Naval Facilities Engineering Systems Command Hawaii

Groundwater Model Report Addendum
Red Hill Bulk Fuel Storage Facility
JBPHH, Oahu, Hawaii

March 17, 2025

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Acronyms and Abbreviations

.cbb	MODFLOW cell-by-cell flow binary file
.rec	PEST run record file
µg/L	micrograms per liter
CF&T	contaminant fate and transport
DON	Department of Navy
EPA	Environmental Protection Agency, United States
FOS	Flow Optimization Study
ft	foot/feet
ft/d	feet per day
ft^2	square feet
GHB	general head boundary
GUI	graphical user interface
mgd	million gallons per day
NAHS	Navy ‘Aiea Hālawa Shaft
RHS	Red Hill Shaft
RMSE	root mean squared error
TPH	total petroleum hydrocarbons

1.0 Introduction

This Groundwater Model Report Addendum addresses interim comments received regarding the September 2024 Groundwater Model Report (DON 2024). The comments originate from email communications between the U.S. Environmental Protection Agency (EPA) and the Navy on October 9, 2024 and November 1, 2024 and from comments made during the November 13, 2024 Red Hill Subject Matter Expert Quarterly Meeting. The comments have been divided into two categories: those relating to errors or requests for clarification, and those constituting suggestions.

Comments from the first category are discussed in greater detail in Sections 2.0 through 6.0, with explanations and examples of how the model results are affected. Those comments pertain to water budget flux targets for model calibration with PEST, general head boundary (GHB) condition assignments, variogram parameters, the use of geologic data, and heterogeneity artifacts when translating to the MODFLOW grid.

The second set of comments are discussed in Section 7.0 and suggest alternative methodologies that could be used. These comments are briefly discussed, and potential approaches are proposed to evaluate these suggestions in future versions of the model. These comments relate to the effect of the impermeable bottom boundary of the model, the potential use of SISIM's Markov-Bayes method for conditioning soft data, and model recalibration using biodegradation in the contaminant fate and transport (CF&T) model.

2.0 Water Budget Flux Targets for PEST

2.1 Summary of Comment

The October 9, 2024 email from EPA to the Navy included comments pertaining to the inclusion of flux targets into the model calibration process with the PEST software suite (Watermark Numerical Computing, 2023). The regional groundwater flow model (GWFM) calibration used estimates from the conceptual water budget to develop flux targets for inflows from the southeast boundary and outflows to Kalauao Springs. Each of the 44 stress periods was assigned a target flux at the last time step for each of the two boundary condition reaches. The comments noted that in the PEST run record file (.rec), outputs were recorded for only 7 of the 44 targets for each boundary reach, and that some were extracted to the incorrect times, as shown on Figure 2-1.

2.2 Cause of Issue

The root cause of the issue is an incompatibility between custom output control in the MODFLOW code and "targetpestu," the utility included with the Groundwater Vistas (Rumbaugh & Rumbaugh, 2020) graphical user interface (GUI), which extracts simulated values at target locations corresponding to observed values from binary model output files. Custom output control was used to reduce file sizes and model run times by writing the cell-by-cell flow binary file (.cbb) only at the last time step of each stress period. Records from the PEST run indicate that targetpestu may have required all time steps to be written out to the .cbb file, resulting in missing or mismatched simulated values.

2.3 Implications for Model Results

Although 37 of the 44 flux targets at each boundary reach received no simulated value, the seven targets that did receive simulated values were included in the PEST calibration process. Although some of the times were mismatched, there was relatively little change in the fluxes between stress periods. The result of this issue is that 37 of the targets had large residuals that did not change with parameter modification during the PEST parameter estimation process, but the seven targets that did receive corresponding simulated values, although matched to incorrect times, were reasonably close to the intended values. The average simulated value was 4.3 million gallons per day (mgd) for the southeast boundary inflow and 13.1 mgd for Kalauao Springs, both falling with the range of target values. Despite the internal calculation issue related to the target values, PEST was still able to match conceptual targets well, and there are no significant impacts to the results. (Note that an additional issue of the flux calculations due to the GHB assignment did affect the results and is discussed in Section 3.0, but is unrelated to this issue.)

2.4 Solution

In future model versions, this issue will be corrected by writing out the cell-by-cell flows for each time step. It has been confirmed that this corrects the calculations for simulated flux values extracted by the targpestu routine. Additional work may also be conducted to identify a solution that would allow for the use of custom output control with targpestu, thereby reducing the size of the .cbb files and maintaining reduced run times.

3.0 General Head Boundary Assignment

3.1 Summary of Comment

The October 9, 2024 email from EPA to the Navy included a comment pertaining to the misassignment of the reach number for the GHB at node number 188,806 in the regional GWFM (there are 204,344 total active nodes in the regional GWFM) (Figure 3-1). Note that this node number changes to 1,357,356 when the nested grid is included (there are 1,473,039 total active nodes when the nested grid is included). This caused the outflow from node 188,806, located on the northwest boundary to be accounted for as if it were located on the southeast boundary of the model domain.

3.2 Cause of Issue

The root cause of the GHB accounting issue was the misassignment in the Groundwater Vistas interface of the GHB at node 188,806 (which is far below the groundwater surface in layer 35) to boundary reach 0 (southeast boundary) rather than reach 1 (northwest boundary). After creation of the initial MODFLOW files, a Python script was used to modify head assignments to GHBs, which were based on reach number. Because node 188,806 was assigned the incorrect reach number, it was incorrectly assigned a boundary head associated with the southeast boundary, rather than the northwest, resulting in a head approximately 0.7 foot (ft) lower than adjacent GHB cells. Post-processing of the water budget was similarly conducted based on reach number, which resulted in the outflow from this individual node to be subtracted from the reported inflows of the southeast boundary.

3.3 Implications for Model Results

Impacts to the model results include those to the flow field caused by the misassigned GHB head and those to the reported water budget. The head value assigned to node 188,806 (0.7 ft lower than adjacent cells) resulted in a local groundwater sink. The majority of the water thus simulated as exiting this node originated from the northern corner of the model domain in layer 36, as shown in the reverse particle tracking from node 188,806 on Figure 3-2. The total quantity of groundwater flowing out of this node was 22.4 mgd. While this quantity of water is significant, the node is located approximately 2 miles west of Hālawa Shaft, 3 miles west of Red Hill Shaft (RHS), and approximately 600 ft below the groundwater potentiometric surface. A groundwater divide forms in the simulation between this node and the two supply wells, as shown on Figure 3-2. As a result of this divide, impacts were primarily near the northern model boundary, away from the primary features of interest, and impacts to the flow fields around Hālawa Shaft and RHS were therefore not significant. Additional testing was conducted comparing model calibration statistics between the reported model and the GHB-corrected model. The resulting calibration statistics for heads and drawdowns at the model targets were very similar between the two models, as detailed below.

Calculation of the model water budget both in the calibration process and in subsequent reporting was affected by the misassignment of the GHB reach at node 188,806, causing the outflow from the node to be subtracted from the inflow to the southeast GHB. The result was a reported inflow from the southeast GHB of 4.3 mgd when the correct inflow was 26.7 mgd. Outflow from the northwest GHB then also increased by the same 22.4 mgd. Overall flow through the model increases from approximately 73 mgd to 95 mgd, an approximately 30% increase in total water flux (Chart 3-1).

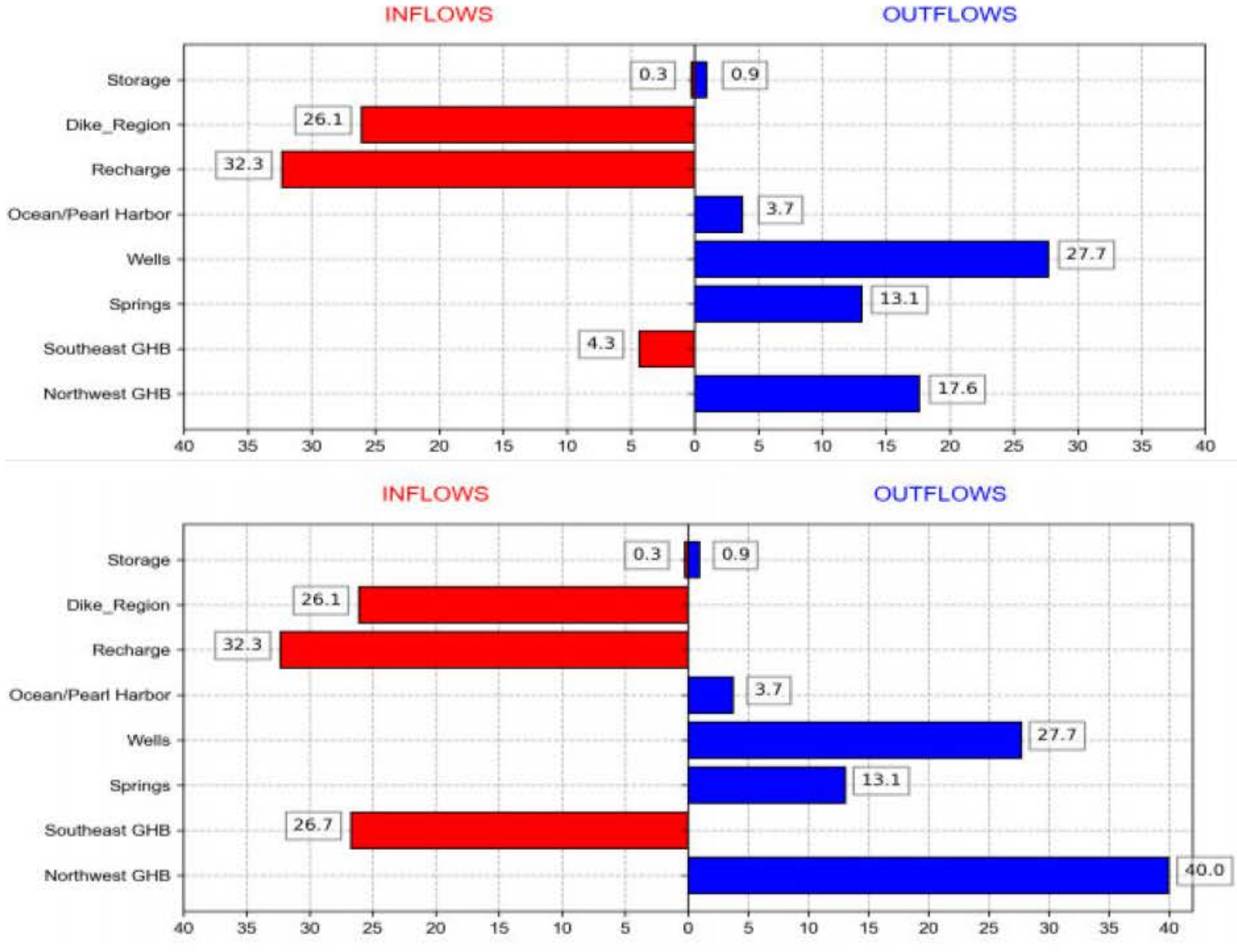

Chart 3-1: Reported Average Water Budget (top) and Corrected Average Water Budget (bottom) from Regional GWFM

Although the impacts of this issue on the model simulation results are limited to the reported water budget, the incorrect inflows were used during the model calibration process with PEST. Impacts to the model calibration were tested by re-running regional model calibration with the corrected GHB node. Head calibration statistics are presented in Table 3-1 and Table 3-2 for the reported and recalibrated models, respectively. A comparison of the calibrated parameters is shown in Table 3-3. Calibration statistics, while not identical, are generally very similar. Root mean square error (RMSE) of basal aquifer wells varies between the two models by 0.00 to 0.03 ft, i.e., a negligible amount. Calibrated parameters are also similar, with the largest changes related to the basalt weathering parameters. The weathering depth was increased from 736 to 1,126 ft, but the weathering reduction factor below streams was reduced from 6,624 to 2,236.

Table 3-1: Reported Model Head Calibration Statistics

Parameter	**Red Hill Wells - 2017/2018**	**Red Hill Wells - 2021/2022**	**Red Hill Wells – Flow Optimi-zation Study**	**Red Hill Wells - All Time Periods**	**Regional Wells - All Time Periods**	**All Basal Wells - All Time Periods**	**Transitional Wells - All Time Periods**	**Downweighted Wells - All Time Periods**	**Confining Unit - All Time Periods**	**All Wells - All Time Periods**
Residual Mean (ft)	0.03	-0.11	-0.17	-0.12	-0.09	-0.11	0.16	1.11	41.49	1.48
Absolute Residual Mean (ft)	0.13	0.20	0.19	0.19	0.20	0.19	0.24	1.11	41.53	1.73
Residual Standard Deviation (ft)	0.17	0.24	0.20	0.22	0.23	0.22	0.32	0.15	30.54	9.76
Sum of Squared Residuals (ft^2)	18	74	161	253	76	329	148	156	667,870	668,503
RMSE Error (ft)	0.18	0.26	0.26	0.25	0.25	0.25	0.35	1.12	51.48	9.87
Minimum Residual (ft)	-0.79	-0.88	-0.88	-0.88	-2.10	-2.10	-0.46	0.79	-0.65	-2.10
Maximum Residual (ft)	0.28	0.42	0.36	0.42	1.20	1.20	1.07	1.37	90.58	90.58
Number of Observations	592	1077	2357	4040	1271	5311	1175	125	252	6863
Range in Observations	2.14	1.80	1.46	2.64	7.19	7.19	1.71	0.87	97.72	104.53
Scaled Residual Standard Deviation (%)	8.05%	13.29%	13.70%	8.30%	3.16%	3.08%	18.62%	17.00%	31.26%	9.34%
Scaled Absolute Residual Mean (%)	6.29%	11.05%	13.19%	7.04%	2.76%	2.63%	13.89%	127.23%	42.50%	1.66%
Scaled RMSE Error (%)	8.19%	14.56%	17.84%	9.48%	3.41%	3.46%	20.75%	128.35%	52.68%	9.44%
Revised Scaled Residual Mean (%)	1.54%	-5.96%	-11.43%	-4.58%	-1.29%	-1.59%	9.18%	127.23%	42.46%	1.42%
Correlation Coefficient	0.86	0.59	0.55	0.74	0.98	0.96	0.42	0.87	0.57	0.83

Table 3-2: Recalibrated Model Head Calibration Statistics

Parameter	**Red Hill Wells - 2017/2018**	**Red Hill Wells - 2021/2022**	**Red Hill Wells – Flow Optimi-zation Study**	**Red Hill Wells - All Time Periods**	**Regional Wells - All Time Periods**	**All Basal Wells - All Time Periods**	**Transitional Wells - All Time Periods**	**Downweighted Wells - All Time Periods**	**Confining Unit - All Time Periods**	**All Wells - All Time Periods**
Residual Mean (ft)	-0.04	-0.14	-0.17	-0.15	-0.05	-0.12	0.14	1.07	43.62	1.55
Absolute Residual Mean (ft)	0.12	0.22	0.22	0.20	0.16	0.19	0.24	1.07	44.20	1.83
Residual Standard Deviation (ft)	0.16	0.25	0.22	0.23	0.25	0.23	0.34	0.18	32.89	10.35
Sum of Squared Residuals (ft^2)	17	89	186	293	80	373	160	148	751,096	751,778
RMSE Error (ft)	0.17	0.29	0.28	0.27	0.25	0.27	0.37	1.09	54.59	10.47
Minimum Residual (ft)	-0.57	-0.92	-0.93	-0.93	-2.04	-2.04	-0.48	0.70	-1.91	-2.04
Maximum Residual (ft)	0.42	0.51	0.46	0.51	1.21	1.21	1.14	1.40	91.51	91.51
Number of Observations	592	1077	2357	4040	1271	5311	1175	125	252	6863
Range in Observations	2.14	1.80	1.46	2.64	7.19	7.19	1.71	0.87	97.72	104.53
Scaled Residual Standard Deviation (%)	7.65%	13.95%	15.05%	8.59%	3.43%	3.27%	20.08%	20.23%	33.66%	9.90%
Scaled Absolute Residual Mean (%)	5.62%	12.10%	14.87%	7.69%	2.17%	2.67%	13.79%	123.42%	45.24%	1.75%
Scaled RMSE Error (%)	7.84%	16.03%	19.22%	10.20%	3.50%	3.69%	21.61%	125.05%	55.87%	10.01%
Scaled Residual Mean (%)	-1.72%	-7.92%	-11.96%	-5.50%	-0.71%	-1.71%	8.02%	123.42%	44.64%	1.48%
Correlation Coefficient	0.82	0.54	0.49	0.72	0.98	0.95	0.44	0.82	-0.056	0.61

Table 3-3: Reported and Recalibrated Parameter Values

Parameter	Reported	Recalibrated	Unit
Weathering Depth	736	1,126	ft
Weathering Factor	6,624	2,236	—
Basalt Longitudinal Hydraulic Conductivity	18,546	17,994	ft/d
Basalt Horizontal Anisotropy Ratio	13.8	15.3	—
Basalt Vertical Anisotropy Ratio	50.0	50.0	—
Basalt Specific Yield	7.4	6.7	%

ft/d feet per day

Impacts were primarily noted in the water budget where southeast boundary inflows were reduced from 26.7 mgd to 11.4 mgd but were still larger than the target of 2.0−4.9 mgd. A summary of the average water budget across all stress periods is presented on Chart 3-2. The final 11.4 mgd inflow from the southeast GHB from the recalibrated model is comparable to previous model versions where the GHB misassignment issue was not present. These results indicate that the GHB misassignment issue was only partially responsible for southeast GHB inflows exceeding conceptual estimates, while other conceptual or structural discrepancies account for the remainder of the difference. The flux targets and water budget estimates, with the exception of spring flow rates, are conceptual and not values that can be directly measured. The values obtained from those estimates are intended to provide general guidance to the overall model water budget and are not considered fixed accurate targets. It is possible that conceptual estimates are oversimplified and not as accurate at the calibrated model values.

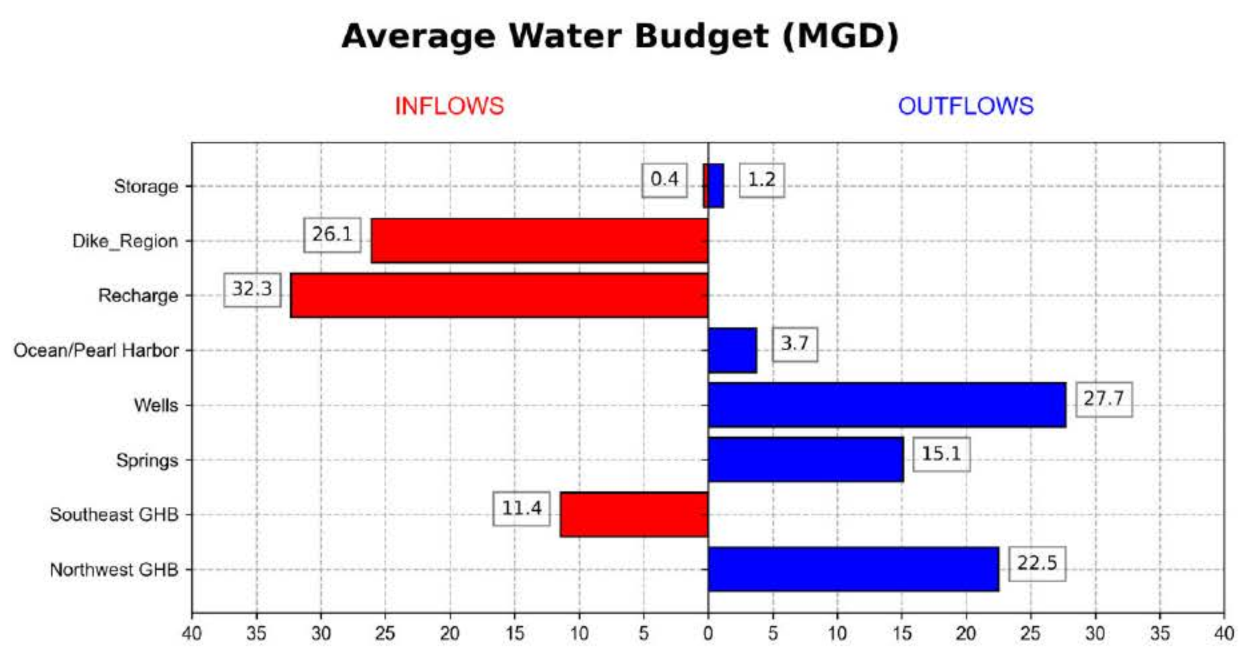

Chart 3-2: Average Water Budget for Recalibrated Model

Impacts on the forward particle tracking results were evaluated by comparing the reported and corrected base models (with homogeneous anisotropic basalt properties) by tracking 64 particles originating at the water table surface in a grid distributed evenly over the tank farm. Table 3-4 presents the differences between the percentage of capture at various boundaries or pumping wells, as well as the differences in travel times to each respective destination. Percentage of particles captured did not change under any pumping condition except for the scenario of RHS and Navy ʻAiea Hālawa Shaft (NAHS) off and Hālawa Shaft on, when the percentage of particles captured changed by a maximum of 1.6%. Particle travel times also varied minimally when comparing the average, minimum, maximum and median of all particles, with a maximum change in travel time of 15.8 days.

Table 3-4: Comparison of Reported and Recalibrated Particle Tracking Results

	Difference in Percent Capture [a]					Difference in Travel Time from Tank Farm to RHS (days) [b]			
Scenario	**RHS**	**Springs**	**Pearl Harbor**	**Northwest GHB**	**Stagnant**	**Average**	**Min**	**Max**	**Median**
RHS – [redacted] mgd Hālawa Shaft, NAHS off	0.0%	—	—	—	—	-15.1	0.0	-3.3	-0.3
RHS – [redacted] mgd Hālawa Shaft, NAHS off	0.0%	—	—	—	—	-0.1	0.0	0.7	0.0
RHS [redacted] mgd Hālawa Shaft – [redacted] mgd NAHS – [redacted] mgd	0.0%	—	—	—	—	0.0	0.0	2.5	0.1
RHS, NAHS off Hālawa Shaft – [redacted] mgd	0.0%	-1.5%	-1.6%	1.5%	1.6%	1.2	-1.3	15.8	2.3
RHS, Hālawa Shaft, NAHS off	0.0%	0.0%	0.0%	0.0%	—	0.1	-0.3	8.1	-0.6

Notes:
— indicates that no particles were captured by the boundary.
[a] Percent Capture: Difference in percent captured is calculated as (original percent capture) – (recalibrated percent capture). Negative values indicate more particles captured when recalibrated. Positive values indicate fewer particles captured when recalibrated.
[b] Travel time: Difference in travel time calculated as (original travel time) – (recalibrated travel time), i.e., positive values indicate shorter travel time.

Impacts to predictive CF&T simulations were evaluated in the same manner as particle tracks, by comparing the reported and recalibrated base models with homogeneous anisotropic basalt properties. The predictive CF&T scenarios under five pumping conditions were compared. Results are presented in Table 3-5. The maximum increase in total petroleum hydrocarbon (TPH) concentration was evaluated for each model cell comparing the original to the corrected version. The largest change was 30 micrograms per liter (µg/L), indicating that the results are not significantly different between the two model versions.

Table 3-5: Comparison of Reported and Recalibrated CF&T Results

Scenario	**Pumping Configuration**	**Maximum TPH Concentration Increase (µg/L)**
1	RHS – [redacted] ; Hālawa Shaft, NAHS off	5.4
	RHS – [redacted]; Hālawa Shaft, NAHS off	2.8
	RHS [redacted]; Hālawa Shaft – [redacted]; NAHS – [redacted]	2.6
	RHS, NAHS off; Hālawa Shaft – [redacted]	6.7
	RHS, Hālawa Shaft, NAHS off	8.5
2	RHS – [redacted]; Hālawa Shaft, NAHS off	19.2
	RHS – [redacted]; Hālawa Shaft, NAHS off	9.9
	RHS [redacted]; Hālawa Shaft – [redacted]; NAHS – [redacted]	9.1
	RHS, NAHS off; Hālawa Shaft – [redacted]	23.7
	RHS, Hālawa Shaft, NAHS off	30.4

The comparisons discussed in this section demonstrate that the impacts of the GHB misassignment are most observable in the water budget. No significant changes were noted comparing model calibration statistics between models with and without the GHB issue. Furthermore, recalibration of the model brought the simulated water budget in closer alignment to the conceptual estimates with respect to the southeast GHB, while no significant differences were noted in model calibration, particle tracking, or predictive CF&T simulation results.

3.4 Solution

The problem has been resolved by correctly assigning node 188,806 to GHB reach 1, which rectifies issues pertaining to both model calibration and reporting of results.

The difference between the estimated and simulated southeast boundary inflow is lessened but not completely eliminated by the resultant reduction of the inflow from (b) (3) (A) [redacted], compared to the conceptual estimate of (b) (3) (A) [redacted]. Note that this difference between the model setup and conceptual estimates is not an error because the conceptual estimates are not field-measured values that must be matched, but instead represent reasonable bounds on the calibration of the water budget. Some additional flexibility in the water budget may be considered in future model versions, such as allowing increased inflows to be distributed between both the southeast GHB and the dike region boundary, which is currently set as a specified flux and was not subject to calibration. Inflows from these boundaries are estimated based on USGS recharge calculations (Engott et al. 2017). These recharge estimates in the dike region, where the majority of the water originates, predict recharge to be between 30% and 50% of rainfall. It is unlikely that the percentage of rainfall that enters the water table as recharge is significantly greater than this, but variations in the range of 10%−20% are reasonable. Further consideration will be given to both the conceptual water budget as well as the methods used to match the estimates in the model calibration process.

4.0 Variogram Generation

4.1 Summary of Comment

The November 1, 2024 email from EPA to the Navy noted a discrepancy in the variogram parameters that were found in the SISIM input files as compared to the stated values in the report text. As EPA indicated, the difference is small: the SISIM input file indicates correlation lengths of 8,000, 2,000, and 12 ft in the dip, strike, and vertical directions, respectively; the report indicates correlation lengths of 8,000, 1,000, and 10 ft in the respective dip, strike, and vertical directions.

4.2 Cause of Issue

This discrepancy has been reviewed, and it was confirmed that the SISIM input file values are correct and the report values had not been updated from values used during an earlier stage of work.

4.3 Implications for Model Results

There are no impacts on model results in the report, which relies upon the correct values.

4.4 Solution

The correct values for correlation lengths are 8,000, 2,000, and 12 ft in the dip, strike, and vertical directions, respectively, consistent with the SISIM input file.

5.0 Use of Geologic Data

5.1 Summary of Comment

EPA's November 1, 2024 email to the Navy asked for clarification regarding how the barrel log data were used for the heterogeneity evaluation and generation.

5.2 Clarification

As described in Section 3.1.5 of the Groundwater Model Report (DON 2024), various sets of data with information on heterogeneity at a certain scale and direction were used to generate variograms:

- Boring log data were used to describe vertical correlation distances because those data are the most reliable and detailed indicator of vertical correlation over the vertical scales of interest, with the highest available resolution of the various data sets.
- Boring logs were also used to condition the SISIM simulations, to ensure that the simulated heterogeneity realizations honor the boring information in those particular locations that have detailed geological logs.

The MrLavaLoba simulations were used to calculate horizontal correlations over regional horizontal scales. Note, however, that there are limitations in the barrel log data. For example, it is not clear what scale of precision is implied, and some material was simply labeled as "rock." For these and other reasons MrLavaLoba results were not used for vertical correlations.

- Variograms at intermediate and shorter horizontal scales were generated from both barrel log data and boring log data. The boring log data were emphasized for correlation length scales comparable to boring spacing, and barrel log data were used to adjust or supplement the boring log data at shorter spatial scales.
- Because the barrel logs depict locations in the vadose zone well above the aquifer, they were not used to condition the SISIM simulations, which were used to generate structure-imitating basalt heterogeneity realizations in the saturated zone.

All these variograms were integrated into an overall 3D variogram applicable to saturated basalt at all simulated spatial scales. The individual variograms can be provided upon request, and the authors are available to describe how they were integrated.

6.0 Heterogeneity Artifacts from Converting SISIM to MODFLOW

6.1 Summary of Comment

EPA noted that portions of the SISIM output matrix contained anomalous values ("-99") and asked for clarification regarding the origin and treatment of these anomalous values.

6.2 Cause of Issue

SISIM was used to generate 50 high-resolution structure-imitating realizations of basalt heterogeneity. SISIM generated matrices of categorical indicators in a three-dimensional, uniform rectangular grid, where each indicator represents low-permeability massive basalt ("0") or high-permeability clinker ("1"). Each matrix spans a 240 × 250 × 520 cell subdomain containing a total of 31,200,000 cells with the dimensions of 25 × 25 × 2.5 ft. Each realization was then scaled up (reduced in resolution) and used in MODFLOW to evaluate the potential effects of basalt heterogeneity on groundwater flow.

SISIM was originally designed to process much smaller matrices than 30 million cells. The anomalous "-99" values represent a limitation of the SISIM code, akin to an out-of-memory or array dimension exceedance issue. After detecting these values in the matrix, attempts were made to re-compile the SISIM code to accommodate the large grid to be generated, which was only partially successful: portions of each SISIM matrix continued to be assigned -99 values. Analysis was performed to confirm that the generated values other than "-99" were valid. Upon inspection of the positions of the "-99" values, it became clear that the heterogenous features were still being successfully resolved by the cells with values other than "-99", because the anomalous "-99" values tended to be flanked by non-"-99" values in the matrix. Consequently, a post-processing routine was implemented in MATLAB that replaced all -99 values with linearly interpolated values based on the values of neighboring cells. Because the cell dimensions are much smaller than the correlation lengths of the heterogenous features, the resulting interpolation is robust with little or no loss of predominant heterogeneity features.

Upon additional review, it became apparent that the MATLAB routine successfully post-processed the SISIM matrix in all areas of the subdomain except for the last column of the matrix, corresponding to the southwest-most column of the nested grid. Because this column is at the edge of the SISIM grid and no simulated values were generated on the "out-of-grid" side of the column, MATLAB was unable to perform this calculation, which resulted in an error in the "-99" replacement computations. In this one column, such replaced values created an unusual pattern, one that also resulted in a similar scaled-up pattern in the MODFLOW hydraulic conductivity assignments at this location.

6.3 Implications for Model Results

The impact on the reported model results were tested by using a temporary solution whereby the impacted southwestern column of the nested grid, where the "-99" artifacts were present, was replaced with the hydraulic properties of the homogeneous basalt. Calibration statistics and particle tracking results were compared for two realizations: 1 and 10. The corrected models also included the GHB corrections discussed in Section 3.0. Table 6-1 and Table 6-2 present head calibration statistics for the reported and corrected Realization 1 models. Table 6-3 and Table 6-4 present head calibration statistics for the reported and corrected Realization 10 models.

Table 6-1: Reported Model Head Calibration Statistics for Realization 1, Prior to Heterogeneity Issue Correction

Parameter	Red Hill Wells - 2017/2018	Red Hill Wells - 2021/2022	Red Hill Wells – Flow Optimi-zation Study	Red Hill Wells - All Time Periods	Regional Wells - All Time Periods	All Basal Wells - All Time Periods	Transitional Wells - All Time Periods	Downweighted Wells - All Time Periods	Confining Unit - All Time Periods	All Wells - All Time Periods
Residual Mean (ft)	0.01	-0.13	-0.19	-0.15	-0.06	-0.13	0.19	1.16	41.52	1.48
Absolute Residual Mean (ft)	0.13	0.22	0.22	0.20	0.19	0.20	0.23	1.16	41.58	1.74
Residual Standard Deviation (ft)	0.19	0.25	0.21	0.23	0.29	0.25	0.28	0.13	30.58	9.77
Sum of Squared Residuals (ft2)	21	87	192	300	109	409	130	169	669,210	669,919
RMSE Error (ft)	0.19	0.28	0.29	0.27	0.29	0.28	0.33	1.16	51.53	9.88
Minimum Residual (ft)	-0.82	-0.93	-0.93	-0.93	-2.14	-2.14	-0.51	0.89	-0.67	-2.14
Maximum Residual (ft)	0.50	0.39	0.28	0.50	0.51	0.51	1.05	1.44	90.60	90.60
Number of Observations	592	1077	2357	4040	1271	5311	1175	125	252	6863
Range in Observations	2.14	1.80	1.46	2.64	7.19	7.19	1.71	0.87	97.72	104.53
Scaled Residual Standard Deviation (%)	8.70%	14.06%	14.29%	8.72%	3.99%	3.45%	16.17%	14.74%	31.29%	9.35%
Scaled Absolute Residual Mean (%)	6.23%	12.05%	14.83%	7.75%	2.65%	2.80%	13.68%	132.85%	42.55%	1.67%
Scaled RMSE Error (%)	8.71%	15.87%	19.49%	10.33%	4.07%	3.86%	19.48%	133.65%	52.74%	9.45%
Scaled Residual Mean (%)	0.62%	-7.36%	-13.25%	-5.53%	-0.83%	-1.74%	10.87%	132.85%	42.50%	1.42%
Correlation Coefficient	0.78	0.53	0.51	0.71	0.97	0.95	0.59	0.88	0.56	0.82

Table 6-2: Model Head Calibration Statistics for Realization 1 with Heterogeneity Issue Corrected

Parameter	Red Hill Wells - 2017/2018	Red Hill Wells - 2021/2022	Red Hill Wells – Flow Optimi-zation Study	Red Hill Wells - All Time Periods	Regional Wells - All Time Periods	All Basal Wells - All Time Periods	Transitional Wells - All Time Periods	Downweighted Wells - All Time Periods	Confining Unit - All Time Periods	All Wells - All Time Periods
Residual Mean (ft)	0.05	-0.10	-0.16	-0.11	-0.09	-0.11	0.20	1.20	41.55	1.50
Absolute Residual Mean (ft)	0.15	0.21	0.20	0.19	0.20	0.19	0.24	1.20	41.59	1.74
Residual Standard Deviation (ft)	0.19	0.25	0.21	0.23	0.26	0.24	0.28	0.13	30.57	9.77
Sum of Squared Residuals (ft2)	22	80	165	268	95	363	143	182	669,594	670,281
RMSE Error (ft)	0.19	0.27	0.26	0.26	0.27	0.26	0.35	1.21	51.55	9.88
Minimum Residual (ft)	-0.78	-0.90	-0.89	-0.90	-2.10	-2.10	-0.46	0.94	-0.65	-2.10
Maximum Residual (ft)	0.50	0.41	0.33	0.50	0.70	0.70	1.08	1.49	90.63	90.63
Number of Observations	592	1077	2357	4040	1271	5311	1175	125	252	6863
Range in Observations	2.14	1.80	1.46	2.64	7.19	7.19	1.71	0.87	97.72	104.53
Scaled Residual Standard Deviation (%)	8.76%	14.13%	14.21%	8.73%	3.59%	3.31%	16.57%	14.83%	31.29%	9.35%
Scaled Absolute Residual Mean (%)	6.96%	11.59%	13.41%	7.29%	2.81%	2.71%	14.04%	137.64%	42.57%	1.67%
Scaled RMSE Error (%)	9.02%	15.20%	18.07%	9.75%	3.81%	3.64%	20.38%	138.43%	52.75%	9.45%
Scaled Residual Mean (%)	2.20%	-5.61%	-11.17%	-4.35%	-1.27%	-1.52%	11.88%	137.64%	42.52%	1.43%
Correlation Coefficient	0.77	0.52	0.51	0.71	0.98	0.95	0.56	0.88	0.56	0.82

Table 6-3: Reported Model Calibration Statistics for Realization 10, Prior to Heterogeneity Issue Correction

Parameter	Red Hill Wells - 2017/2018	Red Hill Wells - 2021/2022	Red Hill Wells – Flow Optimi-zation Study	Red Hill Wells - All Time Periods	Regional Wells - All Time Periods	All Basal Wells - All Time Periods	Transitional Wells - All Time Periods	Downweighted Wells - All Time Periods	Confining Unit - All Time Periods	All Wells - All Time Periods
Residual Mean (ft)	0.01	-0.11	-0.18	-0.14	-0.00	-0.10	0.15	1.07	41.53	1.49
Absolute Residual Mean (ft)	0.15	0.20	0.21	0.20	0.17	0.19	0.22	1.07	41.58	1.73
Residual Standard Deviation (ft)	0.21	0.25	0.22	0.24	0.25	0.25	0.28	0.14	30.56	9.77
Sum of Squared Residuals (ft2)	27	82	190	300	78	378	119	147	668,9657	669,609
RMSE Error (ft)	0.22	0.28	0.28	0.27	0.25	0.27	0.32	1.08	51.52	9.88
Minimum Residual (ft)	-1.16	-0.92	-0.92	-1.16	-1.97	-1.97	-0.68	0.78	-0.66	-1.97
Maximum Residual (ft)	0.26	0.41	0.31	0.41	2.33	2.33	0.99	1.31	90.60	90.60
Number of Observations	592	1077	2357	4040	1271	5311	1175	125	252	6863
Range in Observations	2.14	1.80	1.46	2.64	7.19	7.19	1.71	0.87	97.72	104.53
Scaled Residual Standard Deviation (%)	10.06%	13.99%	14.80%	8.96%	3.45%	3.42%	16.51%	16.03%	31.27%	9.34%
Scaled Absolute Residual Mean (%)	7.25%	11.36%	14.14%	7.52%	2.40%	2.67%	13.05%	123.39%	42.55%	1.66%
Scaled RMSE Error (%)	10.07%	15.35%	19.42%	10.33%	3.45%	3.71%	18.65%	124.42%	52.73%	9.45%
Scaled Residual Mean (%)	0.56%	-6.34%	-12.57%	-5.13%	-0.04%	-1.44%	8.68%	123.39%	42.50%	1.42%
Correlation Coefficient	0.73	0.53	0.44	0.69	0.98	0.95	0.57	0.88	0.56	0.82

Table 6-4: Model Head Calibration Statistics for Realization 10 with Heterogeneity Issue Corrected

Parameter	Red Hill Wells - 2017/2018	Red Hill Wells - 2021/2022	Red Hill Wells – Flow Optimi-zation Study	Red Hill Wells - All Time Periods	Regional Wells - All Time Periods	All Basal Wells - All Time Periods	Transitional Wells - All Time Periods	Downweighted Wells - All Time Periods	Confining Unit - All Time Periods	All Wells - All Time Periods
Residual Mean (ft)	0.04	-0.09	-0.16	-0.11	-0.01	-0.09	0.18	1.09	41.54	1.51
Absolute Residual Mean (ft)	0.17	0.20	0.19	0.19	0.18	0.19	0.23	1.09	41.59	1.73
Residual Standard Deviation (ft)	0.22	0.25	0.22	0.24	0.26	0.25	0.29	0.14	30.55	9.76
Sum of Squared Residuals (ft2)	29	78	169	278	87	365	136	151	669,097	669,748
RMSE Error (ft)	0.22	0.27	0.27	0.26	0.26	0.26	0.34	1.10	51.53	9.88
Minimum Residual (ft)	-1.13	-0.90	-0.90	-1.13	-1.98	-1.98	-0.64	0.79	-0.64	-1.98
Maximum Residual (ft)	0.31	0.46	0.36	0.46	2.46	2.46	1.04	1.33	90.61	90.61
Number of Observations	592	1077	2357	4040	1271	5311	1175	125	252	6863
Range in Observations	2.14	1.80	1.46	2.64	7.19	7.19	1.71	0.87	97.72	104.53
Scaled Residual Standard Deviation (%)	10.22%	14.20%	14.82%	9.05%	3.65%	3.45%	17.00%	16.21%	31.26%	9.34%
Scaled Absolute Residual Mean (%)	8.15%	11.12%	12.94%	7.20%	2.53%	2.62%	13.53%	125.13%	42.56%	1.66%
Scaled RMSE Error (%)	10.42%	15.02%	18.31%	9.93%	3.65%	3.65%	19.87%	126.17%	52.73%	9.45%
Scaled Residual Mean (%)	2.07%	-4.91%	-10.76%	-4.10%	-0.18%	-1.19%	10.31%	125.13%	42.51%	1.44%
Correlation Coefficient	0.71	0.51	0.44	0.68	0.98	0.95	0.53	0.88	0.56	0.82

Minor differences are apparent between the reported and corrected models: for example, the maximum RMSE change among groups of basal aquifer wells was 0.02 ft. Other statistical measures are similarly minor and insignificant in terms of model calibration.

To assess the effect of the “-99” interpolation issue on particle tracking, all realizations were run through the five pumping well configurations with the erroneous row of values replaced with the values for homogeneous basalt. The corrected models also included the GHB corrections discussed in Section 3.0. The difference in percentage of particles arriving at each boundary condition as an average across all realizations were compared to the reported model (reported minus corrected), as presented in Table 6-5. The results indicate that the differences between the original and corrected model are not significant, particularly with respect to capture at RHS and Hālawa Shaft. The three pumping configurations with RHS pumping all showed an increase in percent capture in the corrected models, but the maximum difference was 4.4% under the scenario with RHS pumping at [redacted]. The largest differences in percent capture among other models were related to discharge at the northwest GHB and springs, with the corrected models generally demonstrating fewer particles exiting the northwest GHB and a corresponding increase in particles exiting from the springs. Overall, the results in Table 6-5 indicate that the corrected models demonstrated flow paths directed slightly more down-ridge compared to the reported model.

Table 6-5: Comparison of Reported and Corrected Particle Tracking Results

Scenario	Difference in Average Percent Capture [a]						
	RHS	**Northwest GHB**	**Stagnant**	**Pearl Harbor**	**Springs**	**Hālawa Shaft**	**Other Wells**
RHS – [redacted]mgd Hālawa Shaft, NAHS off	4.40%	-1.80%	-1.90%	-0.70%	—	—	—
RHS – [redacted]mgd Hālawa Shaft, NAHS off	1.40%	—	-1.40%	—	—	—	—
RHS [redacted]mgd Hālawa Shaft – [redacted]mgd NAHS – [redacted]mgd	1.20%	—	-1.20%	—	—	—	—
RHS, NAHS off Hālawa Shaft – [redacted]mgd	-1.50%	-19.30%	0.20%	-5.60%	25.60%	0.00%	0.60%
RHS, Hālawa Shaft, NAHS off	-1.90%	-13.20%	-0.40%	6.70%	8.80%	—	—

Notes:
— indicates that no particles were captured by the boundary.
[a] Percent Capture: Difference in percent captured is calculated as (original percent capture) – (recalibrated percent capture). Negative values indicate more particles captured when recalibrated. Positive values indicate fewer particles captured when recalibrated.

To visualize the impacts on particle tracking results, particle tracks are presented for two realizations, Realization 1 and Realization 10, under the pumping configuration where RHS, Hālawa Shaft, and NAHS were all off. This scenario is where the most particles traverse the column of the model grid where the erroneous values were assigned. Results are presented on Figure 6-1 for Realization 1 and Figure 6-2 for Realization 10. Corrected particle tracks are plotted in red on top of the previously reported particle tracks in blue. Local differences are apparent in the figures; however, as discussed previously, these differences do not result in significant differences to final particle destinations, and generally the corrected models result in more down-ridge flow paths.

6.4 Solution

For future modeling efforts, the MATLAB code has been modified to calculate the replacement values for the cells in the last column using the simulated values of the closest neighboring cells only on the "in-grid" side of the column.

7.0 Other Topics to Be Addressed in Future Model Versions

7.1 Effect of Model's Impermeable Bottom Boundary

During the November 13, 2024 Red Hill Subject Matter Expert Quarterly Meeting, a comment was made regarding the high basalt hydraulic conductivity values relative to values used in other models. It was questioned whether the impermeable model bottom boundary could be affecting the model calibration. This could occur, for example, if the drawdown cones of the pumping wells, particularly RHS and Hālawa Shaft, extend to the model bottom boundary, reflecting off of the no-flow boundary and exaggerating drawdown. The calibration process would then require higher hydraulic conductivity values to match the observed drawdown data. In future model versions, the impacts of the impermeable boundary will be evaluated by adding layers to the bottom of the model and checking whether drawdown propagates to greater depths.

The model calibration process incorporated information from an evaluation of drawdown data at RHS collected during the flow optimization study. Estimates of hydraulic conductivity in the longitudinal direction ranged from approximately 6,000 ft/d to 22,600 ft/d. These calculations require many assumptions and are inversely proportional to accompanying estimates of horizontal anisotropy while further affected by the assumption of the contributing aquifer thickness. The average of these estimates, 12,878 ft/d, was used as a preferred value for regularization with the PEST software. Regularization refers to adding prior "soft" information to the calibration process which helps guide calibration and reduce non-uniqueness of the calibrated model. Further analysis of the drawdown data will be conducted to refine prior hydraulic conductivity estimates while additional weighting can be placed on those estimates for regularization, if appropriate. Additionally, sensitivity analysis was used to evaluate parameter changes on the model results, imposing varying constraints, such as fixing the longitudinal hydraulic conductivity at 4,500 ft/d, the value used by Oki (2005) in a different model with a different domain. Generally, fixing the conductivity at that alternate value resulted in poorer match to the calibration data set for this site. This process of evaluating various potential parameter ranges will continue to be used to account for the irreducible uncertainty and non-uniqueness of the results that are present in any modeling effort; evaluation of the impacts of assumptions will continue to be conducted to better understand the model results.

7.2 Potential Use of Markov-Bayes Method

The October 9, 2024 email from EPA to the Navy commented that SISIM includes a Markov-Bayes option for coding soft data for inclusion in the simulations. EPA noted that there can be challenges using this method with large data sets and non-linear relationships, but it has the potential to produce heterogenous features with a greater degree of continuity. EPA asked if this approach was attempted with the MrLavaLoba results or with the barrel log data. To date, this SISIM option has not been used, but its utility will be explored in future modeling work.

However, it is noted that the barrel log data depict locations in the vadose zone and therefore lie outside the aquifer heterogeneity simulation grid. Because of this, conditioning on such data would have minimal influence on heterogeneity simulation within the current saturated-zone model grid. In addition, while MrLavaLoba simulation provides information to characterize the horizontal correlation structure of heterogeneity, conditioning on such information might not be appropriate since other processes that affect land surface topography over time (e.g., weathering between lava flows) are not included in the MrLavaLoba simulations.

7.3 Model Recalibration Using Biodegradation

During the November 13, 2024 Red Hill Subject Matter Expert Quarterly Meeting, questions were raised regarding not modeling biodegradation, particularly during CF&T calibration. Degradation was excluded, while porosity and dispersivity were calibrated parameters. Degradation of dissolved TPH in the aqueous phase was excluded for several reasons, most importantly because the dissolved TPH-diesel range organic data reported by the laboratories include the undifferentiated sum of petroleum and polar breakdown products. Degradation beyond the laboratory-measured TPH ranges is not confirmed to have occurred to a significant degree during the 5-month period of the history-matching process following the May 2021 release; if this were the case, the choice of dispersivity values might partially compensate for degradation, potentially resulting in a somewhat less conservative model. In future modeling work, further forensic analysis will be performed on TPH data to supplement or improve data sets used for model calibration. Ideally, conservative tracer test results would be used to calibrate aquifer specific properties, such as porosity and dispersivity, prior to simulation of TPH, which would then allow calibration of TPH specific parameters such as degradation to be conducted independently of potentially correlated flow and transport parameters. Sensitivity analysis may also be used to understand potential impacts of degradation.

8.0 References

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Oki, D. S. 2005. *Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii*. Scientific Investigations Report 2005-5253. U.S. Geological Survey.

Figure 2-1: Excerpt from EPA Comments on Flux Targets

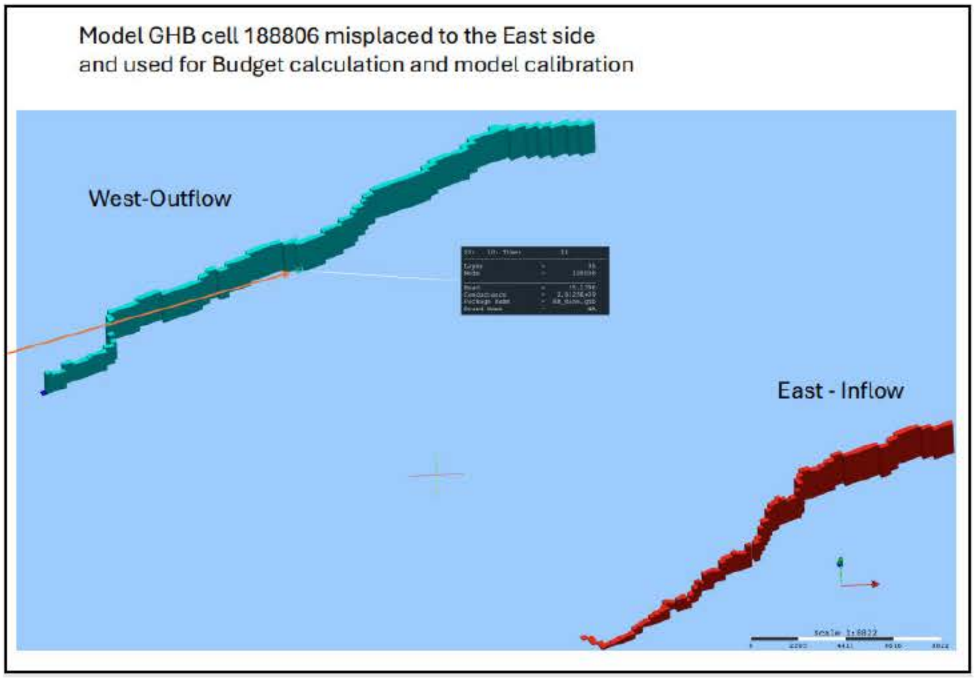

Figure 3-1: Excerpt from EPA Comments on GHB Assignment

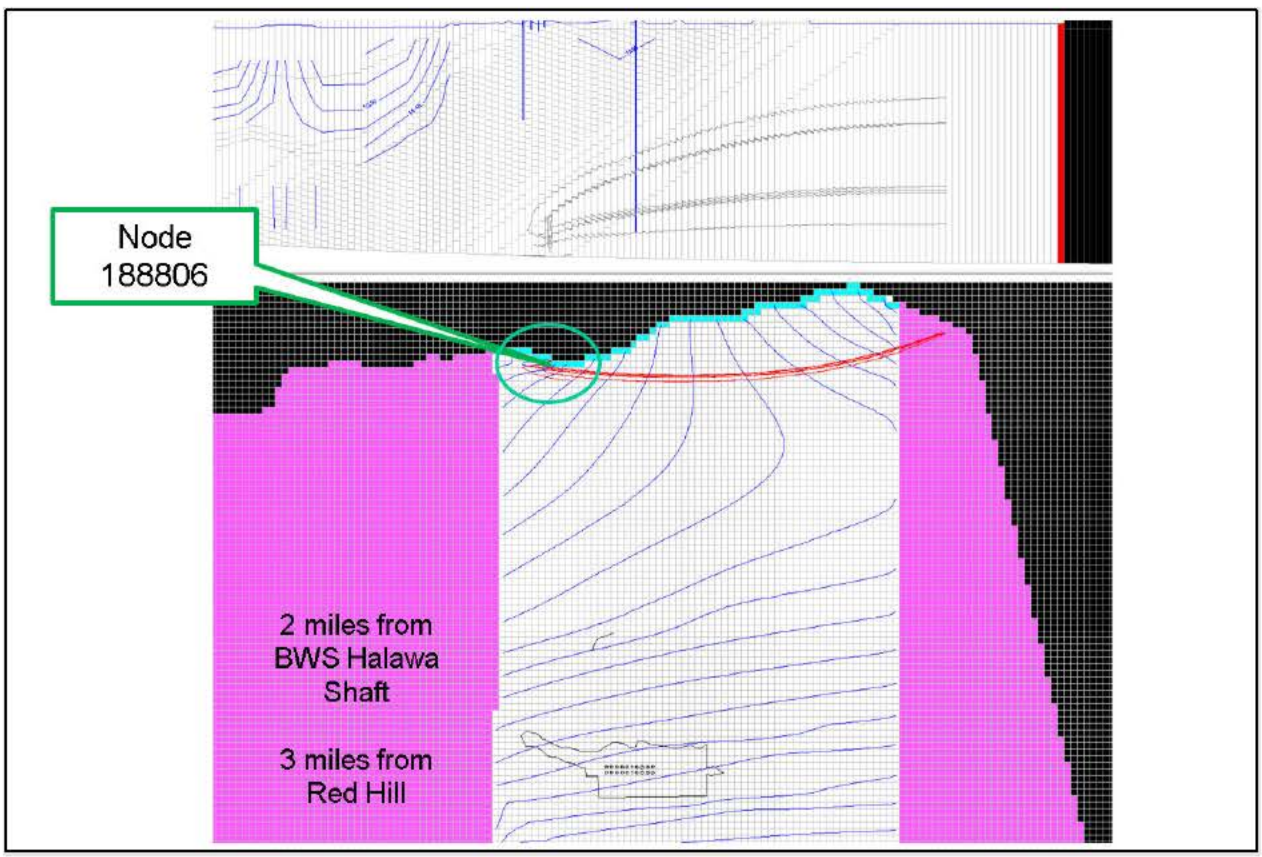

Figure 3-2: Reverse Particle Tracking Results from Node 188,806 (Layer 35 in Plan View)

Figure 6-1: Forward Particle Tracking from Tank Farm - Realization #1 - Red Hill Shaft Off, Hālawa Shaft Off, Navy 'Aiea Hālawa Shaft Pumping Off

Figure 6-2: Forward Particle Tracking from Tank Farm - Realization #10 - Red Hill Shaft Off, Hālawa Shaft Off, Navy 'Aiea Hālawa Shaft Pumping Off