UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 9
SAN FRANCISCO, CA 94105

February 18, 2025

Rear Admiral Marc Williams
Deputy Commander
Navy Closure Task Force – Red Hill
850 Ticonderoga Street, Suite 110
Joint Base Pearl Harbor-Hickam, Hawai'i 96860
(Sent via Electronic Mail)

Subject: U.S. Environmental Protection Agency Review of *Draft Groundwater Model Report, Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor Hickam, Hawaii*, dated September 24, 2024 (revised September 26, 2024)

Dear Rear Admiral Williams:

Thank you for submitting the *Groundwater Model Report, Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor Hickam, Hawaii*. The submittal was prepared on behalf of NAVFAC Hawaii by AECOM Technical Services and included a report, responses to regulatory comments and supporting appendices. The model is a critical component supporting the work under the Phase II Closure Plan required under the 2023 Administrative Consent Order. Our comments on the model are provided below.

U.S. Environmental Protection Agency's (EPA's) consultant, S.S. Papadopulos & Associates, Inc (SSP&A) reviewed the model, report and supporting materials and their comments are attached. The model and accompanying documents are sizeable in content and continue to be reviewed by both SSP&A and EPA. Additional comments on the model will likely be provided to Navy beyond those presented in this letter. EPA is aware of the challenges of characterizing and quantifying groundwater flow and contaminant transport in the volcanic terrain of Southern Oahu. EPA appreciates the Navy's recent efforts to develop a numerical model that better incorporates and represents the complexities of this hydrogeologic environment. The September 2024 groundwater flow model (GWFM) is the most comprehensive, best supported version of the model submitted to date and represents significant progress in developing an accurate, functional model of groundwater flow and contaminant transport at Red Hill. Groundwater modeling is inherently an iterative process, and EPA is optimistic that through additional refinement, calibration and validation, the model will be a useful tool for guiding the site investigation at Red Hill, evaluating past impacts and present risks to drinking water resources, and selecting a suitable long-term remedy for groundwater contamination. It is important to note that the model is just one of many lines of evidence used to support critical decisions.

Significant Revisions to the GWFM. In response to regulatory agency (RA) and subject matter expert (SME) reviews and input on previous modeling efforts, Navy added to or significantly revised several aspects of the model including the following:

- **Refined numerical grid**. The addition of the fine nested and support grid improves resolution in the vicinity of the Red Hill facility and important drinking water sources and provides greater flexibility to represent geologic features and processes.
- **Quantification of basalt anisotropy**. The analysis presented in the report provides an additional line of evidence and support for the range of values used in this version of the GWFM.
- **Explicit representation of basalt heterogeneity**. The methods and workflow described in the report for representing the basalt aquifer geo-fabric constitute a comprehensive response to concerns regarding simulating the basalt as either homogeneous-anisotropic or smoothly varying heterogeneous media.
- **Addition of a vadose zone contaminant release model.** Although the analysis presented in the report is highly conservative and most pertinent to past releases, going forward the vadose zone model provides a framework that can be refined and also adapted to predict potential future impacts to groundwater resulting from remobilization of residual contamination.
- **Addition of a saturated-zone (dissolved) contaminant fate and transport (CF&T) modeling**. CF&T modeling presented in the report demonstrates the utility of modeling for evaluating the mass-conservative migration of dissolved fuel constituents as one method for evaluating the potential future risk posed to potential receptors via the groundwater migration pathway.

Specific comments on the GWFM presented below are supported by the attached SSP&A memo, which should be consulted for additional details and context to the comments provided in the body of this letter.

Basalt Heterogeneity
Responding to RA requests to improve the representation of the structural heterogeneity within the Koolau basalts, the Navy employed a multi-step process to improve the representation of basalt heterogeneity within the nested grid of the model domain. Based on the presentations in the report it is difficult to discern whether the sequential indicator simulation software (SISIM) realizations accurately reproduced the physical characteristics of typical Hawaiian-type flows simulated by MrLavaloba. EPA requests the Navy implement the following recommendation.

<u>Recommendation #1:</u> To assure the physical characteristics of lava flows observed in the barrel logs and produced by the MrLavaloba simulations are accurately reproduced in the SISIM realizations, please provide and compare the variograms based on the barrel logs and MrLavaloba simulations to the SISIM posterior variograms.

As discussed in the SSP&A memo, the continuity of basalt material types, particularly the clinker zones, generated by the SISIM realizations is an important attribute influencing the simulation of groundwater flow and contaminant fate and transport. To ensure that the continuity of the clinker zones generated through the SISIM realizations is consistent with both expectations based on site geological mapping and the MrLavaloba simulations. EPA requests the Navy implement the following recommendations.

Recommendation #2:
"First, a method should be added to the post-processing of the SISIM realizations at the SISIM grid scale, and the outcome of these realizations following their translation to the fine Box Model grid, to compute a measure reflecting the longitudinal continuity of basalt material types that can be compared with both the barrel log data (when interpolated to produce a continuous grid) and the MrLavaLoba realizations to determine whether longitudinal continuity was preserved by the simulation procedure."

Second, the SISIM program includes a Markov-Bayes method for coding soft data to include in geostatistical simulations. While there can be challenges using this method with large data sets or non-linear relationships, its use can lead to more continuity in realizations. Testing of this method with the MrLavaLoba data or with the barrel log data (interpolated) as the soft data is recommended to provide greater continuity in future realizations if continuity is not evident in the current realizations as determined using a suitable continuity measure."

Simulating Red Hill shaft (RHS) Capture Zone

Accurate simulation of the extent of the RHS capture zone continues to be a specific objective of the GWFM and is essential to understanding the extent to which the water supply tunnel hydraulically influences, contains, and is vulnerable to contamination beneath Red Hill. The 2024 model has greatly improved representation of the water supply tunnel and the likely distribution of flow. However, the model does not accurately reproduce the vertical hydraulic gradients and apparent confined conditions observed in P-series transition wells, RHMW-15, and the east end of the water supply tunnel. Regarding the simulation of RHS capture zones and the influence of vertical flow SSP&A had the following comment:

"It is important, however, that Navy and its contractors continue to evaluate and interpret the groundwater elevations obtained from wells surrounding RHS, which were down-weighted in the 2024 model calibration. Measurements obtained from the P-series of wells, together with those from RHMW-15, and other wells located in the vicinity of RHS, indicate consistent vertical (typically, upward) gradients that suggest a strong potential for upward flow into RHS if hydraulic connectivity (natural, or otherwise) allows it. Such flows could lead to very different estimates of capture than obtained using the base model." To better account for the inferred vertical component of flow in RHS and refine estimates of RHS capture, EPA requests the following.

Recommendation #3:
Describe a strategy for refining the model to improve simulation of the vertical heads and confined conditions observed at Red Hill and within the Red Hill Shaft water supply tunnel. In the interim, please implement an alternative approach to isolating the extent of capture developed at the water table by RHS. *"While the geological realizations do a better job of simulating observed flows within and around RHS, if it is not possible to accurately represent the complex conditions around RHS a pragmatic approach to adjusting the simulated extent of capture developed at the water table by*

RHS when pumping may be to reduce the simulated pumping rate by a proportion representing the vertical flows."

Confined Conditions, Elevated heads, Vertical Gradients, and Vertical Flows

Calibration of the 2024 GWFM has focused primarily on data collected from wells screened at the water table representing unconfined conditions that are in strong hydraulic connections with the regional basal aquifer, and de-emphasizing wells that are screened at greater depths and appear to exhibit confined conditions. Consequently, the model does not accurately simulate upward gradients in the vicinity of RHS and the resulting potential for upward flow at Red Hill. SSP&A had the following comment regarding the calibration of different categories of wells:

"The groundwater monitoring network presents a wide spectrum of groundwater levels that include (a) water levels representing the regional, unweathered, basalt aquifer and typically encountered between about 18 and 20 feet above mean sea level (ft-amsl); (b) water levels that are elevated above this regional aquifer surface but demonstrate hydraulic response to pumping and can be referred to as elevated but connected to the regional aquifer; (c) water levels that are elevated above this regional aquifer surface and demonstrate little or no hydraulic response to pumping and are likely perched; (d) water levels from wells screened below the water table that are elevated above this regional aquifer surface and demonstrate hydraulic response to pumping and appear to represent a locally-confined but nonetheless hydraulically connected condition. The 2024 model emphasizes the simulation of regional aquifer conditions – i.e., "well type (a)", which is understandable given that a primary objective is to simulate the transport and fate of contaminants within the regional aquifer. However, data obtained from well type (d) indicate that local to the Red Hill Facility there is potential for substantial upward flows if natural or anthropogenic conditions enable it. The 2024 Model Report and accompanying model files demonstrate a fairly poor simulation of these wells (which include RHMW15-5a, RHMW15-4, RHP-07, and RHP-02, for example), as a consequence of down-weighting of the data associated with them."
EPA requests a response to the recommendation.

Recommendation #4:
"Given the potential value of the data obtained from these wells to understanding the local conceptual site model (CSM), the current inability of the current flow model to represent these responses suggests that the local CSM should be revisited to determine what conditions lead to these responses and then additional simulation efforts should be made using the current model by adjusting calibration weights or other aspects of the calibration process.

Spatial Distribution of Groundwater Recharge

EPA requests a response to the recommendation.

Recommendation #5:
It's noted that the groundwater recharge estimates developed by the USGS[1] and incorporated into the GWFM are based on elevation, land use and soil type, and do not consider the receiving capacity of the underlying bedrock. The variability in receiving capacity of the bedrock can result in "rejected recharge" that moves laterally, infiltrating the vadose zone and recharging groundwater in a different area than where it fell. This spatial redistribution of groundwater recharge has the potential to influence groundwater flow directions and is not accounted for by the model. Please discuss this uncertainty, its potential influence on model results, and approaches to represent this condition in future modeling efforts.

Boundary Fluxes

The boundary fluxes are not well constrained and the sensitivity of model predictions to boundary assumptions has not been evaluated. Navy acknowledges epistemic uncertainty in lateral boundary flux estimates, but concludes: "….*the error associated with these calculations is considered acceptable*."

Recommendation #6:
To demonstrate the error is indeed acceptable and does not significantly influence model results in the vicinity of Red Hill, EPA recommends conducting a sensitivity analysis on boundary flux scenarios. EPA requests that Navy work with RAs and SMEs to identify several sets of plausible alternative boundary conditions for the sensitivity analysis.

Flow Model Calibration Methods and Data

Water Level Targets

Accurately simulating the shape of measured drawdown and recovery curves in response to groundwater pumping can be a convincing demonstration of model calibration. However, meaningful comparison of simulated and measured drawdown and recovery requires greater temporal resolution than used in previous attempts at GWFM calibration. While the time discretization of the 2024 GWFM is greatly improved for this purpose, the definition of calibration targets may hamper the calibration process. In particular, the hydraulic response soon after initial pump start-up and shut-down provide particularly important information that is best captured using variable-length time steps and calibration targets, such as distributed across a logarithmic time scale. To improve transient model calibrations and better evaluate model representation of aquifer properties, EPA requests the Navy implement the following recommendation.

[1] USGS, Engott et al., 2015 Spatially Distributed Groundwater Recharge for 2010 Land Cover Estimated Using a Water-Budget Model for the Island of Oʻahu, Hawaiʻl, Scientific Investigations Report 2015-5010

Recommendation #7:
For future modeling, calibration targets should be defined on a variable time-spacing (similar to logarithmic distribution of measurements collected during an aquifer test) where a time-step (or calibration-target interval) multiplier is used to emphasize the shape of the response curve.

Vertical Gradients

Previous modeling efforts have focused on simulating horizontal groundwater flow at the regional water table. However, head data collected at well clusters indicate the presence of vertical gradients and a significant component of flow to RHS is derived from a confined aquifer beneath the RHS water supply tunnel. These field observations indicate vertical flow is an important element of the groundwater system in the vicinity of Red Hill and that it needs to be accounted for to accurately simulate capture zones and local contaminant fate and transport. SSP&A had the following comment on the simulation of vertical gradients in the vicinity of Red Hill:

'When attempting to reproduce measured vertical head differences, two primary hydraulic parameters are typically adjusted during the calibration process: those are, vertical anisotropy (or vertical hydraulic conductivity) and horizontal hydraulic conductivity – or, using the structure implemented in the 2024 flow model, the reduction of horizontal hydraulic conductivity due to basalt weathering. As discussed earlier and reported in 2024 Model Report (Section 2.3.5.4), simulated vertical head differences lead to consistently smaller vertical gradients than computed from the measured heads and this leads to vertical head differences presenting the largest contribution of misfit to the calibration objective function (2024 Model Report Table 2-6). The calibrated vertical anisotropy is estimated to be 50. This is not a particularly high value, and one that may not be sufficiently high to reproduce measured vertical gradients. This value of 50 is also equal to the specified lower bound for that parameter in the calibration, which suggests that the calibration process implemented using the PEST software was attempting to decrease anisotropy, the opposite of what would be expected in order to create larger vertical head differences, rather than increase it. This contrarian behavior suggests that the calibration process was inhibited from making changes that would be expected to bring about the desired outcome. Possible causes for this include local structural limitations, an ill-conditioned inverse problem leading to solution instability, or other factors."

Recommendation #8:
The probable causes for the inferred vertical anisotropy values and for the calibration process meeting a prescribed bounding value, should be investigated and the findings reported out.

Groundwater Elevation Data Presentation and Model Calibration

Computing calibration statistics such as the root-mean-squared error (RMS) from head data provides a useful metric for tracking relative improvements in model performance and comparing between different observation types and their contribution to the calibration objective function. However, statistics such as the RMS do not provide a direct measure of how well the model predicts inferred directions of groundwater flow at the scale of Red Hill. EPA believes the comparison of contoured head maps simulated by the model to those generated by interpolating field observations will assist in evaluating this aspect of model calibration. EPA requests that Navy incorporate the recommendations below.

Recommendation #9.
"First, outputs from the 2024 groundwater flow model could be compared to the interpolated contours to identify areas where there is good correspondence – which generally lends support to those interpretations in the area of overlap – or where there is very poor correspondence – suggesting that patterns may be poorly represented using one or other (or possibly both) methods. Second, the interpolated water levels can be incorporated into the flow model calibration as "targets", with a weight that is derived from the kriging standard deviations (KSDs) obtained from the interpolation routine."

Vadose Zone Modeling
Several elements of the vadose zone model are very conservative including the large volume releases, rapid and relatively complete migration to the water table, absence of phase-partitioning, weathering, and biodegradation in the vadose zone. Collectively, these simplifying assumptions result in unrealistically large contaminant sources reaching the water table from hypothetical fuel releases at and around the fuel storage tanks. Given the Red Hill underground storage tank system has been defueled, eliminating the risk of large catastrophic releases, EPA requests that the Navy implement the following recommendation.
Reconstructive simulations are needed to ensure the CF&T model is representative. Future models should emphasize the likely presence, quantities, and role of residual LNAPL contamination.

Recommendation #10:
"While reconstructive simulations are still necessary to ensure that the CF&T model is representative, greater emphasis should in future modeling studies be placed on the likely presence, quantities, and role of residual LNAPL contamination."

Total petroleum hydrocarbon (TPH) Forensic Analysis
Attempts to identify sources of contamination, groundwater transport rates and characterize risks are confounded at Red Hill by the likely presence of multiple sources of various ages and TPH compositions. To better discern sources of contamination, the rate and direction of contaminant transport and characterize risk, additional forensic analyses should be conducted on groundwater samples. EPA requests the Navy implement the following recommendation.

Recommendation #11:
"Given the various potential contributors to TPH contamination across the diesel and oil ranges in particular, and the complex relationship between multi-component TPH sample results and risk, it is recommended that the TPH forensic analysis presented in the 2024 Model Report be further expanded to include specific constituents of fuel such as naphthalenes and tri-methyl-benzenes (TMBs), alkylated PAHs among others, which though present at lower concentrations than the various total TPH measures, are more directly indicative of (recent) releases".

Contaminant Fate and Transport Modeling

The CF&T modeling used very conservative assumptions that appear to yield unrealistic predictions of the extent and magnitude of petroleum migration in groundwater. The large source terms generated by the vadose zone model compounded by assumptions there is no interaction with the aquifer matrix or biodegradation in groundwater yield unrealistic estimates of contaminant migration. In their comments SSP&A indicated: "..*the predictions of risk to, and concentrations at Hālawa Shaft are considered to be excessively conservative."*

Precipitation-driven remobilization of residual contamination in the vadose zone will continue to feed groundwater plumes beneath Red Hill. Although the mass of contamination in the vadose zone is unknown and the subject of future investigations, groundwater monitoring data collected since the system was defueled is providing important information for characterizing fluctuations in the extent and magnitude of the groundwater contamination over time. EPA believes this data should be used to inform groundwater source terms for CF&T analyses.

<u>Recommendation #12:</u> Work with RAs and SMEs to develop consensus opinions on reasonable assumptions and parameter ranges for the CF&T modeling.

Misalignment Between the 2024 Model Report and Accompanying Model Files

During their review of the September 2024 Model report and files, SSP&A identified the following structural issues with the model that subsequently were communicated to the Navy and its contractor. *"First, with regard the box model heterogeneity implementation. During the model review, it was noted that hydraulic conductivity in adjacent cells between the coarse model and nested cells is in some places widely different. This is most evident at the final row of the fine grid area (see Figure 11). It appears that the conversion of the output from the SISIM simulations to the box model produced some local artifacts.*

Second, with regard to boundary inflows: The 2024 Model Report (Table 2-4) lists the average inflow from the south-eastern boundary and outflow to the north-west boundary to be 2.1 and 9.0 million gallons per day (mgd), respectively. These values were intended to be used as targets during the calibration process and compared to the simulated values in 2024 Model Report. It was noted that inflow and outflow actually specified for steady state conditions were set to be 3.0 and 12.2 mgd, respectively, which differ from the reported average conditions. It was also identified that one model cell (188806) from the north-west outflow boundary was misplaced and used for budget calculations for the south-east inflow boundary (Figure 12), and that flow model output control package (OC) was not being properly read leading to errors postprocessing the boundary flows."

<u>Recommendation #13:</u> Because these boundaries represent important elements of the model water budget, on 09 October 2024 via email, EPA recommended to Navy and its contractors that these boundary errors be addressed and the model recalibrated.

Continued Model Refinement and Field Verification Studies

Due to the hydrogeologic complexity of the Red Hill area, it is particularly important to conduct field studies that evaluate and verify key assumptions and predictions of the model. SSP&A had this comment:

"*New data will continue to become available – including recent new well drilling, recent field testing (e.g., well borescope studies), additional field tests that are in the planning stages (e.g., point-to-point tracer studies) - and these data will further contribute to site knowledge and may refine or update the CSM. Analysis and interpretation of the data obtained from these ongoing studies is critical to corroborating or improving the model. Therefore, efforts must be continued to incorporate data from both completed and planned field tests in a simulation-verification approach in a continuing effort to bring the modeling efforts to a successful conclusion."* To ensure the studies meaningfully contribute to model validation and are conducted in a systematic and timely manner, EPA suggests the following.

Recommendation #14:
Navy and its contractors work with RAs and SMEs to identify field validation study objectives, methods and areas of investigation. Navy submits for RA review and approval a proposed scope of work and schedule for conducting the evaluations followed by individual work plans for each study.

Modeling Objectives and Response to Community Concerns

Detections of PAHs in the Board of Water Supply Aiea wells have raised concerns in the community that petroleum contamination from Red Hill is far more extensive than previously understood and that it threatens public water supplies well beyond Red Hill Shaft. While EPA has not identified a connection between the PAH detections in the Aiea wells and releases from Red Hill, the Agency believes it is important to communicate and graphically depict to the public, our current understanding of the extent and magnitude of groundwater contamination resulting from releases at Red Hill. EPA generally supports the framework of the CF&T analyses presented in Section 5.4.2 and Figures 5-8 through 5-10 of the modeling report and would like to continue to build on that approach.

Recommendation #15:
• Update groundwater model to reflect new site information, model validation and calibration. • Further evaluate and refine release scenarios described in Section 5 of the report. • Further evaluate and refine CF&T parameters and assumptions. • Delineate an "area of groundwater concern" centered on Red Hull that conservatively encompasses impacts to the basil aquifer from historical releases and potential future remobilization of residual contamination. • Identify a network of sentinel wells to monitor conditions at the boundaries of this "area of concern" to provide an ongoing demonstration that groundwater impacts are confined within it.

To facilitate Model development, EPA recommends Navy, EPA staff and their respective contractors meet directly to address and resolve modeling concerns (with a frequency and schedule to be determined).

Path Forward

Near Term

- Correct the errors in boundary cell inflows and outflows identified by SSP&A, rerun the model and evaluate changes to the model results including water budget, calibration and particle tracking. Provide a response letter and technical memorandum describing the corrections made to the model and their influence on model results by **March 31, 2025**.
- Respond to EPA comments on the model report by **March 31, 2025.**

Mid-Term

Modelers from the Navy's team meet directly with RAs and SMEs to workshop modeling topics requiring further consideration. Work towards achieving consensus opinions on key model assumptions, features and processes including but not limited to:

- Field investigations and data collection to validate model CSM and predictions.
- Representation of physical and hydraulic properties of saprolitic features.
- Representation of Boundary conditions.
- Petroleum contamination fate and transport processes.

EPA would like to begin these workshops in April 2025 and will work with Navy and others to develop finalize topics and schedules.

- Identify methods and develop work plans and **schedules** with SME input regarding field methods and data collection to validate model predictions (e.g. tracer tests, pump tests). There is often significant lead time required to implement these field investigations. EPA requests that draft scope of work and schedule for conducting the field investigations be submitted by **May 15, 2025**.

Long-Term

Update and calibrate the model based on workshops, field data, and newly available lithologic information; Evaluate Fitness of model for application of CF&T.

- Rerun release and CF&T scenarios considering all reasonable hydrogeologic CSMs and graphically depict the combined area of concern by **November 1, 2025.**
- Continue model refinement as new information becomes available, then evaluate model fitness for identifying contaminant source areas and evaluating remedial alternatives.

If you have any questions regarding this letter, please contact me at russi.tonya@epa.gov or (415) 972-3706.

Sincerely,

/s/

Tonya Russi
Red Hill Project Coordinator
U.S. Environmental Protection Agency, Region 9

Enclosure: Comments on *"Groundwater Model Report, Red Hill Bulk Fuel Storage Facility"* (September 26, 2024) and Accompanying Groundwater Model Files

cc (via email only):

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S.S. PAPADOPULOS & ASSOCIATES, INC.
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Prepared November 30, 2024

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Subject: Comments on ***"Groundwater Model Report, Red Hill Bulk Fuel Storage Facility"*** (September 26, 2024) and Accompanying Groundwater Model Files

Dear Mr. Cohen:

S.S. Papadopulos & Associates, Inc. (SSP&A) has completed a review of the "*Groundwater Model Report, Red Hill Bulk Fuel Storage Facility*" (Volume 1: Main Report, Appendixes A–C: "2024 Model Report"), revised September 26, 2024, and the accompanying groundwater model files prepared by AECOM Technical Services, Inc (AECOM) on behalf of the Naval Facilities Engineering Command (NAVFAC) Hawai'i. This Comment Letter provides comments on the Navy's Groundwater Flow Model (GWFM) based on review of the 2024 Model Report and supporting model files and also upon cumulative technical reviews conducted of modeling-related deliverables received by the U.S. Environmental Protection Agency (USEPA) prior to 2024. This Comment Letter focuses on providing sufficient comments and recommendations to guide and prioritize follow-up actions.

The 2024 Model Report and accompanying modeling files represent the latest in a series of deliverables describing the development, calibration, and application, of groundwater models representing subsurface conditions surrounding the Red Hill Bulk Storage Facility (RHBSF), Red Hill Shaft (RHS), and other water supply wells in the area. Previous to the current report and associated files, SSP&A most recently reviewed the "*Groundwater Flow Model Technical Memorandum*" dated May 17, 2023 (2023 Model Report). The 2023 Model Report and accompanying files were acknowledged by the Navy to be interim pending the incorporation of several features and simulation capabilities that had been recommended previously by the Regulatory Agency (RA) subject matter experts (SMEs). Some of those comments derive, in whole or in part, from a collection of comments that was initially provided to the Navy and its consultants in August 2018 and has been referred to colloquially as "The Regulator Top Ten". The 2024 Model Report and accompanying model files were intended to address several of the comments provided by USEPA and other RAs that were not incorporated in the 2023 Model Report, together with several of "The Regulator Top Ten" comments.

This review of the 2024 Model Report and the model files focused on undertaking sufficient work to answer the following questions to a reasonable degree of confidence:

1. Is there appropriate alignment between the documentation presented in the 2024 Model Report and the underlying, accompanying, model files?
2. Does the model reasonably represent the current Conceptual Site Model (CSM), including the representation of the features, events, and processes (FEPs) contained therein? This includes determining whether reasonable efforts were made to respond to, and incorporate changes related to, comments that USEPA provided against previous versions of the model report and model files.
3. Is the model fit-for-purpose? If not, is further work necessary, or are more data required, or are there other factors that limit the model's suitability?

The response to the third question is critical: it depends on the evolving modeling objectives, scale, and resolution, which are discussed further below, and it is possible to answer the first two questions in the affirmative yet still not have a model that is suitable for the intended purpose(s). This can arise from multiple factors, including data gaps, poor assumptions, an incomplete or internally inconsistent CSM, and simulation code limitations.

General Considerations and Context

The purpose of the modeling and reporting that is detailed in the 2024 Model Report is to "*…be responsive to the Regulatory Agency (RA) concerns outlined in their March 2022 Groundwater Flow Model Report disapproval letter. In addition, this study should improve the understanding of the direction and rate of groundwater flow within the aquifers around the Facility in support of long-term site management and support risk evaluation based on Contaminant Fate and Transport (CF&T) models.*" (2024 Model Report, Executive Summary [ES]). The 2024 Model Report ES goes on to state that: "*Key components of the model that have been added or updated include regional water budget calculations to inform model boundary conditions; revisions to model grids and layers; use of temperature and chloride data to evaluate source water contributions to Red Hill Shaft (RHS) and Hālawa Shaft; revisions to the model calibration approach that focuses on matching water levels and gradients; and implementation of lava flow structure-imitating heterogeneous basalt. The models also provide a framework where concepts can continue to be tested as new information becomes available.*".

According to the Administrative Order on Consent (AOC) Scope of Work (SOW), Section 7, the original purpose of the GWFM was to: "*improve the understanding of the direction and rate of groundwater flow within the aquifers around the facility*" in part so that it could then be used to support analyses of the transport and fate of contaminants released to the subsurface. The Navy additionally planned to use modeling to "*guide and inform the number and placement of groundwater monitoring wells required to adequately identify possible contaminant migration*" (Section 7.3, AOC SOW). The intent at that time was to consider "new" and "catastrophic" large releases. Modeling through the vadose zone was not envisioned. At that time, RHBSF stored a variety of fuels and was in active use as a storage and transfer facility. Since that time, RHBSF has been almost entirely defueled – i.e., the storage tanks emptied of fuel. As a result, very large volume fuel releases of the size discussed in the AOC and experienced in 2014, 2021, and at other times during the history of the operation of RHBSF are no longer feasible. Given this, some aspects of the modeling objectives have evolved. As a result, while the ability to simulate the historical fate of past large releases is still valuable to model development and credibility, the previously prioritized ability to predict the fate of large future releases is instead replaced by a need to simulate the potential fate of residual contamination residing primarily within the vadose zone and beneath the water table. While a formal principal study analysis has not been conducted, it seems appropriate that the focus of the modeling efforts should now be on:

(1) Using data from past releases to understand and constrain contaminant fate-and-transport (F&T) properties;

(2) Supporting site investigation and characterization efforts, and analyzing the potential presence and quantities of residual contamination and its potential to (re-)mobilize and be transported to potential receptors; and,

(3) Defining the historical and probable maximum area impacted by fuels arising from RHBSF and evaluating the potential risk(s) posed by residual contamination under a range of plausible conditions.

While these activities are underway, modeling should also be able to inform decisions regarding the adequacy of the monitoring network for defining the extent of contamination and detecting any migration, and therefore helping identify data gaps in the monitoring well network that require closure before final site decisions can be made.

The 2024 Model Report was produced during a period representing an evolving transition between priorities and modeling objectives, and as a result the report emphasizes aspects of earlier and more recently evolved modeling objectives.

General Comments

The 2023 Model Report listed previous regulator and SME comments and provided Navy's perspective on the status of responses to those comments, identifying modeling improvements that were in progress and planned for the 2024 model. The 2024 Model Report provides both an abbreviated "composited" listed of comment themes and Navy's perspective on the status of responses to those comment themes (2024 Model Report, Appendix B: *Summary of 2022 Regulator GWFM Comments and Approach*), and additional discussion of comments received and responses prepared (2024 Model Report, Appendix C: *Responses to Regulator Comments and Correspondence from Regulators*). The Navy and its contractors have made reasonable attempts to respond to many comments provided previously by the RA SMEs on earlier deliverables, as summarized in Appendix B and C of the 2024 Model Report. Partly as a result, the model design, structure, and representation of the major FEPs is closer to meeting anticipated flow and transport needs, and the revised model grid (discretization) enables simulations to be completed with high resolution representation of local heterogeneity encompassing key areas of interest including RHS, RHBSF, and the Board of Water Supply (BWS) Halawa Shaft (HS).

The 2024 Model Report, in its presentation and discussion of the major elements of the modeling activities, is the most thorough of the modeling reports submitted to date. The report contains several new sections prepared in part in response to previous comments from the RA SMEs, including sections on basalt heterogeneity, vadose zone modeling, and saturated zone transport modeling including an evaluation of Total Petroleum Hydrocarbon (TPH) data. The Navy and its contractors should be recognized for these substantial improvements and efforts, and comments on these new technical sections are provided later in this Comment Letter.

Despite these commendable efforts, it is important to recognize that some of the comments and recommendations (listed by "theme") presented in Appendix B of the 2024 Model Report remain unresolved. In some instances, the remaining uncertainties do not result from the approach taken to the modeling itself but arise either from the current state of knowledge (e.g., lateral boundary conditions and fluxes) or from challenges encountered in incorporating certain data and information (e.g., the use of geochemical proxies in model corroboration). In other instances, the remaining challenges arise from shortcomings that remain in the CSM and its representation in the groundwater model (e.g., the correspondence of modeled vertical gradients with measured values). These comments are expanded upon below with examples.

Model Structure

A significant previous comment of the RA SMEs on earlier models was with regard to the "structure-following" model grid. The 2024 model grid design – including lateral spacing and vertical layering - is greatly improved compared to earlier model versions. The new refined resolution helps ensure consistent translation from the geological framework to the model and allows for flexibility in potential future model revisions without changing the model grid. For example, reasonable revisions to the geological framework related to the depth and extents of the saprolite or recent volcanics can be implemented by changing model parameters assigned to the existing grid without changing the model layering. Figure 1 depicts model hydraulic properties in the vicinity of Red Hill Facility boundary to illustrate this feature of the updated grid.

As depicted in Figure 2, the 2024 Model Report and accompany files use two integrated model grids: the first, a coarse grid with uniform cells of 250 feet length, and the second, a nested grid that incorporates a much finer spatial resolution in the area of interest encompassing RHBSF, RHS, HS, and other potential receptors. This concept of using multiple grid resolutions is commonly used when finer resolution is needed to investigate specific conditions on the local scale but allows groundwater models to be calibrated efficiently at a larger scale. It is noted that when using this approach, great care must be taken to ensure that there is consistency between the "regional" and "local" hydraulic properties and the fluxes between the coarse and nested grids so that there is a stable and realistic transition between adjacent coarse and fine model cells. The 2024 Model Report describes efforts taken by the Navy and its contractors in this regard.

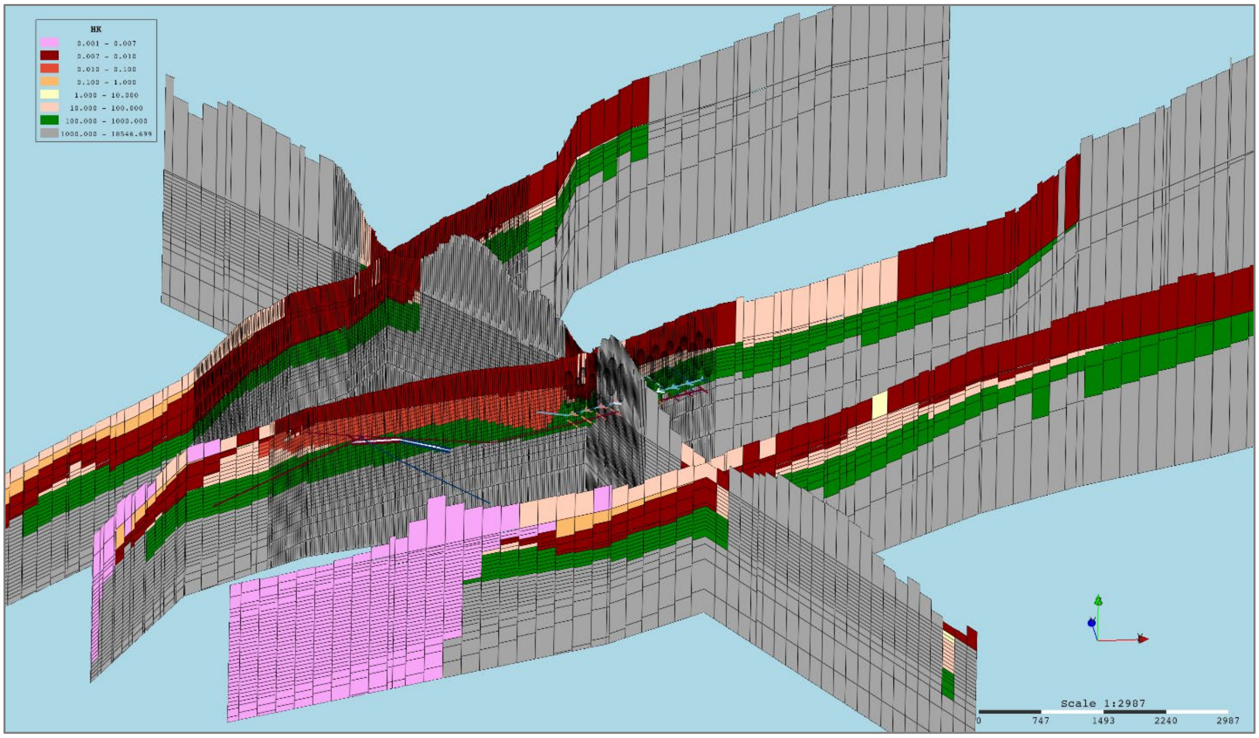

Figure 1. Fence Diagrams through Model Grid

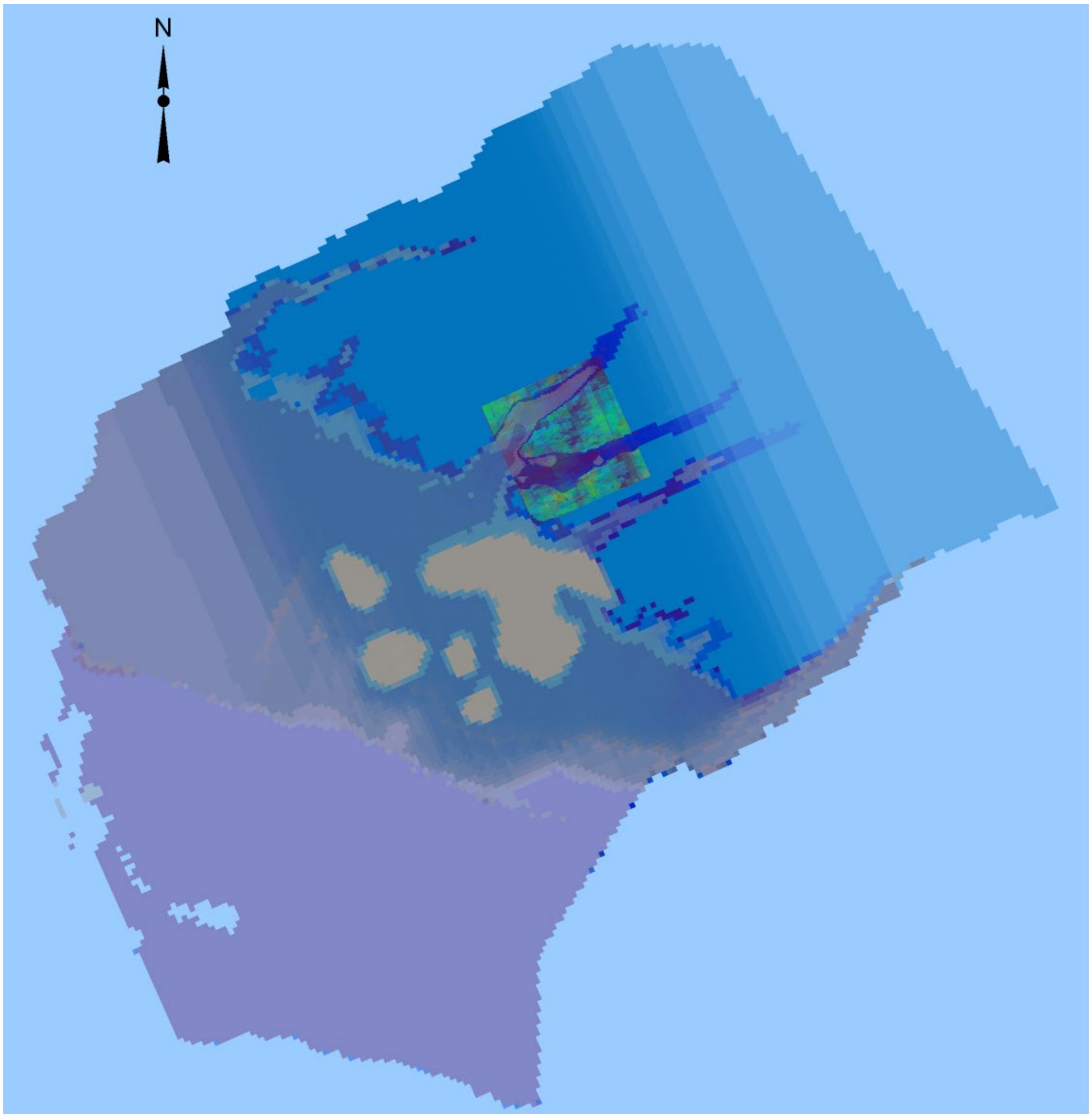

Figure 2. Regional Model Domain and Nested Fine Grid

Basalt Heterogeneity

Consistent with numerous previous RA SME comments and suggestions provided on earlier versions of the model, the 2024 model uses the nested grid region to represent the heterogeneous nature of the basalt aquifer. The stepwise geostatistical approach described in the 2024 Model Report uses the MrLavaLoba lava flow simulator, the RHBSF barrel log records, and the Sequential Indicator Simulation (SISIM) method and program to generate multiple realizations that contrast relative low permeability basalt with clinker that exhibits high permeability. Calculated heterogeneous hydraulic conductivities are then translated into the nested grid model, rerun for each realization and compared to the base simulation represented by the model coarse grid. Figure 3 presents an example of the random walk pattern characteristic of Hawai'ian lava flows as represented by the MyLavaLoba model.

The approach used to represent basalt heterogeneity is generally consistent with comments provided previously by the RA SMEs and meets the intent of those comments to implement a procedure to recognize, characterize, and simulate the effects of basalt heterogeneity on groundwater flow but more importantly on the transport of contaminants dissolved in groundwater but also, potentially, over multiple phases.

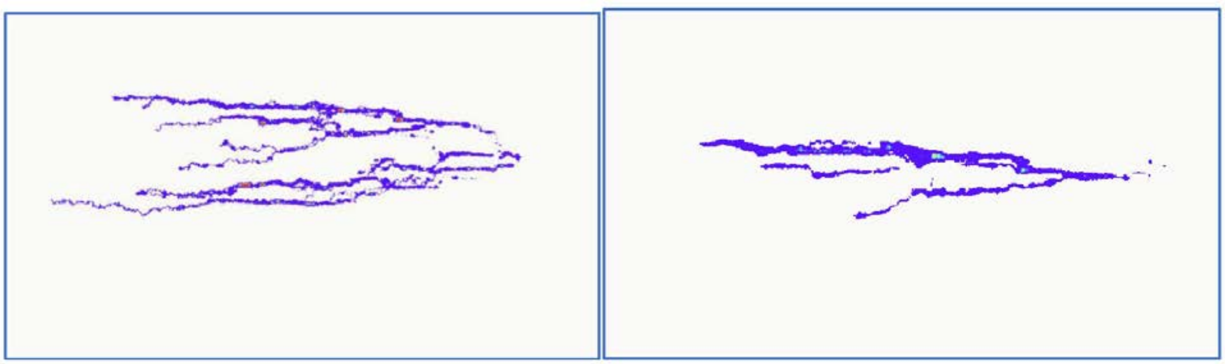

Chart 3-12: Examples of Simulated A'ā (left) and Pāhoehoe Flows (right)

Figure 3. Example Random-Walk Pattern from MrLavaLoba Simulation

In the 2024 Model Report, it is stated that the RHBSF barrel log data, obtained during tank construction in the 1940's, were used in the workflow to generate variograms to guide or corroborate the heterogeneity analyses. During our review, we were able to locate data related to the barrel logs in the files accompany in the report, however we did not proceed to attempt to reproduce the variograms presented in 2024 Model Report Figure 3-5. Additionally, posterior variograms of the SISIM realizations were not located that could be compared with the a-priori variograms developed from the barrel logs and MrLavaLoba realizations.

Nonetheless, visually, review of several of the 50 SISIM realizations suggested that the patterns obtained via the SISIM realization process were broadly consistent with expectations from that process. An important caveat to this conclusion is that the continuity of high-conductivity features is difficult to discern from the files. Continuity can certainly be important to flow, but is often more critical to the plausible representation of contaminant transport, and longitudinal continuity of contiguous high-conductivity materials is expected to arise from the formation of lava flows (as depicted above in Figure 3). In light of this consideration, two recommendations are made here.

First, a method should be added to the post-processing of the SISIM realizations at the SISIM grid scale, and the outcome of these realizations following their translation to the fine Box Model grid, to compute a measure reflecting the longitudinal continuity of basalt material types that can be compared with both the barrel log data (when interpolated to produce a continuous grid) and the MrLavaLoba realizations to determine whether longitudinal continuity was preserved by the simulation procedure. Second, the SISIM program includes a Markov-Bayes method for coding soft data to include in geostatistical simulations. While there can be challenges using this method with large data sets or non-linear relationships, its use can lead to more continuity in realizations. Testing of this method with the MrLavaLoba data or with the barrel log data (interpolated) as the soft data is recommended to provide greater continuity in future realizations if continuity is not evident in the current realizations as determined using a suitable continuity measure.

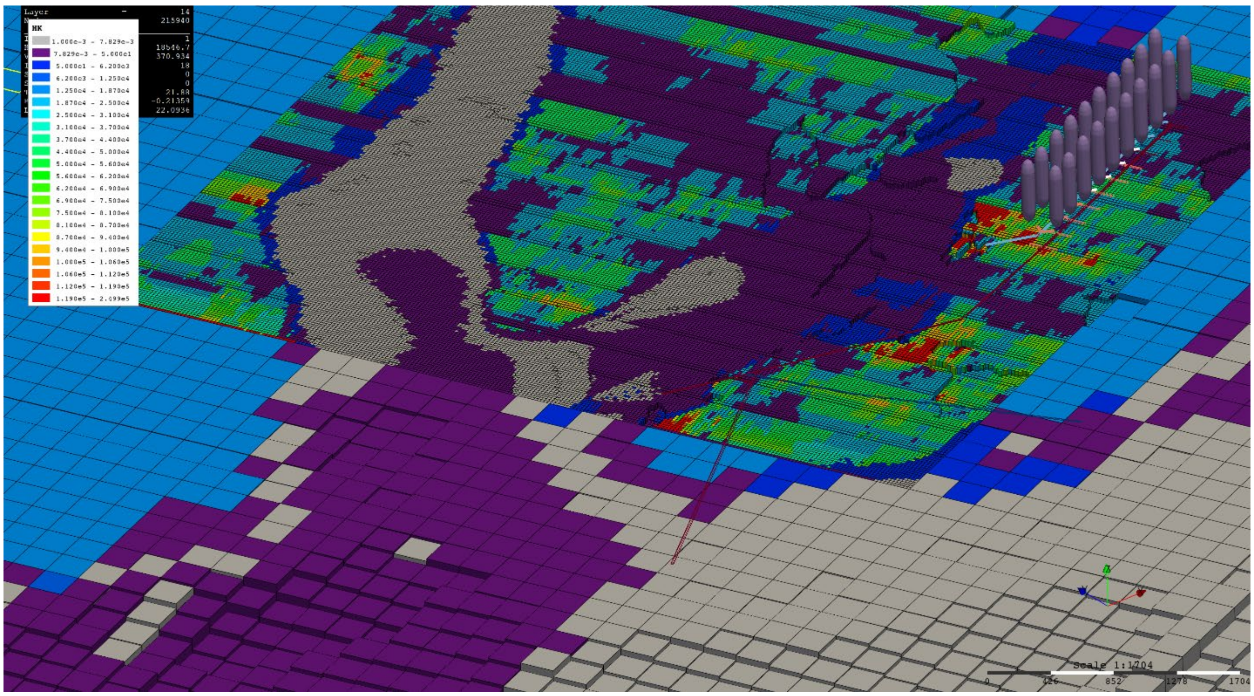

Figure 4. Depiction of Combined Fine and Coarse Grids with Heterogeneity Represented in the Fine Grid Area

Representation of Red Hill Shaft (RHS)

There is considerable potential for misunderstanding the distribution of groundwater inflows to RHS. Records documenting the construction of the tunnel demonstrated that RHS exhibited highly heterogeneous inflows along its length, as a combination of both natural (geologic) conditions and enhancements to flows (such as shot and drill holes). During investigations of RHS following the 2021 fuel releases, divers that entered the tunnel noted a constant flow – under non-pumping conditions – of water from the east to the west end of RHS, which was consistent with expectations based on a combination of tunneling records and groundwater levels from surrounding monitoring wells. Previous work conducted during model reviews suggested that as much as 90%+ of inflow could come from the east limb of RHS, with over 20% being derived as bottom flow – i.e., water that does not enter laterally into the tunnel from the upper part of the water table aquifer.

The ability of the groundwater model to reasonably accurately simulate the effect of pumping at RHS, and the pattern of inflows expected from the surrounding formation, has been a theme of RA

SME comments since at least 2018, and is critical to the accurate representation of the capture zone developed by RHS and proximal contaminant F&T. Since 2018, the Navy and its contractors have made stepwise improvements to the model representation of RHS, including updating the model package that is used to represent the tunnel; representing a large hypothetical clinker zone intercepted by RHS; and adding targets to the model calibration in an effort to ensure modeled inflows to RHS reflect anticipated patterns. In the 2024 Model Report and accompanying files, the approach to representing RHS is further detailed and updated to include the results of the geostatistical representation of basalt heterogeneity in the formation surrounding RHS.

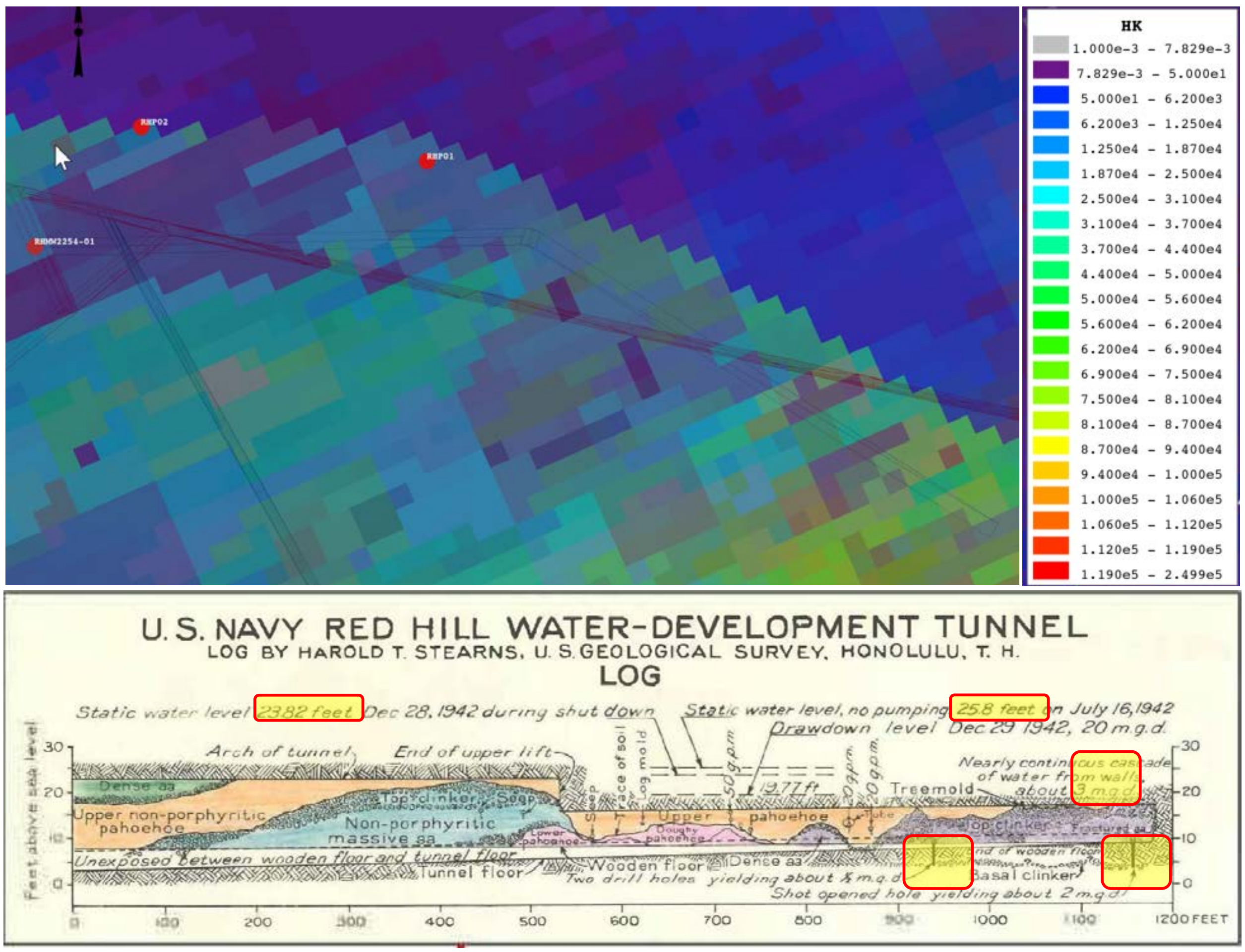

Figure 5. Red Hill Shaft: Tunnel Log, Noted Inflows and Construction-Era Head Levels (Bottom Panel), and Example Heterogeneous Basalt Realization (Top Panel)

Figure 5 depicts the tunnel log for RHS together with noted inflows and construction-era groundwater elevation measurements from the records obtained at the time the tunnel was installed (bottom panel), together with an example heterogeneous basalt realization that was obtained using the combined MrLavaLoba/SISIM workflow described above and in the 2024 Model Report (Top Panel). Recognizing that under such heterogeneous conditions, a “true” picture of subsurface heterogeneity will never be obtained, the Navy and its contractors have improved the numerical representation of RHS via various model updates, including the most recent basalt realizations that include the RHS tunnel log as conditioning data for the SISIM realizations. Although these updates to the representation of RHS in the model do not reflect all known complexities – which include the effect of regional groundwater level declines since RHS was constructed; information regarding passive flows obtained during the 2021/2022 in-tunnel studies; and the presence of strong vertical gradients near RHS demonstrated by some monitoring wells (e.g., RHMW-15, RHP-05) that are not accurately reproduced by the 2024 model – the current representation of RHS is a noteworthy improvement.

It is important, however, that Navy and its contractors continue to evaluate and interpret the groundwater elevations obtained from wells surrounding RHS, which were down-weighted in the 2024 model calibration. Measurements obtained from the P-series of wells, together with those from RHMW-15, and other wells located in the vicinity of RHS, indicate consistent vertical (typically, upward) gradients that suggest a strong potential for upward flow into RHS if hydraulic connectivity (natural, or otherwise) allows it. Such flows could lead to very different estimates of capture than obtained using the base model. While the geological realizations do a better job of simulating observed flows within and around RHS, if it is not possible to accurately represent the complex conditions around RHS a pragmatic approach to adjusting the simulated extent of capture developed at the water table by RHS when pumping may be to reduce the simulated pumping rate by a proportion representing the vertical flows.

Representation of other Features of the Current CSM

<u>Saprolite Properties</u>

The primary groundwater-containing units simulated by the 2024 model are the saturated zone basalts. One feature of the CSM is the role of saprolite – essentially, weathered basalt – in reducing the potential for flow and migration between valleys. Drilling through saprolite historically has revealed perched and elevated head conditions within saprolite, and in places challenges have been encountered discerning when the unweathered regional basalt aquifer has been encountered. The 2024 Model Report acknowledges that the hydraulic properties of the saprolite nonetheless transmit water. Basalt weathering was implemented using an exponential function leading to a continuous profile of hydraulic conductivity from overlying sediments to the bedrock interface. Figure 6 presents a depiction of the profile of weathered basalt and resulting hydraulic conductivity versus depth for the case of bedrock that lies beneath caprock where there is no stream (modified from the 2024 Model Report, Chart 2-2). The parameters of these profiles were estimated as part of the calibration process. This representation goes some way toward representing the inhomogeneous properties of saprolite, and impact of its presence both above and below the regional groundwater table. It is noted, however, that boring through saprolites has often revealed intermittent patterns of weathered versus unweathered basalt – which has led to the challenges identifying the regional aquifer in some places - rather than a smooth continuum. However, it is acknowledged that such intermittent patterns do not suggest that these intervals are laterally continuous; and further, that representing such intermittent patterns would bring additional challenges that may not be warranted given the modeling objectives.

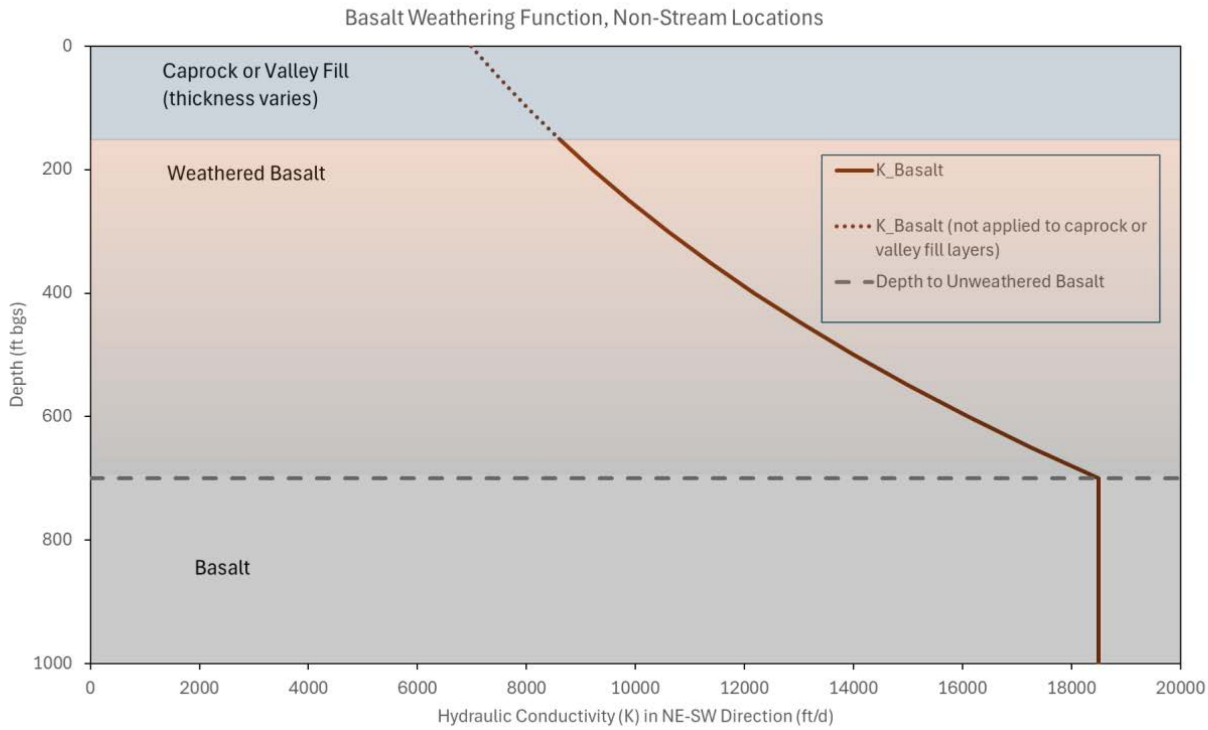

Figure 6. Illustration of Weathered Basalt Hydraulic Conductivity – Example Provided for Bedrock Beneath Caprock (from 2024 Model Report Chart 2-2).

Confined Conditions, Elevated heads, Vertical Gradients, and Vertical Flows

The groundwater monitoring network presents a wide spectrum of groundwater levels that include (a) water levels representing the regional, unweathered, basalt aquifer and typically encountered between about 18 and 20 feet above mean sea level (ft-amsl); (b) water levels that are elevated above this regional aquifer surface but demonstrate hydraulic response to pumping and can be referred to as elevated but connected to the regional aquifer; (c) water levels that are elevated above this regional aquifer surface and demonstrate little or no hydraulic response to pumping and are likely perched; (d) water levels from wells screened below the water table that are elevated above this regional aquifer surface and demonstrate hydraulic response to pumping and appear to represent a locally-confined but nonetheless hydraulically connected condition. The 2024 model emphasizes the simulation of regional aquifer conditions – i.e., “well type (a)”, which is understandable given that a primary objective is to simulate the transport and fate of contaminants within the regional aquifer. However, data obtained from well type (d) indicate that local to the Red Hill Facility there is potential for substantial upward flows if natural or anthropogenic conditions enable it. The 2024 Model Report and accompanying model files demonstrate a fairly poor simulation of these wells (which include RHMW15-5a, RHMW15-4, RHP-07, and RHP-02, for example), as a consequence of down-weighting of the data associated with them. Given the potential value of the data obtained from these wells to understanding the local CSM, the current inability of the current flow model to represent these responses suggests that the local CSM should be revisited to determine what conditions lead to these responses and then additional simulation efforts should be made using the current model structure by adjusting calibration weights or other aspects of the calibration process. A further note on this issue is provided below under "Flow Model Calibration Methods and Data".

Recharge

Recharge from infiltration of precipitation is a significant, but uncertain, component of the water budget within the domain of the 2024 groundwater flow model. Recharge from infiltration of precipitation also forms the basis for the inflows specified at the upgradient (dyke swarm) boundary. The recharge pattern within the model domain is derived from work completed previously by the U.S. Geological Survey (USGS), which is based upon a surface land-use and soils analysis. Such methods calculate a surface infiltration rate which is in many settings reasonably assumed to approximate the rate of recharge at the underlying water table. However, in some settings – particularly, where permeable soils overlay bedrock of lower permeability, or where recharge and groundwater flow is heavily imprinted upon by the bedrock fabric - recharge to the aquifer is a product of both the surface infiltration; the receiving capacity of the immediately underlying aquifer units (which is in turn affected by the geologic properties and potentiometry of those units); the presence/absence of intervening perched units between the land surface and regional principal aquifer.

Boundary Fluxes

The lateral boundary fluxes remain poorly understood. This is not a fault of the groundwater flow modeling approach, but rather a limitation of broader understanding of conditions at the margins of, and beyond, the 2024 groundwater flow model domain. Work is underway at the University of Hawai'i to improve understanding of regional conditions – including regional flow patterns, discharges toward and through the cap rock and springs, and the role of the freshwater-saltwater interface. Until those studies are completed, the best approach to representing the lateral (and bottom) boundary conditions to the Navy's groundwater flow model may be to develop two or three alternatives to test the sensitivity of the key flow and transport predictions within the refined model grid area to plausible alternatives.

Summary

Overall, the 2024 groundwater model represents a substantial improvement over previous modeling submittals, in terms of the model grid and the methods used to represent the major features of the CSM. Despite this, the 2024 flow model still fails to simulate certain observed data that very likely point to remaining shortcomings of the CSM. This is discussed further below.

Flow Model Calibration Methods and Data

Water Level Targets

The main component of the groundwater flow model calibration is the correspondence between simulated and observed groundwater levels, and in particular changes in water levels in response to pumping. The data available for water level and pumping-response calibration – including measured water levels, and multiple periods of on-off extraction cycling - has grown substantially over time. Previous versions of the flow model used a small number of stress periods to represent historical conditions, making it very challenging to discern the model's ability to represent either transient (time-varying) or longer-term average conditions. This was an important critique of the RA SMEs on previous model releases. The 2024 Model Report and accompanying model files present an improved temporal discretization of the groundwater flow model, which reflects variable (on-off) pumping patterns over extended periods. As a consequence, the amplitude of pumping-induced responses can be discerned for the model and how this corresponds to measured data.

Figure 7 (upper panel) illustrates using one specific well as an example, the simulated pumping on-off cycle, together with measured water levels, specified calibration targets, and modeled water levels. It is evident in this instance that the amplitude of the modeled response to pumping is about half the measured amplitude. While this may result from the model discretization and parameterization, it is also possible that this results from the temporal spacing of the calibration targets. It is recommended that in future modeling, the calibration targets are defined on a variable time-spacing simulate to that depicted in the lower panel where a time-step (or calibration-target interval) multiplier is used to emphasize the shape of the response curve. This approach – such as using a logarithmic time scale – is often used in aquifer test analysis, and while it can present challenges to numerical models, it can provide greater opportunity for the calibration to reproduce this pattern leading to a lesser penalty to the calibration and improved ability to also match other components of the objective function.

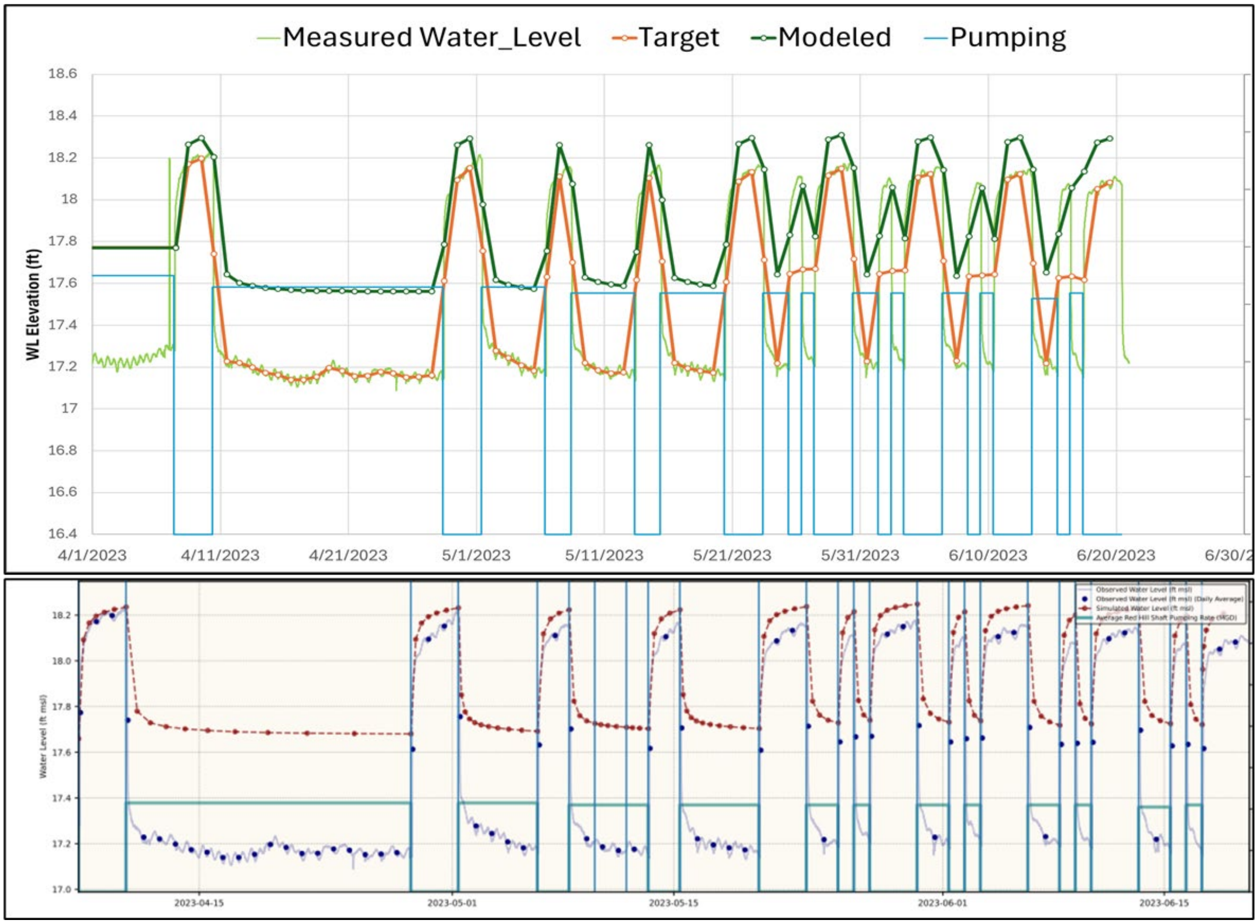

Figure 7. Illustration of Groundwater Elevation Target Spacing in Time (upper panel) and Simulated Patterns (lower panel: modified after 2024 Model Report).

Vertical Head Differences

When attempting to reproduce measured vertical head differences, two primary hydraulic parameters are typically adjusted during the calibration process: those are, vertical anisotropy (or vertical hydraulic conductivity) and horizontal hydraulic conductivity – or, using the structure implemented in the 2024 flow model, the reduction of horizontal hydraulic conductivity due to basalt weathering as discussed earlier and in the 2024 Model Report (Section 2.3.4). As reported in 2024 Model Report (Section 2.3.5.4) simulated vertical head differences lead to consistently smaller vertical gradients than computed from the measured heads; and, this leads to vertical head differences presenting the largest contribution of misfit to the calibration objective function (2024 Model Report Table 2-6). The calibrated vertical anisotropy is estimated to be 50. This is not a particularly high value, and one that may not be sufficiently high to reproduce measured vertical gradients. This value of 50 is also equal to the specified lower bound for that parameter in the calibration, which suggests that the calibration process implemented using the PEST software was attempting to *decrease* anisotropy - the opposite of what would be expected in order to create larger vertical head differences – rather than increase it. This contrarian behavior suggests that the calibration process was inhibited from making changes that would be expected to bring about the desired outcome. Possible causes for this include local structural limitations, an ill-conditioned inverse problem leading to solution instability, or other factors. The probable causes should be investigated to improve the representation of these vertical head differences.

Groundwater Elevation Contours

The construction of groundwater elevation contours via interpolation of water levels measured in monitoring wells has proven difficult at the Red Hill Facility. This arises from many factors including the complex geology, presence of and contrasts between weathered and unweathered basalts, uncertain boundary fluxes (or "background gradients"), anticipated hydraulic anisotropy of the basal basalt aquifer units, and – until more recently - the small number of monitoring wells over a very large geographic area. This presents challenges to inferring groundwater flow patterns, migration directions, and also evaluating the performance of the groundwater model in these respects. This is because preparation of scatter plots and time-series of modeled and measured water levels does not directly represent a comparison between modeled and measured groundwater elevation contours and gradients.

Over time, the monitoring network has grown, leading both to a greater availability of water level data over a wider area, and a smaller typical inter-well spacing reducing the dependence of mapped water levels on the selected interpolation algorithm. Figure 8 depicts interpolated groundwater elevation contours that were prepared several years ago using water level data obtained during 2019, to represent in an approximate manner both non-pumping (upper panel) and pumping (lower panel) conditions. The interpolation used a method that can incorporate in an approximate manner the effects of pumping at RHS, and resistance to groundwater flow resulting from the presence of saprolite below water table. The monitoring network has grown substantially since the time these contours were prepared, and it is expected that interpolation using the current monitoring network would be more reliable than the contours depicted in Figure 8.

Two recommendations are made with regard groundwater elevation data interpolation. First, outputs from the 2024 groundwater flow model could be compared to the interpolated contours to identify areas where there is good correspondence – which generally lends support to those interpretations in the area of overlap – or where there is very poor correspondence – suggesting that patterns may be poorly represented using one or other (or possibly both) methods. Second, the interpolated water levels can be incorporated into the flow model calibration as "targets", with a weight that is derived from the kriging standard deviations (KSDs) obtained from the interpolation routine. These KSDs are typically very small and approach zero near measured data – suggesting the calibration should match measured data, as closely as possible – and increase further away from measured data where the contours become dominated by the interpolation algorithm used. As maps of groundwater levels improve over time, their incorporation in the flow model calibration can help lead to plausible calibration result and a steady improvement in correspondence between modeled and mapped conditions.

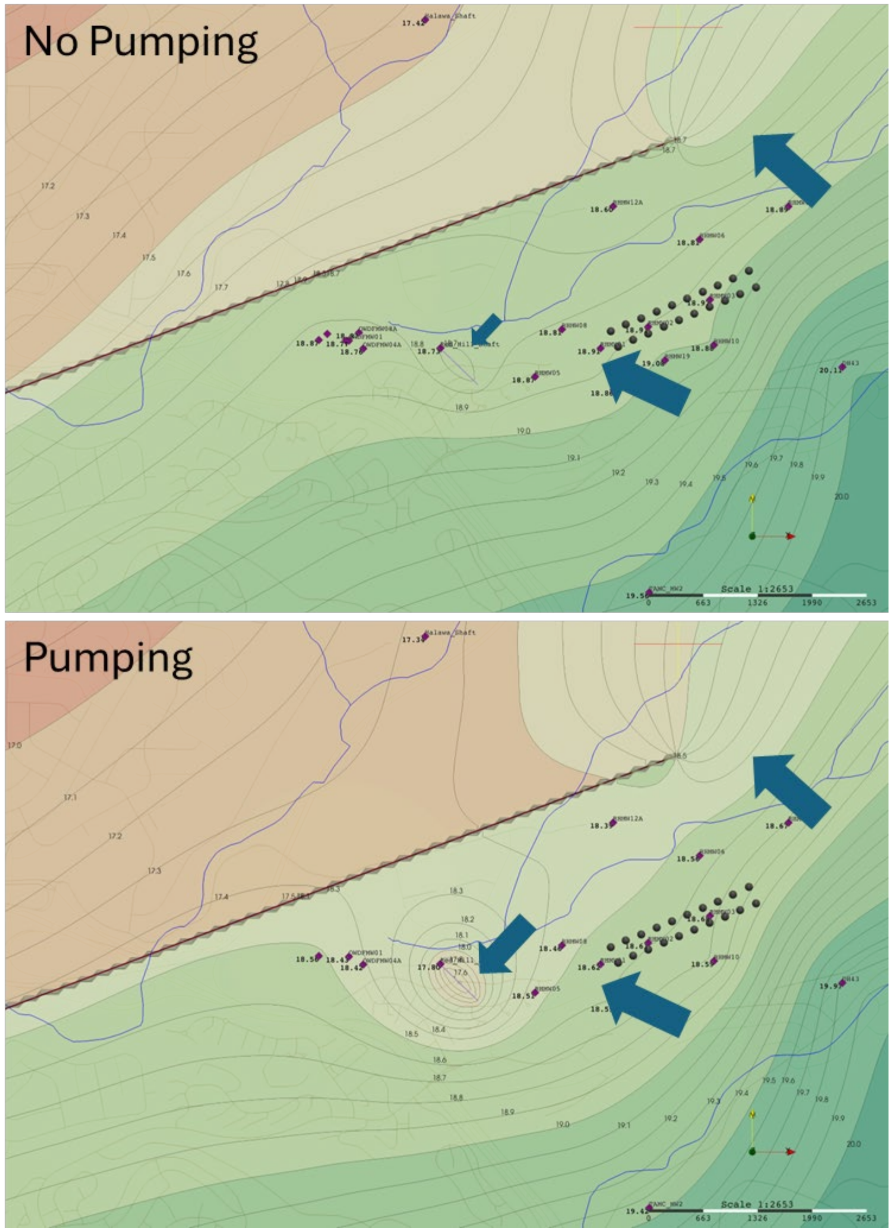

Figure 8. Interpolated Groundwater Elevation Contours Prepared using Data from 2019: Non-Pumping (Upper Panel) and Pumping (Lower Panel) Conditions

<u>Stochastic Realizations and Calibration Statistics</u>

The final note regarding the model calibration refers to the calibration statistics obtained using the stochastic realizations of basalt heterogeneity. First, it is noted that calibration statistics such as root mean squared (RMS) error though commonly used often provide little information regarding calibration performance beyond indicating progress and improvement in these selected statistics. The best interpretation of calibration performance is often provided by reviewing time-series hydrographs and other plots comparing modeled and measured quantities (as was also done in the 2024 Model Report). Setting this aside, calibration statistics were evaluated for stochastic basalt realizations, and some were found to be comparable to or better than the base model calibration statistics (see Figure 9 for a partial comparison). This is an encouraging result for the groundwater flow model, suggesting that plausible basalt heterogeneity can be modeled while still obtaining comparable calibration performance. As noted above, however, it is unclear at this time if the continuity anticipated to occur within the basalt aquifer has been preserved in the realizations, which has important implications for transport modeling.

Notes:
RMSE is greater than homogeneous base model.
RMSE is less than homogeneous base model.

Table 3-3: Comparison of Realizations

Realization No.	RHS Flow Distribution RMSE (%)	Red Hill Wells Head RMSE (ft)	Transitional Wells Head RMSE (ft)	All Basal Wells Head RMSE (ft)	Red Hill Wells Drawdown RMSE (ft)	Ridge Gradients RMSE (ft)	Horizontal Head Differences RMSE (ft)	Vertical Head Differences RMSE (ft)	RHS Flow Distribution RMSE (%)_Rank	Red Hill Wells Head RMSE (ft)_Rank	Transitional Wells Head RMSE (ft)_Rank	All Basal Wells Head RMSE (ft)_Rank	Red Hill Wells Drawdown RMSE (ft)_Rank	Ridge Gradients RMSE (ft)_Rank	Horizontal Head Differences RMSE (ft)_Rank	Vertical Head Differences RMSE (ft)_Rank	Sum of Ranks	Rank
Realization_47	7.1	0.26	0.34	0.25	0.17	3.6E-05	0.23	0.34	5	13	9	4	1	19	3	3	57	1
Realization_13	4.2	0.24	0.35	0.26	0.17	2.6E-05	0.26	0.34	3	2	13	11	1	10	16	3	59	2
Realization_32	13.8	0.26	0.33	0.25	0.17	3.5E-05	0.23	0.34	30	13	5	4	1	18	3	3	77	3
Base	19.8	0.25	0.35	0.25	0.17	2.2E-05	0.23	0.33	50	8	13	4	1	9	3	1	89	4
Realization_10	14.1	0.27	0.32	0.27	0.17	1.6E-05	0.23	0.34	31	25	3	20	1	3	3	3	89	5
Realization_34	19.9	0.25	0.36	0.25	0.17	2.1E-05	0.23	0.33	51	8	19	4	1	7	3	1	94	6
Realization_8	8.3	0.25	0.40	0.24	0.17	1.8E-05	0.23	0.37	12	8	33	2	1	4	3	31	94	7

Figure 9. Comparison of Calibration Statistics for Stochastic Basalt Realizations with the Base Model Calibration Statistics

Vadose Zone Modeling

The 2024 Model Report presents a two-part vadose zone model (VZM) used to quantify the source term over space and time for the saturated zone contaminant fate and transport (CF&T) model: first, a mass balance model to quantify the potential size and shape of a light non-aqueous liquid (LNAPL) lens that forms upon the groundwater aquifer water table under various presumed release scenarios; and second, a partitioning module that calculates LNAPL chemical constituent concentrations in groundwater over time within the footprint of the LNAPL lens. The 2024 Model Report states that "*Because the mass balance model relies on professional judgment for assumptions and model parameters, the mass balance model is called a heuristic model to emphasize that it incorporates elements of professional judgment and was developed for the limited uses described herein.*" Both parts of the VZM model are programmed into Microsoft Excel™ enabling the evaluation of many different scenarios and parameter sets.

As developed and described, the VZM is envisioned to represent in an approximate manner the simplified vertical migration of fuel release in the vadose zone toward the water table, where the soluble components partition. As such, given the largely completed defueling of the RHBSF, the VZM is most suited to providing approximate time-varying constituent loading at the water table from past releases for purposes of loading and calibrating the CF&T model. The following brief comments are provided regarding the VZM:

- The heuristic vadose migration component of the VZM neglects many of the anticipated complexities of the vadose zone at the Red Hill Facility, leading the outputs to be very conservative in the sense of rapidly moving the vast bulk of any release to the water table. While such an approach is understandable in early release evaluations, given that defueling is largely complete and modeling objectives have evolved, such representations have limited utility moving forward. While reconstructive simulations are still required to ensure that the CF&T model is representative, greater emphasis should in future modeling studies be placed on the likely presence, quantities, and role of residual LNAPL contamination.

- In the applications described in the report, and for other potential future applications, given the limitations of the heuristic vadose migration component, the most useful component of the VZM as developed and described is at this time the dissolution component.

Forensic Evaluation of TPH Data

The 2024 Model Report presents an extensive evaluation of historical TPH sample results obtained from monitoring wells and other sampling devices at and around the Red Hill Facility. This discussion builds on previous work presented by the Navy and its contractors and represents a necessary step in the evaluation of TPH and other water quality indicators with regard to the risk posed by specific fuel-related contaminants and their combination; CF&T properties, particularly migration and attenuation rates; and modeling of fuel-related contaminant transport. However, the following brief comments are provided with regard this TPH forensic presentation:

- While partially addressed in previous presentations by Navy and its contractors, and in the 2024 Model Report, the possibility of some TPH concentration changes over time being attributable to other characteristics including local focused precipitation, and remobilization near the water table, is not adequately addressed. As an example, Figure 10 depicts TPH sample results (TPH-d and TPH-d SGC) for RHMW-02 together with monthly precipitation records. Also not shown in this figure is the shut-off of RHS in late November 2024. However, the combined effect of heavy focused precipitation, shut off of RHS, and accumulating departure from normal (wet) conditions appears capable of explaining some periods of increased concentrations both when releases were known to have occurred (e.g., May and November 2021) and when releases of fuel are not known to have occurred (e.g., spring 2023 and spring 2024).

- Given the various potential contributors to TPH concentration variability across the diesel and oil ranges in particular, and the complex relationship between multi-component TPH sample results and risk, it is recommended that the TPH forensic analysis presented in the 2024 Model Report be further expanded to include specific constituents of fuel such as naphthalenes and tri-methyl-benzenes (TMBs), among others, which though present at lower concentrations than the various total TPH measures, are more directly indicative of (recent) releases.

Figure 10. Diesel Range TPH Sample Results both Before (TPH-d: Red Line, Upper Plot) and Following (TPH-d SGC: Green Line, Upper Plot) Silica Gel Cleanup at RHMW-02 together with Monthly Precipitation Records (Blue Bars) and Cumulative Departure from Precipitation Norm (Dark Green Line, Bottom Plot) from a Local Weather Station

Saturated Zone Fate-and-Transport (F&T) Modeling

CF&T modeling as envisioned in the original AOC (2016) was primarily intended to consider the F&T of "new" releases including potential "catastrophic" large releases. Modeling through the vadose zone was not envisioned. At that time, RHBSF stored a variety of fuels and was in active use as a storage and transfer facility. Since that time, RHBSF has been almost entirely defueled. As a result, fuel releases of the type discussed in the AOC and experienced in 2014, 2021, and at other times during the history of the operation of RHBSF are not feasible. Given this, the modeling objectives have evolved. The ability to simulate the historical fate of past large releases remains valuable to model development and credibility – however, the ability to predict the fate of large future releases has been replaced by a need to simulate the potential fate of residual contamination residing within the vadose zone and beneath the water table; and hence the potential migration and risk posed by this residual. Thus, while the transport modeling demonstrates the potential utility of CF&T analyses, the evolving situation will require re-tooling of the CF&T approach undertaken by Navy and its contractors. The following additional comments are provided:

- The presented analyses are very conservative – leading to predictions of unrealistically high concentrations in groundwater beyond the Red Hill Facility – for numerous reasons, including:
    - The methods used to simulate vadose fate and transport in the VZM.

  - As stated in the 2024 Model Report, the conservative representations do "*…not account for any bio-attenuation or other petroleum decay mechanisms*" which commonly occur at fuel release sites.

- Other processes leading to changes in concentrations of TPH (and possibly the component fractions of fuel) are not directly or explicitly considered in the analysis, requiring lateral dissolved phase transport of contamination to account for all change seen in the measured data. These other processes need to be accounted for and may require explicit simulation – particularly the presence and effect of a smear zone or periodically rewetted zone (PRZ).
- Other noted irregularities in TPH data suggest that these data are not suitable for model calibration or validation without further resolution including component fraction forensics and reconciliation of results obtained from different laboratories.

The foregoing comments and suggestions should be discussed and resolved before undertaking further CF&T modeling. Until that time, the predictions of risk to, and concentrations at Hālawa Shaft are considered to be conservatively high.

Misalignment Between the 2024 Model Report and Accompanying Model Files

In the initial review of the groundwater model files two items were noted in the review of the boundary fluxes, these were communicated to the Navy modeling team for their review prior to the submittal of this set of comments. These two items are summarized below.

First, with regard the box model heterogeneity implementation. During the model review, it was noted that hydraulic conductivity in adjacent cells between the coarse model and nested cells is in some places widely different. This is most evident at the final row of the fine grid area (see Figure 11). It appears that the conversion of the output from the SISIM simulations to the box model produced some local artifacts. This matter was communicated to the Navy and its contractors during the model review, and corrections are in progress.

Second, with regard to boundary inflows. The 2024 Model Report (Table 2-4) lists the average inflow from the south-eastern boundary and outflow to the north-west boundary to be 2.1 and 9.0 million gallons per day (mgd), respectively. These values were intended to be used as targets during the calibration process and compared to the simulated values in 2024 Model Report. It was noted that inflow and outflow actually specified for steady state conditions were set to be 3.0 and 12.2 mgd, respectively, which differ from the reported average conditions. It was also identified that one model cell (188806) from the north-west outflow boundary was misplaced and used for budget calculations for the south-east inflow boundary (Figure 12), and that flow model output control package (OC) was not being properly read leading to errors postprocessing the boundary flows. Because these boundaries represent important elements of the model water budget it was recommended to Navy and its contractors during the completion of this model review that these matters be addressed and the model recalibrated.

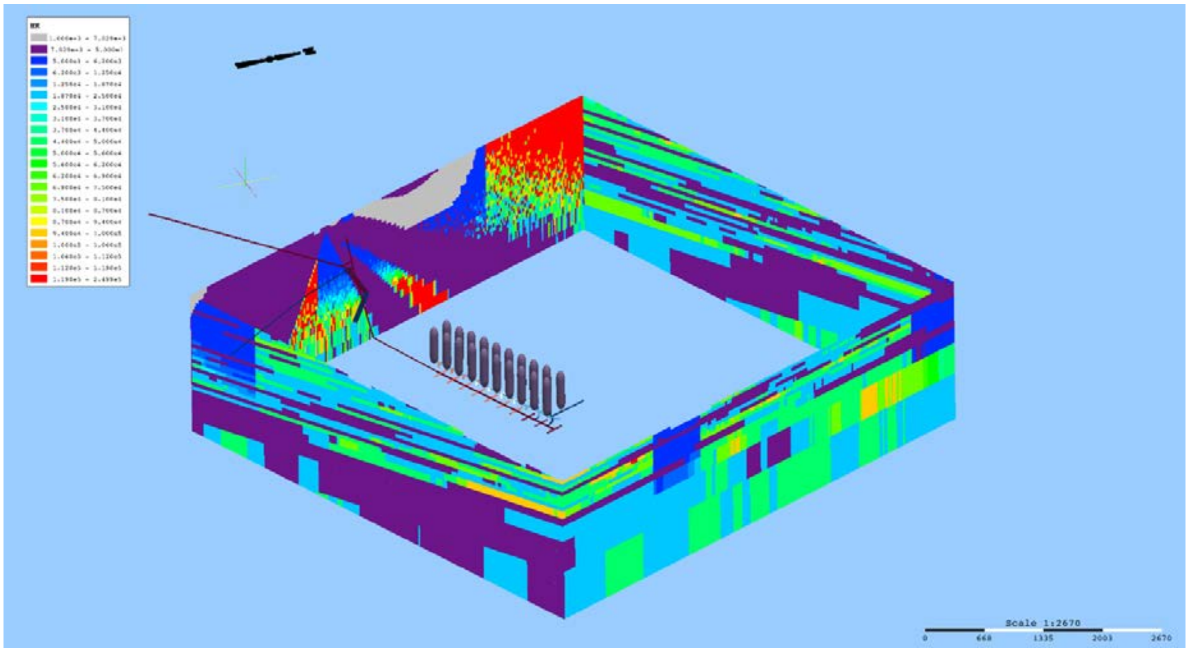

Figure 11. Box Model Hydraulic Conductivity Fence Diagram

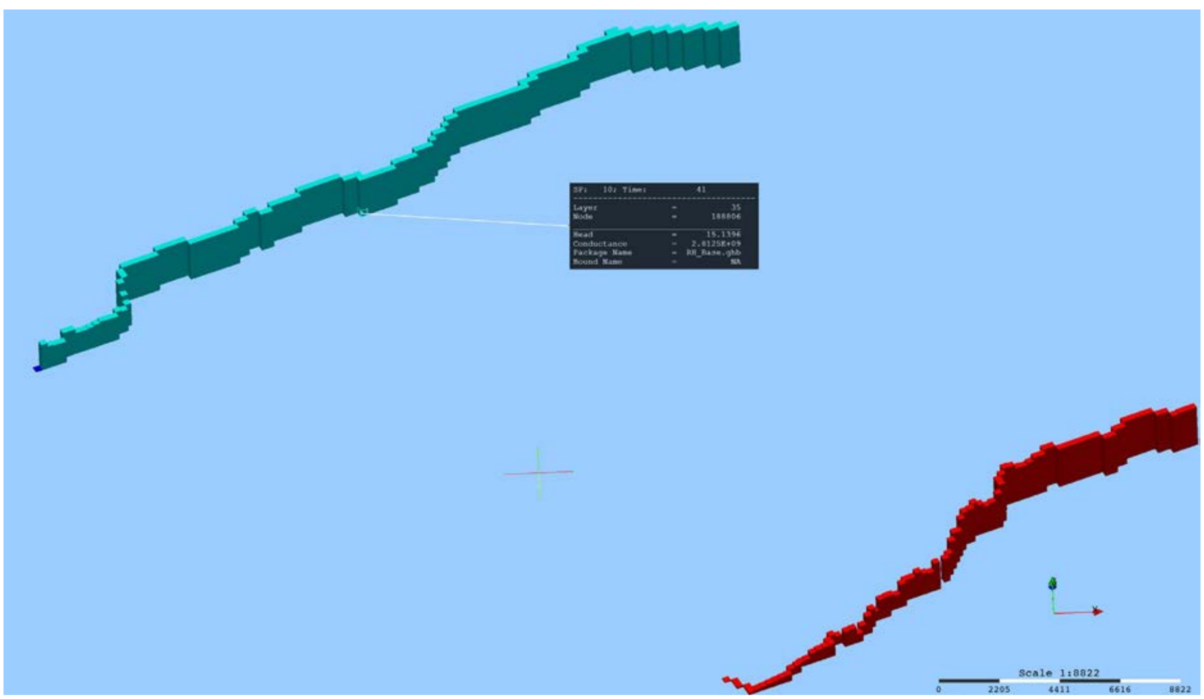

Figure 12. GHB Boundary and Location of Misplaced Cell

Fitness for Purpose

The determination of fitness for purpose is still under consideration. At the time of this review, the calibration does not reflect certain conditions described in the 2024 Model Report and the transport model attempts to match data that may not represent net migration. Note: Due to the complexities of the CSM, the work of multiple experts, and ongoing data collection, our understanding of the CSM continues to develop.

In conclusion, the essential structure and major features appear commensurate with the intended uses, and the basalt texture development process appears to be suitable for generating realizations at almost any scale, which should provide value to the ongoing site assessment and characterization phases of work. However, new data will continue to become available – including recent new well drilling, recent field testing (e.g., well borescope studies), additional field tests that are in the planning stages (e.g., point-to-point tracer studies) - and these data will further contribute to site knowledge, and may refine or update the CSM. Analysis and interpretation of the data obtained from these ongoing studies is critical to corroborating or improving the model. Therefore, efforts must be continued to incorporated data from both completed and planned field tests in a simulation-verification approach in a continuing effort to bring the modeling efforts to a successful conclusion.

In the meantime, the identification of misalignments between the 2024 Model Report and the accompany model files indicates that the workflow that has evolved in the development and issuance of modeling deliverables creates some concerns for quality control. The project overall would benefit from ongoing in-stream review of model progress, including correspondence and interaction between the RA SMEs and the Navy technical consultants.

I hope that the foregoing comments are useful and can further the development of a suitable groundwater flow and contaminant transport modeling platform for use at the Red Hill facility.

Sincerely,

S.S. PAPADOPULOS & ASSOCIATES, INC.

/s/

Matthew Tonkin, PhD

President and Principal Hydrogeologist