DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

DEPARTMENT OF THE NAVY
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NAVY REGION HAWAII
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September 7, 2017

CERTIFIED NO: 7016 0910 0001 0899 9587

Mr. Bob Pallarino
U.S. Environmental Protection Agency, Region IX
75 Hawthorne Street
San Francisco, CA 94105

Mr. Steven Y.K. Chang, P.E., Chief
State of Hawaii Department of Health
Solid and Hazardous Waste Branch
919 Ala Moana Boulevard, Room 210
Honolulu, HI 96814

Dear Mr. Pallarino and Mr. Chang:

SUBJECT: ADMINISTRATIVE ORDER ON CONSENT STATEMENT OF WORK SECTION 6 AND SECTION 7, GROUNDWATER MODEL EVALUATION PLAN, RED HILL BULK FUEL STORAGE FACILITY (RED HILL), JOINT BASE PEARL HARBOR-HICKAM, OAHU, HAWAII

The Groundwater Model Evaluation Plan for Red Hill pursuant to the Administrative Order on Consent (AOC) Statement of Work (SOW) Section 6, Investigation and Remediation of Releases, and Section 7, Groundwater Protection and Evaluation is enclosed.

The Groundwater Model Evaluation Plan describes the development of the groundwater flow and contaminant fate and transport (CF&T) models for AOC SOW Section 6 and Section 7. The objectives of the current modeling efforts are to increase understanding of short- and long-term groundwater flow conditions and potential CF&T to support the feasibility evaluation of various remedial alternatives in response to the January 2014 leak and potential future fuel releases.

If you have any questions, please contact Aaron Y. Poentis of our Regional Environmental Department at (808) 471-3858 or at aaron.poentis@navy.mil.

Sincerely,

R. D. HAYES, III
Captain, CEC, U.S. Navy
Regional Engineer
By direction of the
Commander

Enclosure: Groundwater Model Evaluation Plan, Red Hill Bulk Storage Facility, Joint Base Pearl Harbor-Hickam, Oahu, September 8, 2017

Red Hill Administrative Order on Consent, Groundwater Model Evaluation Plan Deliverable

Section 6.2 Investigation and Remediation of Releases Scope of Work
Section 7.1.2 Groundwater Flow Model Report Scope of Work
Section 7.2.2 Contaminant Fate and Transport Model Report Scope of Work
Section 7.3.2 Groundwater Monitoring Well Network Scope of Work

In accordance with the Red Hill Administrative Order on Consent, paragraph 9, DOCUMENT CERTIFICATION

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system or those persons directly responsible for gathering the information, the information submitted is, to be the best of my knowledge and belief, true, accurate, and complete. I am aware that there are significant penalties for submitting false information including the possibility of fines and imprisonment for knowing violation.

Signature: ______________________________

CAPT Richard Hayes III, CEC, USN
Regional Engineer, Navy Region Hawaii

Date: 9/7/2017

Groundwater Model Evaluation Plan, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, 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 6.2, Section 7.1.2, Section 7.2.2, and Section 7.3.2

September 8, 2017
Revision 00

NAVFAC
Naval Facilities Engineering Command
NAVFAC HAWAII

Comprehensive Long-Term Environmental Action Navy
Contract Number N62742-12-D-1829, CTO 0053

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Groundwater Model Evaluation Plan, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, 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 6.2, Section 7.1.2, Section 7.2.2, and Section 7.3.2

September 8, 2017
Revision 00

Prepared for:

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Comprehensive Long-Term Environmental Action Navy
Contract Number N62742-12-D-1829, CTO 0053

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ACRONYMS AND ABBREVIATIONS

µg/L	micrograms per liter
AEP	Attenuation Evaluation Plan
AOC	Administrative Order on Consent
AVGAS	aviation gasoline
BTEX	benzene, toluene, ethylbenzene, and xylenes
BWS	Board of Water Supply, City and County of Honolulu
CF&T	contaminant fate and transport
CLN	Connected Linear Network
COPC	chemical of potential concern
CSM	conceptual site model
CWRM	Commission on Water Resource Management, State of Hawaiʻi
	Department of Land and Natural Resources
DLA	Defense Logistics Agency
DLNR	Department of Land and Natural Resources, State of Hawaiʻi
DO	dissolved oxygen
DOH	Department of Health, State of Hawaiʻi
DON	Department of the Navy, United States
EAL	Environmental Action Level
EDR	Existing Data Summary and Evaluation Report
EPA	Environmental Protection Agency, United States
EPM	equivalent porous medium
ft	foot/feet
ft/d	foot/feet per day
GHB	general-head boundary
GIS	geographic information system
GMEP	Groundwater Model Evaluation Plan
GMS	Groundwater Modeling System
GWFMWG	Groundwater Flow Modeling Working Group
HGU	hydrogeologic unit
HSSM	Hydrocarbon Spill Screening Model
JBPHH	Joint Base Pearl Harbor-Hickam
JP	Jet Fuel Propellant
LNAPL	light non-aqueous-phase liquid
m	meter
MCL	Maximum Contaminant Level
ME	mean error
mg/L	milligrams per liter
mgd	million gallons per day
MNA	monitored natural attenuation
MOGAS	motor gasoline
msl	mean sea level
MtBE	methyl tertiary-butyl ether
NAP	natural attenuation parameter
NAPL	non-aqueous-phase liquid
NATO	North Atlantic Treaty Organization
NAVFAC	Naval Facilities Engineering Command
NSFO	Navy Special Fuel Oil
NSZD	natural source-zone depletion

PEST	Parameter Estimation
RMSE	root mean squared error
RT3D	Reactive Transport in 3-Dimensions
SFB	specified-flux boundary
SHB	specified-head boundary
SME	subject matter expert
SOW	scope of work
SSRBL	Site-Specific Risk-Based Level
SWAP	Source Water Assessment Program
SWI2	Seawater Intrusion 2 (Package for MODFLOW)
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)
TUA	tank upgrade alternatives
U.S.	United States
UIC	Underground Injection Control
USGS	United States Geological Survey
WP	work plan

1. Introduction

This *Groundwater Model Evaluation Plan* (GMEP) describes development of the groundwater flow and contaminant fate and transport (CF&T) models for the Investigation and Remediation of Releases and Groundwater Protection and Evaluation at Red Hill Bulk Fuel Storage Facility ("the Facility"), Joint Base Pearl Harbor-Hickam (JBPHH), Hawai‘i. The Facility is owned and operated by the United States (U.S.) Navy (DON; Navy) and is funded by Defense Logistics Agency (DLA). This modeling effort will be conducted in two stages, with the initial effort focused on development of a flow model, which will be followed by development of a contaminant fate and transport (CF&T) model.

The *Work Plan/Scope of Work* (WP/SOW) (DON 2017a) presents the process, tasks, and deliverables that address the goals and requirements of Statement of Work Sections 6 and 7 of the *Administrative Order on Consent* (AOC) *In the Matter of Red Hill Bulk Fuel Storage Facility* (EPA Docket No: RCRA 7003-R9-2015-01; DOH Docket No: 15-UST-EA-01). The AOC was issued by the U.S. Environmental Protection Agency (EPA) Region 9 and State of Hawai‘i Department of Health (DOH) (EPA Region 9 and DOH 2015) to the Navy/DLA in response to a release of an estimated 27,000 gallons of Jet Fuel Propellant (JP)-8 from one of the Facility's 12.5-million-gallon underground fuel storage tanks (Tank 5) that was confirmed and reported to DOH on January 23, 2014. The bottoms of the Facility's 20 tanks are located approximately 100 feet (ft) above a major groundwater aquifer, which is used to feed both Navy and the City and County of Honolulu drinking water sources.

The investigation is being performed by the Navy/DLA and specifically addresses AOC Statement of Work Section 6, Investigation and Remediation of Releases, and Section 7, Groundwater Protection and Evaluation. The investigation's overall process, tasks, and schedule are presented in the WP/SOW (DON 2017a). The planning activities described in the WP/SOW include preparation of nine documents, referred to as derivative deliverables, which will address specific aspects of the planning process; this GMEP is one of the derivative deliverables. A flowchart showing the sequencing of derivative deliverables is presented on Figure 1; additional information is provided in the WP/SOW.

Two of the tasks identified in the WP/SOW are (a) *Update the Existing Groundwater Flow Model* and (b) *Update the Contaminant Fate and Transport Model and Evaluate Whether to Perform a Tracer Study*. The existing groundwater flow and CF&T models for the Facility were originally developed during 2005–2007 by the University of Hawai‘i (DON 2007). This GMEP describes the plan for updating the groundwater modeling using data generated since 2007. The update will include, where appropriate, significant changes to the existing model including the use of new modeling codes. Where assumptions were previously made in the 2007 modeling effort that cannot be verified with actual data or technically defensible hydrogeologic interpretation, a conservative assumption will be made in the revised model. Objectives of the current modeling effort are to better understand the short- and long-term flow conditions as well as potential contaminant transport so that measures to remediate and contain any potential contaminant plume associated with fuel releases from the Facility can be properly evaluated.

Modeling conducted for this work will follow industry accepted protocols and guidelines for groundwater flow model development, calibration, and application. Published and accepted guidelines will be followed for groundwater flow modeling (ASTM 2000b; Reilly and Harbaugh 2004), setting initial and boundary conditions (ASTM 2002e, 2002d), calibrating the model (ASTM

2002a, 2002b), conducting a sensitivity analysis (ASTM 2002c), and documenting the modeling effort (ASTM 2000a).

This GMEP was prepared for DLA under Naval Facilities Engineering Command (NAVFAC) Hawaii. It was prepared under contract number N62742-12-D-1829, contract task order 0053 of the Comprehensive Long-Term Environmental Action Navy IV program.

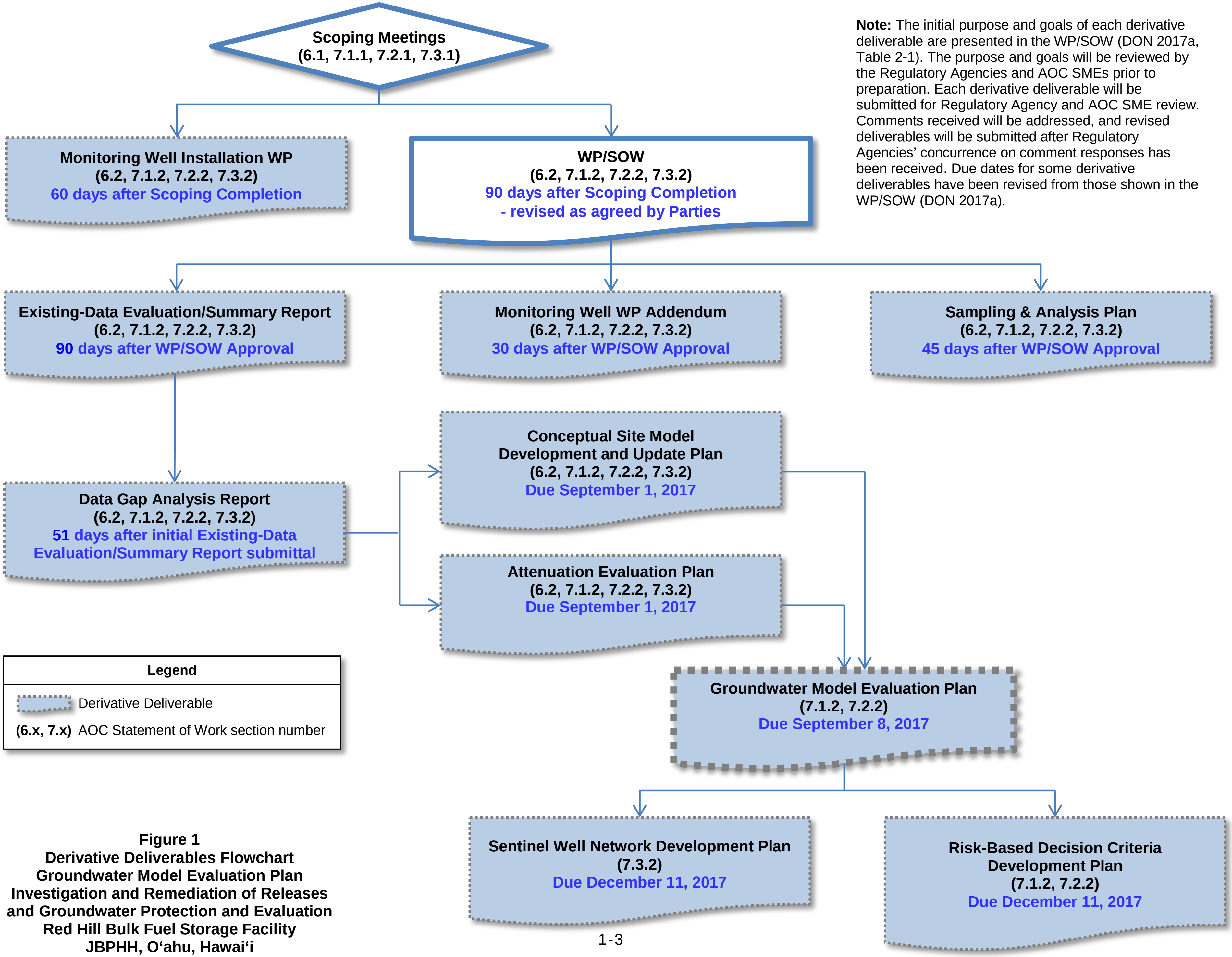
1.1 MODELING DOMAIN BOUNDARY

Figure 2 shows the planned updated modeling area in relation to the Facility. The model boundary locations were discussed, evaluated and adjusted collaboratively with the Regulatory Agencies and AOC Regulatory Agencies' Subject Matter Experts (SMEs). This GMEP reflects the Navy's decision based on various technical discussions conducted during the June 2017 meetings of the Groundwater Flow Modeling Working Group (GWFMWG) (reported in *Groundwater Model Progress Report 02* [DON 2017e]) and further refinements of the modeling approach discussed in the subsequent GWFMWG meeting on August 17, 2017.

1.2 DOCUMENT ORGANIZATION

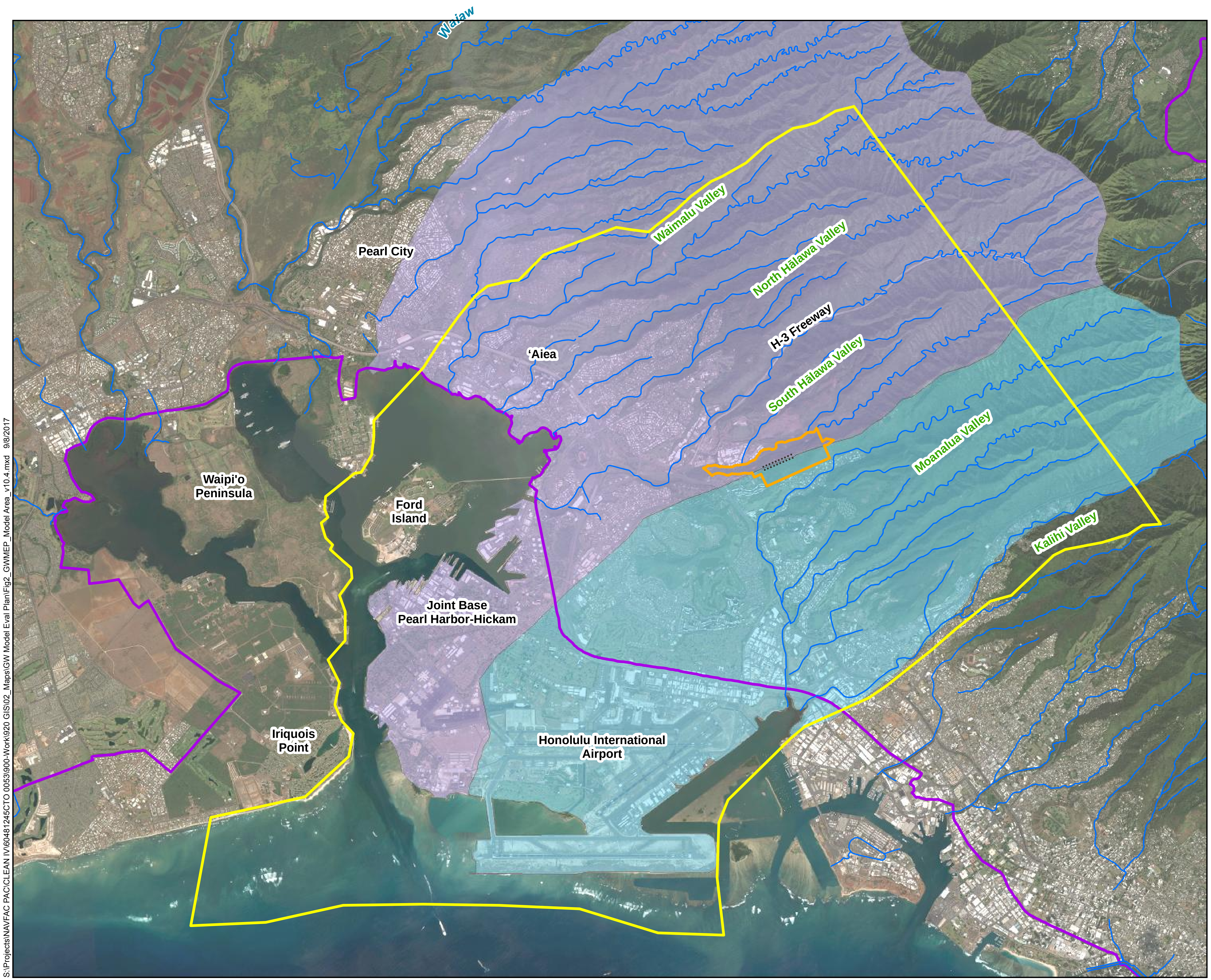
The remainder of this document is organized as follows:

- Section 2 outlines the objectives of the current groundwater modeling effort.
- Section 3 summarizes previous modeling efforts for the site.
- Section 4 describes the technical approach for refining the groundwater flow model.
- Section 5 describes the technical approach for refining the CF&T model.
- Section 6 identifies the reporting that will present the modeling results.
- Section 7 lists references for literature cited in the text, tables, and figures.



Note: The initial purpose and goals of each derivative deliverable are presented in the WP/SOW (DON 2017a, Table 2-1). The purpose and goals will be reviewed by the Regulatory Agencies and AOC SMEs prior to preparation. Each derivative deliverable will be submitted for Regulatory Agency and AOC SME review. Comments received will be addressed, and revised deliverables will be submitted after Regulatory Agencies' concurrence on comment responses has been received. Due dates for some derivative deliverables have been revised from those shown in the WP/SOW (DON 2017a).

Figure 1
Derivative Deliverables Flowchart
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases
and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



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Location Map

Legend

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. DON 2007. *Red Hill Bulk Fuel Storage Facility Final Technical Report.* Prepared by TEC, INC. for DON (August).

Figure 2
Groundwater Modeling Area
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

2. Objectives of the Planned Groundwater Modeling

The activities described in this GMEP are intended to satisfy the AOC Section 7 objectives and provide a decision tool that can be used into the future for understanding, evaluating, and managing potential future releases of contaminants to groundwater from the Red Hill Facility.

The overall objective of the planned groundwater modeling is to incorporate more recent and definitive hydrogeologic and attenuation data into a refined model to further evaluate groundwater flow and contaminant movement from the Facility to potential receptors. This modeling will help ascertain potential risk to water supply as a result of a potential range of releases from the Red Hill Bulk Fuel Storage Facility under a range of reasonable pumping and source conditions within the model domain. This modeling will support a comprehensive exposure assessment and provide the basis for the refinement of Site-Specific Risk-Based Levels (SSRBLs) to support the feasibility evaluation of various remedial alternatives in response to the January 2014 leak and potential future fuel releases (EPA Region 9 and DOH 2015).

This groundwater model will be used to evaluate capture zones related to key water supply wells under a range of pumping conditions. Analytical models will be used to estimate the distance that a hypothetical plume of non-aqueous-phase liquid (NAPL) could move along the groundwater surface under a range of release scenarios. This information and related source information will be used by the model to determine conditions that would not result in an exceedance of the Maximum Contaminant Levels (MCLs) or State of Hawai‘i Tier 1 Environmental Action Levels (EALs) at receptors (e.g., drinking water) identified in the conceptual site model (CSM).

The model will also be used to inform decisions related to potential remediation alternatives. An additional modeling objective is to support an evaluation of potential tank upgrade alternatives (TUA) decisions. The evaluation will also describe effects of potentially feasible remedial alternatives on groundwater flow and capture zones, as warranted. As part of the investigation, the potential for groundwater flow northward from the Facility will also be evaluated. Modeling will also address future vulnerability to hypothetical releases within a range of pumping conditions under AOC Statement of Work Section 8 (EPA Region 9 and DOH 2015).

The updated groundwater flow and CF&T model will provide better estimates of the migration rates of dissolved hydrocarbon compounds and simulation of concentrations/flux of chemicals of potential concern (COPCs) with distance from the Facility. New data and studies will improve the understanding of groundwater flow and COPC attenuation processes, and will be integrated into the updated CSM. The updated groundwater model will reflect these additional data and the refined CSM.

3. Previous Groundwater Studies

The *Existing Data Summary and Evaluation Report* (EDR) (DON 2017b) describes the available data for hydrogeology and chemistry that are pertinent for the groundwater modeling, including the following:

- Geologic framework in the groundwater flow modeling area
- Hydraulic properties of hydrogeologic units (HGUs)
- Hydrologic features in the groundwater flow modeling area
- Spatial distribution of groundwater levels, hydraulic heads, and hydraulic gradients
- Spatial and temporal influence on groundwater levels, hydraulic heads, and hydraulic gradients from pumping of water supply wells within the modeling domain
- Groundwater sources and sinks
- Chemical data for groundwater
- Groundwater contaminant fate and transport parameters

Additional hydrogeologic and chemical data are currently being collected as described in the WP/SOW (DON 2017a) to address uncertainties described in the *Data Gap Analysis Report* (DON 2017d) and the *CSM Development and Update Plan* (DON 2017i). Much of these data will be applicable and useful for refining and updating the groundwater flow model. The *Attenuation Evaluation Plan* (AEP) (DON 2017h) describes additional data and analyses that will be used to support the groundwater CF&T modeling.

3.1 CONCEPTUAL SITE MODEL

All of the available information will be integrated with the new data being collected to develop a new CSM, as described in the *CSM Development and Update Plan* (DON 2017i). The CSM will then be used to develop and refine the numerical groundwater flow model. Data and analyses obtained as part of natural attenuation studies described in the AEP (DON 2017h) will then be incorporated into the fate and transport model. As additional future data become available, they will also be incorporated into the CSM, since the CSM is a “living” document. This subsection provides a summary of hydrogeologic information pertinent to the CSM of groundwater flow. More detailed information and data are provided in the EDR (DON 2017b).

The principal aquifer beneath the Facility area consists of highly permeable zones in the basaltic lava of the Koʻolau Formation, which are hydrologically interconnected to various degrees across the site. The Koʻolau Formation consists almost entirely of basaltic lava flows, including pāhoehoe and aʻā lava along with highly permeable clinker zones. In addition, previous regional studies have reported that dikes occur in the Central Oʻahu groundwater flow system, which have the potential to impede groundwater flow in some areas (Oki 1998). The dike-intruded basalt has been mapped by the U.S. Geological Survey (USGS) (Izuka et al. 2016) to be more than 2 miles northeast of the Facility.

The aʻā lava flows may also act as localized confining layers in the basal aquifer system with unconfined conditions present just a few feet away. Rock core logs and photos indicate that interbedded flows of different types of lava likely flowed from different directions at different times, and may have been weathered between flow events, potentially forming weathered soil horizons. These basalt types and lava flow processes can cause the layered basalt to contain both relatively impermeable and highly permeable zones. Previous modeling efforts in the area have successfully used an equivalent porous medium approach to simulate groundwater flow under these conditions.

The Facility is near the boundary of the Waimalu and Moanalua Aquifer Systems of the Pearl Harbor and Honolulu Aquifer Sectors, respectively; these aquifer areas underlie the Waimalu, North Hālawa, South Hālawa, Moanalua, and Kalihi Valleys, as shown on Figure 2. The valleys on either side of the ridges are a result of fluvial erosion of lava flows and are filled with alluvium and colluvium, which are typically underlain by saprolite (clayey, highly weathered basalt) and basaltic lava. Valley fill sediments are generally fine-grained and are of relatively low hydraulic conductivity compared to that of the basalt aquifer. Where deep-cut valleys extend well below the water table, they may act as barriers to groundwater flow and contaminant transport. Where exposed to weathering, especially beneath the valley fill and streams, fine-grained saprolite zones may also create barriers to groundwater flow and contaminant transport.

The Facility is located inland and to the east of the Hawai‘i State Underground Injection Control (UIC) Line as shown on Figure 2. The UIC Line indicates the border between groundwater that is, and is not, considered a potential source of drinking water. Although the State of Hawai‘i considers aquifers shoreward of the UIC Line to not be a potential source of drinking water, the EPA does not recognize this boundary and considers the area shoreward of the UIC Line to be a potential source of drinking water.

At the Facility, the bottoms of the underground fuel storage tanks are approximately 100 ft above the groundwater table. Red Hill ridge is an administrative boundary between these aquifer systems, but is not actually a hydrogeologic boundary because there are no geochemical or physical attributes that differ between these two aquifers at this location (DON 2007).

These aquifer systems provide potable water supply to O‘ahu. Water supply wells identified within the groundwater flow modeling area are included on Figure 3(a,b,c). Of these wells, the following are of primary interest for the modeling effort (Section 4.2.3):

- Navy Supply Wells 2254-01 (Red Hill Shaft) and 2255-32 (‘Aiea Halawa Shaft) are owned by NAVFAC Hawaii and supply potable water to JBPHH.
- Well 2354-01 (Hālawa Shaft) and Moanalua Wells 2153-04, -10, -11, and -12 are owned by the City and County of Honolulu Board of Water Supply (BWS) and provide municipal drinking water.

These wells were installed prior to 1975 (DON 2017b). Currently, it is presumed that these wells represent the most significant exposure pathway to human receptors due to their known or suspected pumping influence on the aquifer beneath the Facility, the size of their drinking water distribution system(s), distance to the Facility, and potential groundwater flow location relative to the Facility. The Navy Red Hill Shaft probably is at a higher risk relative to the others.

As described in DON (2007), the water table surface is strongly influenced by pumping within the Red Hill area. In May 2006, the groundwater hydraulic gradients were nearly directly to the south when Red Hill Shaft was not pumping (May 12–19, 2006). When the pump was activated (May 20–26, 2006), the gradient shifted to the west, in the direction of Red Hill Shaft.

Although useful information was provided by previous groundwater studies at the Facility, uncertainty remains in the groundwater levels and hydraulic gradients in the site vicinity (due to extremely flat water level gradients), as detailed in the EDR (DON 2017b), *Data Gap Analysis Report* (DON 2017d), and the *CSM Development and Update Plan* (DON 2017i). Resolving this uncertainty is an important objective of planned investigations that include resurveying the wells (DON 2017c) and conducting synoptic water level measurements (USGS 2017). Both revised top of casing elevations and groundwater data obtained from new monitoring wells will be used to further define the actual groundwater flow directions and update the groundwater flow model. The synoptic water level study will also improve understanding of flow resulting from various pumping conditions.

The CSM developed for the 2007 Facility investigation (DON 2007) is being updated as part of the current investigation (DON 2017i); nevertheless, its basic features remain relevant. As suggested by the 2007 CSM, the migration pathways of potential concern are:

- Migration of soil vapor from NAPL in the unsaturated zone and basal groundwater through fractured bedrock to indoor and ambient air
- Migration of leachate to a stream or seeps at ground surface
- Migration of leachate through contaminated unsaturated bedrock to the basal aquifer
- Migration of NAPL released from the tanks through the unsaturated zone to or near to the basal aquifer, and dissolution into basal groundwater from a light non-aqueous-phase liquid (LNAPL) plume on the water table
- Migration of petroleum-related COPCs dissolved in groundwater to nearby potable water supply and other wells

The previous investigations ultimately concluded that the migration of petroleum COPCs dissolved in groundwater to nearby potable water wells was the only pathway considered to be potentially complete and capable of exposing potential sensitive receptors, namely consumers of drinking water. However, other pathways may also be potentially complete and will be addressed in the CSM and risk assessment evaluations.

3.2 GROUNDWATER MONITORING, WATER LEVELS

The groundwater elevations measured in monitoring wells completed directly beneath the tanks have generally ranged from approximately 17.0 to 21.9 ft mean sea level (msl). The ground surface above the tank farm is approximately 420–560 ft msl, thus the water table lies approximately 400–540 ft below ground surface, and approximately 100 ft below the bottoms of the tanks. The groundwater table beneath the tanks is deeper than the elevation of adjacent valley streams (DON 2007), indicating that transport of Facility tank contaminants in the basal groundwater flow system to the valley streams will not occur.

Groundwater levels near the Facility are strongly influenced by supply well pumping. Groundwater level measurements taken in May 2006 were re-evaluated in 2010 to prepare revised water table potentiometric maps for the site area for pumping and non-pumping conditions (DON 2010). When pumps at Red Hill Shaft were operating at normal capacity (approximately 4 million gallons per day [mgd]), the hydraulic gradients indicated possible components of groundwater flow to the west-northwest as well as to the southwest. When the pumps in Red Hill Shaft were pumping at an increased rate of approximately 10 mgd, this substantially increased the drawdown near the pumping well and created a hydraulic capture zone centered at the infiltration gallery, which increased the southwesterly groundwater flow gradient in and around the Facility. During the May 2006 pumping test period, the highest pumping rates reported for Red Hill Shaft approached 20 mgd for several periods for as long as 1 day. During those periods, the largest drawdown measured at Red Hill Shaft was approximately 7 ft (DON 2007).

Farther northwest of the Facility, the BWS Hālawa Shaft is a municipal drinking water source for south O‘ahu. The results from a regional groundwater pumping test conducted in May 2006 did not indicate any hydraulic response in the BWS Hālawa Deep Monitoring Well 2255-40, located north of North Hālawa Stream, during pumping of Red Hill Shaft (DON 2007). Conversely, wells monitored near the Facility did show a clear hydraulic response to pumping of Red Hill Shaft. Data from installation of proposed new monitoring wells described in the *Monitoring Well Installation Work Plan Addendum 02* (DON 2017g) will help ascertain whether valley fill sediments in North or South Hālawa Valleys extend to depths below the water table and may act as barriers to groundwater flow.

Data from a more recent pumping test study conducted by the USGS (May 2015) indicate the possibility that pumping of the Hālawa Shaft may have caused or contributed to water level changes detected in the area of South Hālawa Valley north of the Facility. This issue will be further evaluated as part of the planned work, which includes the synoptic water level study currently being implemented by the USGS (USGS 2017).

3.3 HYDRAULIC PROPERTIES

The groundwater flow properties of the aquifers and aquitards in the vicinity of the Facility depend mainly on the material composition and geologic processes that created and may have subsequently modified characteristics of the materials.

3.3.1 Basal Aquifer

The basal aquifer is composed of igneous rock in these forms: lava flows, dikes, pyroclastic deposits, and saprolite. In this region, the lava flows are either of the pāhoehoe or the a‘ā type. Massive a‘ā and pāhoehoe flows of low permeability alternate with rubbly a‘ā clinker beds, some of which may have high permeability.

The hydraulic conductivity (also referred to as permeability) of the lavas depends on thickness of the flows and clinker zones, frequency and extent of fractures, as well as extent of weathering and formation of saprolite in the clinker zones. Although less common, pāhoehoe lava tubes can create localized preferred pathways for groundwater flow. Hydraulic conductivity typically ranges from several hundred to several thousand feet per day (ft/d) in highly permeable dike-free lavas, and is orders of magnitude higher in the horizontal direction than in the vertical direction (DON 2007). In the Facility vicinity, the arithmetic mean, geometric mean, and median values of hydraulic conductivity for dike-free volcanic rocks were respectively 1,700, 900, and 1,200 ft/d (DON 2007). Horizontal hydraulic conductivity tends to be several times greater parallel to lava flows than perpendicular to the flows (Nichols, Shade, and Hunt Jr. 1996). The 2005 USGS groundwater model (Oki 2005) used a value of 1,500 ft/d for horizontal transverse hydraulic conductivity and a value of 4,500 ft/d for horizontal longitudinal hydraulic conductivity in the Pearl Harbor area, for a longitudinal to transverse anisotropy of 3. Recent USGS modeling (Oki 2005) used a vertical hydraulic conductivity value for the volcanic rock aquifer of 7.5 ft/d, which is 600 times lower than the horizontal longitudinal hydraulic conductivity.

Although not present beneath the Facility, pyroclastic rocks include ash, cinder, spatter, welded tuff, and larger blocks, and typically have significantly lower permeability and may affect localized groundwater flow directions. Saprolite is widespread throughout the Facility area at and near the ground surface; it is a soft, clay-rich, thoroughly weathered volcanic rock that may be as much as 100–300 ft thick and has very low hydraulic conductivity (DON 2007).

3.3.2 Dike-Impounded Aquifer Systems

Although dikes are not known to exist within the groundwater model domain, the following discussion is included for completeness. To the northeast of the northeastern model boundary, outside the planned model area, the USGS and other previous studies have reported dike-impounded (intruded) aquifer systems in the basalt, as depicted on Figure 4 (Izuka et al. 2016). Dikes are thin, near-vertical sheets of massive, low-permeability rock that intrude existing rocks and have cooled beneath the surface. Dikes are generally less than 10 ft wide and can extend vertically and laterally for long distances. They impede the flow of groundwater due to their lower permeability. Within a dike complex, dikes intersect at various angles. Dikes tend to channel groundwater flow parallel to the general trend of the dikes. Hydraulic conductivity is greater along the strike of the dike than perpendicular to the strike and the average conductivity decreases as the number of dikes increases toward the center of the rift zone. The overall hydraulic conductivity of an entire dike complex can be as low as 0.01 ft/d. The hydraulic conductivity of a single intrusive dike was estimated to be even several orders of magnitude lower (DON 2007). The number of dikes can exceed 1,000 per mile in the center of the rift zone, but it sharply decreases in the outer part. However, single, widely scattered dikes can extend farther from the designated dike complex (Takasaki and Mink 1985).

Dike-impounded aquifer systems occur near eruption centers where low-permeability dikes have intersected more permeable volcanic flows. The dike systems compartmentalize groundwater and occur as much as 1,600 ft msl on O‘ahu. Groundwater within dike-impounded aquifer systems primarily includes freshwater, but in places may include underlying brackish water and saltwater. Groundwater may discharge from the dike-impounded system to downgradient aquifers or water systems; in stream valleys where dike compartments are exposed, the groundwater may discharge directly to streams (Gingerich and Oki 2000).

3.3.3 Valley Fill Sediments

Sedimentary deposits are also important in influencing groundwater flow in the basal aquifers in some areas, particularly deep-cut alluvium-filled streams valleys (DON 2007). Following periods of extensive erosion, the larger valleys were deeply incised. Some of these valleys were filled in by marine and terrestrial sediments in times when the relative sea level was substantially lower or higher than today. The bottoms of the sediments in many stream valleys extend significantly below the water table, and since the fills have a lower overall permeability than the underlying lava flows, they can act as barriers to groundwater flow and contaminant transport (DON 2007).

Hydraulic conductivity estimates of the alluvium range from 0.019 to 0.37 ft/d (Wentworth 1938). The USGS groundwater model (Oki 2005) used 0.058 ft/d for both horizontal and vertical hydraulic conductivity in the Pearl Harbor area (note that these values are several orders of magnitude lower than those reported for the basaltic aquifer) and also showed valley fill depths exceeding 100 ft below sea level in some valleys. In most cases, the lower range of this estimate reflects the effective hydraulic conductivity, which contrasts with that of the surrounding flank lavas, making the valley-fill deposits a barrier to groundwater flow. Underlying the valley fills are layers of highly weathered basalt (saprolite), which are low-permeability units that further impede groundwater flow and contaminant transport.

The valley fill sediments can have a controlling influence on flow of groundwater across the valleys. Since this control is somewhat uncertain, additional data are being collected regarding the extent of the fill beneath the water table and the influence of the valley sediments on water level changes resulting from pumping on either side of the valley. Due to the uncertainty related to valley fill thickness and associated permeability, model runs will consider a range of scenarios related to valley fill thickness, vertical extent, and permeabilities. As field data related to this issue becomes available, that information will be integrated into the model.

3.3.4 Caprock

To the west of the Facility are substantial thicknesses of heterogeneous sediments occurring on the coastal plains in southern O‘ahu around Pearl Harbor. These terrestrial and marine sediments, welded tuff, and reef limestone deposits form a 1,000-ft-thick wedge, commonly referred to as caprock, that overlies the lava flows of the basalt aquifer. Overall, the caprock has lower hydraulic conductivity than the basaltic rocks, and it overlies and confines the basal aquifer in the Pearl Harbor and Honolulu areas. Hydraulic conductivity of the caprock spans several orders of magnitude depending on material type (DON 2007). The older alluvium, including fine-grained muds and saprolite, can have hydraulic conductivities ranging from approximately 0.01 to 1 ft/d. Sands have an estimated hydraulic conductivity ranging from 1 to 1,000 ft/d. Coral gravels and reef limestone deposits have hydraulic conductivities of several thousands of ft/d. Although the permeability of the components is diverse, the overall effect of the caprock is one of a low-permeability formation that acts as an overlying confining unit atop the basal aquifer near the coastline, as evidenced by artesian groundwater and springs around Pearl Harbor.

3.4 PREVIOUS NUMERICAL GROUNDWATER FLOW MODELING

Working with local experts from the University of Hawai‘i Water Resources Research Center, the Navy previously developed a 3-D numerical groundwater flow model for the Facility (Rotzoll and El-Kadi [2007]; published in DON [2007]). Two flow models were created. A regional groundwater flow model was developed to define the boundary conditions for the smaller, more detailed local model of area surrounding the Facility. The regional model was modified from the DOH’s Source Water Assessment Program (SWAP) model for the island of O‘ahu (R. B. Whittier et al. 2004), simulating steady-state conditions covering the 10-year period from 1996 to 2005. The local model was developed to simulate both steady-state and transient conditions in the area of specific interest for Red Hill.

The local groundwater model utilized the USGS’s three-dimensional finite-difference groundwater modeling software MODFLOW 2000, and the model was set up based on hydrogeology information available at that time. Groundwater information and recharge estimates were obtained from Giambelluca (1983) and Shade and Nichols (1996), then updated for current land use (Rotzoll and El-Kadi 2007). Flow characteristics were also obtained from other literature (Nichols, Shade, and Hunt Jr. 1996; Oki 1998).

Parameter values for hydraulic conductivity and porosity were applied for three main materials: basalt, valley fill, and caprock, and then the model was calibrated to dynamic flow conditions using the results of a regional pump test to estimate values for specific storativity and specific yield for the same materials. Calibration of the 2007 flow model was facilitated by using the parameter estimation algorithm Parameter Estimation (PEST) (Doherty 2000). Table 3-1 presents the hydraulic parameter values in the final calibrated local scale numerical flow model (DON 2007).

Table 3-1: Hydraulic Parameters Developed from Model Calibration

Hydrogeologic Unit	Horizontal, Transversal K (ft/d)	Horizontal, Longitudinal K (ft/d)	Vertical K (ft/d)	Effective Porosity	Specific Storage (ft^{-1})	Specific Yield
Caprock	115	115	115	0.10	3.05 × 10-5	0.10
Valley Fill	0.066	0.066	0.066	0.15	1.52 × 10-5	0.12
Basalt	1,476	4,428	7.4	0.05	1.07 × 10-5	0.031

K	hydraulic conductivity
ft^{-1}	per foot

Figure 5 illustrates the model-simulated 10-year capture zones for potable water wells in the vicinity of the Facility that were simulated using the previous flow model (DON 2007). These simulations may change once the revised model is calibrated using new data including groundwater elevation data from new wells, revised elevations and groundwater elevation data from previously existing wells, and the synoptic water level study data (USGS 2017). The 2007 model simulations indicated that Red Hill Shaft captures groundwater flowing westward beneath South Hālawa Valley, and that the BWS Hālawa Shaft (2354-01) captures groundwater flowing westward beneath North Hālawa Valley. These simulations also showed that the BWS Moanalua wells (2153-10, 2153-11, and 2153-12) capture groundwater flowing westward beneath Moanalua Valley. Those 2007 model results are currently being questioned, and the development of the new model as described in this plan will include re-evaluation of capture zones created by water supply wells in the vicinity of Red Hill.

As part of the 2005–2007 Facility investigation, in addition to the groundwater flow model, a groundwater flow and contaminant transport model was developed to evaluate the threat to surrounding potable water wells and to support a Tier 3 assessment of future risk to the potable water production wells (DON 2007). MODFLOW was used to model groundwater flow in the aquifers surrounding the Facility. A multi-species reactive transport model developed by the Battelle Pacific Northwest National Laboratory, the Reactive Transport in 3-Dimensions (RT3D) simulator, was used to model solute (i.e., dissolved contaminant) transport and natural attenuation of hydrocarbons, including degradation of hydrocarbon compounds in both oxygenated and anaerobic groundwater.

The results of the Tier 3 Risk Assessment reported in DON (2007) indicated that NAPL would have to migrate to the groundwater surface in sufficient quantities to create a LNAPL plume extending to within approximately 1,100 ft of the Red Hill Shaft infiltration gallery before benzene could present a potentially unacceptable risk to groundwater (based on the EALs, which are considerably more stringent than the MCLs).

3.5 EVALUATION OF FUEL SOURCES

According to records, the main fuel types stored in the Facility tanks have been diesel oil, Navy Special Fuel Oil (NSFO), Navy Distillate, JP-5, JP-8 (North Atlantic Treaty Organization [NATO] F-24), and F-76 (Diesel No. 2 Fuel Oil) except for Tank 17, which contained Aviation Gasoline (AVGAS) and Motor Gasoline (MOGAS) between 1964 and 1969, and Tank 18, which contained AVGAS between 1964 and 1968. AVGAS and MOGAS are highly volatile, gasoline-based fuels, which present potential explosion concerns within the enclosed tunnels of the Facility. Both have a much higher concentration of highly soluble and mobile compounds known as aromatic hydrocarbons than do kerosene- and diesel-based fuels. Benzene, toluene, ethylbenzene, and xylenes (BTEX) are examples of aromatic hydrocarbons that can be easily degraded in groundwater. The

Navy does not have current plans to store AVGAS or MOGAS at the Facility in the future. Soon after year 2000, JP-5, JP-8, F-24, and F-76 were the only fuels stored in the fuel storage tanks at the Facility. Currently, the tanks contain JP-5, F-24, and F-76 fuels (DON 2017e).

Gasoline (MOGAS) contains approximately 35 percent aromatic hydrocarbons, of which 19 percent is BTEX. By comparison, JP-5 contains approximately 6.8 percent aromatic hydrocarbons, less than 1 percent BTEX, and less than 0.02 percent benzene; and diesel-based fuels contain even less aromatic hydrocarbons (Potter and Simmons 1998). In addition, diesels and JP fuels do not contain lead or methyl tertiary-butyl ether (MtBE). An important transport mechanism is the effective solubility of a fuel, which is the highest concentration of petroleum hydrocarbons that can be expected to dissolve in water. The solubility limits for gasoline and JP-5 are 93 and 4.5 milligrams per liter (mg/L), respectively. The solubility limit for benzene in JP-5 is 0.75 mg/L (DON 2007). These concentrations would be reached only if NAPL were to be present in sufficient quantities to come into direct contact and establish equilibrium with water. BTEX in JP-5 and JP-8 is rapidly degraded by natural attenuation mechanisms, such as by the metabolism of microbes naturally present in the groundwater under both aerobic and anaerobic conditions. Groundwater modeling will evaluate the effects of various potential future releases of compounds dissolved from the fuel after reaching the water table.

As of February 2016, the revised COPC list of compounds for the periodic Red Hill groundwater monitoring includes TPH-gasoline range organics (TPH-g), TPH-d, TPH-residual range organics (TPH-o), BTEX (i.e., benzene, toluene, ethylbenzene, and total xylenes), 1-methylnaphthalene, 2-methylnaphthalene, and naphthalene (EPA Region 9 and DOH 2016). Additional COPCs to be analyzed include lead scavengers (1,2-dichloroethane and 1,2-dibromoethane) for new monitoring wells installed since February 2016 (i.e., RHMW08, RHMW09, and RHMW10) for a minimum of 1 year, and fuel additive COPCs phenol and 2-(2-methoxyethoxy)-ethanol for all monitoring wells. Although BTEX has been monitored continuously throughout the long-term groundwater monitoring program, it has been consistently non-detect in most samples from the Red Hill groundwater monitoring network. For the groundwater samples in which BTEX compounds have been detected, the concentrations have been at very low levels, well below the screening criteria, even at monitoring well RHMW02, which is located adjacent to Tank 5.

Three existing monitoring wells (RHMW01, RHMW02, and RHMW03) were installed into the basal aquifer within the lower access tunnel in the vicinity of the tanks. Although measurable levels of NAPL have never been reliably detected in any of the vicinity wells, dissolved petroleum compounds (COPCs) have been detected in samples collected from wells in the tank area, with the highest concentrations measured at RHMW02, which is located adjacent to Tanks 5 and 6 (DON 2007).

Methane has been observed in groundwater samples collected from sampling locations RHMW225401, RHMW01, RHMW02, and RHMW03. Methane is an indicator compound for active anaerobic biodegradation of petroleum. Anaerobic degradation is expected to occur only after aerobic degradation has used up all the available dissolved oxygen in the groundwater. The presence of methane suggests that biodegradation (a component of natural attenuation) is actively occurring in the groundwater beneath the tanks in the residual NAPL source area. A depletion of dissolved oxygen (DO) near these wells along with relatively high DO levels in groundwater outside the source area further indicates that active biodegradation is occurring in the area.

Since the previous modeling efforts, a substantial amount of additional groundwater chemistry data from directly beneath the Facility have been obtained as the groundwater monitoring program has progressed and new wells have been installed (existing Red Hill monitoring well locations are shown on Figure 3b). Routine sampling and analysis on a minimum quarterly basis has been conducted at sampling point RHMW2254-01 and at wells RHMW01, RHMW02, RHMW03, and RHMW04 since 2005; at RHMW05 since 2009; at RHMW06 and RHMW07 since 2014; at RHMW08 and RHMW09 since late 2016; and at RHMW10 since early 2017. Additional new multi-level monitoring wells (RHMW01R, RHMW07D, and RHMW11–RHMW20) are currently being proposed for installation (DON 2017g). These additional data will be analyzed for use with the CF&T model.

3.6 PREVIOUS REACTIVE TRANSPORT SIMULATIONS (2007)

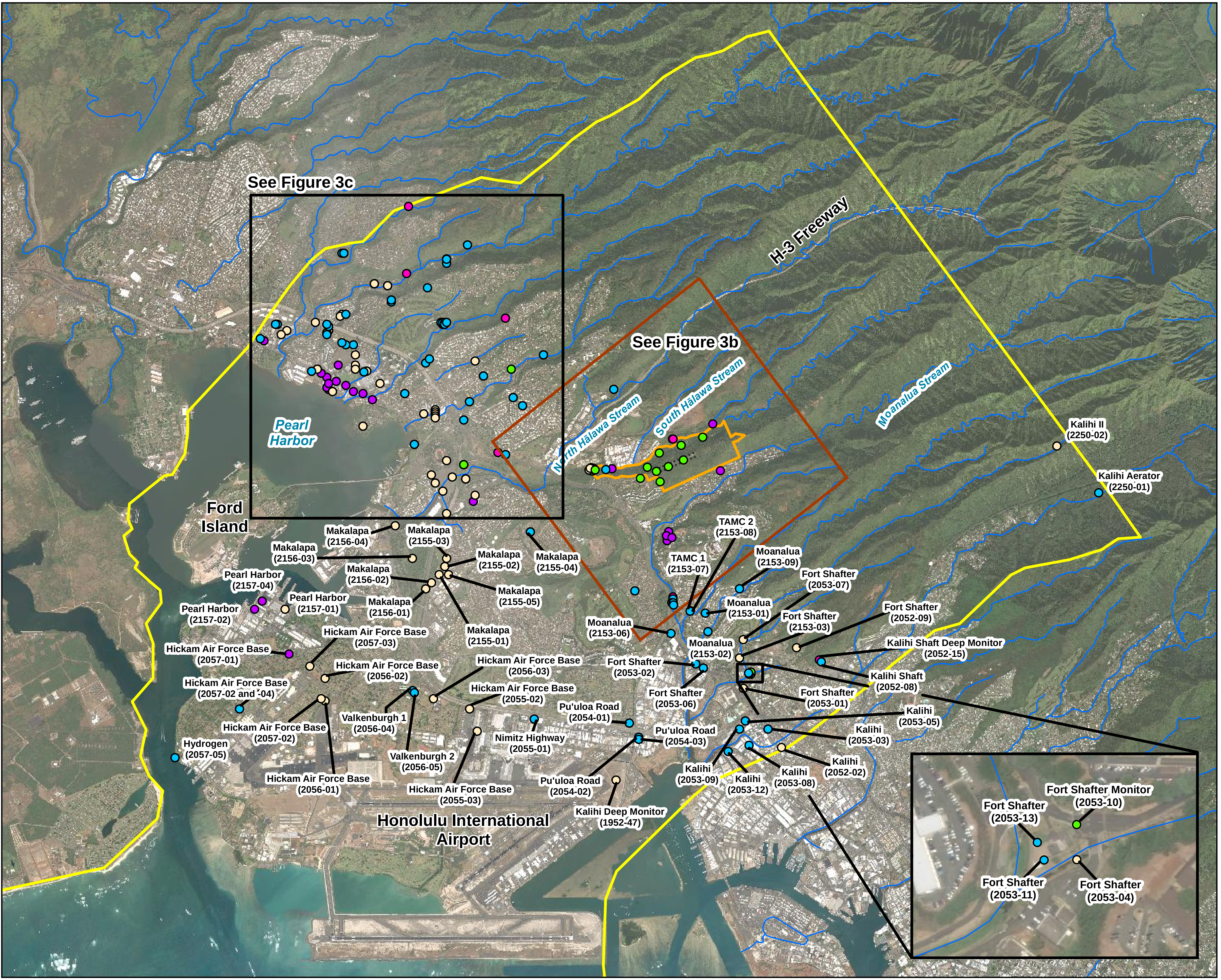
Previous modeling efforts included simulating capture zones and natural attenuation mechanisms in groundwater using the localized MODFLOW groundwater model, MODPATH and RT3D (DON 2007). In 2007, MODPATH was used to for computing groundwater flow velocity and delineating the 10-year capture zones, which were delineated for Red Hill Shaft, Hālawa Shaft, and the Moanalua Wells, as shown on Figure 5. For those simulations, virtual particles were inserted in the cells intersected by well screens and the Red Hill infiltration gallery, and then tracked backward along flow paths for 10 years to delineate the edge of the pumping well capture zones. Those modeling results indicated that, under normal hydrologic conditions, Red Hill Shaft is the only drinking water source that would be impacted by contamination foreseeably migrating from the Facility.

RT3D was used to evaluate benzene and TPH transport in groundwater (DON 2007). RT3D simulates the degradation of hydrocarbons based on the availability of aerobic and anaerobic electron acceptors within the aquifer and the stoichiometry required for natural microbial degradation. Solute transport modeling parameters were developed as follows:

- Since the aquifer of concern is within a fractured basalt matrix, retardation was not included in the simulation. (Although it was not modeled, retardation could be significant within the valley fill alluvium and underlying saprolite.)
- Hydrodynamic diffusion was calculated by estimating the dispersivity of similar basalt cores from Central Oʻahu, and comparing the results to the literature value (Souza and Voss 1987). Taking the geometric mean of these measurements gave a longitudinal dispersivity of 112 ft. The transverse and vertical dispersivities were set to 11.2 ft and 1.12 ft, respectively.
- A uniform value of 4% was used for the effective transport porosity, consistent with previous USGS reports (Oki 2005).
- Natural attenuation rates were computed from degradation stoichiometry and rates calibrated for another NAPL degradation study at Hill Air Force Base, Utah (Guoping et al. 1999).

The RT3D simulations were conducted with the goal of estimating the concentrations of benzene and TPH in the Facility monitoring wells that would result in exceedances of health-based action levels in groundwater at the Red Hill Shaft infiltration gallery. The result of these simulations indicated that a LNAPL plume would have to reach the groundwater surface and then migrate to within 1,100 ft of the infiltration gallery before the benzene concentrations would exceed drinking water criteria in groundwater at the edge of the infiltration gallery. These simulations further indicated that JP-5 dissolved in infiltrating leachate from the Facility would not impact Red Hill Shaft due to natural attenuation and hydrodynamic dispersion in groundwater.

A letter report, *Re-evaluation of the Tier 3 Risk Assessment/Groundwater Model & Proposed Course of Action* (DON 2010), summarized a re-evaluation the groundwater model results and the Tier 3 risk assessment presented in DON (2007), as required by the Red Hill *Groundwater Protection Plan* (DON 2008, 2014). The re-evaluation of groundwater flow direction and gradient verified a local flow direction from the tanks toward Red Hill Shaft, and also indicated, based on well data available at that time, a component flowing to the northwest that could be transporting dissolved hydrocarbons in a direction that was not then being monitored. (Subsequently, two new monitoring wells, RHMW06 and RHMW07, were installed by the Navy in South Hālawa Valley immediately north of the Facility to address this issue [DON 2015].) The 2010 letter report established that the Tier 3 risk assessment/groundwater model, while not reflecting the entire groundwater flow field, did simulate the most conservative flow direction. The re-evaluation recommended continued refinement of groundwater flow directions and gradients as appropriate following the collection of additional data and/or changing conditions in the Facility contaminant trends (DON 2010).



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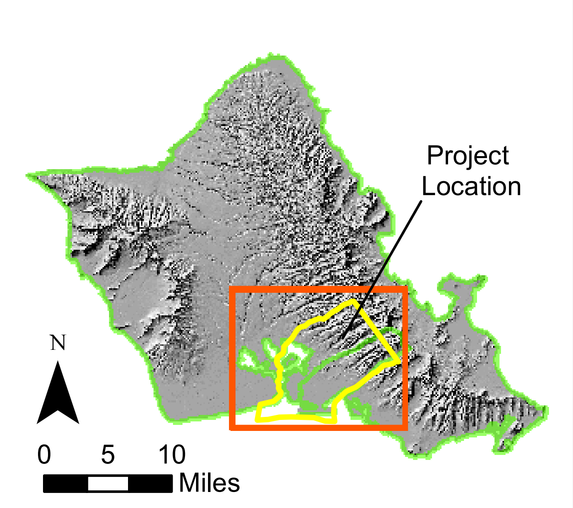
Location Map



Legend

- ● Supply Well
- ● Deep Monitor Well
- ● Monitor Well
- ○ Abandoned Well
- ● Other Well
- ▭ Model Area
- ▭ Red Hill Bulk Fuel Storage Facility Boundary
- ▭ Model Primary Area of Interest
- ▭ 2004 DOH SWAP Model Boundary
- ● Red Hill Fuel Storage Tank
- — Stream

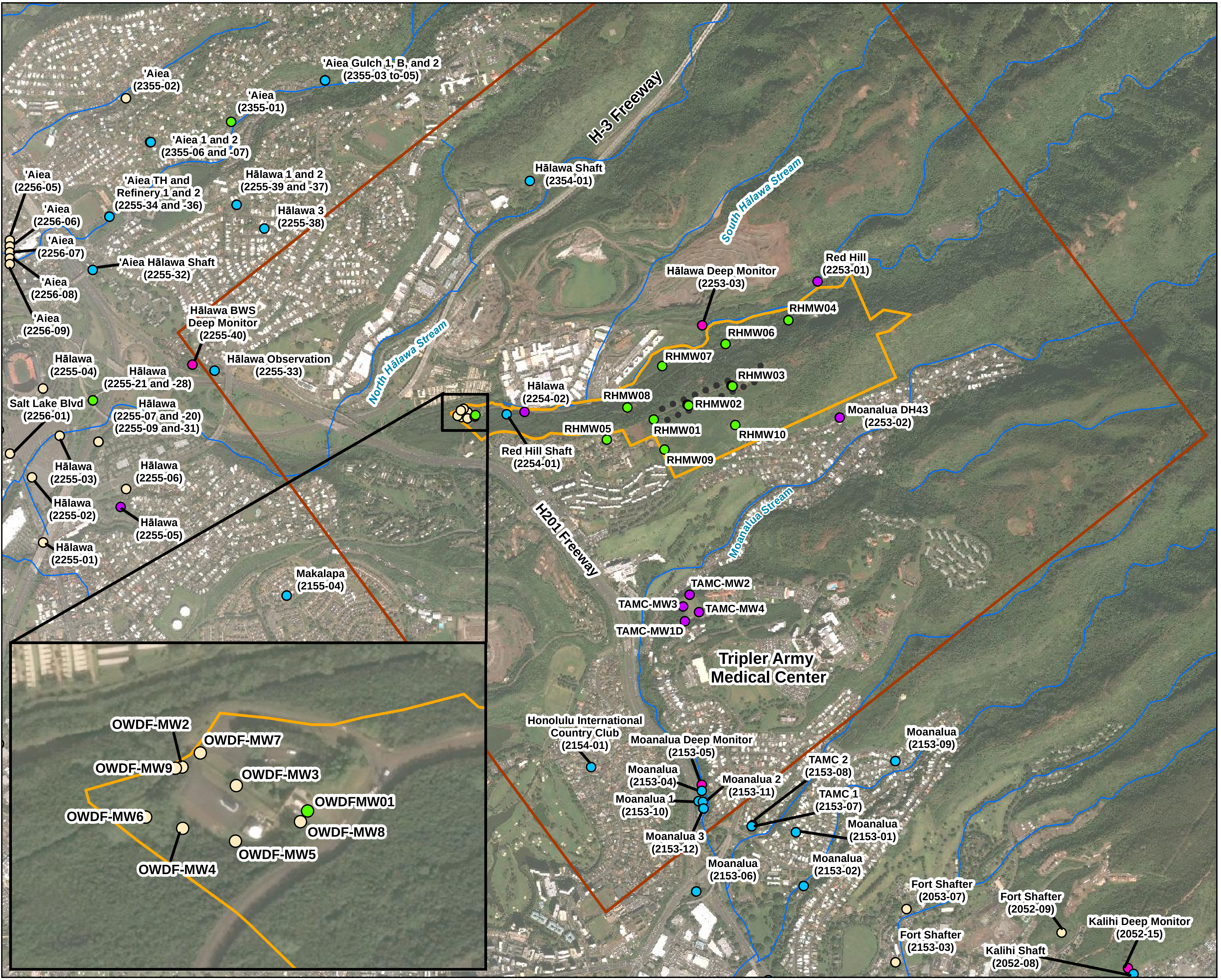
Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS.
   Publication_Date: 2015

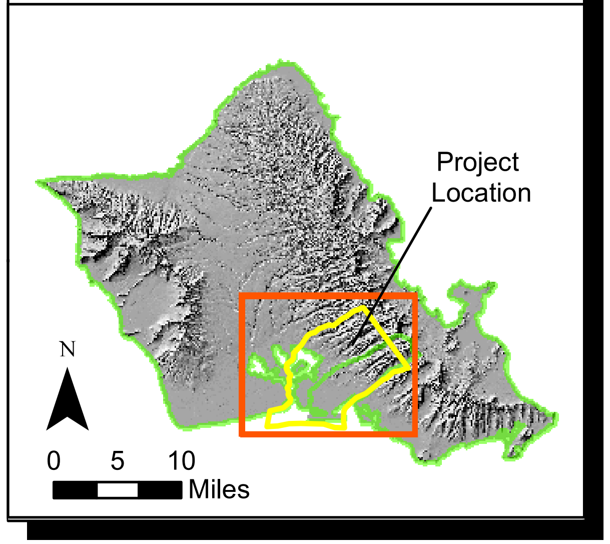
N

0 2,000 4,000 8,000 Feet

Figure 3a
Model Area Wells
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Location Map



Legend

● Supply Well

● Monitor Well

● Deep Monitor Well

● Abandoned Well

● Other Well

▭ Model Area

▭ Red Hill Bulk Fuel Storage Facility Boundary

▭ Model Primary Area of Interest

▭ 2004 DOH SWAP Model Boundary

● 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

0 750 1,500 3,000 Feet

Figure 3b
Model Area Wells - Primary Area of Interest
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases
and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

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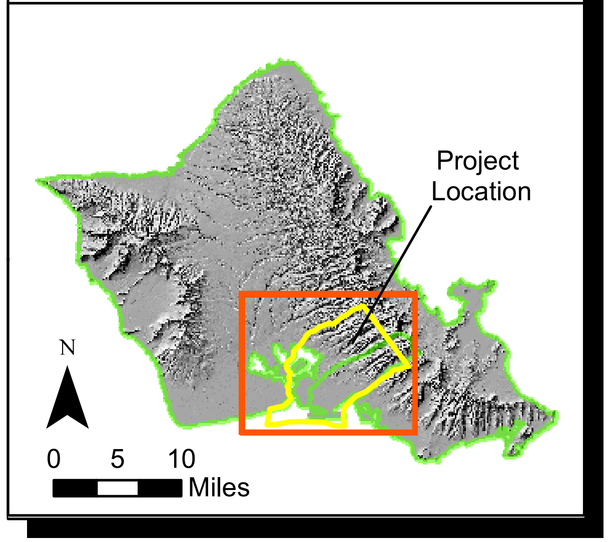
Location Map



Legend

- ● Pumping Well
- ● Monitor Well
- ● Deep Monitor Well
- ● Abandoned Well
- ● Other Well
- ▭ Model Area
- ▭ Red Hill Bulk Fuel Storage Facility Boundary
- ▭ Model Primary Area of Interest
- ▭ 2004 DOH SWAP Model Boundary
- — Stream

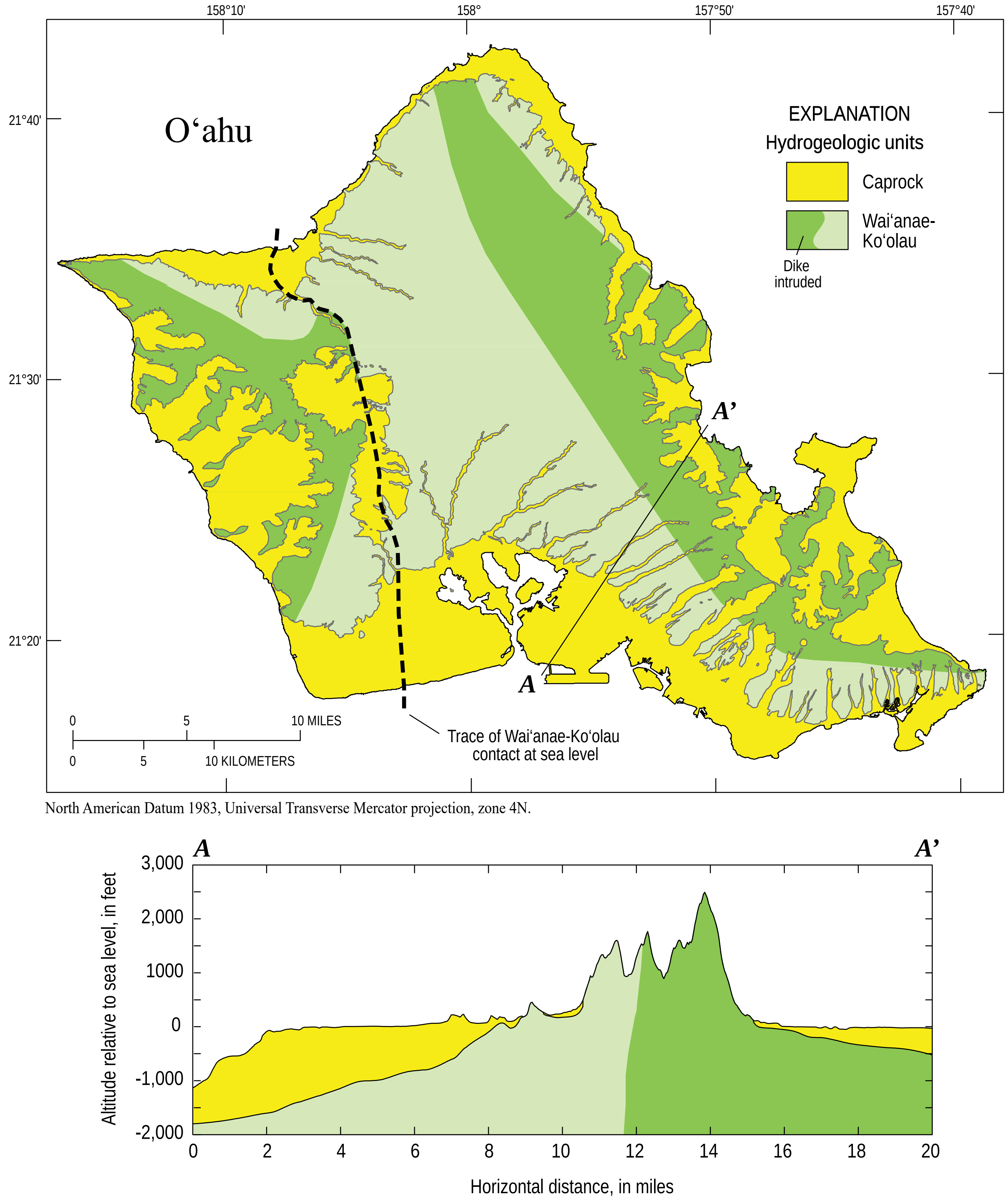
Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

Feet
0 1,000 2,000

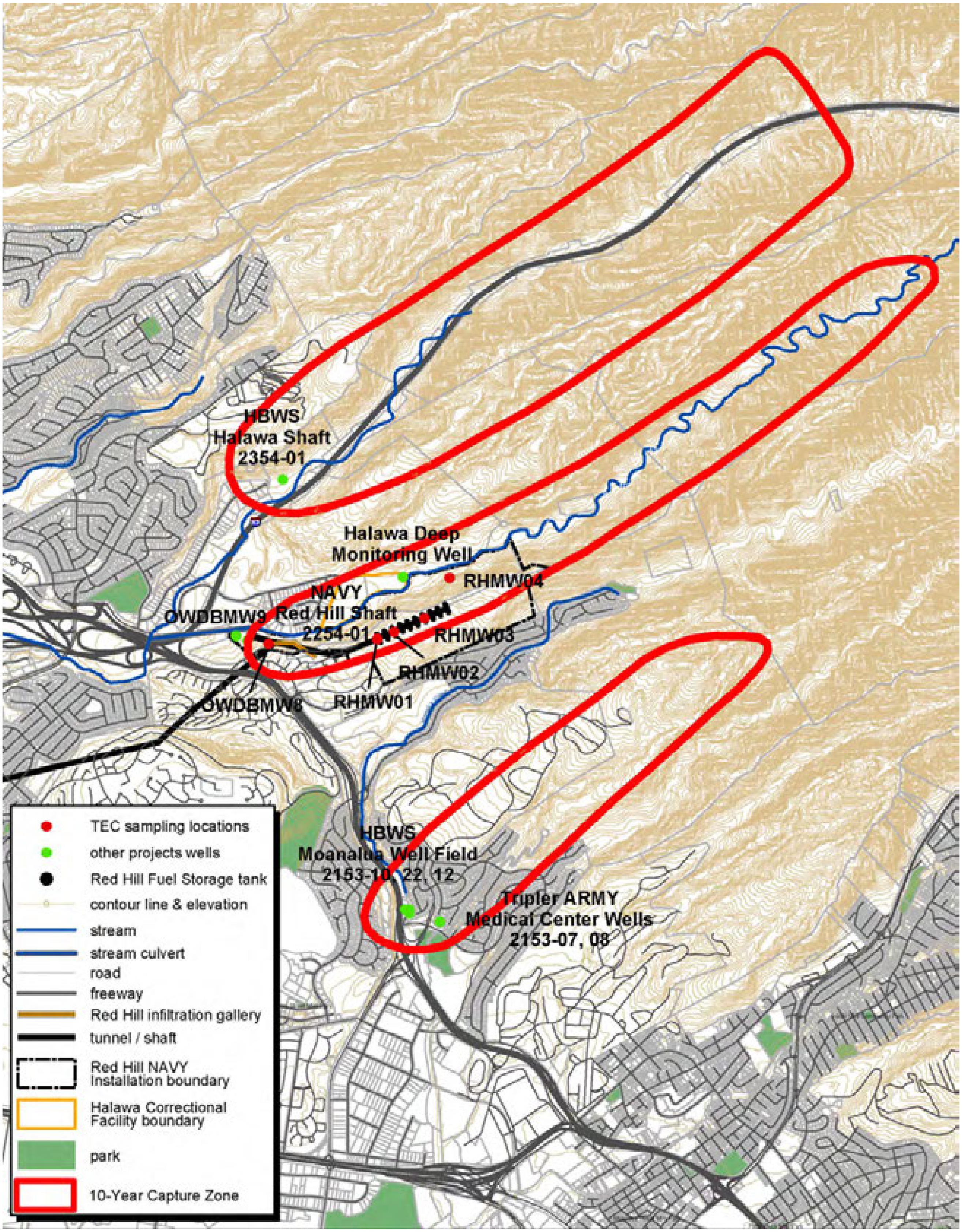
Figure 3c
Model Area Wells - Northwest Area
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



North American Datum 1983, Universal Transverse Mercator projection, zone 4N.

Source: Izuka et al. (2016), Figure 32.
Hydrogeologic-unit outlines modified from the geologic map of Sherrod and others (2007). Trace of Wai'anae-Ko'olau contact from D.S. Oki, USGS written commun., 2014. Map-view extent of dike-intruded area based on Takasaki and Mink (1985) and Hunt (1996), with additional interpretation of data from Stearns (1939), Sherrod and others (2007), Flinders and others (2013), and the National Water Information System database; cross sectional depiction of dike intrusion is speculative.

Figure 4
Map of the Hydrogeologic Units on O'ahu, Hawai'i, Showing Dike-Intruded Areas
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Source: DON 2007, Appendix M

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Figure 5
Local 2007 Model Simulated Ten-Year Capture Zones for Area Wells
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases
and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

4. Technical Approach for Refining the Groundwater Flow Model

Substantial effort has already been expended to develop and apply the 2007 groundwater models, which are based on time-tested models and accurately reflected the observed data (DON 2007). This GMEP has been prepared to describe updates to the previous 2007 model including using MODFLOW-USG (Panday et al. 2013), which is a more current version of MODFLOW; addressing the perceived limitations of the 2007 models; and incorporating the new hydrogeology data available since 2007 and those now being collected, as described in the WP/SOW (DON 2017a). During preparation of this GMEP, the existing MODFLOW, MODPATH, and RT3D models were evaluated and found useful for developing the refined modeling plan described herein.

The planned modeling approach is currently being discussed in a series of GWFMWG meetings, which include input from SMEs from the USGS, Hawai‘i DOH, State of Hawai‘i Department of Land and Natural Resources (DLNR), Commission on Water Resource Management (CWRM), BWS, University of Hawai‘i, and the Navy. The GWFMWG was formed to engage SMEs in highly technical discussions related to various modeling issues. The Navy would then consider technical feedback from the group and make appropriate decisions to support the modeling objectives. Further technical discussions in GWFMWG meetings may change some details of the approach described in this GMEP document.

New site data, including any useful and reliable data obtained by other parties, will be incorporated into the numerical model to reflect known site features, hydrogeology, and groundwater conditions. Should hydraulic barriers be encountered, their effect on groundwater flow will be evaluated and integrated into the model. Of particular importance is the synoptic groundwater level study being implemented by the USGS (USGS 2017) as well as the newly planned wells (Westbay systems). The study was initiated in July 2017 and is planned through at least October 2017. Data from that study will be an essential part of model calibration.

After calibrating the updated MODFLOW model to match the newly available site data and conceptual hydrogeology model, the updated MODFLOW model will be applied to meet the modeling objectives. Refined model development, calibration, and application are as described in the following subsections.

4.1 MODEL CODE SELECTION

To meet the groundwater modeling objectives, the computer code MODFLOW-USG (Panday et al. 2013) will be utilized to simulate groundwater flow. The groundwater flow component of MODFLOW-USG is well tested, is accepted by the modeling community, and can be downloaded from the USGS website (USGS 2016). Other versions of the MODFLOW model, including MODFLOW 2005 (Harbaugh 2005) and MODFLOW-NWT (Niswonger, Panday, and Ibaraki 2011) were also discussed with the GWFMWG in August 2017. MODFLOW-USG has been selected because it is an updated version of MODFLOW that provides several advantages for this modeling effort. For instance, MODFLOW-USG resolves the problems of re-wetting of dry cells during the iterative solution process of steady-state or transient groundwater flow simulations, which occur with MODFLOW-2005 and older versions. Also its unstructured grid capability allows greater definition in the area of interest without overburdening the model with unnecessary grid cell computations in areas of less interest along the model margins, providing a more efficient model without loss of accuracy or resolution where needed.

The unstructured grid capability of MODFLOW-USG adds flexibility to MODFLOW, a well-established and widely accepted numerical groundwater flow modeling program developed by the

USGS. Like MODFLOW, the MODFLOW-USG model solves the groundwater flow equations in three dimensions using the following assumptions:

- Groundwater flow is laminar and can be described by Darcy's Law.
- Groundwater density and viscosity are constant.
- The aquifer is compressible and elastic.
- The bedrock aquifer layers (i.e., layers representing highly fractured and highly permeable bedrock) behave as equivalent porous media.

Although the site aquifer properties are highly heterogeneous, the available information from large-scale pumping tests and previous modeling results indicate that the equivalent porous medium (EPM) modeling approach in MODFLOW-USG can simulate flow at the site in sufficient detail to address the modeling objectives. Previous modeling efforts (DON 2007) showed that the MODFLOW model was able to reasonably match the patterns of time-series drawdown data from the long-term area-wide pumping test conducted in May 2006 (DON 2007, Appendix K).

The MODFLOW-USG model provides several benefits that will help achieve the modeling objectives:

- It is in public domain; has been extensively tested, verified, and documented; and is widely accepted by regulatory agencies.
- It allows modification of the code and addition of new modules for specialty applications.
- The cell-by-cell flow feature of the code can be used to evaluate flow and head changes associated with various withdrawal scenarios.
- Aquifer heterogeneity and anisotropy can be specified and calibrated to match site data.
- The layer property flow module incorporated in MODFLOW-USG is capable of simulating groundwater flow in heterogeneous anisotropic aquifers.
- The Connected Linear Network (CLN) Package of MODFLOW-USG simulates wells penetrating single or multiple aquifer or model layers, pumping-well drawdown, wellbore effects and well efficiency.
- MODFLOW-USG is compatible with PEST to perform calibration and uncertainty analyses. PEST is non-linear parameter estimator that iteratively minimizes the error between observed and computed features, such as water levels and fluxes, by adjusting selected parameters within preset bounds.
- MODFLOW-USG is compatible with MODPATH version 7.0 (Pollock 2016) to conduct capture zone and particle tracking analyses.
- MODFLOW-USG incorporates solute transport modules that are as capable as MT3DMS for meeting modeling objectives.
- MODFLOW-USG is integrated into the Groundwater Modeling System (GMS) modeling framework which is being used for this study. GMS includes MODFLOW-2005 and MODFLOW-NWT models, and, therefore, the conceptual model developed within GMS for MODFLOW-USG can be readily converted to the other MODFLOW versions if needed.
- MODFLOW-USG solves for steady-state and transient conditions.

The GMS version 10 software platform will be used as a graphical user interface for pre- and post-processing of the model input and output data. This interface is capable of importing background images, scatter points, borehole data, and geographic information system (GIS) spatial data. The 2007 model had used GMS, version 6.0; therefore, the model was readily accessible with the updated GMS version for further refinement as discussed here.

The USGS is currently developing a regional groundwater model to simulate the effects of groundwater pumping on saline water present at the base of the Pearl Harbor aquifer and to provide a tool for managing groundwater pumping to minimize adverse effects of saline water intrusion on groundwater quality. To the extent that information from that USGS model is available within the AOC timeframe, data and results from that model will be evaluated and incorporated into this planned modeling effort.

4.2 MODEL BOUNDARIES, LAYERS, AND GRID

Two flow models were created for the previous modeling effort (DON 2007). As described in Section 3.4, the regional model was modified from the DOH's SWAP model for the island of O‘ahu (R. B. Whittier et al. 2004), simulating steady-state conditions covering the 10-year period from 1996 to 2005. The 2007 local model was developed to simulate both steady-state and transient conditions in the area of specific interest for Red Hill. The areas covered by both those 2007 models are shown on Figure 6.

During June 2017, the GWFMWG met to discuss and decide upon the model area extent and the types of boundaries to be used along the sides of the updated groundwater flow model (DON 2017f). In the August 2017 GWFMWG meeting there were further discussions on model extent and boundary conditions. The conceptual groundwater flow model described here reflects the Navy's decision based on technical feedback from the SMEs at the GWFMWG.

The bottom boundary condition of the model and the southwest boundary location were discussed at the meetings. The original model of Rotzoll and El-Kadi (2007) extended only up to the coastline where a constant head condition was prescribed. The GWFMWG had a desire to move this boundary location further offshore to include simulation of freshwater exiting into the ocean. The GWFMWG also requested use of the Seawater Intrusion 2 (SWI2) Package (Bakker et al. 2013) of MODFLOW to simulate a sharp interface at the bottom of the freshwater model domain.

The southwest boundary of the model domain is extended farther offshore in this evaluation plan as per the SMEs' suggestion. However, an evaluation of the SWI2 Package determined that it was impractical to use for the current modeling objectives and that there are other methods and assumptions that are commonly used in coastal aquifer resource analyses in Hawai‘i, as well as elsewhere, to account for underlying saltwater. Two such methods include: (1) use of an equivalent freshwater heads to simulate saltwater intrusion at depth; and (2) use of a no-flow boundary across the sharp interface location, such that the model only simulates the freshwater portions of the aquifer system. Both approaches were presented to the GWFMWG at the August 2017 meeting. After discussion, the Navy selected approach (2), whereby the bottom boundary of the model follows the interpreted sharp interface between seawater and freshwater. This is a defensible approach for groundwater flow, particle tracking, and transport simulations in coastal or saline settings; this approach has been previously used, tested, published, and is widely accepted by the scientific community in Hawai'i (Glenn et al. 2013; Ghazal et al. 2017; Robert B. Whittier et al. 2010; R.B. Whittier et al. 2015) and elsewhere (Brakefield et al. 2013; Paschke 2007).

The location of the sharp interface between freshwater and seawater was estimated by Rotzoll and El-Kadi (2007) as per the Gyben-Herzberg approximation (DON 2007). The depth of this interface was estimated to be at approximately -400 ft msl along the shoreline and slopes downward to greater depths with distance inland, to reach a depth of about -800 ft msl in the Facility area. This surface is used in the current model and has been extrapolated in offshore locations beyond the Rotzoll and El-Kadi (2007) model boundary. The southwest model boundary of the updated model has been extended offshore to the location where this extrapolated interface crosses the elevation of the top of the model, which is the sea floor in this offshore boundary location. This will allow the calibrated model to reflect hydraulic heads and gradients along the shoreline, spring discharge along the shore, and subsea groundwater discharge.

4.2.1 Model Area Boundaries

The 2007 groundwater modeling report (Rotzoll and El-Kadi 2007) and the archived modeling files (MODFLOW, MODPATH, and RT3D model files) have been reviewed and compared with current geologic and hydrogeological data to identify if/where changes are needed for boundary conditions, model layers, aquifer properties, calibration data, and water budgets. For the 2007 groundwater modeling, specified-head boundary (SHB) conditions were assigned along each side of the local model. Each SHB extends vertically from the top of the upper model layer to the bottom of the lowest model layer (Rotzoll and El-Kadi 2007).

Groundwater modeling reports from the USGS (Oki 2005) indicate that natural hydrogeologic features exist along the northwestern and southeastern model boundaries of the 2007 model, which are within the planned model area. For the 2007 model, the northwestern model boundary was located along the center of Waimalu Valley, which is approximately 2.5 miles from the Facility and approximately 1.8 miles north of Hālawa Shaft at the closest point. The USGS regional model (Oki 2005) assigned a valley-fill barrier along the bottom of Waimalu Valley on the basis of well logs, and extended the valley fill to approximately 200–330 ft below msl beneath the valley from the Pearl Harbor shore to a point approximately 2.7 miles up-valley from the shore.

For the new planned modeling approach, the most recent USGS regional numerical model or the 2004 Regional SWAP model (R. B. Whittier et al. 2004) will be used as a starting point and will be refined per the CSM to help establish boundary conditions along the perimeter of the updated model. The planned model boundaries will be extended outward from those used for the 2007 local model, as shown on Figure 6. Each of these boundaries is located along natural hydrogeologic features and is more than 2 miles from the Facility.

Based on technical feedback during the GWFMWG meetings in June and August 2017, the boundaries are as follows:

- *Northeast:* Along the northeast side of the dike-free basalt area mapped by the USGS in Izuka et al. 2016 (same location as the 2007 model [Rotzoll and El-Kadi 2007]).
- *Southeast:* Along the southeast ridge of Kalihi Valley, approximately 2.5 miles south of the Facility.
- *Southwest:* Extending generally south from the Pearl City Peninsula, following Iroquois Point, and extending offshore along the sea floor to where the saltwater interface intercepts the seafloor.
- *Northwest:* Along the northwest ridge of Waimalu Valley, approximately 3 miles northwest of the Facility; then southward along the eastern shoreline of Pearl City Peninsula.

As shown on Figure 6, the northeast boundary of the updated model will be set at same location as that in the 2007 model, which is approximately 2 miles or more to the northeast of the Facility. This boundary is just to the west of (outside) the area mapped by the USGS (Izuka et al. 2016) as dike-intruded basalt. Thus, the model domain extends within the area of dike-free basalt, which is described by the USGS as a regionally continuous aquifer of generally higher permeability than the dike-intruded areas (Izuka et al. 2016). The northeast boundary will be set as a specified-flux boundary (SFB). Initial estimates of flux for the model will be evaluated from the conceptual model of flow across the dike intruded area and from the DOH regional SWAP model (R. B. Whittier et al. 2004) or the USGS regional SUTRA model (Oki 2005).

The southeastern boundary of the updated model will be located along the southeast ridge of Kalihi Valley (approximately 2.5 miles or more south of the Facility); approaching the shoreline it will join the 2007 model boundary, which was located along the middle of Kalihi Valley. The USGS regional model used Kalihi Valley as the southern boundary, and specified it as a no-flow boundary to reflect the presence of a deep valley fill barrier, which likely exceeds 1,000 ft thickness (Oki 2005).

The northwestern boundary of the updated model will be a general-head boundary (GHB) located along the northwest ridge of Waimalu Valley, which is further northwest than that of the 2007 model, more than 2.5 miles from the Facility; it will extend southwestward along the shore as shown on Figure 6.

The southwestern boundary of the updated model will lie offshore at a location where the sea floor meets with the sharp interface position, so that the model may simulate only freshwater flow. There is no flow across the sharp interface position at the lateral boundary. However, a GHB condition will be provided at all offshore cells in the top model layer to allow freshwater to exit into the ocean.

4.2.2 Model Layers

As described in the EDR (DON 2017b), three HGUs exist in the model area:

- Caprock
- Valley Fill (modeled as a separate unit from caprock)
- Basalt (dike-free flank lava)

To represent these HGUs, the 2007 model consisted of seven layers. The top elevation of the first model layer was defined by land surface topography. Where valley fill or caprock is underlain by basalt, the bottom of the layers for the valley fill and caprock were determined as described by Rotzoll and El-Kadi (2007) using structural contours for the top of the basalt from Oki (2005).

For valley fill in the 2007 model, the depths of sediments in the five major valleys were based on topography and linear regression analyses for Waimalu, North Hālawa, South Hālawa, Moanalua, and Kalihi Valleys (Rotzoll and El-Kadi 2007). The valley fill elevations used for this model layer were consistent with borehole observations at various locations, including Waimalu Valley (Oki 2005) and North Hālawa Valley (Izuka 1992).

In the 2007 model, basalt layers are present throughout the area of interest. In areas where no valley fill or caprock is present, there are five basalt layers, the lowest of which extends down to the base of the 2007 model. The bottom of each basalt layer was set by calculated fractions of the distance between water table and bottom boundary (Rotzoll and El-Kadi 2007). Where the valley fill is present, the underlying basalt is represented by extremely thin layers extending below the fill. On the southwest side of the model area, the basalt layers become thinner below the caprock and valley fill, and the basalt layers terminate beneath the Pearl Harbor shoreline.

Based on technical discussions and feedback from prior GWFMWG meetings, the Navy has decided that the refined model will have five layers, unless the updated CSM and additional information indicate a different approach is needed for the layers. The model layers will be consistent with the most recent hydrogeology report by the USGS (Izuka et al. 2016). For the updated model area, the USGS report defines two HGUs, the Caprock HGU and the Basalt HGU. According to this USGS report, each HGU consists of geologic materials having similar hydraulic properties. The Caprock HGU includes valley fill sediment with the caprock formations described in reports by previous investigations.

Figure 7 illustrates the planned model layers along a profile oriented southwest–northeast across the model area. Figure 8 shows the planned model layers along a southeast–northwest profile.

In the updated groundwater model, the Caprock HGU (consisting of both caprock and valley fill) will be represented by Layer 1, and the initial estimates for hydraulic parameter values in that layer will be consistent with those reported by the USGS (Izuka et al. 2016). The geometry of Layer 1 will be consistent with the Caprock HGU as defined by Izuka (2016), wherever the Caprock HGU overlies the Basalt HGU. However, where valley fill sediment is distinguishable as a distinct geologic unit underlying stream valleys above the coastal plain, the hydraulic properties of Layer 1 will be assigned parameter values consistent with valley fill sediment reported by investigations prior to Izuka (2016). Layer 1 will be inactive in the area where the caprock and valley fill are absent.

Model layers 2 through 5 will be set within the Basalt HGU. Layer 2 will be the uppermost active layer in areas where the water table is in the Basalt HGU or where the caprock or valley fill are absent. In those areas, the base of Layer 2 will be set approximately 30 ft below the water table. Where the Caprock HGU is present in the coastal plain area, the base of Layer 2 will be set approximately 30 ft below the base of Layer 1. The base of Layer 3 will be set 60 ft below the base of Layer 2 throughout the model area. The base of Layer 4 will be set 120 ft below the base of Layer 3 throughout the model area. Layer 5 will extend to the model bottom, which will be set as a no-flow boundary at the estimated freshwater/seawater interface.

The top and bottom elevations of the model layers will be refined based on the updated CSM (DON 2017i), now in progress, and on hydrogeologic data described in the EDR (DON 2017b). The available data include geologic logs from existing wells, more recent monitoring wells installed by the Navy, and the subsurface maps for the Caprock and Basalt HGUs provided in the recent USGS report (Izuka et al. 2016). After the new wells are installed with multi-level Westbay systems, the thickness and elevation of the model layers may be adjusted locally to more closely agree with the actual well intake intervals.

4.2.3 Model Grid

In the 2007 model, grid cells were approximately 30 meters (m) × 60m in the tank farm area and approximately 10m × 10m near Red Hill Shaft. In refining the new model, the grid cell size will be reduced to approximately 10m × 10m (30 ft × 30 ft) throughout the area of interest surrounding the Facility to provide more detailed resolution of flow model simulations and more realistic solute transport simulation results.

4.3 WATER BALANCE

The refined numerical flow model will reflect the CSM groundwater flow components and water balance. In the 2007 numerical model, the total groundwater inflow to the local model area was essentially equal to the groundwater outflow from the model under steady-state conditions. The difference between all water fluxes in and all water fluxes out of the 2007 model was less than 0.008 mgd (Rotzoll and El-Kadi 2007). The refined model is also expected to achieve a close balance of groundwater inflows and outflows.

4.3.1 Groundwater Recharge

In addition to flux assigned along the model boundaries, groundwater recharge was an important source of groundwater influx throughout the 2007 model area. Recharge rates were assigned to the upper model layer using rainfall-recharge regressions developed by Shade and Nichols (1996), with updated land use (Rotzoll and El-Kadi 2007). For the modeling refinement, the groundwater recharge component of the water balance will be updated based on the information from more recent USGS reports and additional data planned for collection in addition to an evaluation of conditions surrounding the site as described below.

The recent USGS reports provide a more detailed analysis of groundwater recharge, including maps of estimated mean annual recharge rates for the model area. One report (Izuka et al. 2016) presents a map of recharge rates for recent conditions (2010 land cover, 1978–2007 rainfall). Another USGS report (Engott et al. 2015) provides a comprehensive water budget analysis of infiltration and provides estimates of the spatial distribution of groundwater recharge rates. Results of the USGS analyses include maps covering the entire modeling area that show recharge rates estimated for drought and average climatic conditions. Information on these maps will be used for refining the groundwater flow model. The USGS indicated that the recharge estimates are being updated because of an error found in selected input files for the water-budget model used to compute groundwater recharge, which affects the recharge estimates. Revisions to the geospatial datasets of groundwater recharge for O‘ahu are being made at this time and should be completed by the end of the year.

For the refined groundwater model, the recharge rates reported by the USGS studies cited above will be incorporated into the groundwater model initially, but those recharge rates will need to be further evaluated and may need to be modified in some areas to account for anthropogenic effects possibly not considered by the USGS. For instance, it appears that the low permeability of the thick saprolitic soil overlying the Red Hill ridge was not accounted for by the USGS study. Additional infiltration tests are now being planned for surface soil above the Facility. Also, the USGS study does not appear to consider the accumulation and infiltration of storm water runoff in the open pits of the Halawa Quarry, which likely increases groundwater recharge rates in those areas. Cement plant operations just east of the quarry show substantial areas of crushed rock washing near the cement plant where process water, which is discharged during operations, accumulates, and infiltrates. Seepage from those areas would substantially increase groundwater recharge rates locally. Extensive pavement areas in the Halawa Industrial Park and Hālawa Correctional Facility increase runoff from those areas and concentrate the runoff flow to other areas. South of the Correctional Facility, Hālawa Stream is lined with concrete, which restricts stream bed seepage. In combination, these surface features alter local groundwater recharge rates and may affect groundwater flow directions. Thus the effects of these features on recharge need to be incorporated into the CSM for groundwater flow. New wells proposed in the quarry area, any data on water usage obtained from the quarry, stream gauge data, and data on surface cover will help to better evaluate local recharge. If data are obtained that indicate these features affect groundwater levels, the effects will be reflected in the updated numerical model during calibration.

4.3.2 Pumping Well Locations and Rates

Groundwater discharge from the model area occurs primarily by pumping of water supply wells as well as discharge to springs and outflow from the seafloor. In the 2007 steady-state calibrated model, each pumping well was assigned the average pumping rate for the period 1996–2005. For the planned modeling, the pumping rate of each well will be updated based on available information from the Hawai‘i DLNR CWRM, USGS, and BWS. The average and maximum pumping rate for each extraction well will be established based on the historical pumping records available from CWRM, USGS, Navy, Army, Air Force, and/or BWS. Planned pumping rates determined from BWS publications for future water resource needs will be considered for the predictive scenario simulations.

According to the USGS (Izuka et al. 2016), the CWRM database of user-reported water withdrawals was used to compile groundwater pumping information. For the period after 2000, the USGS worked closely with CWRM to ensure that the most current data were analyzed for the 2016 USGS study (Izuka et al. 2016). Withdrawal values for wells with data, along with well-construction information, were compiled from CWRM’s database. Even though the report by Izuka et al. (2016) does not contain pumping information for individual wells, the information has been requested from the CWRM, USGS, and BWS, and information provided will be incorporated into the refined groundwater flow model.

The model refinement will include reviewing the well intake intervals for all wells and re-assigning the intake intervals to specific model layers. Pumping rates will be allocated to the model based on the new data.

4.3.3 Spring Discharge

Natural groundwater discharge also occurs as diffuse seepage near the coast, but the estimated rates of discharge from seeps and springs is not provided in the recent USGS reports (Engott et al. 2015; Izuka et al. 2016). A previous report by the USGS (Oki 2005), however, does provide some information on natural rates of groundwater discharge. According to that report, discharge from the Pearl Harbor springs is directly dependent on the head in the aquifer: discharge is high when head in the aquifer is high, and discharge is low when head in the aquifer is low. Using linear-regression equations developed by Oki (1998), groundwater discharge rates from the major springs were simulated in the regional groundwater flow model (Oki 2005). In the 2007 local Red Hill groundwater model (Rotzoll and El-Kadi 2007), the spring discharge rates were based on the regression analysis by the USGS (Oki 1998).

The USGS model-simulated values (Oki 2005) will be used for refining the Red Hill model unless better estimates of groundwater spring discharge are available from the USGS studies currently underway.

4.3.4 Boundary Inflows and Outflows

The upcoming groundwater modeling evaluation will refine the hydraulic properties of the boundaries along the perimeter of the model area based on USGS model-simulated values. Unless more applicable information becomes available from USGS modeling studies currently underway, the refined model boundaries will be based on our current conceptual understanding of the water levels in the aquifer and on information from the USGS model by Oki (2005) and the regional SWAP model (R. B. Whittier et al. 2004).

4.4 MODEL PARAMETERS

Hydraulic parameter values in the existing groundwater flow model (Table 3-1) will be refined as needed to incorporate the new information, including the groundwater monitoring data, new well logs, geologic mapping, and aquifer test data. The model parameter values will be adjusted during calibration to match the groundwater levels and hydraulic gradients at the site consistent with the updated CSM.

4.5 CALIBRATION

After setting up the numerical flow model to represent the CSM hydrogeologic framework, hydraulic parameter values will be assigned in the model based on the available data, which include those described in the EDR (DON 2017b) and those obtained from other data collection activities in progress. As described in the *CSM Development and Update Plan* (DON 2017i), all the new information will be integrated to refine the CSM for geology, hydrogeology, and groundwater flow. Aquifer properties will be set in the numerical model to reflect the CSM, and calibration of the model will proceed to reflect the new groundwater level data.

A steady-state groundwater flow model will be calibrated first to quasi-steady state groundwater flow conditions established during the synoptic water level study. This model will be applicable to evaluate impacts of various release scenarios, pumping scenarios, or recharge conditions that may be encountered at the site. A transient model calibration will then be performed to reflect seasonal conditions over a period of 1 year, depending on available data. The transient model will use the steady-state model results as starting conditions, and a “wind-up” period of 1 year will be applied before the calibration simulation. This transient model will be applicable to evaluate impacts of various short-term (monthly to seasonal) changes in pumping or recharge conditions that may be encountered at the site. For calibration of the steady-state model, all available pertinent data will be used including historical data so that no pertinent data will be ignored. Long-term water level trends will be evaluated and older data extrapolated onto the current time-frame to include all available information. However, the quality of data will also be considered during the calibration effort. A higher weight will be assigned to the recent synoptic water level data due to its high quality and a lower weight will be applied to the extrapolated data or wells with older survey information.

Water-level data from both onsite and offsite wells will be used for calibration, including those from the synoptic water level study described in the WP/SOW (DON 2017a). Figure 9 shows the well locations that are currently planned as model calibration points. The synoptic study, currently underway, involves measuring groundwater levels and elevations in 23 monitoring and supply wells while also collecting pumping rate data at each of the water supply wells including periods of non-pumping and pumping under normal and higher than normal operations, at Red Hill Shaft, Hālawa Shaft, and Moanalua area wells (USGS 2017).

Model calibration will be performed using manual trial-and-error procedures as well as the automated parameter estimation code, PEST (Doherty 2014). If practical, as determined by preliminary calibration simulations, the model calibration procedure may include a methodology of highly constrained parameterization using pilot points and regularization. Localized aquifer property data from previously reported aquifer tests will also be incorporated into the calibrated model. The model will be calibrated to water level data, flow gradients and directions approximated using triangulation computations at nearby monitoring wells, and estimates of spring fluxes.

Prior to calibration, each monitoring well (or multi-level Westbay sampling point) in the model area will be assigned to a model layer based on the well screen elevation and well logs, if available. Once the wells have been assigned to model layers, water level elevations (heads) collected over a period of time will be used as calibration targets.

Ideally, the synoptic groundwater level study will provide sufficient data for calibrating the model. Hydraulic parameter values will be adjusted following a systematic iterative process such that the model simulations compare closely with the available site data, including the new data obtained since the 2007 model was developed. These new data will include groundwater levels from monitoring wells installed after 2007, including those from non-pumping periods, and other available hydrogeologic information. Groundwater level elevations will be based on the new resurveyed well head measurement points.

During calibration, model-simulated water levels, flow gradients, and spring fluxes will be compared to the respective observed conditions, and model hydraulic parameters will be adjusted between simulations until the model simulates conditions similar to those observed in the updated data. Data from the May 2006 Red Hill Shaft pumping test and the May 2015 Hālawa Shaft pumping test will also be evaluated and compared to the calibrated model simulations.

Recharge rates, boundary conditions, and hydraulic conductivity values (including those of valley fill) will be adjusted during the calibration process. Recharge rates already calculated by the USGS from existing sources (Engott et al. 2015; Izuka et al. 2016) will initially be incorporated into the model directly, at least initially, and will be adjusted within a reasonable range during the model calibration to reflect local anthropogenic features or soil types not considered by the USGS analyses.

Statistical analyses of water levels and mathematical simulation residuals will be used to evaluate the quality of the calibration. Several statistical criteria will be used during the calibration, including minimizing the mean error (ME), and root mean squared error (RMSE) or the standard deviation. The ME will provide the average of the residuals; and the RSME provides a measure of the overall spread of residuals. A regression coefficient between simulated and observed water levels will also be determined to evaluate goodness of fit. Spatial distribution of modeled residuals will also be plotted to determine spatial bias in the modeled results.

4.6 SENSITIVITY AND UNCERTAINTY ANALYSIS

After the flow model calibration and predictive analyses (discussed next) are complete, a sensitivity and uncertainty analysis will be performed to evaluate parameters of significance and quantify the uncertainties resulting from the estimated hydraulic properties, boundary conditions, and other modeling parameters. During the sensitivity analysis, calibrated values for select model input parameters will be varied to evaluate the resulting change in model calibration, as well as in the model prediction (e.g., the capture zone of a well for a particular scenario). The model parameters to be evaluated include, but are not limited to, hydraulic conductivity, recharge, and boundary conditions. In particular, the hydraulic conductivity will likely be a critical parameter controlling groundwater flow. The sensitivities will further be categorized per ASTM (2002c) guidelines to evaluate parameters of importance to predictions that may not be significant during calibration. Such parameters have the highest degree of uncertainty to the predictions and therefore may need to be better characterized.

The potential effect of a valley-fill barrier in Hālawa Valley will also be evaluated in the sensitivity analysis. This analysis may include alternate hypothetical valley-fill barrier configurations, ranging from lower permeability valley fill that extends below the water table to the absence of a valley fill barrier. The acquisition of new data based on well installations and hydraulic testing will be utilized to better refine the model. This analysis will also include evaluating the potential effects of possible hydraulic barriers associated with the caprock formation and other lower-permeability volcanic rocks (i.e., Honolulu Volcanic Series, saprolite).

Specific parameters or boundary conditions for the sensitivity analysis will be recommended in the periodic *Groundwater Flow Model Progress Reports* after the model calibration results are evaluated.

The sensitivity analyses will also help to provide reasonable bounds for simulation scenarios that use a reasonable range of values for the hydrogeologic parameters or boundary conditions. This could include, for example, the range of capture zones that may result for a particular pumping scenario. Conducting a more formal predictive uncertainty analysis will also be evaluated. A non-linear constrained Monte Carlo analysis using PEST was suggested by some of the SMEs. This procedure uses the preliminary calibrated model to generate several other models that also generally fit the observation data. These models are then used to evaluate the predictions of interest, to determine the probability of occurrence of a particular outcome.

4.7 PREDICTIVE FLOW MODELING

In the 2007 modeling, two future pumping rate scenarios were used. The first scenario used the 10-year average pumping rates, with withdrawal rates of 11.5 mgd for Hālawa Shaft, 4.4 mgd for Red Hill Shaft, 3.7 mgd for Moanalua Wells, and 7.4 mgd for Kalihi Shaft. For the second scenario, the pumping rates were increased to maximum sustainable rates, with withdrawal rates of 16 mgd for Hālawa Shaft, 16 mgd for Red Hill Shaft, 10 mgd for Moanalua Wells, and 16 mgd for Kalihi Shaft (Rotzoll and El-Kadi 2007). The archived 2007 model files indicate the total well pumping in this maximum scenario was 116.7 mgd.

For the upcoming predictive modeling, the refined calibrated groundwater flow model will be used to simulate groundwater flow conditions that could be caused by increased pumping from existing supply wells (as described in the BWS [2016] *Water Master Plan*), hypothetical new water supply wells, and potential extraction systems for remedial alternatives. These simulations will include future pumping rate scenarios for normal water demand conditions and high pumping rates during drought conditions. The flow model output will be processed to prepare simulated potentiometric maps of the water table. Particle tracking will also be conducted for the predictive simulations using MODPATH (version 7), to characterize groundwater flow paths, capture zones of production wells, and flow velocities/travel times. The following model scenarios are anticipated:

- *Existing (Base) conditions:* The calibrated steady-state flow model with transient particle tracking will be used first to evaluate the effects of the current pumping on water levels, flow directions and capture zones at supply wells.
- *Future Pumping Scenario 1, increased pumping from existing wells:* The calibrated flow model with transient particle tracking will be used to evaluate groundwater levels, hydraulic gradients, and flow patterns / capture zones for potential increased pumping rates representing high water demand from existing water supply wells during drought conditions. Future pumping rates will be discussed with SMEs in future meetings.
- *Future Pumping Scenario 2, increased pumping from a hypothetical new supply well* (if appropriate)*:* The calibrated steady-state flow model with transient particle tracking will be used to evaluate hypothetical groundwater levels, hydraulic gradients, and groundwater flow patterns / capture zones under normal climate and demand conditions if a new supply well

were to be installed at a location and at an extraction rate to be determined. The well location will be evaluated based on the BWS (2016) *Water Master Plan* and discussions with SMEs.

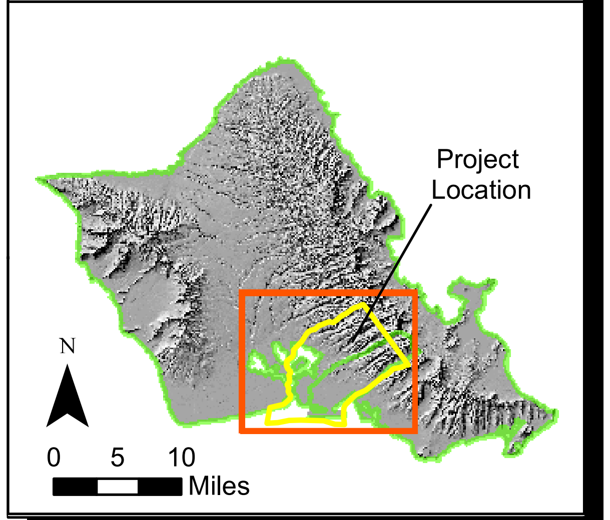
- *Future Pumping Scenario 3, remedial alternative analysis:* The calibrated steady-state flow model with transient particle tracking will be used to evaluate potential groundwater levels, hydraulic gradients, and groundwater flow patterns / capture zones under potential remedial alternative scenarios, which will be determined in the future.
- *Short-term (seasonal) analysis:* The transient calibrated flow model with transient particle tracking will be used to evaluate short term seasonal impacts due to changes in pumping during a year. Current conditions for pumping and recharge will be cycled through several years in the flow simulation to provide a transient flow field for particle tracking analyses. This simulation is intended to evaluate short-term impacts of future decisions.

The particular details of the above Future Pumping Scenarios, such as extraction rates and potential extraction well locations, will be described in the *Groundwater Flow Model Progress Reports*, and will be discussed in upcoming GWFMWG meetings. The Navy will evaluate technical considerations expressed by the SMEs and will make related decisions that meet the Navy’s modeling objectives.

Predictive groundwater flow modeling with particle tracking and CF&T models will also be used in supporting an updated site-specific risk assessment to establish risk-based levels for the COPCs, the development of which will be detailed in a forthcoming *Risk-Based Decision Criteria Development Plan* (Figure 1). As described in Section 5, the flow fields for the various predictive simulations discussed above will be used with the CF&T modeling to determine how solute concentrations change through space and time considering the governing processes of advection, dispersion and decay.

As needed, this updated groundwater flow model will also be applied to simulate the effects of remedial alternatives on groundwater flow and drawdown capture zones to support a feasibility study, if required. Although it is uncertain at this time whether groundwater remediation will be required, the flow model will be useful in evaluating potential risk and remedial alternatives that involve natural attenuation or other remediation options.

Location Map



Legend

🟨	Planned Model Boundaries
⬚	2007 Model Boundary
🟧	Red Hill Bulk Fuel Storage Facility Boundary
🟩	2004 DOH SWAP Model Boundary
●	Red Hill Fuel Storage Tank
—	Stream
—	Southwest to Northeast Cross Section (Figure 7)
—	Northwest to Southeast Cross Section (Figure 8)

Notes

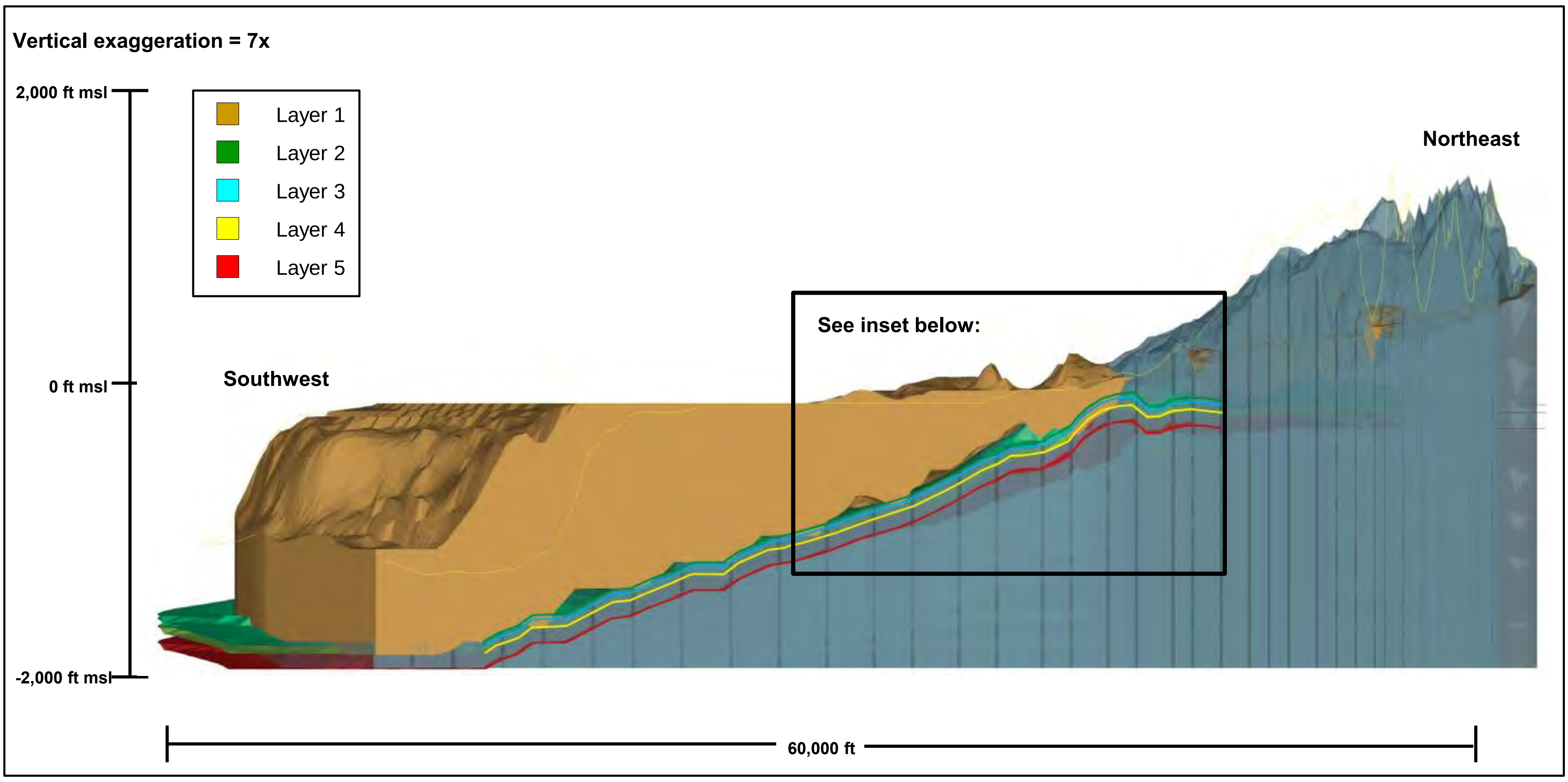
1. Map projection: NAD 1983 UTM Zone 4N
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 3,500 7,000 14,000 Feet

Figure 6
Planned Groundwater Model Boundaries Compared to the 2007 Model
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

S:\Projects\NAVFAC PAC\CLEAN IV\60481245CTO 0053\900-Work\920 GIS\02_Maps\GW Model Eval Plan\Fig6_GWMEP_2017 vs 2007 Model_rev.mxd 9/8/2017



Note: Cross section location shown on Figure 6.

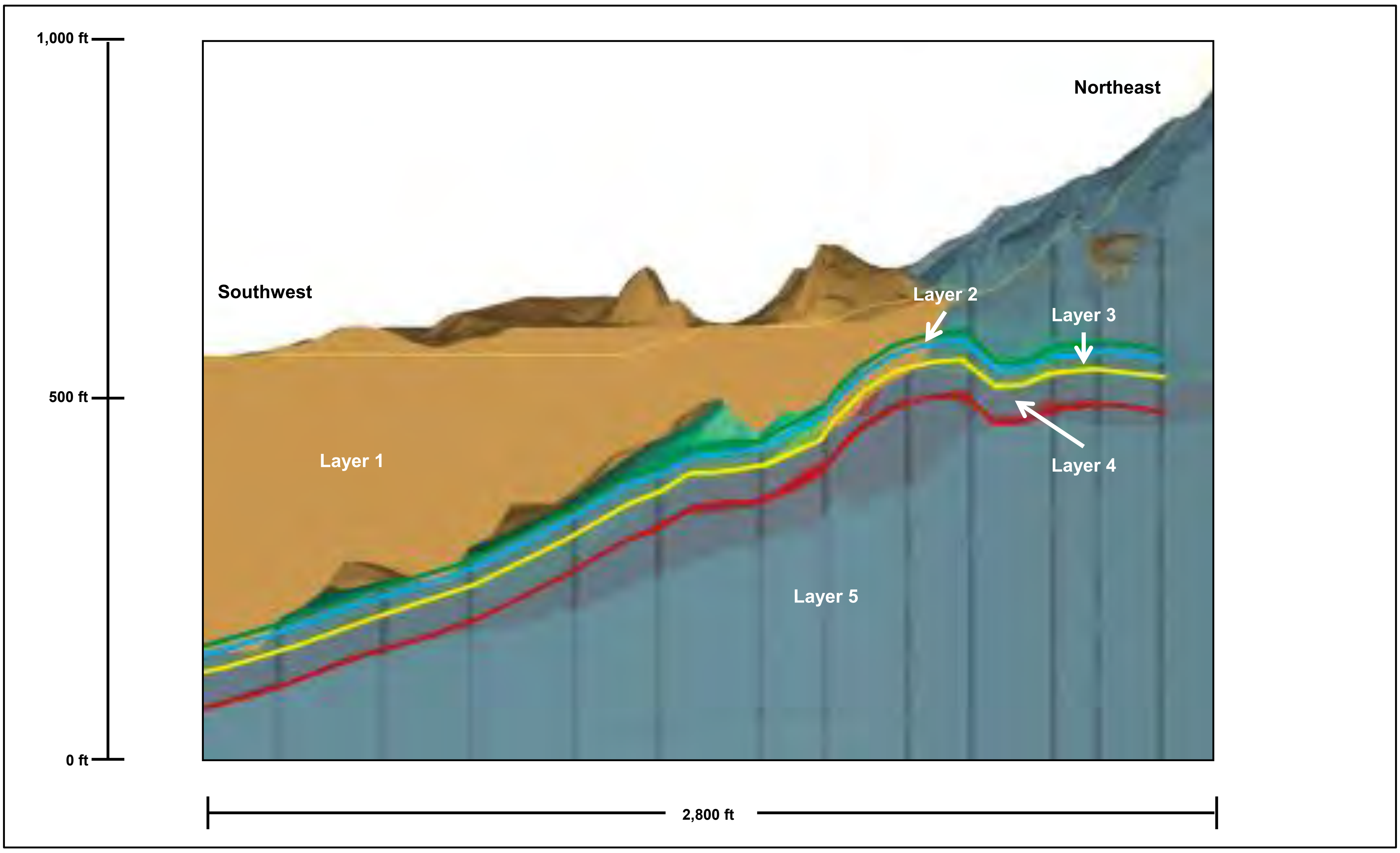
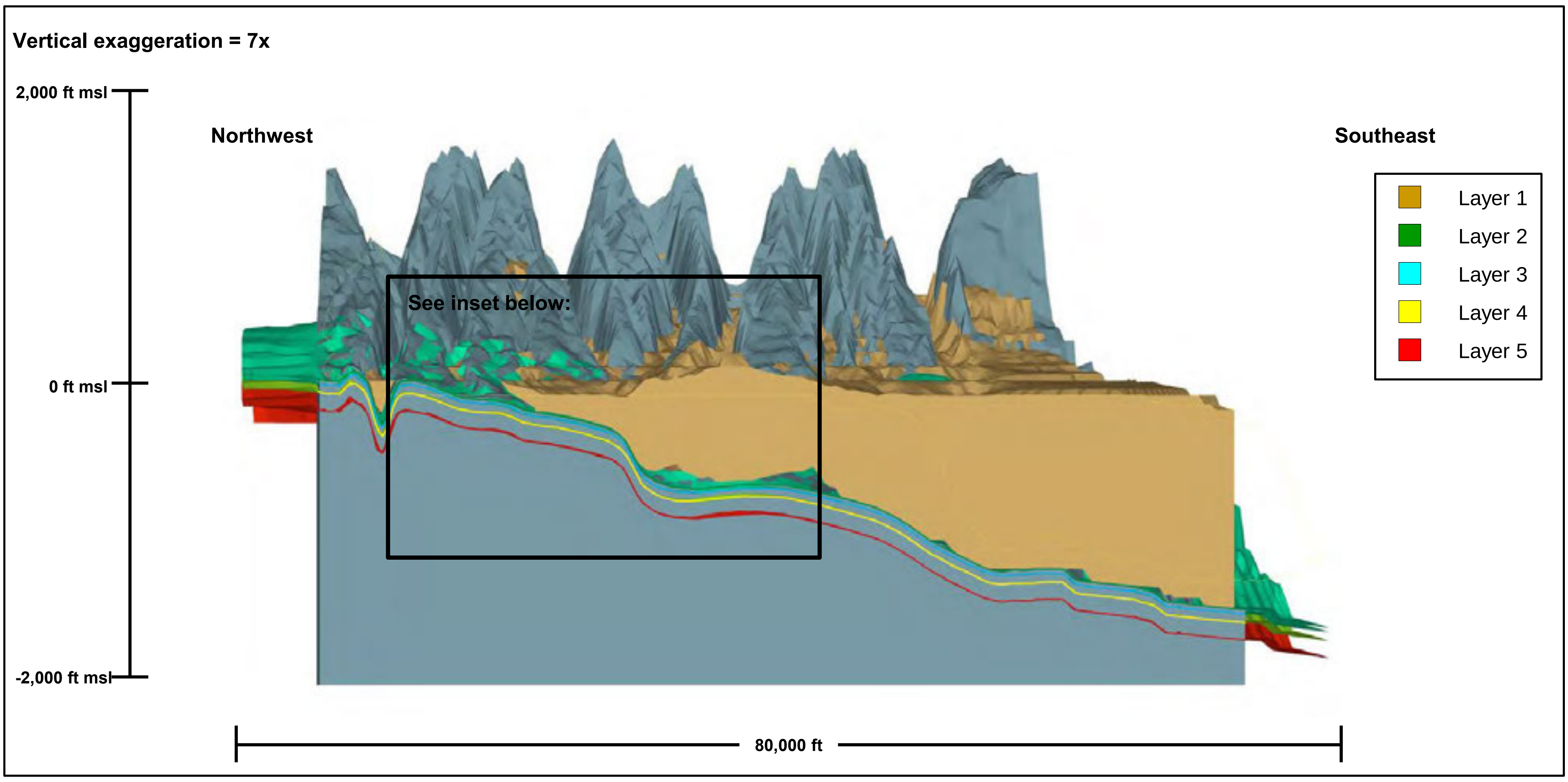


Figure 7
Planned Model Layers, Southwest to Northeast Profile
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases
and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, Hawaiʻi



Note: Cross section location shown on Figure 6.

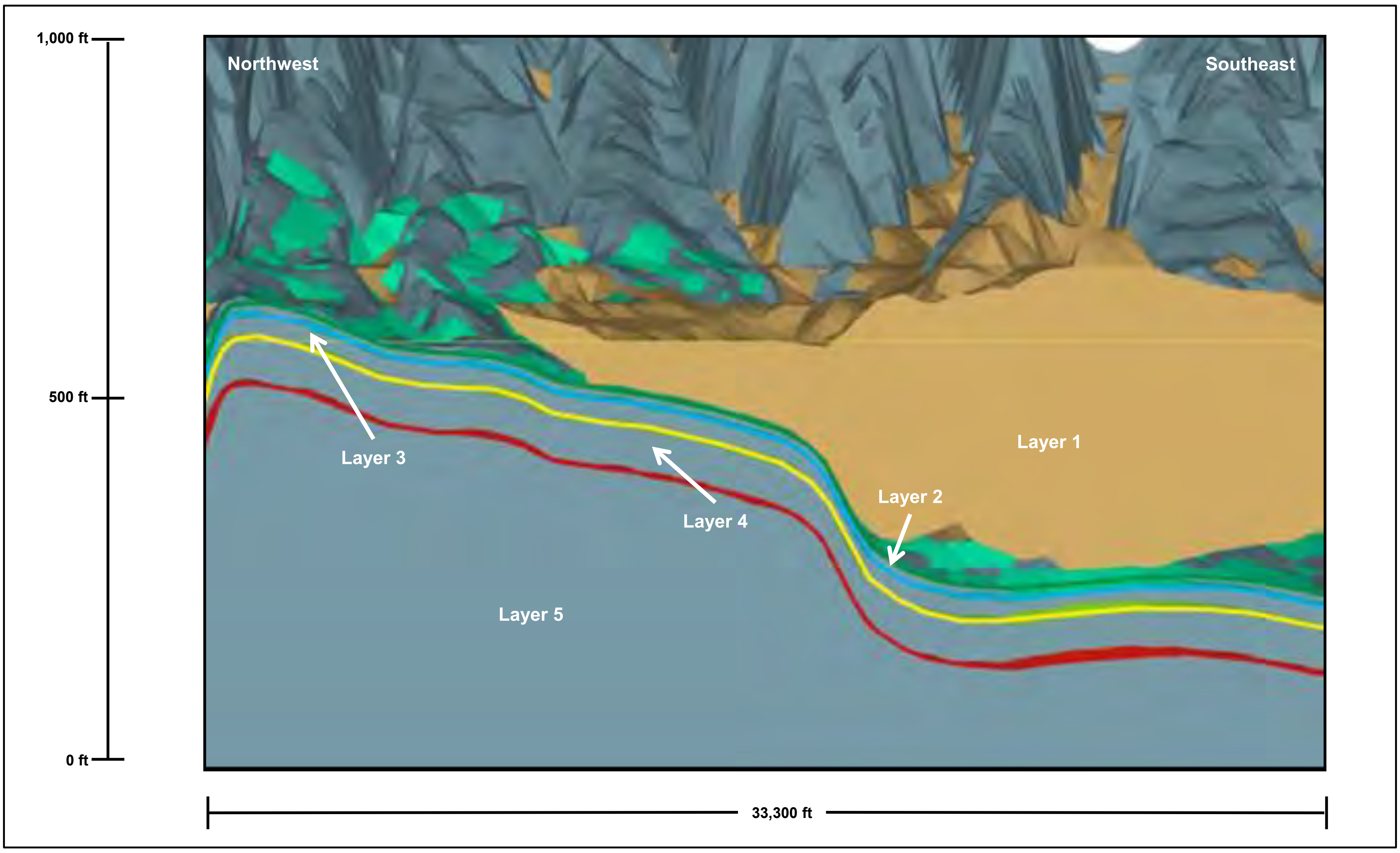
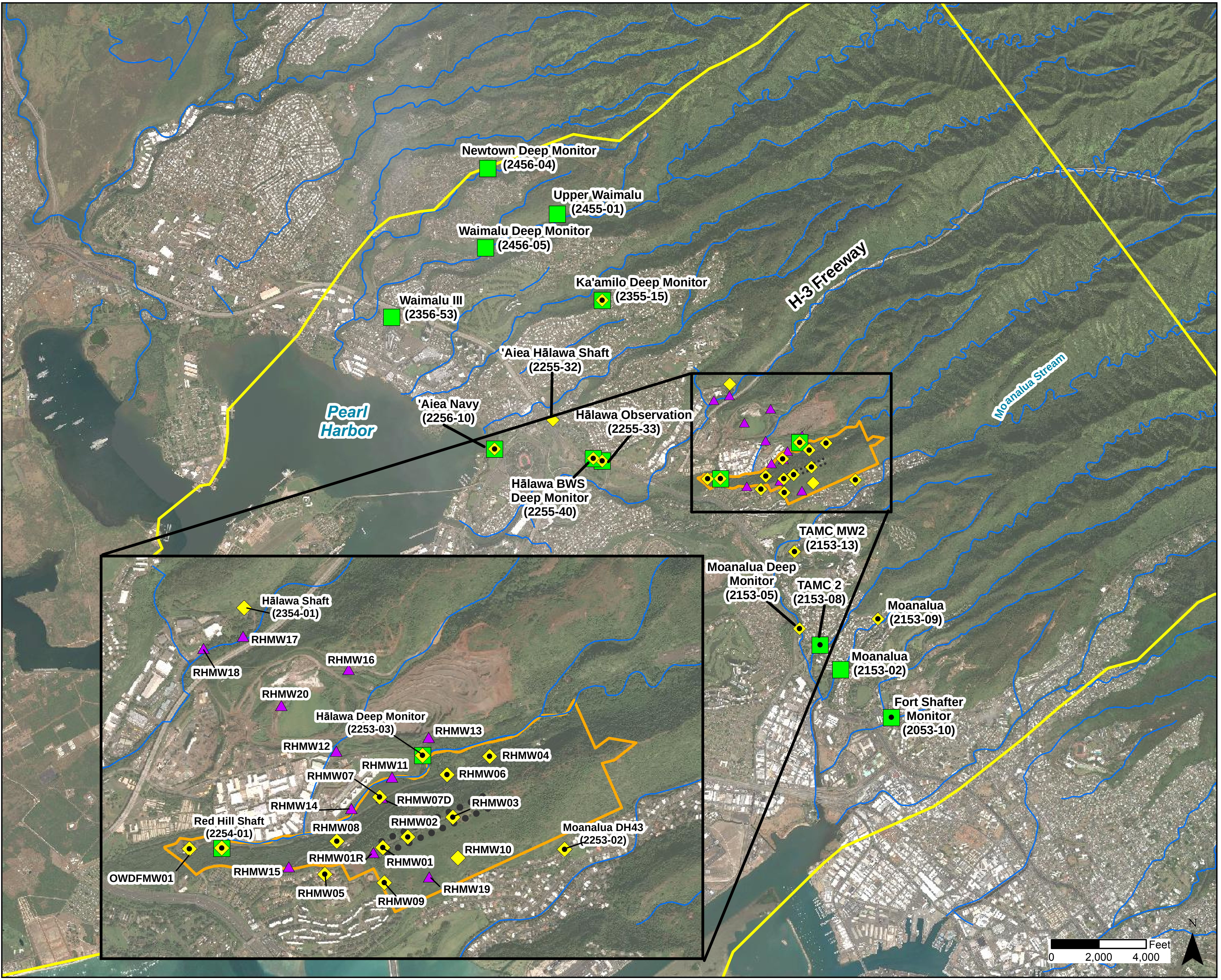
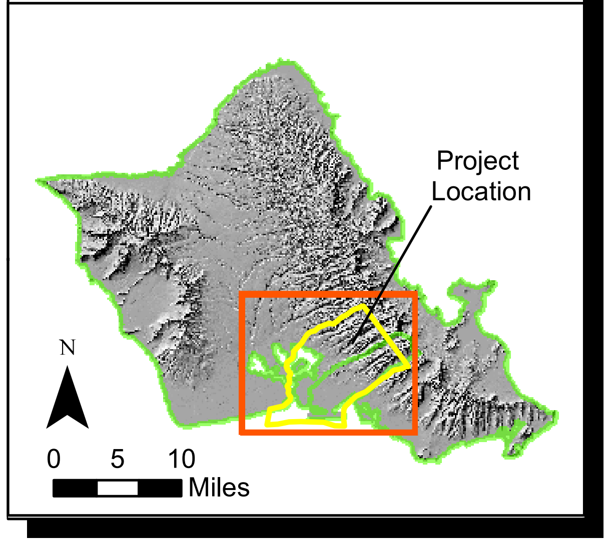


Figure 8
Planned Model Layers, Northwest to Southeast Profile
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases
and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



Location Map



Legend

◆	Proposed 2017 Synoptic Groundwater Survey Well
🟩	USGS Synoptic Monitor Well
◆	November 18, 2016 Synoptic Survey and Proposed 2017 Synoptic Groundwater Survey Well
🟩	USGS Synoptic Monitor and November 18, 2016 Synoptic Survey Well
🟩	Proposed 2017 Synoptic Groundwater Survey and USGS Synoptic Monitor Well
🟩	November 18, 2016 Synoptic Survey, Proposed 2017 Synoptic Groundwater Survey, and USGS Synoptic Monitor Well
▲	Proposed Observation Well
☐	Model Area
☐	Red Hill Bulk Fuel Storage Facility Boundary
☐	2004 DOH SWAP Model Boundary
●	Red Hill Fuel Storage Tank
—	Stream

Notes

1. Map projection: NAD 1983 UTM Zone 4N
2. DigitalGlobe, Inc. (DG) and NRCS.
   Publication_Date: 2015
3. USGS Synoptic Monitor Wells recorded groundwater measurements on October 31, 2002, May 15, 2003, August 17, 2011, and April 26, 2012.

Figure 9
Groundwater Model Calibration Wells
Groundwater Model Evaluation Plan
Investigation and Remediation of Releases
and Groundwater Protection and Evaluation
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

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5. Technical Approach for Refining the Contaminant Fate and Transport Model

Hydrocarbon compounds can migrate in groundwater, primarily as dissolved solutes along groundwater flow lines. Transport processes include advection, hydrodynamic dispersion causing mixing with the basal aquifer, retardation as equilibrium partitioning between solid and liquid phases, and degradation due to natural processes such as biodegradation, known as natural attenuation. Additional data collection and studies to evaluate natural attenuation processes at the Facility are described in the AEP (DON 2017h). The results of these attenuation studies will be used as input to the CF&T model. To evaluate contaminant migration in groundwater, CF&T processes will be modeled using a 3-D solute transport model (i.e., the solute transport code in the beta version of MODFLOW-USG) in conjunction with output from the refined groundwater flow model (Section 4).

The previous CF&T modeling study showed that both aerobic and anaerobic degradation are strong components of the geochemical groundwater system in the basal aquifer beneath the Facility (DON 2007). These biological reactions in the subsurface are well documented in the petroleum industry, and use of first-order decay is proposed. The decay coefficient, in turn, will be quantified from the site-specific natural attenuation studies (DON 2017h) and published literature that investigate these detailed reactions.

In developing this GMEP, the available 2007 model input and output files were obtained and preliminarily reviewed to evaluate their usability for meeting the AOC objectives. Based on an initial review, the 2007 model files appear to be usable as the starting point for creating the refined model. When this CF&T model refinement effort starts, the model input files will be compared with the most current natural attenuation data (representing both natural source-zone depletion [NSZD] and monitored natural attenuation [MNA]) developed as part of the AEP (DON 2017h) as well as groundwater monitoring data, including planned measurements of natural attenuation parameters (NAPs) in the new monitoring wells. The updated CF&T model will use the updated groundwater flow model. The new site data for groundwater quality will be used to update the CF&T model to reasonably represent the site groundwater conditions, and applied to meet the CF&T modeling objectives as described below.

5.1 OBJECTIVES

The primary objective of the CF&T modeling is to assist in evaluating the potential water quality effects and relative risk to potential receptors of groundwater migrating from areas affected by fuel leaks from the Facility, including a quantitative analysis of the currently occurring natural attenuation processes. This effort will also be used to support an updated site-specific risk assessment. This risk assessment will address the potential migration of dissolved COPCs from the Facility during anticipated pumping scenarios. For this objective, the model will have the capability to incorporate the pumping of new hypothetical water supply wells, or increased pumping in various aquifers per the BWS's *2016 Water Master Plan* (BWS 2016). Another objective of the updated CF&T model is to support a potential feasibility study of remedial alternatives, including predicting the water quality changes of implementing feasible remedial alternatives. Relatedly, the model can also be useful to inform contingency planning that may be conducted under AOC Statement of Work Section 8 (EPA Region 9 and DOH 2015).

5.2 MODEL SELECTION

The previous CF&T modeling study (DON 2007) used RT3D to perform a series of simulations to estimate the distance dissolved fuel compounds would travel from a hypothetical LNAPL plume before degrading to less than regulatory limits. The model simulated contaminant transport and mass reduction by natural attenuation for two contaminants, TPH and benzene. TPH was selected because it had been detected at concentrations exceeding action levels in monitoring wells located near the Facility tanks. Although it is only a minor constituent of JP-5, benzene was also selected for the previous modeling (DON 2007).

The 2007 CF&T modeling effort assumed preset stoichiometric coefficients for kinetic-limited degradation for BTEX and the NAPs. The model results were found to be very sensitive to changes in NAP degradation rates and stoichiometric coefficients, and those values may vary greatly based on groundwater conditions at the site. Neither the stoichiometric coefficients nor the reaction rates could be determined from the site-specific data available at that time (DON 2007). Unknown variability in the stoichiometric coefficients for the NAPs, TPH, and BTEX created substantial uncertainties in the results of the reactive transport model. To reduce these uncertainties but still meet the modeling objectives, the planned CF&T modeling will use first order degradation rates obtained from natural attenuation studies to compute solute decay.

The CF&T modeling will therefore begin with a detailed evaluation of those data to develop a conceptual model describing the natural attenuation processes as outlined in the AEP (DON 2017h). Any changes to the CF&T modeling suggested by new data will be presented along with recommendations in a *Groundwater Flow Model Progress Report*, for Regulatory Agency review.

The upcoming CF&T model refinement plans to utilize the solute transport module that is available in the beta version of MODFLOW-USG. This solute transport module has similar capabilities to the MT3DMS model (Zheng and Wang 1999; Zheng 2010; Zheng, Weaver, and Tonkin 2010). Like MT3DMS, the solute transport module is a three-dimensional multispecies transport model that uses the flow field generated by MODFLOW to solve the three-dimensional advection-dispersion equations for solute migration. The transport module can also simulate sorption, degradation, and other chemical reactions of contaminants dissolved in groundwater.

To further validate use of the transport routines available in the beta version of MODFLOW-USG, the calibrated CF&T model will be compared to results from a MODFLOW-NWT / MT3D simulation for the same hydrogeologic setup. All of these codes are available within the GMS framework, and therefore, conversion from one set of codes to another is straightforward. The advantages of proceeding with MODFLOW-USG otherwise, include robust and efficient simulations for developing and calibrating the Red Hill model and for evaluating various scenarios of interest.

In applying MODFLOW-USG, the refined CF&T model will use technically defensible assumptions for decay rates of COPCs as developed through the natural attenuation evaluation. Currently, the available time-series data appear to provide a basis for estimating degradation rates to model migration of TPH-d and naphthalene using MODFLOW-USG. A final list of COPCs to be modeled will be developed following discussions with modeling and risk assessment SMEs. The CF&T model area will be the same as the groundwater flow model area. As described in Section 4, the flow model layers, geometry, grid cells, and initial parameter values will be refined to represent the updated conceptual model of groundwater flow and the new hydrogeology data to be collected from the site vicinity. Therefore, the CF&T modeling will employ MODFLOW-USG, unless future data or information suggests otherwise.

5.3 CONTAMINANTS TO BE SIMULATED

The CF&T modeling will include COPCs, to be determined after discussion with the SMEs, based on a combination of toxicity, mobility, and sources. As described in Section 4.7, the base flow modeling scenario will be run based on current steady-state conditions. Selection of the two constituents for the CF&T modeling will be done in coordination with the Regulatory Agencies and SMEs considering all available Red Hill monitoring well data.

5.4 MODEL PARAMETERS

The existing CF&T model (DON 2007) incorporated the parameter values shown in Table 5-1. The proposed CF&T modeling will maintain these parameter values, unless more definitive site-specific data are collected to justify changes.

Table 5-1: Transport Parameters Used in CF&T Model

Hydrogeologic Unit	Longitudinal Dispersivity (m)	Transverse Dispersivity (m)	Vertical Dispersivity (m)	Effective Porosity (unitless)
Caprock	5	0.5	0.05	0.10
Valley Fill	3	0.3	0.03	0.15
Basalt	34 [a]	2	0.2	0.05

m meter

[a] The DON 2007 report indicates longitudinal dispersivity of 34 m; however, model files show a value of 20 m.

5.4.1 Source Term

The CF&T source term and solute transport parameters will be evaluated as part of the technical approach described in the AEP (DON 2017h). Within the transport model, source-area contributions can be simulated by including either a concentration over a specified area or a constant concentration in the same area. For active sources, it is anticipated that the refined model will use a constant concentration or, if time-series data support it, a declining concentration for the source term. Each COPC concentration specified in the source term of the model will be based on the groundwater concentrations at those source areas that have exhibited elevated levels of the COPCs or high-end values estimated based on solubility. The Hydrocarbon Spill Screening Model (HSSM) and other modeling efforts considered for natural attenuation and NSZD will also be used to provide estimates of a source term for the groundwater CF&T model. Following the data collection and technical approach described in the AEP, the groundwater contaminant mass flux at the edge of the Facility will be estimated and incorporated into the CF&T model.

The CF&T predictive modeling will include a series of simulations assuming hypothetical fuel releases, which will also assume that NAPL could reach the groundwater surface. The purpose of these simulations is to evaluate the size of a hypothetical fuel plume on the groundwater surface that could cause dissolved COPC levels in groundwater to exceed the MCL or EAL in downgradient supply wells (based on discharged water at the tap). This process is further described in Section 5.6.

5.4.2 Sorption

Sorption processes were not simulated in the previous CF&T modeling (DON 2007). This is reasonable in the basaltic formation underlying Red Hill because advection and dispersion are the dominant processes for contaminant migration in groundwater at this site. Sorption is expected to be only a minor natural attenuation process because the basalt lava material has very low reactivity with constituents dissolved in fresh groundwater, except in weathered clinker zones with a high clay content. Attempting to realistically simulate sorption is unlikely to change the CF&T results, and thus simulation of sorption is not planned for the updated CF&T modeling effort.

Sorption can, however, be a very important process influencing CF&T in the alluvium and underlying saprolite in Hālawa and Moanalua Valleys. If contaminant transport in these directions is indicated, sorption will be modeled in these geologic units.

5.4.3 Porosity

Effective porosity is important for solute transport because this parameter represents the interconnected pore space in the aquifer through which groundwater may flow. The total porosity of basaltic rocks represents all the void spaces in the rock, including vesicles, joints and cracks, separation at the contact between flows, and lava tubes. Total porosity of lava on O‘ahu ranges between 5 and 50 percent. However, the effective porosity is typically much lower because many of the pore spaces are not hydraulically interconnected. A common value used for effective porosity in Hawaiian basalt aquifers is 0.05 (Oki 1998; R. B. Whittier et al. 2004) or 0.04 (Oki 2005). Unless more definitive site-specific data become available, the modeling refinement will initially use the same values for effective porosity as those from the previous CF&T model (DON 2007), which are listed in Table 5-1.

5.4.4 Dispersivity

Dispersivity of dissolved constituents within the groundwater tends to spread out the plume. Values for dispersivity (which often varies in the longitudinal, transverse, and vertical directions) are dependent on the plume's length, width, and thickness, as well as matrix properties. Dispersivity values will be estimated based on the size of the plume being simulated (longitudinal < 20 percent of the plume length, transverse < 10 percent of the width, and vertical < 10 percent of the transverse dispersivity).

Hydrodynamic dispersion of a groundwater plume results from local variations in hydraulic conductivity and tortuous interstitial spaces through which groundwater migrates in porous media. Dispersion is the product of dispersivity and groundwater flow velocity. For the previous CF&T model, estimates of dispersivity were computed using stochastic analysis of rock core logs from the U.S. Air Force's environmental investigations at the Waikakalaua and Kīpapa Fuel Storage Annexes. In that case, rock cores taken from three drill holes 290–700 ft deep were used for a stochastic analysis to estimate a correlation between hydraulic conductivity and dispersion (TEC 2001) following the method described by Domenico and Schwartz (1990). The stratigraphy of the boreholes was divided into three different rock types and hydraulic conductivities:

- Massive basalts, which were assigned a horizontal hydraulic conductivity value of 3.9 ft/d, based on infiltration tests done on fractured flood basalts in the Snake River Plain of Idaho (Podgorney et al. 2013).
- Clinker zones, which were assigned a horizontal hydraulic conductivity of 5,250 ft/d, a value that is consistent with clean gravels (Freeze and Cherry 1979).
- Vesicular lavas, which were assigned a horizontal hydraulic conductivity of 2,460 ft/d; this value was calculated using the two previously described hydraulic conductivity values so the effective hydraulic conductivity of the entire formation was equal to the model-calibrated value of 1,500 ft/d (TEC 2001).

The stochastic analysis indicated a dispersivity value of 50 ft. The upper limit of dispersivity was the value estimated by Souza and Voss (1987), who estimated a longitudinal value for unweathered basalt of 250 ft, based on the apparent thickness of the freshwater to saltwater transition zone. The existing transport model took the geometric mean of the upper and lower values of longitudinal dispersivity, for a final value of 112 ft.

Dispersivity is a property of the aquifer and is typically anisotropic. Near-horizontal layering of the lava flows in the site vicinity causes dispersion in the vertical direction to be significantly less than in the horizontal direction. Also, dispersion is greater in the direction of groundwater flow (longitudinal dispersion) than in the direction perpendicular to groundwater flow (transverse dispersion). Souza and Voss (1987) estimated a vertical to longitudinal ratio of 0.004, and stated that the transverse dispersivity value varies between 0.05 and 0.33 of the longitudinal dispersivity value. In the previous transport model, values for longitudinal dispersivity were specified to be 5, 3, and 34 meters for caprock, sediment, and basalt, respectively. The model also applied a transverse to longitudinal dispersivity ratio of 0.1 and a vertical to longitudinal dispersivity ratio of 0.01 (DON 2007). These values will remain the same until more definitive information becomes available.

5.4.5 Degradation

As discussed in Section 5.2, available time-series data for groundwater concentrations beneath the Facility indicate historical fuel leaks caused a release of petroleum-related constituents to the groundwater, notably TPH-d and naphthalene, in monitoring wells underlying the tanks and, to a lesser extent, in the nearby area to the west of the Facility. Available data also show decreasing concentrations both over time and with distance from the tanks, which is likely attributable to ongoing natural attenuation. For example, concentrations of these constituents in monitoring wells RHMW01 and RHMW02 decreased steadily from 2005 to 2013. Together with the spatial distribution of NAP concentrations, these data appear to indicate natural attenuation mechanisms have and continue to degrade petroleum-related constituents in the groundwater.

Additional data are to be collected as described in the AEP (DON 2017h) and will help to better evaluate natural attenuation processes related to NSZD and MNA. The updated model will be run using MODFLOW-USG with the advection and dispersion parameters initially held constant, and then with the degradation rates adjusted to obtain a match with the time-series data from the onsite monitoring wells. Appropriate degradation rates will be used in the simulations based on existing data, the natural attenuation evaluations, and data to be collected during this investigation. A range of potential values will be modeled to evaluate uncertainty.

5.4.6 Initial Concentrations

The chemical parameter values in the CF&T model will be set consistent with the available data and chemical characteristics of the groundwater, including NAPs and COPCs in the source area, and the conceptual model for groundwater, geology, and NAPL. These initial conditions will also be estimated from various analytical solutions as outlined in the AEP (DON 2017h).

5.5 CALIBRATION

The CF&T model will first be validated by history matching the behavior and migration of solutes in groundwater under Red Hill. Transport modeling parameters (e.g., dispersivity and porosity), and chemical parameters (e.g., degradation rates) will be adjusted to simulate the observed extent of the groundwater plume and how it changes through time. Contaminant source characterization will also be considered in evaluating historical behavior of solutes in groundwater. The CF&T model will then be used for predictive transport simulations to evaluate the impact of different release scenarios and various pumping and weather regimes, assess solute migration, and evaluate remedial scenarios for cleanup and capture.

5.6 TRANSPORT SIMULATIONS

To assist in evaluating the potential water quality effects of groundwater migrating from areas potentially affected by fuel leaks from the Facility, hypothetical fuel release scenarios will be modeled to evaluate water quality changes in downgradient supply wells. This modeling will proceed after calibrating the groundwater flow to available site data. The CF&T predictive modeling will be performed similar to that previously conducted (DON 2007) and will include conducting a series of model simulations to evaluate the migration of hypothetical source-area plumes.

These simulations will include a step-wise sequence of scenarios with increasing fuel extent beneath the Red Hill tank farm area. These scenarios will include hypothetical fuel releases, which will be evaluated for LNAPL extent utilizing various analytical solutions. For each release scenario, the NAPL will be assumed to reach the groundwater surface at the start of the simulation, and dissolved COPC concentrations in the source area will be assigned based on solubility limits provided by published references. The modeled concentrations at the potential receptor points (drinking water) will be compared to water quality criteria (MCLs and EALs). This evaluation will evaluate the size of a fuel plume that, if it were to reach the water table beneath the tank farm, could cause dissolved COPC levels in groundwater to exceed the respective MCLs or EALs in downgradient supply wells with appropriate mass flux considerations.

It is anticipated that the CF&T model predictions will be used to update the SSRBLs for the COPCs. This will include simulating the migration of dissolved COPCs from the Facility under various pumping scenarios. Further detail on the procedure for updating these risk-based levels will be presented in the forthcoming *Risk-Based Decision Criteria Development Plan* (Figure 1). The updated CF&T model will also be used to support a potential feasibility study, if required, of remedial alternatives, including monitored natural attenuation. The model can also help contingency planning conducted under AOC Statement of Work Section 8 (EPA Region 9 and DOH 2015).

The CF&T model will be applied to the flow model scenarios listed in Section 4.7 to predict groundwater concentrations of COPCs under those scenarios.

5.7 SENSITIVITY ANALYSIS

Sensitivity analyses will be performed for CF&T parameters to evaluate the uncertainty associated with the model input parameters, including hydraulic conductivity, recharge, porosity, dispersivity, and degradation. The process for this analysis will be similar to that reported for the 2007 CF&T modeling (DON 2007). Results of the sensitivity analysis will be ranked and described qualitatively.

6. Reporting

Two separate reports, including a *Groundwater Modeling Report* and a *Contaminant Fate and Transport Model Report* will be prepared to provide the following:

- Description of model construction, including boundary conditions, well details and flow rates
- Flow model calibration results
- Description of flow model sensitivity analyses
- Description of transport model calibration and sensitivity analysis, including parameter development
- Groundwater flow model predictive simulation results
- CF&T model predictive simulation results
- Conclusions and recommendations
- Pertinent model files, to be included in digital format

A comprehensive exposure assessment in the CSM and groundwater flow and CF&T modeling using information derived from natural attenuation studies described in the AEP (DON 2017h) will provide the basis further evaluating the SSRBLs (to be described in the forthcoming *Risk-Based Criteria Development Plan*; see Figure 1); this process will consider not only the 2014 Tank 5 release but also hypothetical future releases of various rates and volume, as detailed in Section 5.7. This evaluation will be used to address future vulnerability under AOC Statement of Work Section 8 (EPA Region 9 and DOH 2015).

The model will also support an evaluation of remedial alternatives that may be required to address the 2014 Tank 5 release, based on the results of the investigation. The evaluation, if required, will detail the effects of feasible remedial alternatives on groundwater flow and capture zones.

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