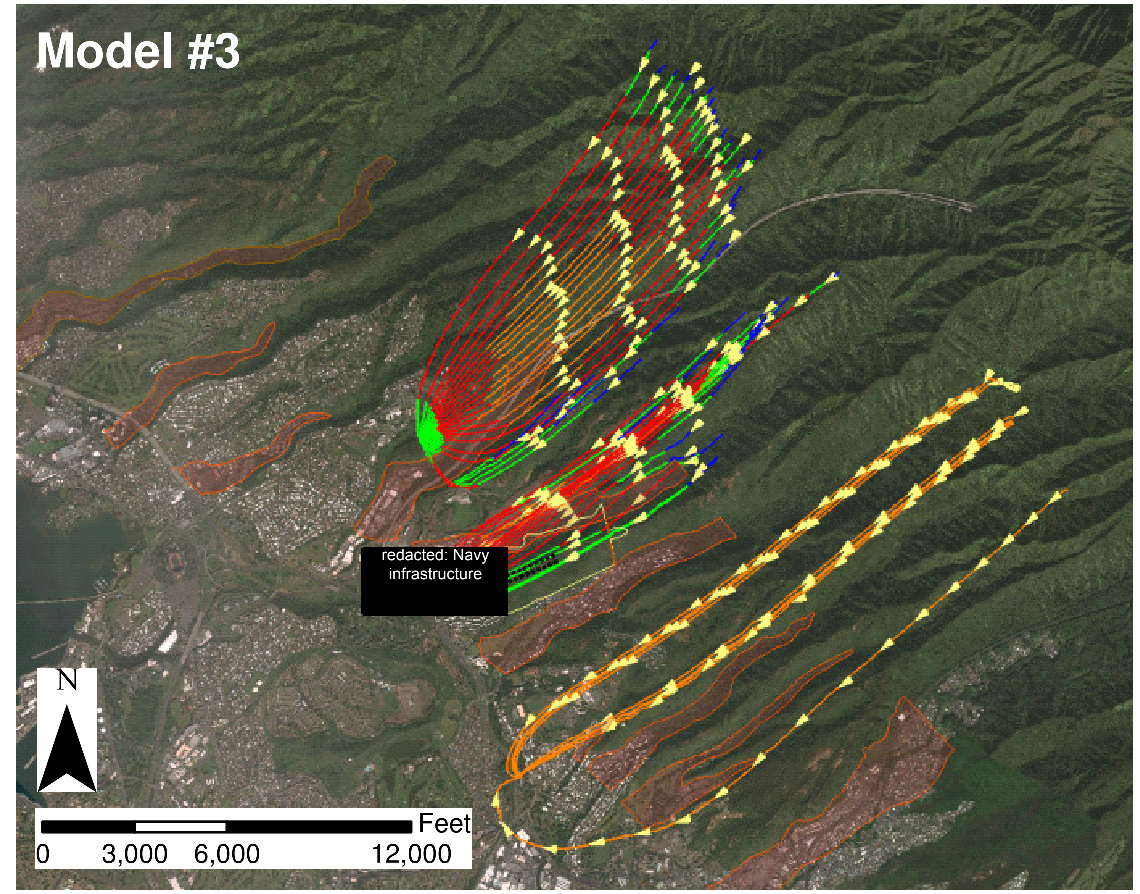

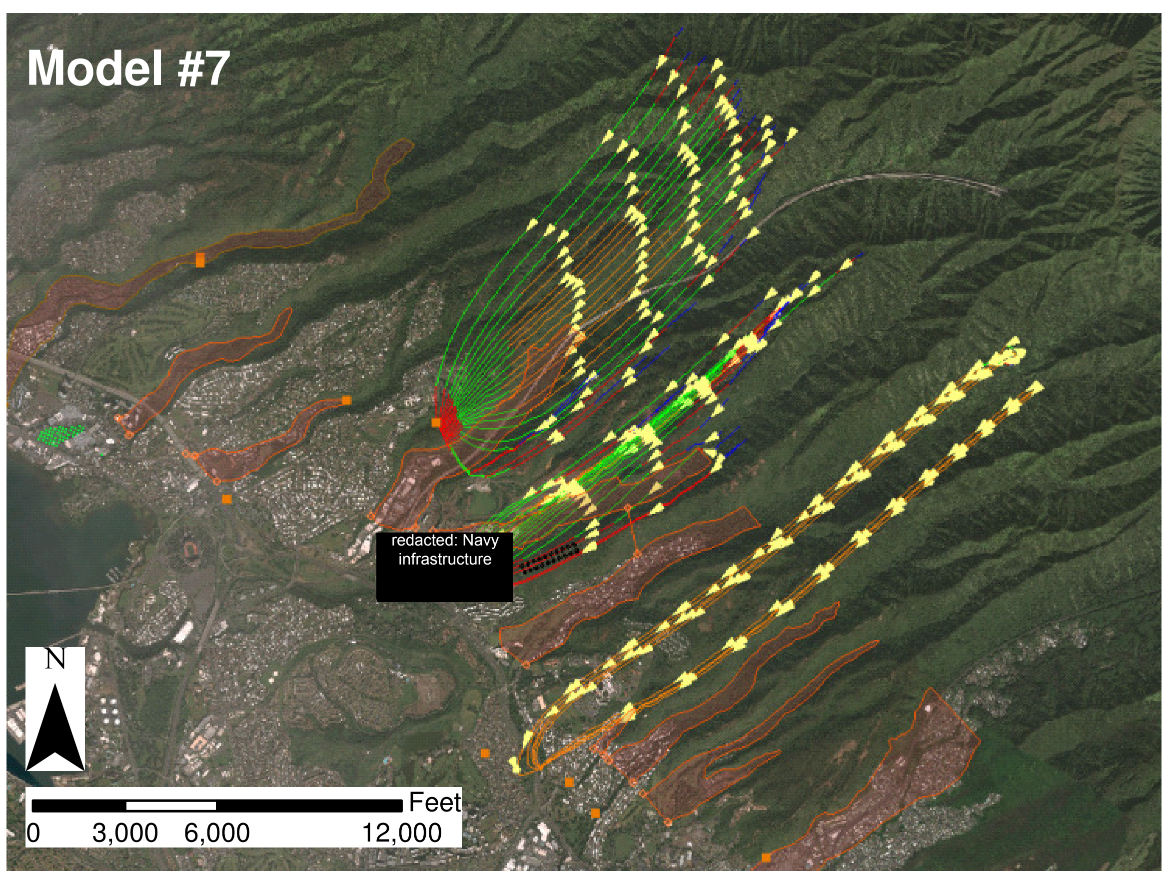

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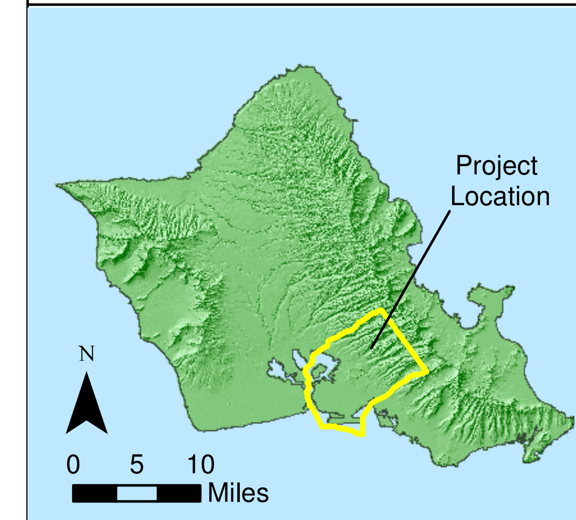

Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.8-1
GHB Stage V: 2017 Interpolated Northwest and Southeast Stages with Higher Northwest Basalt Stage (Model #7) -
Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
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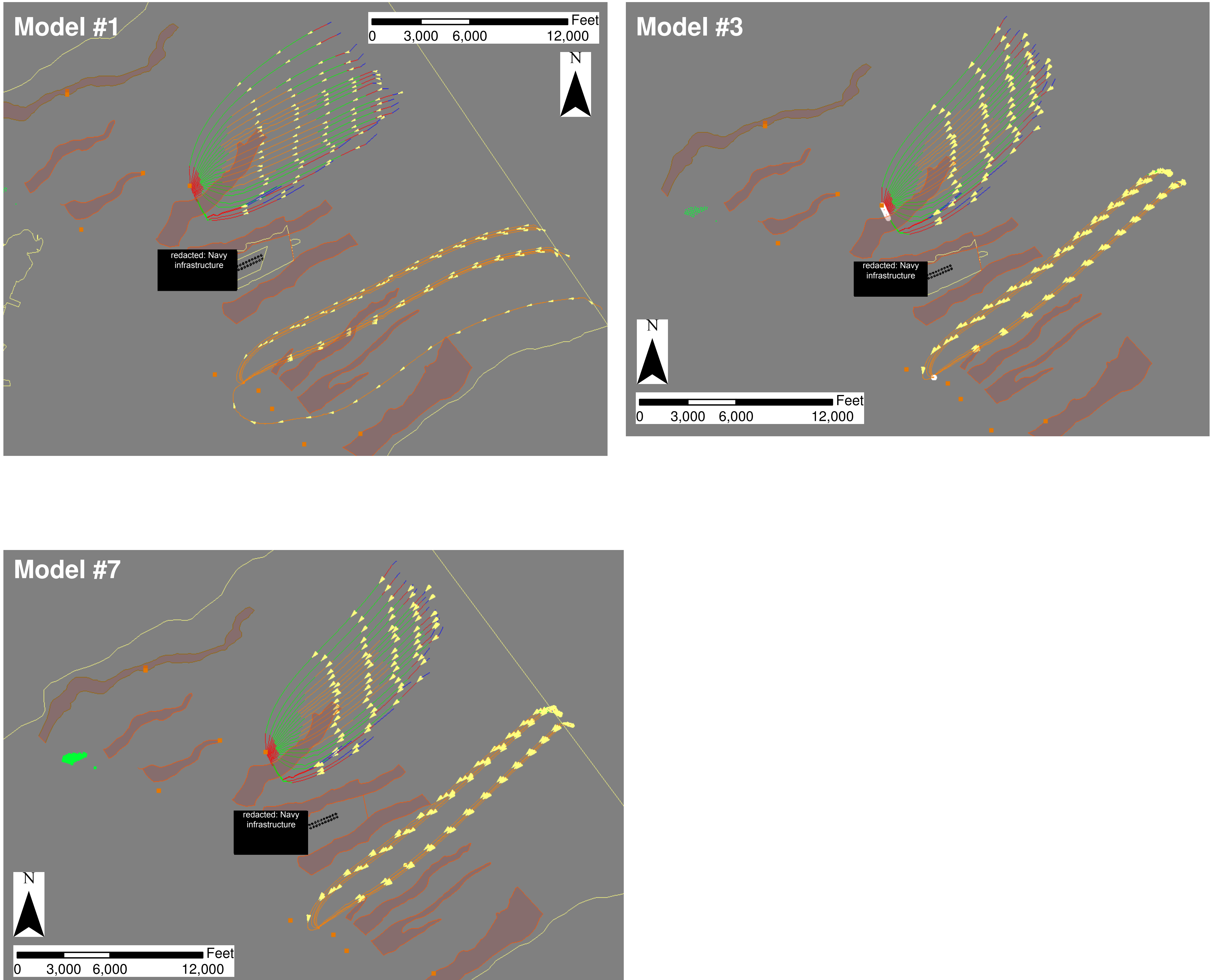

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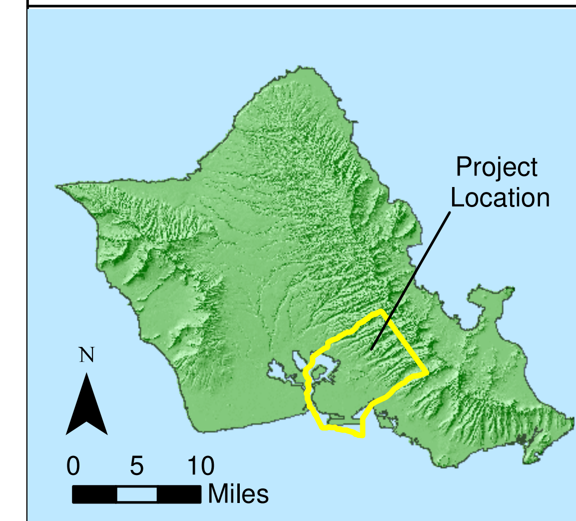

Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.8-2
GHB Stage V: 2017 Interpolated Northwest and Southeast Stages with Higher Northwest Basalt Stage (Model #7) -
Source Water Zones for Red Hill Shaft
Not Pumping Scenario
Appendix A
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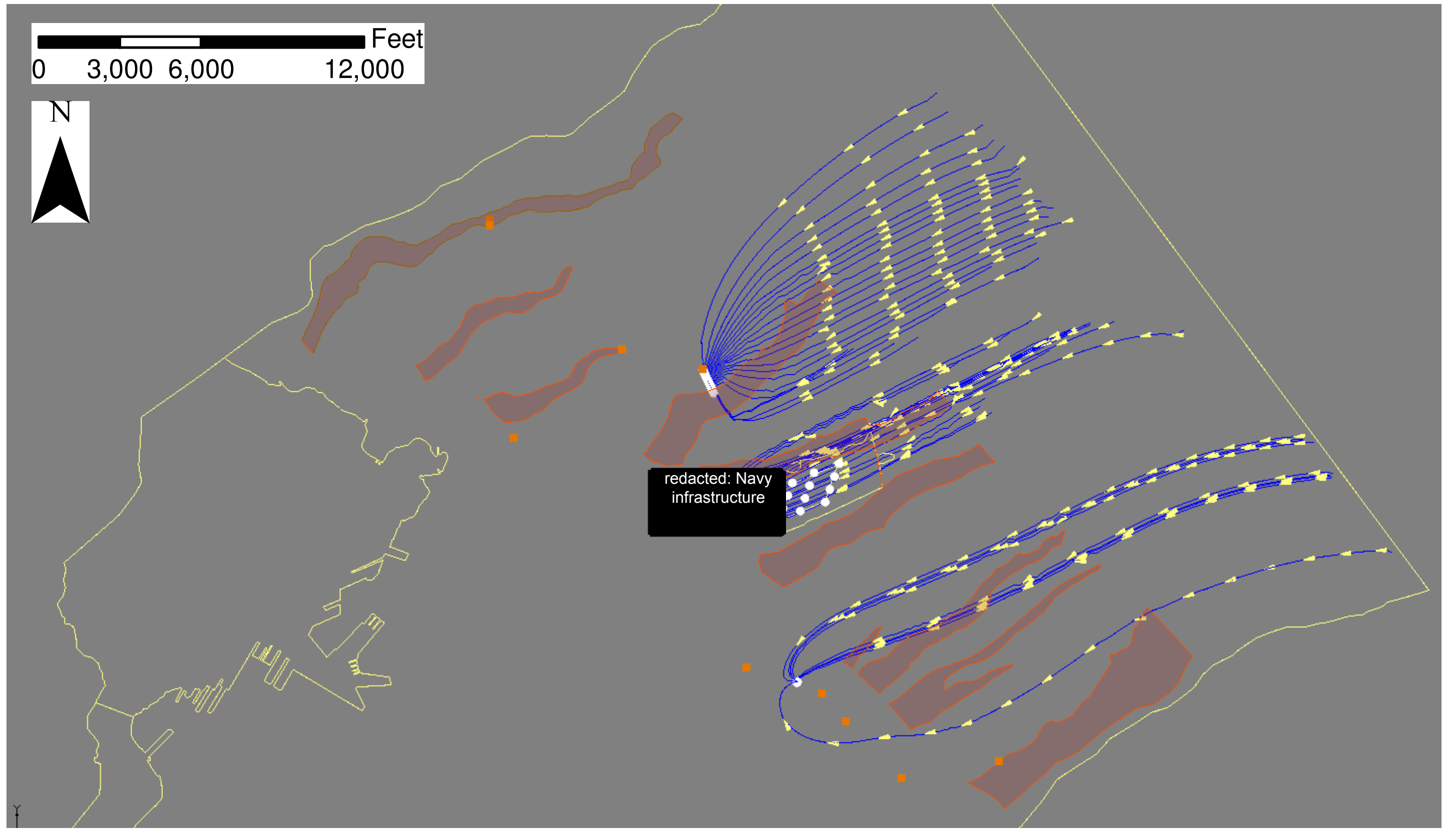
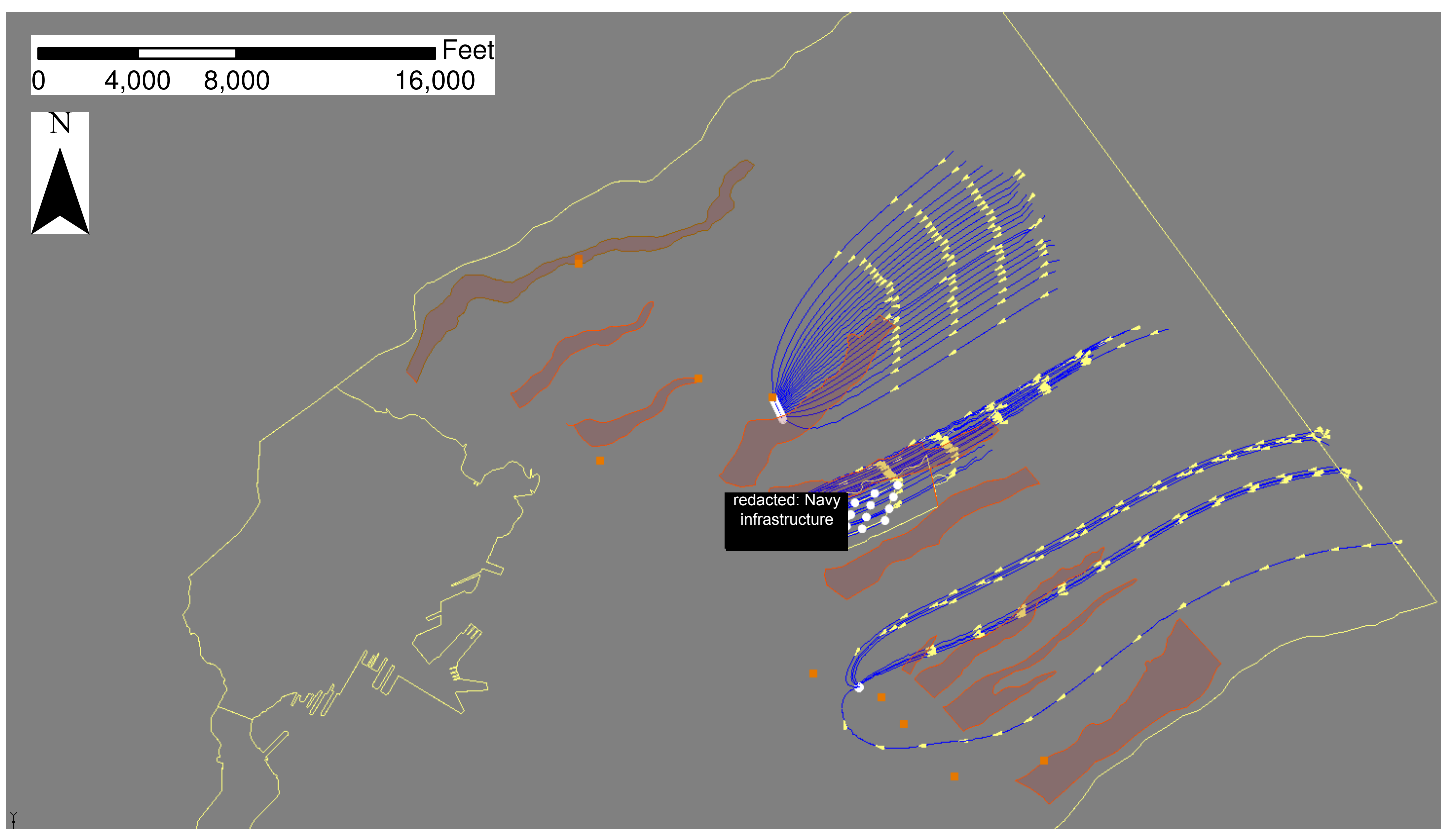
\\Honolulu.na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig6.4.8-2_GHBStageI_2017_InterpModel3_SWZforRHS_NOTpumping.mxd 7/24/2018

Model #1



Model #8



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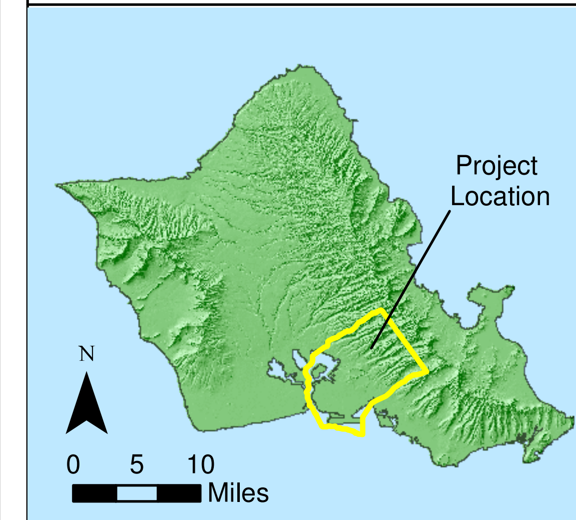


Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Particle

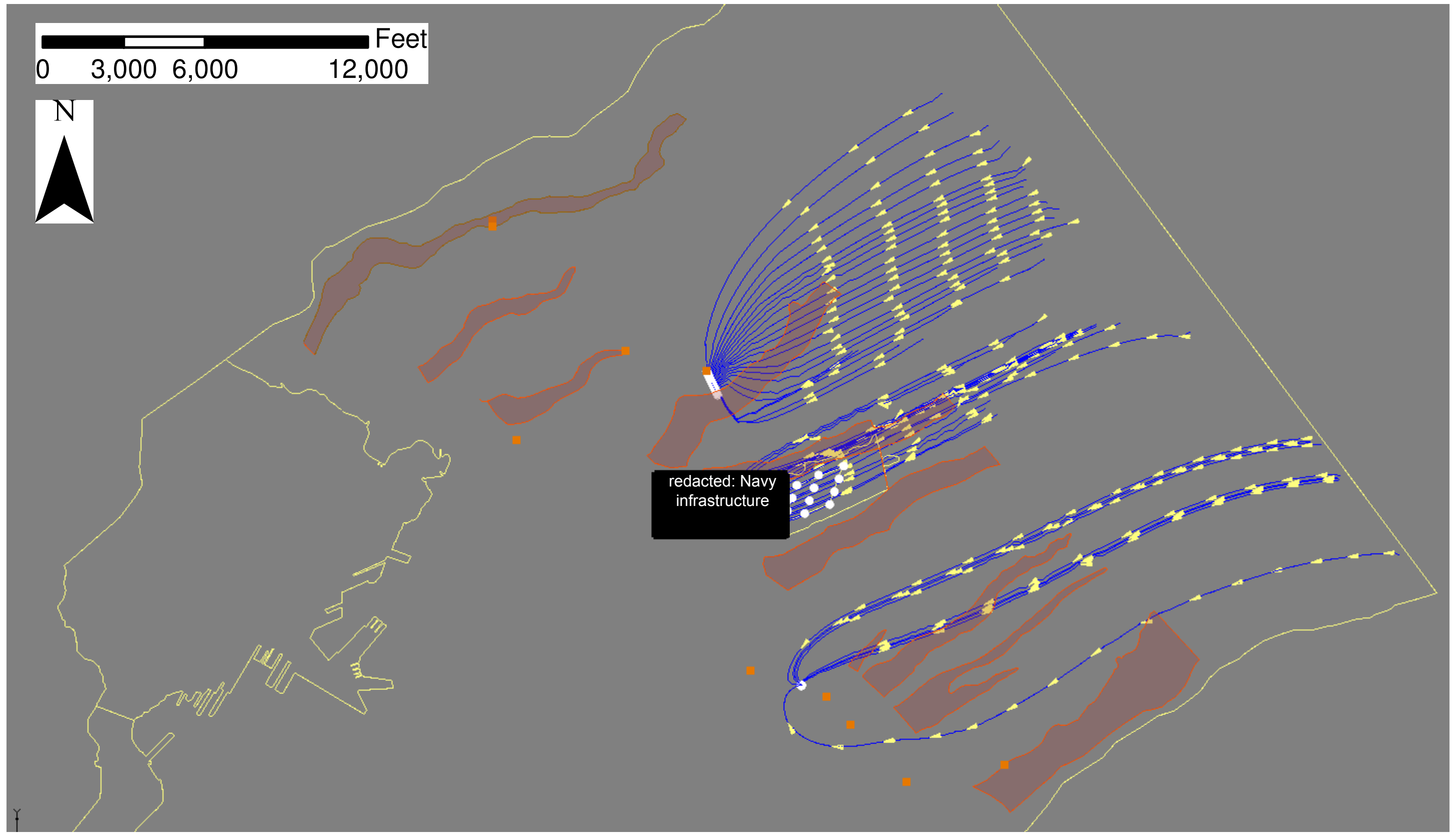
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

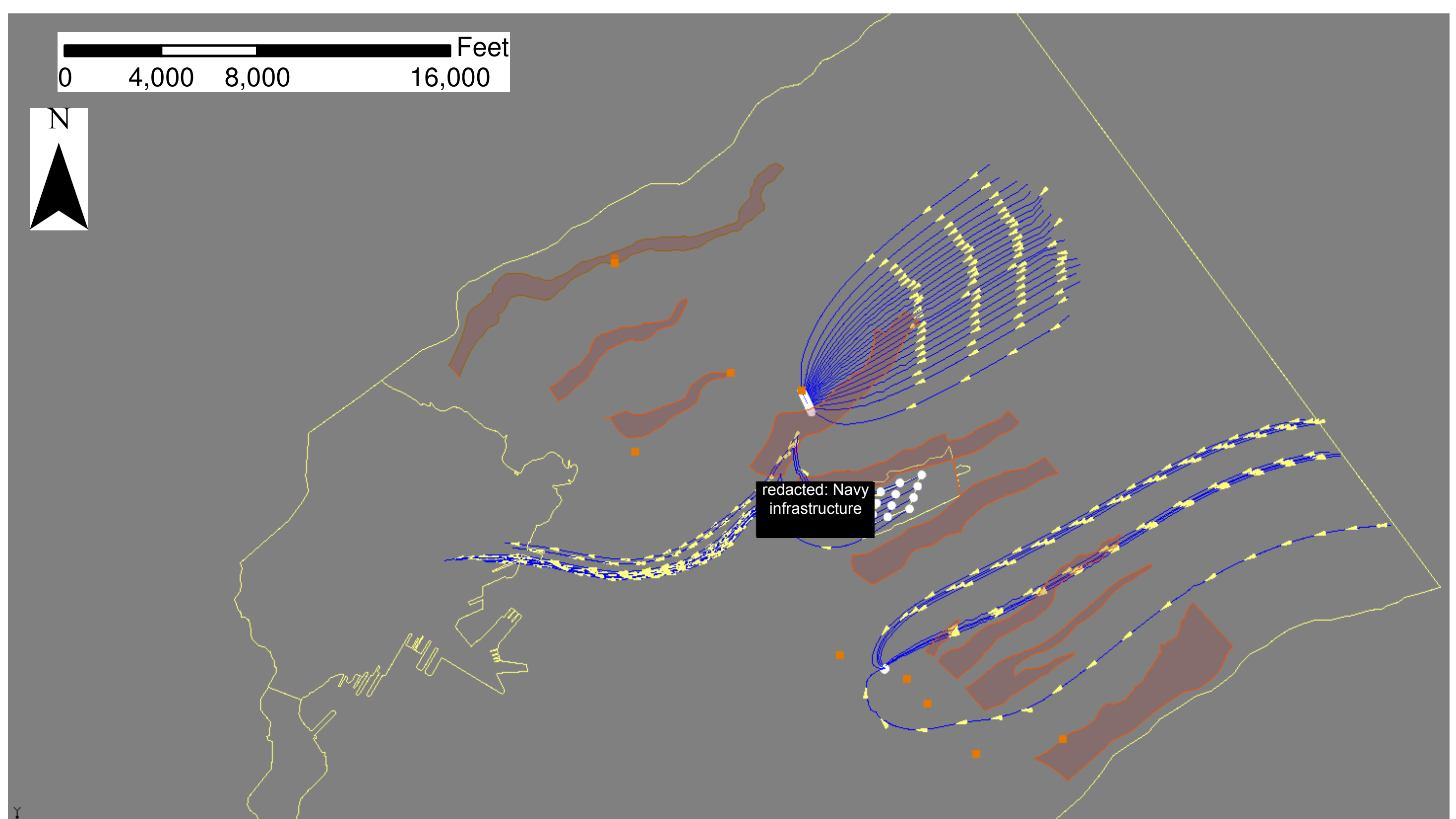
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.9-1
Presence of Saprolite (Model #8) - Source Water Zone for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

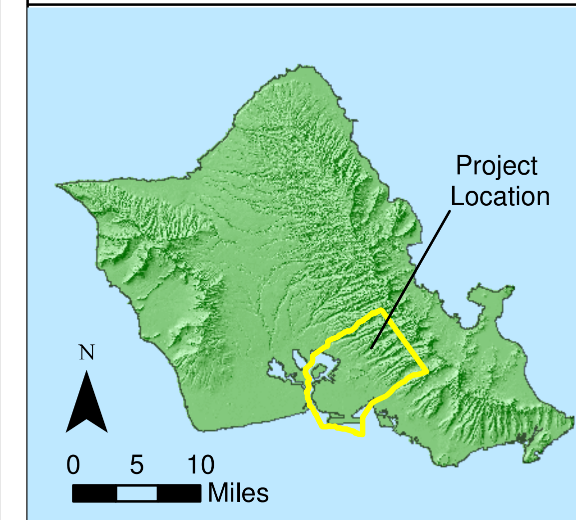
Model #1



Model #8



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Particle

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.9-2
Presence of Saprolite (Model #8) - Source Water Zone for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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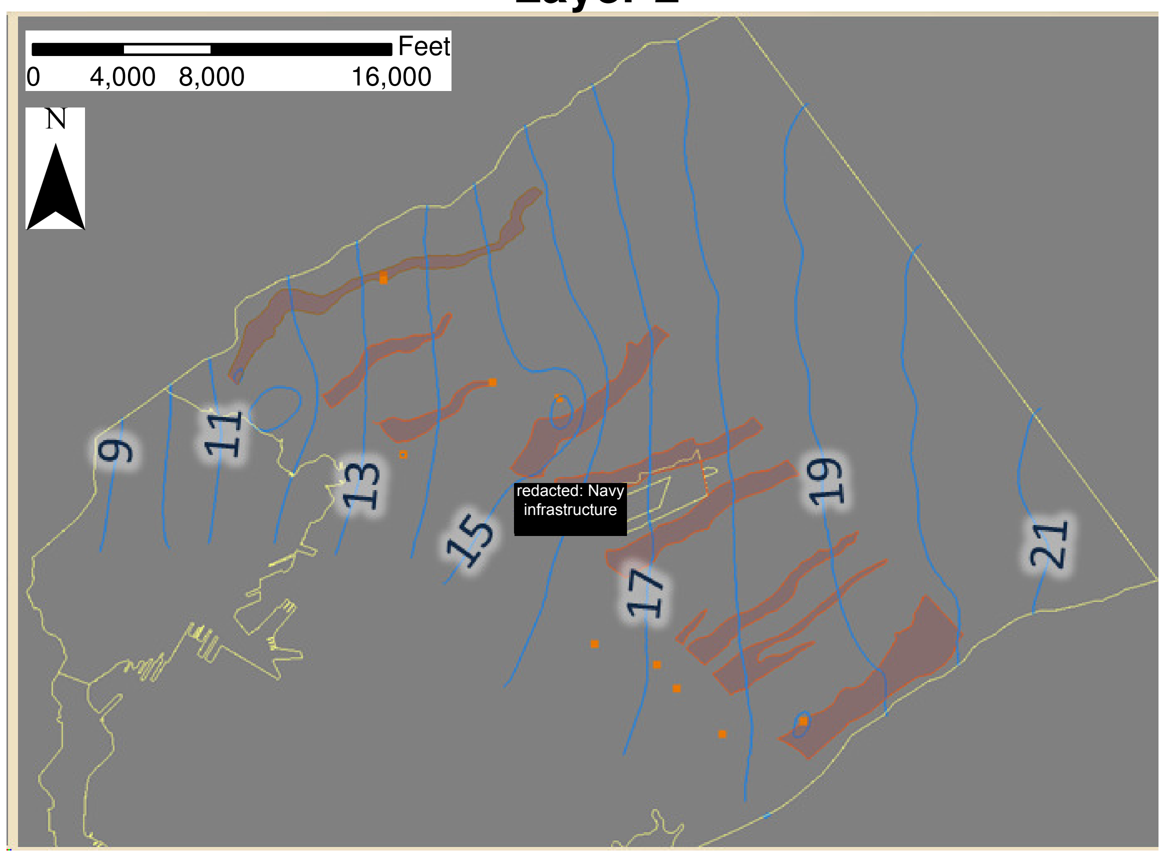
Layer 2



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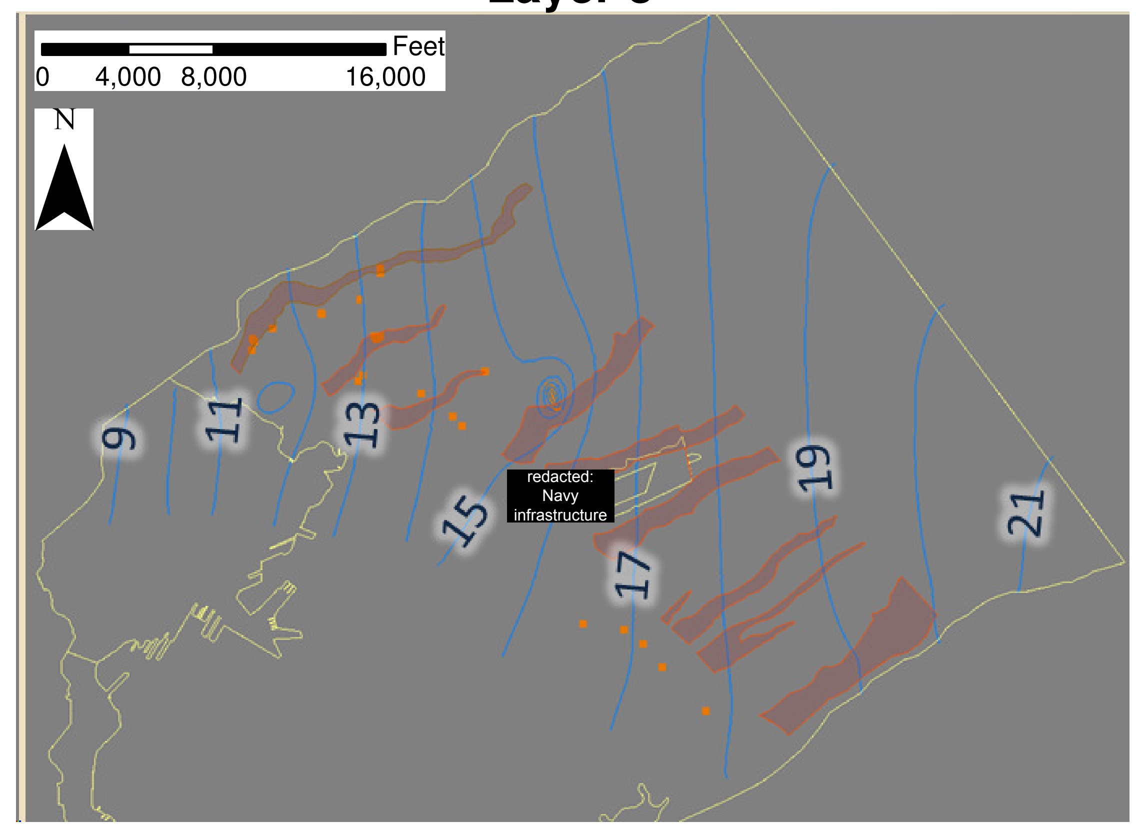
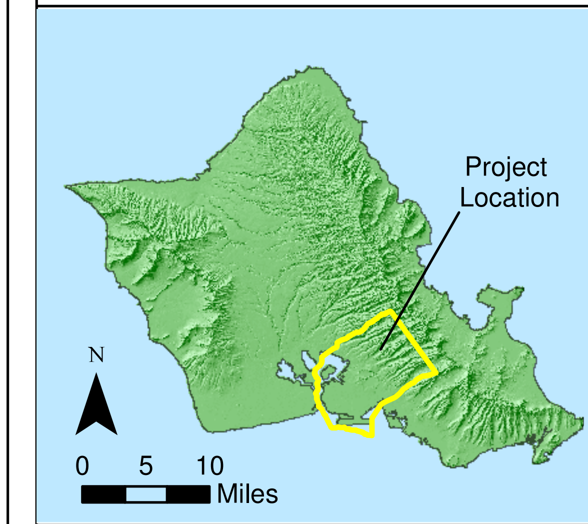


Location Map



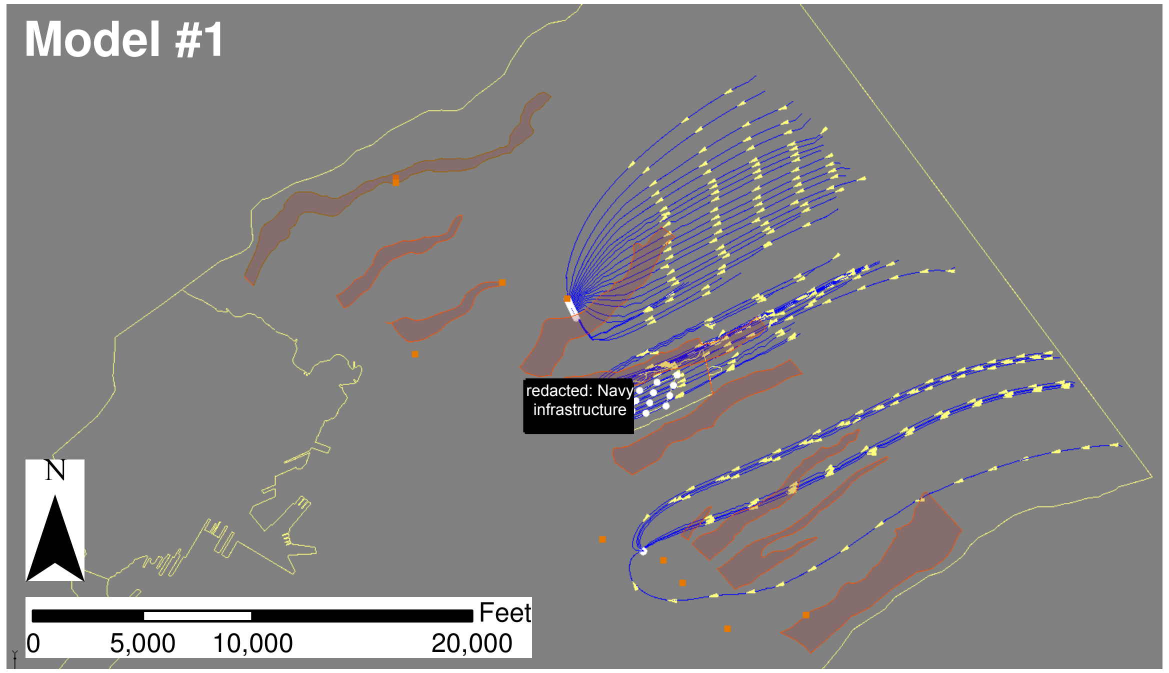
Legend

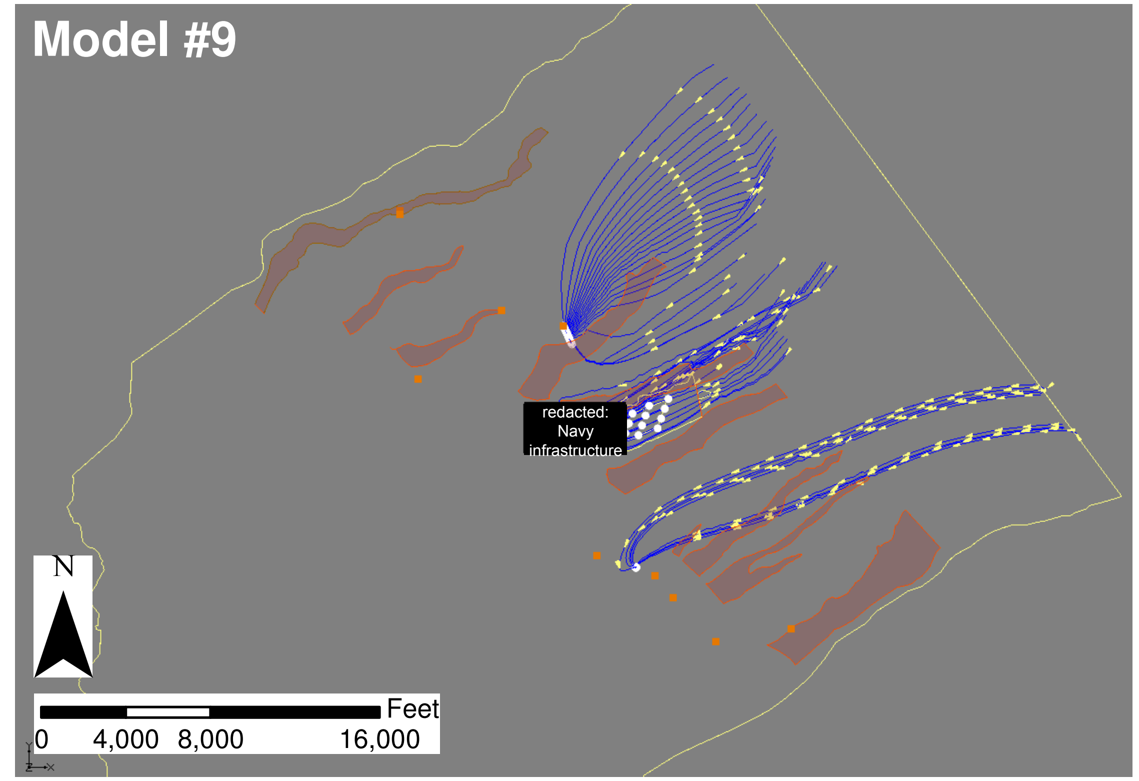
- Water Level Contours (feet above mean sea level)
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

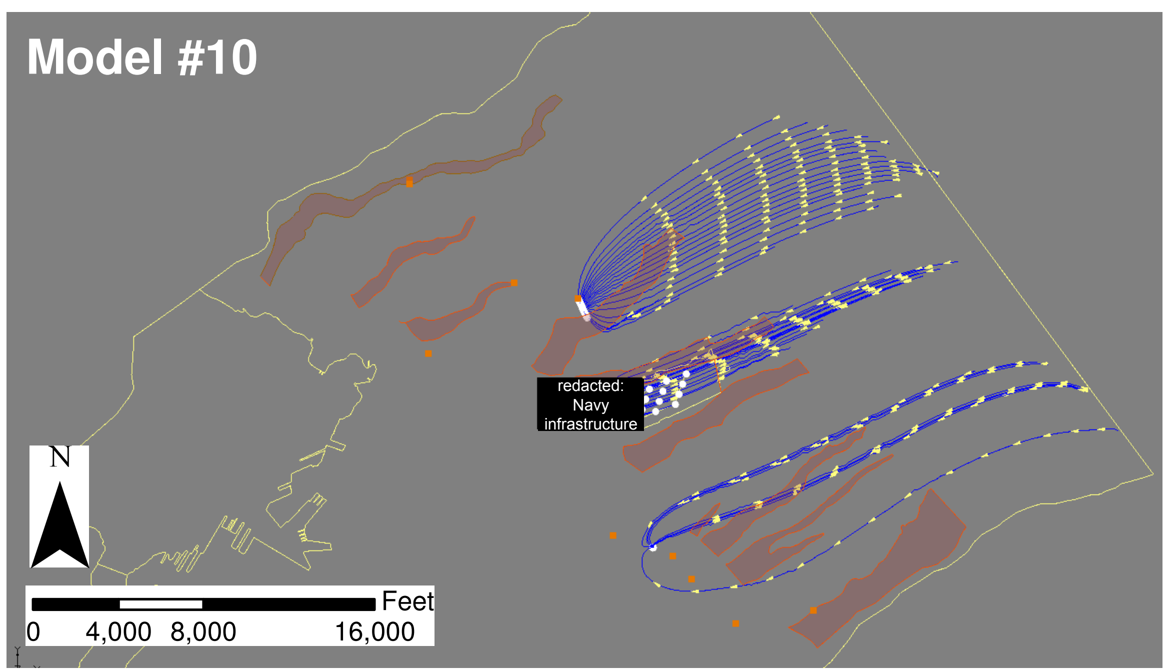
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

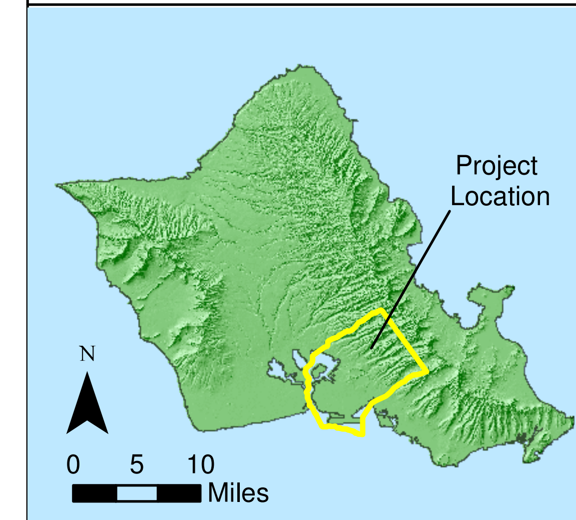
Figure 6.4.9-3
Presence of Saprolite (Model #8) - 2017 Water Level Contours for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI







Location Map



Legend

- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.10-1
Kv of Basalt (Model #9 & Model #10) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
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JBPHH, O'ahu, HI

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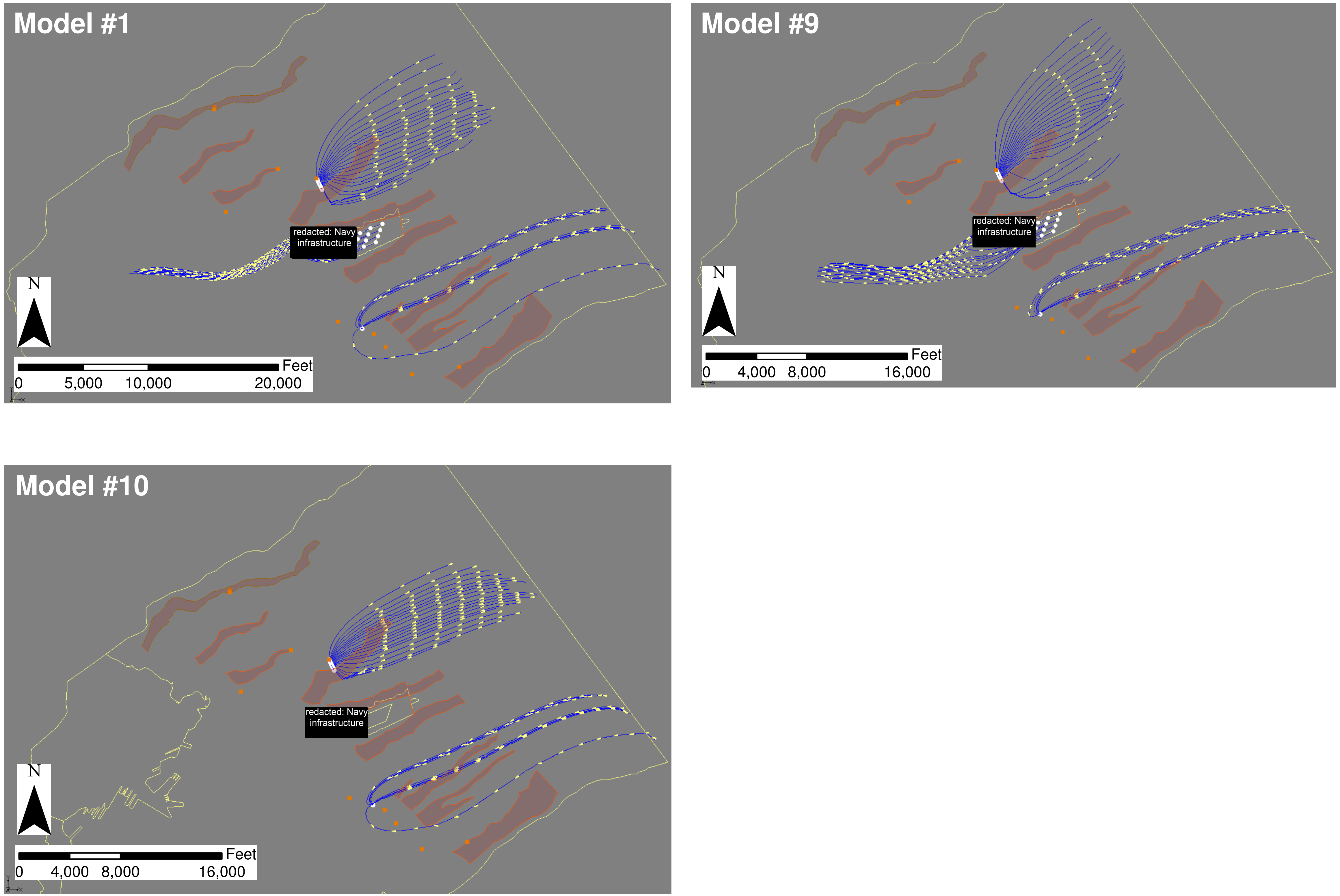
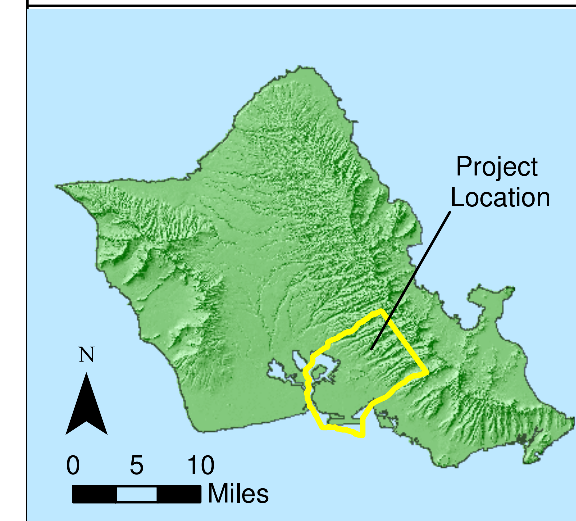


Location Map



Legend

- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.10-2
Kv of Basalt (Model #9 & Model #10) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
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JBPHH, O'ahu, HI

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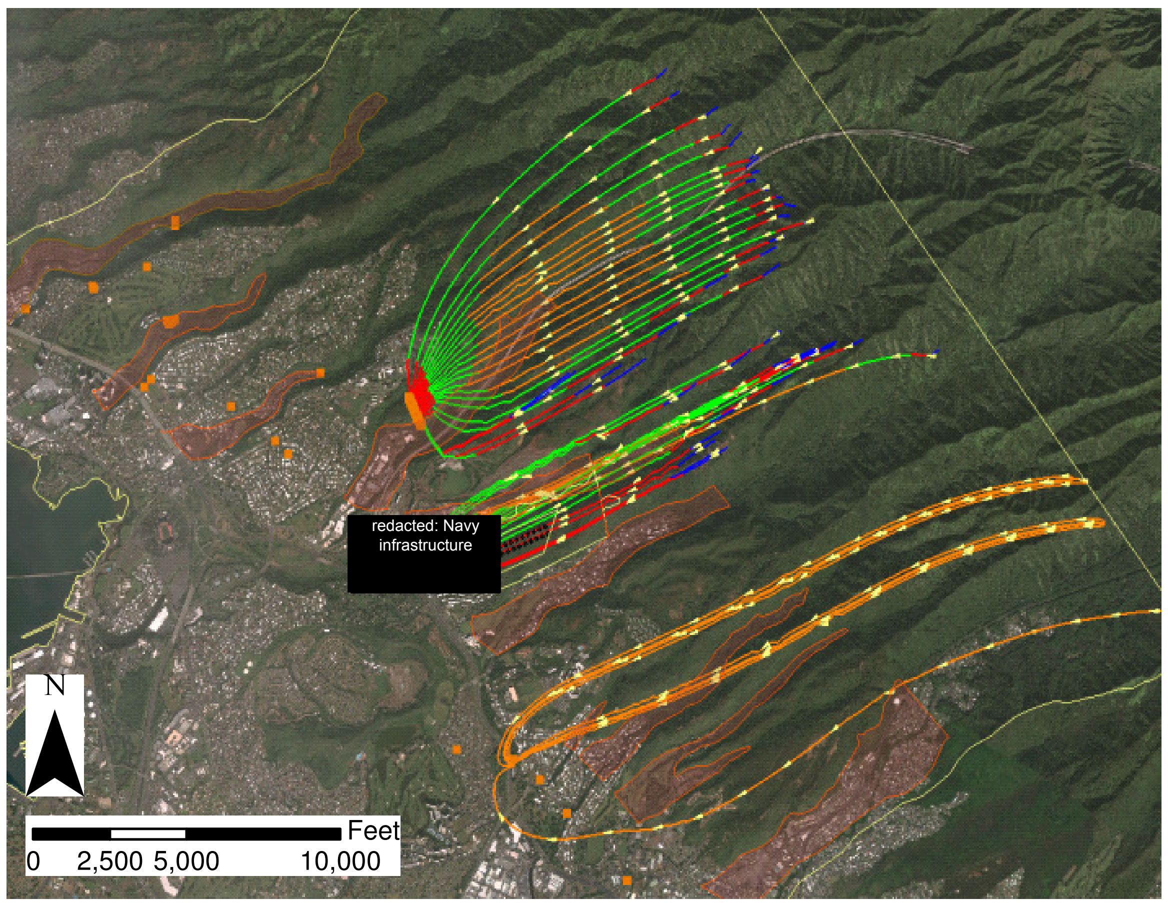
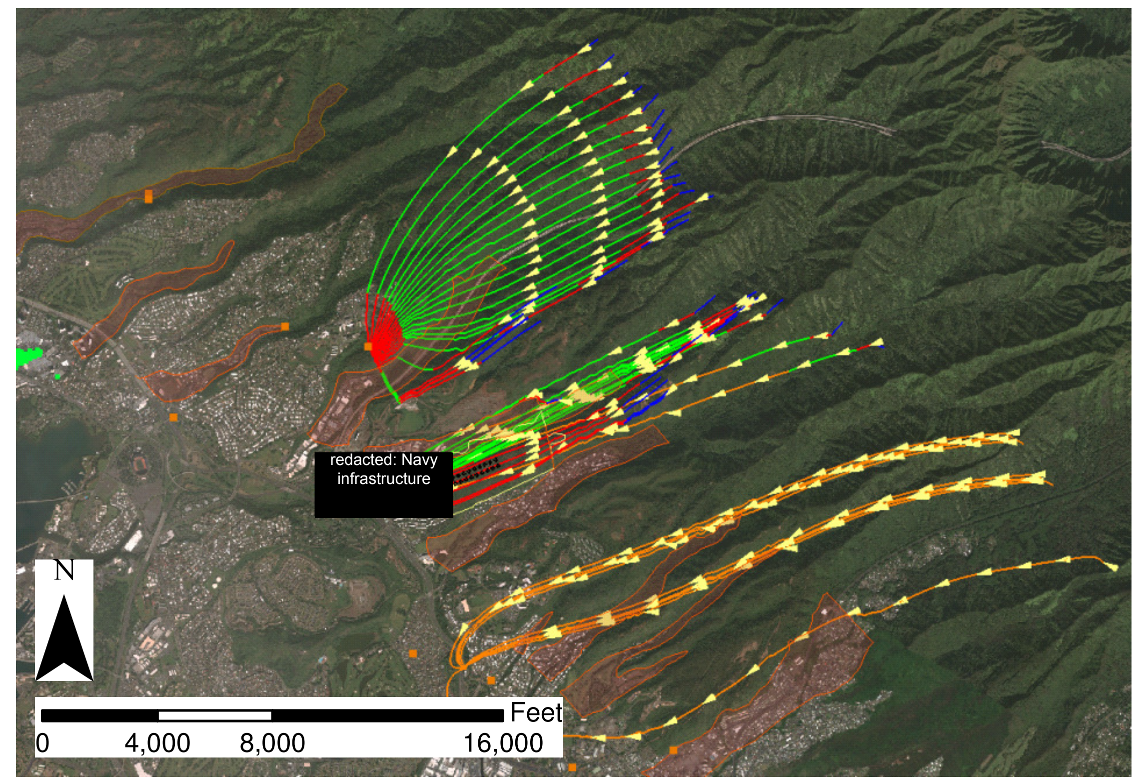
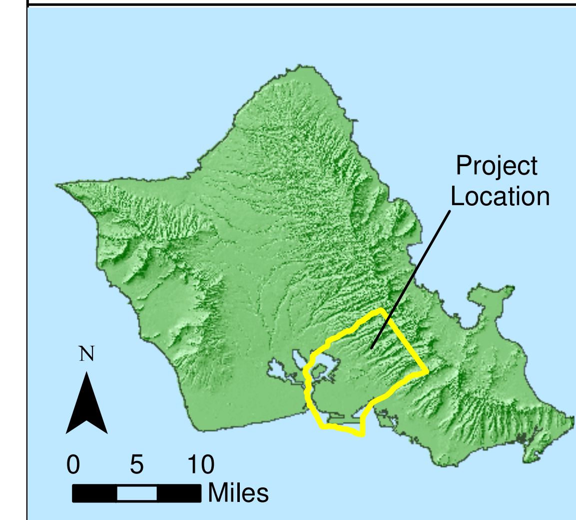
Model #1



Model #11



Location Map



Legend

Pathline Colors:

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- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

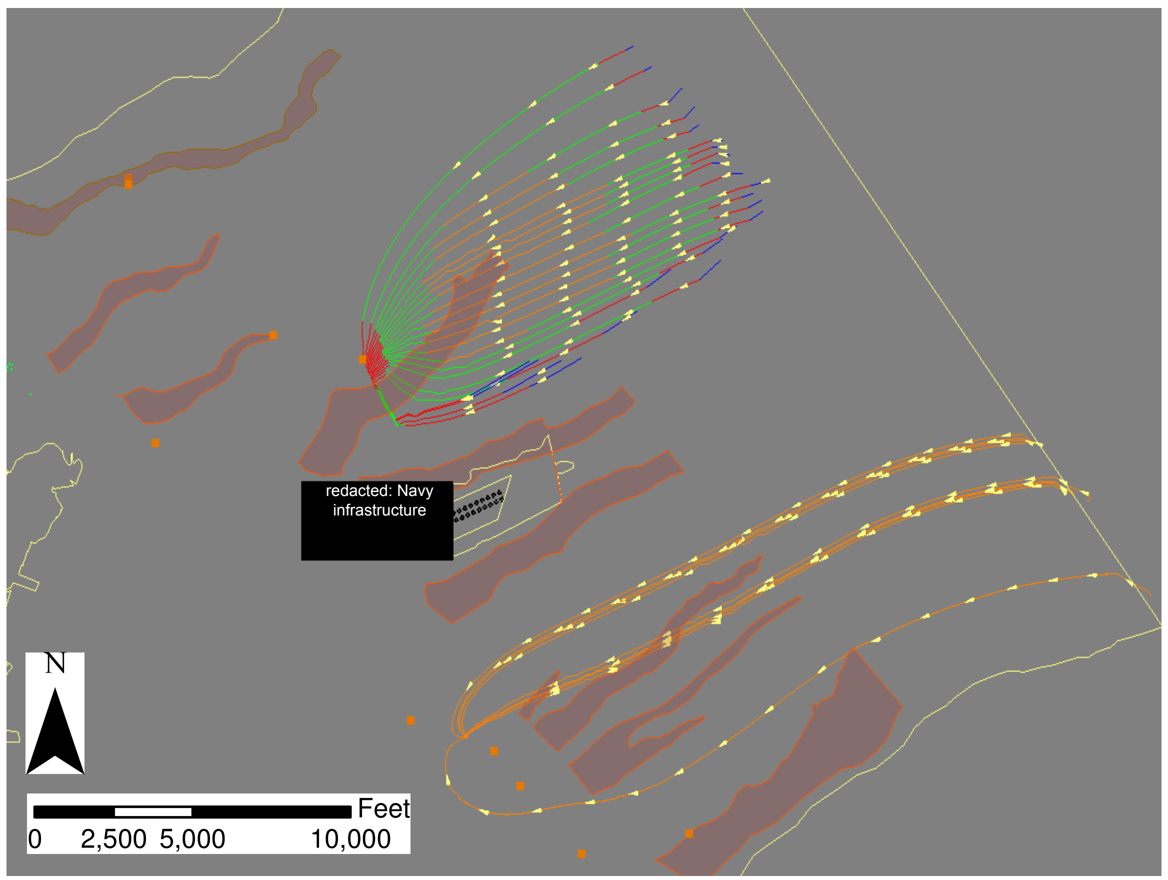
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

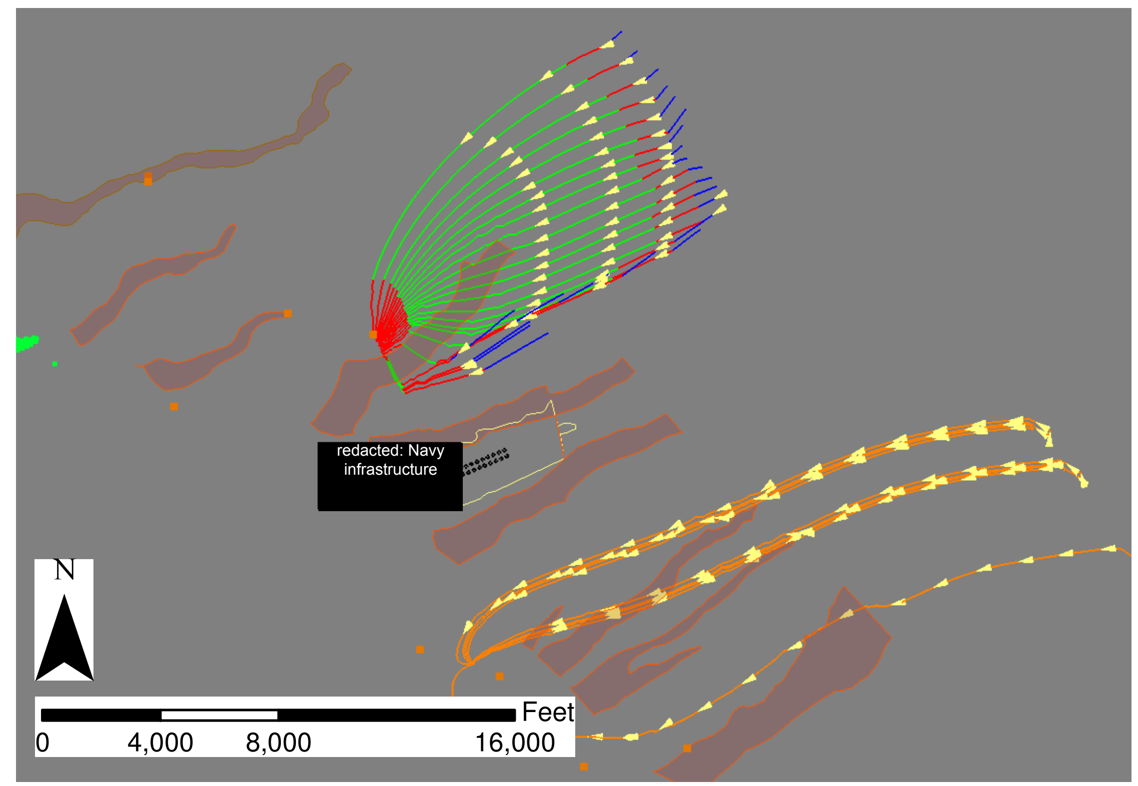
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.11-1
Kh of Basalt (Model #11) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

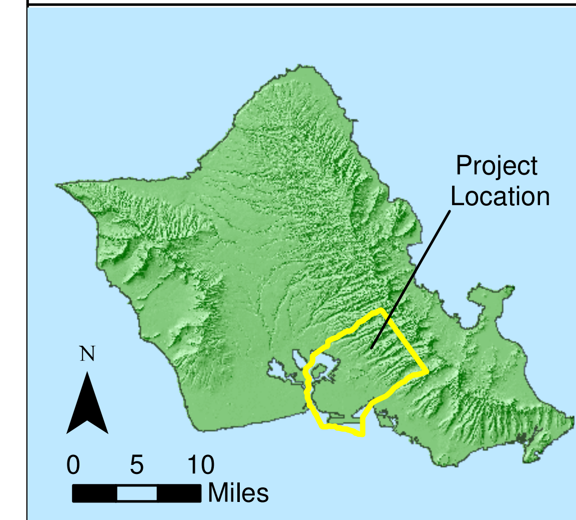
Model #1



Model #11



Location Map



Legend

Pathline Colors:

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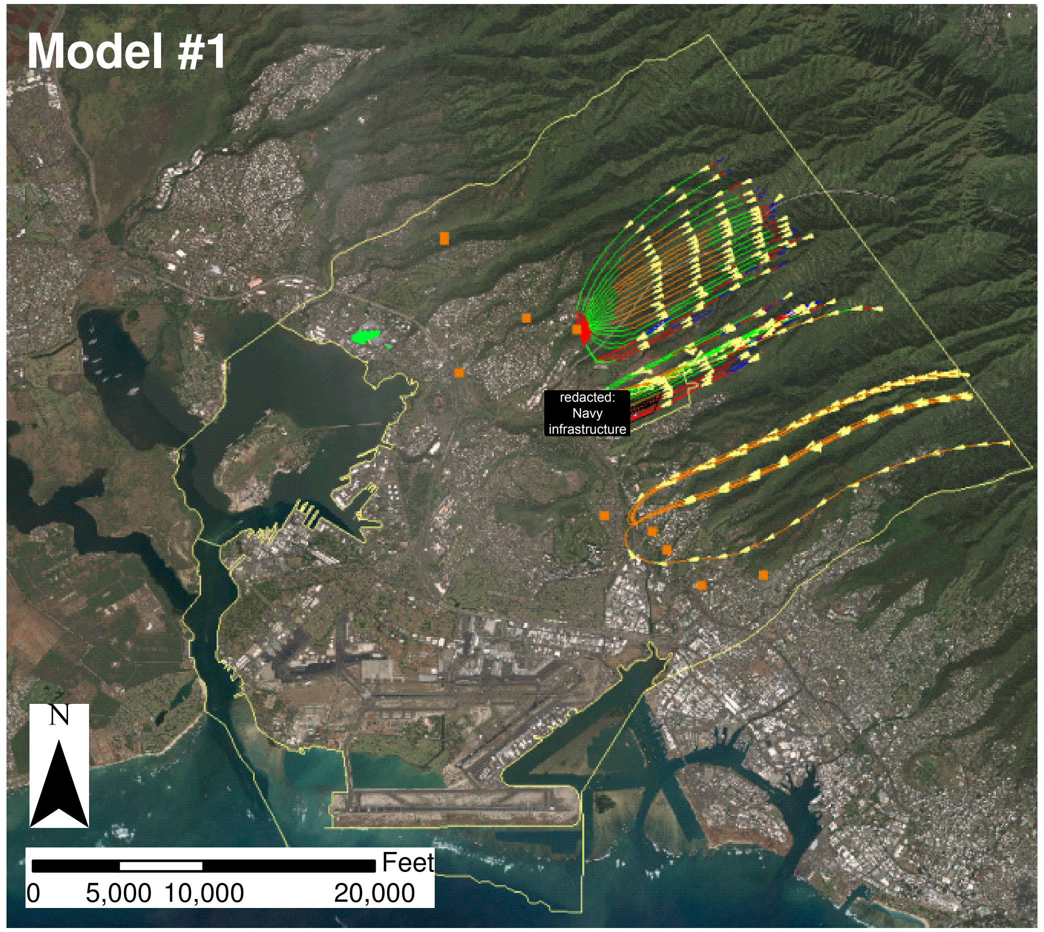
- Layer 3
- Layer 4
- Layer 5

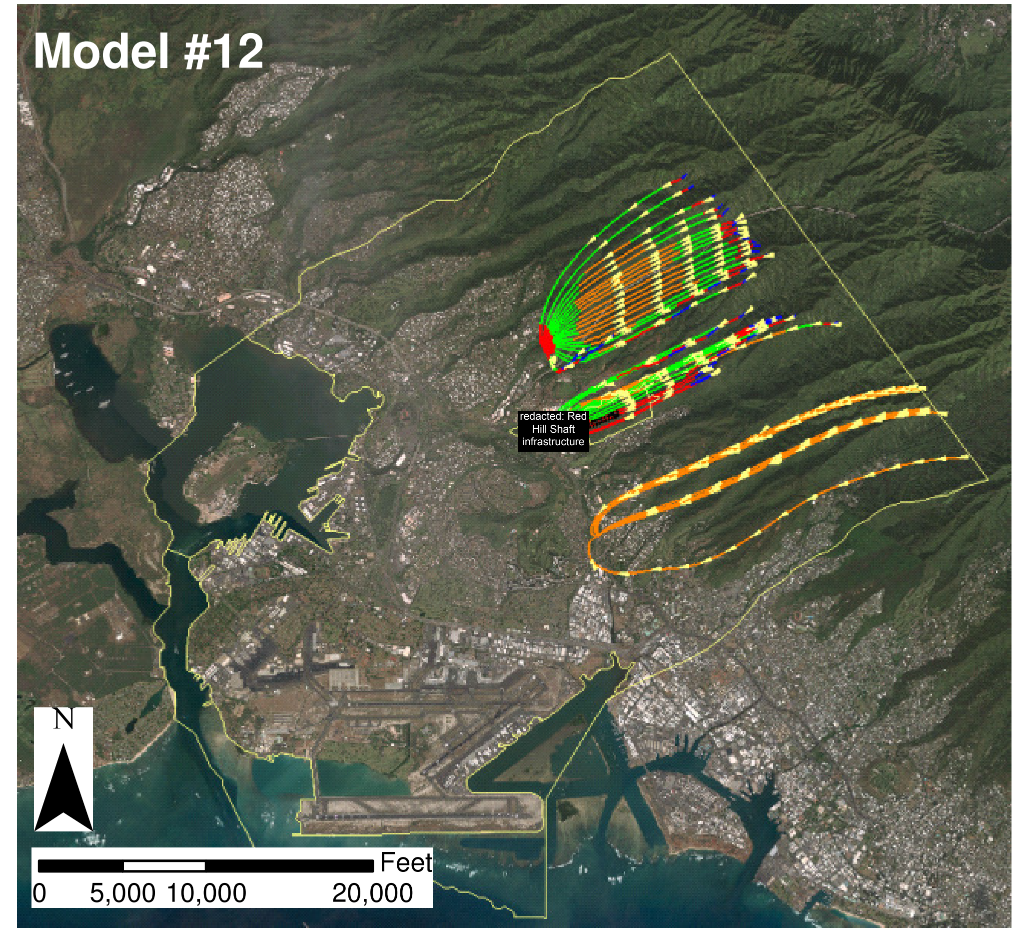
1-year Time Intervals
Red Hill Fuel Storage Tank
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

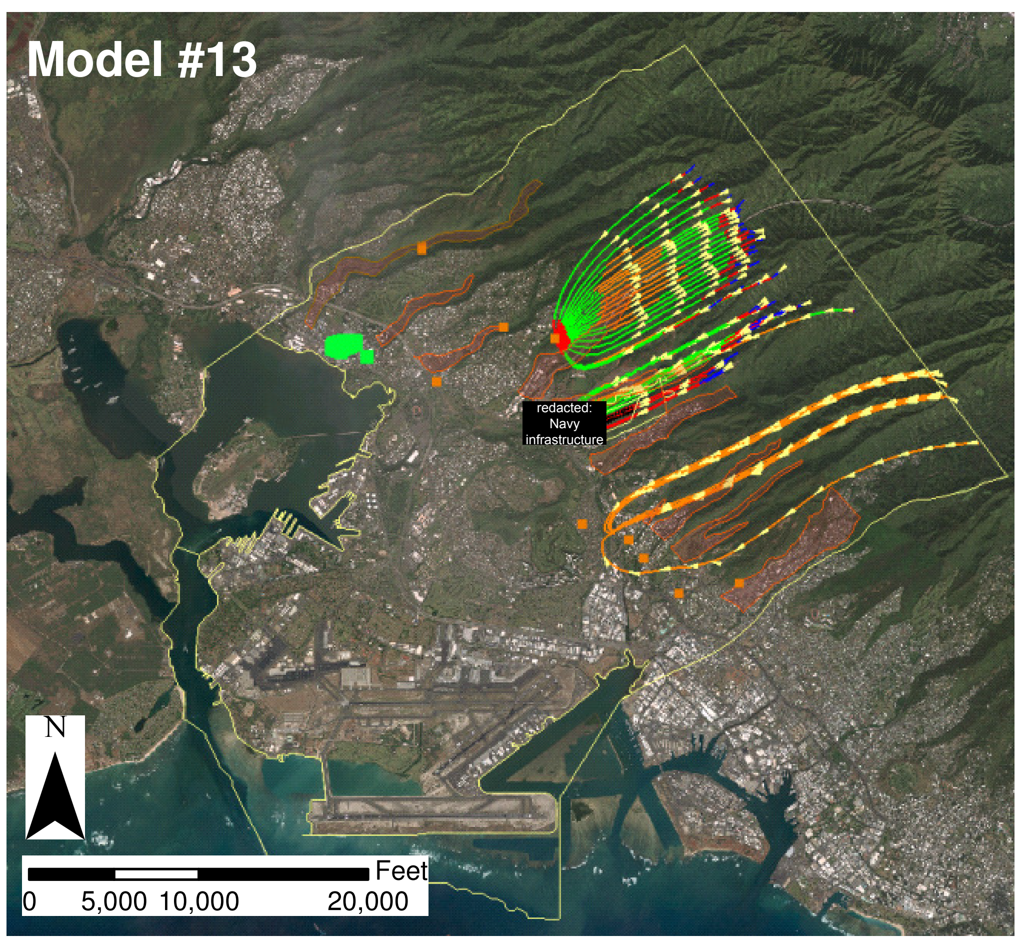
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.11-2
Kh of Basalt (Model #11) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI







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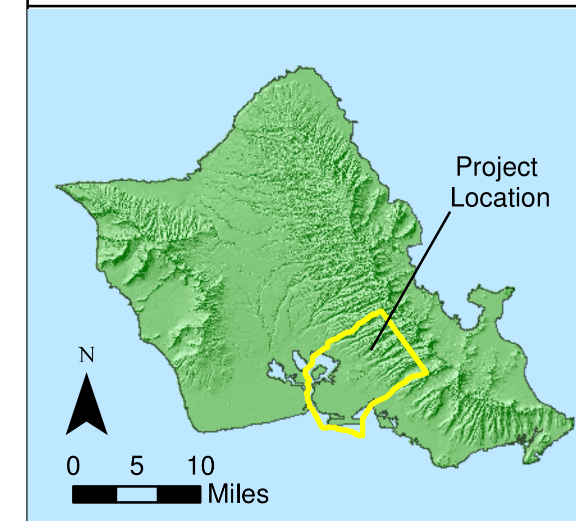

Legend

Pathline Colors:
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- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.12-1
K of Saprolite (Model #12 & Model #13) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
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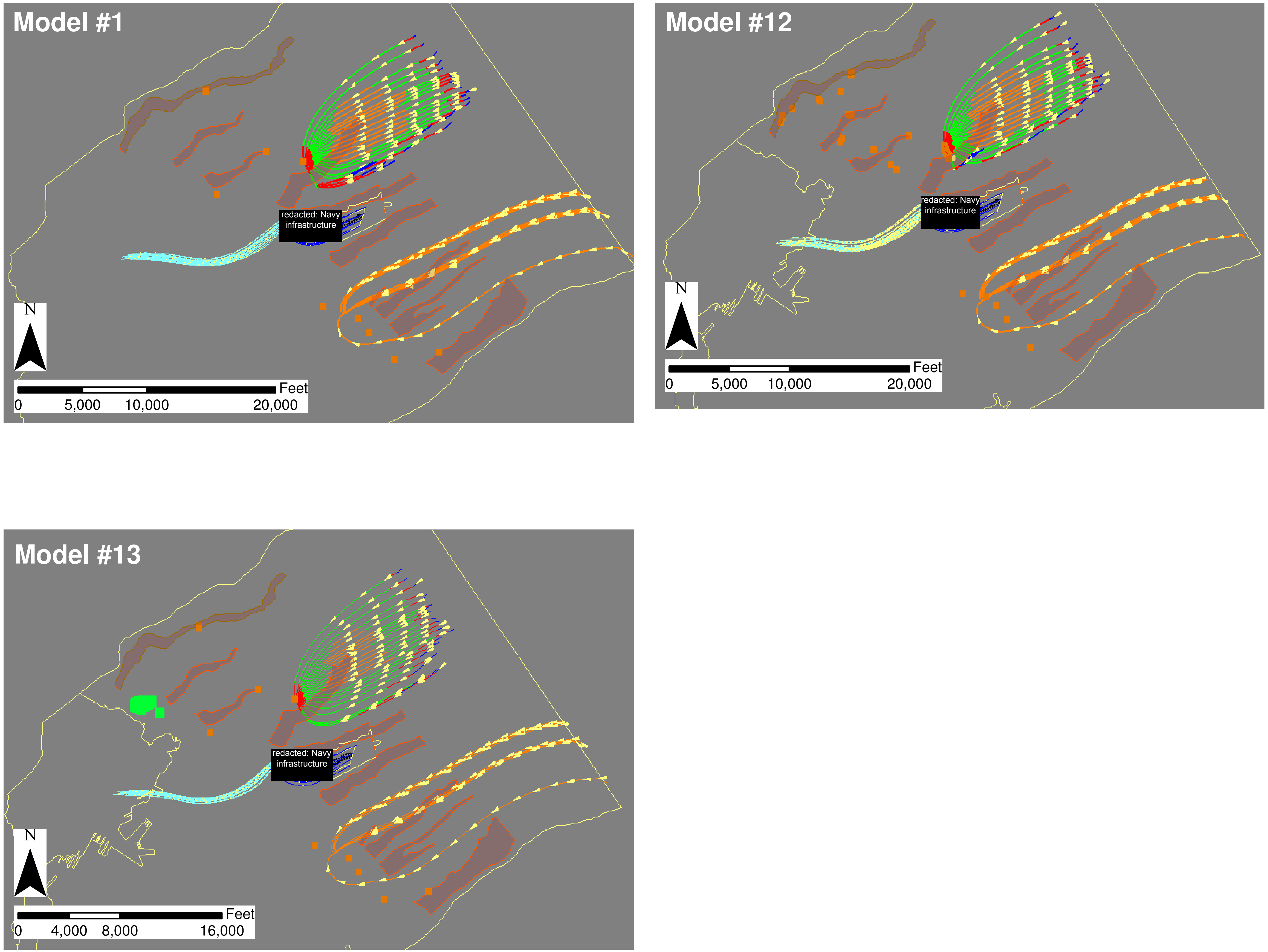

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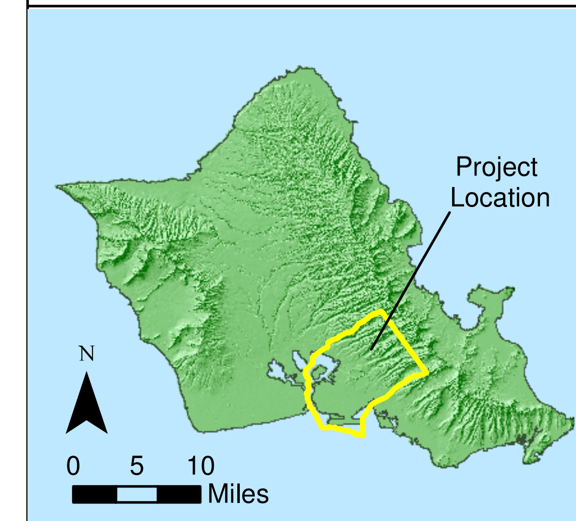

Legend

Pathline Colors:

- Layer 1
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- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.12-2
K of Saprolite (Model #12 & Model #13) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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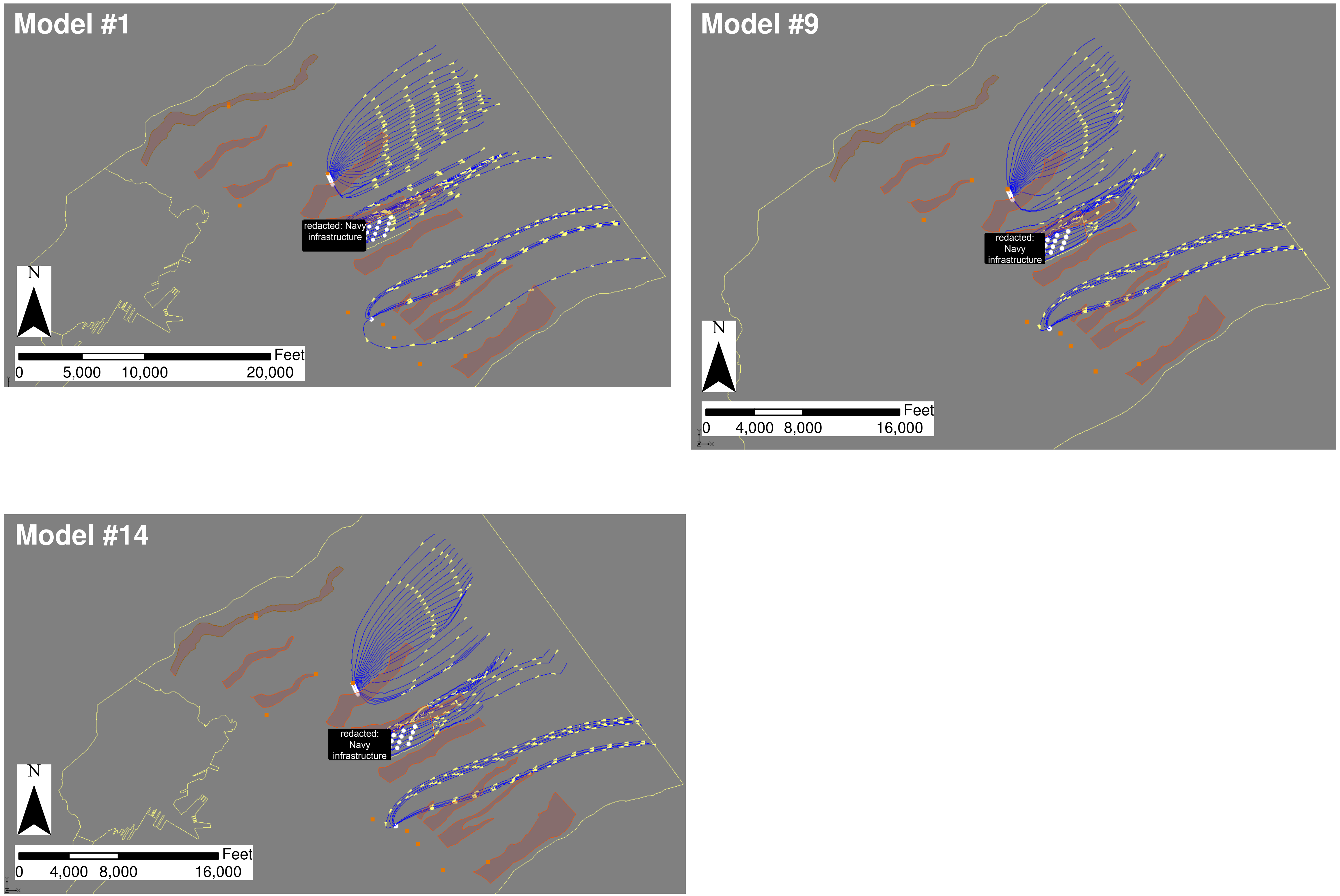
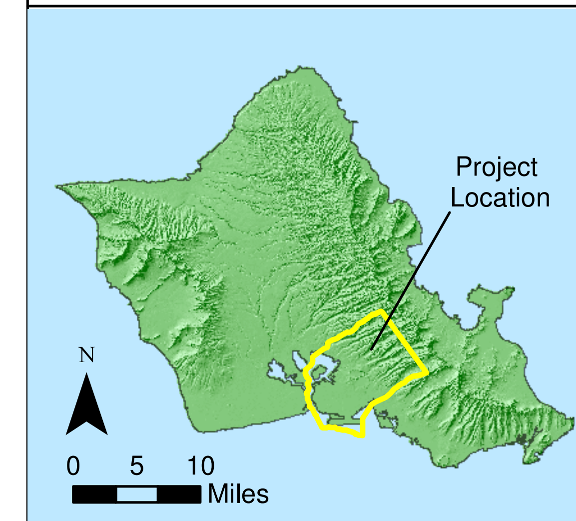


Location Map



Legend

- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.13-1
Lower Kv of Basalt and Higher K of Saprolite (Model #14) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
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JBPHH, O'ahu, HI

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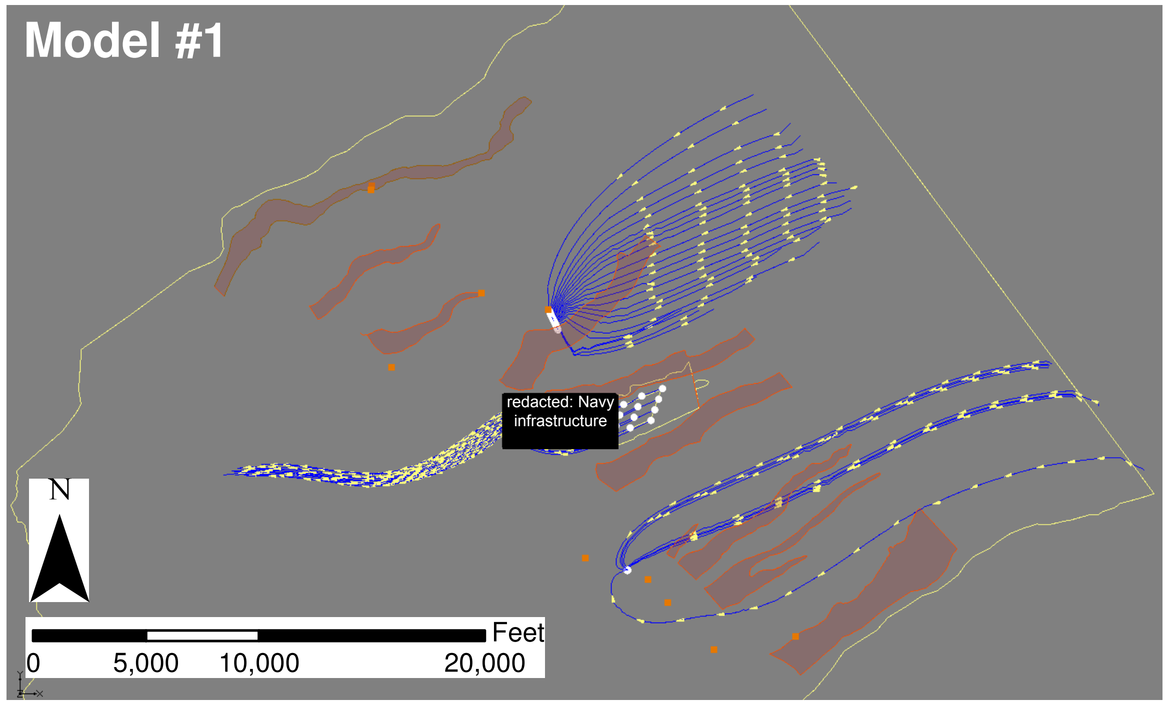

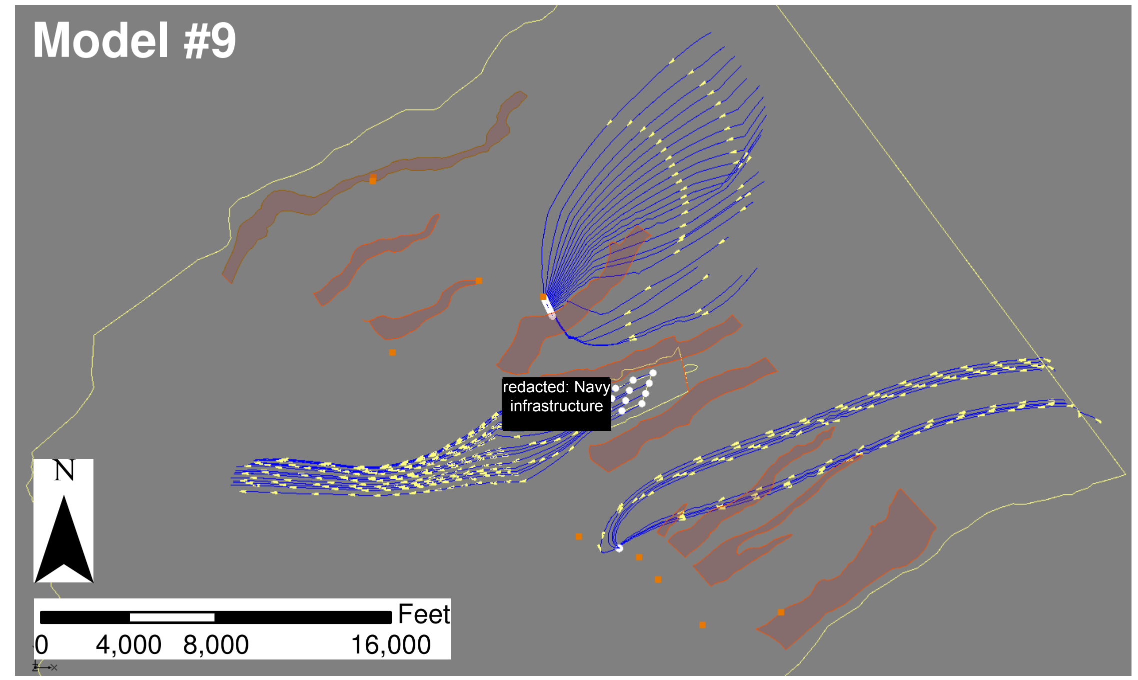

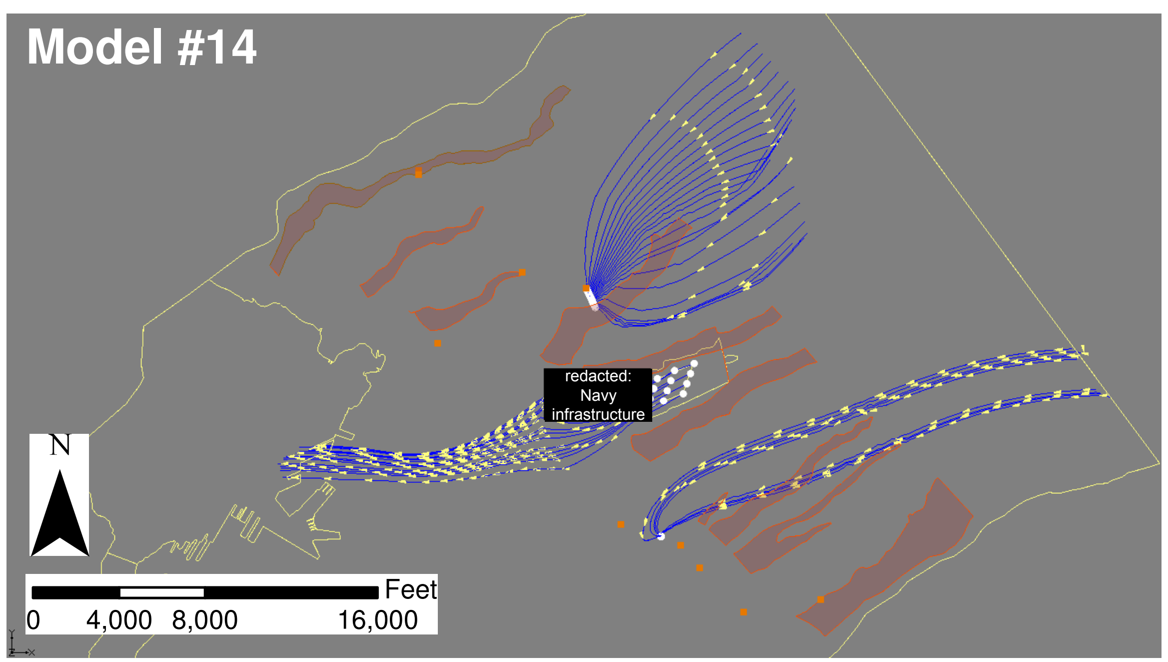

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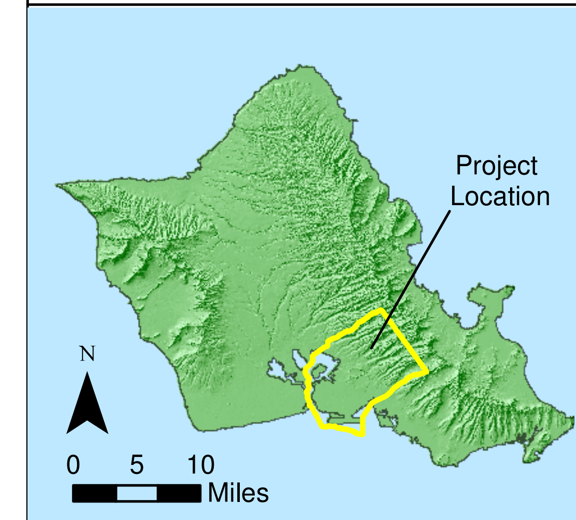


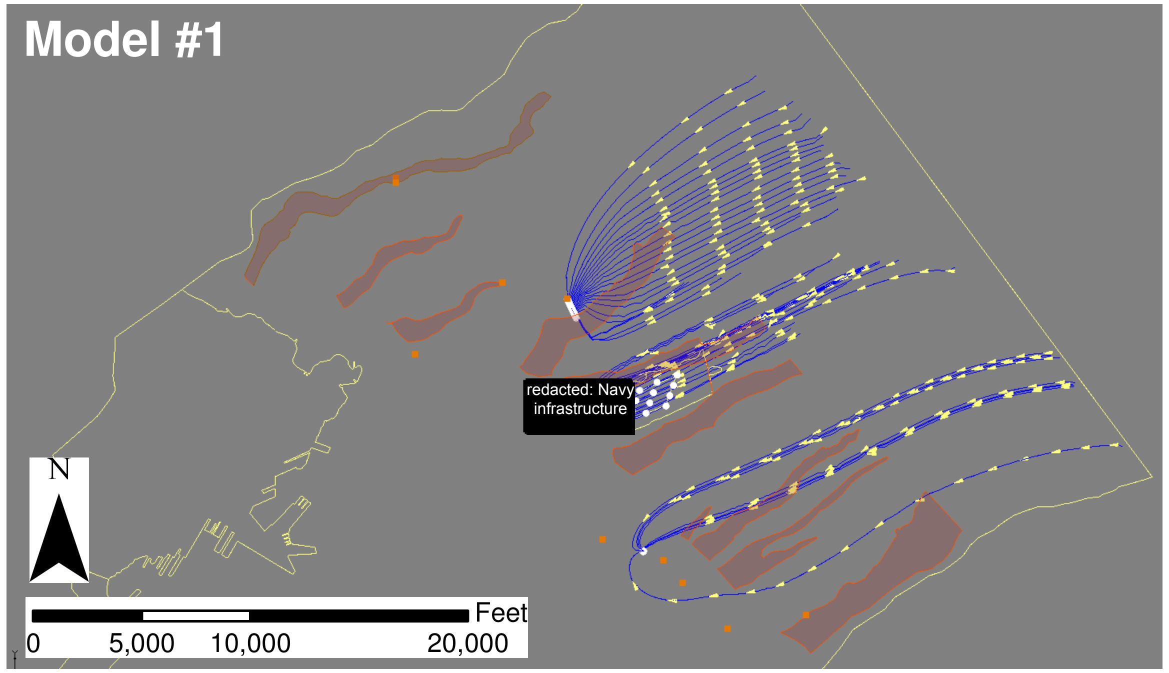
Legend

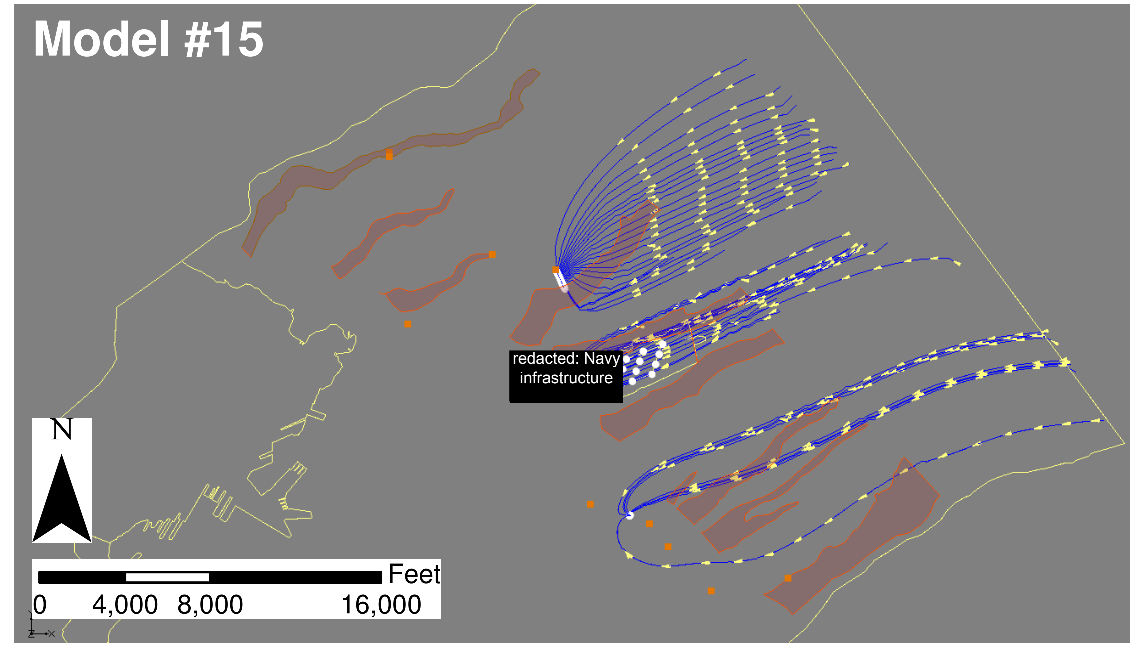
- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

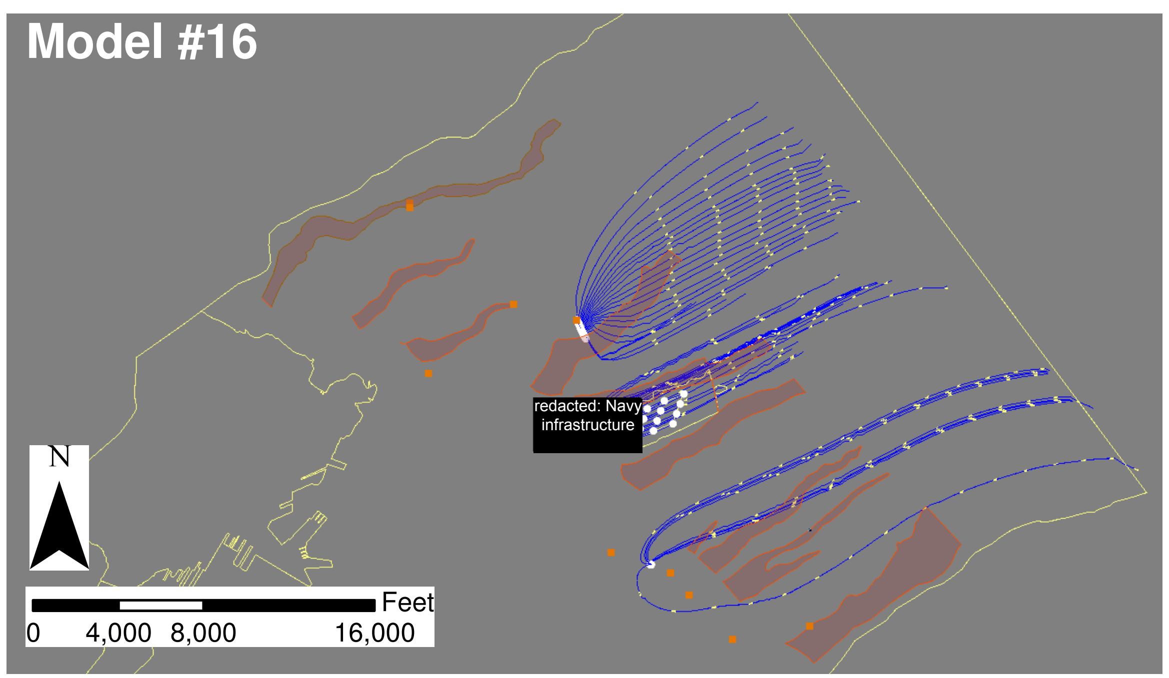
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

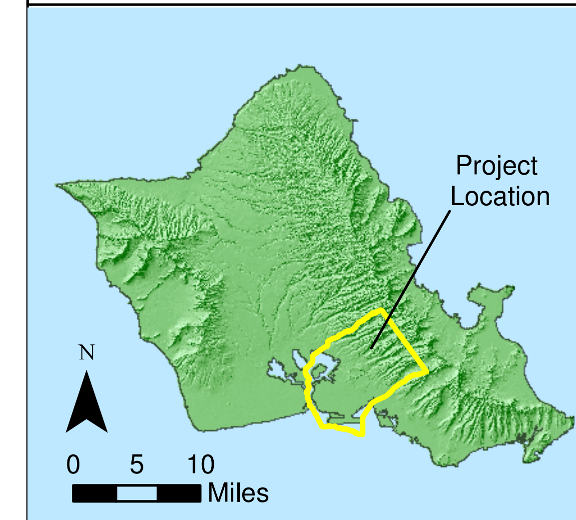
Figure 6.4.13-2
Lower Kv of Basalt and Higher K of Saprolite (Model #14) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI







Location Map



Legend

- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.14-1
Offshore GHB Conductance (Model #15 & Model #16) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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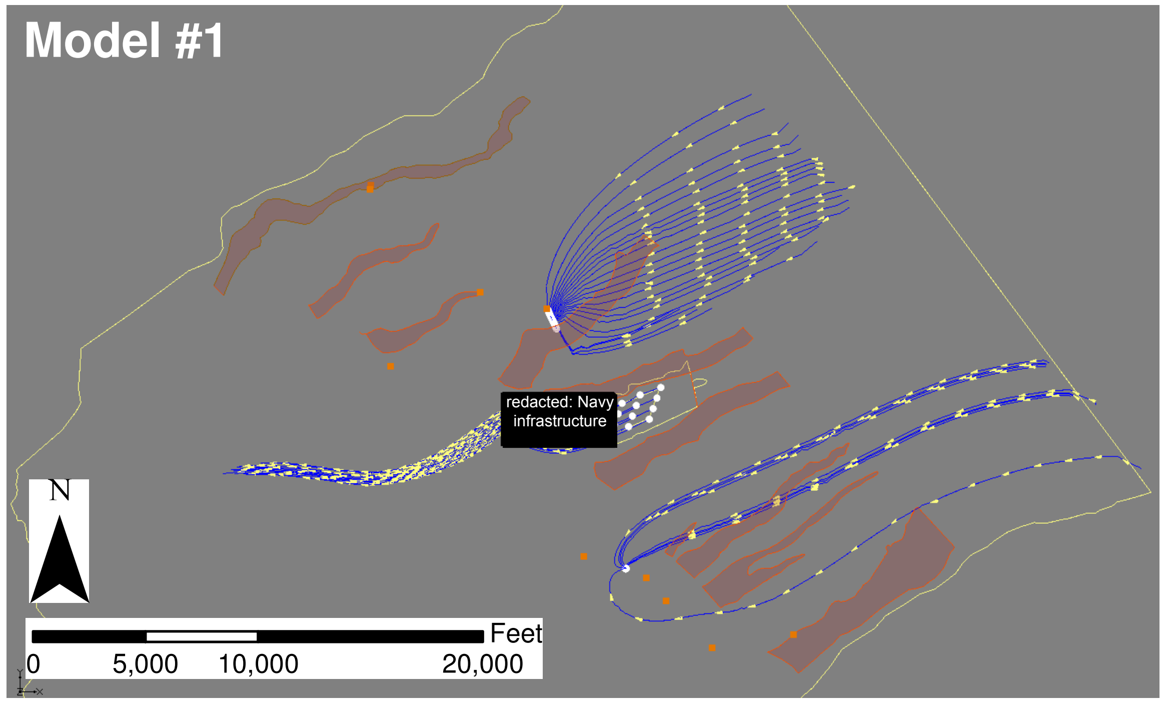

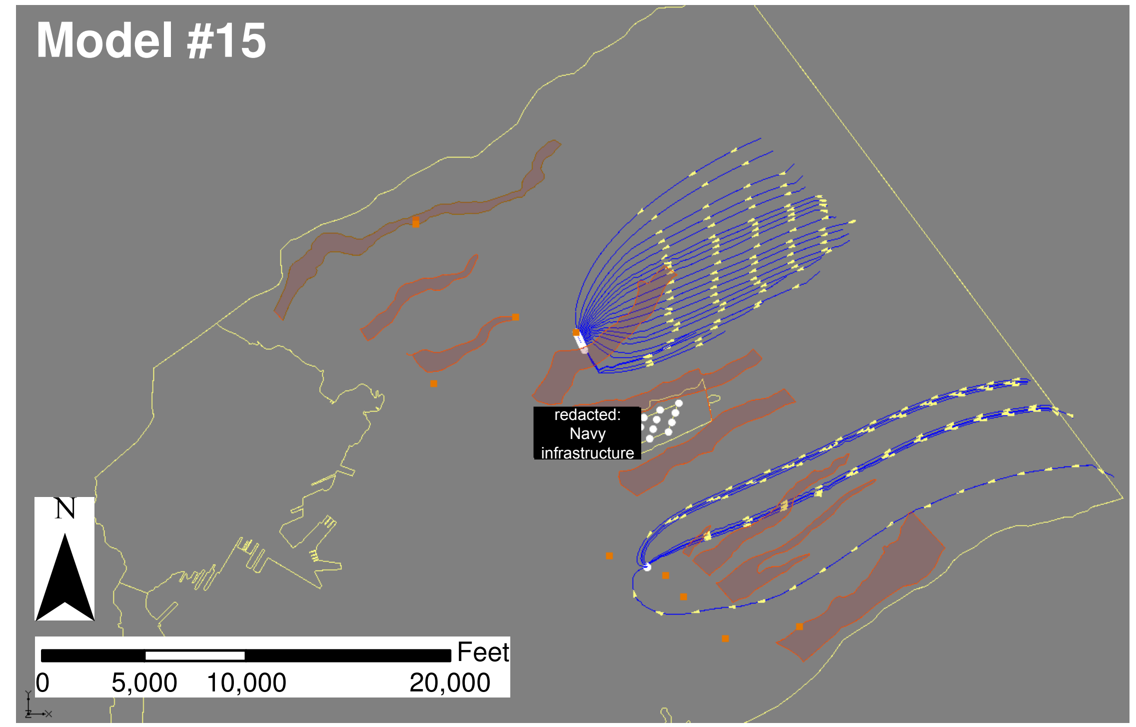

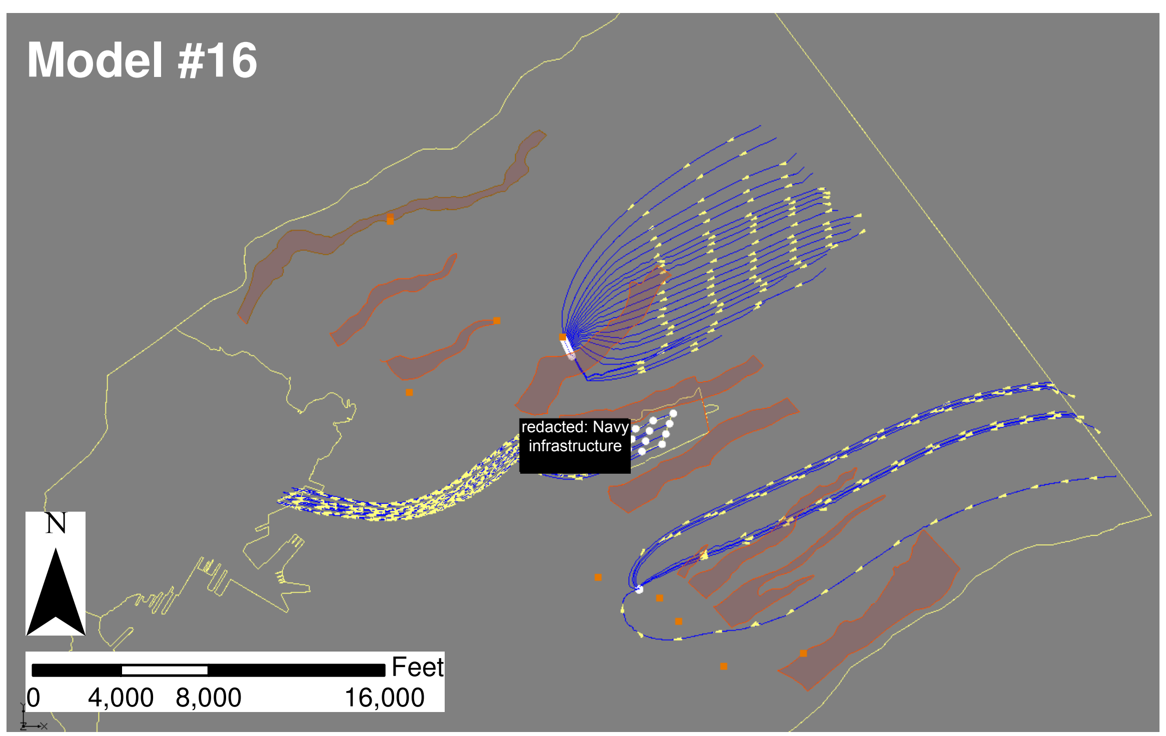

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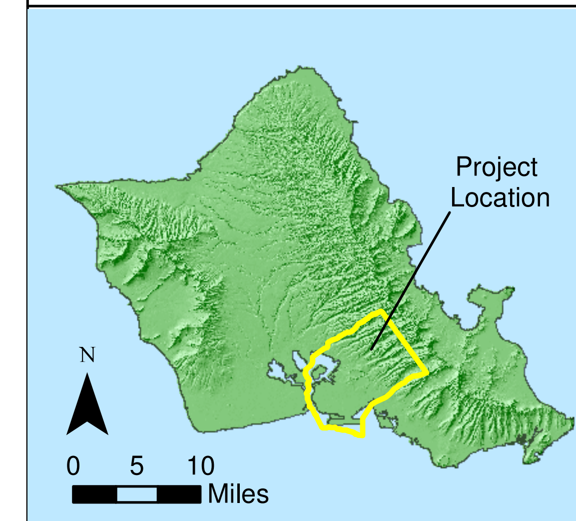


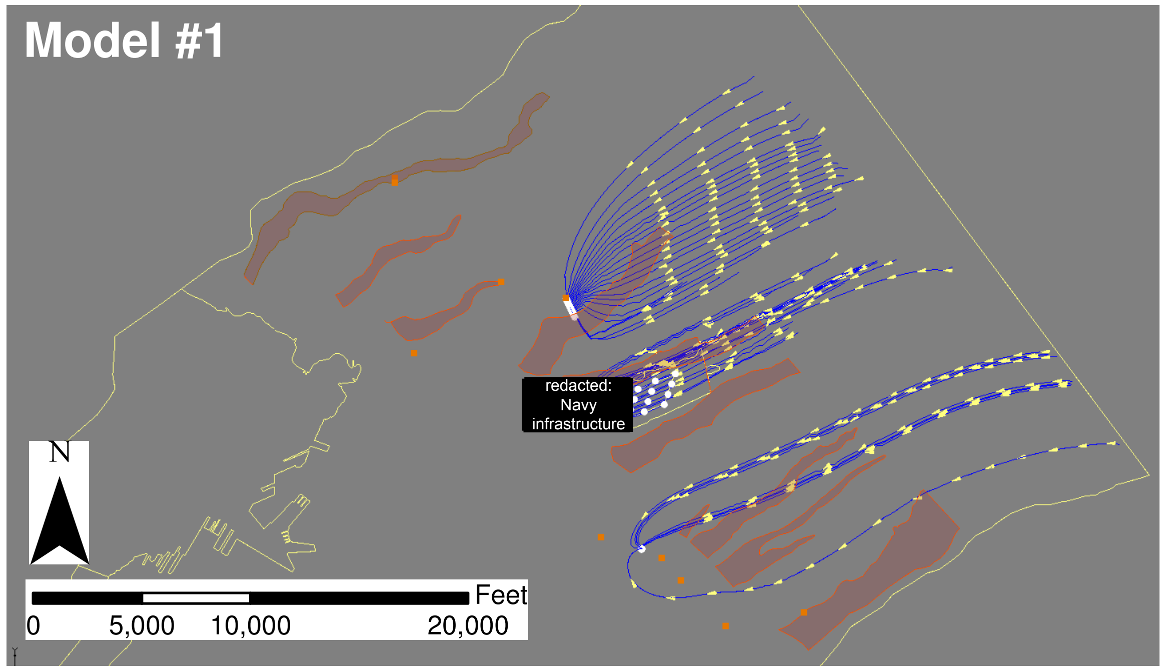
Legend

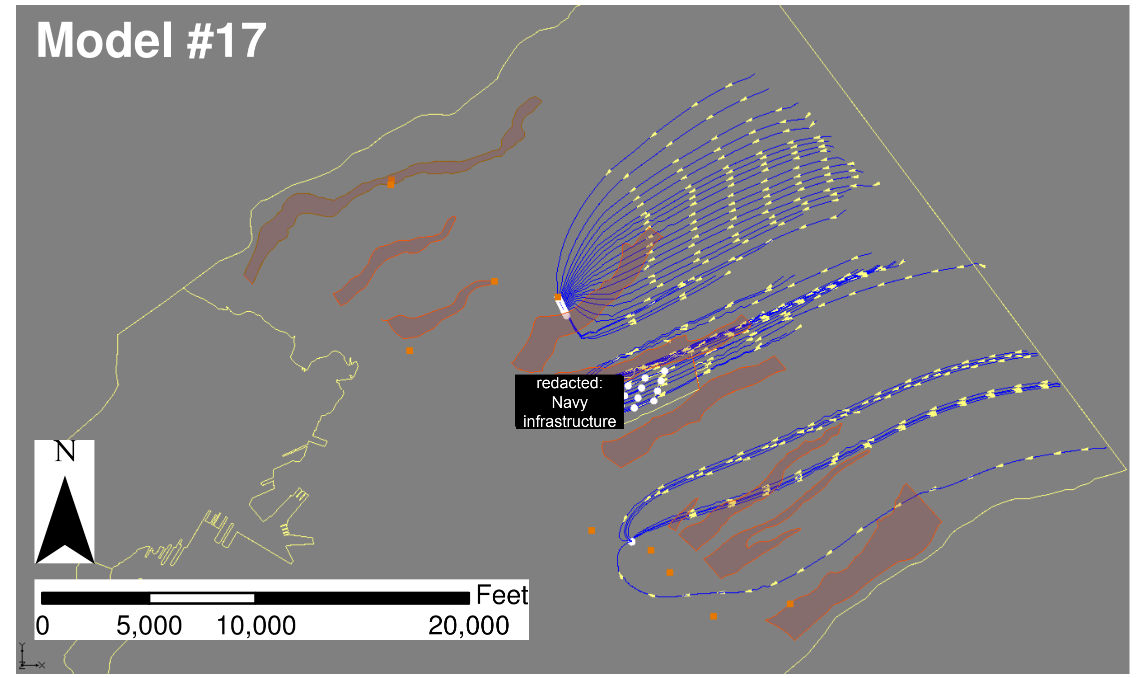
- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

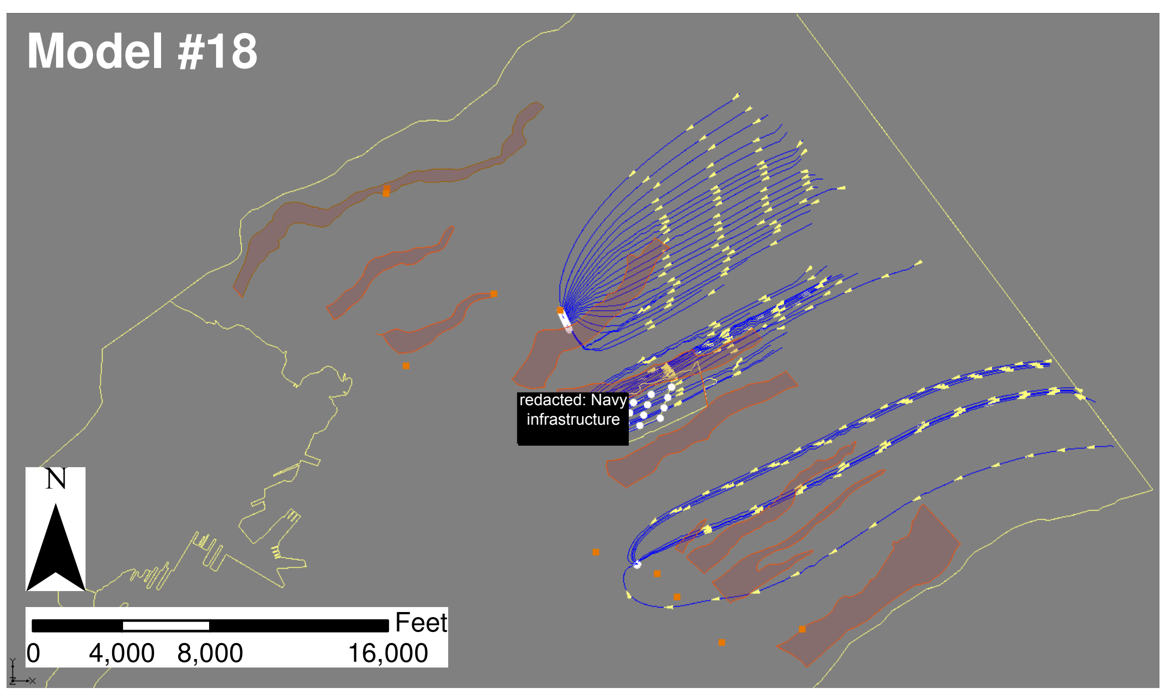
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.14-2
Offshore GHB Conductance (Model #15 & Model #16) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI







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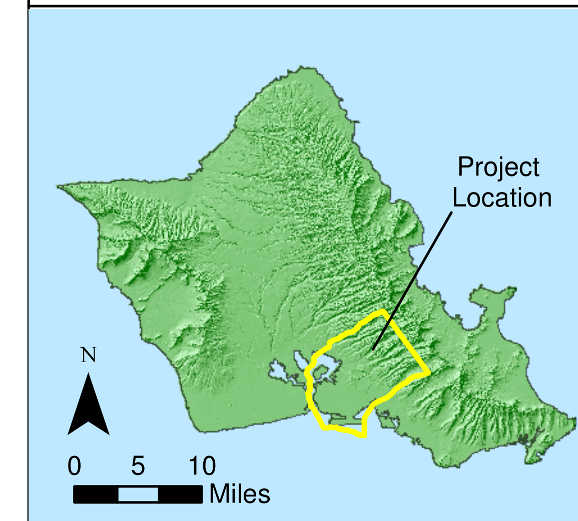

Legend

- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.15-1
Recharge (Model #17 & Model #18) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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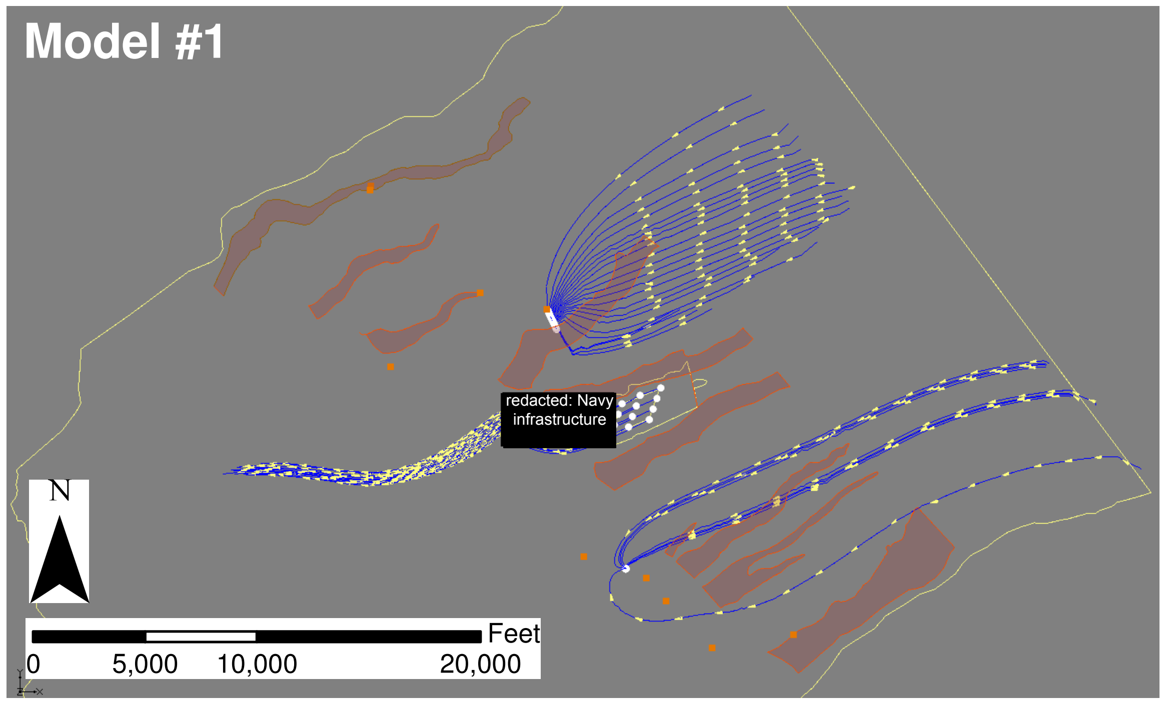
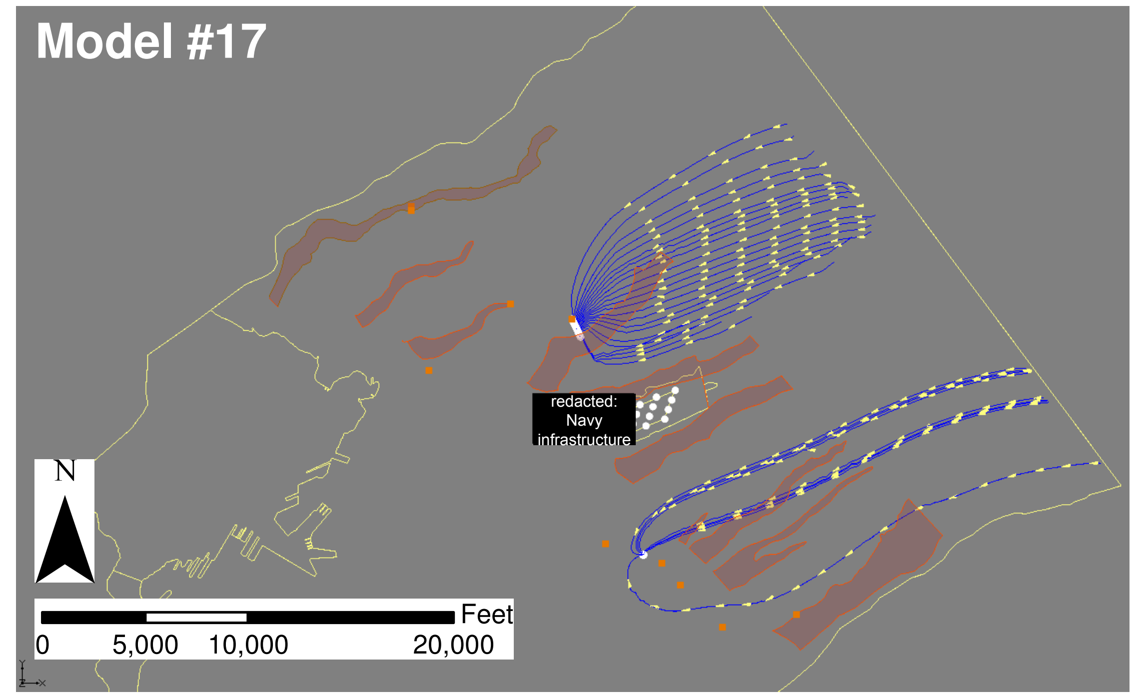
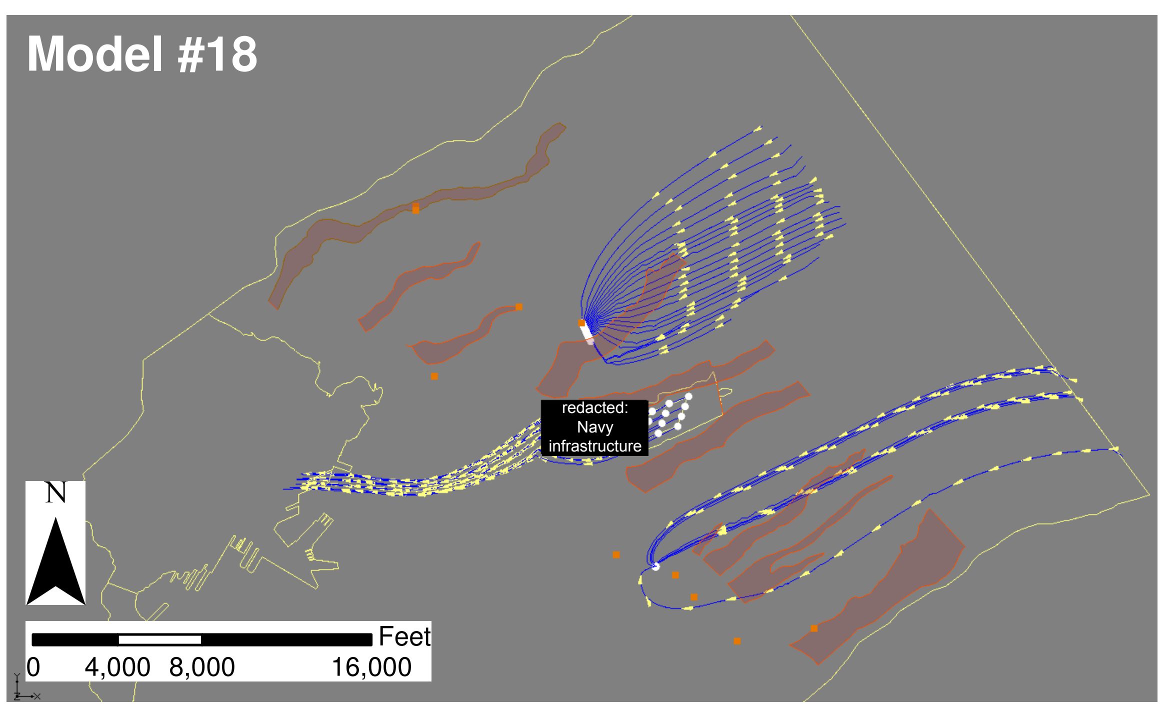
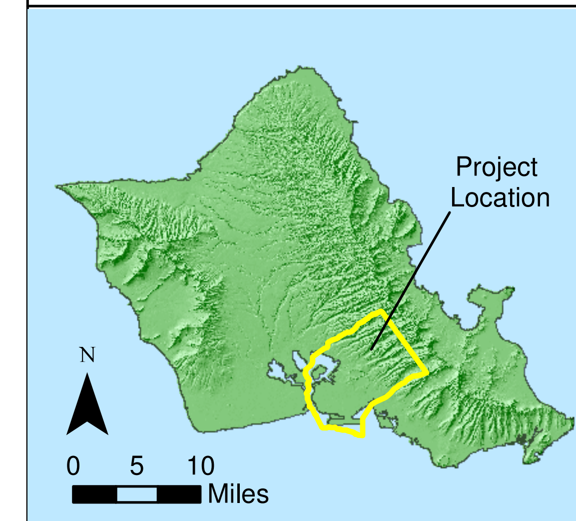






Location Map



Legend

- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.15-2
Recharge (Model #17 & Model #18) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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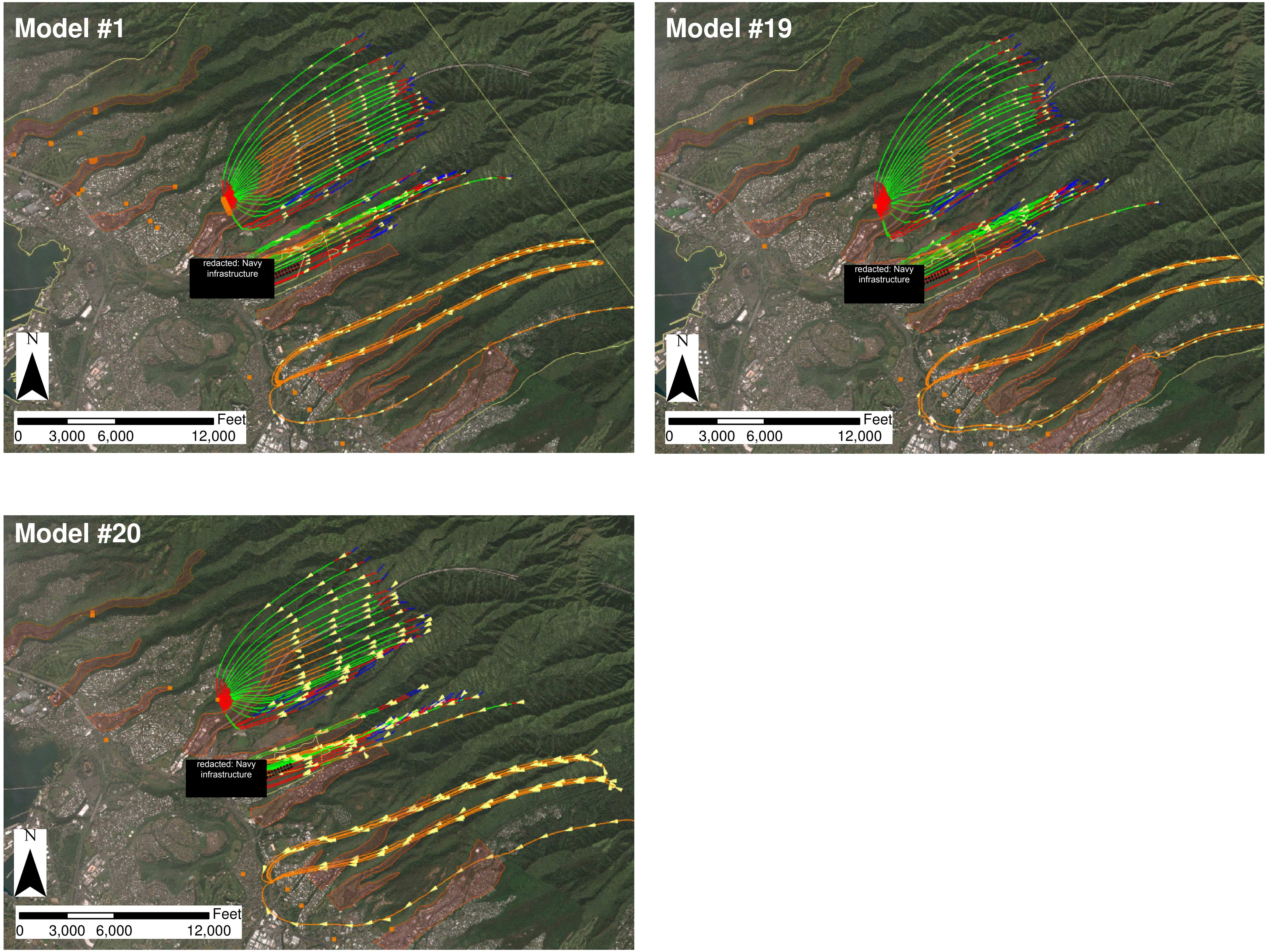
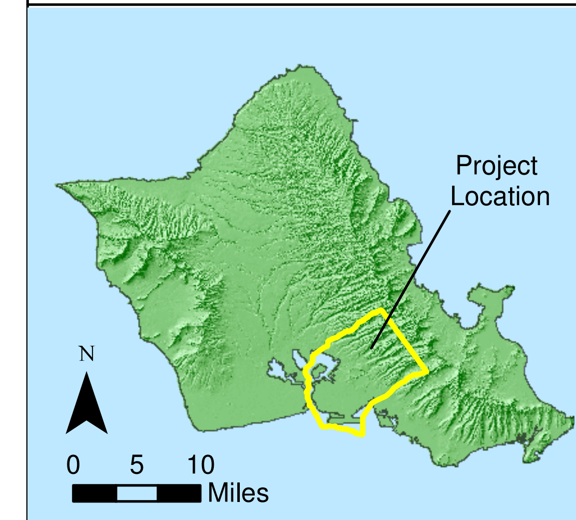


Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Particle

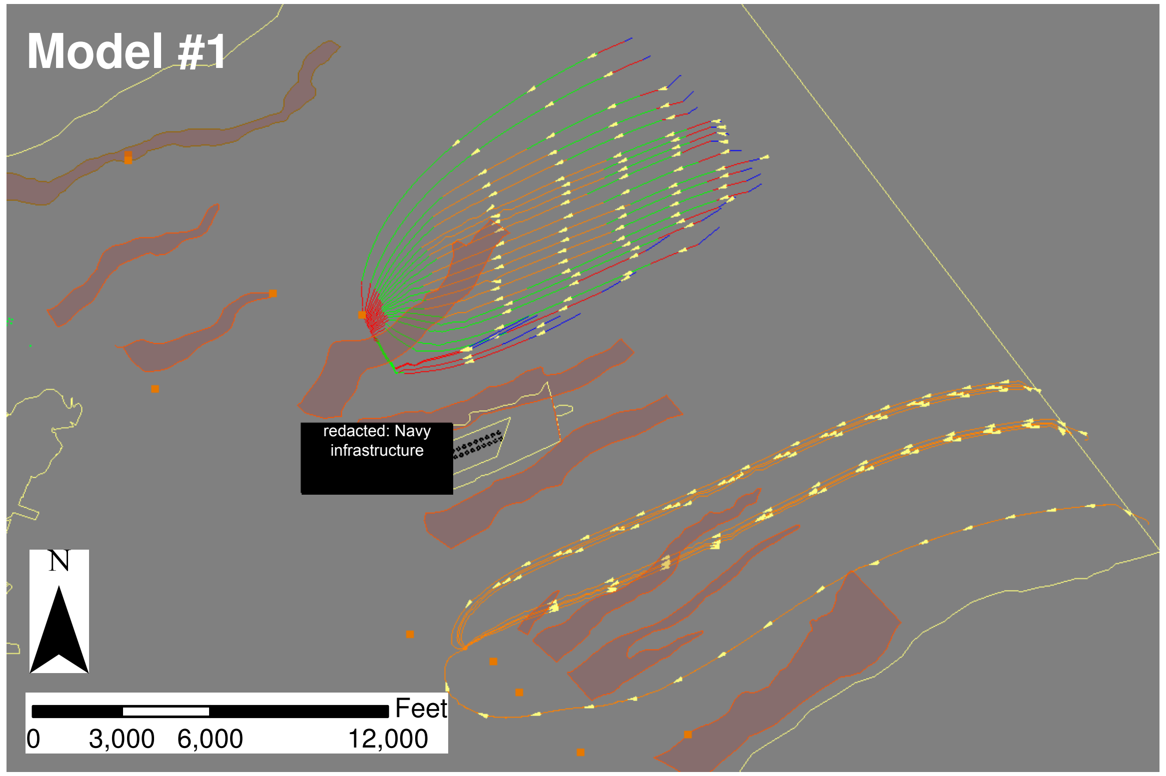
Red Hill Fuel Storage Tank

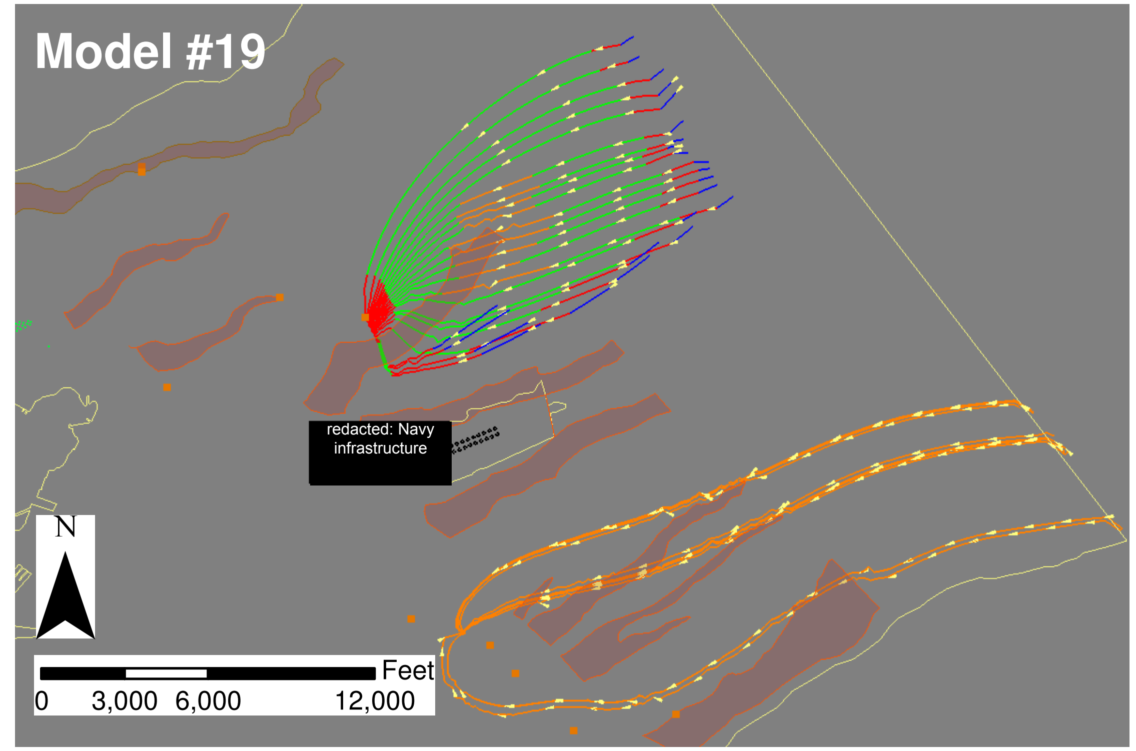
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

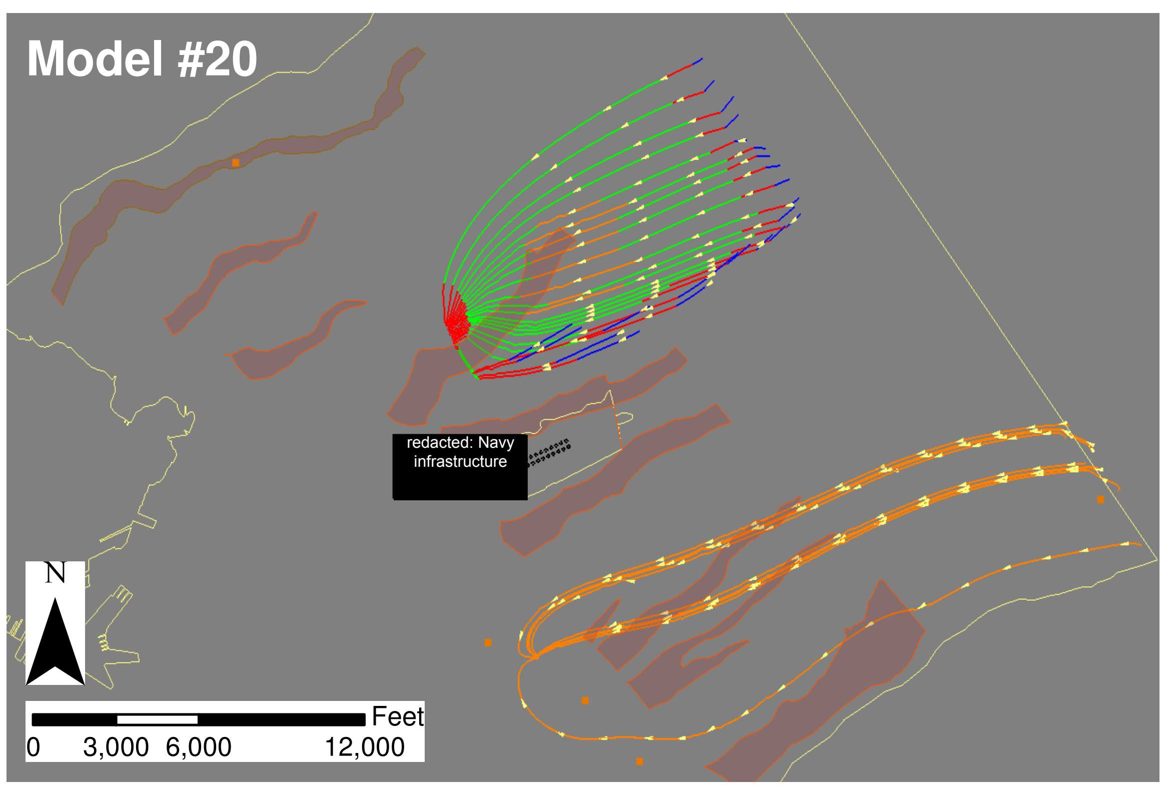
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

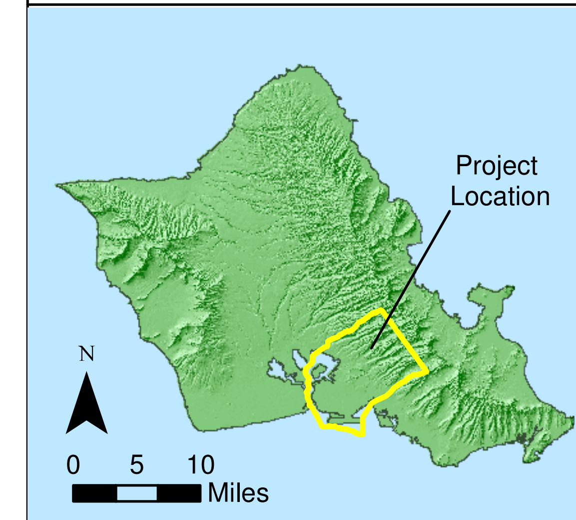
Figure 6.4.16-1
Basalt Horizontal Anisotropy (Model #19 & Model #20) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI







Location Map



Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Particle

Red Hill Fuel Storage Tank

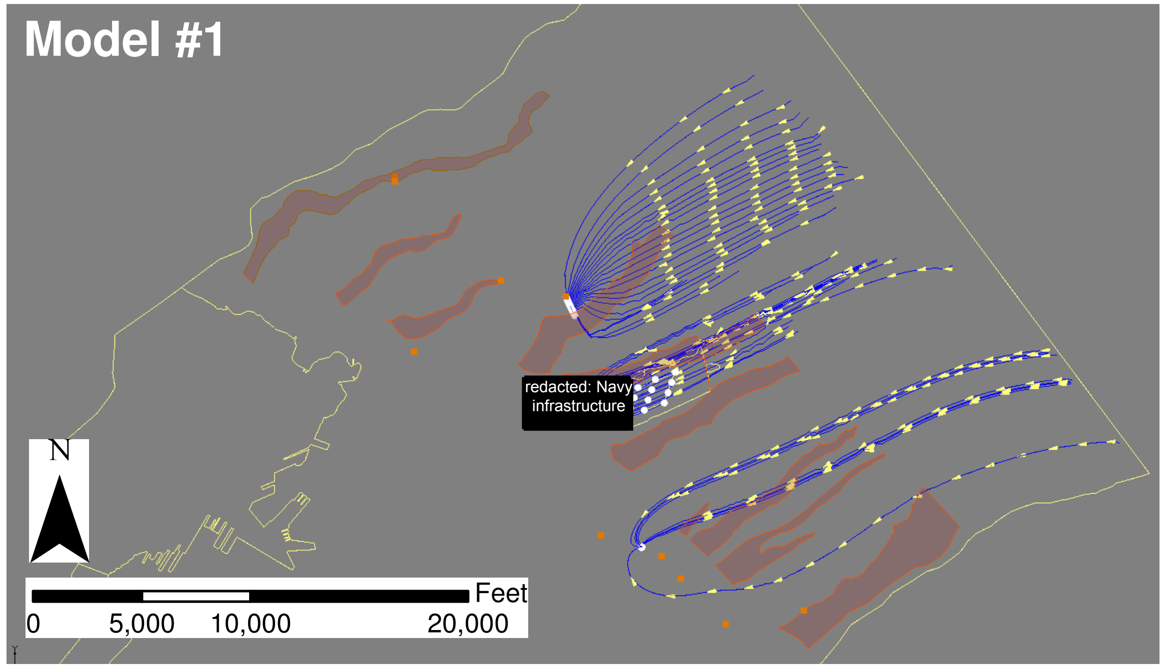
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

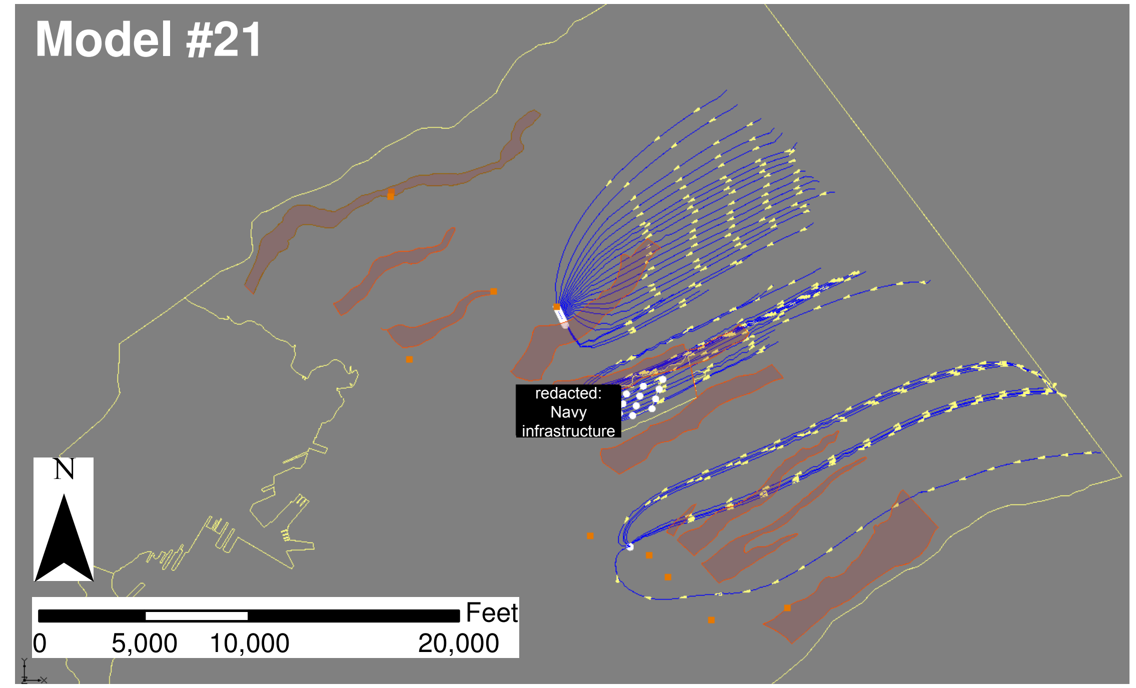
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.16-2
Basalt Horizontal Anisotropy (Model #19 & Model #20) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

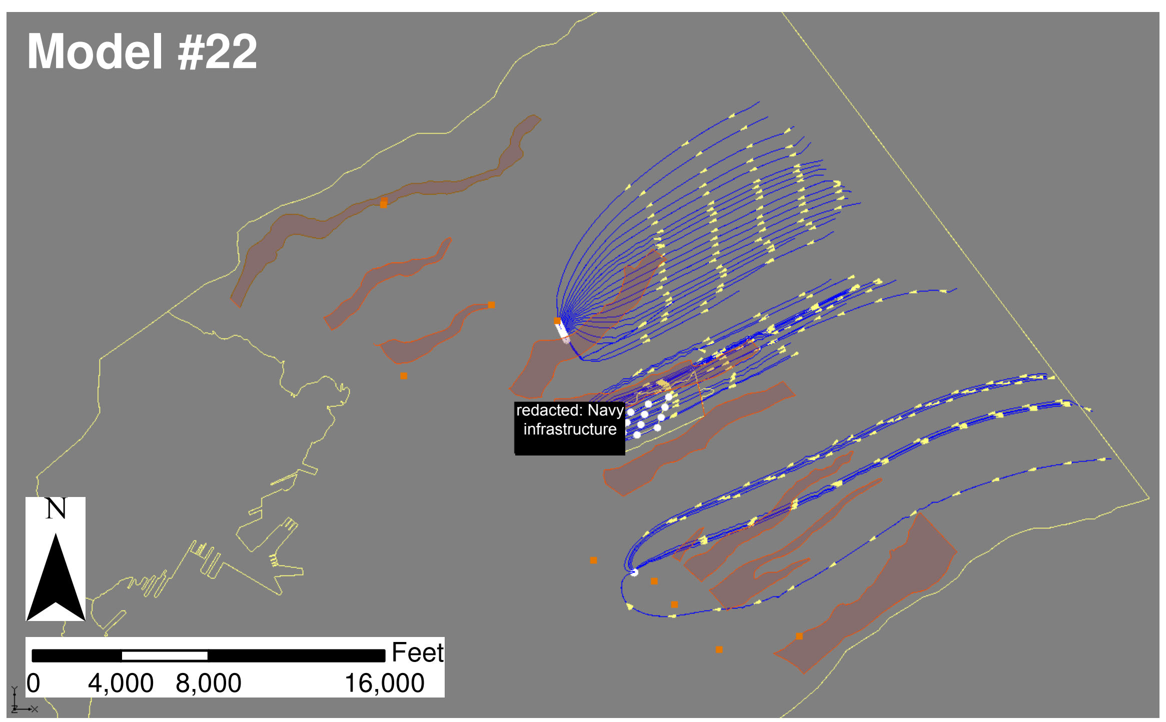
Model #1



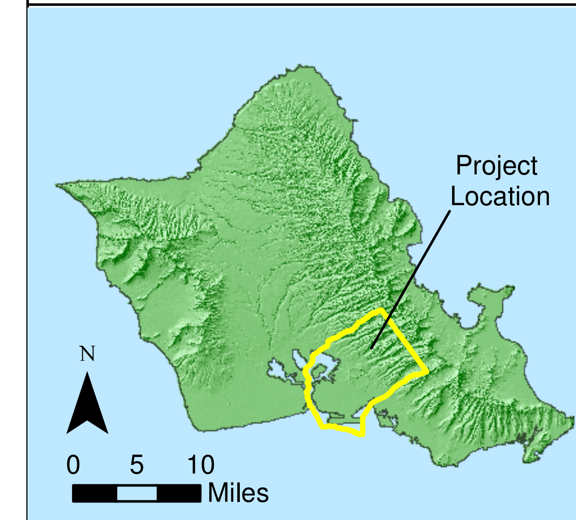
Model #21



Model #22



Location Map



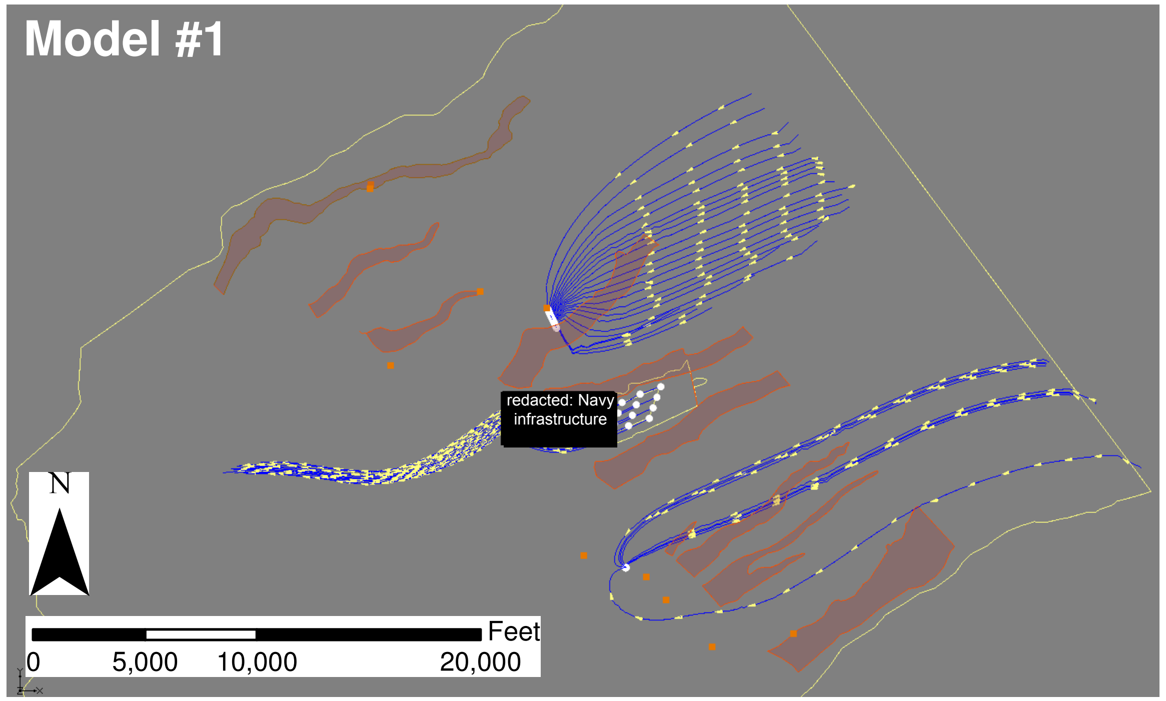
Legend

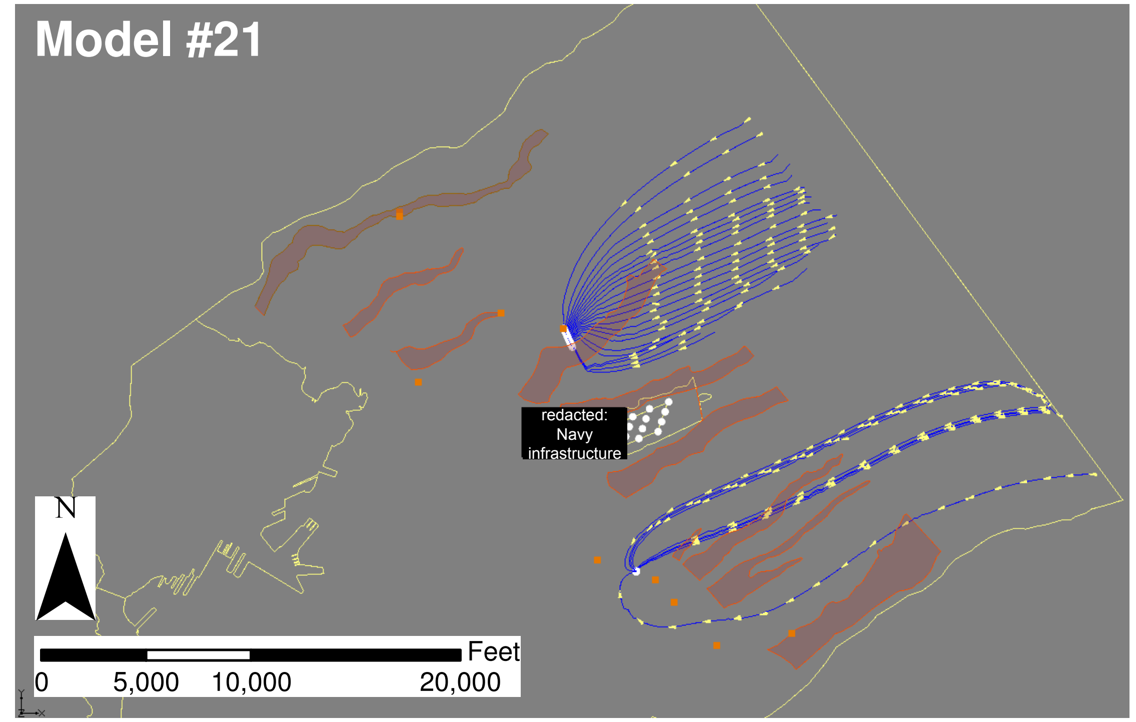
- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

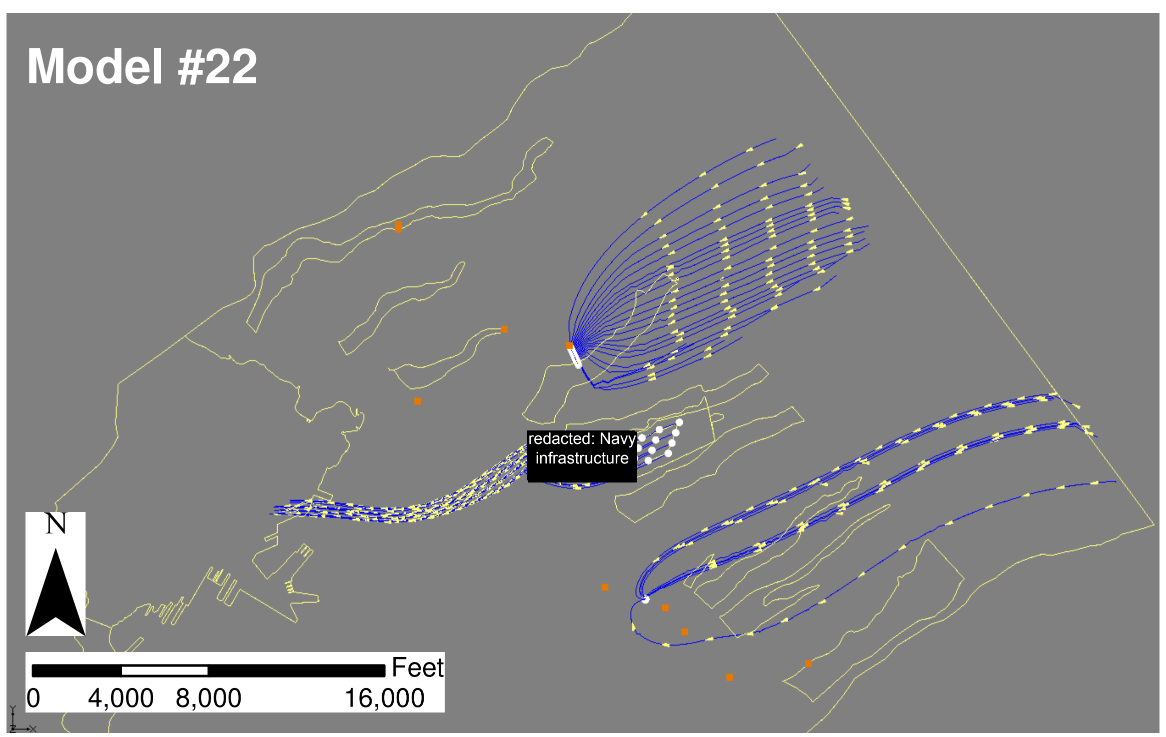
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.17-1
NE Boundary Inflow (Model #21 & Model #22) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI







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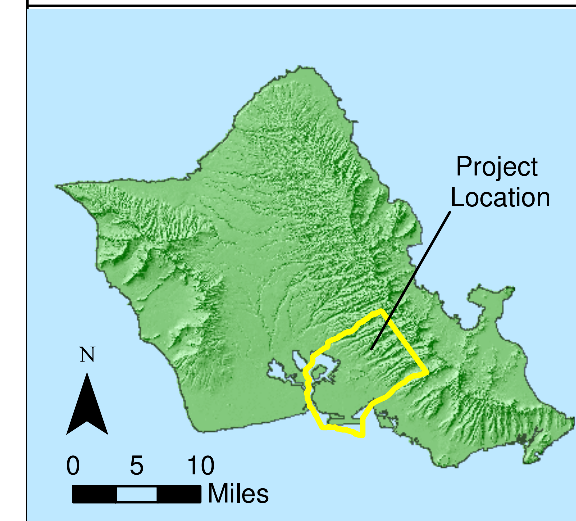

Legend

- Pathline
- 1-year Time Intervals
- Particle
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.17-2
NE Boundary Inflow (Model #21 & Model #22) - Source Water Zones for Red Hill Shaft
Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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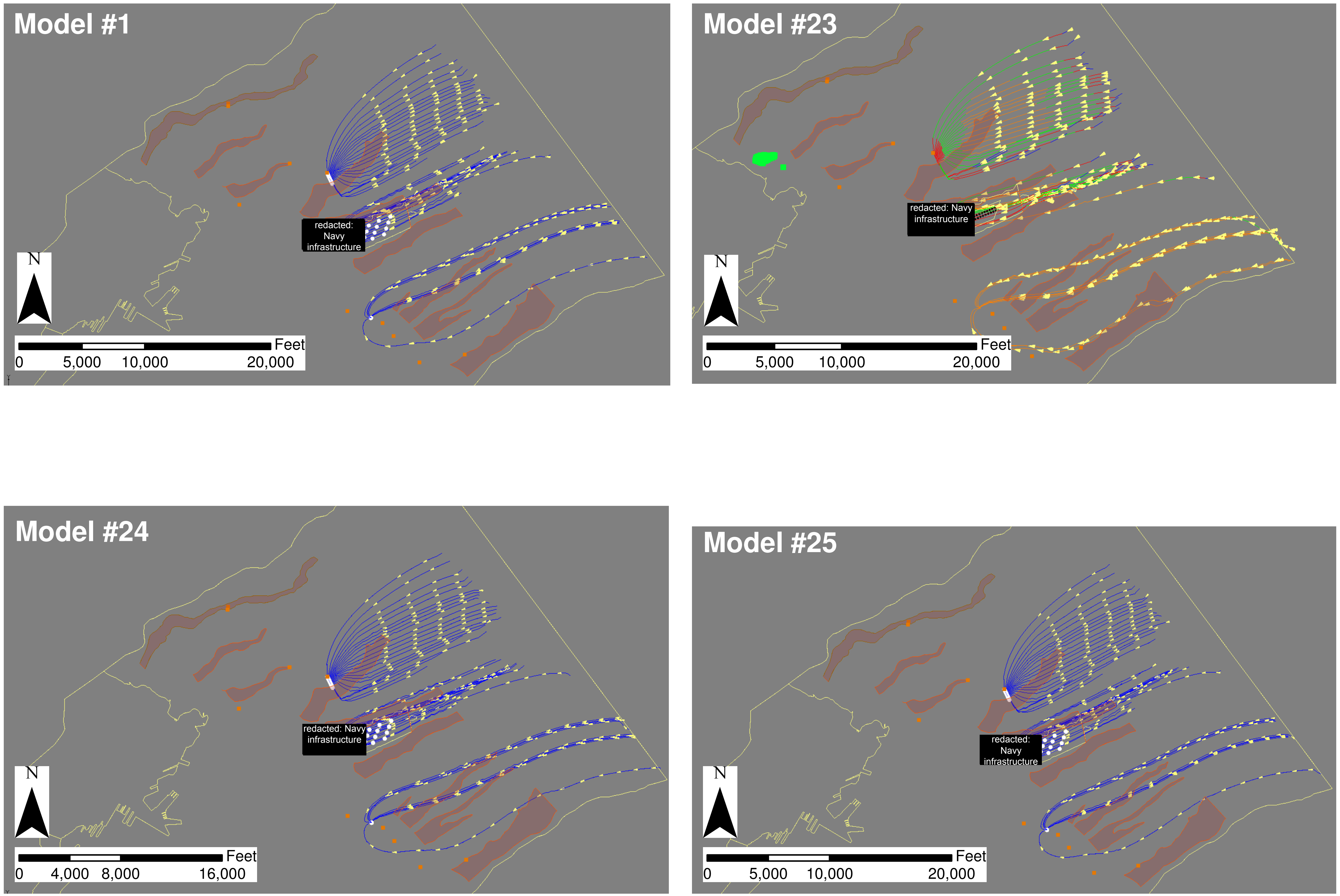
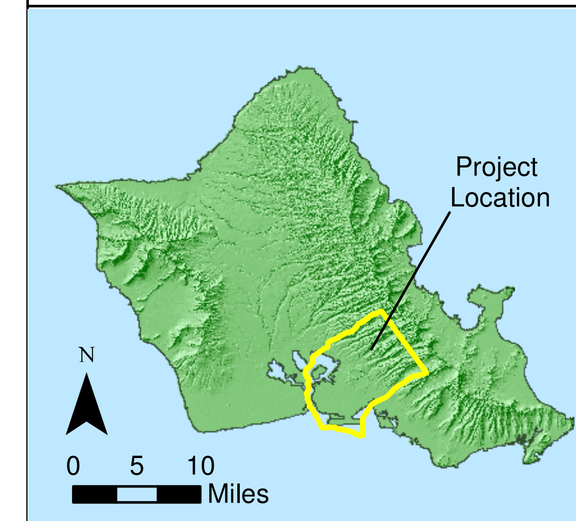


Location Map



Legend

Pathline Colors:

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- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Particle

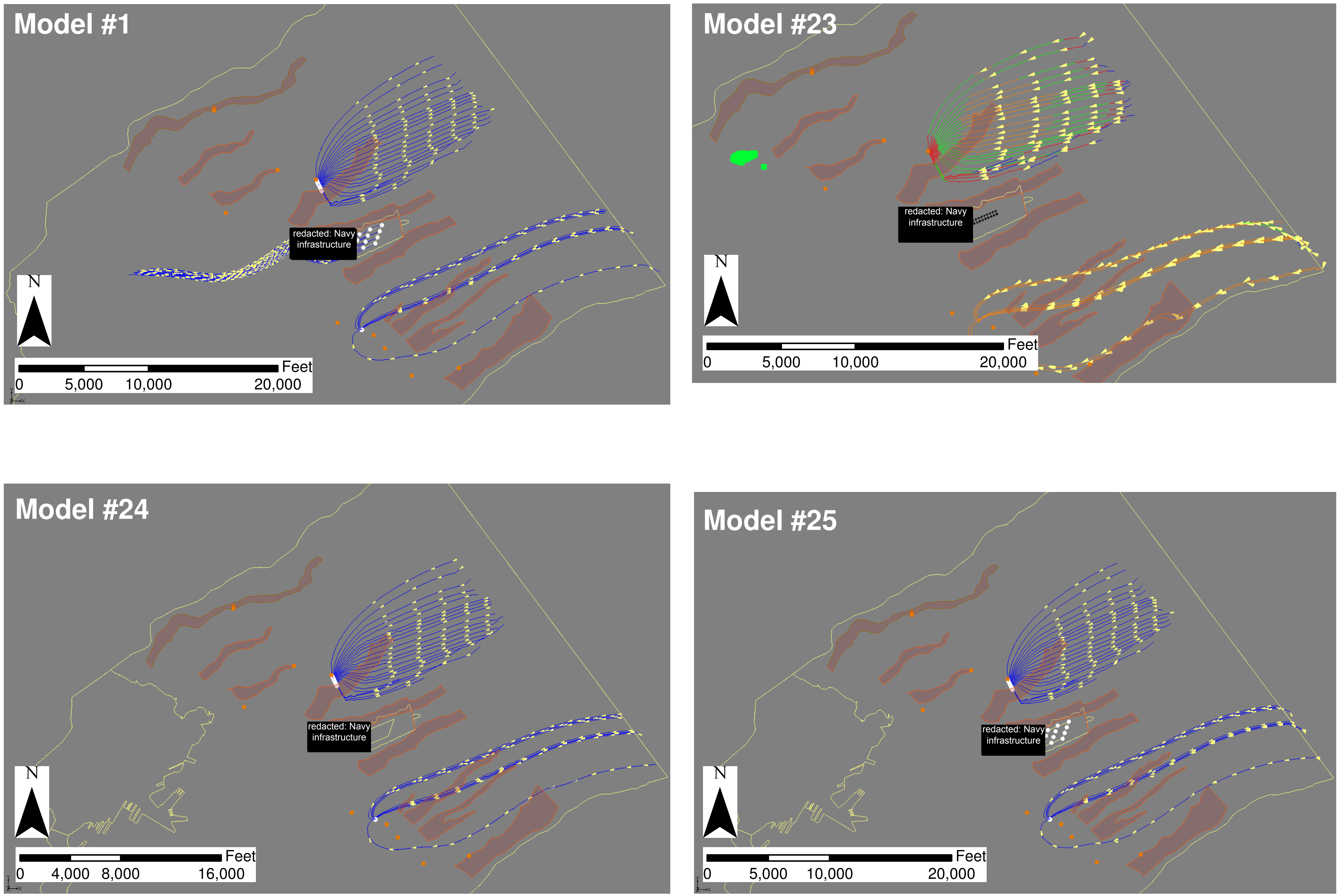
Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

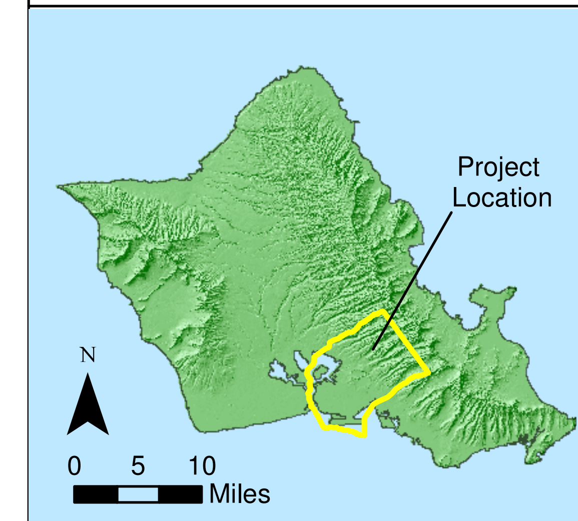
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.18-1
Kh of Caprock (Model #23, Model #24, & Model #25) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Particle

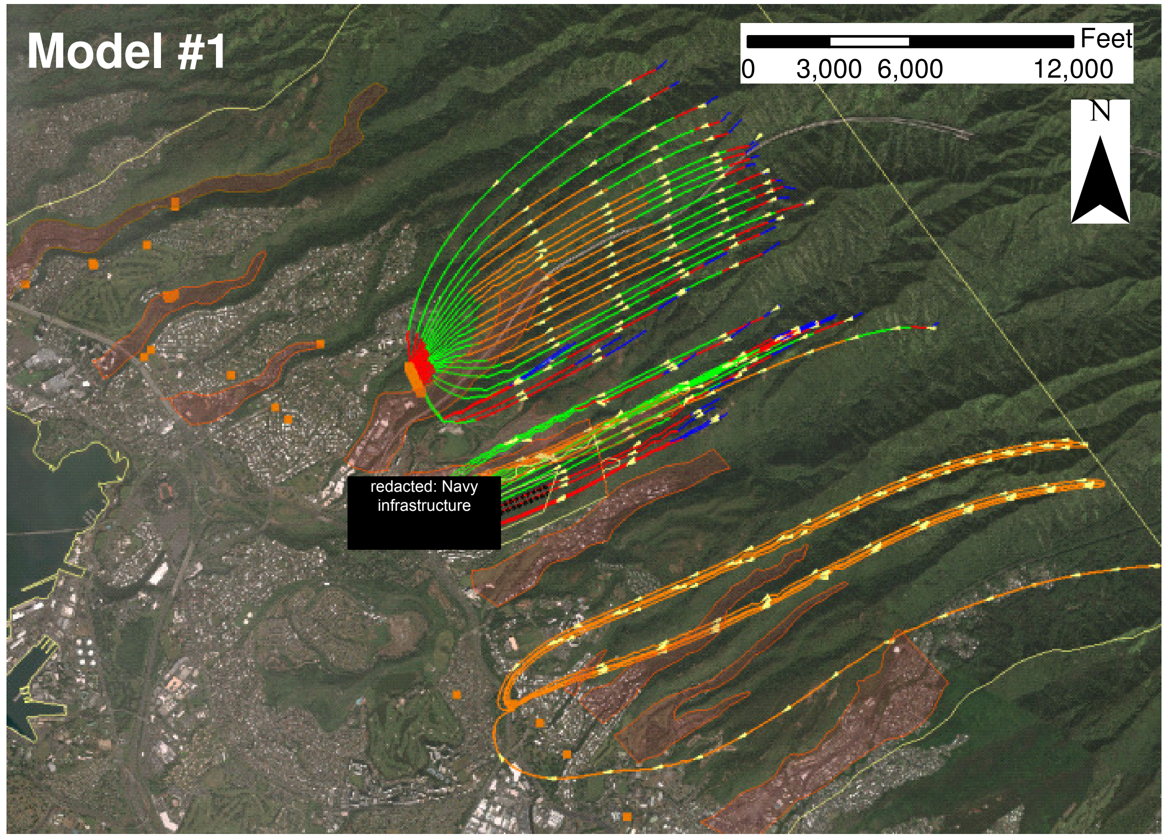
Red Hill Fuel Storage Tank

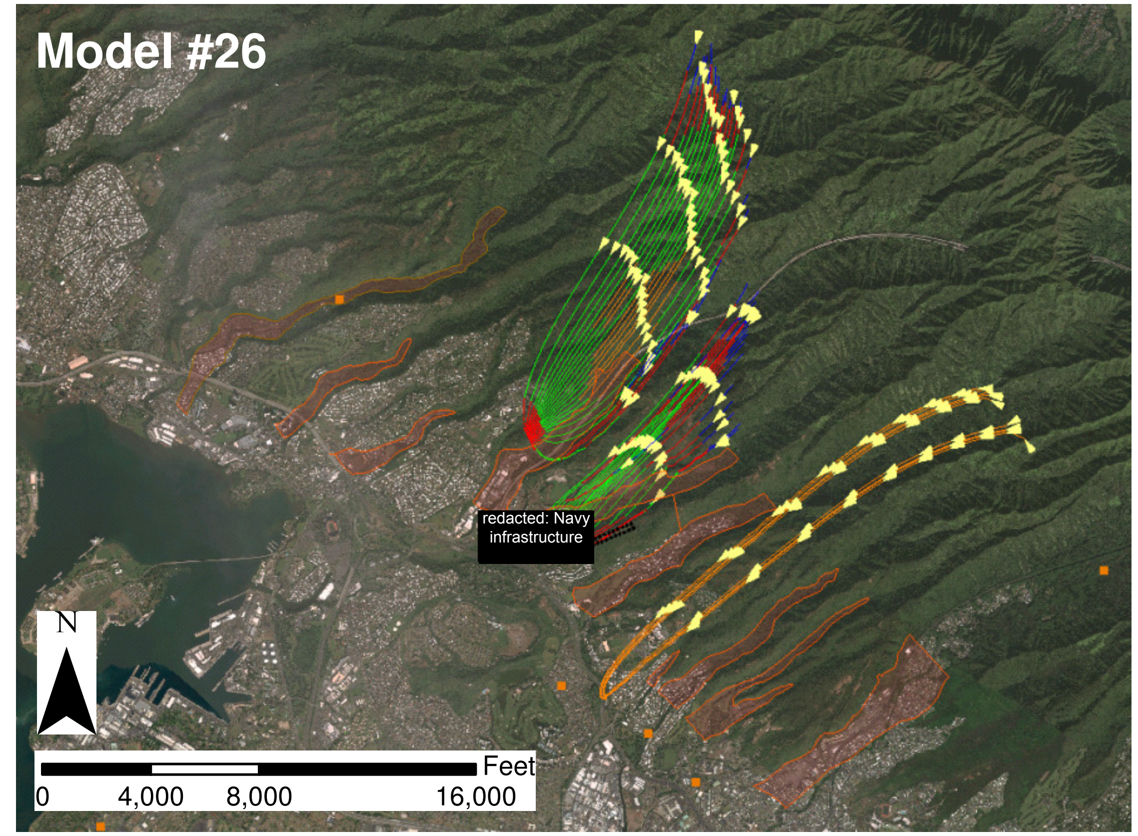
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

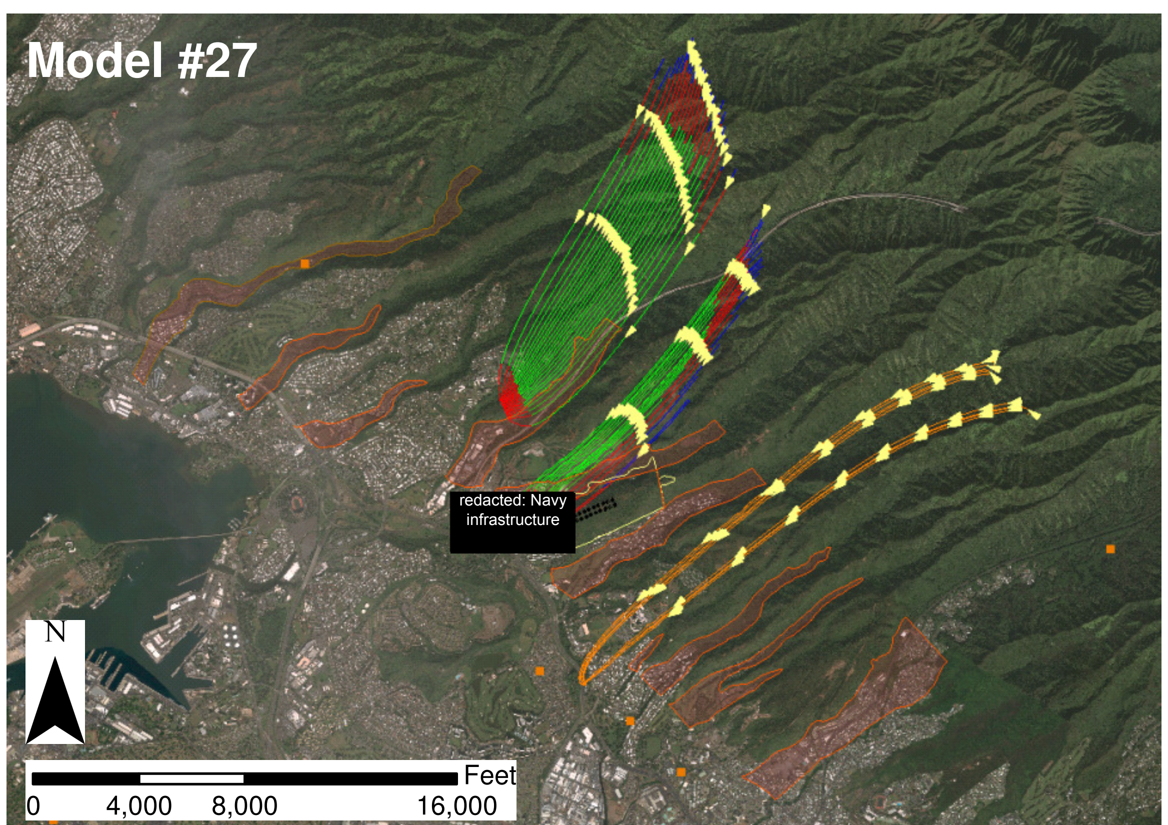
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.18-2
Kh of Caprock (Model #23, Model #24, & Model #25) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI







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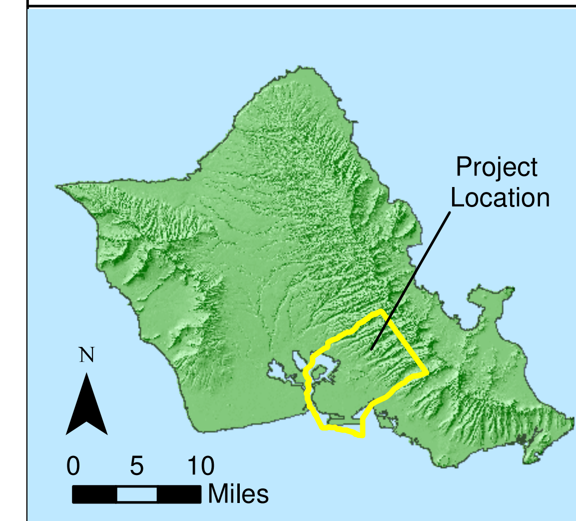


Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

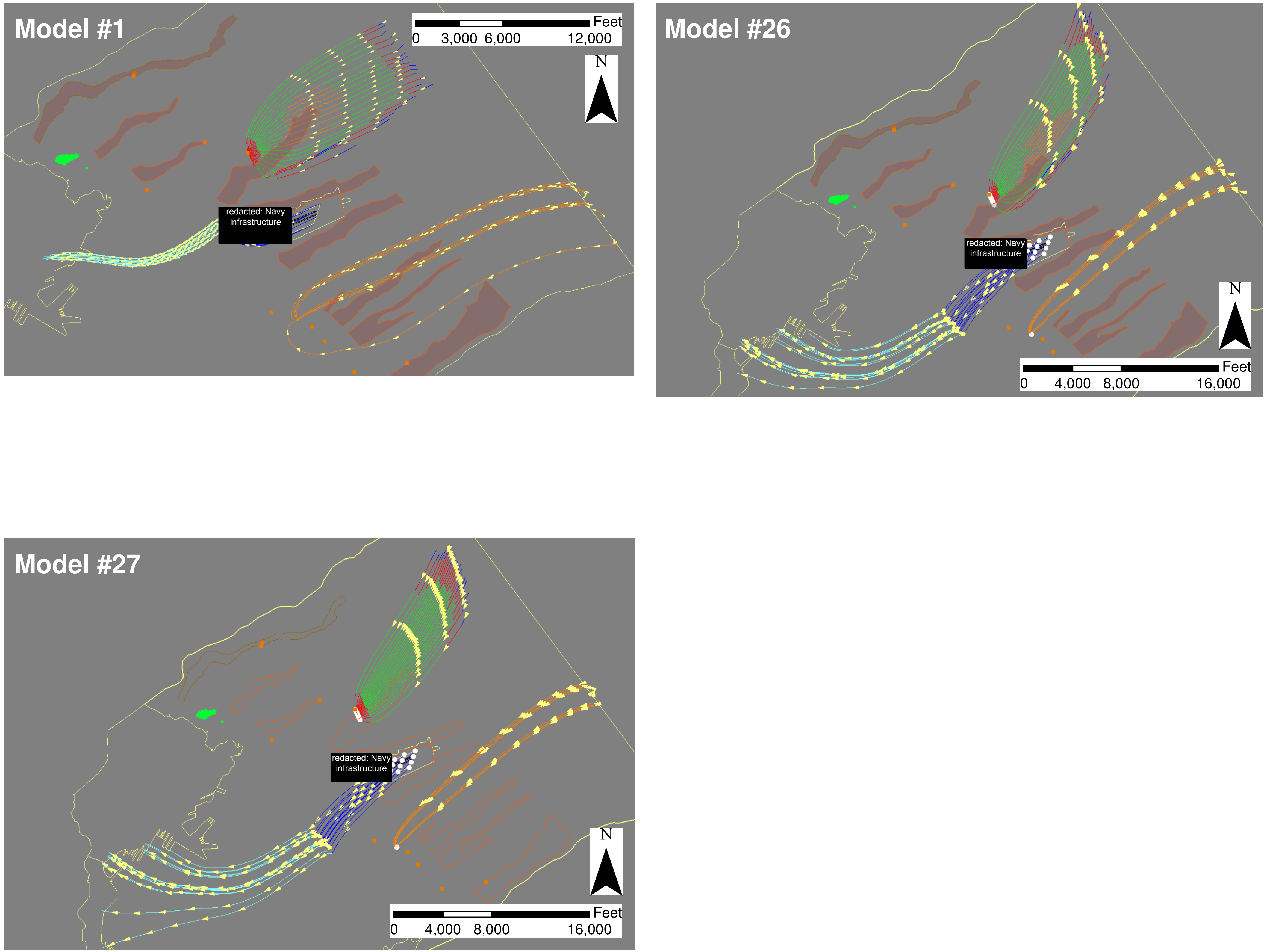
Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.19-1
Zonation of Caprock (Model #26 & #27) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



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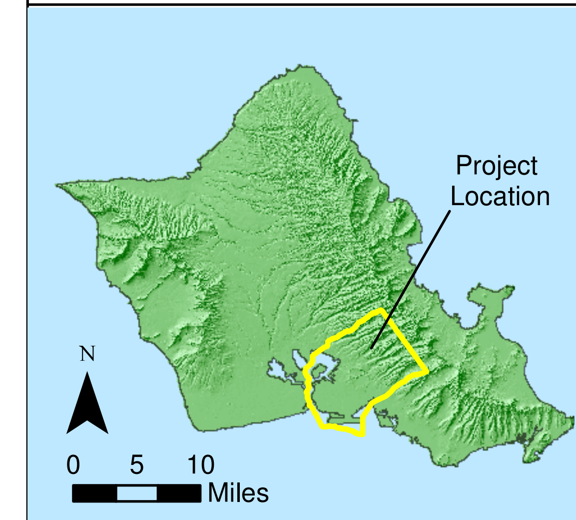


Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

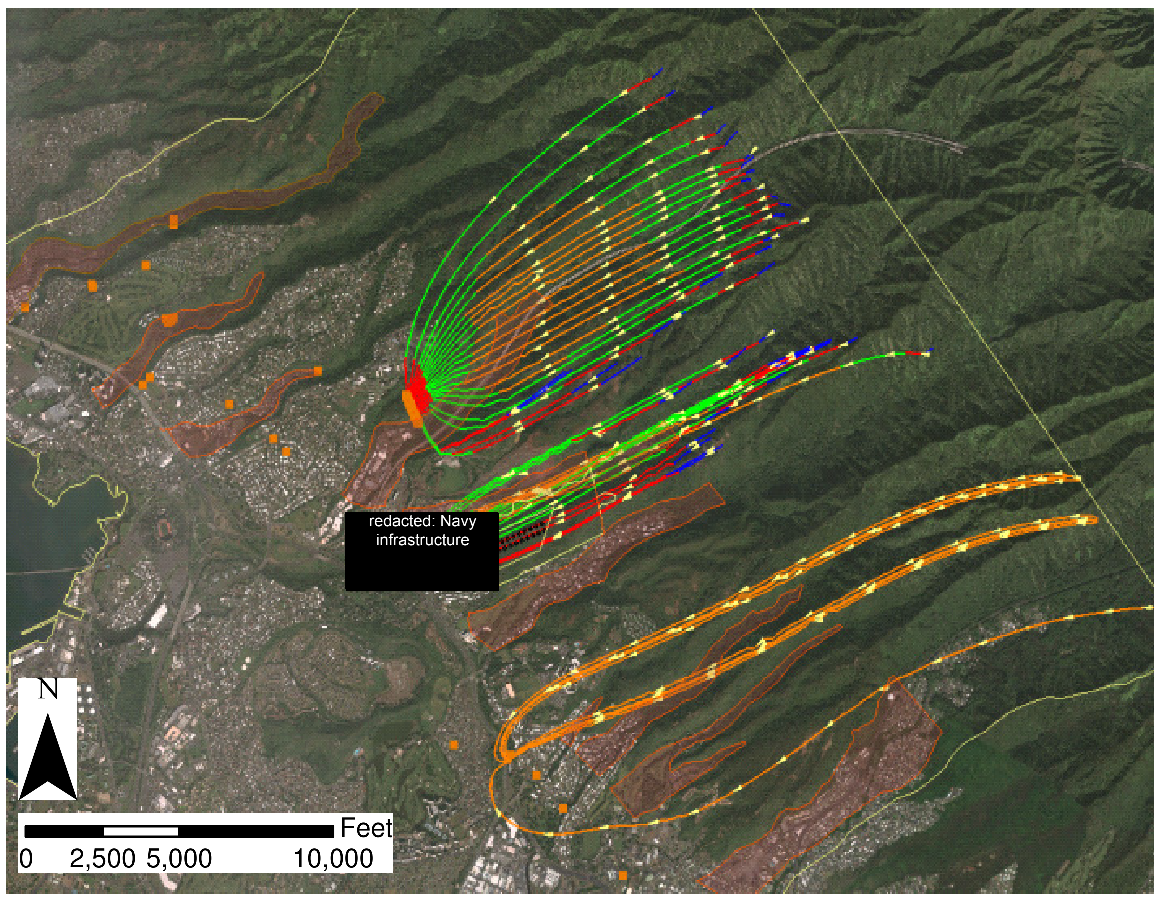
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

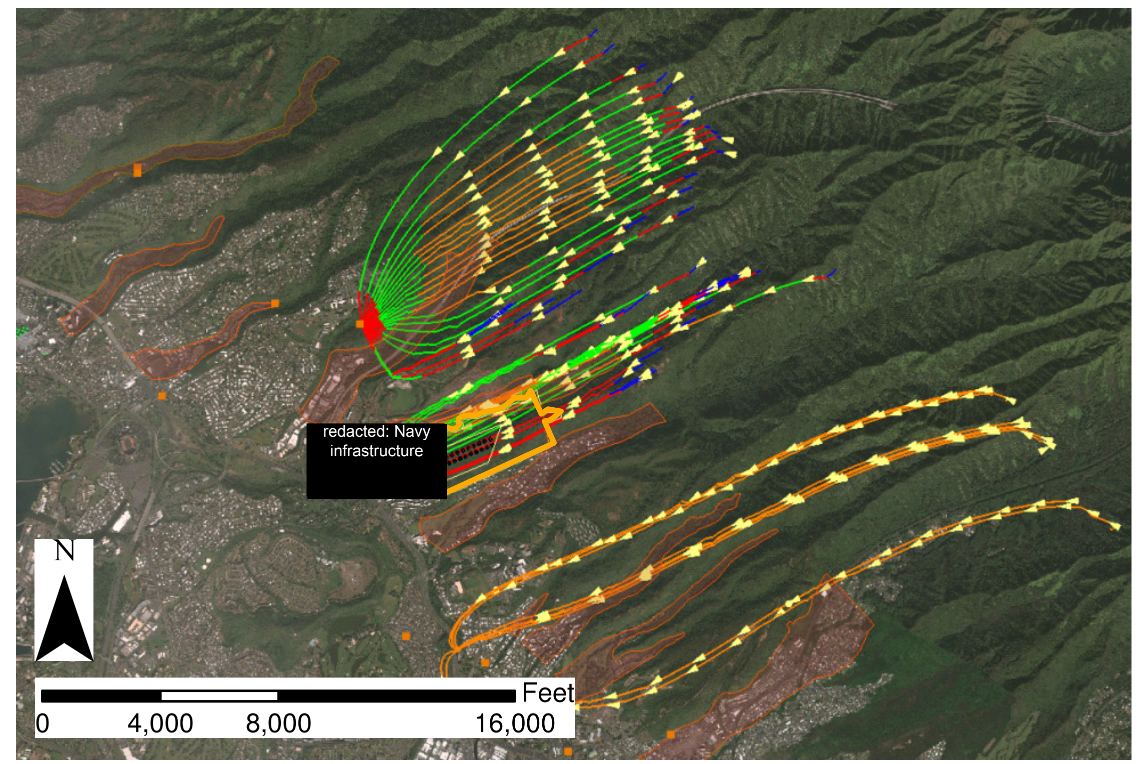
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.19-2
Zonation of Caprock (Model #26 & #27) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

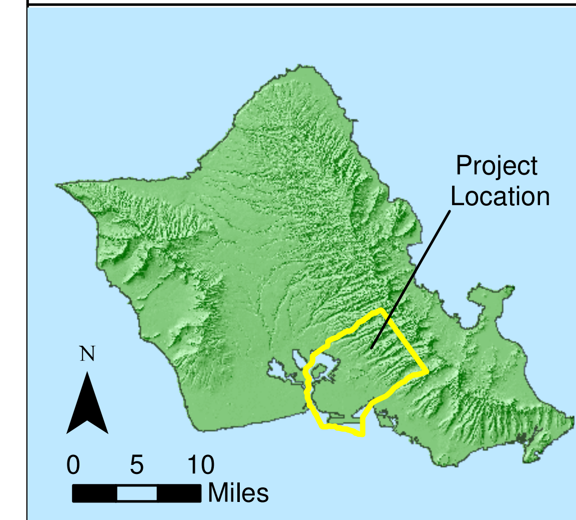
Model #1



Model #28



Location Map



Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

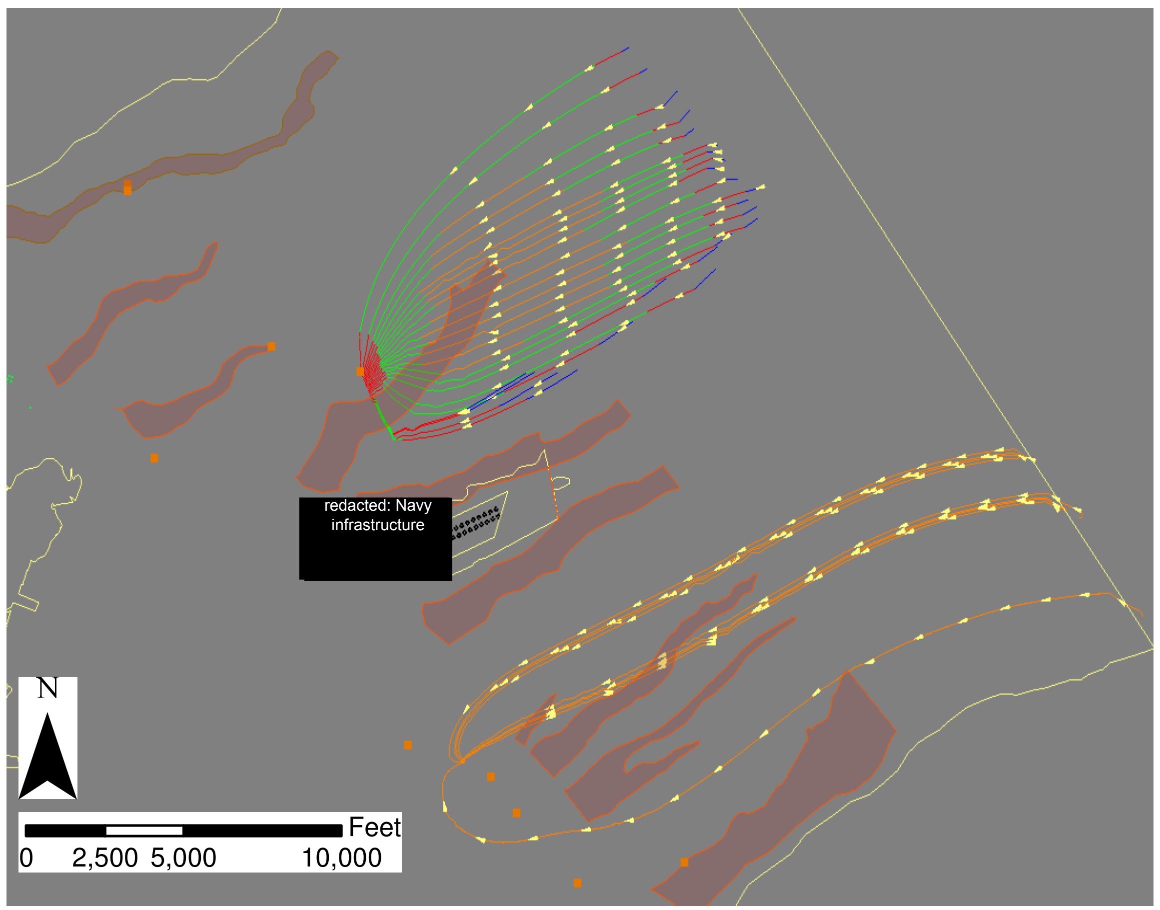
- 1-year Time Intervals
- Red Hill Fuel Storage Tank
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

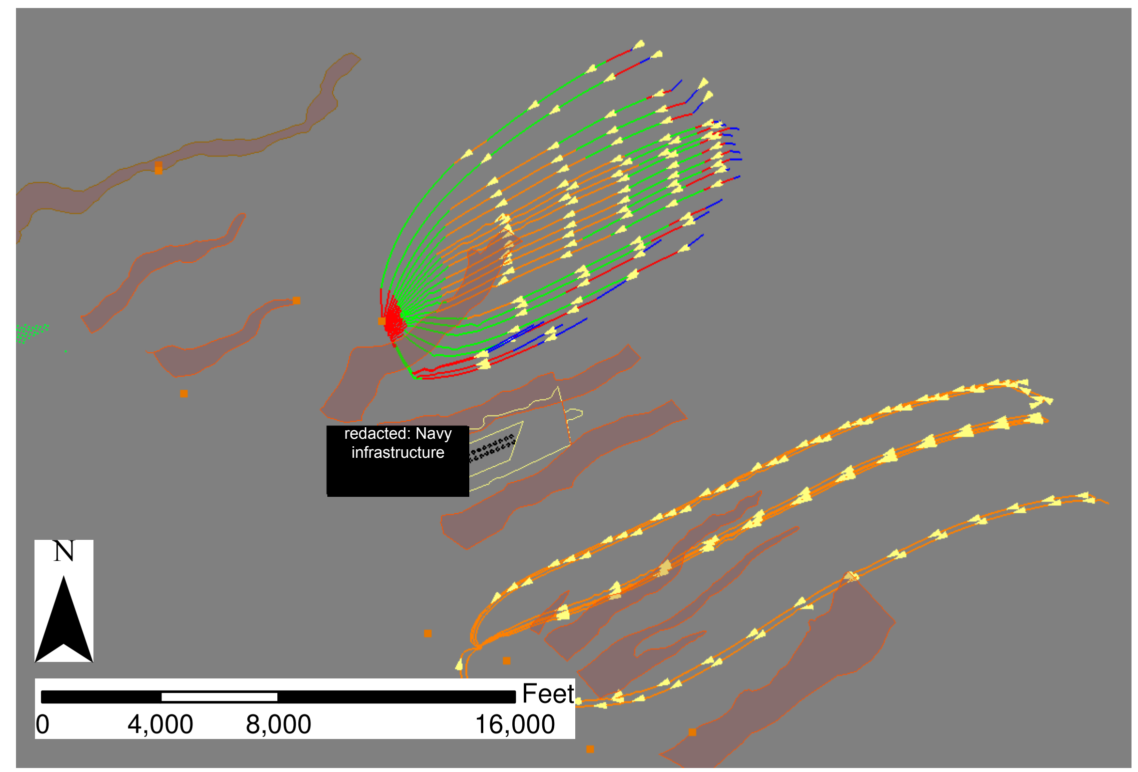
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.20-1
Model Bottom Elevation (Model #28) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

Model #1



Model #28



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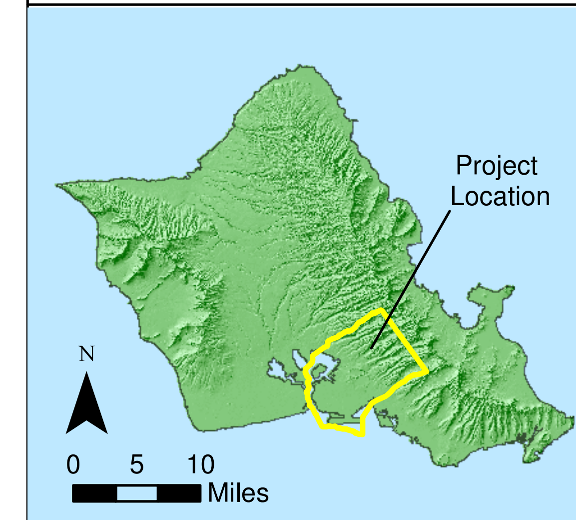


Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

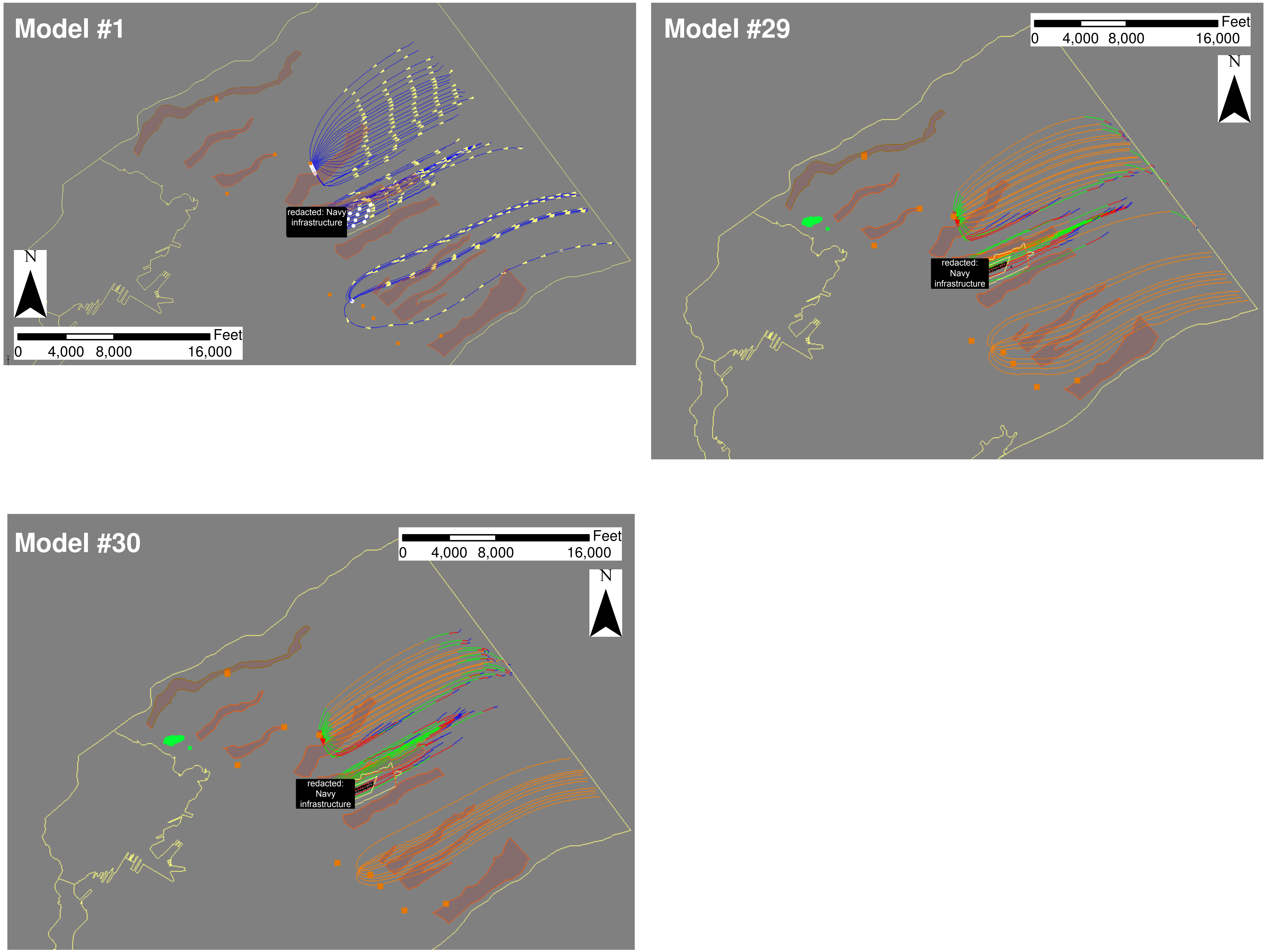
Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

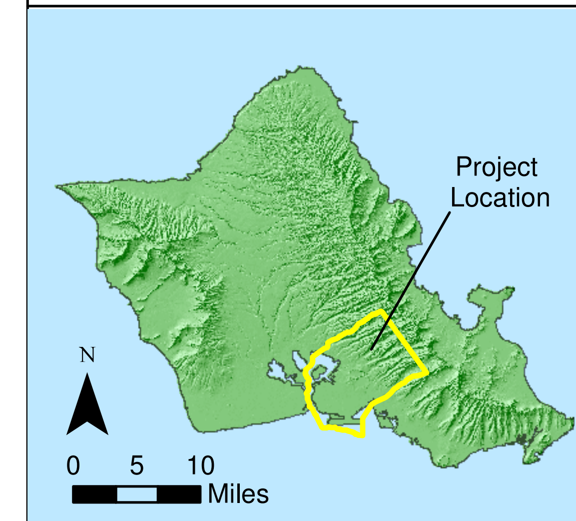
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.20-2
Model Bottom Elevation (Model #28) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.21-1
Combined Recharge and Northeast Boundary Inflow (Model #29 & Model #30) - Source Water Zones for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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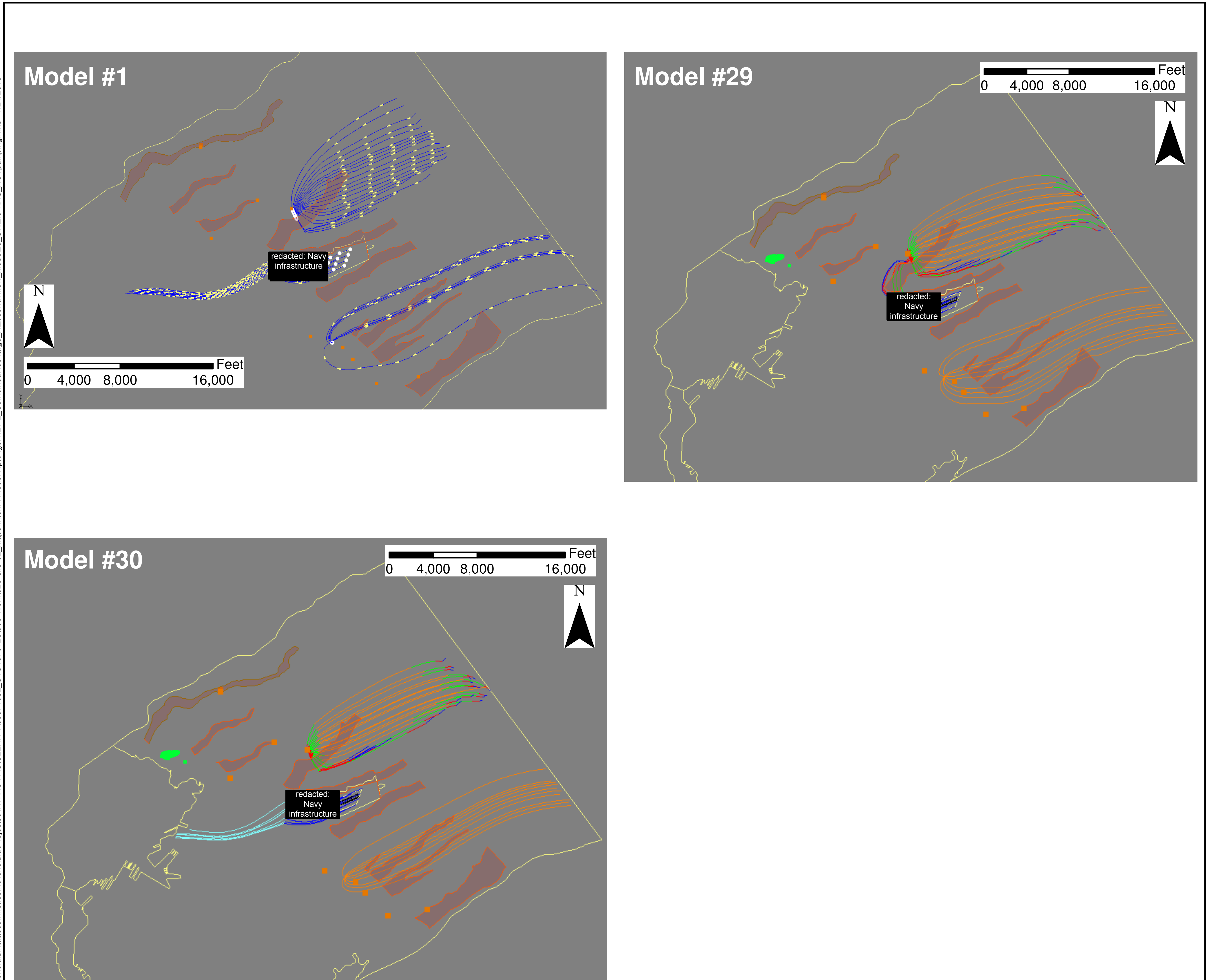
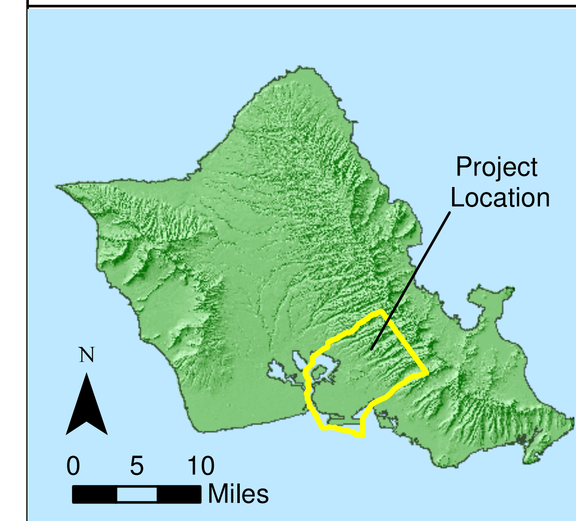


Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

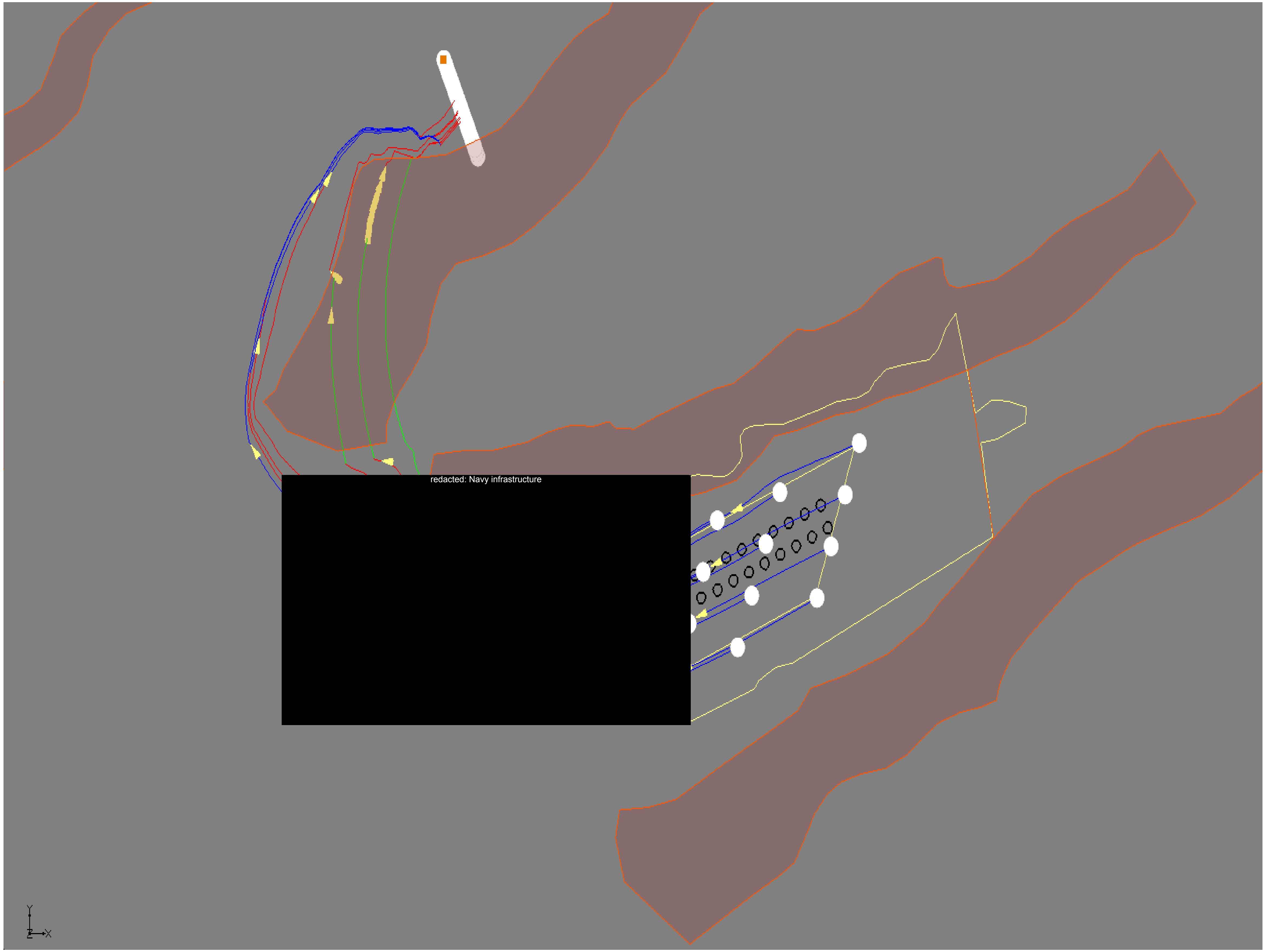
Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.4.21-2
Combined Recharge and Northeast Boundary Inflow (Model #29 & Model #30) - Source Water Zones for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



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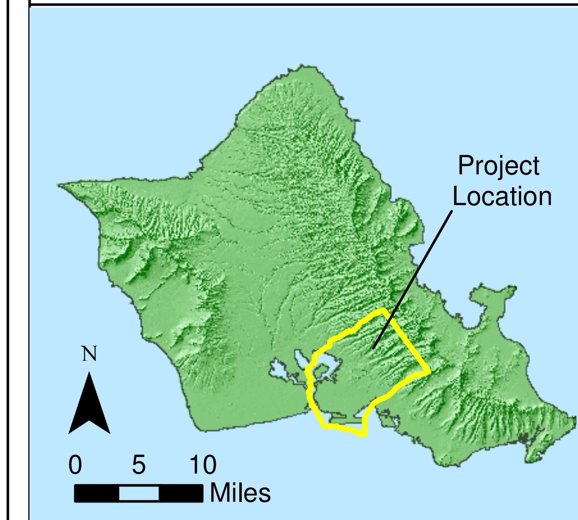
Location Map



Legend

- Particles
- 1-year Time Intervals
- Layer 2 Pathlines
- Red Hill Fuel Storage Tank
- Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Particles are released at water tabel within the source water zones.
4. Layer 2 foward particle tracks.

N

0 500 1,000 2,000 Feet

Figure 6.4.21-3
Combined Recharge and Northeast Boundary Inflow(Model #29) - Source Water Zones for Red Hill Shaft Not Pumping Scenario: Zoom in at Red Hill
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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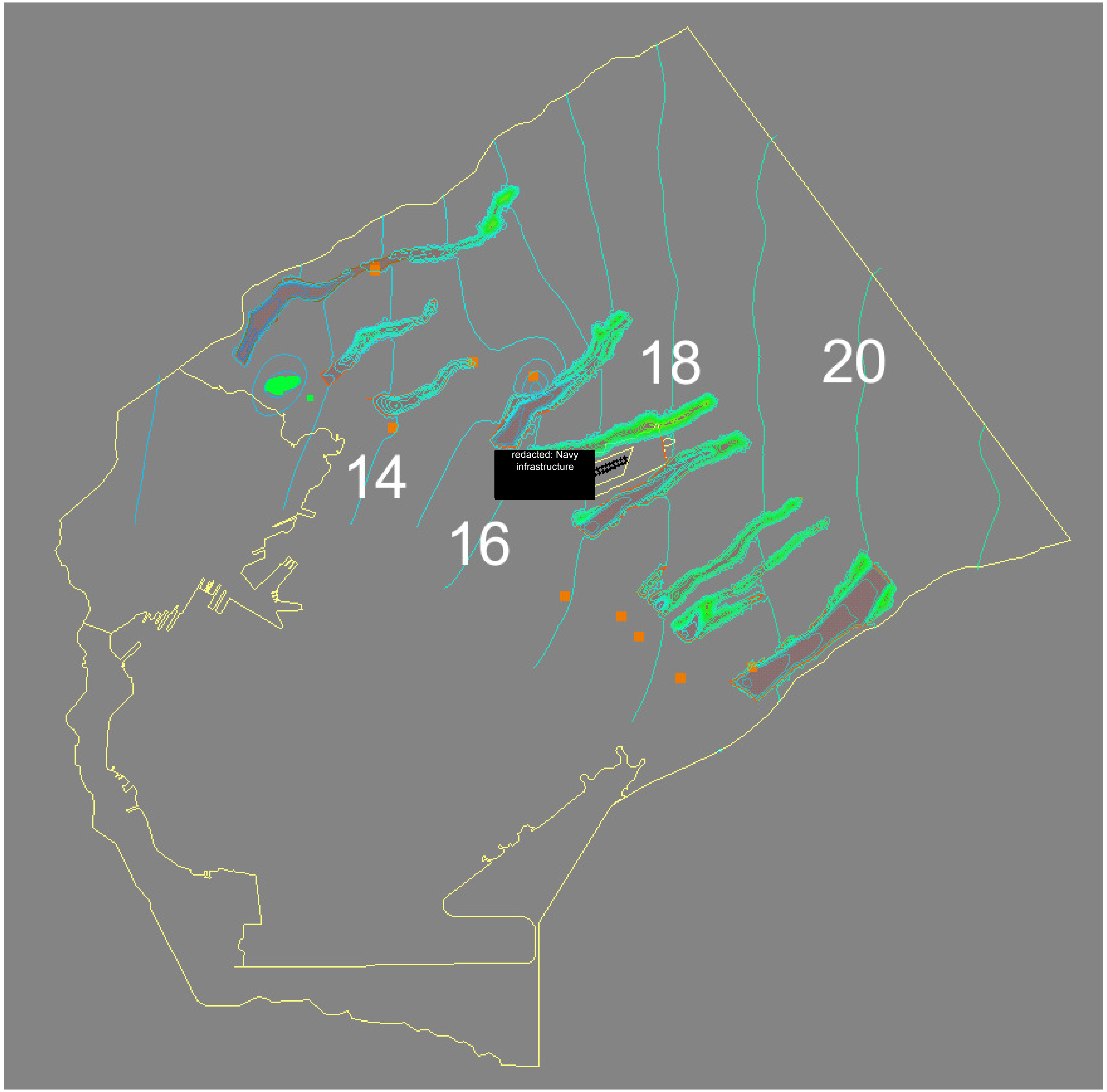
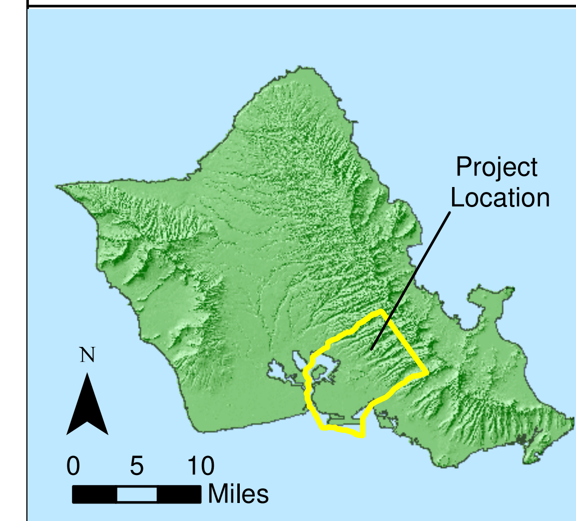


Location Map



Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

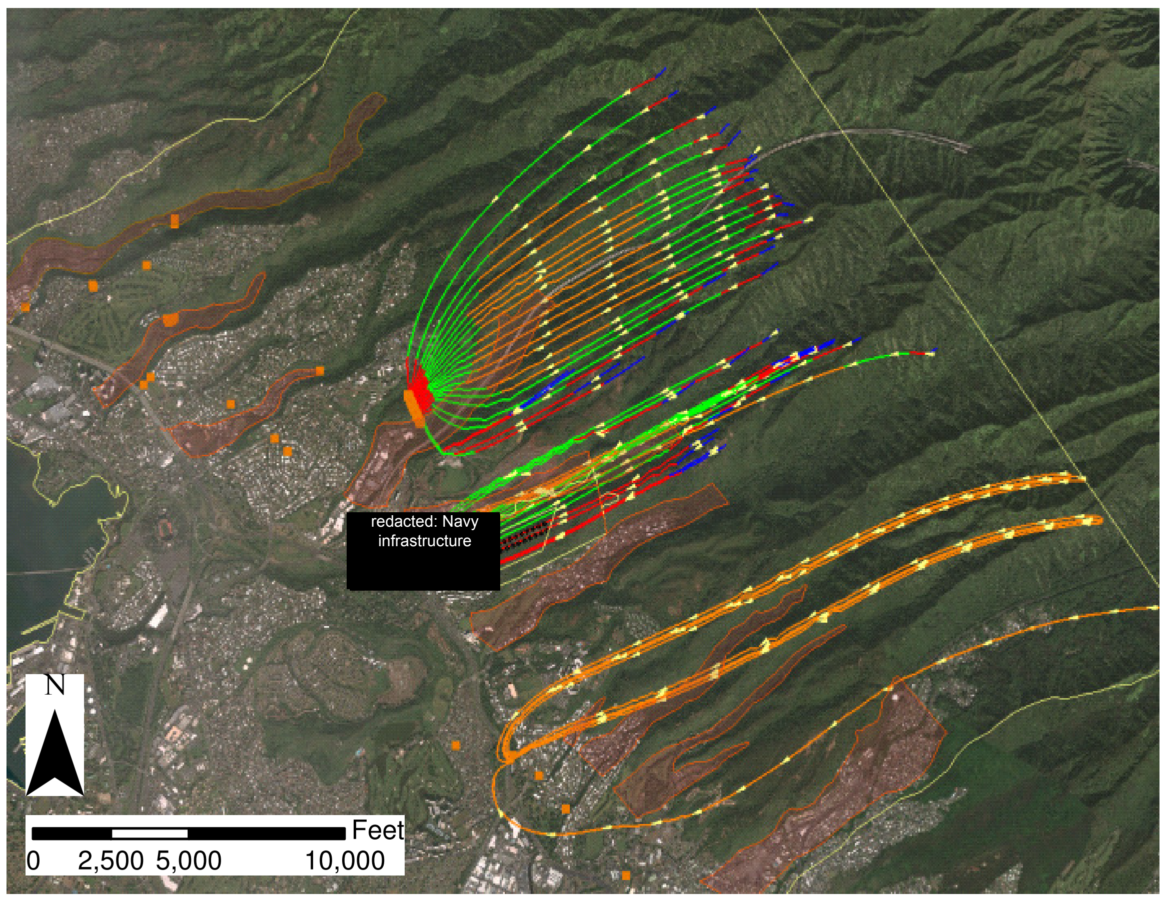
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are in feet above mean sea level.

N

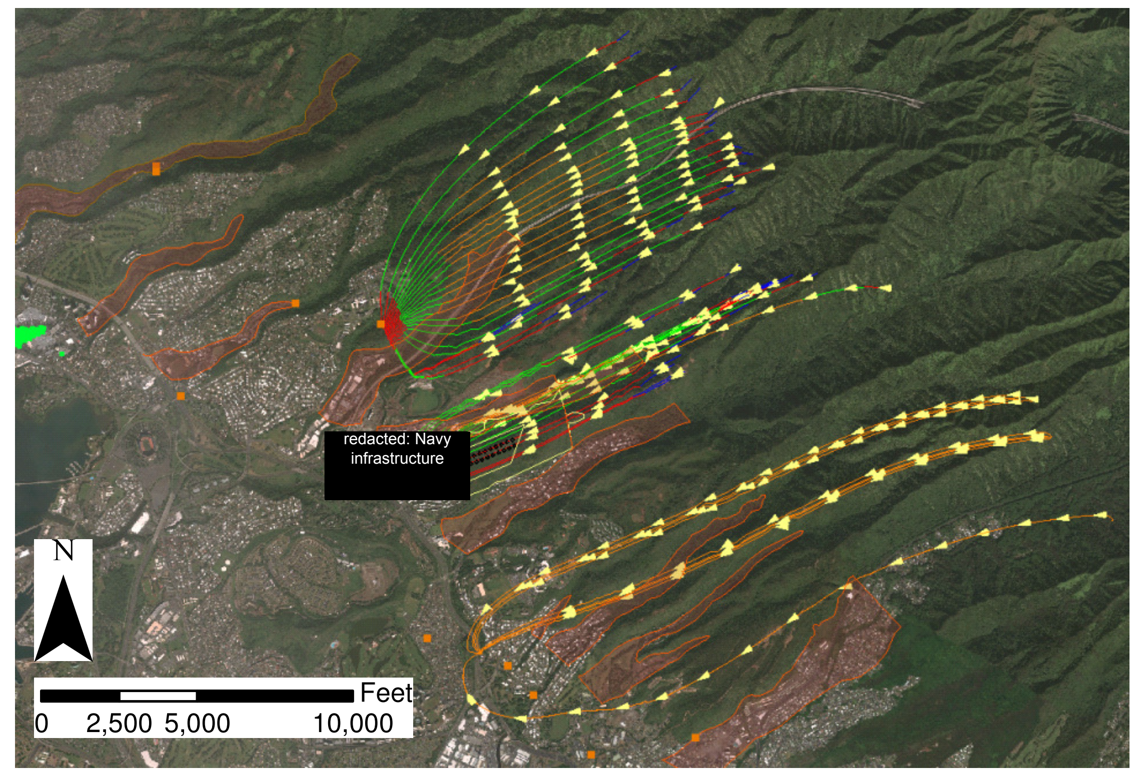
0 4,000 8,000 16,000 Feet

Figure 6.4.21-4
Combined Recharge and Northeast Boundary Inflow (Model #29) - Water Level Contours in Model Layer 2 for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

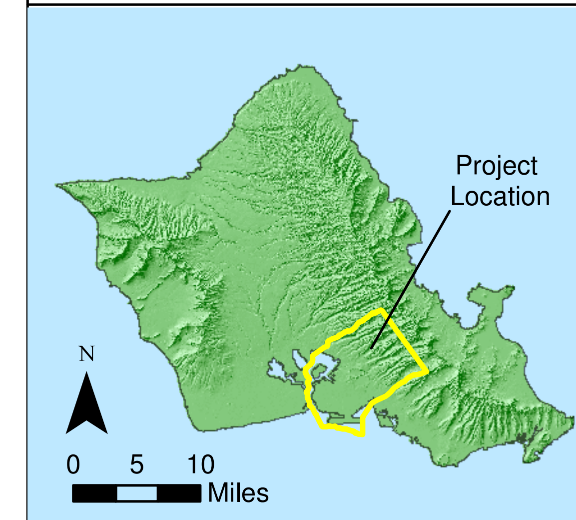
Model #1



Model #31



Location Map



Legend

Pathline Colors:

- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

1-year Time Intervals

Red Hill Fuel Storage Tank

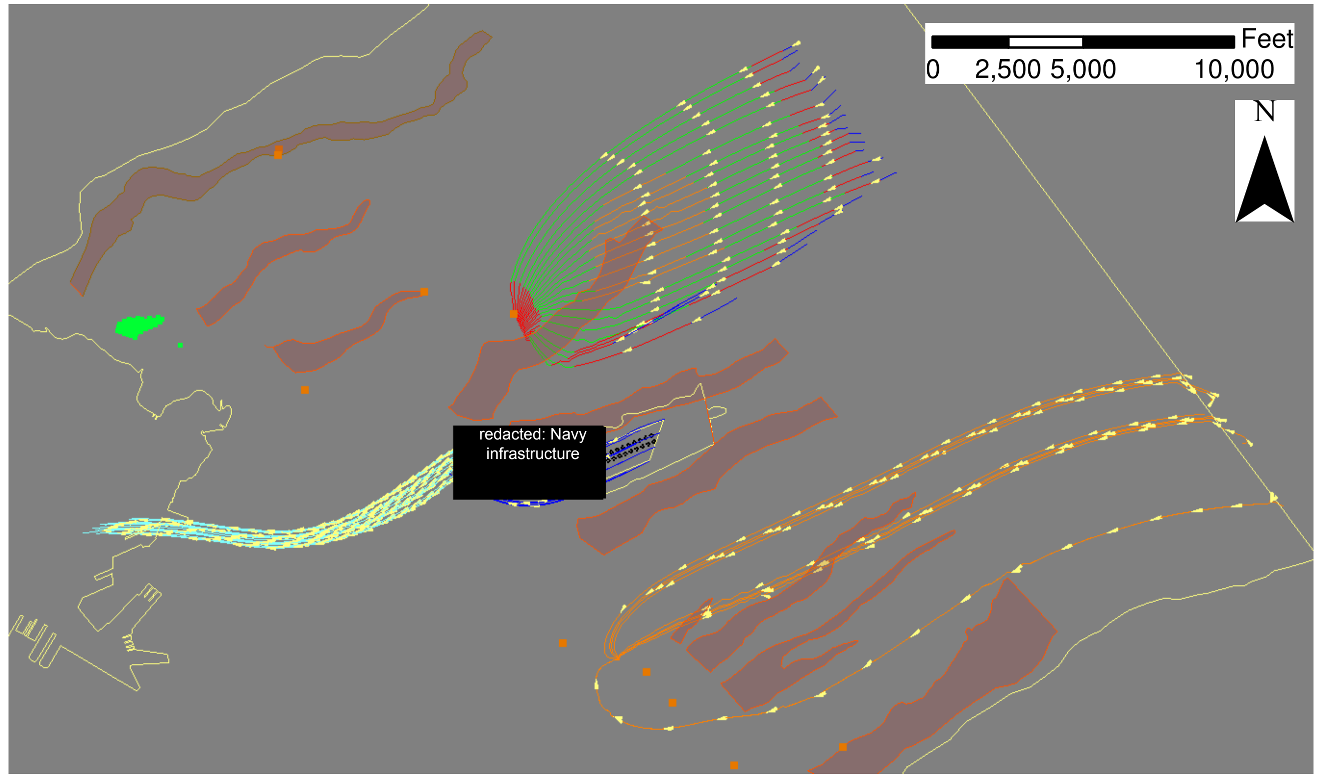
Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

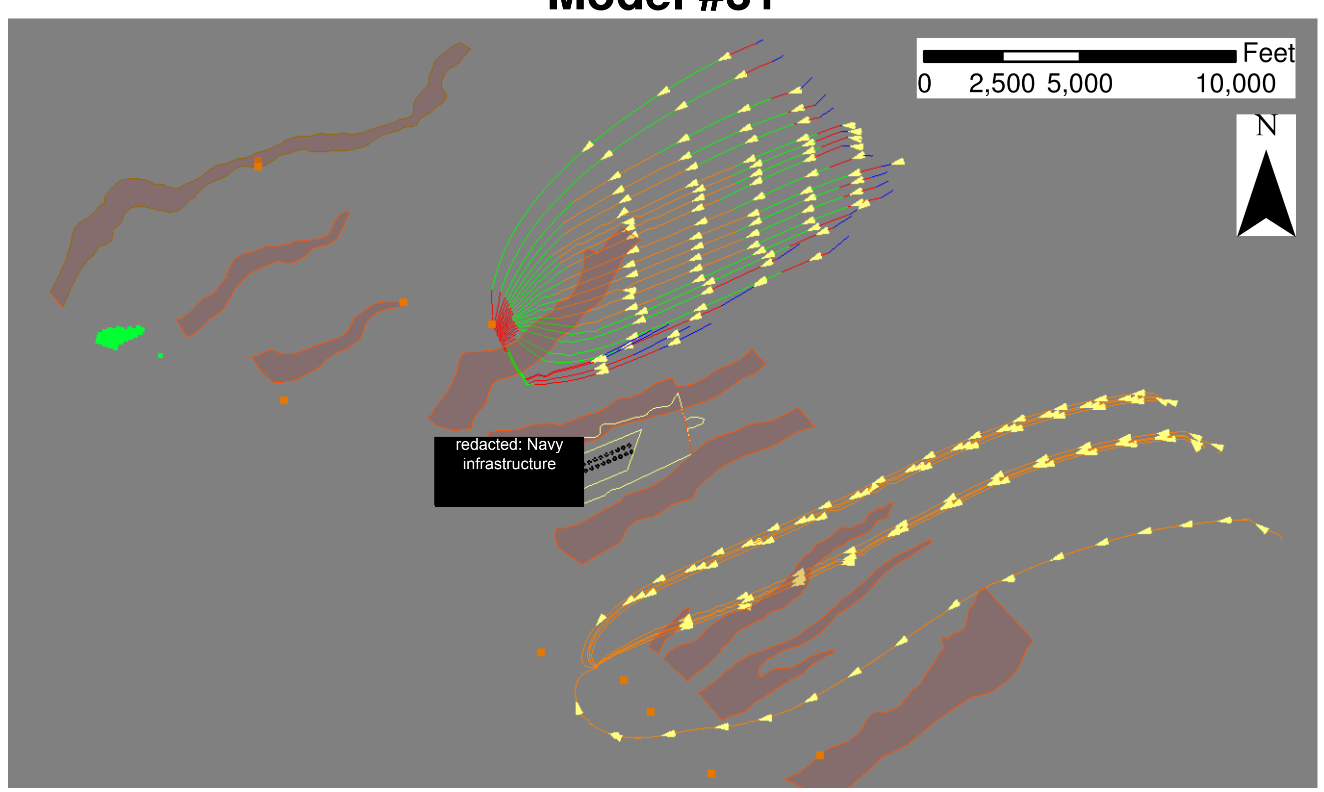
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Hālawa Shaft at - 2 feet above mean sea level.
4. Red Hill Shaft at 3 feet above mean sea level.

Figure 6.4.22-1
Sensitivity to Shaft Elevation (Model #31) - Capture Zones with Red Hill Shaft On
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

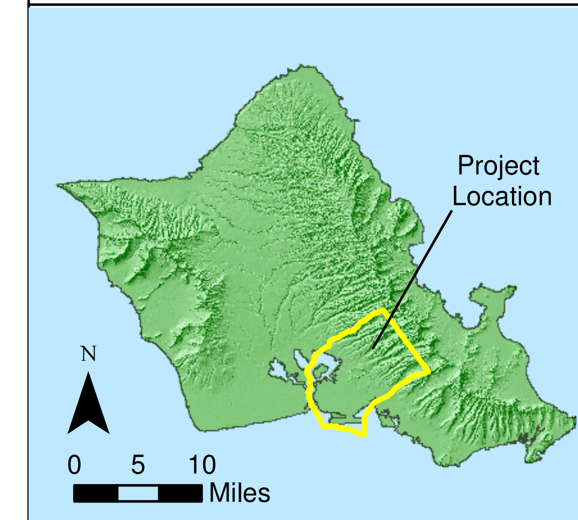
Model #1



Model #31



Location Map



Legend

Pathline Colors:
- Layer 1
- Layer 2
- Layer 3
- Layer 4
- Layer 5

- 1-year Time Intervals
- Red Hill Fuel Storage Tank
- Model Boundary and Red Hill Bulk Fuel Storage Facility Boundary

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Hālawa Shaft at - 2 feet above mean sea level.
4. Red Hill Shaft at 3 feet above mean sea level.

Figure 6.4.22-2
Sensitivity to Shaft Elevation (Model #31) - Capture Zones with Red Hill Shaft Off
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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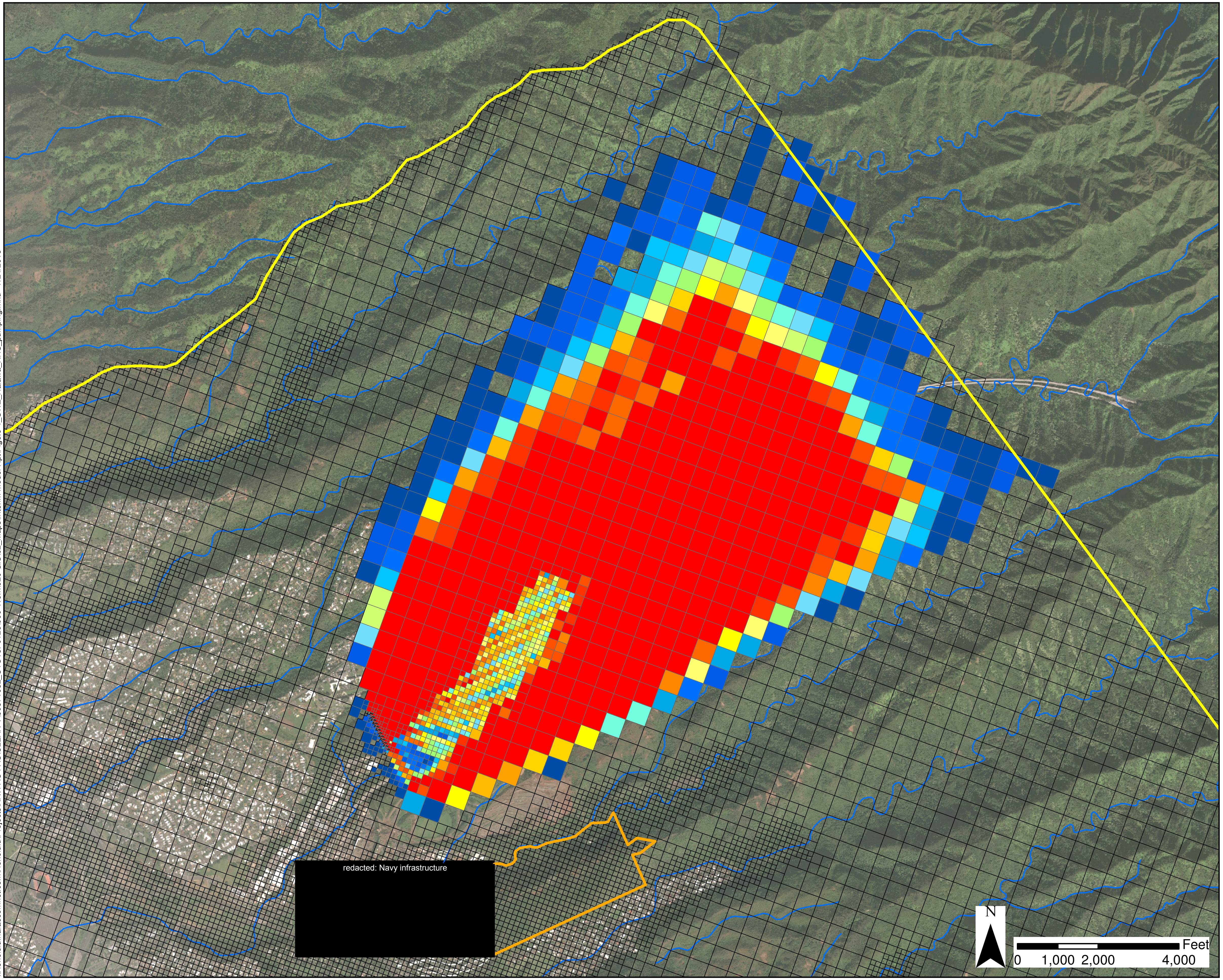
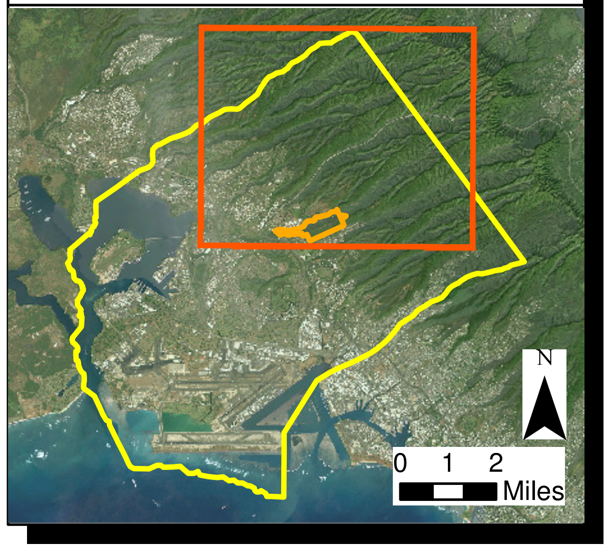


\\Honolulu\na.aecomnet.com\Honolulu\Projects\NAVFAC PAC\CLEAN V\60571032_CTO18F0126\900-Work\920 GIS\02_Maps\Interim Model Rpt\Fig6.6-1_SWZ_Halawa_RHS_pumping.mxd 7/24/2018

Location Map



Legend

Probability Distribution:

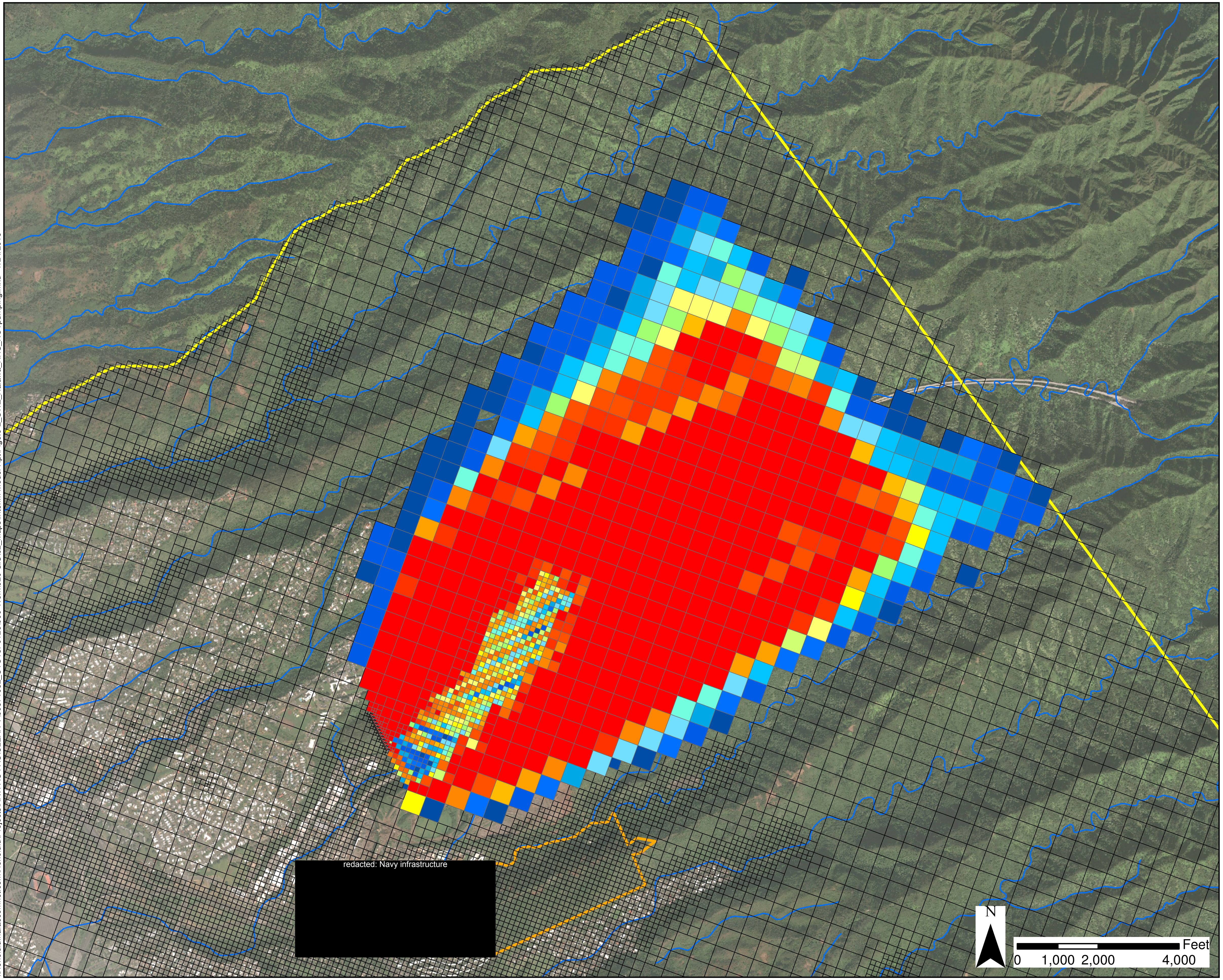
- < 0.0500
- 0.0501 - 0.1000
- 0.1001 - 0.1500
- 0.1501 - 0.2000
- 0.2001 - 0.2500
- 0.2501 - 0.3000
- 0.3001 - 0.3500
- 0.3501 - 0.4000
- 0.4001 - 0.4500
- 0.4501 - 0.5000
- 0.5001 - 0.5500
- 0.5501 - 0.6000
- 0.6001 - 0.6500
- 0.6501 - 0.7000
- 0.7001 - 0.7500
- 0.7501 - 0.8001
- 0.8001 - 0.8500
- 0.8501 - 0.9000
- 0.9001 - 0.9500
- 0.9501 - 1.000

- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

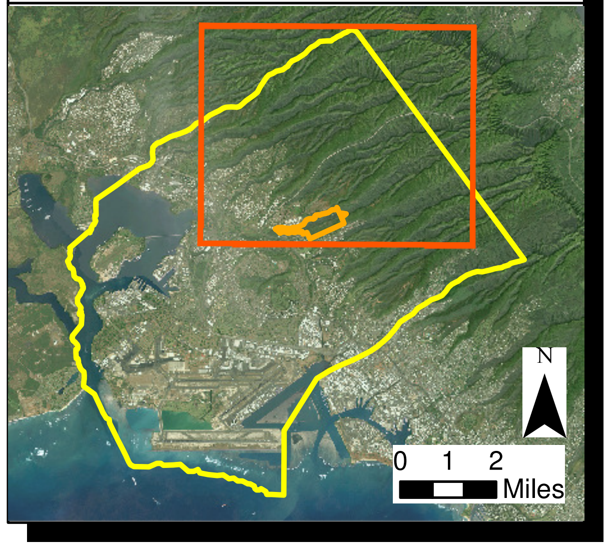
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-1
Probability Distribution Map for Source Water Zone of Hālawa Shaft for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



Location Map



Legend

Probability Distribution:

- < 0.0500
- 0.0501 - 0.1000
- 0.1001 - 0.1500
- 0.1501 - 0.2000
- 0.2001 - 0.2500
- 0.2501 - 0.3000
- 0.3001 - 0.3500
- 0.3501 - 0.4000
- 0.4001 - 0.4500
- 0.4501 - 0.5000
- 0.5001 - 0.5500
- 0.5501 - 0.6000
- 0.6001 - 0.6500
- 0.6501 - 0.7000
- 0.7001 - 0.7500
- 0.7501 - 0.8001
- 0.8001 - 0.8500
- 0.8501 - 0.9000
- 0.9001 - 0.9500
- 0.9501 - 1.000

- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-2
Probability Distribution Map for Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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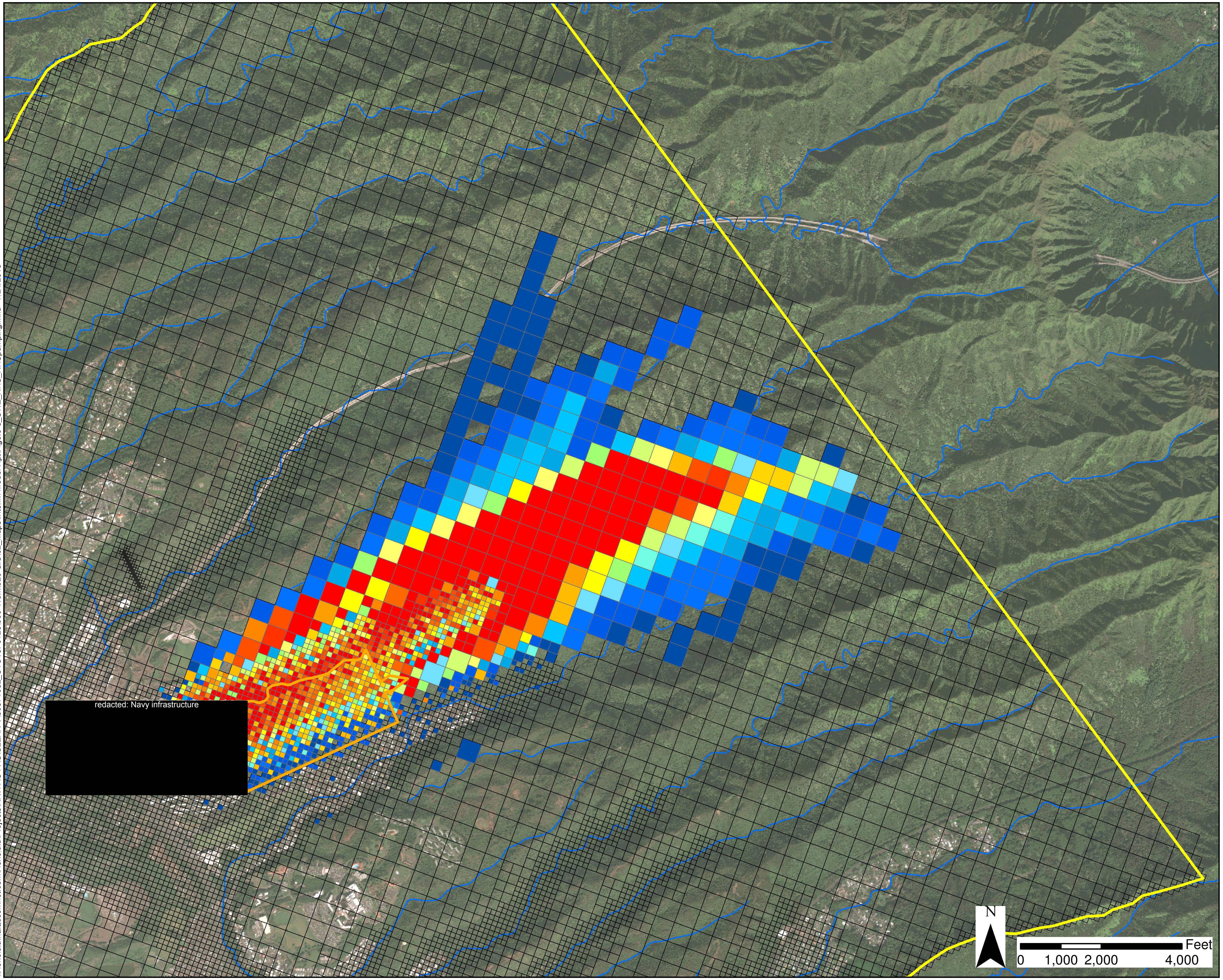

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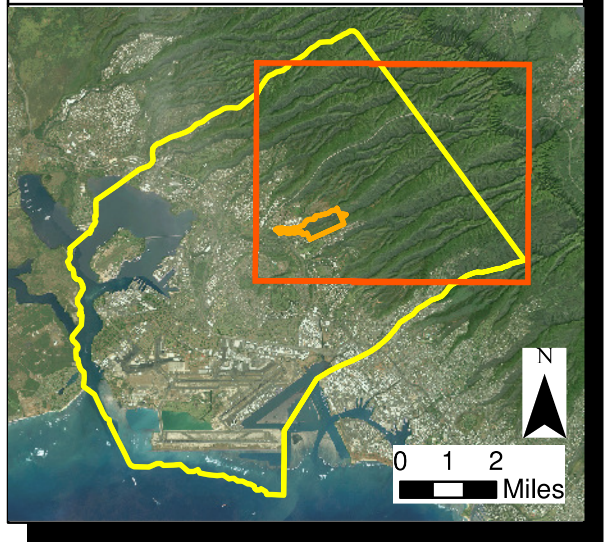
Location Map



Legend

Probability Distribution:

- < 0.0500
- 0.0501 - 0.1000
- 0.1001 - 0.1500
- 0.1501 - 0.2000
- 0.2001 - 0.2500
- 0.2501 - 0.3000
- 0.3001 - 0.3500
- 0.3501 - 0.4000
- 0.4001 - 0.4500
- 0.4501 - 0.5000
- 0.5001 - 0.5500
- 0.5501 - 0.6000
- 0.6001 - 0.6500
- 0.6501 - 0.7000
- 0.7001 - 0.7500
- 0.7501 - 0.8001
- 0.8001 - 0.8500
- 0.8501 - 0.9000
- 0.9001 - 0.9500
- 0.9501 - 1.000

- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-3
Probability Distribution Map for Source Water Zone of Red Hill Shaft for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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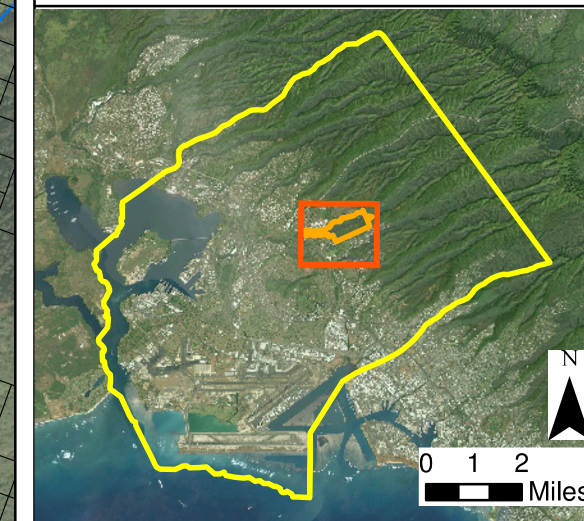
Location Map



Legend

Probability Distribution:

<0.0500	0.5001 - 0.5500
0.0501 - 0.1000	0.5501 - 0.6000
0.1001 - 0.1500	0.6001 - 0.6500
0.1501 - 0.2000	0.6501 - 0.7000
0.2001 - 0.2500	0.7001 - 0.7500
0.2501- 0.3000	0.7501 - 0.8000
0.3001 - 0.3500	0.8001 - 0.8500
0.3501 - 0.4000	0.8501 - 0.9000
0.4001 - 0.4500	0.9001 - 0.9500
0.4501 - 0.5000	0.9501 - 1.000

Model

Red Hill Bulk Fuel Storage Facility Boundary

Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-4
Probability Distribution Map for Migration of Groundwater from Beneath the Facility
Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations
for the Red Hill Bulk Fuel Storage Facility
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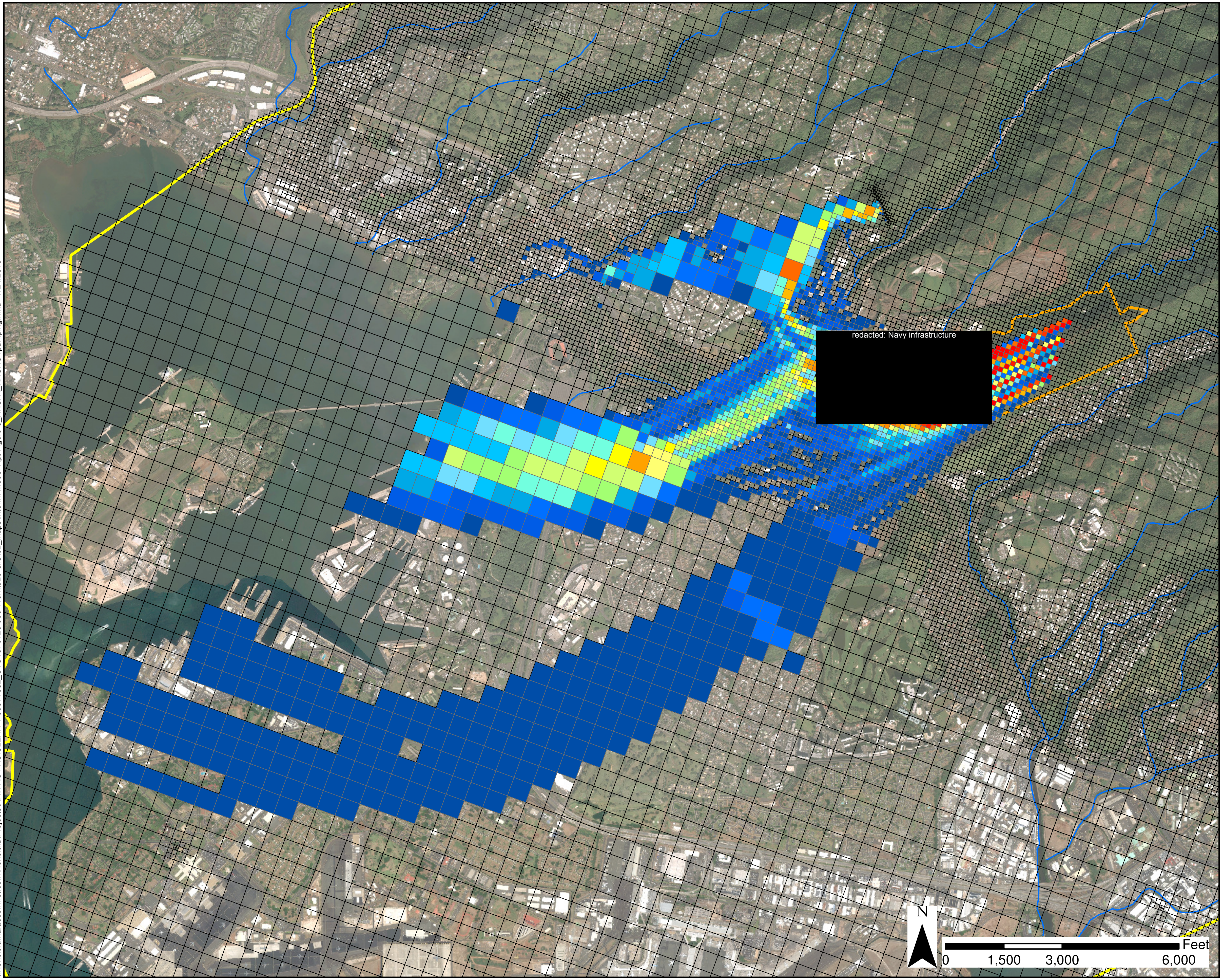
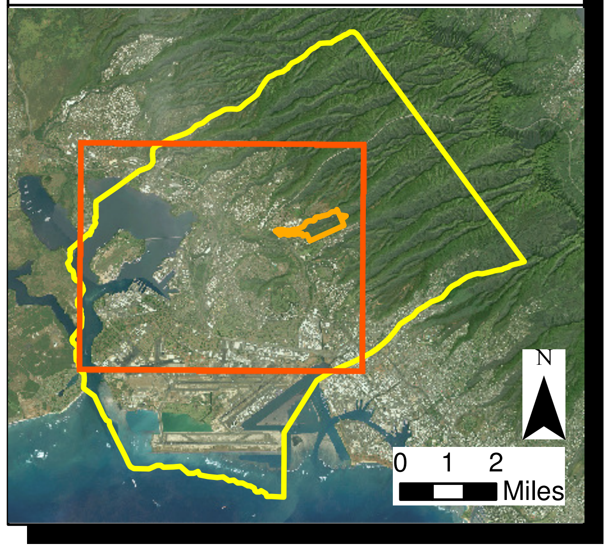


Location Map



Legend

Probability Distribution:

- < 0.0500
- 0.0501 - 0.1000
- 0.1001 - 0.1500
- 0.1501 - 0.2000
- 0.2001 - 0.2500
- 0.2501 - 0.3000
- 0.3001 - 0.3500
- 0.3501 - 0.4000
- 0.4001 - 0.4500
- 0.4501 - 0.5000
- 0.5001 - 0.5500
- 0.5501 - 0.6000
- 0.6001 - 0.6500
- 0.6501 - 0.7000
- 0.7001 - 0.7500
- 0.7501 - 0.8001
- 0.8001 - 0.8500
- 0.8501 - 0.9000
- 0.9001 - 0.9500
- 0.9501 - 1.000

- Model
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-5
Probability Distribution Map for Migration of Groundwater from Beneath the Facility
Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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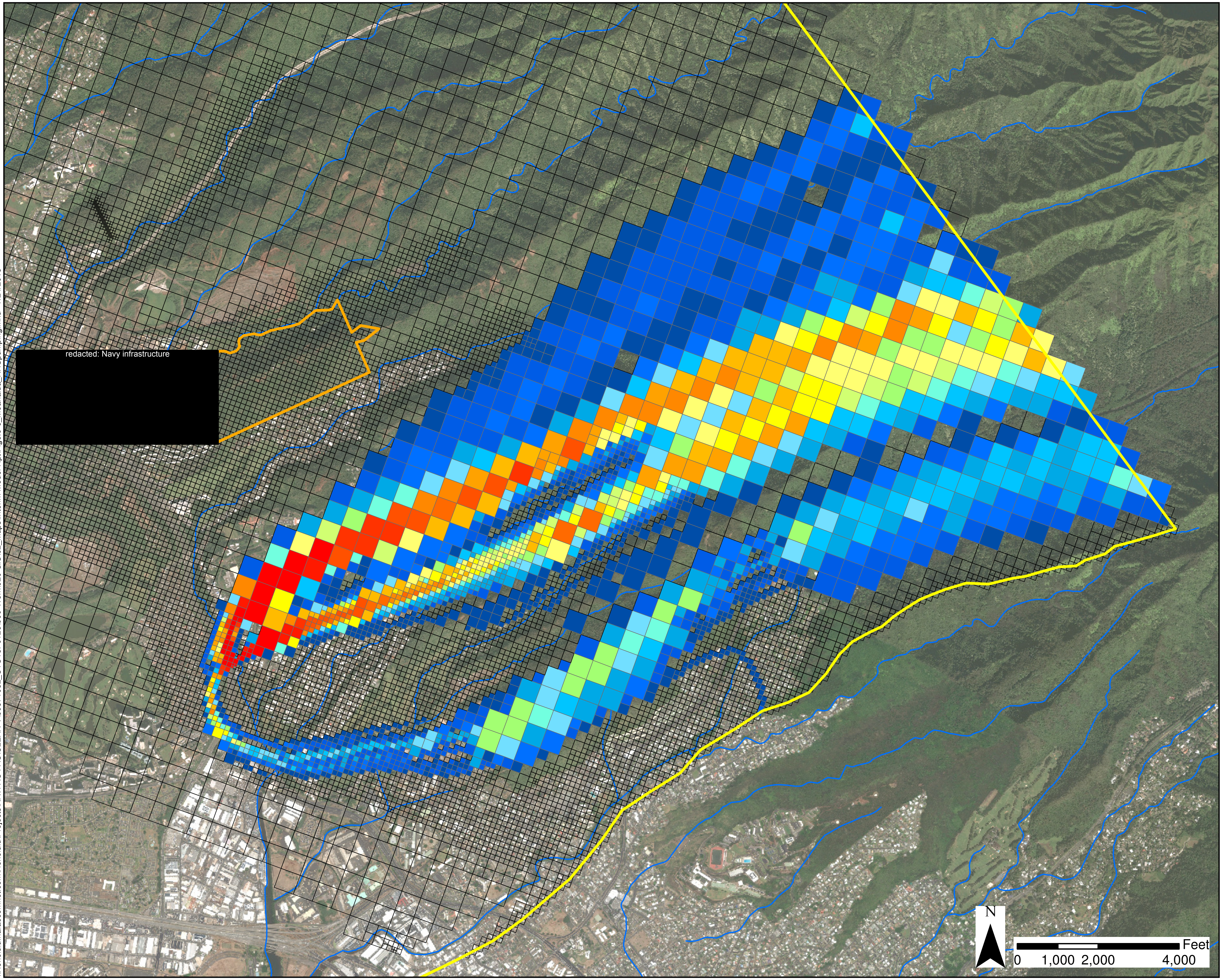
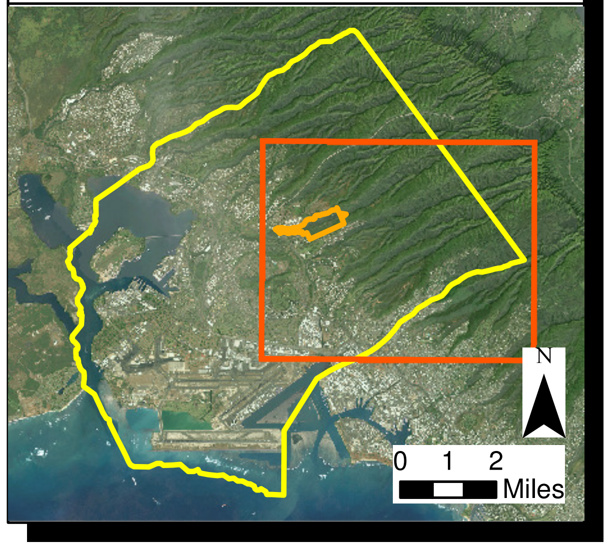


Location Map



Legend

Probability Distribution:

- < 0.0500
- 0.0501 - 0.1000
- 0.1001 - 0.1500
- 0.1501 - 0.2000
- 0.2001 - 0.2500
- 0.2501 - 0.3000
- 0.3001 - 0.3500
- 0.3501 - 0.4000
- 0.4001 - 0.4500
- 0.4501 - 0.5000
- 0.5001 - 0.5500
- 0.5501 - 0.6000
- 0.6001 - 0.6500
- 0.6501 - 0.7000
- 0.7001 - 0.7500
- 0.7501 - 0.8001
- 0.8001 - 0.8500
- 0.8501 - 0.9000
- 0.9001 - 0.9500
- 0.9501 - 1.000

- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-6
Probability Distribution Map for Source Water Zone of the Moanalua Wells for Red Hill Shaft Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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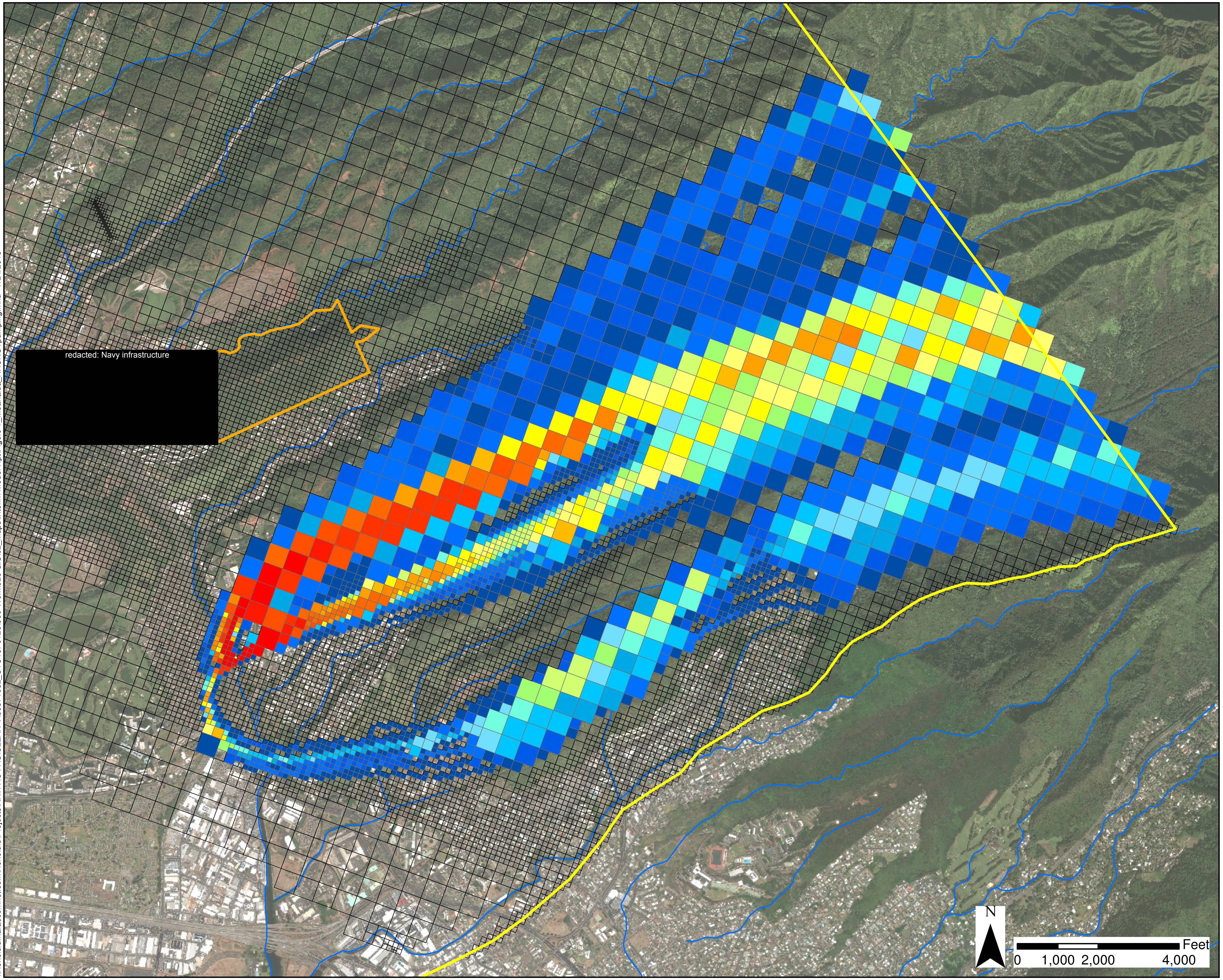
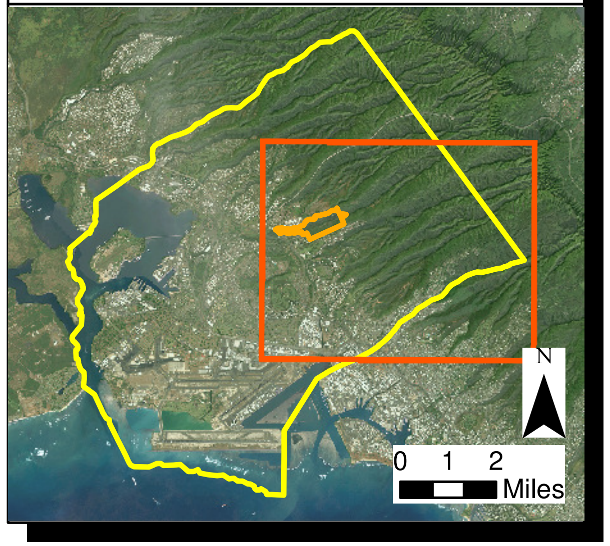


Location Map



Legend

Probability Distribution:

- < 0.0500
- 0.0501 - 0.1000
- 0.1001 - 0.1500
- 0.1501 - 0.2000
- 0.2001 - 0.2500
- 0.2501 - 0.3000
- 0.3001 - 0.3500
- 0.3501 - 0.4000
- 0.4001 - 0.4500
- 0.4501 - 0.5000
- 0.5001 - 0.5500
- 0.5501 - 0.6000
- 0.6001 - 0.6500
- 0.6501 - 0.7000
- 0.7001 - 0.7500
- 0.7501 - 0.8001
- 0.8001 - 0.8500
- 0.8501 - 0.9000
- 0.9001 - 0.9500
- 0.9501 - 1.000

- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-7
Probability Distribution Map for Source Water Zone of the Moanalua Wells for Red Hill Shaft Not Pumping Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
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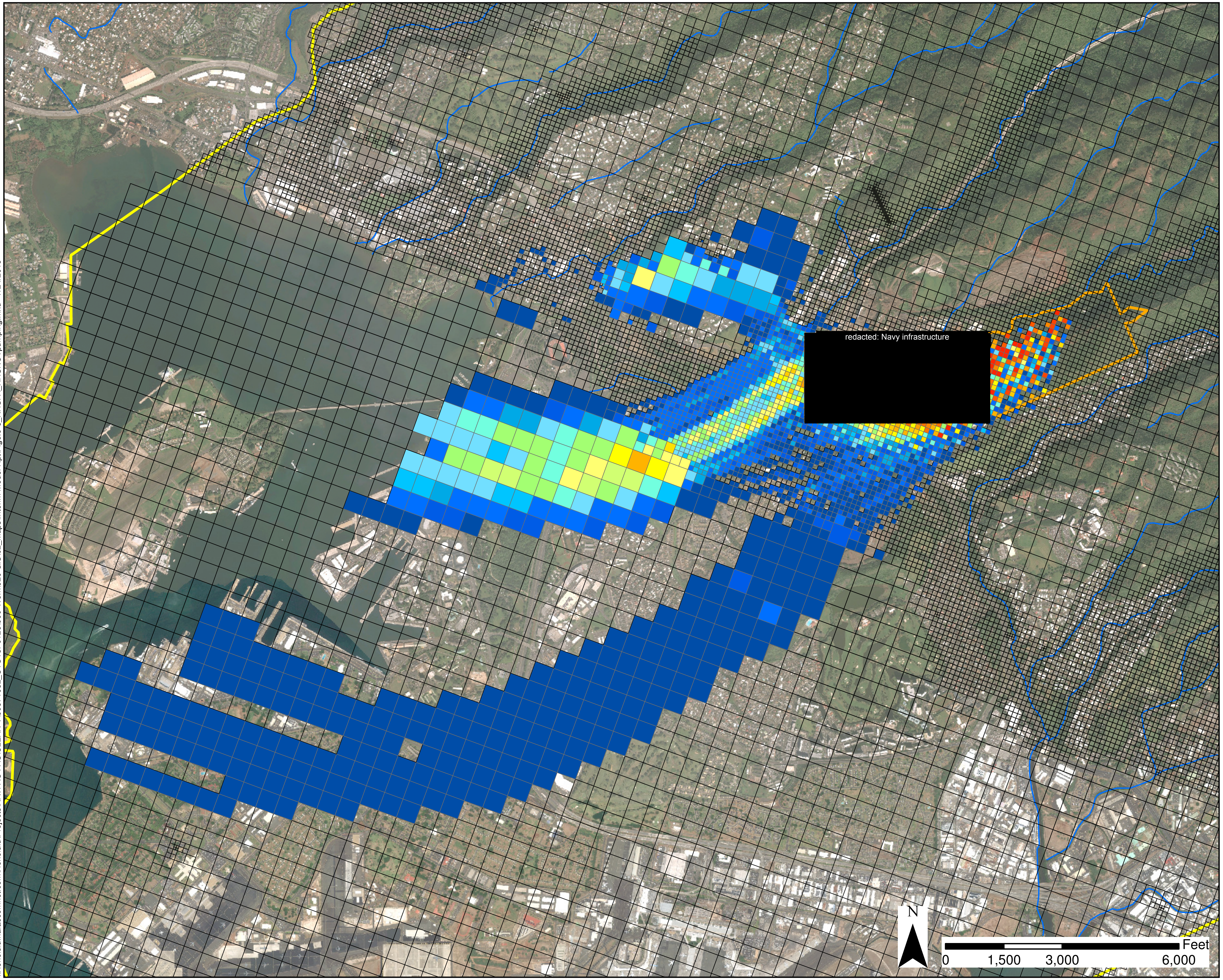
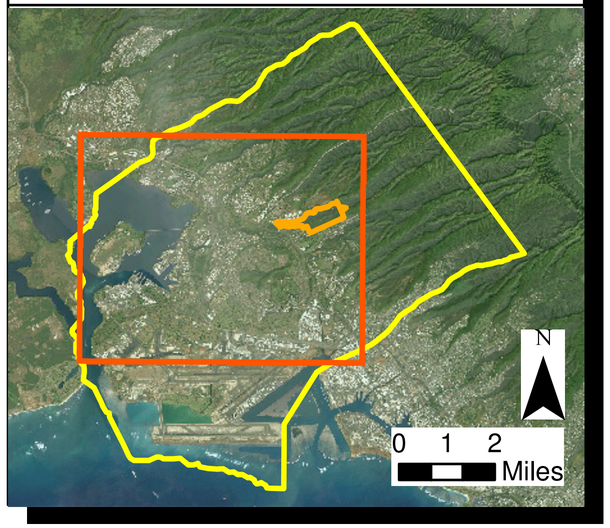


Location Map



Legend

Probability Distribution:

- < 0.0500
- 0.0501 - 0.1000
- 0.1001 - 0.1500
- 0.1501 - 0.2000
- 0.2001 - 0.2500
- 0.2501 - 0.3000
- 0.3001 - 0.3500
- 0.3501 - 0.4000
- 0.4001 - 0.4500
- 0.4501 - 0.5000
- 0.5001 - 0.5500
- 0.5501 - 0.6000
- 0.6001 - 0.6500
- 0.6501 - 0.7000
- 0.7001 - 0.7500
- 0.7501 - 0.8001
- 0.8001 - 0.8500
- 0.8501 - 0.9000
- 0.9001 - 0.9500
- 0.9501 - 1.000

- Model Area
- Red Hill Bulk Fuel Storage Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 6.6-8
Probability Distribution Map for Migration of Groundwater from Beneath the Facility Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at a Steady Rate of 10 MGD Scenario
Appendix A
Interim Groundwater Flow Model Report
Groundwater Protection and Evaluation Considerations for the Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

Appendix B:
Hypothetical Sudden Release Analysis

EXECUTIVE SUMMARY

Historical results from the Red Hill Long-Term Monitoring (LTM) Program and other Facility investigations (including the Red Hill Conceptual Site Model [CSM]; DON 2018) have been used to evaluate the fate of prior releases from the Facility tanks including the 2014 release of approximately 27,000 gallons of Jet Fuel Propellant (JP)-8 from Tank 5. These data in turn, have been used estimate the possible impact of a hypothetical future sudden release from a tank. Specifically, a hypothetical future sudden release volume has been estimated that would be protective of Red Hill Shaft and other water supply wells (i.e., no exceedances of risk-based decision criteria [RBDC]). The likely fate and transport of a future sudden release was evaluated based on two interpretations of the 2014 Tank 5 release:

- *Evaluation 1 - Vadose Zone Retention Capacity:* Available monitoring data indicates that the 2014 release of approximately 27,000 gallons of JP-8 from Tank 5 was likely retained within the top one-third of the vadose zone between the lower access tunnel and the water table with no significant impact to groundwater. No LNAPL was observed in any monitoring well, and there was no to little impact in dissolved constituents as measured prior to and after the release as part of the forensics analysis. Based on this finding, the 2014 release was used to estimate the vadose zone holding capacity for light non-aqueous-phase liquid (LNAPL) along with site-specific geologic data and data from scientific literature. This holding capacity was then used to evaluate the LNAPL volume that would be retained mostly or exclusively in the vadose zone for a hypothetical future release resulting in no significant impact to groundwater. A Monte Carlo model (Attachment 2) was used to obtain a range of release volumes accounting for uncertainty in vadose zone holding capacity and other site parameters.
- *Evaluation 2 - Possible Impact to Groundwater:* Based on feedback from State of Hawaiʻi Department of Health (DOH) and other stakeholders, the fate and transport of a hypothetical future release was evaluated based on a second interpretation of the 2014 release. For this interpretation, the 2014 release was conservatively assumed to have impacted groundwater at the Facility (although forensic analysis of the data indicates it is likely that the 2014 release did not impact groundwater and impacts to groundwater are more likely attributable to historical leaks) and variations in concentrations of dissolved chemicals of potential concern (COPCs) following the release were attributed to this release. The likely impact of a hypothetical future release was evaluated assuming a linear relationship between release volume and magnitude of impact to Red Hill Shaft.

Under either evaluation of the 2014 Tank 5 release, the 27,000-gallon release of jet fuel:

- Did not result in the observation of LNAPL in any of the monitoring wells and the Facility.
- Did not result in any measurable increase in COPC concentrations in Red Hill Shaft.

These observations indicate that a hypothetical future sudden release from a Facility fuel tank would have to be larger than the 2014 release in order to result in an exceedance of RBDC in Red Hill Shaft and other water supply wells. The relative release volume would also increase as a function of release distance from Red Hill Shaft relative to the 2014 Tank 5 release. The two evaluations focused on understanding and quantifying this "margin of safety" associated with the 2014 release in order to estimate the volume of a hypothetical future sudden release that would not result in an exceedance of the RBDCs at Red Hill Shaft (Table ES-1).

Table ES-1: Volume of a Hypothetical Future Sudden Release that Would be Protective of Red Hill Shaft

Estimate Type	Evaluation 1 (gallons)	Evaluation 2 (gallons)
More Conservative and Protective Low-End Volume	48,000	27,000
Reasonably Conservative and Protective Mid-Range Volume	**150,000**	**88,000**
Less Conservative High-End Volume	400,000	920,000

- The more conservative volume estimate was based on a combination of conservative assumptions that serve to significantly overestimate the potential for a hypothetical future release to cause an unacceptable impact; therefore, this volume should be considered protective for all tanks with a very high degree of confidence.
- The reasonably conservative mid-range estimate was based on a mix of conservative and realistic assumptions that serve to provide a reasonably conservative overestimate the potential for a hypothetical future release to cause an unacceptable impact; therefore, this volume should be considered protective for all tanks with a high degree of confidence.
- The less conservative estimate used realistic assumptions and accounts for uncertainty in input parameters using a less conservative approach. The less conservative volume is likely to be protective a hypothetical release from a tank located further away from Red Hill Shaft (e.g., Tanks 11–20).

The following is recommended to account for prior release:

- *Tanks with Strong Evidence of Prior Releases* (Tanks 5, 9, 11, 13, 14, and 16): Reduce the hypothetical future release volume by 25%.
- *Tanks with Weaker Evidence of Prior Releases* (Tanks 2, 3, 4, 5, 6, 7, 8, 12, 18, and 20): Reduce the hypothetical future release volume by 10%.

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ACRONYMS AND ABBREVIATIONS

µg/L	microgram per liter
cp	centipoise
COPC	chemical of potential concern
CSM	conceptual site model
DOH	Department of Health, State of Hawai‘i
FGS	fine-grained sediment
ft^3	cubic foot
JP	Jet Fuel Propellant
LNAPL	light non-aqueous-phase liquid
LOD	limit of detection
LTM	long-term monitoring
msl	mean sea level
NAPL	non-aqueous-phase liquid
NSZD	natural source-zone depletion
PID	photoionization detector
ppbv	parts per billion by volume
RBDC	risk-based decision criteria
USGS	United States Geological Survey
VOC	volatile organic compound

1. Introduction

1.1 Technical Background

To better understand hypothetical risks associated with different potential releases, a quantitative calculation of the ability for Red Hill to hold fuel (called light non-aqueous-phase liquid [LNAPL]) in the case of a hypothetical fuel tank release from the Facility has been conducted. Two separate holding capacity calculations were performed:

- The LNAPL holding capacity for a hypothetical large, sudden release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. The calculations and results of this analysis are described below.
- The LNAPL holding capacity for a hypothetical small chronic release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. This calculation is dependent on the natural source-zone depletion (NSZD) rate at the Facility and is described in Appendix C, Hypothetical Chronic Release Analysis.

1.2 Study Objectives

The objective of the analysis described in this appendix was to determine the maximum hypothetical sudden release that would not result in unacceptable risk to users of groundwater in the vicinity of the Facility.

2. Fate and Transport of LNAPL at the Facility

The likely fate and transport of LNAPL from a hypothetical future release has been evaluated base on (1) a general understanding of LNAPL transport processes at the Facility and (2) two interpretations of the fate and transport of LNAPL from the 2014 Tank 5 release.

- *Evaluation 1, Vadose Zone Retention Capacity*: Available monitoring data indicates that the 2014 release of approximately 27,000 gallons of JP-8 from Tank 5 was likely retained within the top one-third of the vadose zone between the lower access tunnel and the water table with no significant impact to groundwater. Based on this finding, the 2014 release was used to estimate the vadose zone holding capacity for LNAPL. This holding capacity was then used to evaluate the LNAPL volume that would be retained in the vadose zone for a hypothetical future release. A Monte Carlo model was used to obtain a range of release volumes accounting for uncertainty in vadose zone holding capacity and other site parameters.
- *Evaluation 2, Possible Impact to Groundwater*: Based on feedback from State of Hawai'i Department of Health (DOH) and other stakeholders, the fate and transport of a hypothetical future release was evaluated based on a second interpretation of the 2014 release. For this interpretation, the 2014 release was assumed to have impacted groundwater at the Facility (although forensic analysis of the data indicates it is likely that the 2014 release did not impact groundwater and impacts to groundwater are more likely attributable to historical leaks) and variations in concentrations of dissolved chemicals of potential concern (COPCs) following the release were attributed to this release. The likely impact of a hypothetical future release was evaluated assuming a linear relationship between release volume and magnitude of impact to groundwater.

The methods and assumptions for the two evaluations are summarized and compared in Table 1.

Table 1: Comparison of Evaluation Assumptions and Evaluation Methods 1 and 2

Evaluation 1	Evaluation 2
Accounts for ~11 degree geologic dip to SSW Accounts for geological media and associated properties	No consideration of geology Heterogeneous distribution of LNAPL reaching groundwater
2014 Tank 5 Release used to determine specific retention of basalt for LNAPL Minimal LNAPL in groundwater	Assumes impacts to GW from 2014 Tank 5 Release
Uses statistical approach for modeling (Monte Carlo Analysis)	Uses Mass Flux approach for modeling
No impact outside of Red Hill Shaft Capture Zone	No RBDC exceedances at Red Hill Shaft
Accounts for prior releases from individual tanks	Does not account for prior releases

RBDC risk-based decision criteria

2.1 GENERAL UNDERSTANDING OF LNAPL FATE AND TRANSPORT

Any LNAPL releases from the Red Hill Bulk Fuel Storage Facility (the "Facility") will generally move through High-Permeability A'ā Clinker and High-Permeability Thin Pāhoehoe Flows along the top of low-porosity, low-permeability lava beds controlled by the key features and processes below excerpted from the Red Hill Conceptual Site Model (CSM) (DON 2018):

- The Facility's fuel storage tanks are situated in the vadose zone, which is approximately 100 feet (ft) thick in the area, and are surrounded by volcanic rock that consists of relatively thick, dense, massive basalt flows, with basaltic a'ā clinker zones of variable thickness.
- Permeability is typically highest in the relatively thick, unweathered rubbly a'ā clinker zones and intensely fractured zones or lava tubes of pāhoehoe flows.
- Pāhoehoe lava flows are characterized as fluid, relatively low-viscosity flows. The cooled rock is vesicular and ropy, and has a smoothly undulating surface. Numerous elongate voids can be present that form in the horizontal, longitudinal direction, thereby creating preferential pathways. Pāhoehoe flows are formed from relatively rapidly flowing basaltic lavas that tend to be relatively thin and spread out laterally.
- High permeability commonly occurs in thin pāhoehoe flows (large number of interflow zones), rubbly a'ā flow base and tops (i.e., a'ā clinker zones), and highly fractured rocks.
- A'ā lava flows are characterized by an interior or core of solid, dense, massive rock with exterior top and bottom coarse rubble or clinker zones.
- As the higher viscosity lava in the core travels downslope, the clinkers are carried along at the surface. At the leading edge of an a'ā flow, however, these cooled fragments tumble down the steep front and are buried by the advancing flow.
- Clinker at the periphery of an a'ā flow may provide local avenues of high vertical permeability.
- The interior portions of larger, thicker clinker zones would be less affected by the weathering processes described by the United States Geological Survey (USGS) (Hunt Jr. 1996) because those clinkers would be more distant from subaerial exposure at the land surface. Thus, interior portions of larger, thicker clinker zones would contain little fine-grained sediment (FGS), and thus may have extremely high permeability and high effective porosity.

- Clinker zones are similar to layers of coarse well-sorted gravel, where layered sequences of flows can result in widespread beds with high horizontal permeability. However, thinner clinker beds are often highly weathered throughout the entire thickness of the bed.
- Non-aqueous-phase liquid (NAPL) would enter and move preferentially through clinker zones of high permeability and high effective porosity. Macro-pores pose the least capillary water resistance and thus are the preferred pathways. After NAPL moves downward through macro-pores to the top of a dense, low-porosity, low-permeability lava bed, the NAPL would move down-dip and spread laterally along the base of the permeable clinker.
- Thinner clinker beds are often highly weathered throughout the entire thickness of the bed. The FGS in the weathered clinkers would have a high capillary threshold entry pressure because water is tightly held by capillary tension in a FGS matrix.

3. Site Specific Analysis of Geology for Evaluation 1

For Evaluation 1, the geologic media in the Facility were divided into five different media types based on the ability to transmit and hold LNAPL (Table 2):

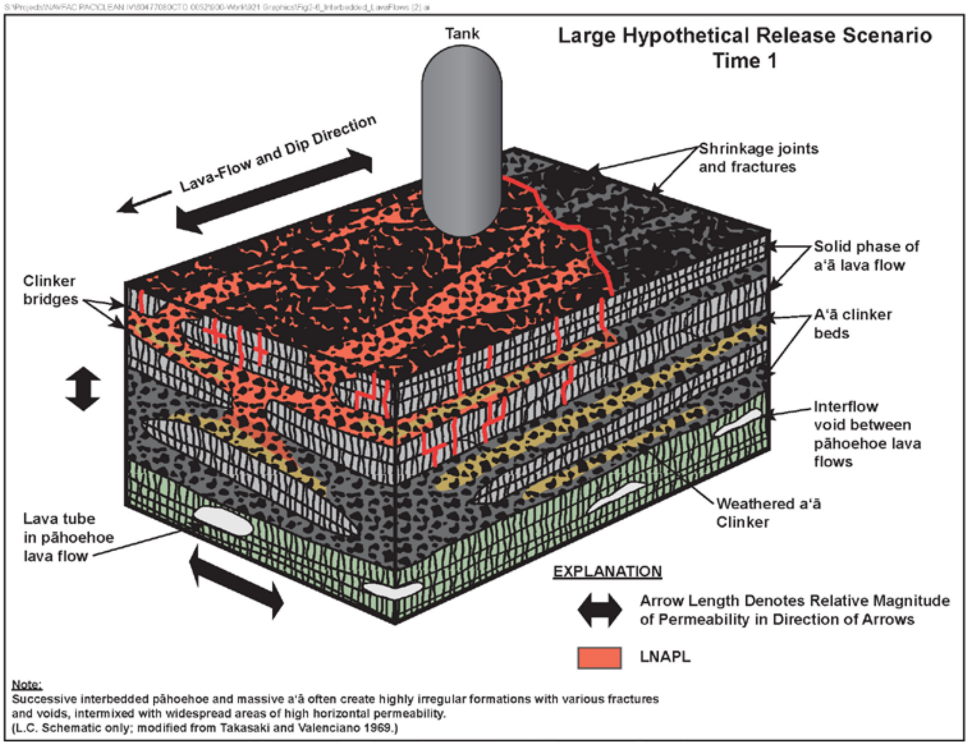
Table 2: Geologic Media Types in the Facility Area

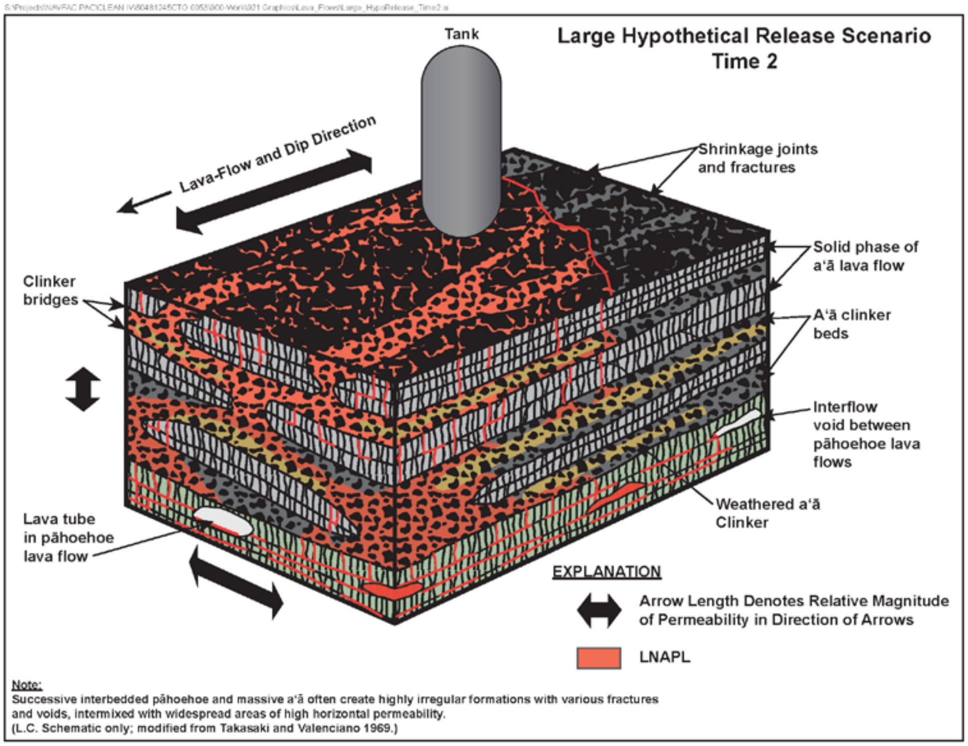
Media Type	Ability to Transmit, Hold LNAPL	Estimation of Holding Capacity for Evaluation 1
Massive A‘ā Flows	Limited	Assumed to be zero
A‘ā Clinker with Fine Grained Sediments (FGS)	Limited LNAPL Transmissivity and Holding Capacity	Assumed to be zero
High-Permeability A‘ā Clinker	High	Based on published literature
Massive Pāhoehoe Flows	Limited	Assumed to be zero
High-Permeability Thin Pāhoehoe Flows	High	Estimated based on evaluation of 2014 Tank 5 release

Total A‘ā includes Massive A‘ā flows, A‘ā Clinker with FGS, and High-Permeability A‘ā Clinker. Clinker is used to describe the Total Clinker, both A‘ā Clinker with Fine-Grained Sediments and High-Permeability A‘ā Clinker. Total Pāhoehoe includes Massive Pāhoehoe Flows and High-Permeability Thin Pāhoehoe Flows.

Considering the geologic media in the Facility, a large, sudden release was assumed to have these transport characteristics:

- The release will spread both horizontally and vertically, but with a strong horizontal component due to the anisotropic nature of the lava flows, where the horizontal hydraulic conductivity is between 200 and 600 times greater than vertical hydraulic conductivity (Souza and Voss 1987; Oki 2005). Vertical flow will be downward via clinker bridges and fractures (Figure 1).
- Lateral migration in the vadose zone will generally be in the down-dip direction of the lava beds. In addition, the LNAPL will spread laterally (i.e., transverse to the dip). The longitudinal transmissivity (i.e., in the direction of the dip) of the basalt formations is higher than the transverse transmissivity (e.g., Figure 1) (Hunt Jr. 1996; DON 2007; Oki 2005). Based on this difference, a 3:1 ratio for the length to width ratio was used for Evaluation 1 of the holding capacity analysis such that the lateral width is one-third of the migration length in the down-dip direction.





Source: adapted from Hunt Jr. 1996

Note: (top) Arrow length shows the relative magnitude of the permeability in different directions: highest in the direction of the lava flows, lowest vertically; (bottom) red demonstrates possible LNAPL pathways based on conceptual site model in interbedded lava flows at Red Hill.

Figure 1: Conceptual LNAPL Migration

- In the vadose zone, the dip direction of the lava flows is to the south-southwest (i.e., (approximately 200 degrees from north) with a dip of between 10 and 13 degrees). A dip of 11 degrees was used for the release scenario evaluation.
- Most of the holding capacity will be in High-Permeability A‘ā Clinker Zones and High-Permeability Thin Pāhoehoe flows. Massive A‘ā, Clinker with FGS, and Massive Pāhoehoe zones have much less LNAPL holding capacity. The holding capacity for these three geologic layer types was conservatively assumed to be zero for Evaluation 1.

In order to quantify the retention capacity of the basalt surrounding the tanks, the amount of each type of media was estimated using monitoring well boring logs. Analysis of logs for the elevation range 300–48 ft mean sea level (msl) provided an estimate of what percentage of the basalt was pāhoehoe vs. a‘ā. In addition, the percentage of clinker in the Total A‘ā was estimated. Because these percentages varied over different depth intervals, the Facility vadose zone was divided into four zones (Figure 2) and estimates were made for each of these zones.

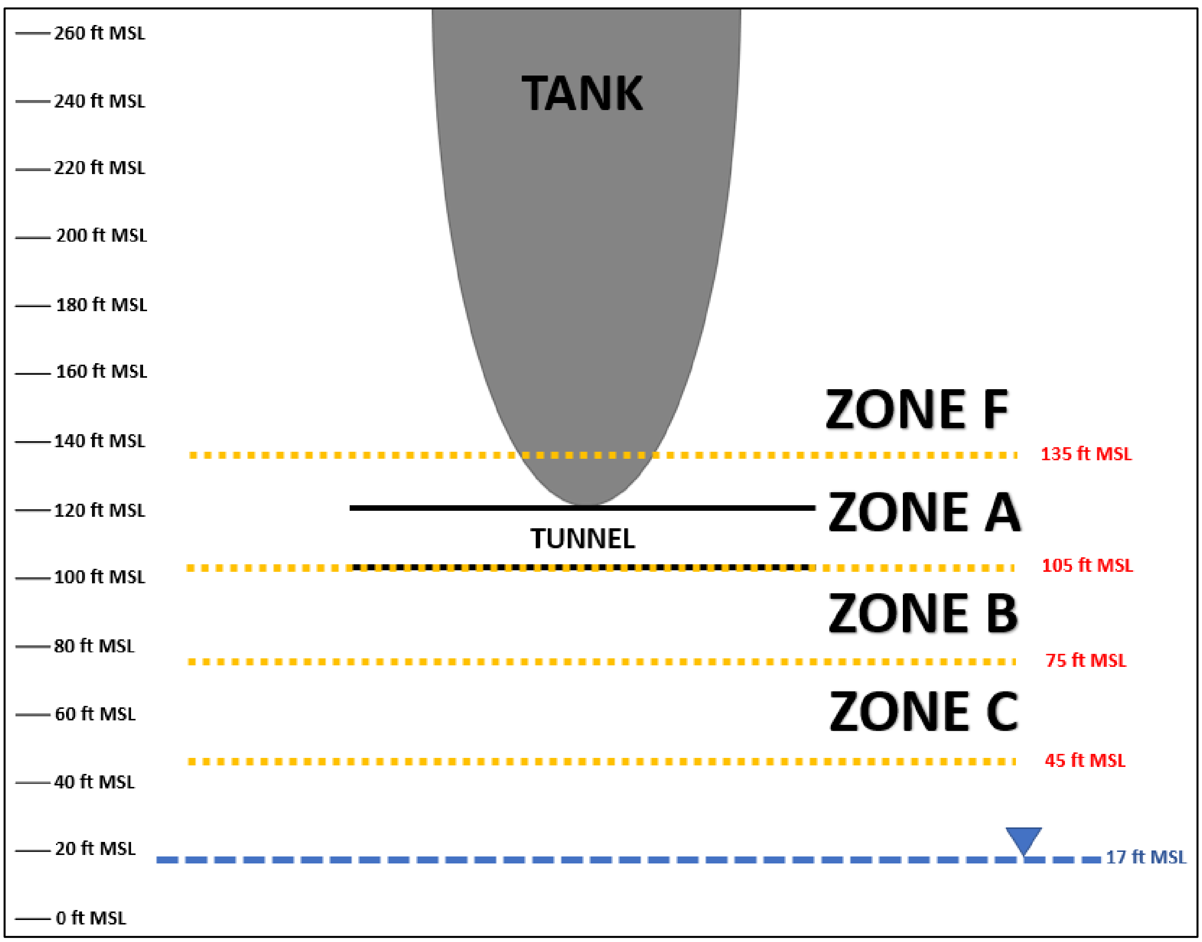


Figure 2: Elevations of the Four Geologic Zones Relative to a Tank

Geologic Zones A, B, and C have a thickness of 30 ft. Geologic Zone F has a thickness defined from the elevation of the release to 135 ft msl.

The distribution of the different media within each zone was approximated using two sources of information: (1) a geologic model based on boring logs and other information developed for an area of 720 ft by 720 ft down-dip of Tanks 1 and 2 (Table 3); and (2) an interpretation of the clinker material from RHMW09 (RHMW09 is the only high-quality geologic log in this area).

Table 3: Approximate % Total Pāhoehoe, % Total A'ā, and % Clinker as % Total A'ā in the Four Geologic Zones

Geologic Zone	Elevation Range (ft msl)	% Total Pāhoehoe	% Total A'ā	% Clinker as % of Total A'ā
F	300–138	11%	89%	29%
A	138–108	70%	30%	23%
B	108–78	63%	37%	0.1%
C	78–48	80%	20%	10%

Source: AECOM (2017)

The boring log for RHMW09 (see Figure 3 for location) was used to estimate the percentage of clinker that is highly permeable and able to hold LNAPL (Table 3). Based on the nature of Hawaiian basalt flows, the percentage of pāhoehoe that is highly permeable and able to hold LNAPL was assumed to be 90% for all four elevation ranges (i.e., only 10% was assumed to be Massive Pāhoehoe) (Table 4).

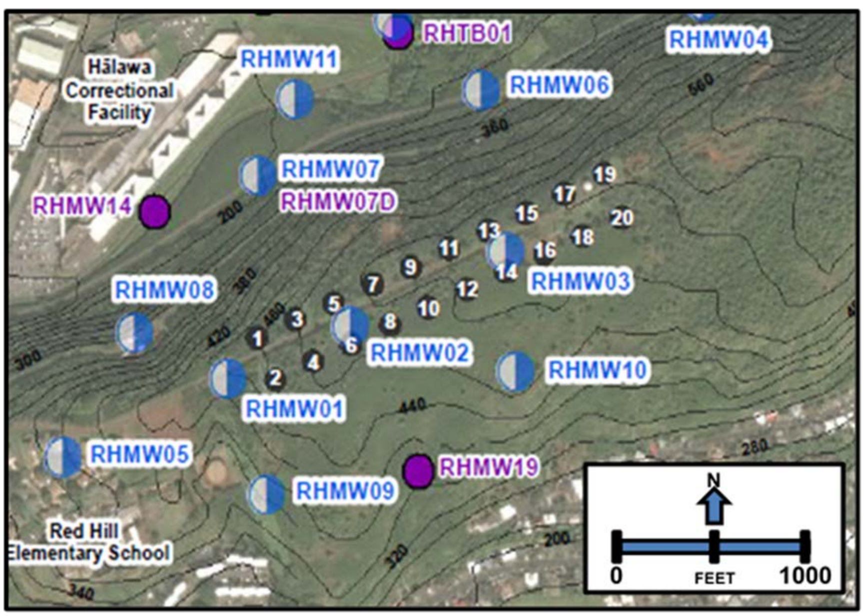


Figure 3: Facility Map Showing RHMW09, the Monitoring Well Used to Determine Geological Characteristics of Basalt in Facility

Table 4: High-Permeability Fraction in the Four Geologic Zones

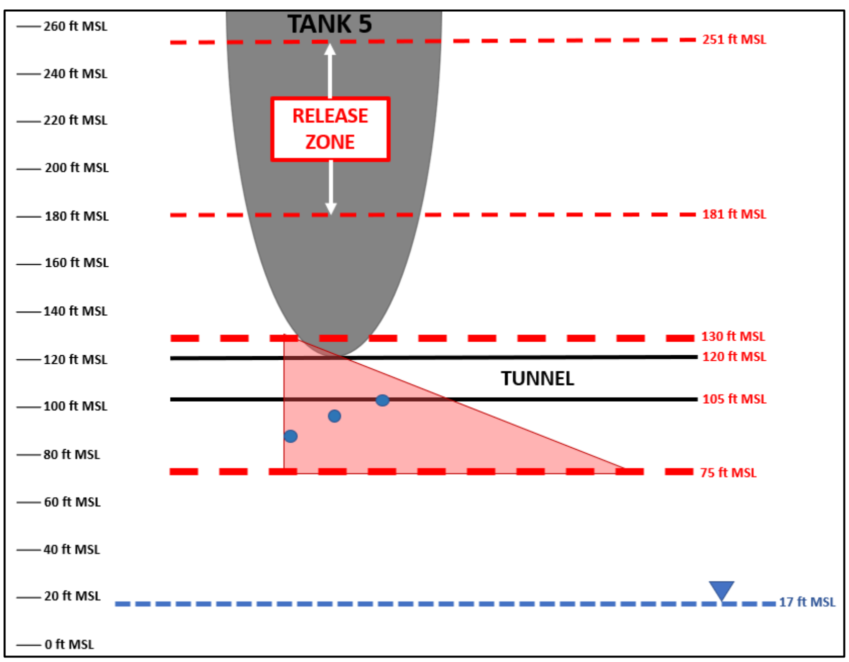
Geologic Zone	Elevation Range (ft msl)	High-Permeability Thin Pāhoehoe as % of Total Pāhoehoe	High-Permeability A'ā Clinker as % of Total Clinker
F	300–138	90%	40%
A	138–108	90%	40%
B	108–78	90%	40%
C	78–48	90%	40%

The elevation ranges and percentages of each type of geologic media at the Facility are used and further developed in Sections 3.1, 4.4.3, and 4.4.4.

3.1 APPLICATION OF TANK 5 RELEASE DATA TO ESTIMATE SPECIFIC RETENTION OF LNAPL FOR EVALUATION 1

In order to calculate the holding capacity of the high vadose zone, the specific retention of the High-Permeability Thin Pāhoehoe Flows was calculated based on the data provided by the 2014 tank release:

- The release occurred somewhere between 251 and 181 ft msl. For Evaluation 1, the LNAPL is assumed to have entered the basalt somewhere near the bottom of the tank at approximately 130 ft msl; this is the most conservative assumption and is supported in part by the description of the January 2014 release in the CSM (DON 2018). These elevations are presented on Figure 4.



Note: Soil vapor probes shown as blue dots at approximate elevations of 101 ft msl, 92 ft msl, 84 ft msl. Red triangle shows assumed LNAPL retention "wedge". (Base length not drawn to scale.)

Figure 4: 2014 Tank 5 Release Schematic

- Thermal NSZD data from RHMW02 indicated that LNAPL was present approximately 30 ft below the tunnel under Tank 5 (CSM Appendix B.1; DON 2018). Based on this observation, the approximately 27,000 gallons of JP-8 released from Tank 5 was assumed to have been retained within the vadose zone between the elevations of 130 ft msl (i.e., the assumed point of entry into the basalt) and 75 ft msl (i.e., the bottom of the LNAPL zone based on the Thermal NSZD data) (Figure 3-5 of the memorandum).

- Each tank has three angled soil vapor wells, approximately 25 ft apart with the middle probe below the center of the tank, as shown on Figure 3-2 of the memorandum. The tanks are 100 ft diameter and constructed with 200-ft spacing.
- Soil vapor data as shown on Figure 6-1 of the memorandum were collected in the months immediately following the January 2014 Tank 5 release. These data indicate the presence of LNAPL below Tank 5 (i.e., very high photoionization detector [PID] readings) and indicate that the LNAPL most likely did not migrate under the tanks surrounding Tank 5 (i.e., much lower PID readings below Tanks 3,4,6,7,8). Each square has the volatile organic compound (VOC) concentration in parts per billion by volume (ppbv) for the soil vapor well under each tank with the highest PID reading. The magnitude of VOC concentrations for Tank 5 are always one to two orders of magnitude larger than the VOC concentrations for the surrounding tanks, indicating the presence of LNAPL below Tank 5 but no LNAPL (or at most trace levels) below the adjacent tanks. The shading of the squares does not signify that LNAPL saturated or covered the entirety of the 200 ft × 200 ft square on Figure 5.

01/15/14			225,000							
			6,424							
01/30/14		9,444	176,000	6,539	2,408	374	1,109	1,025	2,980	
	11	165	3,046	2,952	483	270		139	2,116	697
02/24/14		5,290	100,000	1,187	330	307	116	65	4,069	
	135	163	6,165	601	165	215		65	3,241	571
03/05/14		26,800	217,000	4,406	1,614					
	1	536	7,204	3,097	365					

Figure 5: Example of Soil Vapor Data (01/15/14 is the Soil Vapor Point After the 2014 Tank Release)

Based on these observations, the volume of basalt impacted by the Tank 5 Release was assumed to have a total vertical thickness of 55 ft, a width of 183 ft (so as not to go under Tanks 3 and 6), and a length down-dip of 288 ft (based on the geologic dip of 11 degrees or 19%). The 2014 release was assumed to fill a triangular wedge in the vadose zone with these specified dimensions. The wedge has a total volume of approximately 1,420,000 cubic feet (ft^3). Further explanation for the shape of the release is provided in Section 3.

The amount of each type of geologic media in the triangular wedge was determined based on the release elevations as shown on Figure 4 and the geologic zones described in Section 3. The geologic zones were not aligned with the geologic dip but retained the orientation depicted on Figure 2 (parallel to the water table).

The LNAPL in the 2014 Tank 5 Release migrated into only two of the geologic zones, A and B. The relevant geologic breakdown for these zones is presented in Table 5.

Table 5: Geologic Media Percentages in Zones A and B

Geologic Zone	Volume of Pāhoehoe (%)	Volume of Total A‘ā (%)	Volume of Clinker in Total A‘ā (%)	Volume of High-Permeability Pāhoehoe (%)	Volume of High-Permeability Clinker (%)
A	70%	30%	23%	90%	40%
B	63%	37%	0.1%	90%	40%

The calculation of the volume of Zone A and Zone B for the Tank 5 Release LNAPL retention wedge is presented in Attachment 1. The volume breakdown of each geologic media is presented Table 6.

Table 6: Volume of Each Type of Media within Tank 5 Release LNAPL Retention Wedge

Geologic Zone	Volume of Pāhoehoe (ft^3)	Volume of Total A‘ā (ft^3)	Volume of Clinker in Total A‘ā (ft^3)	Volume of High-Permeability Pāhoehoe (ft^3)	Volume of High-Permeability Clinker (ft^3)
A	210,000	88,000	20,000	190,000	8,100
B	710,000	420,000	420	640,000	170

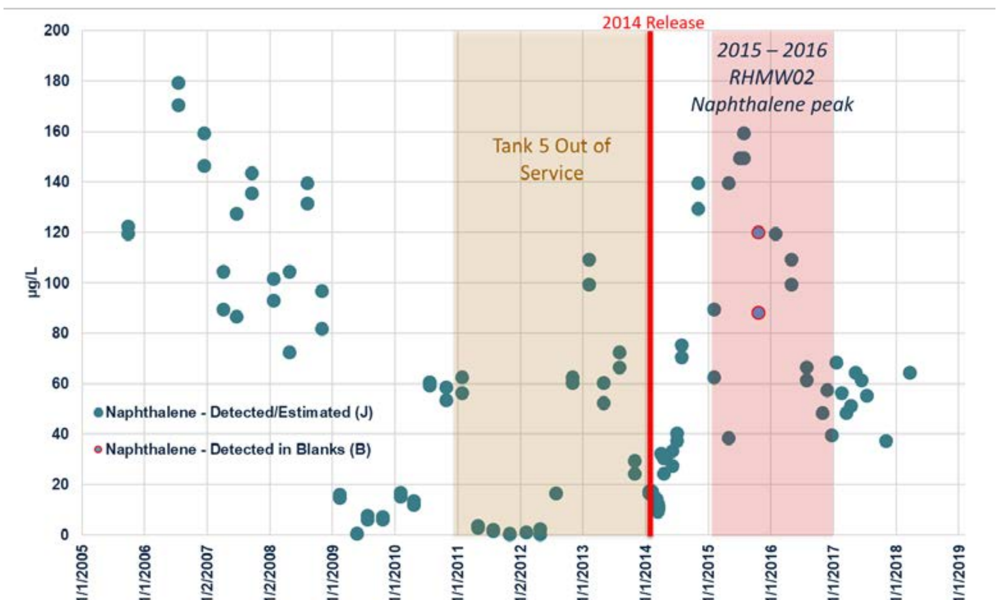
Based on the porosity and LNAPL residual saturation in High-Permeability A‘ā Clinker further discussed in Section 4.4.4, the total available High-Permeability A‘ā Clinker in the wedge held 1,700 gallons of LNAPL. The remaining 25,300 gallons of LNAPL released in 2014 were assumed to be retained within in the High-Permeability Pāhoehoe. By dividing the total volume of available High-Permeability Pāhoehoe by the remaining gallons of LNAPL, the specific retention of LNAPL within the High-Permeability Pāhoehoe was determined as 0.031 gallon per ft^3 of basalt. This result can also be expressed as a more intuitive metric of “inverse specific retention.” This metric indicates how many cubic feet of High-Permeability Pāhoehoe are needed to retain one gallon of LNAPL. The inverse specific retention of the High-Permeability Pāhoehoe is 33 ft^3 of basalt/gallon of LNAPL.

The estimation of the specific retention of High-Permeability Pāhoehoe does not assume that the entire impacted volume in the vadose zone was filled in a uniform manner, but rather is based on the extent of LNAPL migration from the Tank 5 release inferred based on available investigation results. Therefore, this specific retention value accounts for site specific geology and heterogeneity in migration pathways. The resulting specific retention is not the “field capacity” of the basalt (i.e., it does not reflect the maximum retention capacity expected if the basalt were completely filled with LNAPL and then allowed to gravity drain). By basing the specific retention of the High-Permeability Pāhoehoe on the 2014 Tank Release, the resulting holding capacity accounts for the incomplete filling associated with an actual release accounting for flow planes and fracture bypassed in a release.

3.2 Application of Tank 5 Release Data to Estimate Impacts to Red Hill Shaft for Evaluation 2

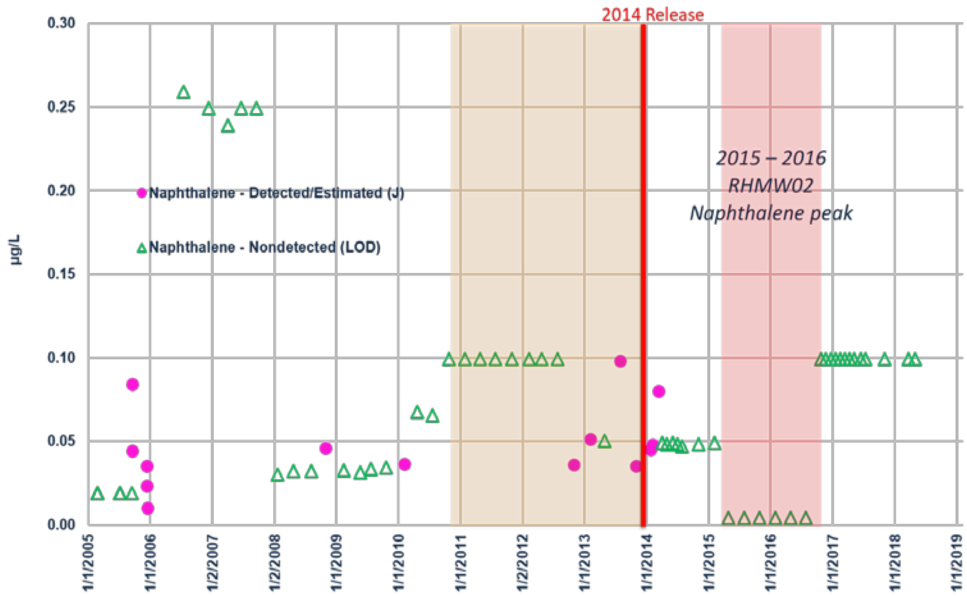
As discussed in Section 5.2 of CSM Appendix B.7 (DON 2018), the available monitoring dataset, considered as a whole, indicates that it is likely the 2014 Tank 5 release did not result in an impact to groundwater that was measurable above the existing impacts associated with older releases. However, based on feedback from DOH and other stakeholders, for Evaluation 2, the 2014 release of approximately 27,000 gallons from Tank 5 is assumed to have impacted groundwater at the Facility (although forensic analysis of the data indicates it is likely that the 2014 release did not impact groundwater and impacts to groundwater are more likely attributable to historical leaks). This evaluation focuses on naphthalene concentrations in RHMW02 and Red Hill Shaft because naphthalene is the individual COPC detected most frequently and at the highest concentration, and Red Hill Shaft captures all the groundwater from the area in and around the tanks. Naphthalene monitoring results for RHMW02 and Red Hill Shaft are presented on Figure 6 and Figure 7.

Evaluation 2 does not rely on any specific assumptions regarding the fate and transport of LNAPL for the 2014 Tank 5 release. However, LNAPL was not observed in any monitoring wells following the release.



Note: Concentrations in micrograms per liter (µg/L).

Figure 6: Naphthalene Concentration vs. Time Data at RHMW02



Note: Concentrations in µg/L.

Figure 7: Naphthalene Concentration vs. Time Data at Red Hill Shaft

4. Hypothetical Sudden Release Evaluation 1 - Methods and Results

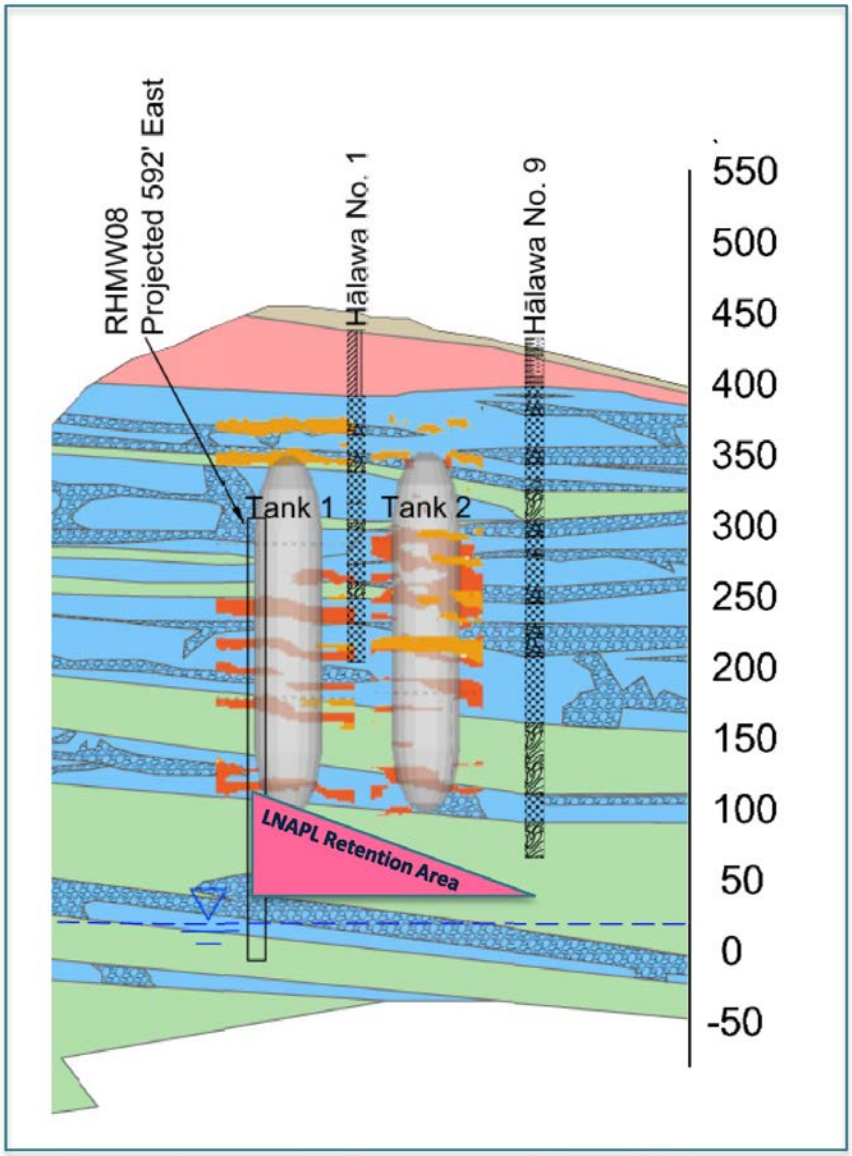
In addition to the specific retention analysis described in Section 3, the following assumptions and constraints were applied to Evaluation 1.

4.1 Assumed Nature of Sudden LNAPL Release

LNAPL holding capacity volumes were calculated for a hypothetical large, sudden release from Tank 2 to be protective of Red Hill Shaft. Tank 2 was used because it is the closest tank to Red Hill Shaft still in operation. The holding capacity for soils beneath tanks further up the hill would likely increase as the unsaturated zone thickness increases. The hypothetical, large sudden release was assumed to occur over a time scale of hours to days creating a pressure head sufficient to drive LNAPL into the adjacent basalt. Migration was assumed to occur laterally, down-dip and vertically toward the water table (Figure 8).

4.2 Shape of LNAPL Release in the Vadose Zone

As discussed in Section 3.1, Evaluation 1 uses the observations associated with the 2014 Tank 5 release indicating that a relatively large volume of LNAPL can be retained within the vadose zone.



Notes: Dark lines show borings that were used to construct cross section and do not indicate the location of water extraction wells.
Cross section sources: Hālawa No. 1, 9: (Macdonald 1941); red and orange around tanks represent clinker identified in As-Built Barrel Logs (DON 1943).

Figure 8: Approximate Lateral (Down-Dip) and Vertical Migration of LNAPL for Evaluation 1 for Most Likely Case

In addition to vertical migration through fractures and clinker bridges, the hypothetical large, sudden release was assumed to spread across dip and migrate down-dip due to the pressure of the released LNAPL and higher Kh of the layered basalt. The resulting area of impact would have a complex shape that could be approximated as a triangle, an ellipse, or a rectangle, with some fraction of the footprint area located up-dip of the release (Figure 9). All three of these footprints can be designed with the same area laterally while maintaining a similar width and down-dip length. As a result, when given the same vertical height, the shapes would have similar volumes resulting in similar LNAPL holding capacities.

Note: All three potential shapes have the same area and hold the same amount of LNAPL.

Figure 9: LNAPL Footprint Shapes Aligned to Dip of Lava Flows

For Evaluation 1, the area of the LNAPL footprint was modeled as a rectangle (bottom right panel on Figure 9). To account for the 11 degree geologic dip, the release volume was modeled to migrate into a wedge in the vadose zone as shown on Figure 10. The rectangular area was angled at 11 degrees following the geologic dip.

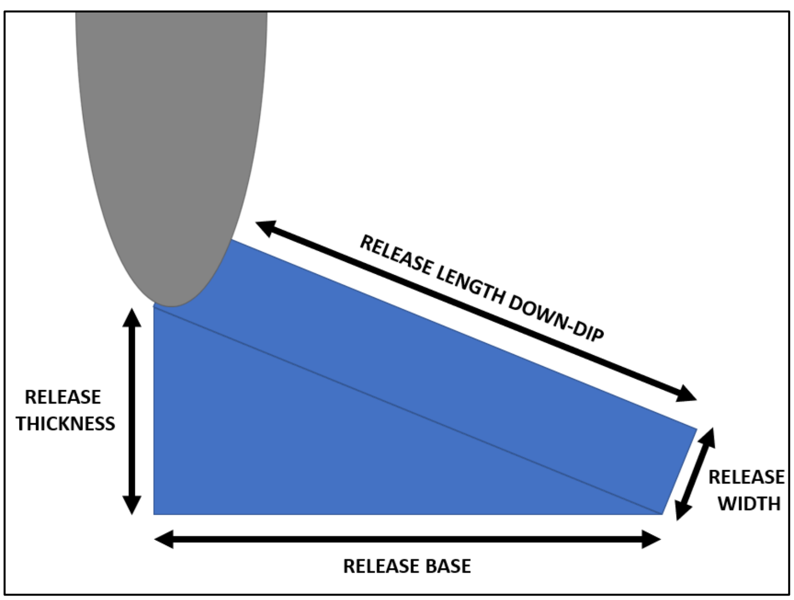


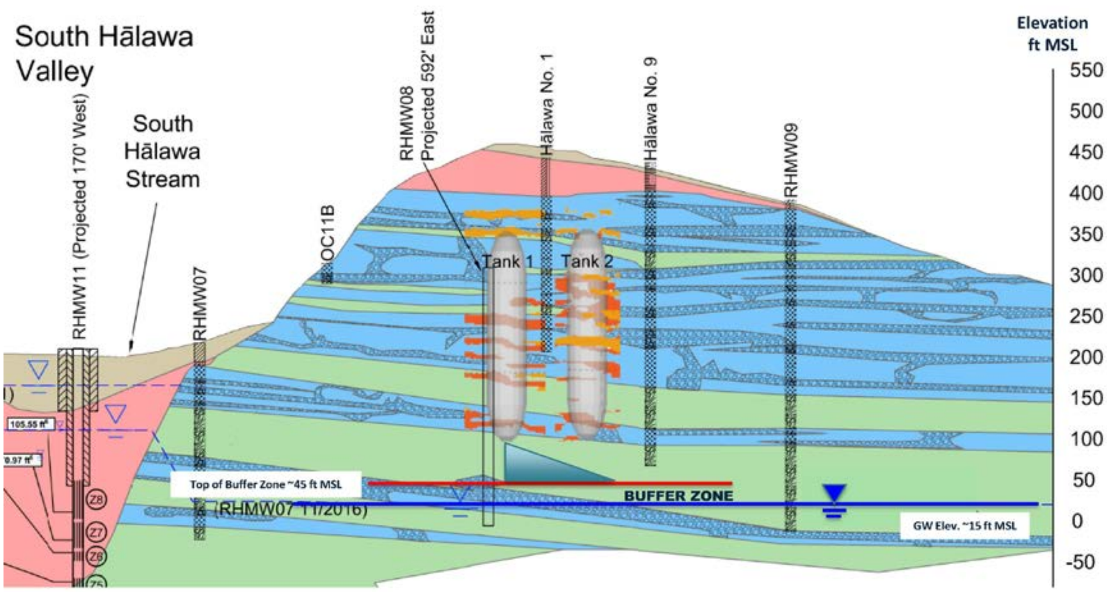
Figure 10: High Vadose Zone Wedge Schematic

4.3 EXTENT OF IMPACT CONSTRAINTS USED FOR RELEASE SCENARIO EVALUATION 1

For Evaluation 1, the volume of a hypothetical sudden, future release protective of groundwater at Red Hill Shaft was defined as the volume of LNAPL that would be retained within the vadose zone (i.e., mostly within the wedge shown on Figure 10) with minimal impacts to groundwater. In order to determine a release volume that would result in a minimal impact to groundwater, the following constraints were imposed on the size of this wedge:

1. *Minimal Migration of LNAPL to Groundwater:* Evaluation 1 calculated the volume of a hypothetical sudden, future release that would be retained mostly within the vadose zone. As discussed in Section 3, the LNAPL holding capacity of the basalt was estimated based on the inferred migration of LNAPL associated with the 2014 Tank 5 release. It was assumed that, after accounting for variability in the types of basalt within different geologic layers, the empirical LNAPL holding capacity determined for the Tank 5 release would be applicable to future releases.

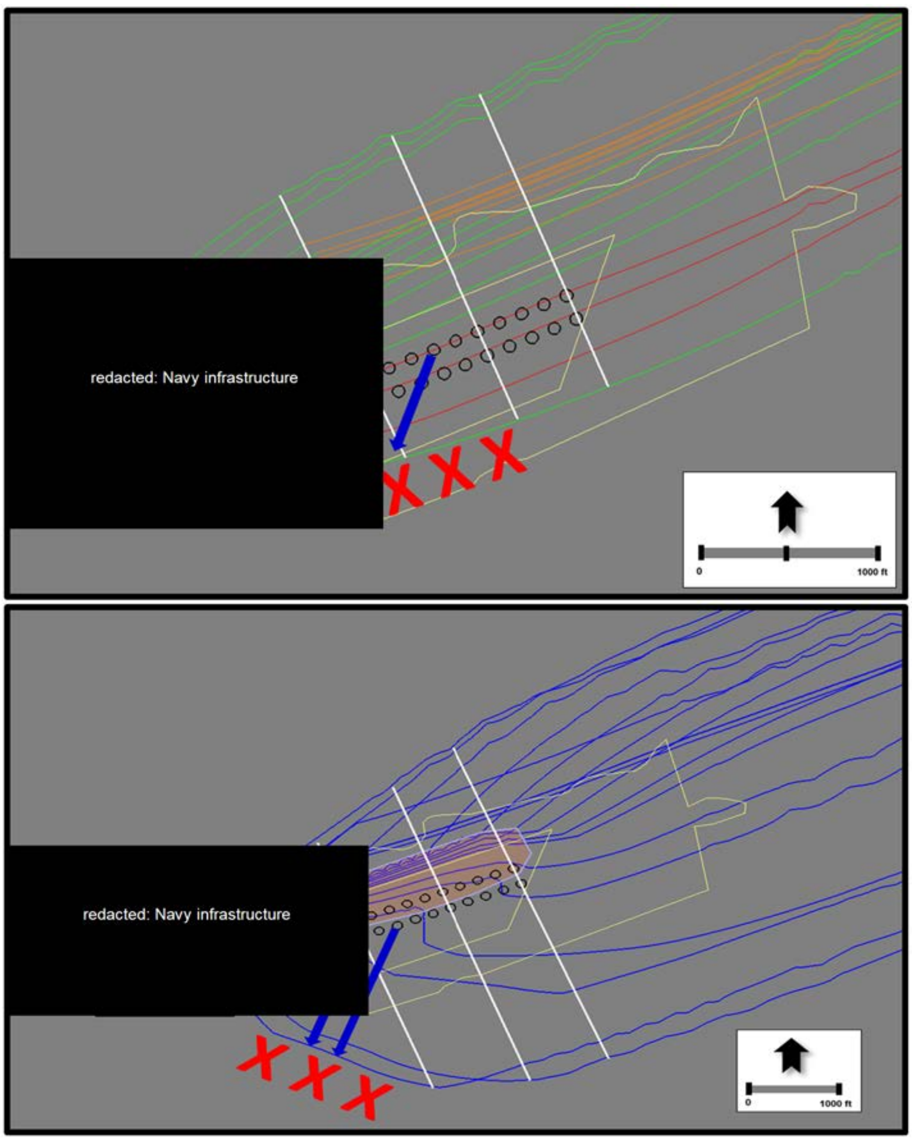
   While the bulk of the hypothetical future LNAPL release was assumed to be retained within a defined volume based on this empirical holding capacity, it was recognized that flow heterogeneity is likely to result in smaller amounts of LNAPL migration outside this volume. In order to minimize the impact to groundwater while accounting for this heterogeneity in LNAPL migration, a 30-ft vertical buffer was established between the top of the groundwater table and the lowest elevation to which the LNAPL can migrate (Figure 11). No holding capacity was assumed for this buffer zone, thereby providing an additional safety factor in the calculation. Note that even if a small amount of LNAPL were to reach the water table, natural attenuation of the resulting dissolved constituent plume would provide an additional safety factor for this calculation. As a very conservative approach, natural attenuation of COPCs in groundwater beneath the tanks to Red Hill Shaft was not accounted for at this time, even though there is strong evidence of ongoing natural attenuation in groundwater.



Notes: Approximate location of the most likely case LNAPL retention wedge shown in blue.
Figure source: CSM Figure 6-5
Cross section sources: RHMW07: (DON 2015); RHMW09: (DON 2017); Hālawa No. 1, 9: (Macdonald 1941); Outcrop OC11B: field notes 2017; as-built barrel logs (DON 1943)
measured groundwater elevation

Figure 11: Buffer Zone Between Base of LNAPL Retention Wedge and Water Table

2. *No Migration of LNAPL Outside of the Red Hill Shaft Capture Zone:* As shown on Figure 12, the tanks lie within the Red Hill Shaft Capture Zone (normal pumping conditions). However, a very large LNAPL release migrating south-southwest in the direction of the geologic dip could potentially migrate beyond the southern boundary of this capture zone. Two models were considered: Base Model and Clinker Model (Figure 12). In order to estimate the size of a hypothetical future sudden release that would not migrate beyond this capture zone boundary, the length of the LNAPL retention wedge was set to a length of less than or equal to the distance from the release tank to the capture zone boundary. The distance from Tank 2 to the southern capture zone boundary (as estimated using the interim groundwater flow model, both versions) is shown in Table 7. The Monte Carlo analysis (described in Section 4.4) included the capture zones for both model variations.



Note: For both panels, blue arrows follow the direction of the geologic dip and red Xs illustrate release scenario model constraint of no LNAPL migration outside of the capture zone.

Figure 12: Red Hill Shaft Groundwater Capture Zone Estimated Using the Interim Groundwater Flow Model - (top) Base Model Case and (bottom) Clinker Model Case

Table 7: Maximum Release Lengths Down-Dip for Tank 2

GW Flow Model	Maximum Release Length Down-Dip (ft)
Base	700
Clinker	1,600

3. *Previous Releases Already Fill Some of the Vadose Zone Holding Capacity:* For each individual tank, the release volume has been adjusted to reflect the vadose zone holding capacity likely already occupied by past historical releases. This adjustment is described in Section 4.6.
4. *Up-Dip Migration:* The vadose zone retention wedge was assumed to never extend beyond the edge of the tank in up-dip direction of the geological layers.

4.4 Release Volume Calculations

For Evaluation 1, the volume of a hypothetical sudden, future release protective of groundwater at Red Hill Shaft has been defined as the volume of LNAPL that would be retained within the vadose zone (i.e., mostly within the wedge shown on Figure 10) with minimal impacts to groundwater. To account for uncertainty associated with the site geology and other factors associated with the vadose zone LNAPL holding capacity, calculation input parameters were defined using a range of values covering the most likely value and the probable range. A Monte Carlo analysis was used to determine a range of release volumes consistent with the range of input parameter values.

4.4.1 Monte Carlo Analysis

Because of the uncertainty in some of the input data, a commonly used statistical analysis called the Monte Carlo technique was used to develop the most likely range of LNAPL holding capacities for a large, sudden hypothetical release. The Monte Carlo technique is a method of analyzing and quantifying uncertainties in model outputs due to the uncertainties in the input parameters (Rong, Wang, and Chou 1998). This technique uses random selection within a probability distribution between a specified range to obtain an approximation for the parameter of interest (EPA 1997; Bergin and Milford 2000). This technique allows one to enter a potential range for input data rather than relying on a single value.

In the Monte Carlo approach, an input parameter is defined using a statistical distribution rather than a single value. Repeated random sampling of the distributions is performed. For this evaluation, key input parameters were defined using a triangular distribution where the randomly selected input value is more frequently closer to the most likely value and less frequently reflects extreme ends of the specified range (either extreme on the high side of the statistical distribution or extreme on the low side of the statistical distribution). The calculations are run thousands of times with each run called a "realization" of the system being modeled. With a large number of possible distributions, a statistical description of the answer can be provided, yielding the most likely answer along with a range that reflects the level of uncertainty in all the input data.

In 1997, the EPA published the "Guiding Principles for Monte Carlo Analysis" for environmental applications, stating:

> Such probabilistic analysis techniques as Monte Carlo analysis, given adequate supporting data and credible assumptions, can be viable statistical tools for analyzing variability and uncertainty in risk assessments.

For the LNAPL holding capacity analysis, Monte Carlo analysis was performed using an Excel add-in (Structured Data LLC, n.d.) (Attachment 2). Triangular distributions were developed for key input data where three values were applied based onsite data, values in the scientific literature, or engineering judgment:

1. *The least conservative value* (the value that would represent an extreme value, unlikely but possible) that would increase the LNAPL holding capacity
2. *The most likely value* (the most likely value for that parameter) the most accurate estimation of actual LNAPL holding capacity
3. *The more conservative value* (the value that would represent an extreme value, unlikely but possible) that would decrease the LNAPL holding capacity

In this discussion, conservative values are those that underestimate the LNAPL holding capacity. When the Monte Carlo analysis is run in this way, the result is not a single value but a statistical distribution of the values. For this project, the median (middle) value of all the different "realizations" was used as the working estimate for the holding capacity in each scenario.

4.4.2 Determining LNAPL Retention Wedge Volume

As discussed in Section 4.2, Evaluation 1 assumed that a hypothetical release would migrate through a wedge-shaped volume defined by the release elevation (or, more precisely, the elevation at which the release leaves the edge of the tank and enters the basalt) and the dip angle of the geologic layers. The volume of LNAPL from a hypothetical sudden release that would be retained mostly in the vadose zone depends on the elevation at which the release enters the basalt. Because this value is uncertain, it was included as a variable in the Monte Carlo analysis covering a range of possible values:

1. *Least conservative value: 245 ft msl* - This is the elevation of the midpoint of the tank. Any release occurring at a higher elevation is assumed to migrate along the outside of the tank before entering the basalt at this elevation.
2. *Most likely value*: *160 ft msl* - This elevation is near the base of the tank and is the elevation at which the tank curves sharply inward (reference the report with the tank drawing). Any release occurring at a higher elevation is assumed to migrate along the outside of the tank before entering the basalt at this elevation or at a lower elevation.
3. *More conservative value: 105 ft msl* - This is the elevation of the base of the lower access tunnel. This would account for a failure of a pipeline within the lower access tunnel.

For Evaluation 1, the base of the LNAPL retention wedge was set at a fixed elevation of 45 ft msl (approximately 30 ft above the top of the water table). This approximately 30-ft buffer distance accounts for heterogeneity in the vadose zone and possible fingering of a release through individual flow fractures. A buffer was used to ensure that the resulting calculated release volume would be retained primarily within the vadose such that fingering outside of the LNAPL retention wedge would result in, at most, minor impacts to groundwater.

For each iteration of the Monte Carlo analysis, the total volume of the LNAPL retention wedge is defined by (1) the selected release elevation (between 105 ft and 245 ft msl), (2) the elevation of the base of the LNAPL retention wedge (45 ft msl), (3) the migration distance in the down-dip direction (calculated based on the difference between the release elevation and the base elevation and 11 degree dip of the geologic layers, and (4) lateral spreading equal to one-third of the migration length in the down-dip direction. For example, the dimensions for the most likely release elevation of 160 ft msl are: 600-ft release length down-dip, 590-ft base, and a 200-ft release width. An example of this volume calculation is provided in Attachment 1. The range of possible volumes for the LNAPL Retention Wedge is 970,000 ft^3 (based on the more conservative release height) to 36,000,000 ft^3 (based on the least conservative release height).

4.4.3 Determining the Geologic Composition of the LNAPL Retention Wedge

As discussed in Section 3, within the LNAPL retention wedge, the LNAPL was assumed to be retained within the High-Permeability A'ā Clinker and the High-Permeability Thin Pāhoehoe Flows. Therefore, further analysis was conducted to determine the volume of these media within the LNAPL retention wedge.

As illustrated on Figure 13, the specific geologic zones covered by the LNAPL retention wedge depend on the elevation at which the hypothetical LNAPL release enters the basalt and the elevation of the buffer zone. As shown in the figure, a release entering the basalt at a higher elevation (e.g., 160 ft msl, near where the vertical portion of the tank transitions to the bottom curved portion) would impact geologic zones F, A, B, and C, while a release entering the basalt at a lower elevation (e.g., 105 ft msl, below the tunnel) would impact only zones B and C.

A hypothetical release entering the basalt at an elevation of 160 ft msl (i.e., the most likely value from Section 4.4.2) would impact a wedge with a total volume of 6,800,000 ft^3 (using a base elevation of 45 ft msl). This seems like a reasonable assumption, given that the thermal signature in RHMW02 (near Tank 5) starts at the top of the well (indicating that soils would be affected above this elevation) and that there was staining on the wall of the tunnel above the bottom of Tank 5. The volume for each of the geological zones is shown in Table 8.

Table 8: Volumes of Geological Zones for a Hypothetical Release Elevation of 160 ft msl

Zone	Tank 2 (ft^3)
F	320,000
A	1,200,000
B	2,200,000
C	3,100,000

Note: See Attachment 1 for an explanation of the zone volume calculations.

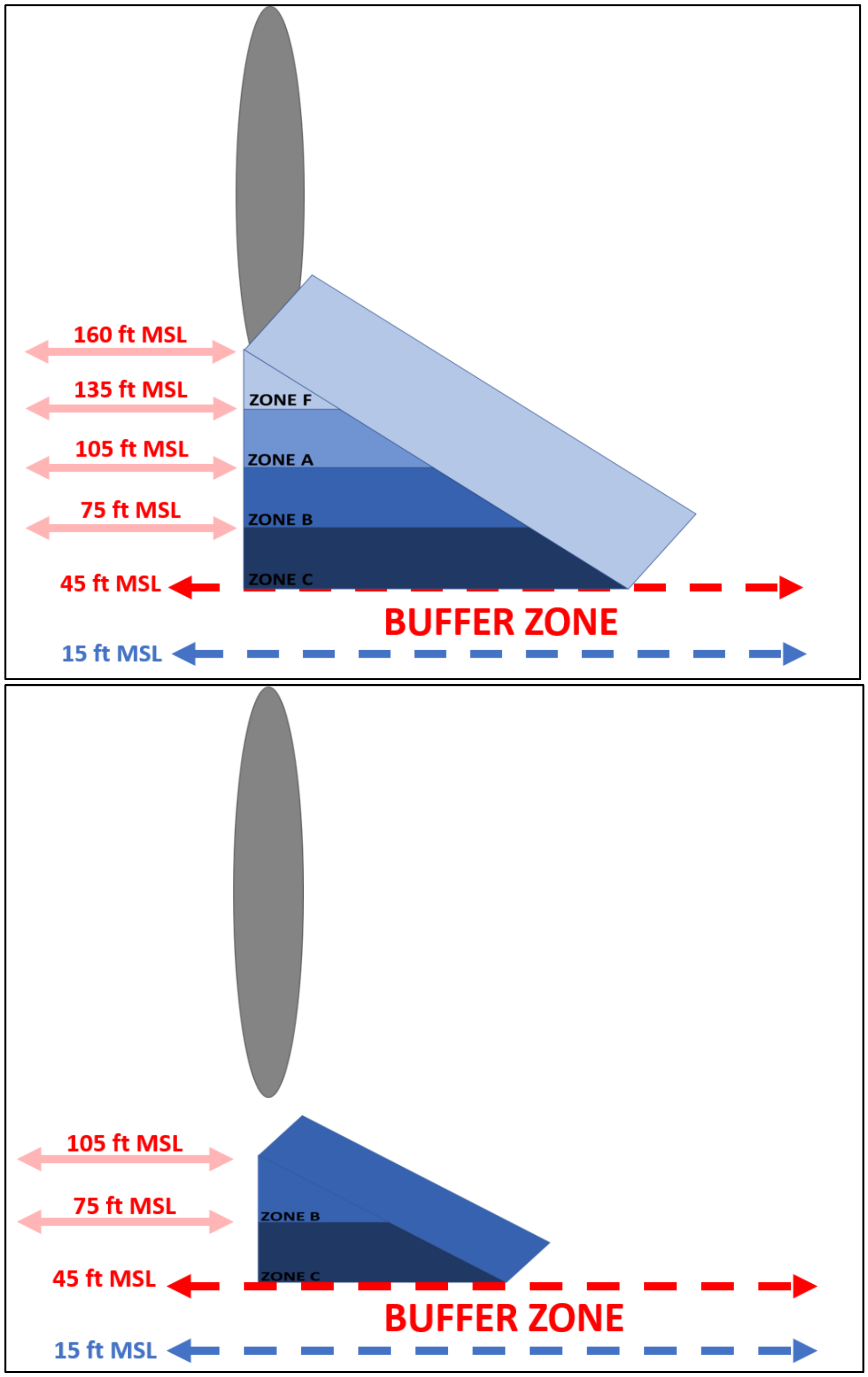


Figure 13: Geological Zones in the LNAPL Retention Wedge for a Hypothetical LNAPL Release from Tank 2 Entering the Basalt at Elevations of (top) 160 ft msl and (bottom) 105 ft msl

As discussed in Section 3.1, each of these geologic zones has a different proportion of Massive Pāhoehoe, High-Permeability Thin Pāhoehoe Flows, Massive A'ā, Clinker with FGS, and High-Permeability A'ā Clinker. Table 3 and Table 4 present the best estimate values for each zone. To account for uncertainty in these values, ranges were used in the Monte Carlo analysis (Table 9).

Table 9: Ranges of Values Used in the Monte Carlo Analysis

Zone	Least Conservative	Most Likely	More Conservative
% Total Pāhoehoe			
F	17%	11%	6%
A	100%	70%	35%
B	95%	63%	32%
C	100%	80%	40%
High-Permeability Thin Pāhoehoe Flows (as a percent of Total Pāhoehoe)			
F	99%	90%	75%
A	99%	90%	75%
B	99%	90%	75%
C	99%	90%	75%
Total A‘ā Clinker (as a percent of Total A‘ā)			
F	47%	29%	14%
A	5%	23%	0%
B	1%	0.11%	0.03%
C	0%	10%	2%
High-Permeability A‘ā Clinker (as a percent of Clinker)			
F	60%	40%	20%
A	60%	40%	20%
B	60%	40%	20%
C	60%	40%	20%

Note: For each Monte Carlo iteration, Total A‘ā is calculated as 100% - Total Pāhoehoe.

The most likely values are the same as those presented in Section 3.

For Total Pāhoehoe, High-Permeability Thin Pāhoehoe Flows, Total A‘ā Clinker, and High-Permeability A‘ā Clinker the less conservative values were 150% of the most likely value and the more conservative values were 50% of the most likely value. For % Clinker in Total A‘ā, the range of values was determined by dividing the Clinker in the given zone by the Total A‘ā in the zone. A triangular distribution was not generated for the Total A‘ā was not run in RiskAMP as it was calculated based on the Total Pāhoehoe values.

4.4.4 Determining Volume of LNAPL Held in High-Permeability A‘ā Clinker

To determine the volume of LNAPL held in the High-Permeability A‘ā Clinker in the retention wedge, the porosity and residual saturation of LNAPL of High-Permeability A‘ā Clinker were used.

A range of values were used to create a triangular distribution in the Risk Amp Model for both characteristics (Table 10).

Table 10: High-Permeability A‘ā Clinker Characteristics

Variable	Zone	Less Conservative	Most Likely	More Conservative	Unit
Porosity of High-Permeability A‘ā Clinker	All	0.60	0.50	0.25	(-)
LNAPL Residual Saturation in High-Permeability A‘ā Clinker	All	0.15	0.056	0.01	(-)

Porosity of High-Permeability A‘ā Clinker Units: The “most likely” value is 0.5 based on laboratory values (Ishizaki, Burbank, Jr., and Lau 1967). The “more conservative” case uses an estimated value of 0.25, half of the “most likely” value. The “less conservative” case uses an estimated value of 0.6.

Residual Saturation of High-Permeability A‘ā Clinker Units: The LNAPL residual saturation is defined as the fraction of the pore space that retains the LNAPL after LNAPL flow stops. Residual saturation from gravels was used to develop the triangular distribution for the vadose zone. The most likely value of 0.056 was the mean of 12 environmental gravel samples (11 of which contained measurable LNAPL) reported by Brady and Kunkel (2003). The “less conservative” value of 0.152 was the maximum value from the same source. The “more conservative” value is half of the value reported in gravel data interpreted by Brost and DeVaull (2000) from a lab experiment originally performed by Fussell et al. (1981). Their value of 2% for residual saturation was reduced by half as a conservative measure.

For each zone, the volume of available High-Permeability A‘ā Clinker was multiplied by the porosity and residual saturation of High-Permeability A‘ā Clinker. The result was the volume of LNAPL held in the High-Permeability A‘ā Clinker in each zone.

4.4.5 Determining Volume of LNAPL Held in High-Permeability Thin Pāhoehoe Flows

The volume of LNAPL retained in the High-Permeability Pāhoehoe Flows was calculated as the volume of High-Permeability Thin Pāhoehoe Flows in each zone divided by the inverse specific retention. The most likely value for inverse specific retention, 33 ft^3 of basalt per gallon of LNAPL, was the value calculated in Section 3.1. To account for the uncertainty in the inverse specific retention, this value was divided by a factor of two to provide a “less conservative” estimate and then multiplied by two to get a more conservative estimate (Table 11).

Table 11: High-Permeability Pāhoehoe Characteristics

Variable	Less Conservative	Most Likely	More Conservative
Inverse Specific Retention for High-Permeability Pāhoehoe	66	33	17

4.4.6 Overview of Calculation Steps

In summary, the following variables were determined for the Monte Carlo analysis using a triangular distribution through the RiskAMP software:

- % A‘ā Clinker as a % of Total Clinker
- % High-Permeability A‘ā Clinker
- % Massive Pāhoehoe Flows
- % High-Permeability Thin Pāhoehoe Flows

- Porosity of High-Permeability A'ā Clinker
- LNAPL Residual Saturation of High-Permeability A'ā Clinker
- Inverse Specific Retention for High-Permeability Thin Pāhoehoe Flows
- Release Elevation

For the most sensitive input parameters, the "most likely" value was selected to be reasonably conservative and the most "conservative value" was selected to be highly conservative. For example, the "most likely" release elevation was selected to be close to the bottom of fuel tank and the "more conservative" release elevation was selected as the elevation of the elevation of the bottom of the lower access tunnel. This conservative bias in the input distributions ensured that the large majority of the individual Monte Carlo iterations would also be conservative and protective.

Monte Carlo simulations were performed using the RiskAMP software. A total of 10,000 realizations were performed for each analysis. The Latin Hypercube option, a numerical technique that improves the accuracy of the distribution of the tails was used.

For each zone, the volume of LNAPL held in the two highly permeable media were summed. The volume of LNAPL in each zone was then summed to obtain the LNAPL holding capacity. The RiskAMP software was run on the total LNAPL held in the retention wedge.

4.5 EVALUATION 1 RESULTS

Each of the 10,000 Monte Carlo realizations yielded a separate estimate of the volume of LNAPL from a future hypothetical sudden release that would be retained mostly within the vadose zone resulting in, at most, minimal impacts to groundwater. These 10,000 realizations were utilized to determine three release volume estimates.

4.5.1 More Conservative and Protective Low-End Release Volume Estimate

The 10th percentile release volume from the Monte Carlo analysis (48,000 gallons) was selected as the more conservative and protective low-end release volume estimate for a sudden release that would be retained mostly within the vadose zone. The Monte Carlo process yields this low-end release volume estimate only when the random input value selection process yields a more conservative end input value for several of the input parameters included in the Monte Carlo analysis. As a result, this release volume can be considered very conservative and very protective.

Finding: A hypothetical sudden release of 48,000 gallons of jet fuel would be mostly retained in the vadose zone and would be protective for users of groundwater; *very high confidence.*

4.5.2 Conservative and Protective Mid-Range Release Volume Estimate

The 50th percentile release volume from the Monte Carlo analysis (150,000 gallons) was selected as the conservative and protective mid-range release volume estimate for a sudden release that would be retained mostly within the vadose zone. Because the input parameter distributions for key input parameters were biased toward the conservative side of the uncertainty, the 50th percentile release estimate volume can be considered protective with high confidence.

Finding: A hypothetical sudden release of 150,000 gallons of jet fuel would be mostly retained in the vadose zone and would be protective for users of groundwater; *high confidence.*

4.5.3 Less Conservative High-End Release Volume Estimate

The 90th percentile release volume from the Monte Carlo analysis (400,000 gallons) was selected as the less conservative high-end release volume estimate for a sudden release that would be retained mostly within the vadose zone. Although a release of this volume would likely be mostly retained within the vadose zone, there is less confidence that such a release would have only a minimal impact on groundwater. It is more likely that this higher-end release volume would be protective for a hypothetical release from one of the tanks further away from Red Hill Shaft (i.e., Tanks 11–20).

Finding: A hypothetical sudden release of 400,000 gallons of jet fuel would be mostly retained in the vadose zone and would be protective for users of groundwater; *lower confidence.*

4.6 Effect of Prior Releases on a Hypothetical Future Release

As discussed in Section 3 of the main report, the available investigation results and LTM data provide evidence of historical releases of LNAPL and one more recent release (i.e., the 2014 Tank 5 release). The occurrence of historical fuel releases (i.e., releases that may have occurred before 1998–2002) has been characterized through the completion of angled borings below each tank between 1998 and 2002 (see Figure 14). These results indicate historical LNAPL releases from several of the tanks; however, the timing and magnitude of these releases cannot be determined. As shown on Figure 3:

- LNAPL staining and/or sheens were observed below Tanks 01 (no longer in service), 09, 11, 13, 14, and 16 → *Strong Evidence of Prior Releases.*
- Petroleum odors (but no staining or sheens) were observed below Tanks 02, 03, 04, 05, 06, 07, 08, 12, 18, 19 (no longer in service), and 20 → *Weaker Evidence of Prior Releases.*
- No evidence of petroleum impacts was observed below Tanks 10, 15, and 17.

The LTM monitoring dataset indicates that it is likely that no releases have impacted groundwater since 2005 and only one recent release impacted the below-tank soil vapor wells since 2008 (i.e., the 2014 release from Tank 5).

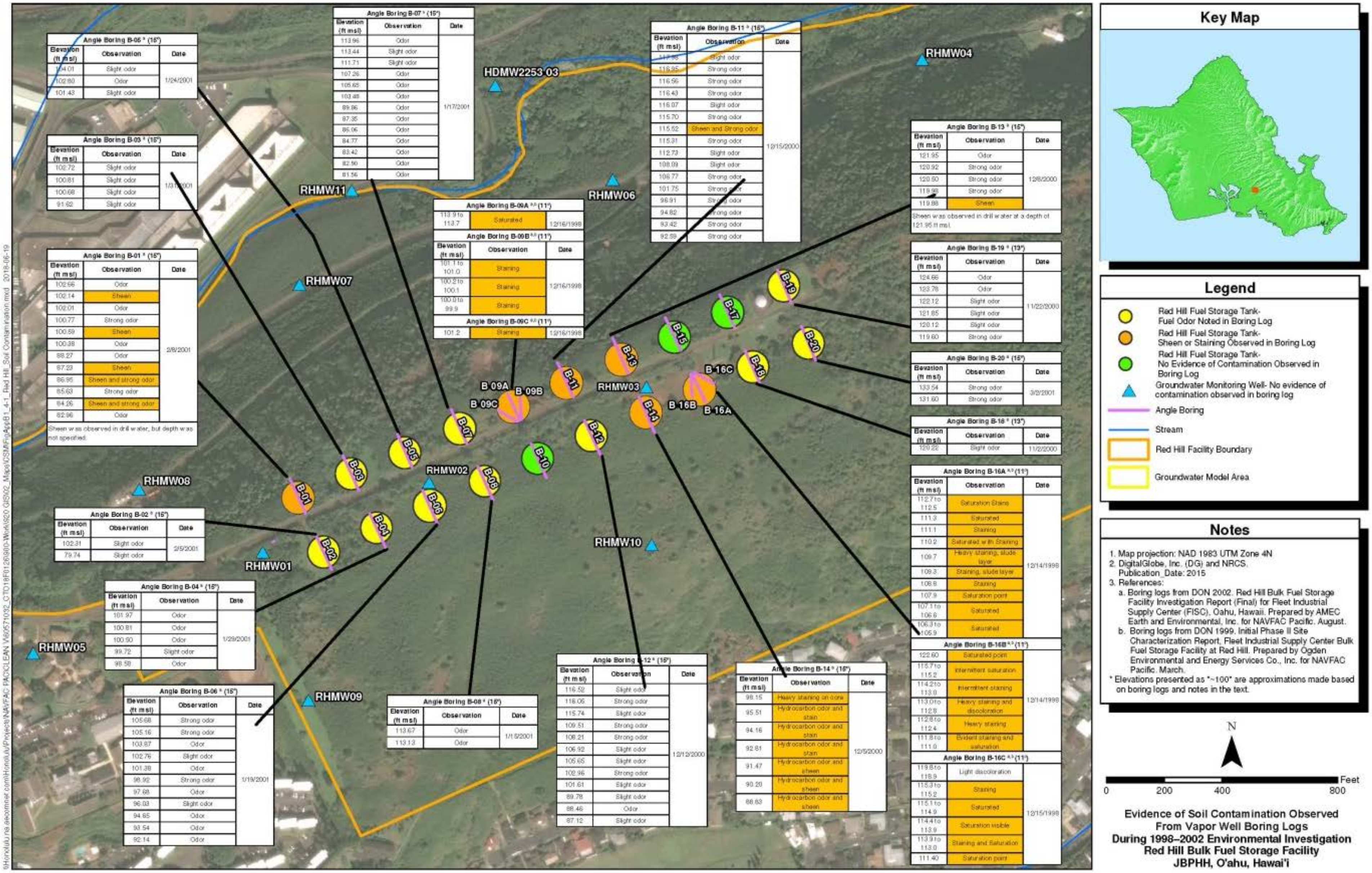


Figure 14: Evidence of Soil Contamination Observed at Each Tank (DON 1999, 2002)

These prior releases likely occupy some of the LNAPL holding capacity within the vadose zone reducing the volume for a hypothetical future release that would be retained in the vadose zone before impacting groundwater. The following factors were considered for estimating how much of the vadose zone retention volume is likely occupied by prior releases:

- Based on the temperature profiles for Facility wells, LNAPL is inferred to be present within the top 30–40% of the vadose zone between the lower access tunnel and the water table (i.e., within a depth interval of 70–110 ft msl). The absence of heat generation below an elevation of 70 ft msl indicates minimal amounts of LNAPL below this depth (see main report Section 3 and CSM Appendix B.1; DON 2018).
- The available monitoring data indicate that the LNAPL present in the subsurface (including the 2014 Tank 5 release) has undergone extensive physical weathering (i.e., volatilization of light-end constituents) and biological weathering (see main report Section 3 and CSM Appendix B.3; DON 2018). This indicates that, within the area impacted by prior releases, 50% to 80% of the LNAPL has been degraded or volatilized.
- Biodegradation of LNAPL within the vadose zone in ongoing (main report Section 6 and CSM Appendix B.1 and B.2; DON 2018). As a result, the portion of the vadose zone LNAPL holding capacity occupied by prior releases will continue to decrease over time.

Based on these considerations, the following is recommended to account for prior release:

- *Tanks with Strong Evidence of Prior Releases (Tanks 9, 11, 13, 14, and 16):* Reduce the hypothetical future release volume by 25%.
- *Tanks with Weaker Evidence of Prior Releases (Tanks 2, 3, 4, 5, 6, 7, 8, 12, 18, and 20):* Reduce the hypothetical future release volume by 10%.

For tanks with strong evidence of prior releases, a reduction of 25% is suggested. LNAPL was assumed to have migrated to the top 30–40% of the vadose zone between the lower access tunnel and water table. The LNAPL was partially degraded or volatilized reducing the LNAPL remaining in the vadose zone. Based on those assumptions, 25% of the vadose zone was assumed to still be filled with LNAPL.

For tanks with weaker evidence of prior releases, a reduction of 10% was assumed as a conservative measure, as no staining or sheen was observed beneath the tanks.

5. Sudden Release Evaluation 2 Methods and Results

As discussed in Section 3.2, Evaluation 2 uses the assumption that the 2014 Tank 5 release did impact groundwater (per Regulatory Agency comments) resulting in an increase in dissolved naphthalene concentrations in RHMW02. As previously stated in this document, forensic data do not indicate this to be the case, especially considering the forensic analysis of the data. Based on this assumption, the observed naphthalene concentrations in Red Hill Shaft from 2014 to 2018 have been used to develop estimates of hypothetical future sudden LNAPL release volumes that would not cause an RBDC exceedance in Red Hill Shaft.

5.1 Evaluation of Naphthalene Monitoring Results

This evaluation focuses on naphthalene concentrations in RHMW02 and Red Hill Shaft because naphthalene is the individual COPC detected most frequently and at the highest concentration. Therefore, within the context of the Evaluation 2 assumption that the 2014 Tank 5 release did impact groundwater, naphthalene appears to be the most appropriate indicator COPC.

From the initiation of the LTM in 2005 through May 2018, naphthalene was detected in Red Hill Shaft samples in 12 of 63 monitoring events at concentrations ranging from 0.011 to 0.099 µg/L. For the remaining Red Hill Shaft sampling events, naphthalene was reported as non-detect with a limit of detection (LOD) ranging from 0.005 µg/L to 0.26 µg/L. However, the review of LTM results conducted for the CSM identified a significant degree of uncertainty regarding the reliability analytical results indicating detections of COPCs at very low concentrations of less than 0.1 µg/L (CSM Appendix B.7; DON 2018). Many, and possibly all, of these low detections appear to be artifacts and not indicative of the actual presence of these COPCs in groundwater. The monitoring record for Red Hill Shaft provides strong evidence that naphthalene has not been at a concentration of greater than 0.1 µg/L during the time period of 2005 to present; however, there is some uncertainty concerning the occasional presence or absence of naphthalene in Red Hill Shaft at concentrations of less than 0.1 µg/L. Regardless of this uncertainty, for Evaluation 2, all detections of naphthalene in Red Hill Shaft were assumed to indicate the actual presence of naphthalene in groundwater. Using this assumption, Evaluation 2 focused on the monitoring results for the three time periods shown in Table 12:

Table 12: 2013 Naphthalene Concentrations at Red Hill Shaft

Date	Naphthalene (µg/L)
2013: Year Preceding Tank 5 Release (January 2013 to December 2013)	
1/29/13	0.052 J
4/23/13	*<0.051*
7/23/13	0.099 J
10/22/13	0.036 J
Average	0.059*
2014: Year After Tank 5 Release (January 2014 to December 2014)	
01/16/2014	0.046 J
01/29/2014	0.049 J
03/6/2014	0.081 J
03/26/2014	<0.050
04/22/2014	<0.049
05/28/2014	<0.050
06/24/2014	<0.049
07/22/2014	<0.048
10/28/2014	<0.049
Average	0.052*
2015–2016: Post-Tank 5 Release Period with Highest Naphthalene Concentration in RHMW04 (April 2015 to July 2016)	
4/21/2015	<0.0050
7/21/2015	<0.0050
10/20/2015	<0.0050
1/20/2016	<0.0050
4/20/2016	<0.0050
7/20/2016	<0.0050
Average	0.005*

* LOD used as proxy for non-detect results.

As described below, these monitoring periods were used to determine three hypothetical large sudden release LNAPL volumes would not cause unacceptable impacts (defined as an exceedance of the naphthalene RBDC of 0.17 µg/L) at Red Hill Shaft: low-end, mid-range, and high-end release volumes.

5.2 Evaluation of Release Location

Evaluation 2 uses a simplifying assumption that the impact to Red Hill Shaft from a hypothetical future sudden release would be similar to (or proportional to) the impact from the 2014 Tank 5 release. Evaluation 2 does not explicitly account for the difference in the distance to Red Hill Shaft between different tanks. As shown in Table 13, the tanks vary in distance to Red Hill Shaft and, as a result, the travel time within groundwater also varies.

Table 13: Distance to Red Hill Shaft for Base Case and Clinker Groundwater Model

Tanks	Model	Distance to Red Hill Shaft (ft)	Travel Time (days)
1/2	Base Case	700	65
	Clinker	1,600	45
5/6	Base Case	800	95
	Clinker	1,900	45
9/10	Base Case	820	150
	Clinker	2,100	70
19/20	Base Case	900	280
	Clinker	2,900	130

Note: Travel time based on Interim Groundwater Flow Model.

For Tanks 2, 3, and 4, the use of the Tank 5 release for evaluation of future releases is potentially slightly non-conservative. However, the difference in distance and travel time is small suggesting that difference in release location is likely to have little effect on the impact to Red Hill Shaft. For the higher numbered tanks (i.e., Tanks 9/10 and above), the distance and travel time to Red Hill Shaft is significantly larger than for Tank 5. As a result, a release from these more distant tanks is less likely to impact to Red Hill Shaft.

5.3 Most Conservative and Protective Low-End Release Volume Estimate

The low-end release volume estimate was developed by comparing the average naphthalene concentration in Red Hill Shaft in 2013 (the year before the Tank 5 release) to the average concentration in 2014 (the year after the Tank 5 release). In 2014, the average naphthalene concentration in Red Hill Shaft was 0.052 µg/L, lower than the average concentration of 0.059 µg/L in 2013. This comparison indicates that the Tank 5 release resulted in no increase in naphthalene concentration in Red Hill Shaft. This observation indicates that a hypothetical future release of a similar magnitude would also result in no increase in concentration.

Finding: A future release of 27,000 gallons of jet fuel would not cause an exceedance of RBDC at Red Hill Shaft; *very high confidence.*

5.4 Conservative and Protective Mid-Range Release Volume Estimate

The mid-range release volume estimate considers only the monitoring results from 2014, the year after the Tank 5 release. Based on the assumption that the very low detections of naphthalene were indicative of the actual presence of naphthalene in Red Hill Shaft (very conservative as this is not supported by historical results), the 2014 average naphthalene concentration in Red Hill Shaft was 0.052 µg/L. For the mid-range estimate, this naphthalene concentration was assumed to be attributable to the Tank 5 release. In other words, it was assumed that the naphthalene concentration would have been zero in the absence of the Tank 5 release, which is very conservative as previously stated.

It was further assumed that, for a future release, the naphthalene concentration in Red Hill Shaft would be a linear function of the release volume. Based on this assumption, the hypothetical future release volume that would result in a naphthalene concentration that equaled (but did not exceed) the RBDC could be calculated as follows:

$$RBDC \div C_{avg\ 2014} = 0.17\frac{\mu g}{L} \div 0.052\frac{\mu g}{L} = 3.3\ times$$
$$3.3 \times 27{,}000\ gallons = 88{,}000\ gallons$$

Finding: A future release of 88,000 gallons of jet fuel would not cause an exceedance of RBDC at Red Hill Shaft; *high confidence.*

5.5 LESS CONSERVATIVE HIGH-END RELEASE VOLUME ESTIMATE

The high-end release volume estimate considered only the Red Hill Shaft monitoring results from March 2015 to July 2016. This is the post-Tank 5 release time period during which naphthalene concentrations in RHMW02 increased and then decreased (Figure 15). Although a lines-of-evidence evaluation indicates that this increase and decrease was not associated with the Tank 5 release, the DOH contaminant fate and transport subject matter expert has described this increase and decrease as "a classic breakthrough curve" and requested an evaluation based on the assumption that this was associated with the Tank 5 release.

During this same period, the naphthalene concentration in Red Hill Shaft was non-detect with a LOD of 0.005 µg/L (Figure 15 and Table 12).

For the less conservative evaluation, it was assumed that (1) naphthalene was present in Red Hill Shaft during this time period at a concentration equal to the LOD (0.0005 µg/L) and (2) for a future release, the naphthalene concentration in Red Hill Shaft would be a linear function of the release volume. Because the assumed naphthalene concentration in Red Hill Shaft was far below the RBDC, the assumption that the future concentration would be a linear function of the release volume is highly uncertain and may be non-conservative. However, this assumption was used to provide a range of future release volumes.

Based on this assumption, the hypothetical future release volume that would result in a naphthalene concentration that equaled (but did not exceed) the RBDC could be calculated as follows:

$$RBDC \div C_{avg\ 2015/16} = 0.17\frac{\mu g}{L} \div 0.005\frac{\mu g}{L} = 34\ times$$
$$34 \times 27{,}000\ gallons = 918{,}000\ gallons$$

Finding: A future release of 920,000 gallons of jet fuel would not cause an exceedance of RBDC at Red Hill Shaft; *low confidence.*

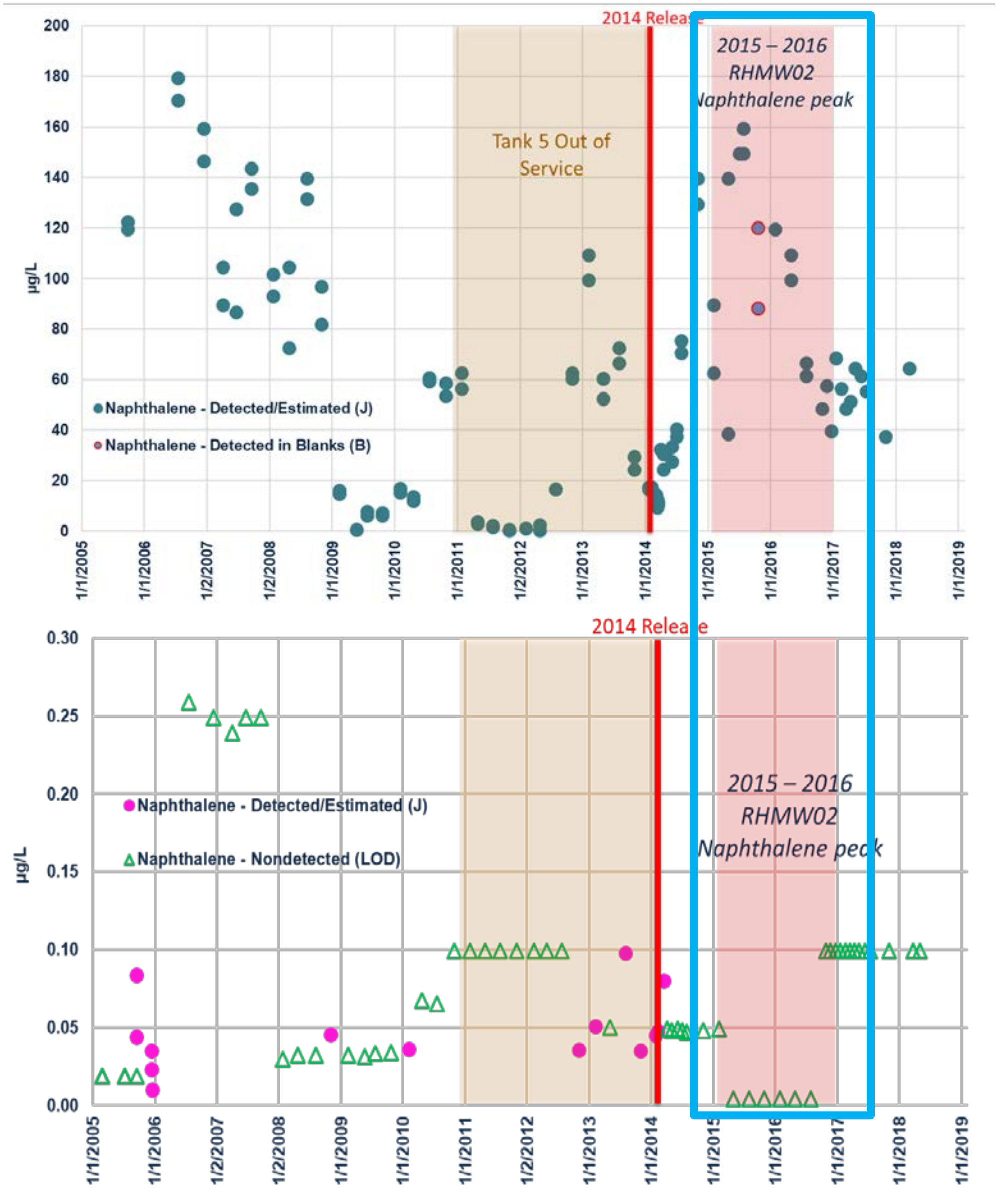


Figure 15: (top) Naphthalene Concentrations in RHMW02, Highlighting Naphthalene Breakthrough Curve from 2015–2016; (bottom) Naphthalene Concentrations in Red Hill Shaft, Highlighting Naphthalene Concentrations from 2015–2016 Corresponding to the Breakthrough Curve Observed in RHMW02

6. Conclusions

Historical results from the Red Hill LTM Program and other Facility investigations have been used to evaluate the fate of prior releases from the Facility tanks including the 2014 release of approximately 27,000 gallons of JP-8 from Tank 5. These data in turn, have been used estimate the possible impact of a hypothetical future sudden release from a tank. Specifically, a hypothetical future sudden release volume has been estimated that would be protective of Red Hill Shaft and other water supply wells (i.e., no exceedances of RBDC). The likely fate and transport of a future sudden release was evaluated based on two interpretations of the 2014 Tank 5 release:

- *Evaluation 1, Vadose Zone Retention Capacity*: Available monitoring data indicates that the 2014 release of 27,000 gallon of JP-8 from Tank 5 was likely retained within the top one-third of the vadose zone between the lower access tunnel and the water table with no significant impact to groundwater. Based on this finding, the 2014 release was used to estimate the vadose zone holding capacity for LNAPL along with site specific geologic data and data from scientific literature. This holding capacity was then used to evaluate the LNAPL volume that would be retained mostly or exclusively in the vadose zone for a hypothetical future release resulting in no significant impact to groundwater. A Monte Carlo model was used to obtain a range of release volumes accounting for uncertainty in vadose zone holding capacity and other site parameters. This approach is very conservative as it does not consider natural attenuation in groundwater.
- *Evaluation 2: Possible Impact to Groundwater*: Based on feedback from DOH and other stakeholders, the fate and transport of a hypothetical future release was evaluated based a second interpretation of the 2014 release. For this interpretation, the 2014 release was assumed to have impacted groundwater at the Facility (although forensic analysis of the data indicates it is likely that the 2014 release did not impact groundwater and impacts to groundwater are more likely attributable to historical leaks) and variations in dissolved COPC concentrations following the release were attributed to this release. The likely impact of a hypothetical future release was evaluated assuming a linear relationship between release volume and magnitude of impact to Red Hill Shaft.

Under either evaluation of the 2014 Tank 5 release, the approximately 27,000-gallon release of jet fuel:

- Did not result in the observation of LNAPL in any of the monitoring wells and the Facility.
- Did not result in any measurable increase in COPC concentrations in Red Hill Shaft.

These observations indicate that a hypothetical future sudden release from a Facility fuel tank would have to be larger than the 2014 release in order to result in an exceedance of RBDC in Red Hill Shaft and other water supply wells. The two evaluations focused on understanding and quantifying this "margin of safety" associated with the 2014 release in order to estimate the volume of a hypothetical future sudden release that would be protective of Red Hill Shaft (Table 14).

Table 14: Volume of a Hypothetical Future Sudden Release that Would be Protective of Red Hill Shaft

Estimate Type	Evaluation 1 (gallons)	Evaluation 2 (gallons)
More Conservative and Protective Low-End Volume	48,000	27,000
Conservative and Protective Mid-Range Volume	**150,000**	**88,000**
Less Conservative High-End Volume	400,000	920,000

- The more conservative volume estimate was based on a combination of conservative assumptions that serve to significantly overestimate the potential for a hypothetical future release to cause an unacceptable impact; therefore, this volume should be considered protective for all tanks with a very high degree of confidence.
- The conservative mid-range estimate was based on a mix of conservative and realistic assumptions that serve to provide a reasonably conservative overestimate the potential for a hypothetical future release to cause an unacceptable impact; therefore, this volume should be considered protective for all tanks with a high degree of confidence.

- The less conservative estimate utilized realistic assumptions and accounts for uncertainty in input parameters using a less conservative approach. The less conservative volume is likely to be protective a hypothetical release from a tank located further away from Red Hill Shaft (e.g., Tanks 11–20).

The following is recommended to account for prior release:

- *Tanks with Strong Evidence of Prior Releases* (Tanks 5, 9, 11, 13, 14, and 16): Reduce the hypothetical future release volume by 25%.
- *Tanks with Weaker Evidence of Prior Releases* (Tanks 2, 3, 4, 5, 6, 7, 8, 12, 18, and 20): Reduce the hypothetical future release volume by 10%.

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Attachment 1:
Explanation of Specific Retention LNAPL Retention Wedge Calculations

Goal: To determine the dimensions and the volume of high permeability media in the LNAPL Retention Wedge for the 2014 Tank 5 Release.

STEP 1: ESTABLISH 2014 TANK 5 RELEASE ELEVATIONS

Figure 1 illustrates the elevation breakdown of the 2014 Tank Release, as described in Section 3 of TUA Appendix B, and the geologic zones included in the estimated LNAPL retention wedge.

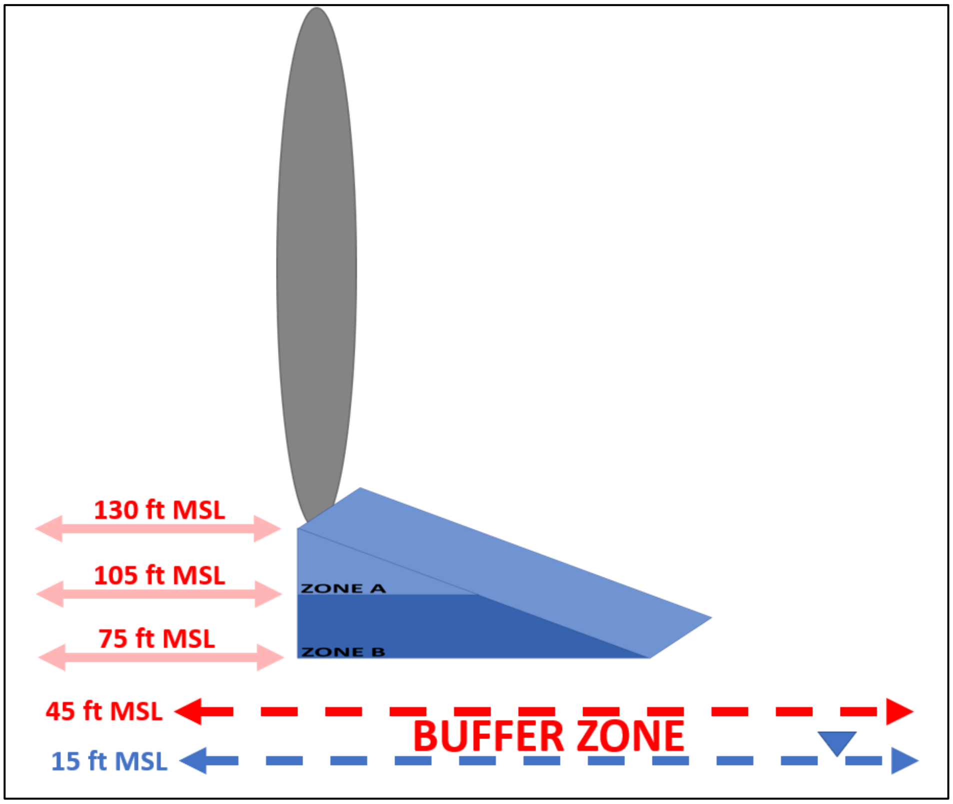


Figure 1: Schematic of LNAPL Retention Wedge for 2014 Tank 5 Release

The 2014 Tank 5 Release was estimated to enter the basalt at approximately 130 ft msl. The LNAPL was assumed to migrate to 75 ft msl, the bottom elevation of the release. The bottom of the LNAPL retention wedge is at the bottom elevation of the release. The top of the LNAPL retention wedge is at the top elevation of the release.

STEP 2: CALCULATE THE DIMENSIONS OF THE 2014 TANK 5 RELEASE LNAPL RETENTION WEDGE

Based on the top and bottom elevations of the release, the dimensions of the wedge were calculated as follows:

$$\boldsymbol{Release\ Thickness} = 130\ ft\ - 75\ ft = \mathbf{55\ ft}$$

$$\boldsymbol{Release\ Base} = \frac{55\ ft}{\tan(11°)} = 282.95\ ft = \mathbf{283\ ft}$$

$$\boldsymbol{Release\ Length} = \frac{55\ ft}{\sin(11°)} = 288.25 = \mathbf{288\ ft}$$

As stated in Section 3.1 of TUA Appendix B, the release width for Evaluation 1 was 1/3 of the migration length in the down-dip direction. However, for the specific retention calculation, the width is assumed to be 183 ft based on the estimated lateral migration of the 2014 Tank 5 release.

Table 1: 2014 Tank 5 Release LNAPL Retention Wedge Dimensions

Dimension	Value (ft)
Release Thickness	55
Release Base	283
Release Length Down-Dip	288
Release Width	183

Using the dimensions presented in Table 1, the total volume of the wedge can be calculated:

$$Retention\ Wedge\ Volume = \frac{1}{2} \times Release\ Base \times Release\ Thickness \times Release\ Width$$

$$Retention\ Wedge\ Volume = \frac{1}{2} \times\ 283\ ft\ \times 55\ ft\ \times 183\ ft = 1{,}423{,}948\ ft^3$$

STEP 3: DETERMINE GEOLOGIC ZONES INCLUDED IN THE 2014 TANK 5 RELEASE LNAPL RETENTION WEDGE

To determine which geologic layers are included in the LNAPL retention wedge, the top and bottom elevations of each zone are compared to the top and bottom elevation of the release with the following checks. These checks operate under two assumptions:

- All hypothetical releases have a bottom elevation between 45 ft msl and 75 ft msl.
- All hypothetical releases enter the basalt at 105 ft msl or higher.

The top and bottom of each geologic zone are shown in Table 2.

Table 2: Geologic Zone Elevations

Zone	Top Elevation (ft msl)	Bottom Elevation (ft msl)
Zone F	305	135
Zone A	135	105
Zone B	105	75
Zone C	75	45

For Zone F:

Rule 1: If the top elevation of the release is greater than 135 ft msl, the bottom elevation of Zone F, Zone F is included in the LNAPL retention wedge. The top elevation of Zone F is the top elevation of the release. The bottom elevation of Zone F is 135 ft msl.

For Zone A:

Rule 1: If the top elevation of the release is greater than 135 ft msl, the top elevation of Zone A, Zone A is in the LNAPL retention wedge and the top elevation of Zone A in the LNAPL retention wedge is 135 ft msl.

OR

Rule 2: If the top elevation of the release is greater than 105 ft msl and less than 135 ft msl, Zone A is in the LNAPL retention wedge and the top elevation of Zone A is equal to the top elevation of the release. The bottom elevation of Zone A is 105 ft msl.

For Zone B:

Rule 1: If the top elevation of the release is greater than or equal to 105 ft msl, Zone B is in the LNAPL retention wedge and the top elevation of Zone B is 105 ft msl.

OR

Rule 2: If the top elevation of the release is less than 105 ft msl and greater than 75 ft msl, Zone B is in the LNAPL retention wedge and the top elevation of Zone B is equal to the top elevation of the release.

For Zone C:

Rule 1: If the bottom elevation of the release is greater than or equal to 45 ft msl and less than 75 ft msl, Zone C is in the LNAPL retention wedge, and the bottom elevation of Zone C in the LNAPL retention wedge is equal to the bottom elevation of the release. The top elevation of Zone C is 75 ft msl.

OR

Rule 2: If the bottom elevation of the release is 75 ft msl, Zone C is not in the LNAPL retention wedge.

These rules were applied to the 2014 Tank 5 Release:

- Top Elevation of 2014 Tank 5 Release (TE) = 130 ft msl
- Bottom Elevation of 2014 Tank 5 Release (BE) = 75 ft msl

Zone F:

Rule 1:	TE > 135 ft msl	130 ft msl > 135 ft msl	**NO**

NOT INCLUDED: Zone F is **NOT** in the LNAPL retention wedge for the 2014 Tank 5 Release.

Zone A:

Rule 1:	TE > 135 ft msl	130 ft msl > 135 ft msl	**NO**
Rule 2:	TE >105 ft msl AND TE ≤ 135 ft msl	130 ft msl > 105 ft msl 130 ft msl ≤ 135 ft msl	**YES**

INCLUDED: Zone A is in the LNAPL retention wedge for the 2014 Tank 5 Release. The top elevation of Zone A is **130 ft msl**. The bottom elevation of Zone A is **105 ft msl**.

Zone B:

Rule 1:	TE ≥ 105 ft msl	130 ft msl ≥ 105 ft msl	**YES**
Rule 2:	TE < 105 ft msl AND TE ≥ 75 ft msl	130 ft msl < 105 ft msl 130 ft msl ≥ 135 ft msl	**NO**

INCLUDED: Zone B is in the LNAPL retention wedge for the 2014 Tank 5 Release. The top elevation of Zone B is **105 ft msl**. The bottom elevation of Zone B is **75 ft msl**.

Zone C:

Rule 1:	BE ≥ 45 ft msl AND BE < 75 ft msl	75 ft msl ≥ 45 ft msl 75 ft msl < 75 ft msl	**NO**
Rule 2:	BE = 75 ft msl	75 ft msl = 75 ft msl	**YES**

NOT INCLUDED: Zone C is **NOT** in the LNAPL retention wedge for the 2014 Tank 5 Release.

Table 3 provides a summary of the geologic zones and their respective elevations in the LNAPL retention wedge.

Table 3: Geologic Zones in 2014 Tank 5 Release LNAPL Retention Wedge

Zone	In the Wedge?	Top Elevation	Bottom Elevation
Zone F	Not Included	—	—
Zone A	Included	130 ft msl	105 ft msl
Zone B	Included	105 ft msl	75 ft msl
Zone C	Not Included	—	—

— not applicable

Step 4: Calculate the Volume of Each Geologic Zone in the 2014 Tank 5 Release LNAPL Retention Wedge

The volumes of Zone A and B were calculated using the top and bottom elevation of each zone in the LNAPL retention wedge. As shown on Figure 1, the volume of each zone within the wedge was assumed to be trapezoidal pyramid. The volume of each zone was calculated using the formula for the area of a trapezoid multiplied by the release width as shown below (Figure 2).

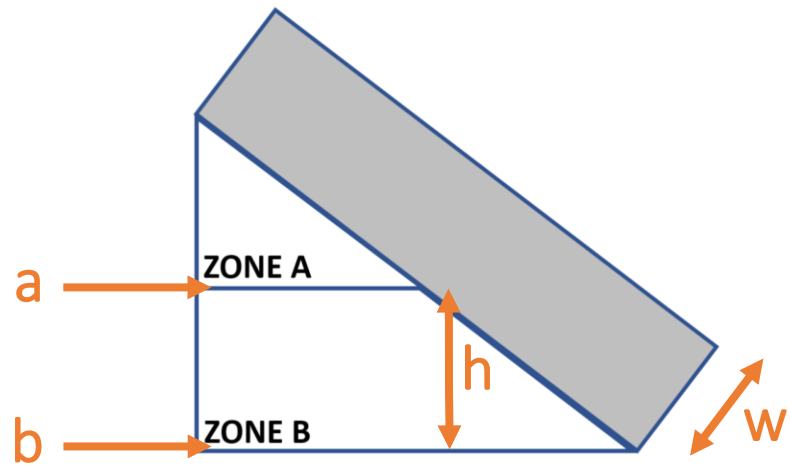


Figure 2: Variables Used for Calculation of Trapezoid Volumes

First, the thicknesses of Zone A and Zone B were calculated.

$$Thickness\ of\ Zone\ A = 130\ ft\ msl - 105\ ft\ msl = 25\ ft$$
$$Thickness\ of\ Zone\ B = 105\ ft\ msl - 75\ ft\ msl = 30\ ft$$

Then the top and bottom base lengths for each zone were calculated.

The base lengths were found by first defining the equation for the hypotenuse of the wedge. For any given point on the release base length, the corresponding elevation in the wedge was found using the following equation:

$$elevation = -\tan 11° \times base\ length + top\ elevation\ of\ release$$
$$elevation = -\tan 11° \times base\ length + 130\ ft\ msl$$

To determine area of each zone, the base lengths for the top and bottom elevations of each zone were calculated.

$$Zone\ B\ base\ length\ at\ bottom\ elevation = b = \frac{(75\ ft\ msl - 130\ ft\ msl)}{-\tan 11°} = 283\ ft$$
$$Zone\ B\ base\ length\ at\ top\ elevation = a = \frac{(105\ ft\ msl - 130\ ft\ msl)}{-\tan 11°} = 129\ ft$$
$$Zone\ A\ base\ length\ at\ bottom\ elevation = b = \frac{(105\ ft\ msl - 130\ ft\ msl)}{-\tan 11°} = 129\ ft$$

The base length of Zone A at the top elevation (a) is zero.

Last, the volume of each zone was calculated.

$$Volume\ of\ Zone\ A = \frac{(0\ ft + 129\ ft)}{2} \times 25\ ft \times 183\ ft = \mathbf{294,204\ ft^3}$$

$$Volume\ of\ Zone\ B = \frac{(129\ ft + 283\ ft)}{2} \times 30\ ft\ \times 183\ ft = \mathbf{1,129,744\ ft^3}$$

STEP 5: DETERMINE THE VOLUME OF HIGHLY PERMEABLE MEDIA IN EACH GEOLOGIC ZONE

Geologic media type percentages were used to determine the volume of Total Aʻa, Total Pāhoehoe, Clinker, High Permeability Clinker, and High Permeability Thin Pāhoehoe Flows in Zone A and Zone B.

The percentages of Total Pāhoehoe, High Permeability Clinker as a percentage of Clinker, and High Permeability Thin Pāhoehoe Flows as a percentage of Total Pāhoehoe were known inputs, as shown in Table 4.

Table 4: Geologic Media Type Percentages in Zones A and B

Zone	Total Pāhoehoe	% High Permeability Clinker	% High Permeability Thin Pāhoehoe Flows
Zone A	70%	40%	90%
Zone B	63%	40%	90%

The percentage of Total Aʻa and percentage of Clinker as a percentage of Total Aʻa are not known and were calculated:

$$\%\ Total\ A'a = 1 - \%\ Total\ P\bar{a}hoehoe$$

$$\boldsymbol{Zone\ A}\ \%\ \boldsymbol{Total\ A'a} = 1 - 70\% = \mathbf{30\%}$$

$$\boldsymbol{Zone\ B}\ \%\ \boldsymbol{Total\ A'a} = 1 - 63\% = \mathbf{37\%}$$

To determine the % Clinker in the Total Aʻa, % of Clinker in the entire wedge was divided by the % of Total Aʻa in the entire wedge. This step was needed because the breakdown of geologic media given by AECOM provided % Total Pāhoehoe and % Total Clinker for given elevation ranges. Clinker is a subset of the Total Aʻa in the subsurface.

$$\boldsymbol{Zone\ A}\ \%\ \boldsymbol{Clinker}\ as\ a\ percentage\ of\ Total\ A'a = \frac{\%\ Total\ Clinker}{\%\ Total\ A'a} = \frac{7\%}{30\%} = \mathbf{23\%}$$

$$\boldsymbol{Zone\ B}\ \%\ \boldsymbol{Clinker}\ as\ a\ percentage\ of\ Total\ A'a = \frac{\%\ Total\ Clinker}{\%\ Total\ A'a} = \frac{0.04\%}{37\%} = \mathbf{0.11\%}$$

To determine the % Clinker in the Total Aʻā, % of Clinker in the entire wedge was divided by the % of Total Aʻā in the entire wedge. This step was needed because the breakdown of geologic media given by AECOM provided % Total Pāhoehoe and % Total Clinker for given elevation ranges. Clinker is a subset of the Total Aʻā in the subsurface.

$$\boldsymbol{Zone\ A}\ \%\ \boldsymbol{Clinker}\ as\ a\ percentage\ of\ Total\ A'a = \frac{\%\ Total\ Clinker}{\%\ Total\ A'a} = \frac{7\%}{30\%} = \mathbf{23\%}$$

$$\boldsymbol{Zone\ B}\ \%\ \boldsymbol{Clinker}\ as\ a\ percentage\ of\ Total\ A'a = \frac{\%\ Total\ Clinker}{\%\ Total\ A'a} = \frac{0.04\%}{37\%} = \mathbf{0.11\%}$$

A summary of the percentages of each geologic media type is presented in Table 5.

Table 5: Complete Percentage Breakdown of Geologic Types in Zones A and B

Zone	% Total Pāhoehoe	% Total A‘a	% Clinker as a percentage of Total A‘a	% High Permeability Clinker	% High Permeability Thin Pāhoehoe Flows
Zone A	70%	30%	23%	40%	90%
Zone B	63%	37%	0.11%	40%	90%

The volume of High Permeability Clinker and volume of High Permeability Thin Pāhoehoe Flows were then calculated:

Zone A:

$$Volume\ of\ Total\ A'a = \%\ Total\ A'a \times Volume\ of\ Zone\ A = 30\% \times 294{,}204\ ft^3 = 88{,}261\ ft^3$$

$$Volume\ of\ Clinker = \%\ Clinker \times Volume\ of\ Total\ A'a = 23\% \times 88{,}261\ ft^3 = 20{,}300\ ft^3$$

$$\boldsymbol{Volume\ of\ High\ Permeability\ Clinker} = \%\ High\ permeability\ Clinker \times Volume\ of\ Clinker = 40\% \times 20{,}300\ ft^3 = \mathbf{8{,}120\ ft^3}$$

$$Volume\ of\ Total\ P\bar{a}hoehoe = \%\ Total\ P\bar{a}hoehoe \times Volume\ of\ Zone\ A = 70\% \times 294{,}204\ ft^3 = 205{,}943\ ft^3$$

$$\boldsymbol{Volume\ of\ High\ Permeability\ P\bar{a}hoehoe} = \%\ High\ Permeability\ P\bar{a}hoehoe \times Volume\ of\ Total\ P\bar{a}hoehoe = 90\% \times 205{,}943\ ft^3 = \mathbf{185{,}349\ ft^3}$$

Zone B:

$$Volume\ of\ Total\ A'a = \%\ Total\ A'a \times Volume\ of\ Zone\ B = 37\% \times 1{,}129{,}744\ ft^3 = 418{,}005\ ft^3$$

$$Volume\ of\ Clinker = \%\ Clinker \times Volume\ of\ Total\ A'a = 0.11\% \times 418{,}005\ ft^3 = 418\ ft^3$$

$$\boldsymbol{Volume\ of\ High\ Permeability\ Clinker} = \%\ High\ permeability\ Clinker \times Volume\ of\ Clinker = 40\% \times 418\ ft^3 = \mathbf{167\ ft^3}$$

$$Volume\ of\ Total\ P\bar{a}hoehoe = \%\ Total\ P\bar{a}hoehoe \times Volume\ of\ Zone\ B = 63\% \times 1{,}129{,}744\ ft^3 = 711{,}739\ ft^3$$

$$\boldsymbol{Volume\ of\ High\ Permeability\ P\bar{a}hoehoe} = \%\ High\ Permeability\ P\bar{a}hoehoe \times Volume\ of\ Total\ P\bar{a}hoehoe = 90\% \times 711{,}739\ ft^3 = \mathbf{640{,}565\ ft^3}$$

The volumes of each geologic media in both zones are summarized in Table 6.

Table 6: Geologic Media Type Volumes in Zones A and B

Zone	Volume of Total Aʻa (ft^3)	Volume of Clinker (ft^3)	Volume of High Permeability Clinker (ft^3)	Volume of Total Pāhoehoe (ft^3)	Volume of High Permeability Thin Pāhoehoe Flows (ft^3)
Zone A	316,282	72,745	20,098	754,621	679,159
Zone B	130,933	131	52	222,112	199,901

The volume of High Permeability Clinker and High Permeability Thin Pāhoehoe Flows were then used in Evaluation 1 to determine the volume of LNAPL retained in the high vadose zone retention wedge.

Attachment 2:
Monte Carlo Analysis

GSI Job No. 4902
Issued: 10

ATTACHMENT 2

Cells with red text indicate that the iterative value is the result of the triangular distribution.

	Input	More Conservative	Most Likely	Less Conservative	Iterative Value	Unit	Triangular/Calculated	Source
Defining Parameters	*Assume Distance to Capture Zone Boundary*	*700*	*700*	*1,609*	*N/A*	*ft*	*Key Information*	Based on Interim GW Flow Model, Base Case for More Conservative/Most Likely, Clinker Case for Less Conservative
	Assumed Elevation of NAPL Entry in Basalt	*105*	*160*	*245*	*N/A*	*ft MSL*	*Key Information*	More Conservative: bottom of tunnel, Most Likely: elevation of bottom tank curve, Less Conservative: middle of tank
Wedge Dimensions	**Top Elevation**	105	160	245	124	ft MSL	**Triangular**	Values correspond to the **Assumed Elevation of LNAPL Entry in Basalt**
	Bottom Elevation	45	45	45	45	ft MSL	Calculated	Assumed to be 45 ft MSL for all three cases
	Release Base Length	309	592	1,029	404	ft	Calculated	Based on geologic dip of 11 degrees
	Release Entirely Within Capture Zone?	YES	YES	YES	YES	-	**CHECK**	All wedges are entirely within the capture zone
	Release Length Down-Dip	314	603	1,048	412	ft	Calculated	Based on geologic dip of 11 degrees
	Release Width	105	201	349	137	ft	Calculated	Ratio of 3:1 for length down-dip to release width
	Release Thickness	60	115	200	79	ft	Calculated	
Geology	**Inverse Specific Retention**	66	33	17	34	ft3 basalt/gallon LNAPL	**Triangular**	Calculated in *Specific Retention* tab. Note the range from more conservative to less conservative reflects uncertainties in the geologic input data and the release volume. Range is based on professional judgment.
	High Perm Clinker Porosity	0.25	0.50	0.60	0.56	-	**Triangular**	Most likely (0.5) taken from Ishizaki, 1987. More Conservative value was estimated. Less Conservative value was estimated.
	High Perm Clinker LNAPL Residual Saturation	0.01	0.06	0.15	0.10	-	**Triangular**	Most likely (0.056) is equal to the median LNAPL residual saturation value taken from Brady and Kunkel, 2003. Less conservative value (0.152) is the maximum LNAPL residual saturation value from Brady and Kunkel, 2003. More conservative value (0.01) is equal to half the value for LNAPL residual saturation determined by Brost and DeVaull (2001) based on a lab experiment performed by Fussel et al. (1981). The value of 2% for residual saturation was reduced by half as a conservative measure.
Zone F	**Zone F Top Elevation**	Not in Wedge	160	245	0	ft MSL	Calculated	
	Zone F Bottom Elevation	Not in Wedge	135	135	0	ft MSL	Calculated	
	Zone F Thickness	0	25	110	0	ft	Calculated	
	Base Length at Bottom Elevation	0	129	566	0	ft	Calculated	
	Average Base Length	0	64	283	0	ft	Calculated	Average of top and bottom elevation base lengths
	Zone F Volume	0	322,980	10,874,593	0	ft3	Calculated	Zone area modeled as trapezoid
Zone A	**Zone A Top Elevation**	Not in Wedge	135	135	124	ft MSL	Calculated	
	Zone A Bottom Elevation	Not In Wedge	105	105	105	ft MSL	Calculated	
	Zone A Thickness	0	30	30	19	ft	Calculated	
	Base Length at Top Elevation	0	129	566	0	ft	Calculated	
	Base Length at Bottom Elevation	0	283	720	96	ft	Calculated	
	Average Base Length	0	206	643	48	ft	Calculated	Average of top and bottom elevation base lengths
	Zone A Volume	0	1,240,243	6,740,450	121,933	ft3	Calculated	Zone area modeled as trapezoid
Zone B	**Zone B Top Elevation**	105	105	105	105	ft MSL	Calculated	
	Zone B Bottom Elevation	75	75	75	75	ft MSL	Calculated	
	Zone B Thickness	30	30	30	30	ft	Calculated	
	Base Length at Top Elevation	0	283	720	96	ft	Calculated	
	Base Length at Bottom Elevation	154	437	875	250	ft	Calculated	
	Average Base Length	77	360	797	173	ft	Calculated	Average of top and bottom elevation base lengths
	Zone B Volume	242,656	2,170,425	8,358,158	711,515	ft3	Calculated	Zone area modeled as trapezoid
Zone C	**Zone C Top Elevation**	75	75	75	75	ft MSL	Calculated	
	Zone C Bottom Elevation	45	45	45	45	ft MSL	Calculated	
	Zone C Thickness	30	30	30	30	ft	Calculated	
	Base Length at Top Elevation	154	437	875	250	ft	Calculated	
	Base Length at Bottom Elevation	309	592	1029	404	ft	Calculated	
	Average Base Length	232	514	952	327	ft	Calculated	Average of top and bottom elevation base lengths
	Zone C Volume	727,969	3,100,607	9,975,866	1,347,131	ft3	Calculated	Zone area modeled as trapezoid
	Total Wedge Volume	970,625	6,834,255	35,949,067	2,180,580	ft3	**CHECK**	Sum of zone volumes
	Total Wedge Volume Check	970,625	6,834,255	35,949,067	2,180,580	ft3	**CHECK**	Volume modeled as a triangular wedge
Zone F	**% Pahoehoe**	5.5%	11.0%	16.5%	7.74%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Pahoehoe	75.00%	90.00%	99.00%	90.80%	%	**Triangular**	Taken from Geologic Data Tab
	Volume of High Perm Pahoehoe	0	31,975	1,776,365	0	ft3	Calculated	Calculated. Most conservative Zone F LNAPL Volume in High permeability Pahoehoe is equal to zero because most conservative Zone F volume is equal to zero
	Volume of LNAPL in High Perm Pahoehoe	0	940	52,214	0	gal LNAPL	Calculated	Uses the triangular value of the inverse specific retention
	% Total A'a	94.5%	89.0%	83.5%	92.3%	%	Calculated	
	% Clinker in A'a	14%	29%	47%	34%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Clinker	20%	40%	60%	50%	%	**Triangular**	Taken from Geologic Data Tab, note that high perm clinker is a subset of clinker
	Volume of Total A'a	0	287,452	9,080,285	0	ft3	Calculated	
	Volume of High Perm Clinker	0	33,590	2,544,655	0	ft3	Calculated	
	Volume of LNAPL in High Perm Clinker	0	1,966	148,935	0	ft3 LNAPL	Calculated	
	Volume of LNAPL in High Perm Clinker	0	14,705	1,114,031	0	gal LNAPL	Calculated	Conversion
	Total Volume of LNAPL in Zone F	0	15,645	1,166,245	0	gal LNAPL	Calculated	Sum of LNAPL in High Perm Clinker and High Perm Pahoehoe
Zone A	**% Pahoehoe**	35%	70%	100%	50%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Pahoehoe	75%	90%	99%	84%	%	**Triangular**	Taken from Geologic Data Tab
	Volume of High Perm Pahoehoe	0	781,353	6,673,046	51,499	ft3	Calculated	Calculated. Most conservative Zone F LNAPL Volume in High permeability Pahoehoe is equal to zero because most conservative Zone F volume is equal to zero
	Volume of LNAPL in High Perm Pahoehoe	0	22,967	196,144	1,514	gal LNAPL	Calculated	Uses the triangular value of the inverse specific retention
	% Total A'a	65%	30%	0%	50%	%	Calculated	
	% Clinker in A'a	5.38%	23.33%	0.00%	2.06%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Clinker	20%	40%	60%	37%	%	**Triangular**	Taken from Geologic Data Tab, note that high perm clinker is a subset of clinker
	Volume of Total A'a	0	372,073	0	60,797	ft3	Calculated	
	Volume of High Perm Clinker	0	34,727	0	463	ft3	Calculated	
	Volume of LNAPL in High Perm Clinker	0	2,033	0	27	ft3 LNAPL	Calculated	
	Volume of LNAPL in High Perm Clinker	0	15,203	0	202	gal LNAPL	Calculated	Conversion
	Total Volume of LNAPL in Zone A	0	38,170	196,144	1,716	gal LNAPL	Calculated	Sum of LNAPL in High Perm Clinker and High Perm Pahoehoe
Zone B	**% Pahoehoe**	32%	63%	95%	73%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Pahoehoe	75%	90%	99%	94%	%	**Triangular**	Taken from Geologic Data Tab
	Volume of High Perm Pahoehoe	57,328	1,230,631	7,819,475	490,458	ft3	Calculated	Calculated. Most conservative Zone F LNAPL Volume in High permeability Pahoehoe is equal to zero because most conservative Zone F volume is equal to zero
	Volume of LNAPL in High Perm Pahoehoe	1,685	36,173	229,842	14,416	gal LNAPL	Calculated	Uses the triangular value of the inverse specific retention
	% Total A'a	69%	37%	5%	27%	%	Calculated	
	% Clinker in A'a	0.03%	0.11%	1.09%	0.10%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Clinker	20%	40%	60%	23%	%	**Triangular**	Taken from Geologic Data Tab, note that high perm clinker is a subset of clinker
	Volume of Total A'a	166,219	803,057	459,699	190,726	ft3	Calculated	
	Volume of High Perm Clinker	10	347	3,009	43	ft3	Calculated	
	Volume of LNAPL in High Perm Clinker	1	20	176	2	ft3 LNAPL	Calculated	
	Volume of LNAPL in High Perm Clinker	4	152	1317	19	gal LNAPL	Calculated	Conversion
	Total Volume of LNAPL in Zone F	1,689	36,325	231,159	14,435	gal LNAPL	Calculated	Sum of LNAPL in High Perm Clinker and High Perm Pahoehoe
Zone C	**% Pahoehoe**	40%	80%	100%	79%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Pahoehoe	75%	90%	99%	87%	%	**Triangular**	Taken from Geologic Data Tab
	Volume of High Perm Pahoehoe	218,391	2,232,437	9,876,107	924,168	ft3	Calculated	Calculated. Most conservative Zone F LNAPL Volume in High permeability Pahoehoe is equal to zero because most conservative Zone F volume is equal to zero
	Volume of LNAPL in High Perm Pahoehoe	6,419	65,619	290,293	27,165	gal LNAPL	Calculated	Uses the triangular value of the inverse specific retention
	% Total A'a	60%	20%	0%	21%	%	Calculated	
	% Clinker in A'a	1.67%	10.00%	0.00%	0.42%	%	**Triangular**	Taken from Geologic Data Tab
	% High Perm Clinker	20%	40%	60%	25%	%	**Triangular**	Taken from Geologic Data Tab, note that high perm clinker is a subset of clinker
	Volume of Total A'a	436,781	620,121	0	285,145	ft3	Calculated	
	Volume of High Perm Clinker	1,456	24,805	0	299	ft3	Calculated	
	Volume of LNAPL in High Perm Clinker	85	1,452	0	18	ft3 LNAPL	Calculated	
	Volume of LNAPL in High Perm Clinker	637	10859	0	131	gal LNAPL	Calculated	Conversion
	Total Volume of LNAPL in Zone F	7,057	76,479	290,293	27,296	gal LNAPL	Calculated	Sum of LNAPL in High Perm Clinker and High Perm Pahoehoe

Total LNAPL	8,746	166,618	1,883,842	43,447	gal of LNAPL
	10%	**20%**	**50%**	**80%**	**90%**
Gallons of LNAPL	48,348	69,443	146,423	293,312	402,504

From Left to Right: lore Conservative, Most Likely, Less Conservative, Current Iteration Holding Capacity Values

Results from RiskAmp Simulation

Appendix C:
Hypothetical Chronic Release Analysis

EXECUTIVE SUMMARY

The capacity of light non-aqueous-phase liquid (LNAPL) degradation for both the vadose zone and the saturated zone has been used to estimate the magnitude of a hypothetical small chronic release that would not result in unacceptable risks to users of groundwater in the vicinity of the Red Hill Bulk Fuel Storage Facility (the “Facility”). This long-term LNAPL degradation capacity was calculated based on the observed attenuation rates for historical releases in the vadose zone.

Because these historical releases have not impacted groundwater users, it was assumed that a hypothetical chronic release that does not increase the total mass of LNAPL in the subsurface over a long time period (years or decades) would also not cause an exceedance of risk-based decision criteria (RBDC) at Red Hill Shaft. In other words, a hypothetical chronic release would be safe as long as the amount of LNAPL released does not exceed the amount of LNAPL degraded through ongoing natural attenuation processes. Key results are:

- Small chronic releases that are retained within the vadose zone, about 2,300 gallons per tank per year can be released from each individual tank without causing unacceptable risks to nearby receptors. This value was calculated based on the vadose zone NSZD rate determined based on temperature measurements made at the Facility. Because the vadose zone LNAPL footprint is confined to the immediate vicinity of the release tank, chronic releases from multiple tanks would degrade independently and be safely sustained without causing adverse effects.
- Although there is additional capacity to degrade LNAPL in the saturated zone, as a conservative measure this assimilative capacity was not included in the hypothetical chronic release analysis.

CONTENTS

FIGURES

ACRONYMS AND ABBREVIATIONS

µmole	micromole
CO_2	carbon dioxide
CSM	conceptual site model
DNAPL	dense non-aqueous-phase liquid
ft	foot/feet
ft^2	square foot
ft^3	cubic foot
mL	milliliter
LNAPL	light non-aqueous-phase liquid
mL	milliliter
msl	mean sea level
NSZD	natural source-zone depletion

1. Introduction

1.1 TECHNICAL BACKGROUND

To better understand hypothetical risks associated with potential releases, a quantitative calculation of the ability for Red Hill to hold fuel (LNAPL) in the case of a hypothetical fuel tank release from the Facility has been conducted. Two separate holding capacity calculations were performed:

- The LNAPL holding capacity for a hypothetical large, sudden release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. The calculations and results of this analysis are described in Appendix B, Hypothetical Sudden Release Analysis.
- The LNAPL holding capacity for a hypothetical small hypothetical release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility. This calculation is dependent on the Natural Source-Zone Depletion (NSZD) rate at the Facility and is described below.

1.2 STUDY OBJECTIVES

The objective of the analysis described in this appendix is to determine the maximum hypothetical small hypothetical chronic release rate that would not result in unacceptable risk to users of groundwater in the vicinity of the Facility.

2. Using Vadose Zone NSZD Rates to Determine Hypothetical Release

2.1 CONCEPTUAL APPROACH

Site monitoring data indicate that historical LNAPL releases at the Facility are being biodegraded in the vadose zone. The observed NSZD rate for these prior releases has been used to estimate the rate at which a hypothetical future release would be degraded. The hypothetical small hypothetical release rate was determined as the release rate that offset by biodegradation so that, at steady-state, the amount of LNAPL being released every day would be equal to the amount of LNAPL being degraded in the vadose zone such that the overall extent of impact would not increase over time (Figure 1).

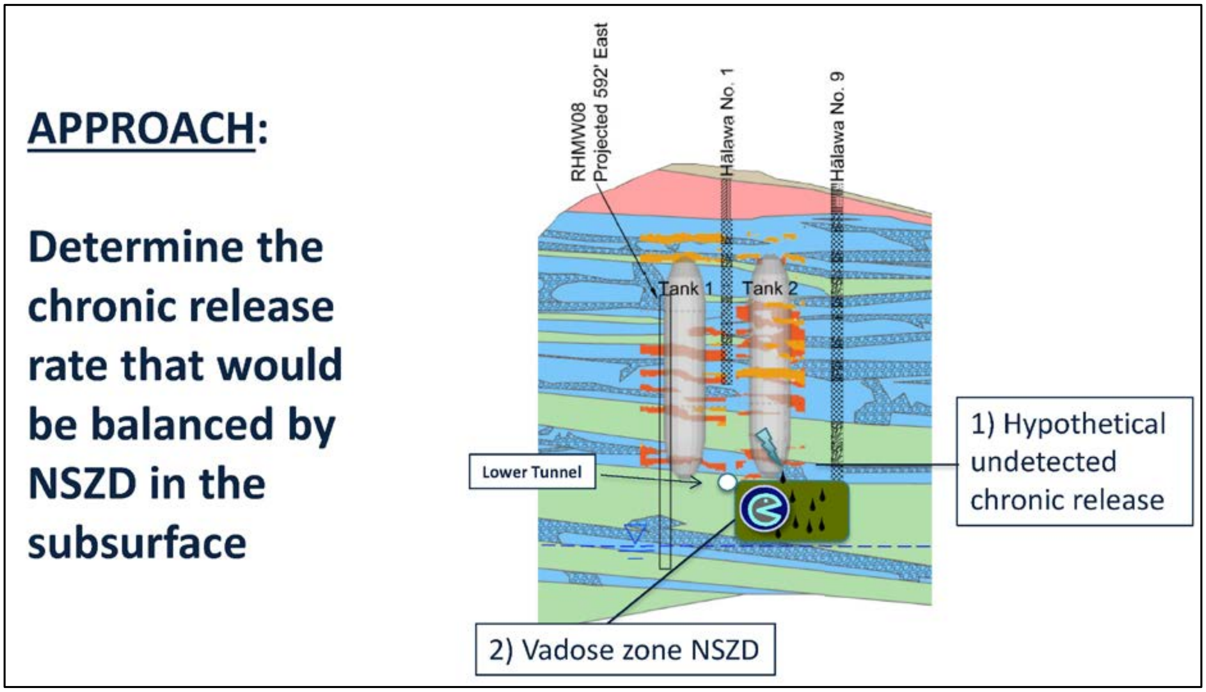


Figure 1: Conceptual Approach for Determination of the Hypothetical Chronic Release Rate

2.2 AVAILABLE NSZD AND LNAPL DATA

In October 2017, an extensive NSZD study was performed at the Facility using two independent measurement techniques (Red Hill Conceptual Site Model [CSM] Appendixes B.1 and B.2; DON 2018). These studies were focused on the current NSZD rate based on the current LNAPL distribution in the subsurface. The highest NSZD (1,500 gallons per acre per year) was observed in the vicinity of monitoring well RHMW03 likely indicating that this portion of the Facility has the highest density of LNAPL within the vadose zone. The thermal NSZD measurements indicated that the heat from biodegrading LNAPL being generated with a depth interval from about 76 to 111 feet (ft) mean sea level (msl) elevation (about 10–45 ft below the floor of the lower access tunnel near RHMW03, which has a top-of-casing elevation of 120.9 ft msl) (Figure 2 and Figure 3). This area generally corresponds to LNAPL observed in drilling fluids and staining in Borings 14, 15, and 16, which penetrated the interval between 120 and about 88 ft msl and all within ~150 ft from RHMW03 (DON 1999, 2002).

Note there has not been any observation of LNAPL accumulation or sheens at monitoring well RHMW03 since it was installed in 2009.

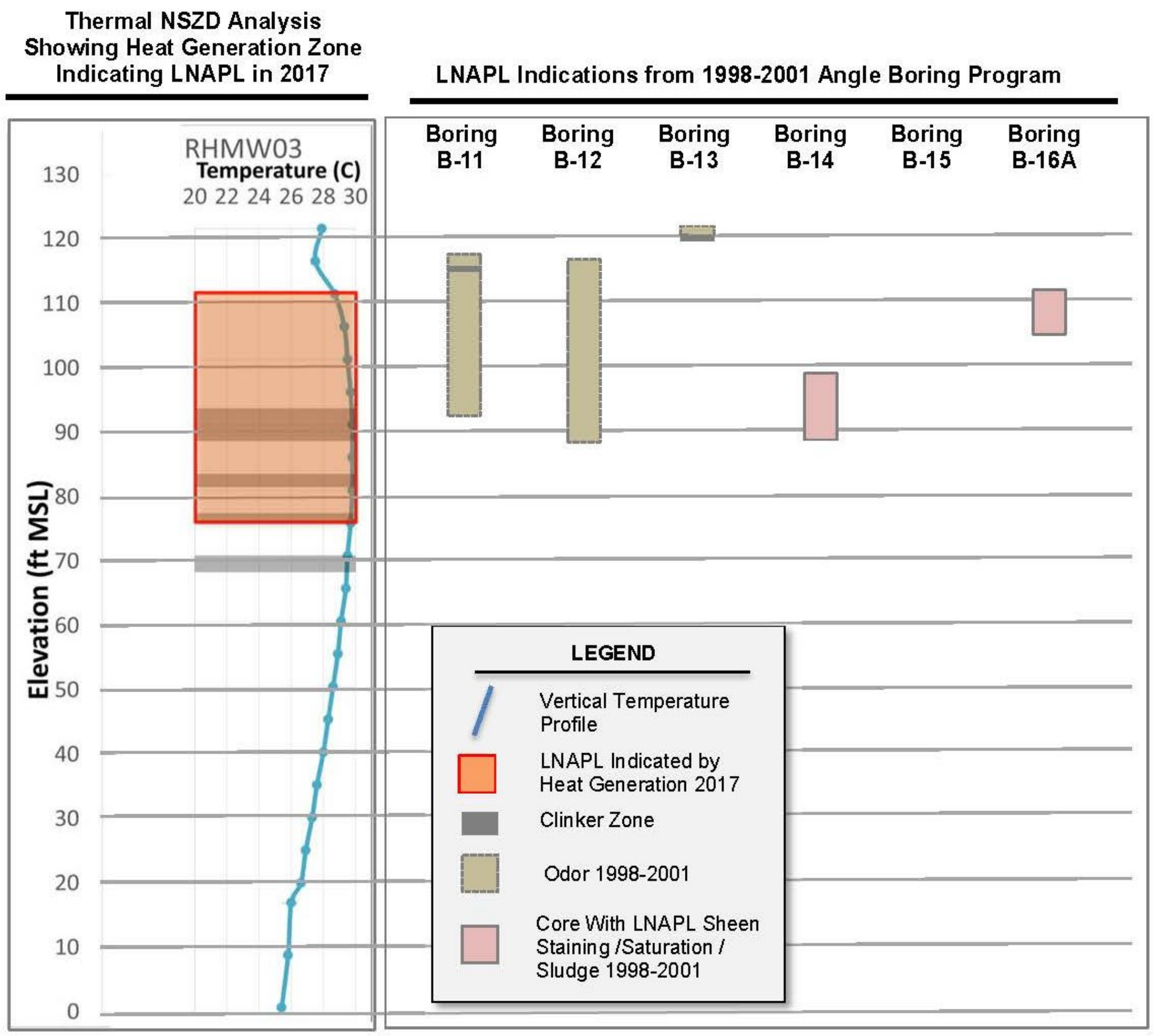


Figure 2: LNAPL Distribution Near Monitoring Well RHMW03 as Indicated from 2017 Thermal NSZD Program (DON 2018, Appendix B.1) and 1998–2001 Angle Boring Program (DON 1999, 2002)

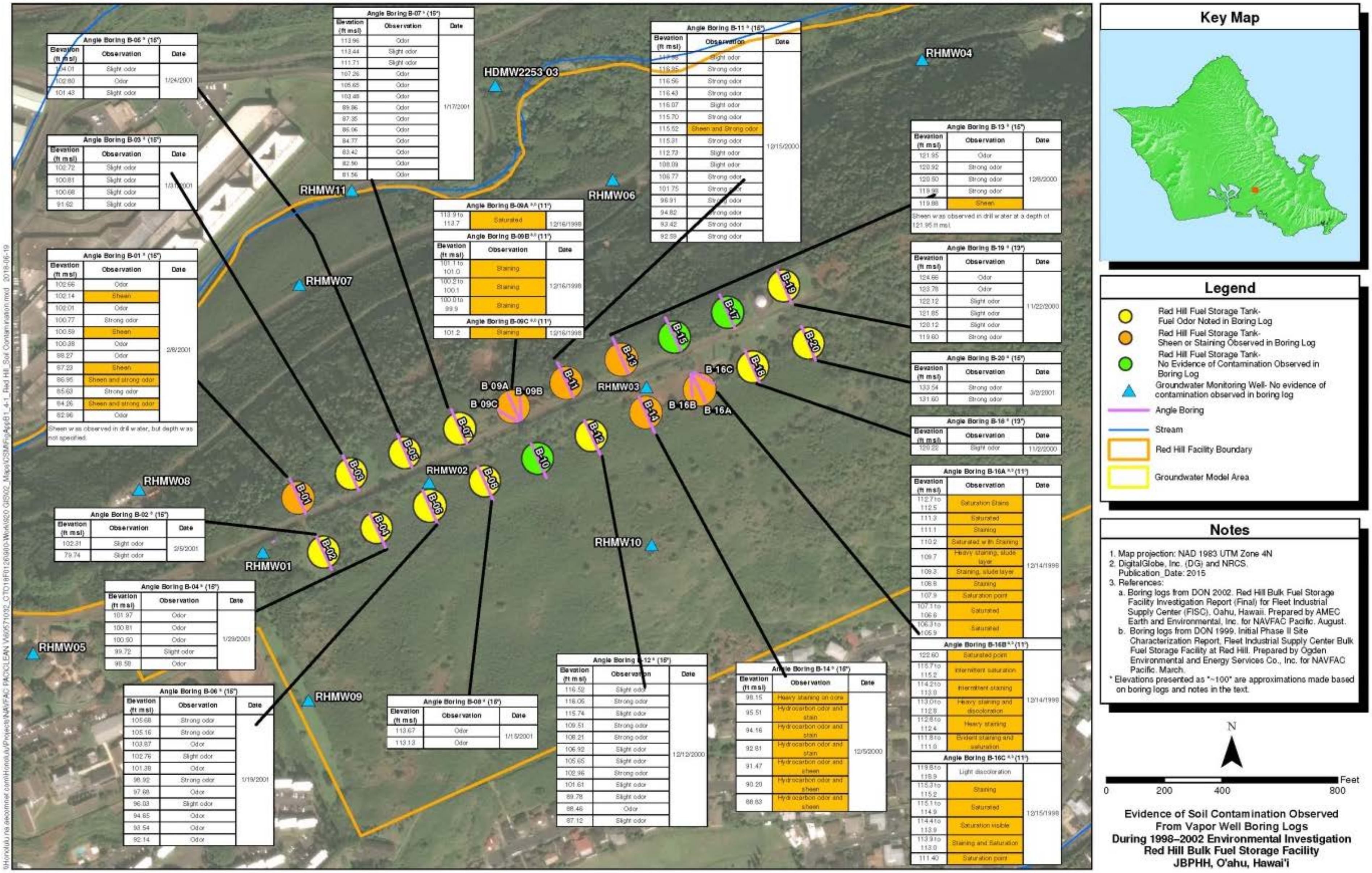


Figure 3: Evidence of Soil Contamination Observed While Drilling Angle Borings (DON 1999, 2002)

2.3 KEY NSZD VS. LNAPL OBSERVATIONS

Overall, the heat generation observed in the upper portion of RHMW03 was the highest at the Facility, indicating:

1. The measured RHMW03 NSZD rate of 1,500 gallons per acre per year was near the median NSZD rate of 1,700 gallons per acre per year from 25 different NSZD field sites compiled by Garg et al. (2017). The rates were calculated using temperature data measured in the vadose zone and groundwater RHMW01 through RHMW03 and one background well (RHMW05). Note that NSZD processes in the vadose zone at the Facility appear to be dominated by aerobic processes (CSM Appendix B.3; DON 2018), while NSZD processes at most other hydrocarbon release sites appears to dominated by anaerobic processes.
2. Based on the soil vapor study as described in the CSM (DON 2018), highly weathered LNAPL from jet fuel releases that occurred more than 15 years ago (the soil boring data in the angle borings were collected in the 1998–2001 timeframe) is still biodegrading at a relatively high rate. Because of the age of these releases and the limited amounts of readily degradable monoaromatics and n-alkanes in the vapor samples collected from below tanks, these data suggest that at least some of the relatively recalcitrant compounds (branched alkanes and cycloalkanes) are being biodegraded. The NSZD model developed by Ng et al. (2014, 2015) and discussed in Garg et al. (2017) provide an explanation for this process where naturally occurring bacteria degrade readily biodegradable compounds first then address more slowly biodegrading compounds in a sequenced manner.
3. Several papers suggest that at least some branched alkanes can be biodegraded aerobically, particularly those with shorter carbon numbers (< C15) (e.g., Marchal et al. 2003; Penet et al. 2006).
4. The heat generation and associated NSZD rate is to the temperature profile in the upper portion of the RHMW03 interval from about 76 to 111 ft msl elevation.

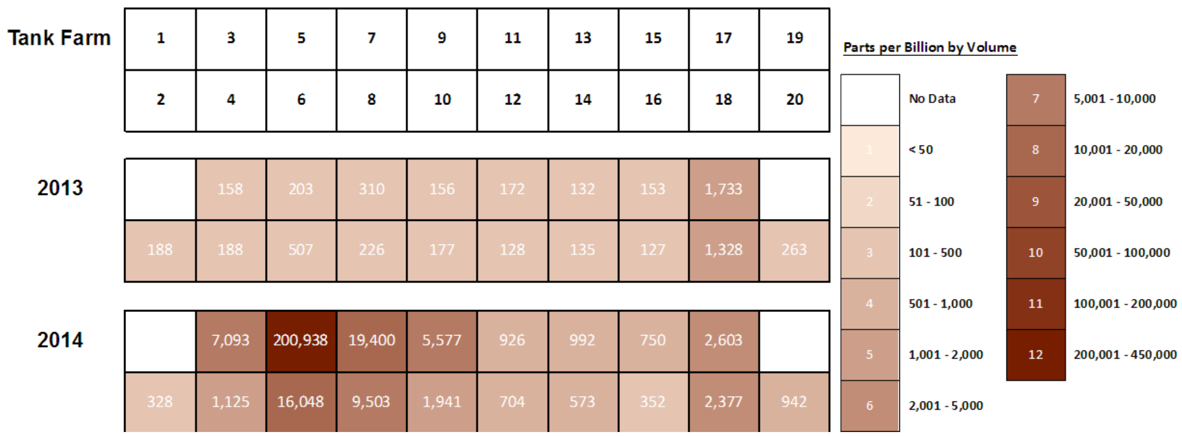
In summary, the interval at RHMW03 between 76 and 111 ft msl elevation (about a 35-ft interval) can be considered an NSZD reactor that is able to biodegrade old, weathered jet fuel at a rate of 1,500 gallons per acre per year. Expressing this NSZD rate in terms of volume rather than area yields an NSZD rate of 9.8×10^{-4} gallons per cubic foot (ft^3) of basalt per year (i.e., 1,500 gal/acre/yr ÷ 43,560 square feet [ft^2] per acre ÷ 35-ft-thick LNAPL zone). For the purpose of the hypothetical chronic release calculation, these data were used to determine the maximum hypothetical release that could occur if all the potential reactor (i.e., the vadose zone interval from 111 ft msl to the water table at about 18 ft msl) filled with LNAPL due to a hypothetical chronic release and therefore subject to biodegradation.

2.4 HYPOTHETICAL CHRONIC LNAPL RELEASE CALCULATION

To evaluate the hypothetical small hypothetical release that would be balanced by vadose zone biodegradation, the observed NSZD rate (9.8×10^{-4} gallons per ft^3 per year) was applied with a modified LNAPL source zone reflecting a representative area of LNAPL associated with a hypothetical chronic release and assuming that LNAPL were able to occupy the full depth of the vadose zone.

A representative area for a hypothetical release was estimated based on the following information:

- Within the depth interval of the below-tank soil vapor wells, the 2014 release of approximately 27,000 gallons of jet fuel from Tank 5 appeared to spread horizontally within a footprint approximately 200 ft × 200 ft in area or less (see Figure 4).
- The site hydrogeology that exhibits significant vertical anisotropy (the ratio of the horizontal to vertical hydraulic conductivity is estimated to range between a factor of 200–600; see Appendix B, Hypothetical Sudden Release Analysis).
- Comparison of controlled dense non-aqueous-phase liquid (DNAPL) release by Poulson and Kueper (1992) who performed small-scale controlled release experiments that showed a small, slow DNAPL release of about 1.6 gallons having a larger footprint than an instantaneous release of the same volume. (Note this release was in a sandy soil without the extreme anisotropy of the geologic media at Red Hill.)



Note: The order of magnitude difference indicates the LNAPL migration zone was focused horizontally in the vicinity of Tank 5 but did extend to the surrounding tanks. Each square is approximately 200 ft × 200 ft in area.

Figure 4: Average PID Values for 2013 (Prior to Jan. 2014 Tank 5 Release) and for 2014 (all values after the Tank 5 release)

Based on the above considerations, it was assumed that a small hypothetical release would spread with an area with a 150-ft × 150-ft area in the vadose zone as it migrated vertically toward the water table. This represents an area of 22,500 ft^2. The thickness of the NSZD zone that was used for the hypothetical release calculation was assumed to be 121 ft msl (i.e., the elevation of the base of Tanks 9/10) to the water table at 18 ft msl (103 ft), the approximate distance from the bottom of the tanks in the middle of the Tank Farm to the water table. This yields a total volume of basalt within the vadose zone occupied by LNAPL of 2.3 million ft^3 (i.e., 150 ft × 150 ft × 103 ft). Although a cubic volume was used in the calculation, the hypothetical release analysis does not directly assume a specific shape for the unsaturated volume impacted by the hypothetical release. In reality, a small hypothetical release would likely migrate laterally along the geologic dip as it moved vertically though fractures and clinker bridges resulting in a complex impacted volume. As long as the total impacted volume is greater than or equal to the assumed 150 ft × 150 ft × 103 ft volume, then the hypothetical chronic release scenario is realistic or conservative.

Overall the small hypothetical release was calculated with the formula below:

$$Q_{chronic\text{-}unsat} = NSZD_{RHMW03} \times Volume$$

where:

$Q_{chronic\text{-}unsat}$	=	calculated hypothetical release rate controlled by vadose zone NSZD processes (gallons per year from any tank)
$NSZD_{RHMW03}$	=	measured volumetric NSZD rate at RHMW03 (9.8×10^{-4} gallons per ft^3 per year)
Volume	=	Volume of basalt within the vadose zone impacted by the hypothetical chronic release (2.3×10^6 ft^3; 150 ft × 150 ft × 103 ft)
$Q_{chronic\text{-}unsat}$	=	9.8×10^{-4} gallons per ft^3 per year * 2.3×10^6 ft^3 = 2,300 gallons/yr

2.5 HYPOTHETICAL SMALL HYPOTHETICAL RELEASE – VADOSE ZONE RESULTS

This calculation shows a small hypothetical release of about 2,300 gallons per year could be released (about 6.3 gallons per day) from a single tank and be continually attenuated by vadose zone NSZD processes without unacceptable risks to nearby receptors. Because the assumed footprint is small, a small hypothetical release of this magnitude could likely be biodegraded by NSZD from several tanks in different parts of the tank farm at the same time.

This calculation is conservative because no attenuation capacity for any LNAPL reaching the saturated zone is included. The saturated zone calculation is presented in Section 2.

2.6 ACCEPTABLE DURATION OF SMALL HYPOTHETICAL RELEASE

Studies of the aerobic biodegradation of gasoline, diesel, and kerosene (e.g., Marchal et al. 2003; Penet et al. 2006) show that most or almost all of the individual constituents can be biodegraded aerobically. This is important point for the hypothetical release calculation, as observations at other LNAPL sites dominated by anaerobic processes do show some compounds biodegrade very slowly or not at all over several decades (e.g., Ng et al. 2014, 2015). Under a long-term hypothetical release scenario, non-biodegradable (low solubility) compounds could, in theory, accumulate and potentially reach the water table.

However, available data show that biodegradation in the vadose zone at the Facility is dominated by aerobic processes: no methane was detected in any soil gas sample taken as part of this project and there are known natural and man-made ventilation processes (e.g., see CSM Appendix B.2; DON 2018) that are active in the vadose zone at the Facility. The scientific literature suggests that most or almost all of the jet fuel constituents are biodegraded to some degree under aerobic conditions (e.g., Marchal et al. 2003; Penet et al. 2006).

If an accumulation of less-biodegradable constituents were to occur due to preferential degradation of more readily degradable jet fuel constituents from a small hypothetical release, the accumulation of these less degradable constituents would be very slow (hundreds of gallons per year at most). As a result, the microbial community would have decades or longer to adapt for utilization of these constituents as an energy resource. Even on a time scale of 100 years, it is unlikely that an accumulation of less-biodegradable constituents from a small hypothetical release would result in migration of LNAPL away from the immediate vicinity of the fuel tanks.

3. Biodegradation within the Saturated Zone

Biodegradation of dissolved constituents is confirmed to be ongoing at the Facility based on the loss of mass between monitoring wells RHMW02 and RHMW01 and/or Red Hill Shaft (CSM Appendix B.4), geochemical indicators (CSM Appendix B.5), and microcosm data (CSM Appendix B.6) (DON 2018). There is also indirect evidence of biodegradation of low solubility jet fuel constituents based on the high dissolved methane concentrations and the research conducted at crude oil release sites (e.g., Ng et al. 2014, 2015; Garg et al. 2017). Elevated levels of methane have been detected in the groundwater at RHMW02 and to a lesser degree at RHMW01 as described in the CSM (DON 2018).

Data from the National Crude Oil Spill Fate and Natural Attenuation Research Site in Bemidji, Minnesota was used to obtain a second independent estimate of the NSZD rate associated with petroleum releases in the saturated zone. At this site, multiple measurements of the carbon dioxide flux to the surface was made and resulted in a seasonally weighted average carbon flux of 1.1 micro moles (µmoles) carbon dioxide (CO_2) per square meter per second (Sihota et al. 2016). Based on the mass balance performed by Ng et al. (2015), about 60% of this surface efflux was due to the oil body at and below the water, or about 0.66 µmole per square meter per second. Performing a stoichiometric conversion using C11H24 as a representative jet fuel compound and using a density of 0.78 gram per milliliter (mL) yielded a potential rate of 405 gallons per acre year for NSZD occurring in the saturated zone at a jet fuel LNAPL release site.

However, because there are uncertainties regarding the holding capacity of LNAPL at the saturated zone, as a conservative measure the hypothetical chronic release calculation did not include the volume of LNAPL that would degrade following migration to the water table. In other words, for the hypothetical release analysis, only the biodegradation of LNAPL in the vadose zone was considered.

4. Conclusions

The LNAPL holding capacity for a small hypothetical release that would not result in unacceptable risks to users of groundwater in the vicinity of the Facility was conservatively calculated based on the measured rate of biodegradation within the vadose zone only. Key results are:

- A small hypothetical release of 2,300 gallons per year (about 6.3 gallons per day) from a single tank would be balanced by biodegradation within the vadose zone. As a result, such a release could occur over a time scale of decades without causing an impact to users of the groundwater.
- Because releases from different tanks would impact different areas within the vadose zone, small hypothetical releases from multiple tanks could all be biodegraded.
- If a larger release were to result in LNAPL migration to the water table, additional biodegradation would occur within the saturated zone. However, this additional biodegradation capacity was not included in the hypothetical chronic release calculation.

The calculation of the hypothetical small hypothetical release volume is supported by attenuation and LNAPL data presented in CSM Appendixes B.1–B.6 (DON 2018) and represents releases that could be sustained indefinitely and be managed by natural attenuation processes at the Facility.

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