Groundwater Flow Model Report, Red Hill Bulk Fuel Storage Facility

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

Administrative Order on Consent in the Matter of Red Hill Bulk Fuel Storage Facility, EPA Docket Number RCRA 7003-R9-2015-01 and DOH Docket Number 15-UST-EA-01, Attachment A, Statement of Work Section 6.2, Section 7.1.2, Section 7.2.2, and Section 7.3.2

March 25, 2020
Revision 00

NAVFAC
Naval Facilities Engineering Command
NAVFAC HAWAII

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

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March 25, 2020
Revision 00

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

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EXECUTIVE SUMMARY

The March 2020 groundwater flow modeling effort was developed to evaluate the flow of groundwater from beneath the Red Hill Storage Facility (the Facility) and compute the source water zones of water supply wells Red Hill Shaft and Hālawa Shaft under various pumping conditions. This effort has been conducted in support of the Investigation and Remediation of Petroleum Product Releases and Groundwater Protection and Evaluation project at the Red Hill Bulk Fuel Storage Facility ("Facility"), Joint Base Pearl Harbor-Hickam (JBPHH), Hawaiʻi. The Facility is owned by the United States (U.S.) Navy (DON; "Navy") and operated by Defense Logistics Agency (DLA).

This report has been prepared to address Statement of Work Section 7.1 of the *Administrative Order on Consent* (AOC) *In the Matter of Red Hill Bulk Fuel Storage Facility* (EPA Docket No: RCRA 7003-R9-2015-01; DOH Docket No: 15-UST-EA-01) (EPA Region 9 and DOH 2015). The AOC was issued by the U.S. Environmental Protection Agency (EPA) Region 9 and State of Hawaiʻi Department of Health (DOH) (EPA Region 9 and DOH 2015) to the Navy/DLA in response to a release of an estimated 27,000 gallons of Jet Fuel Propellant (JP)-8 from one of the Facility's underground fuel storage tanks (Tank 5) that was confirmed and reported to DOH on January 23, 2014. The tanks are located above a major groundwater aquifer, which is used to feed both Navy and City and County of Honolulu drinking water supply wells and shafts.

Following Regulatory Agency approval of this flow model report, the models will be further developed and used to evaluate fate and transport of potential dissolved fuel components in groundwater to help ascertain potential risk to water supply wells as a result of a potential range of releases from the Facility under a range of reasonably conservative pumping conditions within the model domain, and to assist with management decisions related to monitoring and to infrastructure improvements to address potential future fuel releases.

The model domain extends in the northwest to southeast direction from Waimalu Valley to Kalihi Valley, and in the southwest to northeast direction from the ocean and Pearl Harbor, up to but not including a dike-intruded area in the Koʻolau mountains just south of the topographic divide. The model extends vertically from the land surface down to the freshwater/saltwater interface.

The basalt aquifer in the study area behaves as a homogeneous system on a regional scale, with high hydraulic conductivities. Horizontal anisotropy is also high in the direction of lava flow. The basalt is unconfined underneath most of the Facility but is overlain by saprolite and valley fill underneath the valleys, and by a caprock unit farther to the coast. The caprock is composed of alluvial sediments and marine deposits with interspersed Honolulu Volcanic tuff.

Groundwater flow occurs from recharge areas in the mountains to discharge areas in Pearl Harbor and the ocean. Due to the high hydraulic conductivity of basalt, the water table underneath the Facility is flat with very small gradients. Higher water levels due to mounding or perched conditions may be noted in the saprolite and valley fill. Freshwater is confined within the basalt underneath the caprock as it flows toward the sea. Outflow occurs due to pumping, flow to springs, and as diffuse discharge through the caprock into Pearl Harbor and the ocean.

Groundwater flow models described in this report were constructed using all available pertinent regional and local data over the Facility obtained from literature, continued field investigations, and previous modeling studies as described in the Red Hill *Conceptual Site Model* (CSM) report (DON 2019). Water levels from the synoptic study conducted in 2017–2018 were used in model calibration and verification, as those data are considered the most accurate information available (especially related to controlled pumping events). The information was processed using a transfer function-noise (TFN) analysis to remove signatures from barometric pressure and ocean/earth tide fluctuations for water level targets with various pumping conditions at Red Hill Shaft and Hālawa Shaft.

Water level targets establish a base flow condition for the model but do not provide information on flow directions. In an anisotropic system such as in basalt, the flow direction is a function of head gradients as well as anisotropy of the medium. Therefore, water level difference targets were also constructed from these data such that water level gradients can be indirectly established. Also, unit step response functions were derived from TFN processing for pumping at Red Hill Shaft and Hālawa Shaft, which provided hydraulic conductivity information between the observation wells and the respective shaft to establish anisotropy.

The calibrated models were used to evaluate migration of groundwater from beneath the Facility under various regional pumping conditions, as well as to evaluate the source water zones of Red Hill Shaft and Hālawa Shaft, using particle tracking analyses methods.

A multimodel approach was used to evaluate the impact of various conceptual representations, parameter uncertainties, and errors in water level data, especially acute in flat water table environments as exist in the model domain's basalt. With this approach, multiple models were created to assist in evaluating uncertainty and its impact on groundwater migration behavior of interest.

The modeling effort has been conducted with input from various subject matter experts (SMEs). A strong effort was made to address various concerns expressed by SMEs on data and modeling that arose as part of the 2018 interim modeling effort (DON 2018, Appendix A) as well as during ongoing meetings. The models were constructed and used in a conservative manner to err on the side of caution. Simplifications of the CSM in the numerical framework reflect reasonably conservative assumptions considering modeling objectives and available data. Alternate conceptualizations and parameterizations were explored to evaluate the impact of uncertainty and error across a range of conceptualizations to help bound flow condition. Pumping regimes tested for migration behavior were selected to establish conservative capture zones. Low porosity values were used for particle tracking simulations to provide conservative travel times. Migration behavior was analyzed in a steady-state flow field, thus neglecting storage buffering impacts. Subsequent modeling efforts will use these flow models as a basis to evaluate solute transport. These flow models will also be used to further evaluate different scenarios (e.g., pumping rates relative to capture zones).

The models indicated that groundwater from beneath the Facility was captured by Red Hill Shaft when it was pumping at a rate of [redacted] million gallons per day (mgd), which is within its regulatory permitted pumping limits. The models also provided travel time ranges for various scenarios of concern. The shortest travel time (from the Facility tanks closest to Red Hill Shaft) to Red Hill Shaft ranged from 16 to 56 days, whereas the longest travel time (from the Facility tanks farthest from Red Hill Shaft) to Red Hill Shaft ranged from 69 to 228 days.

When Red Hill Shaft is not pumping, groundwater migration underneath the Facility is generally to the west and then turns to the northwest toward Pearl Harbor. There is larger uncertainty of flow direction with distance from the Facility when Red Hill Shaft is not pumping, and the water can be captured by Hālawa Shaft, and/or by other downgradient water supply wells and discharge points. The model also indicated that wells located in Moanalua Valley would not be impacted from a potential future release from Red Hill. When Red Hill Shaft is not pumping, the shortest travel time from the Facility tanks to other receptors ranged from 137 to 883 days, while the longest travel time from the Facility tanks to other receptors ranged from 170 to 1,938 days. These travel times indicate advective flow of water and are not for solute transport, which would also include mechanisms of dispersion, retardation, and decay.

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APPENDIXES (included on CD-ROM)

FIGURES (compiled at end of report)

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ACRONYMS AND ABBREVIATIONS

AOC	Administrative Order on Consent
BWS	Board of Water Supply, City and County of Honolulu
CLN	Connected Linear Network
CSM	conceptual site model
DIS	Discretization
DOH	Department of Health, State of Hawai‘i
EPA	Environmental Protection Agency, United States
FOIA	Freedom of Information Act (5 U.S.C. § 552)
ft	foot or feet
ft/d	feet per day
ft/ft	feet per foot
ft/mi	feet per mile
ft^2	square feet
ft^2/d	square feet per day
GHB	general head boundary
GMS	Groundwater Modeling System
GUI	graphical user interface
ID	identification
JP	Jet Fuel Propellant
K	hydraulic conductivity
K_h	horizontal hydraulic conductivity
K_v	vertical hydraulic conductivity
LNAPL	light nonaqueous-phase liquid
LPF	Layer Property Flow
mgd	million gallons per day
msl	mean sea level
Navy	Department of the Navy, United States
NE	northeast
NW	northwest
PEST	Parameter Estimation software
Q	pumping rate
RMS	root mean square
SE	southeast
Skinrhs	conductance of rock material surrounding Red Hill Shaft
Skinhas	conductance of rock material surrounding Hālawa Shaft
SME	subject matter expert
SMS	Sparse Matrix Solver
SP	Stress Period
SW	southwest
SUTRA	Saturated-Unsaturated Transport
Sy	specific yield
TFN	transfer function-noise
U.S.	United States
USGS	United States Geological Survey

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1. Introduction

1.1 STUDY OBJECTIVES

The Red Hill Bulk Fuel Storage Facility ("Facility") is located along Red Hill ridge between South Hālawa Valley and Moanalua Valley on the island of O'ahu, Hawai'i. The study domain is shown on Figure 1-1 (figures are compiled at the end of this report). The Facility includes 20 steel-lined concrete underground storage tanks located in the unsaturated zone above the water table that store various fuels (e.g., jet, diesel) as described in the Red Hill *Conceptual Site Model* (CSM) report. Previous investigations have indicated evidence of petroleum hydrocarbons in the rock beneath the tanks and in the underlying aquifer, which feeds both Navy and City and County of Honolulu drinking water supply wells and shafts. A release of approximately 27,000 gallons of Jet Fuel Propellant (JP)-8 from Tank 5 was reported in January 2014.

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

Several completed and ongoing environmental investigations have been conducted and continue to be conducted to fulfill the requirements of Sections 6 and 7 of the AOC Statement of Work. An interim groundwater flow model was developed and published in July 2018 (DON 2018, Appendix A) to evaluate the hydrogeologic behavior and explore the impact of multiple parameterizations and conceptualizations on migration of groundwater from the water table beneath the Facility. The interim model helped to facilitate development of the March 2020 groundwater flow model as required by Section 7.1.2 of the AOC Statement of Work. As part of the ongoing flow modeling effort, the Navy is using a multimodel approach. Key conceptual aspects pertaining to various hydrogeologic factors (e.g., tuff cone extent, saprolite/valley fill, permeabilities) were incorporated into various models so that those features could be evaluated relative to potential flow conditions. Also, various conceptual representations of flows and water level gradients were modeled to note hydrogeologic factors necessary to achieve those conditions. While no model is right or wrong, those with a reasonable conceptualization, parameter values, and calibration/verification can be used to help address risk-management questions.

This March 2020 *Groundwater Flow Model Report* will be used to evaluate capture zones of the various water supply wells and to develop associated contaminant fate and transport models (as required by Section 7.2.2 of the AOC Statement of Work) that can help ascertain potential risk to water supply wells and the environment as a result of a potential range of releases from the Facility under a range of reasonable pumping conditions at critical water supply wells or shafts in the vicinity. The objective of this study is to develop the March 2020 groundwater flow model report as per the AOC Statement of Work. This report provides the current status of models and evaluations of capture and advective flow of groundwater from the Facility. The models will be used for the subsequent contaminant fate and transport modeling effort to assist with management decisions related to monitoring and potential remedial actions. They will also be used to evaluate the impact of different pumping scenarios on groundwater flow from the Facility.

1.2 STUDY AREA AND BACKGROUND

The areal extent of the study domain is approximately 9 miles by 6 miles, as shown on Figure 1-1. In the northwest (NW) to southeast (SE) direction, the domain extends from Waimalu Valley to Kalihi Valley. In the southwest (SW) to northeast (NE) direction, the domain extends inland from the ocean and Pearl Harbor up to but not including the dike-intruded area in the Koʻolau Mountains just SW of the topographic divide. The top of the model is the topographic surface, and the bottom of the model is the freshwater/saltwater interface.

Major geologic features represented in the model include basalt, valley fill, saprolite, and caprock. The unweathered basalt is highly heterogeneous at a local scale, consisting of massive basalt and higher-permeability clinker zones and lava tubes. Clinker zones can be tens of feet thick, hundreds of feet in width, and thousands of feet in length and are oriented in the general direction of lava flow. Lava tubes are generally confined to individual pāhoehoe flows and are generally oriented with the basalt flow direction. An analysis of lava tube orientation at Red Hill was conducted and is described in the CSM report (DON 2019). Valleys are cut into the basalt that trend generally in the NE to SW direction. Valley fill underlying the valleys consists of alluvial sediments of lower hydraulic conductivity than the basalt. Saprolite is weathered basalt that underlies the valley fill and is also of lower hydraulic conductivity than basalt. Due to differential weathering, the saprolite hydraulic conductivity is generally lower where it is shallow and increases with depth to where saprolite is not present.

Caprock material overlies the basalt in regions downstream of the valleys. The caprock thickens toward the ocean and consists of lower-hydraulic-conductivity alluvial sediments in the upland regions and higher-hydraulic-conductivity marine sediments (including limestone) nearer the coast, interspersed with Honolulu Volcanic tuff, which is believed to have a low hydraulic conductivity. The underlying tuff cones that intrude through the basalt are also expected to have a relatively low hydraulic conductivity. The geologic conceptual model is detailed in the CSM report (DON 2019).

The regional water flow occurs from recharge areas in the mountains toward discharge areas in Pearl Harbor and the ocean. The water table in the basalt is generally flat, with localized mounding occurring within the saprolite and valley fill. The basalt is unconfined along the ridges but is confined by caprock materials closer to the coast as well as beneath saprolite and valley fill in the incised valleys. Springs and seeps occur near the caprock/basalt interface, with diffuse seepage of freshwater probably occurring beneath Pearl Harbor and in the ocean.

Surface-water features lie within the valleys and are primarily oriented in the NE to SW direction. Streams are ephemeral except high in the mountains where rainfall is abundant, and in the downstream reaches where they intercept groundwater. Surface water / groundwater interaction is low within the streams due to the low hydraulic conductivity of the valley fill and underlying saprolite. In addition, most of the streams in the immediate area have been channelized and lined. The hydrogeologic conceptual model is detailed in the Red Hill CSM report (DON 2019).

1.3 GROUNDWATER MODELING HISTORY

An interim model was developed by the Navy in 2018 to help understand the hydrogeologic system behavior and evaluate critical data needs for the current modeling objectives. This modeling effort is documented in DON (2018, Appendix A). Several field investigations were also conducted during and after the interim modeling effort. These studies were aimed at closing the critical data gaps related to hydrogeology and groundwater migration from beneath the Facility. The studies included extensive literature searches, drilling of additional monitoring wells, synoptic water level studies, initial transfer function-noise (TFN) analyses, review of available test boring reports in the area, geophysical surveys, additional monitoring, and sampling and analyses. Ongoing field efforts are continuing to help further close data gaps.

The interim modeling effort spanned a period of approximately 1 year. The model was built upon previous work with the specific objective of understanding and quantifying the impact of the regional hydrogeology on the modeled area and the local hydrogeology along Red Hill ridge, on the source water zones of critical water supply wells and shafts in the vicinity of the Facility, and on the migration pathways of groundwater from the water table beneath the Facility. The interim modeling study also helped to evaluate the impact of uncertainties and approximations that may be critical to groundwater migration behavior from beneath the Facility. This understanding, along with critical site information and data acquired and assimilated since that effort, form the basis for development of the March 2020 groundwater flow model.

Several groundwater flow models had been developed prior to the interim modeling effort, which are relevant and cover the area of interest. The most updated of these models includes a saltwater intrusion study by the United States Geological Survey (USGS) (Oki 2005) using the Saturated-Unsaturated Transport (SUTRA) model code, and MODFLOW models developed for the Source Water Assessment Program (SWAP) by DOH in 2004, later modified by TEC (DON 2007a; 2007b), and further evaluated by TEC (DON 2010) and Rotzoll (2014). A review of these models as pertinent to the current modeling efforts and objectives is provided in the interim groundwater flow model report (DON 2018, Appendix A).

The SUTRA model developed by the USGS (Oki 2005) includes the region of interest for the current study. The objectives of the SUTRA modeling study were to quantify the salinity profiles of the region and investigate the saltwater intrusion potential of critical public water supply facilities. The model simulated transient conditions from the year 1880 through 2000 using stress period lengths of 5–20 years. The following points from the SUTRA model highlight the hydrogeologic system behavior relevant to the current modeling effort:

- The regional water level gradients were from NE toward the SW within the current study domain.
- The document provides ranges of parameter values appropriate for the region:
  - The regional horizontal hydraulic conductivity value of basalts is large, resulting in relatively flat water-table gradients.
  - The basalt hydraulic conductivity is several times higher in the longitudinal direction of lava flows compared to the perpendicular (transverse) direction.
  - The vertical hydraulic conductivity may be hundreds of times less than the horizontal hydraulic conductivity.
- The saltwater interface as represented by the 50% seawater concentration was simulated to surface approximately at the ocean shoreline. The interface depth increased rapidly farther inland, within the caprock and where basalt is confined. The interface depth was 850–900 feet (ft) in unconfined basalt underneath the Facility area and Hālawa Ridge, which is generally consistent with estimates using the Ghyben-Herzberg Principle. However, the interface was significantly deeper than Ghyben-Herzberg estimates within the confined units in and underneath the caprock due to large vertical flow and gradient conditions from the underlying basalt, through the caprock sediments, to the surface (the Ghyben-Herzberg Principle assumes vertical equilibrium).

- Pumping changes of 5.66 million gallons per day (mgd) at Hālawa Shaft moved the saltwater interface depth by less than 15 ft over 25 years, having negligible impact on the freshwater transmissivity considering the large thickness of the freshwater zone.
- Seasonal water level fluctuations were about 2.5 ft after the year 2000. Apparent water level impacts of up to 0.3 ft can occur within a week due to barometric fluctuations.
- A uniform material property value for each of the geologic units was adequate to calibrate the model to water levels and chloride concentrations measured at select wells. The caprock was segregated into upland alluvial sediments and marine limestone nearer to the shore.
- Calibration was not sensitive to presence/absence or deepening of the valley fill barriers.

The MODFLOW modeling studies of TEC (DON 2007a; 2010) and Rotzoll (2014) were conducted to assess flow behavior from the Facility and to evaluate current and potential future risk to human health associated with petroleum compounds from past or future releases to the environment. This model therefore generally overlies the current study area and was designed for similar objectives. Simulations were conducted for steady-state 1996–2005 average conditions and for transient conditions representing a synoptic study conducted in May 2006. The following points highlight the hydrogeologic system behavior relevant to the current modeling effort:

- The regional water level gradients were from NE toward the SW along Red Hill ridge.
- There was not much change in water levels between 1995 and 2005.
- Calibrated hydraulic parameter values for the local model were similar to those of other models, including the USGS model (Oki 2005) discussed above. Uniform material properties were provided for each of the geologic units including the caprock.
- Sensitivity to hydraulic conductivity of valley fill showed little impact to water levels except immediately within the valley fill.
- A transient simulation to a controlled pumping and synoptic water level measurement study in 2006 indicated that the simulated connectivity across North and South Hālawa Valleys was greater than observed. Thus, the model was more conservative in that direction than was observed, for the given flow conditions.
- Particle capture simulations indicated that the Facility was within the capture zone of Red Hill Shaft and that the Hālawa Shaft capture zone did not extend to the Facility, with or without pumping of Red Hill Shaft.
- Local groundwater gradients along Red Hill ridge analyzed by TEC (DON 2007a) ranged from 0.00046 to 0.00054 foot per foot (ft/ft) (2.4 to 2.9 feet per mile [ft/mi]) with an angle of 204–245 degrees (i.e., generally in the SW direction). A re-evaluation of the hydraulic gradients at Red Hill ridge by TEC (DON 2010) indicated a consistent local water level gradient direction of 270 degrees (i.e., from east to west) with gradient magnitudes of 0.000089–0.00015 ft/ft (0.45–0.8 ft/mi).
- Regional groundwater gradients using a contouring approach applied to seven observation wells indicated a west-NW direction with a local SW direction when Red Hill Shaft was pumping.

1.4 INTERIM GROUNDWATER FLOW MODEL

The interim modeling study (DON 2018, Appendix A) built upon the studies by TEC (DON 2007a; 2007b; 2010) and Rotzoll (2014). A multimodel approach was used to evaluate the impact on groundwater flow of modeling approximations; uncertainty in conceptualization; and variability in parameter values, water levels, and stresses. The models were constructed and calibrated with data available at the time, with input from Agency, stakeholder, and USGS subject matter experts (SMEs). All models were evaluated with respect to simulated groundwater migration behavior from the Facility, and conservative/protective models were considered for further evaluation (based on discussions with Regulatory Agency SMEs) of the impact at the various water supply locations in the vicinity.

In most of the models developed for the interim modeling study, the caprock, valley fill, saprolite, and basalt were simulated as homogeneous materials, as done by previous regional studies of the area. Basalt properties were anisotropic in the lateral and vertical directions to include the impact of smaller-scale heterogeneities resulting from geologic considerations of lava flow, basalt aquifer formation, and weathering. Local-scale heterogeneities were also evaluated by some of the models, including conceptual representations of clinker zones underneath Red Hill, no saprolite beneath the water table, and caprock zonation into upland alluvial sediments and coastal marine sediments.

Modeling challenges included generally flat water-level gradients, high hydraulic conductivities, large local-scale heterogeneities, and scarcity of accurate model-area-wide synoptic data. Therefore, conservative assumptions were made for model development, calibration, and application where data were unavailable or uncertainty was large. Saprolite, which can act as a barrier to flow, is known to extend for several hundred feet beneath the water table within certain sections of North and South Hālawa Valleys and Moanalua Valley; however, the lateral extent and depth were reduced in the interim modeling study to include a conservative approach toward simulating this barrier. Also, high-end values were used in the models for the hydraulic conductivity of saprolite barriers, providing greater potential for cross-valley flow. A sensitivity study model further evaluated the impact of no saprolite barrier. The models were calibrated to steady-state water levels of 2006, 2015, and 2017 annual average conditions and evaluated further against synoptic pumping and water level studies conducted in 2006 and 2015. Evaluation over multiple years indicated that observed and simulated water levels behaved in a similar manner through the years with little change in gradients. Local and regional gradients were also evaluated in a manner consistent with the analyses of TEC (DON 2010), indicating similar results (i.e., results at the seven observation well locations, when contoured, indicated a west-NW direction). Sensitivity studies were conducted to evaluate impact of parameter uncertainty on calibration. The models were recalibrated when possible and used to evaluate their impact on modeling results. Finally, the models were applied to estimate groundwater migration behavior from beneath the Facility for extreme pumping conditions over long-term durations.

A total of 31 steady-state and 12 transient models were developed as part of the interim modeling study evaluation. These models bracketed the estimated parameter ranges for the aquifer materials, the observed long-term water level elevations in monitoring wells, and water level changes observed during the synoptic studies. Each of the steady-state models was further used to assess migration of groundwater from beneath the Facility and source water zone evaluations for cases of extreme pumping at Red Hill Shaft and Hālawa Shaft. The following points highlight the hydrogeologic system behavior of the interim modeling effort:

- The modeled bottom of the freshwater domain is better represented by the USGS numerical model (Oki 2005) than by the Ghyben-Herzberg Principle. This is because high vertical hydraulic gradients exist within the caprock that are accounted for in the Oki (2005) numerical model, while the Ghyben-Herzberg Principle assumes hydrostatic (vertical equilibrium) conditions. Therefore, the March 2020 model was developed using the USGS modeled saltwater interface (50% isochlor) as the bottom of the freshwater model domain.

- Heterogeneity within the caprock was significant to migration behavior of groundwater from beneath the Facility. Therefore, the March 2020 model includes alluvial sediments, marine limestone, and Honolulu Volcanic tuff as major sub-units within the caprock.
- Heterogeneity within the basalt was significant to local flow conditions along Red Hill ridge. Specifically, a clinker zone conceptualized to occur at the water table beneath the Facility and extending to Red Hill Shaft could cause very flat water levels and localized variations in flow gradients. Water level differences between monitoring wells at Red Hill are within a few tenths to hundredths of a foot, resulting in difficulties interpreting local flow directions and gradients and causing an extremely difficult model calibration. This March 2020 modeling effort therefore includes a model that conceptually evaluates the impact of conceptual clinker zones beneath Red Hill on the migration behavior of groundwater from beneath the Facility. This approach was also used for the interim modeling effort, with the conceptual clinker model providing conservative results protective of Red Hill Shaft, which lies along the fast flow pathways. It was not the intent of this approach to use a highly detailed clinker zone as was previously stated; rather, this approach was used as a conservative basis to evaluate the impact of potential fast flow paths.
- Saprolite is an important feature beneath the valleys, although water level calibration was not sensitive to presence of saprolite (except for monitoring well RHMW07, which probably lies within or near the edge of the saprolite), and migration behavior of groundwater from beneath the Facility was only slightly sensitive to the presence and hydraulic conductivity of saprolite. However, this slight sensitivity impacts Hālawa Shaft, and furthermore, due to the sensitive nature of discussions between AOC Party SMEs about the impact of saprolite, the March 2020 model includes two versions of saprolite depth and extent to bracket uncertainty. Reasonable hydraulic conductivity values at the higher end of the range were used as a conservative and protective approach for the saprolite to provide high-end evaluations of flow through these barriers, conceptually conservative to impacts from the Facility at Hālawa Shaft.
- Model layering for the interim model was sufficient to evaluate source water zones of water supply locations and migration behavior of groundwater from beneath the Facility. However, since the March 2020 flow model will be used to evaluate fate and transport behavior of potential solutes from beneath the Facility, a finer vertical discretization was applied in the March 2020 model to provide resolution and capture vertical concentration gradients in groundwater.
- Several models indicated an insensitivity to calibration and groundwater migration behavior. Other models indicated unrealistic results. These sensitivities were not repeated with the March 2020 modeling efforts.

1.5 Interim Data Assimilation Summary

Several field investigations were also conducted during and after the interim modeling effort. These investigations yielded additional critical information on geology, hydrogeology, and water levels that potentially control the migration behavior of groundwater from beneath the Facility. Details are provided in the CSM report (DON 2019). In addition, various field activities and investigations are being planned.

As the interim model was being developed, saprolite depth and extent were considered to be critical parameters that control migration of groundwater from beneath the Facility. North and South Hālawa Valleys lie between the Facility and Hālawa Shaft, and the underlying saprolite may act as partial barriers to flow of groundwater (and light nonaqueous-phase liquid [LNAPL]). Elevated heads in the saprolite and underlying weathered basalt was another important factor for consideration. Also, South

Hālawa Valley and Moanalua Valley flank Red Hill ridge, and the underlying saprolite may create flow paths directing groundwater in the direction parallel to the valleys toward Red Hill Shaft. Thus, saprolite extent and depth were considered parameters significant to Hālawa Shaft and Red Hill Shaft. Saprolite depth and extent would more likely be a barrier to flow of potential LNAPL migration.

A geophysical study was conducted to evaluate the extent and depth of saprolite underneath the valleys adjacent to Red Hill ridge. In addition, multilevel monitoring well RHMW11 was constructed in South Hālawa Valley through the saprolite and into the unweathered basalt. The well was logged to delineate the various underlying materials and monitored at multiple depths to evaluate water levels and estimate the hydraulic conductivities of the different zones. Results from well logging and the geophysical study were integrated into the existing geological framework to better represent saprolite depth and extent for the March 2020 model development. This was conducted with involvement from AOC Party SMEs.

A detailed evaluation was conducted to measure dip azimuth and magnitude of the basalt flows within the model domain. Local- and regional-scale evaluations were conducted with involvement and agreement from AOC Party SMEs on a selected representation for the numerical groundwater flow model.

Heterogeneity within the caprock was also evaluated further to delineate the alluvium, marine sediments, and Honolulu Volcanic tuff. A literature review along with assimilating well logs from within the caprock enabled delineation of the surface spreading of the tuff and the location of tuff cones. The various caprock zones were integrated into the existing geological framework for explicit use in the numerical groundwater flow model. The interpretations of tuff, tuff cones, marine sediment, and alluvium sediment zones were conducted with agreement from AOC Party SMEs.

Water levels beneath the Facility and within adjacent wells are relatively flat with extremely small gradients. Therefore, even small errors in water level measurements can cause a large impact on modeled gradients and directions. Collecting water level information from these wells on an intermittent basis (monthly or seasonal) as was done in the past creates gaps in understanding the local flow behavior especially because all water levels were not collected at the same moment. In addition, barometric pressure influences, earth/ocean tide impacts, datum inaccuracies, and borehole deviation influences all affected the measurements. Furthermore, the pumping regimes of Red Hill Shaft and Hālawa Shaft have an impact on water levels in the vicinity, creating even larger uncertainties depending on the pumping schedules and duration. Therefore, a synoptic study was developed in coordination with SMEs from the Regulatory Agencies and USGS to measure water levels at various wells within the focus area at Red Hill on a frequent basis for controlled pumping regimes at Red Hill Shaft and Hālawa Shaft (USGS 2017). The field work began in mid-2017 with water level data collection efforts continuing through mid-2018. Transducer data continue to be collected from monitoring wells in the area. This synoptic study was conducted with supervision and agreement from AOC Party SMEs and is considered to provide the most accurate and precise water level information at the Facility and in its vicinity obtained to date.

Field work is continuing to help understand the system further, and additional monitoring wells are being installed. This information will be processed and implemented in future studies.

1.6 AOC REVIEW OF INTERIM GROUNDWATER FLOW MODEL

The interim modeling analysis was conducted within a regulatory framework with input on all aspects of model development from AOC Party SMEs as well as City and County of Honolulu Board of Water Supply (BWS) consultants and the USGS. The resulting document and modeling files were further reviewed by AOC Party SMEs, who then presented their comments and a suggested a path forward. Some of their concerns were immediately addressed by conducting additional simulations with the interim model framework to note impacts. Other comments required additional data collection and assimilation, which were conducted to provide information for the March 2020 model development. The concerns were addressed in the March 2020 model as follows:

1. *Predominant dip azimuth and magnitude of basalt in the geologic model:* After re-evaluation of the dip azimuth and magnitude of basalt in coordination with Regulatory Agency SMEs, a dip azimuth of 213.6 degrees was selected for the March 2020 modeling effort.
2. *Saprolite extent and depth:* Additional geophysical and well log data collected since interim model development provide a more accurate representation of the saprolite beneath South Hālawa Valley. This information was assimilated into the conceptual geological model and used in the March 2020 modeling effort. Furthermore, due to uncertainties in saprolite depth, two different configurations were considered (as discussed with the Regulatory Agency SMEs) to evaluate the impact of the alternate interpretations.
3. *Preferential pathways:* Preferential pathways exist at a local scale and can affect local water level gradients and directions. A conceptual clinker model indicated this impact during the interim modeling effort. The March 2020 model also evaluated a conceptual clinker model to consider the impact of preferential pathways on the various potential receptors. A heterogeneous model was also considered to evaluate the impact of local heterogeneities. In addition, various studies were conducted (with input from the Regulatory Agency SMEs) to further evaluate the potential impact of lava tubes beneath the site as a fast transport mechanism. These studies indicated that it is highly unlikely for lava tubes to provide a fast transport mechanism relative to either Red Hill Shaft of Hālawa Shaft.
4. *Representation of caprock:* The interim modeling indicated that delineating the major units within the caprock could have an impact on groundwater flow behavior from beneath the Facility. The AOC Party SMEs also presented this as a concern, and therefore additional evaluation, data collection, and assimilation efforts also focused on delineating the alluvium, marine sediments, and the Honolulu Volcanic tuffs (including the surface tuff and underlying cones). This delineation of the various caprock units was performed in coordination with Regulatory Agency SMEs and was used in the March 2020 model.
5. *Drinking water shaft inflows:* A concern was raised regarding the impact of non-uniform inflows to the drinking water shafts, specifically to Red Hill Shaft. An additional interim model sensitivity analysis was conducted in this regard, and it was observed that non-uniform inflows to the shaft had negligible impact on flow and capture of water from beneath the Facility. The March 2020 model considers non-uniform inflow to Red Hill Shaft as was observed during construction of the water development tunnel.
6. *Calibration to groundwater heads and gradients:* Since groundwater gradients beneath the Facility are relatively flat, it was difficult to discern water level gradients and directions. Synoptic studies conducted in 2006 and 2015 had not considered all the wells or all the pumping and were conducted for a limited data set and duration. Therefore, a comprehensive synoptic study was designed in conjunction with AOC Party SMEs and conducted in 2017–2018 to evaluate and isolate the impacts of all stresses to the system. Results of this study indicated different water level gradients from the earlier synoptic studies from 2006 and 2015, which were used for calibrating the interim model. Therefore, the newer, more controlled data were used for the March 2020 model. Further assimilation and processing of the data were conducted to isolate the impacts of various stresses at the different monitoring well locations and provide a calibration data set with information on drawdowns, which are useful for

determining hydraulic properties. Water levels, head differences, and drawdowns were all evaluated and implemented as targets for calibration of the models in the current work. More importantly, a TFN analysis (based on the most recent synoptic data) was conducted to better define pumping signals in monitoring wells, and this was further used for model calibration and verification in the March 2020 modeling effort (Appendix A and Appendix B, respectively).

7. *Coastal marine boundary discharge:* A concern was raised regarding the impact of freshwater discharge from the system along the coast and in Pearl Harbor. An additional interim model sensitivity analysis was conducted in this regard, with discharge occurring mainly in Pearl Harbor, and another analysis with discharge occurring mainly offshore into the ocean. It was noted that coastal marine discharge distribution impacted flow in the caprock region but not along the ridges farther uphill. Due to this sensitivity and further considering the addition of caprock details in the current study, this sensitivity analysis was also conducted for the March 2020 model.

8. *LNAPL fate and transport:* This concern was mainly regarding LNAPL flow in the vadose zone and not related to the groundwater flow model. It may have implications for the source zone in groundwater solute transport simulations and will be evaluated further at that stage.

9. *Groundwater geochemistry data:* Groundwater geochemistry data were further evaluated to note possible signatures that indicate flow patterns. A multifactor analysis was also conducted that indicates there is little to no similarity in the geochemical signatures between interior Red Hill wells relative to outlying monitoring wells (DON 2020, Appendix E.5). However, there is no consensus yet between the AOC Parties on the groundwater flow directions implied by these signatures.

10. *LNAPL and dissolved-phase distribution:* This concern was mainly regarding LNAPL flow in the vadose zone and not related to the groundwater flow model. It may have implications for the source zone in groundwater solute transport simulations and will be evaluated further at that stage.

There has also been some confusion with terminology, specifically where water level differences, water level gradients, and flow gradients (or direction) are used interchangeably. These terms may be related but are not the same, and therefore it is important to be precise in their discussion for the current study:

- *Water level differences* are the differences in water levels between two specific well locations. They do not define the water level gradient. Locally, at least three wells are required to estimate the average water level gradient and direction between the wells. Regionally, adjacent flow systems may have different water levels independent of water level gradients or flow directions.
- *Water level gradients* show the direction and magnitude of changes in water levels within the domain. Interpolation of water levels between well locations may help interpret the changes in head, but may not depict the water level gradients at local or regional scales because heterogeneities and flow barriers impact gradients, which cannot be depicted accurately by simple interpolation.
- *Flow direction* defines the actual direction of flow of water. In an anisotropic system, as is the current case, the flow gradient is not the same as the water level gradient. Flow occurs regionally from locations of recharge to locations of discharge. However, the larger the anisotropy, the greater is the deviation of flow direction from the head gradient.

The March 2020 groundwater flow model development is discussed in this report. Subsequent sections of this report discuss assimilation of pertinent data, construction of the numerical model, model calibration, and application. The interim modeling analyses were helpful in guiding additional data collection and assimilation. The updated CSM considers this information, which is provided in the updated CSM report (DON 2019). Hydrogeologic data collection and assimilation were also conducted to develop the interim model in the first place. The interim modeling report (DON 2018, Appendix A) is referenced for those details not repeated here.

1.7 MARCH 2020 GROUNDWATER FLOW MODELING APPROACH

Traditionally, groundwater flow modeling for practical water resource or remedial investigations was conducted by developing and calibrating one base-case model that was expected to accurately mimic all groundwater flow conditions at a site. Sensitivity analyses were then performed on the calibration to evaluate the impact of changes in parameter values on calibration. The calibrated base-case model was then used to evaluate various scenarios of interest, while the sensitivity analyses provided information on the impact of uncertainties in parameterization on the model behavior (i.e., whether the model becomes uncalibrated or not as a result of the parameter, conceptual, or boundary change). The sensitivity analyses were further used to evaluate impact of the changed (now uncalibrated) model on the application scenarios. The parameters were then categorized into four “Types” per ASTM sensitivity guidelines (ASTM 2016). This categorization helped to qualitatively understand the uncertainty in results.

This traditional approach has not worked very well in remedial investigation applications for several reasons. First, the subsurface is complex, and available data cannot cover or characterize the subsurface at all scales. Also, data errors and representative spatial scales are not typically recognized. In addition, a model is non-unique, and different geological representations and parameters may fit the available data well but may provide different results for the application scenarios. Furthermore, the experience of previous models was not incorporated, and calibration typically focused on trying to mimic the available data rather than to understand and evaluate the specific objectives of the investigation. Therefore, additional data may not fit the modeled results, and remedial actions may not work as expected. In this regard, expectations of “The Model” were unrealistic, causing disenchantment with the results.

This traditional modeling approach has also had limited success in some disciplines outside of hydrogeology. For example, weather predictions were very poor a few decades ago but have significantly improved in recent times. The three main drivers behind these more accurate predictions are: assimilation and use of additional relevant data, application of a multimodel approach, and continual updating of the models with additional information and understanding. The multimodel approach provides for allowance of uncertainty. A familiar graphic in this regard is the “spaghetti plot” that is often shown on television weather forecasts depicting the paths of hurricanes as computed by various models. These models are then being used by officials to evaluate evacuation decisions at the city, county, state, and federal levels that are critical to the region’s economy and population safety.

The March 2020 groundwater flow modeling was conducted using a multimodel approach to help evaluate uncertainties in conceptualization and parameterization. The multimodel approach goes beyond the traditional approach. With this approach, there is no base-case model. Instead, multiple models were developed and calibrated to bound the range of possible parameter values, field observations, or conceptual representations. Thus, every sensitivity run was also calibrated and is accepted as a plausible model if it fits the conceptualization, has a reasonable parameterization, and matches the observation data. Every model was then also applied for evaluating the migration behavior of water from the water table beneath the Facility and for assessing the capture zones of critical water supply locations. Since the accepted models were calibrated to available data, they may be representative of the hydrogeologic system, based on available data. The calibration also focused on water level gradients and hydrogeologic parameters significant for evaluating flow directions, as is pertinent to the current model application. This was done by using the TFN analysis to deconvolute the signals generated at monitoring wells from pumping of Red Hill Shaft and Hālawa Shaft. Decision makers can then select appropriate models from this multimodel set or weigh them appropriately for conservative evaluations of different objectives at different receptors. The multiple models will also be used for subsequent fate and transport simulations. Additional data acquired and analyzed between the March 2020 model and fate and transport simulations will be evaluated against all or some of the models and additional models may also be considered if the data generate additional questions, concerns, or discrepancies.

The interim flow models also used this multimodel approach to bound the variations in observations, parameter values, and conceptual representations. Because of this approach, the interim modeling effort included models that considered shallower and steeper hydraulic gradients than were evaluated at the time of calibration, and therefore included models that were still applicable when the data were updated. Furthermore, the multimodel approach helped to identify model deficiencies and make improvements with regards to the AOC Party SMEs' concerns as well as additional data that became available, as implemented in the March 2020 model.

The multimodel approach has also been used in other fields of study. For instance, Scavia, DePinto, and Bertani (2016) apply the strategy toward evaluating phosphorous loading in Lake Erie, listing the benefits of a multimodel approach as follows:

- *Problems and data are viewed from different conceptual and operational perspectives.*
- *The level of risk in environmental management decisions is reduced.*
- *Model diversity adds more value to the decision process than model multiplicity.*
- *Findings are stronger when multiple lines of evidence are available.*
- *Using multiple models increases knowledge and understanding of underlying processes.*
- *Average predictions from a set of models are typically better than from a single model.*
- *Information from multiple models can help quantify uncertainty.*
- *Multiple models can expand opportunities for additional stakeholders to participate.*
- *Reconciling differences among models provides insights on key sources and processes.*

The modeling process leading up to and including the March 2020 model report follows the successful path of weather modelers. First, additional relevant data are continually being collected to verify or improve the models. Second, the multimodel approach makes allowance for uncertainties and errors in data. Finally, understanding the differences between the models and continually building on new data and past experience help to evaluate various stakeholder concerns, identify model deficiencies, and make improvements while discarding models that may be inadequate.

Other stochastic approaches were also considered for implementing the March 2020 model. For instance, Null Space Monte Carlo and linearized methods are available with the PEST parameter estimation software. These techniques are more complex and significantly more computationally intensive, they require significantly more effort and time to implement, and therefore they are not practical for available computational resources and schedules. Also, these methods require estimates for probability distributions of parameter values that are difficult to obtain or justify. Furthermore, they generate stochastic fields of parameters that do not provide a systematic understanding of site hydrogeology as is provided by the deliberate conceptual and parameter representations of the multimodel approach.

Model development and application have been guided by the modeling objectives. Voss (2011) states: "…*the best way to go forward with practical management is to rise above groundwater models as final products, and instead, empower hydrologists to provide advice by using groundwater models in simple ways that are intended to elucidate understanding.*" Therefore, the model is considered as a tool for decision making and is useful if it can provide meaningful interpretations of flow behavior and an understanding of flow conditions in the region of interest pertaining to the modeling objectives. Model complexity of the current effort was appropriate to provide this understanding. Previous modeling efforts and the interim modeling study provided valuable guidance in this regard.

2. Numerical Groundwater Flow Model

2.1 INTRODUCTION

The objectives of developing a model for groundwater flow and transport are to assist with risk management of groundwater within the study domain. This section provides an overview of the model and a guide to the rest of the report.

The March 2020 groundwater flow model was built from an understanding of the hydrogeologic system obtained from literature, available field data, and previous modeling studies including models developed by the USGS, DOH, and Navy (including the interim modeling effort). Model complexity was added incrementally to the interim model, starting from evaluations of previous studies. The impact of various assumptions and uncertainties was further evaluated using a multimodel approach, which also helped identify significant controlling hydrogeologic parameters and data gaps.

Model complexity and geological variability occur at multiple spatial scales. The models were developed at an appropriate level of complexity at all these scales, considering the modeling objectives and available data. The various spatial scales of discussion for modeling at Red Hill are presented in the interim modeling report (DON 2018, Appendix A), and some have been introduced in the previous section. Summarizing:

- A *domain-wide scale* encompasses the entire modeled area depicted on Figure 1-1 and includes portions (about a couple of miles) outside the model domain to evaluate boundary conditions and possible impacts. The *regional scale* encompasses Red Hill, Moanalua Valley to the SE, and North and South Hālawa Valleys to the NW up to Kalauao Spring. The regional scale is of interest for the major objectives of the modeling effort as it includes the Facility and the critical water supply locations that may be impacted by potential releases from the Facility.
- The *local scale* of interest for the current study is the Facility outline itself. This scale is the most studied, with the highest density of data availability with regard to geology and water levels. Data collection efforts concurrent with the interim modeling study included local- and regional-scale evaluations to the extent possible, to better understand the local and regional flow characteristics. It is, however, important not to extrapolate local-scale observations to the regional scale.
- The *grid-block scale*, the size of a grid-block or two, is used to discretize the numerical model. The numerical groundwater flow model discretizes the three-dimensional model domain into grid-blocks or cells that represent the respective volumes in the groundwater flow calculations. Model gridding is discussed in Section 4; the horizontal grid-block sizes range from 30–500 ft on a side.
- The *scale of the well / water supply shafts* is modeled explicitly in the current study. A water supply well is represented as a vertical cylindrical conduit extending from the screened-interval top to the screened-interval bottom. Water supply shafts are represented by horizontal cylindrical conduits with known bottom elevation, length, and radius. Therefore, this scale does not pose additional discretization concerns.
- The *sub grid-block scale* is smaller than a numerical grid-block size. In numerical modeling, heterogeneities that occur at a sub-grid-block scale are represented by use of equivalent material properties at the grid-block scale.

Geologic complexity of the model was determined by evaluating past models developed by the USGS, DOH, and Navy and expanding on that information during the interim modeling effort. Sensitivity results of the interim model indicated that zonation of the caprock could have a significant impact on migration of groundwater from beneath the Facility. Therefore, the current modeling effort includes structural complexity within the caprock by explicit representation of the marine sediments, alluvial deposits, and Honolulu Volcanic tuff material within the caprock. The impact of complexity of basalt properties on groundwater migration from the Facility has been explored sufficiently in the current set of models, including different anisotropies, different likely basalt zonation, different boundary conditions and structural impacts of concern to stakeholders, and different heterogeneous basalt representations. These models suggest that additional complexity is not justified at this point unless it is possible to obtain such data that address the uncertainty or sort between them.

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

2.2 SUMMARY OF FLOW MODEL CONCEPTUALIZATION

An evaluation of the CSM in view of the modeling objectives provides the framework for developing the numerical flow model. A review of previous modeling efforts also provides guidance on model construction and expected hydrogeologic behavior. The CSM report (DON 2019) details the model development approach using geological, geophysical, and hydrogeological information, and included updated information from the latest available sampling data. The CSM was developed in an iterative manner, with improvements as more information became available. CSM development was conducted in consultation with AOC Party SMEs. While there may still be disagreements on certain aspects of the CSM, this multimodel approach evaluates the various suggested CSMs in terms of their validity and goodness of fit. A summary pertinent to the groundwater flow model is provided below.

2.2.1 Geologic CSM

The major subsurface geologic features within the model domain include a deep basalt aquifer that was formed by a long period of multiple lava flows hundreds of thousands of years ago. The lava flows had a general south-SW orientation within the model domain. Additional dip azimuth and magnitude evaluations of the basalt aquifer bedding were conducted subsequent to interim model development to further establish this significant aquifer characteristic. In general, the larger-scale information from evaluation of quarry and field measurements showed a dip azimuth of 213.6 degrees with a magnitude of 3 degrees. This azimuth value was used in the March 2020 model and was agreed to by the AOC Party SMEs. The azimuth magnitude was not significant to groundwater flow modeling, as noted in the interim model, but may be significant to unsaturated-zone LNAPL flow modeling. Details are provided in the CSM report (DON 2019).

At the regional scale, the basalt aquifer behaves as a fairly homogeneous system with a higher hydraulic conductivity (by several times) in the direction of lava flows than in the transverse direction. Vertical hydraulic conductivity is even lower. At the local scale at Red Hill, variability has been noted in geologic and water level data, indicating the presence of highly transmissive localized clinker zones that may impact flow. Clinker zones are known to be a few feet to tens of feet in thickness, tens to hundreds of feet in width, and thousands or tens of thousands of feet in length. Localized lava tubes may also cause local and sub-grid-scale transmissive pathways; however, their density and cross-sectional area are considerably smaller than clinker zones, and moreover they are often collapsed below the water table. The orientation of clinker zones and lava tubes are generally in the direction of lava flow. As discussed earlier, several evaluations of lave tubes were conducted and described in the CSM report (DON 2019). These evaluations indicated that it was highly unlikely for lava tubes beneath the tanks to act as fast flow paths for groundwater to impact either Red Hill Shaft or Hālawa Shaft. While much of this analysis was based on observations in the vadose zone, the same dip azimuths and related factors should also apply to the saturated zone. Use of a conceptual clinker zone provides a more conservative evaluation of fast flow paths.

Stream valleys were formed within the basalt over the period of thousands of years. Alluvial deposits (valley fill) accumulated in the stream valleys comprising a lower hydraulic conductivity (compared to unweathered basalt). Chemical weathering of the basalt beneath the valley fill resulting from percolating water underneath the streams produced a lower-permeability saprolite material (underlying the valley fill) that can extend hundreds of feet beneath the water table. The saprolite is differentially weathered, resulting in weathered basalt (not saprolite) transitioning into unweathered basalt. The low hydraulic conductivity of these weathered materials in comparison to the unweathered basalt causes them to behave as hydrogeologic flow barriers, with higher flow more likely to occur beneath them than through them.

Farther toward the coast, the basalt is overlain by a caprock layer that thickens seaward and is composed of terrestrial alluvium, marine sediments, calcareous reef deposits, and pyroclastic rocks of the Honolulu Volcanics that have significantly lower permeability than the basalt. This caprock layer forms a confining unit over the basalt aquifer. Interbedded limestone aquifer units are present within the caprock toward the coast. Interim modeling determined that the results were sensitive to treating caprock as a homogeneous unit, and therefore the caprock was segregated into its major structural components (upland alluvium sediments, marine sediments closer toward the coast, and Honolulu Volcanic tuff overlying the alluvium and marine sediments) for the current modeling effort (DON 2019, Section 5).

2.2.2 Hydrogeologic CSM

Hydrogeologic data are explored in greater detail in Section 3 of this report and in the CSM report (DON 2019). In summary, freshwater flow within the basalt occurs from high recharge areas in the higher elevations toward discharge areas in Pearl Harbor and the ocean. The basalt aquifer is several thousand feet thick, with freshwater floating on top of the denser saltwater at depths of up to 900 ft within the model domain. The depth of freshwater was estimated from modeling efforts by the USGS (Oki 2005) that were focused on evaluating saltwater behavior in the region. The freshwater/saltwater interface becomes rapidly shallower within the caprock, and freshwater exits the subsurface slightly offshore of the coastline to the south.

Inflow of freshwater occurs mostly as a result of recharge of precipitation over the model domain and of lateral subsurface inflow from the dike-intruded area to the NE through the lateral NE boundary. The water table within the upper reaches of the basalt aquifer and locally at Red Hill is fairly flat, resulting from the extremely high hydraulic conductivity of basalt. Water elevations are generally in the 15–20 ft mean sea level (msl) range in the Facility area. However, higher water elevations due to recharge mounding or perching has been noted on the lower-hydraulic-conductivity valley fill or in underlying saprolite and weathered basalt.

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

Localized limestone aquifers exist within the caprock nearer to the coast. These aquifers are composed of marine sediments with interbedded alluvium and are not generally pumped in any substantial manner. Water levels within these marine sediments depend on the depth of the screen interval due to large vertical hydraulic gradients and vary generally between 1 and 5 ft but may be as much as 10 ft above sea level.

2.3 NUMERICAL MODEL FRAMEWORK

The geologic and hydrogeologic CSMs provide an understanding of the hydrogeological system under study, considering the available geologic and hydrogeologic information. The following pertinent information was examined and detailed in the CSM report (DON 2019):

- The geologic structure, hydrogeologic properties, and heterogeneity were described at various scales.
- A synoptic pumping and water level monitoring study (2017–2018) was conducted, and water flow patterns and temporal water level behavior were established for various wells. Transducer data for these monitoring wells continue to be collected.
- Stress-response evaluations were performed using data science methods and traditional hydrogeologic analyses to separate the signals for pumping from other natural stresses and variations.
- Recharge patterns were established by the USGS for various (normal, dry, and current) conditions considering precipitation trends, estimated recharge distribution, land cover, soil types, land use, and topography. These were further examined to evaluate local conditions (e.g., at the nearby Hālawa Quarry) that may not have been considered in the USGS evaluations.
- Discharge patterns were estimated from pumping records, spring-flux observations, and water balance calculations.

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

The numerical groundwater flow model discretizes a three-dimensional model domain (oriented with the dip azimuth) into grid-blocks or cells that represent the respective volumes in the groundwater flow calculations. Areal discretization is governed by considerations of required resolution. Model layering also considers stratigraphic and hydrogeologic influences in addition to required resolution. Model discretization is detailed in Sections 4.1 and 4.2.

A model grid was first constructed to represent the subsurface geologic conditions. The geologic CSM was then translated onto the numerical grid such that the effective cell properties are representative of the aggregate of the aquifer material contained within the cell volume. Anisotropic properties allow for flow conditions to be different in the lateral, transverse, and vertical directions to consider impacts of sub-grid-scale heterogeneity. Large anisotropy also represents the impact of high-conductivity clinker beds in the basalt, aligned with the anisotropy direction. Water flow and migration were modeled to occur only within the primary (mobile) porosities of the grid-block. Subsequent solute transport simulations will evaluate the impact of the secondary porosities (immobile domain) on solute migration. Model parameterization is detailed in Section 4.3.

Calibration and verification metrics and targets for the intended objectives were also established. Calibration targets were developed by deconvolution of the measurements using the TFN approach, while verification metrics considered the transient observed data. The model was calibrated using the PEST software (Doherty 2015) and evaluated against the various qualitative and quantitative metrics pertinent to the study at regional and local scales. The impact of uncertainties, errors, and modeling assumptions was also evaluated via a sensitivity analysis and a multimodel approach. Sensitivity analyses were performed on parameter value bounds, conceptual uncertainties, and boundary stresses, where each sensitivity run was also calibrated. Section 5 details the model calibration effort for the various models that were developed.

The models were applied for evaluating the migration of groundwater from beneath the Facility under various regional pumping conditions using particle tracking analysis methods. The models will further be used for evaluating the fate of potential contaminants in groundwater originating from the Facility using solute transport simulations. The multimodel approach provides a range of outcomes considering the range of uncertainty or errors in model parameters, observation targets, or stresses.

The current modeling effort has been conducted within a regulatory framework. Therefore, the analyses were conducted in a conservative manner to err on the side of caution. Simplifications of the CSM in the numerical framework reflect reasonably conservative assumptions considering modeling objectives and available data. Model calibration was also biased toward conservative representations of the hydrogeology where possible. Alternate conceptualizations and parameterizations were explored to evaluate the impact of uncertainty and error. Model scenarios apply maximum permitted pumping stresses (used average annual pumping rates) for steady-state conditions, which further adds conservatism to the modeling results.

2.4 NUMERICAL MODEL CODE SELECTION

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

The MODFLOW-USG groundwater modeling code (Panday et al. 2013) was selected to develop the numerical groundwater flow model. MODFLOW-USG is an open-source, public-domain groundwater flow modeling code released by USGS in 2013 to accommodate the flexibility of unstructured grids. The code has the ability to meet all simulation objectives and the capability to accommodate the CSM. The upstream weighting formulation with Newton Raphson linearization provides robustness available in the MODFLOW-NWT (Niswonger, Panday, and Ibaraki 2011) version of the MODFLOW suite of codes. An unstructured discretization accommodates nested grids and quad-tree grid-block refinement, providing resolution only where required for optimal simulation efficiency. A public-domain particle tracking routine for MODFLOW-USG (mod-PATH 3DU) available from SSPA (2018) was used to evaluate migration pathways or well capture zones via forward and reverse particle tracking. Transport simulation capabilities will be accommodated by USG-Transport (Panday 2019), which is also available as an open-source, public domain software from the GSI Environmental website (https://www.gsi-net.com/en/component/k2/item/525-update-release-for-usg-transport.html). The software is further interfaced with the PEST software (Doherty 2015), which was used to assist with model calibration. MODFLOW-USG is also interfaced with several commercial GUIs, including the U.S. Army Corps of Engineers' Groundwater Modeling System (GMS) (Aquaveo 2019) and Groundwater Vistas (ESI 2019). The GMS GUI was used during the interim modeling effort; however, the Groundwater Vistas software is being used for the March 2020 model as it provides greater flexibility for the current objectives.

3. Hydrogeologic Data Assimilation

Initial hydrogeologic data within the domain were evaluated to understand what information was available, the accuracy and significance of the various data, and how they may be used in developing and calibrating a numerical groundwater flow model that addresses current issues and concerns in the region. These data and data evaluations included historic and current water level information, pumping data, evaluation of water level gradients, spring fluxes, groundwater recharge, and boundary flows for the study area. Details of the regional data assimilation effort for the groundwater flow model are provided in the interim modeling report (DON 2018, Appendix A).

Additional data acquisition and analysis were conducted since development of the interim model. These studies were aimed at closing critical data gaps related to groundwater migration from beneath the Facility and included:

- Geophysical investigations and well log evaluation for newer wells to evaluate the depth and extent of the saprolite
- Studies on dip azimuth and magnitude of lava flows at various scales to better define the anisotropy direction
- Evaluation of literature and available data for delineating the surficial tuff from alluvium and marine sediments and for defining the tuff cones
- A synoptic study conducted in 2017–2018 that was carefully designed to turn on and shut off critical water supply shafts in the area while carefully monitoring the water level response at the Red Hill monitoring wells and other pertinent wells in the region
- A TFN analysis of the 2017–2018 synoptic study data. The TFN analyses helps with the following:
  - Evaluating the water level response to each hydraulic stress component (e.g., barometric pressure, pumping from shafts, tidal and other influences)
  - Removing non-pumping stress impacts from the water level signal
  - Developing unit step response functions to help with groundwater model calibration
  - Providing preliminary estimates of aquifer hydraulic properties between pumping and monitoring locations, including estimates of horizontal anisotropy

These additional data and analyses are documented in the CSM report (DON 2019). Data acquisition and analyses are continuing, and more monitoring wells are planned for the site. Additional data will be integrated into future models as required.

This section summarizes the hydrogeologic data that were used for development and calibration of the March 2020 model. Monitoring and analyses details are left to the respective source reports (DON 2018, Appendix A; 2019). The geologic evaluations related to saprolite depth and extent and to Honolulu Volcanic tuff delineation are also provided in the CSM report (DON 2019).

3.1 Water Levels, Gradient, and Direction

Regional water levels were obtained from a variety of sources as detailed in the interim modeling report (DON 2018, Appendix A). These helped to establish the general water table elevations in the basalt away from the Red Hill Facility, and within the caprock closer to the coast. Regional water level data also helped to understand the regional and temporal (long-term and monthly) trends, variability, and confidence intervals for long-term information in the basalt and in the caprock. In general, water levels were very flat within the basalt aquifer, with high local variations within the caprock due to large vertical gradients. In addition, relatively high water levels were observed in multilevel wells where monitoring zones correlated with saprolite and weathered basalt. Regional water levels in the basalt had an apparent NW gradient direction across the Facility when contoured using information from seven wells located across the valleys. The interim model produced similar apparent water level gradients when contouring was informed by the same seven well locations. Details on analyses of regional water levels and gradients are available in the interim model report (DON 2018, Appendix A).

Regional water level targets used for the model are noted on Figure 3.1-1[a and b]. Aside from wells from the synoptic study, these values are the same as those used for the 2017 simulation case of the interim modeling effort. Accuracy of these measurements is low considering that they are historical values not concurrent with the current study. Also, the caprock wells are at varying and often unspecified depths, causing large variations in water level measurements because vertical flow gradients through the caprock are high. Finally, these water levels are not of particular significance as they are not in the basalt and far from the regions of interest. Weighting provided to these caprock wells during calibration was therefore lower, and they were also used in a qualitative manner; however, they provided water level values where information was otherwise sparse.

The 2017–2018 synoptic study was used to help establish local water levels and pumping responses, and to deduce water level gradients under various pumping conditions at Red Hill Shaft and Hālawa Shaft. Figure 3.1-2 shows the local water level elevations when Red Hill Shaft was pumping (maximum rate for January 20, 2018), and Figure 3.1-3 shows the local water level elevations when Red Hill Shaft was not pumping (condition on January 15, 2018, which was the longest period during the study that Red Hill Shaft was off). Hālawa Shaft was pumping at the respective average rates for both cases. These water levels were obtained after excluding barometric effects, tidal effects, and noise using the TFN analysis, and were used as targets in model calibration. Water levels are generally about 1 ft higher in wells within Moanalua Valley than in Red Hill. Wells to the NW of Red Hill had water levels that were about 2 ft lower. Aside from RHMW07 (which is a near saprolite well and which exhibits no discernable response to pumping wells as indicated in the data as well as the TFN analysis), RHMW11 Zones 6–9 (which are in saprolite), and Hālawa Deep (which monitors a deeper zone of the aquifer with a large open interval), water levels at Red Hill Facility wells were all within 0.25 ft of each other for Red Hill Shaft pumping or non-pumping conditions, indicating a very flat water table underneath the Facility. These water level measurements may incur errors due to datum or borehole alignment inaccuracies and the low precision of gyroscopic corrections. However, they were given full weighting during calibration because they are at the Facility and are within the region of interest.

A key aspect of the current study is evaluation of migration of water from beneath the Facility and the capture zone of public supply wells in the region. Hydraulic gradients, in conjunction with hydraulic conductivity and anisotropy, control the flow of groundwater within an aquifer. Therefore, in addition to the water levels, the model calibration effort included evaluations that targeted hydraulic conductivity, anisotropy, and hydraulic gradients.

The multi-well pumping test conducted by the 2017–2018 synoptic study provides good drawdown data for computing hydraulic conductivity and anisotropy between Red Hill Shaft, Hālawa Shaft, and the Red Hill monitoring wells, most of which are beneath the Facility. Accuracy of these drawdown data is excellent (possibly up to instrumentation accuracy) because drawdown is a relative condition at a well. Full weighting was provided to this information during calibration due to its significance in evaluating the hydraulic parameters that are critical to evaluations of solute migration velocities and pathways.

Hydraulic gradients were not so apparent from the data because water levels are essentially very flat locally at the Facility, while regionally, there is a possible impact of saprolite and other structural or parametric variations across the valleys. Therefore, water level differences between wells were used as a significant indicator of water level behavior locally and regionally across the domain. Water level differences between wells incur various errors related to datum and measurement errors as well as errors of gyroscopic corrections at each of the wells, which may be additive. However, they were given full weighting due to their significance to the objectives of evaluating solute migration velocities and pathways.

Previous studies had also indicated that apparent water level gradients were very flat underneath the Facility. Flow directions computed from 3-point analyses were spatially variable, indicating impact of local heterogeneity or small measurement errors, as discussed in the interim modeling report (DON 2018, Appendix A). These localized variations were also noted in the 2017–2018 synoptic study data. The apparent local water level gradients over the Facility area as indicated by these well measurements were noted to have a SW direction with components to the NW and SE, and this remained consistent through time when Red Hill Shaft was pumping. When Red Hill Shaft was not pumping, measured values indicated higher water levels at Red Hill Shaft than at some of the Facility wells (this is not seen on Figure 3.1-3 because there was no measurement of water levels for Red Hill Shaft on January 15, 2018, the day depicted on the figure). Local water level details from the previous study are provided in the interim modeling report (DON 2018, Appendix A), and details of the 2017–2018 synoptic study and associated TFN analyses are provided in the CSM report (DON 2019). The TFN analyses were further refined as detailed in Appendix A and used for calibration in this modeling effort. The TFN study had further established that long-term trends in water levels were similar at all monitoring wells, and thus local gradients do not change as a result of seasonal influences. This is also seen from the 2017–2018 synoptic data. The TFN approach was also used for model verification, as detailed in Appendix B.

For the current modeling effort, water level gradients were assessed as differences in synoptic study water level data between wells RHMW04 and all other monitoring wells, and between RHMW01 and all other monitoring wells, as requested by the AOC Party SMEs. Two cases were evaluated: one with Red Hill Shaft pumping and one with Red Hill Shaft not pumping. For both cases, Hālawa Shaft was pumping during those days. The water level differences between monitoring wells for the Red Hill Shaft pumping case (February 18, 2018) are noted on Figure 3.1-4[a and b], and for the Red Hill Shaft not pumping case (January 15, 2018) are noted on Figure 3.1-5[a and b]. These are the same dates used for evaluations of water levels on Figure 3.1-2 and Figure 3.1-3.

Figure 3.1-4a and Figure 3.1-5a show the water level differences between RHMW04 and the remaining monitoring wells at the Facility, with blue lines indicating an apparent gradient toward RHMW04 and red lines indicating an apparent head gradient away from RHMW04. Figure 3.1-4b and Figure 3.1.5b show the water level differences between RHMW01 and the remaining monitoring wells at the Facility, with blue lines indicating an apparent head gradient toward RHMW01 and red lines indicating an apparent gradient away from RHMW01. Differences between the Facility wells are small whether Red Hill Shaft is pumping or not, with larger differences only at well RHMW07, Hālawa Deep Monitor Well, and Moanalua DH43, wells that are either within the saprolite, monitoring the deeper basalt, or across the valley and therefore not considered as the shallow Facility basalt wells of significance to local flow behavior. Also, the apparent gradients at the shallow Facility basalt wells are not consistent (can be uphill or downhill) when Red Hill Shaft is pumping. When Red Hill Shaft is not pumping, the apparent gradients in shallow Facility basalt wells all point uphill toward RHMW04 on Figure 3.1-5a. On Figure 3.1-5b, these apparent gradients all point away from RHMW01 in all directions as though that was an area of high recharge. Therefore, the Facility well water level differences should not be overinterpreted, due to the very small difference values that are within the error limits of water level measurements at any one well.

3.2 PUMPING

Pumping information for the domain was obtained largely during the interim modeling study (DON 2018, Appendix A). That same pumping information is used for the current model update except for Red Hill Shaft and Hālawa Shaft, which use specific calibration-related pumping rates associated with the 2017–2018 synoptic study. Modeled pumping well/shaft locations are provided on Figure 3.2-1. Pumping rates used in the model are shown in Table 3-1. The different stress periods for Red Hill Shaft and Hālawa Shaft pumping are discussed further in Section 4 under model development and calibration.

Table 3-1: Modeled Pumping Rates

Well ID	Well Name	Screen Top (ft msl)	Screen Bottom (ft msl)	2017 Q (mgd)
2052-08	Kalihi Shaft	52	-5	7.70
2053-11	Fort Shafter	-154	-309	[redacted]
2057-04	Hickam Air Force Base	-18	-170	0
2153-02	Moanalua	-59	-269	0.02
2153-05	Moanalua Deep	-30	-1218	0
2153-07	TAMC1	-22	-272	[redacted]
2153-10	Moanalua 1	-114	-264	1.28
2153-11	Moanalua 2	-115	-265	0
2153-12	Moanalua 3	-150	-300	0
2154-01	Honolulu International Country Club	-89	-280	0.40
2255-32	ʻAiea Hālawa Shaft	107	16	[redacted]
2255-37	Hālawa 2	-29	-78	0.88
2255-38	Hālawa 3	-37	-82	0
2255-39	Hālawa 1	-31	-135	0
2355-03	ʻAiea Gulch 1	16	-38	0.77
2355-05	ʻAiea Gulch 2	18	-40	0
2355-06	ʻAiea 1	-32	-102	0.97
2355-07	ʻAiea 2	-30	-100	0
2355-09	Kalauao P1	-61	-253	5.21
2355-10	Kalauao P4	-63	-254	0
2355-11	Kalauao P2	-60	-254	0
2355-12	Kalauao P3	-61	-254	0
2355-13	Kalauao P5	-68	-254	0
2355-14	Kalauao P6	-70	-253	0
2355-16	WG Minami 2007	-102	-202	0
2356-49	Waimalu I-1	-27	-225	0
2356-50	Waimalu I-2	-25	-225	0
2356-54	Pearl CC Golf	-21	-178	0.23

Well ID	Well Name	Screen Top (ft msl)	Screen Bottom (ft msl)	2017 Q (mgd)
2356-55	Kaonohi I-2	-37	-291	0.78
2356-56	Kaonohi I-1	-44	-294	0
2356-58	Ka'amilo 1	-43	-192	0
2356-59	Ka'amilo 2	-42	-192	0
2356-60	Waimalu II-1	-77	-217	0
2356-61	Kaonohi II-1	-78	-218	0
2356-62	Kaonohi II-2	-83	-223	0
2356-63	Waimalu II-2	-179	-204	0
2356-64	Waimalu II-3	-143	-220	0
2356-65	Kaonohi II-3	-83	-223	0
2356-70	Lau Farm	40	-250	0.05
2455-02	Waimalu	-12	-78	0
2455-03	Waimalu	-80	-120	0
Red Hill Shaft SP1	Red Hill Shaft	9	3	[redacted]
Hālawa Shaft SP1 & 2	Hālawa Shaft	10	0	6.57
Red Hill Shaft SP2, 3 & 4	Red Hill Shaft	9	3	0
Hālawa Shaft SP3	Hālawa Shaft	10	0	6.33
Hālawa Shaft SP4	Hālawa Shaft	10	0	0

ID identification
Q pumping rate
SP stress period

3.3 DRAWDOWN AND PUMPING IN HĀLAWA SHAFT AND RED HILL SHAFT

Pumping and water level data were available for the 2017–2018 synoptic study. Synoptic impacts were also examined with then-available data for the interim model. Water level impacts within the pumping shaft provide a good estimate of the hydraulic conductivity surrounding the pumping location, and therefore the impacts were evaluated at Hālawa Shaft and Red Hill Shaft for their respective pumping rates.

A linear relationship between drawdown and pumping at Hālawa Shaft was estimated during the interim model to be 4.4 ft of drawdown for 10 mgd of pumping. The 2017–2018 synoptic study data indicated 3.8 ft of drawdown for every 10 mgd of pumping.

The relationship between drawdown and pumping at Red Hill Shaft was estimated during the interim model to be 1.5–3.5 ft of drawdown for [redacted] mgd of pumping. The 2017–2018 synoptic study data indicated 2.5 ft of drawdown for every [redacted] mgd of pumping. Variability was larger than at Hālawa Shaft, and therefore the water level data at Red Hill Shaft for specific pumping rates may not be as reliable.

Higher hydraulic conductivity values result in a smaller drawdown with a larger radius of influence than lower hydraulic conductivity materials. In that regard, pumping at Hālawa Shaft induces a greater drawdown than pumping at Red Hill Shaft; therefore, the hydraulic conductivity surrounding Red Hill Shaft is generally larger than that surrounding Hālawa Shaft. This is significant in calibrating and evaluating models with respect to each of these potential receptors, and therefore helps to assess the quality of a calibration in terms of the hydraulic connection of the Facility to Hālawa Shaft and Red Hill Shaft.

The water level response at monitoring wells between January 15 and February 10, 2018 (when both Red Hill Shaft and Hālawa Shaft are cycled through on and off phases) is shown on Figure 3.3-1. Specifically, this is the response after excluding barometric effects, tidal effects, and noise using the TFN analysis. Also shown on this figure are the pumping rates at Red Hill Shaft and Hālawa Shaft during this time period. Most water levels trend in a similar manner, and thus water level differences and related gradients are more stable than the water levels themselves. The information on Figure 3.3-1 is also used for model verification, as further detailed in Section 4.6.

3.4 Unit Step Response Functions

The TFN analysis developed unit step response functions at synoptic monitoring wells to changes in pumping at Red Hill Shaft and Hālawa Shaft. Figure 3.4-1 shows the unit step response functions derived from the TFN analyses for Red Hill Shaft pumping at [redacted] mgd, and Figure 3.4-2 shows the unit step response functions derived from the TFN analyses for Hālawa Shaft pumping at 6.33 mgd.

The largest response to Red Hill Shaft pumping is at Red Hill Shaft itself, followed by RHMW08, with the smallest response among the Facility wells at RHMW04. The differences are within a fraction of an inch for many wells, with the largest difference being about 0.25 ft between RHMW08 and RHMW04 at about 20 days.

The largest response to Hālawa Shaft pumping is at Hālawa Shaft itself, with smaller and almost similar responses between monitoring wells beneath the Facility. The response at Red Hill Shaft was not decipherable from the TFN analysis, because the information was masked by the response of Red Hill Shaft itself pumping.

The step responses developed by the TFN analysis for pumping at Red Hill Shaft and at Hālawa Shaft were used for model calibration, as they provide a convenient means of evaluating the individual pumping responses without interference from changes in pumping at other wells or at each other. Also, the unit step response function clearly identifies the hydraulic connection between monitoring points and these pumping locations, thus providing good information on the effective hydraulic conductivity and anisotropy ratios between these monitoring wells and pumping locations.

3.5 Spring Locations and Fluxes within the Model Domain

Although 16 natural springs are located near the SW model boundary, only two springs, Pearl Harbor Spring at Kalauao and Kalauao Spring, are located within the model domain. Both these springs were modeled as drain conditions with a drain elevation of 10 ft. The drain conductance was a calibration parameter. The locations of the springs are shown on Figure 3.5-1. A close-up of the modeled Pearl Harbor Spring at Kalauao is shown on Figure 3.5-2.

To develop spring-flow targets, a regression was evaluated between available flow data and groundwater elevations at the Navy ‘Aiea well during interim model development. Good correlations were noted at several springs by USGS studies including Oki (2005). Average water levels for 2017 at the Navy ‘Aiea well were then used with the regression equation to estimate the spring-flow rates shown in Table 3-2.

Table 3-2: Flow Estimates for Pearl Harbor Spring at Kalauao and at Kalauao Spring (2017)

Year	2017
Water level elevation (ft msl)	16.77
Spring 22 – Pearl Harbor Spring at Kalauao (mgd)	12.20
Spring 25 – Kalauao Spring (mgd)	0.25

3.6 GROUNDWATER RECHARGE

The USGS has assembled maps of recharge for average, current, and drought conditions for O'ahu (Engott et al. 2017). These were created by modeling the water budget components within the domain at a daily timescale. The models and data were obtained from the following sources:

- Average conditions (1977–2007): https://water.usgs.gov/GIS/metadata/usgswrd/XML/sir2015-5010_Oahu_WB_components_avg_climate.xml
- Drought conditions (1998–2002): https://water.usgs.gov/GIS/metadata/usgswrd/XML/sir2015-5010_Oahu_WB_components_drought.xml
- Current conditions (2001–2010): https://www.sciencebase.gov/catalog/item/5a20696de4b09fc93ddbaef8

Figure 3.6-1, Figure 3.6-2, and Figure 3.6-3 show the areal distribution of recharge for average, current, and drought conditions, respectively. The recharge distribution is similar for these different weather conditions, and therefore it is appropriate to uniformly scale the recharge values up or down depending on the weather. The highest recharge occurs in upland areas with lowest recharge toward the coast. This is the case within the model domain as well as to the NW and SE of the model domain. These recharge maps were developed considering several factors including land use, rainfall, irrigation, and evapotranspiration and are the most detailed representations available for areally distributed recharge across the site. Their accuracy at a local level could be questioned, but the trend is appropriate in that most recharge occurs in higher elevations, with less toward the coast. Local deviations in recharge were tested in preparation for the interim modeling study, and the impact was found to be minor; therefore, the recharge maps were used as is for modeling purposes during the interim study as well as the current study. Finally, the TFN analysis also indicated that local precipitation/recharge had no discernable impact to groundwater levels.

Table 3-3 lists the volumetric recharge flux estimated by these three USGS recharge maps over the model domain. The table also includes net recharge flux estimates for the dike-intruded area between the model's NE boundary and the topographic divide that were used to estimate inflow from the NE boundary of the model. Between these three data sets, the highest recharge occurred for average conditions, followed by current conditions, followed by drought conditions. About 60–70% of the inflow occurred as recharge over the model domain, the remaining being NE boundary inflow. Recharge and NE inflow during drought conditions were about 70 and 75% of current conditions, respectively, while areal recharge and NE inflow for average conditions were about 105–110% higher. The current conditions recharge map was used for the model analyses.

Table 3-3: Net Recharge Over Model Domain and NE Inflow Fluxes

Scenario	Model Domain (mgd)	NE Region (mgd)
Average Conditions (1997–2008)	35.3	22.2
Current Conditions (2001–2010)	31.6	20.7
Drought Conditions (1998–2002)	22.2	15.7

3.7 NORTHEAST BOUNDARY INFLOW

Groundwater inflow from the NE model boundary represents inflow from the dike-intruded area. The lateral inflow was assumed to include all groundwater recharge that occurs between the NE model boundary and the topographic divide. Integrating the recharge rate of Figure 3.6-1 over the area between the NE model boundary and the topographic divide gives the volumetric rates presented in Table 3-3. The NE boundary inflow was applied uniformly along the NE boundary of the model.

3.8 CONCEPTUAL WATER BUDGET

The inflow and outflow from the various groundwater flow boundaries were evaluated to establish the long-term water budget components of the domain. Using current conditions for recharge and average pumping at Red Hill Shaft and Hālawa Shaft, the water budget is shown in Table 3-4. The diffuse seepage term was the remainder from the water balance of the domain. Also, inflow and outflow from the lateral NW and SE boundaries were assumed to be negligible for this computation. This is because the stream valleys and underlying saprolite form low-hydraulic-conductivity barriers that are estimated to be several hundreds of feet below the water table in the valleys along the model's NW and SE boundaries (Oki 2005; DON 2007a; 2010). The long-term steady-state water budget indicates that of a total of 52.3 mgd inflow for current conditions, 33.7 mgd (54.5%) are lost to pumping, and 12.5 mgd (24%) flow to the springs within the model domain. These values and percentages will change depending on assumptions of no flow across NW and/or SE boundaries or on the recharge and NE inflow rates. Models tested for the current study also included conceptualization of SE inflow (instead of it being a no-flow boundary) and of reduced recharge (from the drought condition map of the USGS).

Table 3-4: Conceptual Water Budget Over Model Domain

Water Budget Component	Flow (mgd)
Inflow	
Recharge	31.6
NE Inflow	20.7
NW Inflow	0
SE Inflow	0
Total Inflow	*52.3*
Outflow	
Well Discharge	33.71
Pearl Harbor Spring at Kalauao Discharge	12.2
Kalauao Spring Discharge	0.25
Diffuse Seafloor Discharge	6.14
Total Outflow	*52.3*

4. Numerical Model Development

The March 2020 groundwater flow model was developed to assist with evaluation of the migration of potential solutes from the water table at the Facility and estimating the capture zones of adjacent water supply wells and shafts. The groundwater flow model will be used to evaluate migration pathways using particle tracking and also to estimate fate of potential solutes in groundwater beneath and beyond the Facility using transport simulations. The numerical model was designed to accommodate these objectives. Model development also considered experience gained from the interim modeling effort. The modeling software selected for the current study is discussed in Section 2.4. The PEST software was used to calibrate the models. The models were calibrated using a multi-objective approach to appropriately characterize the hydrogeologic system with a complex set of targets that focus on modeling objectives. The targets included regional and local water levels, water level differences (to assist with evaluation of gradients), transient water level responses to changing pumping at Red Hill Shaft and Hālawa Shaft (to assist with evaluation of the hydraulic connection between these shafts and the monitoring wells), drain fluxes at Kalauao Spring and Pearl Harbor Spring at Kalauao (to provide appropriate water budget components that drive where water flows), and the differential flux within the tunnel at Red Hill Shaft (to honor information observed during tunnel development). The targets were further weighted appropriately to focus on project objectives. Due to these complexities, PEST was run by creating Python scripts and editing the PEST control file outside of the Groundwater Vistas framework.

The March 2020 model considered uncertainty in parameter and conceptual representations of the hydrogeologic system by using a multimodel approach. The approach evaluated the impact of several different conceptual models, boundary stress conditions, and parameter values that bracket the hydrogeologists’, modeling team’s, and AOC Party SMEs’ current understanding of the hydrogeologic system, the range of expected parameter and boundary values, and uncertainty in conceptualization or water level observations. The approach involved fixing the conceptual model, boundary, or parameter value under investigation at its uncertainty bounds and then recalibrating the model when possible by adjusting the other parameters, or boundaries, also within reasonable ranges, using PEST. The calibration, conceptual representation, parameterization, and flow balances were then evaluated, and the model was further used for analyses of flow paths and capture. The models therefore identify and provide an understanding of the impact and limitations of various parameters or conceptualizations modeled to represent the available data. The model may be weighted during flow path and capture analyses considering the plausibility or likelihood of that parameter or conceptualization, to gain a collective understanding of the impacts. A model was also further examined to note if it provides more conservative responses than the other models at specific receptors and was flagged for further use in such situations. In addition to evaluating the impact of parameter uncertainties, the multimodel approach also accommodates the various thoughts of different stakeholders and AOC Party SMEs (e.g., simple vs. complex, impact of specific structural features [or what features may be required by a model to honor different conceptualizations of water levels and flow paths], inflow from the SE boundary, offshore vs. Pearl Harbor discharge of water not extracted or accounted in the springs, and lower recharge).

Broad but reasonable limits were set on parameter ranges to provide flexibility for PEST to find an optimal parameter set that best fits the data. Some models may not be calibrated as well as others. Some may have less-refined calibration at finer scales. Some models show steeper fit to the data, while others show a gentler fit. Some parameters hit the maximum or minimum anticipated limits and wanted to go beyond. This provides information on the limitations of a model (or of the modelers’ anticipated limits) but does not invalidate those that have poorer calibration to any of the various metrics. For instance, a uniform basalt property will necessarily provide results that are an average of observed conditions without necessarily fitting the individual data points. Also, data errors and subsequent data corrections may change the data fit, as had occurred during the interim modeling study. Regardless, considering the objectives of the current study, the impact of this average behavior of a uniform basalt conceptualization on the flow paths is the important factor. Therefore, models individually and collectively provide an understanding of the migration behavior of water under different conditions of parameter, data, or conceptual uncertainty or variability.

4.1 Horizontal Gridding

The March 2020 groundwater flow model grid is shown on Figure 4.1-1. The grid is oriented at an angle of 213.6 degrees clockwise from north to align with the orientation of basalt flows that impact the principal direction of horizontal anisotropy, as suggested by the AOC Party SMEs. The interim model grid had an orientation of 200 degrees clockwise from north, which is not much different from the more recently interpreted values.

A maximum grid size of 500 ft was employed for the parent grid, with quadtree refinements performed along the NW and SE lateral boundaries, through the valleys, along Red Hill, Hālawa Hill (the low intervalley ridge separating North and South Hālawa Valleys), around the pumping wells, along Red Hill Shaft and Hālawa Shaft, and at geologic boundaries. Horizontal grid refinement is similar to that of the interim modeling study (DON 2018, Appendix A) except that additional refinement is included in the March 2020 model encompassing the Facility and Hālawa Shaft westward past Kalauao Stream and down to Pearl Harbor.

A two-level quadtree refinement was applied along the NW and SE lateral boundaries, decreasing the cell size from 500 ft to 125 ft. A two-level refinement was also used through the valleys to provide resolution on valley fill and saprolite extent, and along Red Hill and Hālawa Hill ridges to provide resolution in focus areas of interest. A three-level refinement was used around the pumping wells, providing a cell size of 62.5 ft near the wells. This refinement is sufficient around the wells because the Thiem equation is applied within MODFLOW-USG to capture the drawdown within a well that is represented by Connected Linear Network (CLN) cells. To capture the groundwater interactions with water supply shafts, a four-level quadtree refinement was applied along the Red Hill and Hālawa Shafts, reducing the grid size from 500-ft cells to 31.25-ft cells. Figure 4.1-2 depicts examples of the refinements around these features. A two-level refinement was also provided at the boundaries of geologic features such as the surface tuff, tuff cones, and marine and alluvial sediments to better capture anticipated sharp hydraulic gradients. The Discretization (DIS) Package of MODFLOW-USG was used to define the model cells.

4.2 Model Layering

The modeled domain was divided into nine layers as shown schematically on Figure 4.2-1. The land surface forms the top of the model domain and rises from sea level near the coast to over 1,200 ft along the ridges. Bathymetry of Pearl Harbor and offshore regions provided the top of the model domain when not on land. The freshwater/saltwater interface that forms the bottom of the domain was taken as the 50% isochlor level from the USGS SUTRA modeling effort (Oki 2005). The interface is deep in unconfined portions of the basalt (700–900 ft below sea level), and rapidly rises to sea level in offshore portions of the domain.

Layer 1 discretizes the caprock in the downstream areas and the valley fill in the valleys. In regions where caprock or valley fill do not exist, the Layer 1 cells were made inactive (i.e., Layer 1 is not simulated). Topographic surface elevations served as the top of Layer 1 (or the top of Layer 4 where basalt was unconfined). Figure 4.2-2 shows the topographic surface elevation across the model domain. Figure 4.2-3 shows the thickness of Layer 1. The valleys are thicker toward the coast where they intersect the caprock. The thickness of the caprock itself increases from the valleys toward the coast. However, the freshwater thickness within the caprock decreases when the freshwater/saltwater interface intercepts the caprock to surface offshore.

Layers 2 and 3 discretize the saprolite that lies largely underneath the valleys and portions of the caprock. These model layers are absent where saprolite is absent. The saprolite thickness is evenly divided among Layers 2 and 3. Two layers were used to represent the saprolite to allow flexibility for evaluating differential weathering characteristics of the hydraulic properties.

Layers 4 through 9 discretize the basalt aquifer. Multiple layers were used to discretize the basalt to provide finer vertical resolution near the water table for capturing vertical gradients and as required for subsequent solute transport simulations. Layer 4 lies beneath saprolite and beneath the caprock where saprolite is absent, with a thickness of 5 ft where confined. In the unconfined basalt underneath the ridges, the bottom of Layer 4 was no higher than 15 ft msl to provide a thin saturated thickness near the water table and limit the number of dry cells above the water table. This thin layer at the water table will be useful for future fate and transport modeling efforts. Subsequent layer thicknesses were as follows: Layer 5 was 10 ft thick, Layer 6 was 20 ft thick, Layer 7 was 30 ft thick, Layer 8 was 50 ft thick, and Layer 9 was the remaining thickness down to the saltwater interface. Also, the bottom of all layers was defined by the freshwater/saltwater interface with the numerical grid-block cells being inactive (not simulated) when below the interface.

Figure 4.2-4 shows the model grid for Layer 1, indicating that the layer is absent where basalt is unconfined. Also, the figure demarcates the surface representation of tuff, marine, and alluvial sediments, which was discussed with the AOC Party SMEs. Figure 4.2-5 shows the model grid for Layer 4 and demarcates the tuff cones represented in the model, also discussed with the AOC Party SMEs. These tuff cones are extended through all layers down to Layer 9. Figure 4.2-6 through Figure 4.2-10 show the model grid for Layers 5 through 9, respectively. The thickness of these layers pinches out in downstream areas where the saltwater interface is above the layer surface, as noted in the schematic of Figure 4.2-1. Model cells with freshwater thickness of zero were inactivated. The bottom elevation of the model domain is shown on Figure 4.2-11.

The saprolite extent and depth were better defined and more accurately represented in the March 2020 model with recent assimilation of wellbore and geophysical data. However, there was some uncertainty regarding saprolite depth in South Hālawa Valley adjacent to the Facility. Since this is a critical area of the model and saprolite depths are close to the water table, the modeling effort considered two representations of saprolite depth, as discussed with AOC Party SMEs. Figure 4.2-12 shows the bottom elevation of the saprolite for the first representation that interpreted the saprolite in South Hālawa Valley to be deeper, while Figure 4.2-13 shows the second shallower interpretation that was discussed with the AOC Party SMEs. The water table elevation in the Facility area is generally around 15–20 ft. The impact of saprolite depth uncertainty can be evaluated by comparing the results of the two models. In the interim modeling effort, conservative estimates of depth and downstream extent of the saprolite barrier were used since this information was unavailable at that time.

Experience with the interim model guided model layering. Separate layers to represent the saprolite provided more flexibility in designing the grid. Additional layering within the basalt as compared to the interim model layering provides better resolution for subsequent solute transport simulations. Finally, the bottom of the model domain was better represented by the 50% isochlor from the USGS modeling effort than by using the Ghyben-Herzberg vertical equilibrium approximation.

4.3 Model Parameterization

The major hydrogeologic units delineated within the model include the caprock, valley fill, saprolite, and basalt. The geologic setting was detailed in the CSM report (DON 2019) and is summarized in Section 2.2.1 of the current report.

Experience with the interim model guided model parameterization. The caprock, which was considered homogeneous in most of the models developed for the interim modeling effort, was segregated in the March 2020 model into alluvial sediments, marine sediments, and Honolulu Volcanic tuff (overlying alluvial sediments or marine sediments), as shown on Figure 4.2-4. Homogeneous material properties were assigned to each of these caprock units. The material was modeled as horizontally isotropic, with vertical anisotropy resulting from the alluvial and marine depositional environments of the aquifer sub-units that form the caprock. The tuff cones were also included in Layers 2 through 9 as a separate hydrogeologic unit and demarcated on Figure 4.2-5. The model was calibrated such that the hydrogeologic properties reside within reasonable ranges for each of the materials as determined by field experience and past studies, as shown in Table 4-1.

Table 4-1: Model Parameter Ranges

Geologic Material	Unit	Layer	Minimum Value	Maximum Value	Justification
Caprock Kh (marine)	ft/d	1	500	2,500	Based on interim model, literature data, and SME input
Caprock Kv (marine)	ft/d	1	0.001	15	Based on interim model, literature data, and SME input
Caprock Kh (alluvial)	ft/d	1	0.1	20	Based on interim model, literature data, and SME input
Caprock Kv (alluvial)	ft/d	1	0.001	2	Based on interim model, literature data, and SME input
Valley Fills, Kh	ft/d	1	2	200	Based on interim model and literature data
Valley Fills, Kv	ft/d	1	0.01	10	Based on observations, interim model, and literature data
Saprolite, Kh	ft/d	2 and 3	0.1	10	Based on interim model and literature data
Saprolite, Kv	ft/d	2 and 3	0.001	0.1	Based on observations, interim model, and literature data
Tuff extent, Kh	ft/d	1	0.01	200	Based on observations and SME input
Tuff extent, Kv	ft/d	1	0.01	15	Based on observations and SME input
Tuff cone, Kh	ft/d	2 to 9	0.01	50	Based on observations and SME input
Tuff cone, Kv	ft/d	2 to 9	0.001	5	Based on observations and SME input
Basalt, Kh	ft/d	4 to 9	500	20,000	Based on observations, interim model, literature data, and SME input
Basalt, Kv	ft/d	4 to 9	2	200	Based on observations, interim model, literature data, and SME input
GHB South	ft^2/d	1	0.0005	1	Based on interim model and calibration
GHB PH	ft^2/d	1	0.0025	5	Based on interim model and calibration
KalauoSpFarm	ft^2/d	1 to 4	0.01	1,000	Based on interim model and calibration
Kalauao Sp	ft^2/d	1 to 4	1	10,000	Based on interim model and calibration
Recharge multiplier SP1&2	—	1	0.5	1.5	Based on expert judgement for a reasonable range
Recharge multiplier SP3&4	—	1	0.5	1.5	Based on expert judgement for a reasonable range
Basalt anisotropy	—	4 to 9	2	5	Based on interim model and literature data
skinrhs	ft^2/d	6	0.1	1.00×10^8	Based on interim model and calibration
skinhas	ft^2/d	6	0.1	1.00×10^8	Based on interim model and calibration
Caprock Sy (marine)	—	1	0.02	0.2	Based on interim model and literature data
Caprock Ss (marine)	1/ft	1	1.00×10^{-8}	1.00×10^{-3}	Based on interim model and literature data
Caprock Sy (alluvial)	—	1	0.02	0.2	Based on interim model and literature data

Geologic Material	Unit	Layer	Minimum Value	Maximum Value	Justification
Caprock Ss (alluvial)	1/ft	1	1.00×10^{-8}	1.00×10^{-3}	Based on interim model and literature data
Valley Fills, Sy	—	1	0.02	0.2	Based on interim model and literature data
Valley Fills, Ss	1/ft	1	1.00×10^{-8}	1.00×10^{-3}	Based on interim model and literature data
Saprolite, Sy	—	2 and 3	0.02	0.2	Based on interim model and literature data
Saprolite, Ss	1/ft	2 and 3	1.00×10^{-8}	1.00×10^{-3}	Based on interim model and literature data
Tuff extent, Sy	—	1	0.02	0.2	Based on interim model and literature data
Tuff extent, Ss	1/ft	1	1.00×10^{-8}	1.00×10^{-3}	Based on interim model and literature data
Tuff cone, Sy	—	2 to 9	0.02	0.2	Based on interim model and literature data
Tuff Cone, Ss	1/ft	2 to 9	1.00×10^{-8}	1.00×10^{-3}	Based on interim model and literature data
Basalt, Sy	—	4 to 9	0.02	0.2	Based on interim model and literature data
Basalt, Ss	1/ft	4 to 9	1.00×10^{-8}	1.00×10^{-3}	Based on interim model and literature data

ft^2/d square feet per day
Q pumping rate
GHB general head boundary
skinrhs conductance of rock material surrounding Red Hill Shaft
skinhas conductance of rock material surrounding Hālawa Shaft
SP stress period

The valley fill and saprolite were modeled as horizontally isotropic. The vertical hydraulic conductivity value of these units was lower than the horizontal hydraulic conductivity. Valley fill and saprolite material properties were estimated from literature (Table 4-1) and calibrated to qualitative evaluations of the water levels within, as there were few observations within.

Most of the models developed for the interim modeling effort used homogeneous properties to represent the basalt. A similar approach was used in the March 2020 modeling effort. The TFN analyses determined that the basalt acted as an equivalent porous medium. Data at Red Hill are available that indicate possible local-scale heterogeneities; however, there is little information available to indicate how these heterogeneities may propagate at the regional scale. The geologic model indicates that basalt has a regional anisotropy due to the nature and direction of lava flows, with higher hydraulic conductivities in the direction of lava flow that are several times higher than in the directions transverse to lava flow—contributing factors also being the lava tubes and clinker zones that are also generally aligned with the direction of lava flow, and regional features such as valleys also aligned in the general SW direction. Also, past studies (Souza and Voss 1987; Gingerich and Voss 2005; Oki 2005; DON 2007a; 2010) have indicated that homogeneous parameterization was adequate to describe the aquifer conditions at a regional scale, along with valley barriers and strong horizontal anisotropy in the SW direction. The homogeneous basalt models provide an understanding of the hydrogeologic behavior of various conceptualizations and the deviations that occur with increasing levels of complexity.

The hydrogeologic conceptual model indicates local heterogeneities at the water table beneath the Facility with very flat water-level gradients. Also, Red Hill Shaft tunnel inflows show a much higher production of water from the upper (distal) one-third of the tunnel than the lower two-thirds (CSM). Therefore, the heterogeneous basalt models were also included with the study (using the pilot points or conceptual fast-flow pathways) to analyze the impact of localized complexities and whether adding complexity can explain the data. Hydraulic conductivity values and distributions for the various models are detailed in Section 5.

The specific storage was generally simulated as uniform within the various geologic materials. Basalt specific storage was a PEST calibration parameter for the transient model periods.

Particle tracking and solute transport simulations also required estimates of the effective transport porosity. The effective porosity was taken equal to the specific yield for the current modeling efforts. A value of 1% was used for the effective porosity to estimate travel times within the basalt unless otherwise stated (e.g., heterogeneous and clinker zone models).

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

4.4 MODEL BOUNDARY CONDITIONS

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

The recharge distribution map prepared by the USGS for current conditions (shown on Figure 3.6-2) was used for the models. Scaling factors were provided to these recharge values during calibration. The recharge values were applied in the model using the RCH Package of MODFLOW.

A flux boundary condition was applied along the NE lateral model boundary using the WEL package of MODFLOW. This package does not simulate a well, but rather allows for injection or extraction of water from the domain. Inflow from the NE boundary was estimated by considering groundwater recharge from the boundary up to the topographic divide, as detailed in the interim modeling report (DON 2018, Appendix A). The recharge map of current conditions was used to provide the flux. The flux was applied to the lowermost model layer only, for numerical convenience. The water redistributes to all overlying numerical layers at the boundary itself, as was noted in the simulations (also in the interim model).

Water flow across the lateral NW and SE boundaries is assumed to be relatively small since the conceptualized flow direction is parallel to these boundaries. Sensitivity analyses to these boundary conditions were performed in the interim modeling effort; results indicated that either flows were generally low, that there may be local circulation with flow in and out of the boundary, or that flows were unrealistically large to maintain reasonable water level values. However, a conceptual representation of flow across the SE boundary was further considered as a possibility for the March 2020 modeling effort, considering some literature that suggests such a possibility (Mink 1980). Therefore, the NW and SE lateral boundaries were simulated using the GHB Package of MODFLOW to provide the flexibility for boundary flow, but with a very low GHB conductance to simulate minimal flows across the boundary for the other models.

The springs within the model domain were represented using the DRN Package of MODFLOW. Spring fluxes were estimated as detailed in the interim modeling report (DON 2018, Appendix A) and shown in Table 3-2. These spring fluxes were incorporated into model calibration targets.

Water supply wells and shafts within the model domain were simulated using the CLN package of MODFLOW-USG, which simulates vertical or horizontal conduit features such as wells and shafts. The well may be screened in multiple groundwater model layers, and shafts may cross multiple groundwater model cells. Withdrawals are then applied to the CLN cell using the WEL package of MODFLOW. The "AUTOFLOWREDUCE" option of the WEL package was used to prevent water levels from going below the well bottom elevation, and additional constraints were incorporated into the PEST simulations to ensure that all pumping was appropriately simulated. Pumping information within the model domain was assimilated as detailed in the interim modeling report (DON 2018, Appendix A).

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

4.5 Calibration Simulation Setup and Targets

Model calibration was conducted using the PEST parameter estimation software. PEST is a non-linear inverse modeling program that automatically runs the MODFLOW-USG model multiple times, by varying selected input parameters and performing optimization, until the difference between the model outputs and the site-specific observation targets is minimized. The calibration simulations were designed to provide PEST with information on water levels, water level differences, flow to springs, and water level responses to changes in pumping at Red Hill Shaft and Hālawa Shaft, at all monitoring wells of the 2017–2018 synoptic study. Water level and spring-flow information provides the model with the appropriate hydrology. Water level differences between wells helps to evaluate the gradient, which provides the model with information critical to the objectives of evaluating migration behavior of water from beneath the Facility. Water level responses to changes in pumping provide the model with information useful for determining the hydrogeologic parameters (transmissivity, anisotropy, and specific storage) of the basalt, which is also critical for evaluating flow velocity and direction.

Results from the TFN analysis were used to provide water levels for calibration that are cleaned of barometric and ocean/earth tide influences. These water levels were also used to compute head difference targets. The unit step response function generated from the TFN analysis was used for calibration. The entire calibration simulation was set up using four stress periods in the model. Table 4-2 shows the stress period setup.

Table 4-2: Stress Period Setup for Calibration Models

Stress Period #	Time (d)	Description
1	1	Steady state, Red Hill Shaft pumping [redacted] mgd, Hālawa Shaft pumping 6.57 mgd
2	16	Transient response to shutting off Red Hill Shaft
3	17	Steady state, Red Hill Shaft pumping 0 mgd, Hālawa Shaft pumping 6.33 mgd
4	32	Transient response to shutting off Hālawa Shaft

The first stress period of the model was steady state, simulating January 20, 2018 conditions with Red Hill Shaft pumping at [redacted] mgd and Hālawa Shaft pumping at 6.57 mgd. Figure 3.1-1[a and b] show the regional water level targets for this stress period. A lower weighting of 0.3 was initially provided for these regional water level targets during PEST calibration, because they do not specifically pertain to the modeling objectives of estimating migration pathways in the basalt, and furthermore, their accuracy is low. Figure 3.1-2 shows the water level targets pertaining to the synoptic study. These targets were initially included in the model with unit weighting. Figure 3.1-4[a and b] shows the water level differences between the 2017–2018 synoptic study observation wells and RHMW04, and between the synoptic observation wells and RHMW01. The water level differences were initially provided unit weighting for calibration because they are indicative of gradients that govern flow magnitude and direction, which are a primary objective for the model. However, the measurements of absolute water levels or gradients between well pairs may incur errors due to datum measurements and borehole gyroscopic tape corrections for the reasons previously discussed. The spring fluxes at Pearl Harbor Spring at Kalauao and Kalauao Spring were also calibration targets with target values shown in Table 3-2. Weighting on these targets was determined after preliminary PEST simulations such that the flux magnitudes did not overwhelm water level targets in the objective function. Finally, the extraction rates at pumping wells were also included in the PEST multi-objective function to ensure that pumping did not reduce with bottom-hole conditions during calibration.

The second stress period of the model simulated the step response for Red Hill Shaft shutting off. The transient stress period length was 15 days to capture the observed response rather than the extrapolation by the TFN analysis for longer time periods. Figure 3.4-1 shows the associated recovery at the 2017–2018 synoptic study monitoring wells. These recoveries are significant for evaluating the hydrogeologic properties between Red Hill Shaft and the monitoring wells, and therefore unit weighting was applied to these response targets during calibration. The drawdown targets are the most accurate available measurements, up to the calibrated instrument precision, as they are relative conditions and do not incur errors of absolute water level measurement. However, there are very small errors in the TFN analysis itself. These small errors (residuals) were further minimized in the refined TFN analysis (Appendix A) used in the modeling effort.

A third stress period was developed for January 15, 2018 steady-state conditions with Red Hill Shaft not pumping and Hālawa Shaft pumping at 6.33 mgd. Figure 3.1-3 shows the local water level targets for this stress period. These water levels were provided with a unit weighting, as in Stress Period (SP) 1. The recharge factor was adjusted for this stress period to account for the storage term of transient conditions. This is because preliminary simulations indicated that steady state was not achieved for as long as 3 years. Figure 3.1-5[a and b] shows the water level differences between the 2017–2018 synoptic study monitoring wells and RHMW04, and between the wells and RHMW01. The water level differences were also provided with a unit weighting in the PEST calibration as in SP1.

The fourth stress period of the model simulated the step response for Hālawa Shaft shutting off. The transient stress period length was 15 days to capture the observed response rather than the extrapolation by the TFN analysis of later days. Figure 3.4-2 shows the associated recovery at the 2017–2018 synoptic study monitoring wells. As noted earlier, this drawdown information is the most accurate available data and is useful for determining the net effective hydraulic conductivity between Hālawa Shaft and the monitoring wells. A unit weighting was applied to these response targets during calibration.

Qualitative and statistical calibration metrics were used to evaluate each model. Qualitative metrics included comparison of simulated and observed water levels and head differences on a map and visual evaluation of the rebound curves for shutting off pumping at Red Hill Shaft (SP2) and at Hālawa Shaft (SP4). Water levels and head differences help to evaluate how well the gradients may be represented locally at the Facility as well as regionally across valleys. The rebound curves help to evaluate the hydraulic properties between Hālawa Shaft, Red Hill Shaft, and the Facility, which are also important in computation of flow direction and velocities. Statistical metrics include mean error, root mean square (RMS) error, scatter plots, and regression coefficients on observed and simulated water level differences. Statistical metrics help to understand general calibration behavior and facilitate inter-model comparisons.

The XMD linear solver option of the Sparse Matrix Solver (SMS) Package of MODFLOW-USG was used for all simulations. The upstream weighted formulation with Newton-Raphson linearization was used to resolve nonlinearities in a robust manner. Thus, the outer iterations are performed using the Newton-Raphson scheme, while inner iterations are performed using the ORTHOMIN solution option of the XMD solver.

4.6 VERIFICATION SIMULATION SETUP

The transient verification simulations were conducted for the period January 15, 2018 through February 10, 2018. This is the period when both Red Hill Shaft and Hālawa Shaft were cycled through on and off stages for multiple days. Figure 4.6-1 shows the pumping rates and associated water level changes at all 2017–2018 synoptic study monitoring wells. These pumping rates were used for the verification simulation by creating multiple stress periods at Red Hill Shaft and Hālawa Shaft.

Five stress periods were delineated from the data for the verification simulations. The first stress period was a steady-state simulation of conditions when Red Hill Shaft was not pumping for a period of 5 days. Stress period details for this verification evaluation are listed in Table 4-3. Values in the table for Hālawa Shaft and Red Hill Shaft are at average conditions within each stress period, and therefore the small time-scale fluctuations within a stress period were smoothed out. Average 2017 pumping conditions were applied to all the other wells within the domain through all stress periods. Recharge applied for all stress periods was equal to that of the first stress period of the calibrated model. Since there may be transient storage effects, the absolute water levels may be different for the verification model steady-state conditions; however, it provides information on water level changes due to changes in pumping. The simulated water level fluctuations of Figure 4.6-1 were evaluated visually against observations to verify the models.

Table 4-3: Stress Periods for Verification Simulation

Stress Period #	Start Date	End Date	Duration (days)	Total Days	Red Hill Shaft Pumping (mgd)	Hālawa Shaft Pumping (mgd)
1	10-Jan-18	15-Jan-18	Steady state	0	0	6.3131
2	15-Jan-18	19-Jan-18	4.4236	4.4236	[redacted]	6.3146
3	19-Jan-18	27-Jan-18	8.0694	12.4931	[redacted]	6.1997
4	27-Jan-18	6-Feb-18	9.4965	21.9896	[redacted]	0
5	6-Feb-18	10-Feb-18	4.4931	26.4826	[redacted]	12.0889

The TFN approach was also used to verify the model (Appendix B). For this approach, the calibrated model unit step response functions were extracted at the monitoring well and Red Hill Shaft and Hālawa Shaft locations. Using a similar approach as in the TFN modeling (DON 2019), the water level response at each monitoring well due to a hydraulic stress was simulated by the convolution integration of the hydraulic stress time series and the calibrated model unit step response function. The water level response due to pumping of Red Hill Shaft was calculated using the Red Hill Shaft pumping timeseries and the calibrated model unit step response function from SP2. Similarly, the water level response due to Hālawa Shaft was obtained from the Hālawa Shaft pumping timeseries and the calibrated model unit step response function from SP4. The total water level change was modeled by superposition of the water level response timeseries due to pumping changes, barometric and tidal influences as determined by the TFN modeling, and the contribution of unknown sources (i.e., the TFN modeling residual, which cannot be explained by pumping, barometric, or tidal influences).

4.7 PARTICLE TRACKING SIMULATION SETUP

The models were used in the current study to evaluate migration of water from beneath the Facility and hydraulic capture at critical public supply shafts. Specifically, the concerns included evaluation of source water zones for Red Hill Shaft and Hālawa Shaft, pumping rates required at Red Hill Shaft to capture water from beneath the Facility, and time that Red Hill Shaft could remain shut off and still capture water that originated from the Facility after its restart. The mod-PATH3DU (SSPA 2018) particle tracking code was used to perform these evaluations.

Particle tracking is a tool that describes groundwater flow paths. Two types of particle tracking procedures are used in this modeling process. Forward particle tracking involves placing a "conservative" particle at various points that then describe the particles flow going forward over time. Backward particle tracking relies on the placement of particles at a well (or other point of interest) and then using the model to describe the various flow paths going back in time that these particles could potentially take. The envelope created by this method for particles that all flow to a well describe the capture zone for that well.

A reverse particle tracking approach was used to evaluate the source water zones (capture envelopes) of Hālawa Shaft and Red Hill Shaft. The particles were seeded around the shafts and allowed to migrate in the reverse direction of groundwater flow to evaluate its migration pathway toward the shafts. The groundwater flow-field was generated by running the model in steady-state mode for various scenarios, including Red Hill Shaft pumping at [redacted] mgd (slightly below the permitted rate of [redacted] mgd) and Hālawa Shaft pumping at 12 mgd, with various on and off combinations to address the conditions of interest.

A forward particle tracking approach was used to evaluate the migration of water from beneath the Facility. Particles were seeded at the water table beneath the tanks as shown on Figure 4.7-1 and allowed to migrate with groundwater flow. The groundwater flow field was the same as used for the reverse particle tracking models. Capture at Red Hill Shaft for pumping [redacted] mgd was evaluated in this study as an alternative to estimating the rate at which its capture zone would encompass the Facility.

A visual evaluation was performed to estimate the time that Red Hill Shaft could remain shut off and still capture water that originates from the Facility. Specifically, the timing markers of forward particle tracks without Red Hill Shaft pumping were compared with the reverse particle tracks at Red Hill Shaft when it was pumping. The intersection of the two was used as an indicator of water that can be pulled back by Red Hill Shaft. The timing marker of the forward tracks, at the boundary of the reverse track envelope, provides an estimate of the elapsed time limit that Red Hill Shaft can remain off and still maintain capture when turned on. The analyses were performed for particles that originate from the Facility and with particles that originate from the location of Red Hill Shaft itself.

5. Model Calibration and Application for Evaluation of Migration and Capture

The March 2020 groundwater flow multimodel approach was developed to assist with evaluation of groundwater flow from the water table underneath the Facility and for estimating the source water zones of nearby water supply shafts and wells under a range of potential hydrogeologic conditions. In addition, these models can be used to support future fate and transport evaluations. These objectives were taken into consideration during model development and calibration. Models were developed as per discussions in Sections 4.1 through 4.4, and calibrated and verified using the approach discussed in Sections 4.5 and 4.6. Particle tracking was used to evaluate flow behavior, evaluate source water zones, and address various other issues of concern as noted in Section 4.7.

A multimodel approach was used for the March 2020 modeling report to capture (and help bound) the impact of uncertainty in parameter and conceptual representation. Therefore, each model was calibrated to the various calibration targets using PEST. The significant behavior of each model was evaluated by identifying parameters that reach their bounds and evaluating key calibration results as identified in Section 4.5. All models were then applied toward evaluation of migration behavior and source water zones for permitted pumping conditions at key water supply locations, to understand the resulting impact of uncertainty.

Issues addressed by the current model application included:

- Evaluation of the capture zone created by the permitted pumping rate at Red Hill Shaft, and whether it captures all water from the water table beneath the Facility/tank farm footprint when Hālawa Shaft is pumping
- Evaluation of the migration of water from the water table beneath the tanks when Red Hill Shaft is not pumping
- Evaluation of the source water zones of Red Hill Shaft and Hālawa Shaft when both are pumping, and when the other shaft is not pumping
- Evaluation of travel times from the water table beneath the tanks to Red Hill Shaft when Red Hill Shaft is pumping
- Evaluation of travel times from the water table beneath the tanks to other receptors when Red Hill Shaft is not pumping
- Evaluation of the time that Red Hill Shaft can remain turned off and still pull back water that escaped past it when turned back on at average pumping rates
- Evaluation of the time that Red Hill Shaft can remain turned off and still capture water that escaped from the Facility when turned back on at average pumping rates

The models that were simulated as part of the March 2020 deliverable are summarized in Table 5-1. Numbering of the models in this report starts from Model #51 and sequentially increases in the order in which the models were developed (although several models were developed in parallel so there is no strict order to the current number sequencing). This approach helps to keep track of model files appropriately. The earlier model numbers included those that were part of the interim modeling effort (that warranted further evaluation), and subsequent models that helped to address some of the Regulator SMEs' concerns related to groundwater flow modeling. In the following subsections, each model is discussed independently including the calibration, verification, and application results. A summary of all models is provided below.

1 **Table 5-1: List of Models**

Run ID	Description	Significant Features	Calibration and Verification Summary and Conclusions	Application Summary and Conclusions
51	Homogeneous basalt with CSM saprolite	Evaluate regional flow behavior.	—	Water from beneath the Facility is captured by Red Hill Shaft when it is pumping.
51a	Limit horizontal anisotropy (3:1)	Assumed to be a conservative assumption and used in previous modeling efforts.	High head values were simulated low. There was less simulated water level difference in wells across Kalihi Valley, Moanalua Valley, Red Hill, North and South Hālawa Valleys, and Waimalu Valley. Pumping response to Red Hill Shaft was generally underpredicted (higher simulated connectivity), and pumping response to Hālawa Shaft was generally overpredicted (lower simulated connectivity).	Migration from the Facility was to the west and then NW when Red Hill Shaft is off, with some tracks migrating toward Hālawa Shaft and others toward Pearl Harbor.
51b	10:1 anisotropy	Evaluate impact of possible higher horizontal anisotropic conditions.	Model #51b captures the simulated water level differences from SE to NW across valleys better. The model provided NW directional regional head gradients. Pumping response to Red Hill Shaft was generally underpredicted (higher simulated connectivity), and pumping response to Hālawa Shaft was generally overpredicted (lower simulated connectivity).	Migration from beneath the Facility was still to the west and then turned NW when Red Hill Shaft is off. The elongated capture zone of Hālawa Shaft caused by the larger anisotropy intercepted water from the Facility.
51c	Zoned along ridges	Evaluate impact of flexibility along each hill.	Simulated water level difference statistics were better than Model #51a and similar to Model #51b. Model #51c better captures drawdown behavior than Model #51a for Red Hill Shaft, but Hālawa Shaft connectivity was still too large.	Migration from beneath the Facility was to the west and continued toward Pearl Harbor, being intercepted also by wells 2255-39 and ‘Aiea Hālawa Shaft. Migration behavior is different from that of previous models.
51d	Calibrate on anisotropy	Evaluate what value of anisotropy best captures regional water level conditions (17.54 for this model).	PEST would gravitate toward values between 17 and 18 with vertical hydraulic conductivity of 40–70 ft/d during the different calibration runs. The model provided good calibration to regional water levels and differences. Model #51d provides a better match to Red Hill Shaft pumping than Model #51a or Model #51b, but still has too much connectivity between Hālawa Shaft and the Facility.	Migration behavior is similar to model with less (10:1) anisotropy. Larger anisotropy caused capture zones of wells and shafts to be wider.
51e	Zoned along ridges and within valleys	Evaluate impact of additional zonation since zoned conditions of Model #51c did not adequately distinguish itself from the average conditions of homogeneous Model #51a.	Additional zonation from Model #51c can capture regional water level conditions and connectivity between Red Hill Shaft, Hālawa Shaft, and the Facility. Also, the model provided relatively flat gradients at Red Hill due to a damming effect.	Migration from the Facility was to the west and continued toward Pearl Harbor, to discharge into Pearl Harbor Springs when Red Hill Shaft was not pumping.

Run ID	Description	Significant Features	Calibration and Verification Summary and Conclusions	Application Summary and Conclusions
51a–51e	Collective evaluation of the homogeneous models	Evaluate impact of different homogeneous conceptualizations on calibration and migration behavior of water from the Facility.	Collectively, the simulations indicate a basalt anisotropy of about 17 to capture regional water levels and differences. Offshore outflow was larger compared to Pearl Harbor outflow for the higher anisotropy cases (still significantly smaller than other outflows). Zonation of Model #51e provided best fit to all calibration metrics.	Flow occurs down Red Hill ridge from areas of recharge to areas of discharge (wells, springs, Pearl Harbor, or the ocean). Water from the Facility is captured by Red Hill Shaft when it is pumping; however, the different uncertainties evaluated here provide different migration behavior when Red Hill Shaft is not pumping. Zonation of Model #51e altered flow paths and travel times most significantly compared to average homogenous basalt models.
52	Alternate saprolite	Test impact of alternate saprolite extent and depth below water table.	The calibration metrics were not impacted by the range of simulated uncertainty in extent and depth of saprolite beneath South Hālawa Valley.	Results are almost identical to Model # 51a, which was used as the basis for this simulation, with only slight differences in travel times. Saprolite extent and depth did not impact calibration or flow paths of concern within the uncertainty limits tested (20–40 ft) considering that the basalt extends to depths of 600–800 ft beneath it.
53	Heterogeneous basalt	Evaluate impacts of regional- and local-scale heterogeneities using pilot points using random initial parameter distributions.	A heterogeneous model can capture regional water level conditions and connectivity between Red Hill Shaft, Hālawa Shaft, and the Facility.	Migration behavior was similar to that of many other models when Red Hill Shaft was not pumping, with some water from the Facility turning toward Hālawa Shaft, while the rest flowing toward Pearl Harbor Spring at Kalauao, being intercepted by wells 2255-39 and ʻAiea Hālawa Shaft.
54	Heterogeneous basalt	Evaluate alternate impacts of regional- and local-scale heterogeneities using pilot points using initial parameter distributions that block downhill flow from the Facility.	A heterogeneous model can capture regional water level conditions and connectivity between Red Hill Shaft, Hālawa Shaft, and the Facility. The damming effect of water behind Red Hill Shaft was not created, even with starting conditions favorable to such conditions.	Migration behavior was different from all other models when Red Hill Shaft is not pumping, with water from the Facility migrating due NW being captured by Hālawa Shaft. Thus, it was possible to calibrate a model to available data with flow from the Facility toward the NW as per one of the conceptualizations of the flow system.
55	Conceptual clinker zone	Evaluate impact of fast-flow pathway in groundwater beneath the Facility.	PEST would gravitate toward a clinker K-value of about 30,000 ft/d. Red Hill Shaft pumping changes are better predicted at the Facility, indicating better representation of that connectivity.	Flow was controlled to a certain extent by fast flow pathways; however, travel times were sensitive to clinker porosity.
56	Structural alterations to tuff cones	Evaluate impact of a damming effect of tuff cones on flow down Red Hill.	Water level gradients were more to the NW than the homogeneous model (Model #51a), but reverse gradients were not created.	Flow from the Facility was also more to the NW than the homogeneous model (Model #51a), with water from Red Hill Shaft location also migrating to Hālawa Shaft when Red Hill Shaft was off.
57	Recharge uncertainty	Evaluate impact of applying drought condition recharge inflow.	Calibration to regional water levels and water level gradients was good. Connectivity between the Facility and Hālawa Shaft was overpredicted, although less than for Model #51a.	Flow from the Facility and source water zones of Red Hill Shaft and Hālawa Shaft were not significantly impacted, and uncertainty in recharge did not translate to uncertainty in migration behavior.

Run ID	Description	Significant Features	Calibration and Verification Summary and Conclusions	Application Summary and Conclusions
58	Coastal marine discharge variability	Evaluate impact of variability in discharge to ocean and Pearl Harbor.	Calibration to regional water levels and water level gradients was good. Connectivity between the Facility and Hālawa Shaft was overpredicted, although less than for Model #51a.	More discharge to Pearl Harbor than the ocean boundary does not impact the migration behavior of water from beneath the Facility or of the source water zones of key supply shafts.
59	Lateral inflow from SE	Evaluate conceptual model of flow across valleys from Kalihi Valley to Pearl Harbor.	Larger volumes of flow in the domain causes higher flow gradients. During calibration, higher K-values that flatten the gradients resulted in a poorer fit of the drawdown impacts.	Source water zones of Red Hill Shaft and Hālawa Shaft shift to the east. However, the migration of water from the Facility is not significantly impacted by lateral SE inflow.

K hydraulic conductivity

Many of the models were deliberately selected to help evaluate the impact and significance of various uncertainties and conceptual representations of concern to the SMEs. Specifically, Model #51d, Model #52, Model #54, Model #56, Model #58, and Model #59 were developed to address the top 10 concerns of SMEs. The top 10 concerns and the resolution to date are listed in Section 1.6 of the current report. In addition, the models were set up to consider variable flow into Red Hill Shaft, also one of the SMEs' top 10 concerns. The models individually and collectively addressed issues of uncertainty in conceptualization and in parameterization, and further identify the significant parameters and variables governing flow paths of interest from the Facility and toward Red Hill Shaft and Hālawa Shaft. Limitations of the models were evaluated as needed in terms of how well they fit the various calibration metrics, the related implications, and which parameter limits were reached. Homogeneous basalt models with a range of anisotropies evaluated the impact of regionally average properties on water levels, water level gradients, hydraulic conductivities, and flow paths. An alternate saprolite representation helped to understand the impact of uncertainty in saprolite depth and extent beneath South Hālawa Valley on flow across it. Heterogeneous basalt representation models assisted with understanding the impact of variations in basalt properties, and a conceptual clinker model helped to estimate the impact of fast flow paths on migration behavior and travel times. Another model evaluated the structural impact of Honolulu Volcanic tuff in providing a damming effect to downhill migration as a possible conceptual model suggested by SMEs. Other significant uncertainties that were evaluated included the impact of lower recharge, of variability in coastal discharge, and of lateral inflow from the SE model boundary, as was conceptualized by Mink (1980) and also suggested by SMEs.

The general material parameters for the models are shown in Table 5-2, with specific details for a model provided within each section as needed. Light shading in the table reflects values at the lower end of their anticipated range, while dark shading reflects values at the higher end of their anticipated range.

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Table 5-2: Model Material Parameters

Geologic Material	Unit	Layer(s)	Minimum Value	Maximum Value	51a Homogenous Basalt: Limit Horizontal Anisotropy Value	51b Homogenous Basalt: 10:1 Anisotropy Value	51c Homogeneous Basalt: Zoned Along Ridges Value	51d Homogenous Basalt: Calibrate on Anisotropy Value	51e Homogeneous Basalt: Zoned Along Ridges and Within Valleys Value	52 Alternate Saprolite Value	53 Heterogeneous Basalt Value	54 Heterogeneous Basalt Value	55 Conceptual Clinker Zone Value	56 Structural Alterations to Tuff Cones Value	57 Recharge Uncertainty Value	58 Coastal Marine Discharge Variability Value	59 Lateral Inflow from SE Value
Caprock Kh (marine)	ft/day	1	2.00	33,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	2,500	5,000	5,000	5,000
Caprock Kv (marine)	ft/day	1	2.00	33,000	9.45	11.87	10.00	11.87	10.00	9.45	10.00	10.00	9.45	0.18	9.45	9.45	9.45
Caprock Kh (alluvial)	ft/day	1	0.10	1.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	0.10	20.00	20.00
Caprock Kv (alluvial)	ft/day	1	0.60	0.60	20.00	0.10	20.00	0.10	20.00	20.00	20.00	20.00	20.00	0.09	0.10	18.90	20.00
Valley fills, Kh	ft/day	1	0.019	0.37	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	200.00	1.00	1.00	1.00
Valley fills, Kv	ft/day	1	0.058	0.066	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	3.37	0.001	0.001	0.001
Saprolite under valley fill, Kh	ft/day	2 and 3	0.0028	283.00	5.00	10.00	5.00	4.81	5.00	5.00	5.00	5.00	5.00	9.20	5.00	5.00	5.00
Saprolite under valley fill, Kv	ft/day	2 and 3	0.0028	283.00	0.015	0.011	0.010	0.009	0.010	0.015	0.010	0.010	0.035	0.008	0.002	0.003	0.80
Saprolite under caprock, Kh	ft/day	2 and 3	0.0028	283.00	5.00	10.00	5.00	4.81	1.00	5.00	0.80	0.80	5.00	9.20	5.00	5.00	5.00
Saprolite under caprock, Kv	ft/day	2 and 3	0.0028	283.00	0.015	0.011	0.050	0.009	0.025	0.015	0.087	0.038	0.035	0.008	0.002	0.003	0.80
Tuff overlying marine, Kh	ft/day	1	1.00	1,000	500.00	500.00	500.00	500.00	500.00	500.00	500.00	500.00	500.00	200.00	500.00	500.00	500.00
Tuff overlying marine, Kv	ft/day	1	1.00	100.00	0.010	0.10	0.010	0.10	0.010	0.010	0.010	0.010	0.010	0.48	0.010	3.17	0.010
Tuff overlying alluvial, Kh	ft/day	1	1.00	1,000	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	20.00	10.00	10.00	10.00
Tuff overlying alluvial, Kv	ft/day	1	1.00	100.00	0.001	0.10	0.001	0.10	0.001	0.001	0.001	0.001	0.001	0.18	0.001	0.014	0.001
Tuff cone, Kh	ft/day	2 to 9	1.00	1,000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.089	0.001	0.001	0.001
Tuff cone, Kv	ft/day	2 to 9	1.00	100	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.008	0.001	0.001	0.001
Basalt, Kh	ft/day	4 to 9	26.00	85,000	2,828	5,316	Zoned	8,280	Zoned	2,828	Zoned	Zoned	Zoned	3,747	1,814	1,995	2,444
Basalt, Kv	ft/day	4 to 9	7.40	7.50	200.00	66.33	Zoned	54.88	Zoned	200.00	Zoned	Zoned	Zoned	44.54	200.00	198.84	121.26
GHB South conductance	ft^2/d	1			40.00	1,000,000	150.00	999,976	305.05	40.00	402.74	280.81	388.06	188.78	135.69	1.00E-05	1.87
GHB PH conductance	ft^2/d	1			40.00	1,000,000	150.00	999,804	0.32	40.00	0.47	38.06	0.10	62,588	0.39	1,066	207.57
Kalauo Sp Farm conductance	ft^2/d	1 to 4			7,000	10,924	17,000	11,279	13,724	7,000	61,960	11,363	8,026	10,448	7,665	9,461	9,632
Kalauao Sp conductance	ft^2/d	1 to 4			3,000	4,841	7,000	5,883	9.05	3,000	8,523	4,948	3,000	5,399	218.14	4,671	4,198
Recharge multiplier SP1&2	(--)	1			0.83	1.00	1.00	1.00	1.00	0.83	1.00	1.00	0.83	1.00	0.70	0.83	0.83
Recharge multiplier SP3&4	(--)	1			0.56	0.73	0.73	0.70	0.72	0.56	0.72	0.72	0.55	0.73	0.42	0.55	0.56
Basalt anisotropy	(--)	4 to 9			0.33	0.10	Zoned	0.057	Zoned	0.33	Zoned	Zoned	Zoned	0.33	0.33	0.33	0.33
Red Hill Shaft skin 1	(--)	6			3,319	3,319	3,319	3,319	3,319	3,319	3,319	3,319	3,319	3,319	3,319	3,319	3,319
Red Hill Shaft skin 2					12.80	12.80	12.80	12.80	12.80	12.80	3,319	3,319	12.80	12.80	12.80	12.80	12.80
Hālawa Shaft skin	(--)	6			20,721	20,721	20,721	20,721	20,721	20,721	20,721	20,721	20,721	20,721	20,721	20,721	20,721
Caprock Ss (marine)	(--)	1			1.17E-06	9.69E-07	1.17E-06	9.69E-07	1.17E-06	1.17E-06	1.17E-06	1.17E-06	1.17E-06	4.48E-05	1.17E-06	1.17E-06	1.17E-06
Caprock Sy (marine)	1/ft	1	0.10	0.20	0.073	0.095	0.073	0.095	0.07	0.073	0.073	0.073	0.073	0.049	0.073	0.073	0.073
Caprock Ss (alluvial)	(--)	1			1.78E-06	1.72E-06	1.78E-06	1.72E-06	1.78E-06	1.78E-06	1.78E-06	1.78E-06	1.78E-06	1.65E-05	1.78E-06	1.78E-06	1.78E-06
Caprock Sy (alluvial)	1/ft	1	0.10	0.20	0.030	0.022	0.030	0.022	0.030	0.030	0.030	0.030	0.030	0.15	0.030	0.030	0.030
Valley Fills, Ss	(--)	1			6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06	6.91E-06
Valley Fills, Sy	1/ft	1	0.10	0.15	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Saprolite, Ss	(--)	2 and 3			5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06	5.31E-06
Saprolite, Sy	1/ft	2 and 3	0.10	0.10	0.026	0.070	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026	0.026
Tuff overlying marine, Ss	(--)	1			1.27E-06	1.36E-06	1.27E-06	1.36E-06	1.27E-06	1.27E-06	1.27E-06	1.27E-06	1.27E-06	1.52E-05	1.27E-06	1.27E-06	1.27E-06
Tuff overlying marine, Sy	1/ft	1			0.056	0.070	0.056	0.070	0.056	0.056	0.056	0.056	0.056	0.15	0.056	0.056	0.056
Tuff overlying alluvial, Ss	(--)	1			2.41E-06	1.15E-06	2.41E-06	1.15E-06	2.41E-06	2.41E-06	2.41E-06	2.41E-06	2.41E-06	1.52E-06	2.41E-06	2.41E-06	2.41E-06
Tuff overlying alluvial, Sy	1/ft	1			0.061	0.062	0.061	0.062	0.061	0.061	0.061	0.061	0.061	0.015	0.061	0.061	0.061
Tuff cone, Ss	(--)	2 to 9			4.70E-06	7.12E-06	4.70E-06	7.12E-06	4.70E-06	4.70E-06	4.70E-06	4.70E-06	4.70E-06	7.70E-06	4.70E-06	4.70E-06	4.70E-06
Tuff cone, Sy	1/ft	2 to 9			0.058	0.070	0.058	0.070	0.058	0.058	0.058	0.058	0.058	0.026	0.058	0.058	0.058
Basalt, Ss	(--)	4 to 9	0.010	0.030	6.00E-05	9.88E-05	7.00E-05	9.09E-05	Zoned	6.00E-05	Zoned	Zoned	1.01E-04	1.06E-04	1.43E-04	1.19E-04	8.14E-05
Basalt, Sy	1/ft	4 to 9	0.040	0.080	0.01	0.002	0.010	0.010	Zoned	0.010	Zoned	Zoned	0.010	0.010	0.010	0.010	0.010

ft^2 square feet
GHB general head boundary
Kh horizontal hydraulic conductivity
Ky vertical hydraulic conductivity
Ss specific storage
SP stress period
Sy specific yield

Minimum and maximum values from Table 4-1.
Values at or below the minimum value are shaded light gray.
Values at or above the maximum value are shaded dark gray.

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The Honolulu Volcanic tuff material both within near surface materials as well as the cones within basalt at deeper elevations) was provided low-end values in most models as suggested by SMEs. The horizontal hydraulic conductivity of alluvial sediments was at the high end in all models, and the vertical hydraulic conductivity of alluvial sediments was at the high end in most models. Thus, outflow from the basalt in most models occurred into the more permeable alluvial sediments that are in the northern part of Pearl Harbor (see tuff and alluvial sediment extents on Figure 4.2-4). This is a significant difference from the previous homogeneous conceptualization of caprock in most of the models of the interim study. This behavior is also different from that of Model #26 and Model #27 of the interim study, which included zonation of caprock that was consistent with the USGS study (Oki 2005) into marine sediments and alluvial sediments only.

The vertical hydraulic conductivity of basalt was a PEST calibration parameter, and most models calibrated to values significantly higher than the 7.5 ft/d value used in the interim model and other studies (Oki 2005; DON 2010). The specific storage values for all materials were initially PEST calibration parameters; however, only storage properties of basalt can really be calibrated for this model because all transient observations occur only in the basalt. Consequently, the storage properties of models developed later did not include materials other than the basalt as PEST variables. Furthermore, these storage values do not affect any of the objectives of interest, since the migration behavior was examined for steady-state conditions. Also, transient flow would buffer the migration behavior and therefore examination of migration and travel times in a steady-state flow field is generally a conservative approach. For the particle tracking simulations, conservative values of porosity for basalt were used in all models because it is a significant parameter in computing migration speeds, and because it cannot be calibrated from available observations. The porosity used was four times less than the value suggested by literature or previous modeling efforts to include a safety factor. This level of conservatism was provided to account for the possibility of even larger influences of fast-flow pathways than previously suggested.

The material parameter distribution map for Layer 1 is presented on Figure 5-1 and shows the major zonation within the caprock and valley fill. Alluvial deposits are closest to the valleys with marine sediments closer to the ocean. Honolulu Volcanic tuff overlies both marine and alluvial sediments, which are included as separate zones. The caprock zonation was conducted with guidance from AOC Party SMEs. The material parameter distribution map for Layers 2 and 3 representing the saprolite is shown on Figure 5-2. Two saprolite zones were provided to provide distinct hydrogeologic properties to the saprolite beneath the valleys and saprolite beneath the caprock. The material parameter distribution map for Layers 4 through 9 representing the basalt is shown on Figure 5-3. This map indicates uniform basalt properties and variations for models will be discussed within the respective model’s section. The zone representing tuff cones penetrates the basalt and caprock layers (Figure 5-2 and Figure 5-3).

Preliminary calibration simulations were conducted to set up efficient and robust solver parameters and note the general behavior of the model. Such evaluations were also conducted intermittently during calibration of some of the models. The solver settings selected were noted to be robust and efficient through all model simulations. The model was noted to approach steady-state conditions after turning off of Red Hill Shaft or Hālawa Shaft in about 3 years. This is a long time as compared to the unit step response function targets that are in the order of a couple of weeks and to the pumping stress fluctuations that were steady for a maximum of only a few days. Thus, the storage terms were expected to dominate for the drawdown response evaluations, and that was taken into consideration when calibrating and evaluating models. Increasing the vertical hydraulic conductivity of basalt in the model gave less drawdown to Red Hill Shaft (at the Shaft) as well as Facility monitoring wells. The effect was less noticeable for Hālawa Shaft shutdown. A larger specific storage for basalt gave smaller amplitude responses to both Hālawa Shaft and Red Hill Shaft shutdown. These responses were fairly sensitive for a range of reasonable parameter values; therefore, PEST was able to adjust them during calibration simulations, to achieve the response amplitude needed for the various models.

Preliminary calibration simulations also evaluated varying the recharge applied to the model by a multiplying factor applied to the distribution of Figure 3.6-2 that was calibrated within PEST. It was later decided with input from SMEs that the recharge factor should remain fixed. Thus, the recharge factor was fixed to unity in most models and to the preliminary calibrated factor in a few models. A sensitivity to recharge was also evaluated by Model #57, indicating that the hydraulic conductivities adjust accordingly, with little impact to the calibration or migration behavior from beneath the Facility. The TFN analysis also indicated that local recharge had no discernable impact on water levels at the Facility. The recharge factor was reduced for the third stress period to accommodate the large storage term remaining after SP2 with steady-state conditions, such that SP4 can evaluate the unit response of Hālawa Shaft pumping.

The calibration statistics of the models are shown in Table 5-3 Specific statistics shown here include the residual mean error to evaluate the average closeness of fit, the RMS error to evaluate the spread (deviation) in the fit, and the R-squared (regression coefficient) to evaluate the closeness in trends. The statistics are included for the water levels to indicate: how well the general flow behavior is simulated; the water level difference statistics between RHMW04 and the remaining monitoring wells, and between RHMW01 and the remaining monitoring wells as an evaluation measure for gradients; drawdown behavior of Red Hill Shaft pumping as a measure of the connectivity of the wells to Red Hill Shaft; and drawdown behavior of Hālawa Shaft pumping as a measure of the connectivity of the wells to Hālawa Shaft. This tabular representation helps compare the various models for these different metrics and how they may impact the migration behavior of interest. These summaries do not further categorize the impacts in terms of Facility or non-Facility wells; however, figures in the individual model sections help with further details.

The water budget of the models when both Red Hill Shaft and Hālawa Shaft were pumping (SP1) is shown in Table 5-4 For most models, the largest inflow is via recharge followed by NE inflow. The recharge map of Figure 3.6-2 indicates that most of the recharge occurs to the NE of the domain. Thus, water is expected to flow away from the NE portions of the domain. For the model with inflow from the SE, the amount was about 20% of total inflow, which causes a slight deviation in the inflow characteristics of the model. The largest outflow was via well pumping, followed by Pearl Harbor Spring and smaller discharges to Pearl Harbor or to the ocean. Well pumping values in the water budget were different for the different models depending on whether Kalihi Shaft pumping was reduced by the “auto-flow-reduce” feature of MODFLOW-USG, and by how much. Kalihi Shaft is located very close to the SE boundary of the model, and therefore its pumping may be affected by conditions at that boundary; however, it is far from the areas of interest and does not affect the migration behavior of water from underneath the Facility.

Table 5-3: Model Calibration Statistics

Run ID	Description	Comparison of Observed and Simulated Water Levels for Basalt Wells			Scatterplot of Water Level Differences Between Synoptic Study Wells: Difference with RHMW01			Scatterplot of Water Level Differences Between Synoptic Study Wells: Difference with RHMW04			Drawdown Hydrographs: SP2			Drawdown Hydrographs: SP4		
		Mean Residual (ft)	RMS Error (ft)	R-square (-)	Mean Residual (ft)	RMS Error (ft)	R-square (-)	Mean Residual (ft)	RMS Error (ft)	R-square (-)	Mean Residual (ft)	RMS Error (ft)	R-square (-)	Mean Residual (ft)	RMS Error (ft)	R-square (-)
51	Homogeneous basalt															
51a	Limit horizontal anisotropy (3:1)	0.54	0.95	0.60	0.05	0.51	0.74	0.44	0.67	0.79	0.06	0.41	0.82	0.07	0.13	0.96
51b	10:1 anisotropy	0.39	0.82	0.68	0.03	0.38	0.77	0.49	0.60	0.80	0.09	0.54	0.81	0.06	0.10	0.98
51c	Zoned along ridges	0.96	1.22	0.65	0.08	0.43	0.74	0.53	0.66	0.78	0.08	0.53	0.82	0.10	0.18	0.99
51d	Calibrate on anisotropy	0.55	0.88	0.71	0.04	0.38	0.77	0.47	0.59	0.80	0.07	0.50	0.82	0.05	0.09	0.98
51e	Zoned along ridges and within valleys	0.16	0.62	0.75	-0.02	0.38	0.79	0.48	0.60	0.83	0.04	0.25	0.86	-0.01	0.04	0.99
52	Alternate saprolite	0.54	0.95	0.60	0.05	0.51	0.74	0.44	0.66	0.79	0.06	0.41	0.82	0.07	0.13	0.96
53	Heterogeneous basalt	0.13	0.54	0.82	-0.02	0.31	0.88	0.35	0.46	0.90	-0.002	0.08	0.96	-0.01	0.04	0.99
54	Heterogeneous basalt	0.19	0.63	0.76	0.02	0.37	0.84	0.43	0.56	0.88	-0.01	0.09	0.95	-0.0004	0.04	0.99
55	Conceptual clinker zone	0.19	0.69	0.71	0.03	0.45	0.74	0.50	0.65	0.80	0.02	0.14	0.86	0.05	0.08	0.98
56	Structural alterations to tuff cones	-0.06	1.06	0.54	0.002	0.40	0.75	0.48	0.61	0.79	0.09	0.56	0.83	0.02	0.08	0.97
57	Recharge uncertainty	0.21	0.78	0.64	0.001	0.42	0.75	0.53	0.66	0.80	0.07	0.61	0.81	0.03	0.08	0.98
58	Coastal marine discharge variability	0.27	0.78	0.64	0.01	0.41	0.76	0.53	0.65	0.80	0.07	0.56	0.81	0.04	0.07	0.98
59	Lateral inflow from SE	0.26	0.70	0.74	-0.01	0.38	0.77	0.53	0.63	0.80	0.03	0.29	0.81	0.06	0.09	0.98

RMS root mean square
\- no unit of measure

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Table 5-4: Model Water Budgets for Stress Period 1

	Model																									
	51a		51b		51c		51d		51e		52		53		54		55		56		57		58		59	
	Homogeneous Basalt: Limit Horizontal		Homogeneous Basalt: 10:1 Anisotropy		Homogeneous Basalt: Zoned Along Ridges		Homogeneous Basalt: Calibrate on Anisotropy		Homogeneous Basalt: Zoned Along Ridges and Within Valleys		Alternate Saprolite		Heterogeneous Basalt		Heterogeneous Basalt		Conceptual Clinker Zone		Structural Alterations to Tuff Cones		Recharge Uncertainty		Coastal Marine Discharge Variability		Lateral Inflow from SE	
Water Budget Description	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total	mgd	% of Total
Inflow																										
NE Flux	20.7	44.3	20.7	39.8	20.7	39.8	20.7	39.8	20.7	39.8	20.7	44.3	20.7	39.8	20.7	39.8	20.7	44.3	20.7	33.9	20.7	48.5	20.7	44.3	20.7	36.1
Recharge	26.0	55.7	31.3	60.2	31.3	60.2	31.3	60.2	31.3	60.2	26.0	55.7	31.3	60.2	31.3	60.2	26.0	55.7	31.3	51.4	21.9	51.5	26.0	55.7	26.0	45.4
Lateral Southeast Inflow	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	14.7	0.0	0.0	0.0	0.0	10.7	18.6
Total In	*46.7*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*46.7*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*46.7*	*100.0*	*61.0*	*100.0*	*42.6*	*100.0*	*46.7*	*100.0*	*57.4*	*100.0*
Outflow																										
GHB Offshore	2.8	5.9	6.3	12.2	5.1	9.8	6.0	11.6	6.2	11.9	2.8	5.9	7.7	14.8	6.1	11.8	6.2	13.2	6.2	10.2	3.2	7.5	2.8	5.9	6.3	12.2
GHB Pearl Harbor	2.4	5.1	3.6	7.0	4.4	8.4	3.3	6.3	0.02	0.04	2.4	5.1	0.03	0.1	1.7	3.3	0.01	0.01	11.9	19.5	0.02	0.1	2.4	5.1	3.6	7.0
Pearl Harbor Spring	9.4	20.1	9.5	18.3	8.6	16.5	9.5	18.3	12.1	23.2	9.4	20.1	10.3	19.7	10.2	19.6	9.7	20.7	10.0	16.5	8.9	20.9	9.4	20.1	9.5	18.3
Kalauao Spring	0.2	0.3	0.2	0.4	0.2	0.5	0.2	0.4	0.001	0.003	0.01	0.03	0.3	0.6	0.2	0.4	0.2	0.3	0.2	0.4	0.02	0.04	0.2	0.3	0.2	0.4
Well Pumping	32.0	68.6	32.3	62.1	33.7	64.9	33.0	63.4	33.7	64.8	32.0	68.8	33.7	64.8	33.7	64.8	30.8	65.8	32.6	53.5	30.5	71.5	32.0	68.6	32.3	62.1
Total Out	*46.7*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*46.6*	*100.0*	*52.0*	*100.0*	*52.0*	*100.0*	*46.7*	*100.0*	*61.0*	*100.0*	*42.6*	*100.0*	*46.7*	*100.0*	*52.0*	*100.0*

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Discharge to Pearl Harbor and offshore boundaries was only 10% or less of the total discharge for models that had a recharge factor of less than 1. How this amount distributes itself between the offshore boundary and Pearl Harbor in these models is expected to cause little deviation in the general flow behavior. However, this may not be appropriate since pumping would need to be reduced during long-term droughts for other reasons, including conservation and prevention of up-coning of deeper saltwater. The recharge distribution applied in all models is for current conditions, which has an estimated 13% less recharge than for average rainfall conditions (Table 3-3). For models with a recharge factor of unity, discharge to Pearl Harbor and offshore boundaries was 15–20% of the total discharge, which is comparable to discharge at Pearl Harbor Springs at Kalauao. In that case, the distribution of this flux between the ocean boundary and Pearl Harbor may have an influence in the flow pathways. The mass balance error of all models was negligible.

Various significant travel times (relative to simulated release locations in the tank farm) of interest computed by the models are shown in Table 5-5.

Table 5-5: Model Travel Times

Run ID	Description	Travel Time from Tanks to: (days)				Time That Red Hill Shaft Can Remain Turned Off and Still: (days)			
		Red Hill Shaft when Red Hill Shaft is pumping [redacted] mgd		Receptors for Hālawa Shaft pumping at 12 mgd and Red Hill Shaft off		Capture water from the tanks if Red Hill Shaft is turned back on and pumping [redacted] mgd		Pull back water from the distal edge of Red Hill Shaft if Red Hill Shaft is turned back on and pumping [redacted] mgd	
		Low End	High End	Low End	High End	Low End	High End	Low End	High End
51	Homogeneous basalt								
51a	Limit horizontal anisotropy (3:1)	25	121	374	853	172	275	61	65
51b	10:1 anisotropy	19	118	259	375	146	271	73	77
51c	Zoned along ridges	17	94	559	793	116	201	52	54
51d	Calibrate on anisotropy	19	118	254	382	142	277	51	57
51e	Zoned along ridges and within valleys	41	135	883	1,031	150	284	74	78
52	Alternate saprolite	28	121	351	852	165	276	61	65
53	Heterogeneous basalt	47	150	384	1,831	181	357	56	60
54	Heterogeneous basalt	56	228	229	414	87	212	63	65
55	Conceptual clinker zone	21	69	295	1,938	101	187	40	46
56	Structural alterations to tuff cones	16	83	137	170	77	130	43	43
57	Recharge uncertainty	33	129	257	932	165	268	71	75
58	Coastal marine discharge variability	31	122	366	1,494	153	252	72	76
59	Lateral inflow from SE	24	101	251	671	124	178	46	49

All models indicated that water from the Facility is captured by Red Hill Shaft pumping at [redacted] mgd. The shortest travel time from the tanks to Red Hill Shaft ranged from 16 to 56 days among the models, while the longest travel time ranged from 69 to 228 days. When Red Hill Shaft is not pumping, the shortest travel time to other receptors ranged from 137 to 833 days among the models, while the longest travel time ranged from 170 to 1,938 days. This summary does not categorize which receptors were involved with the different models; however, that is evaluated in figures in the individual model sections. The shortest time that Red Hill Shaft can remain turned off and still capture water that escaped from the Facility (tanks) when turned back on with an average pumping rate of [redacted] mgd ranged from 77 to 181 days, while the longest time ranged from 130 to 357 days. The shortest time that Red Hill Shaft can remain turned off and still pull back water that escaped past it when turned on with an average pumping rates of [redacted] mgd ranged from 40 to 74 days, while the longest time ranged from 43 to 77 days. Porosity cannot be calibrated from water level observation data, but such high bulk hydraulic conductivity values would require significantly larger pore spaces to allow easier flow. Correlations are available in literature between porosity and permeability, which were not used in the current study because they do not relate to basalt and clinkers.

Figure 5-4 shows the forward migration of groundwater from beneath the tanks for all models when Red Hill Shaft is pumping at [redacted] mgd and Hālawa Shaft is pumping at 12 mgd. Though there are some differences of trajectories between models, all models indicate that groundwater from beneath the tank farm is captured by Red Hill Shaft pumping at [redacted] mgd.

Table 5-6 shows the model travel times from tanks to each of the receptors for Hālawa Shaft pumping at 12 mgd and Red Hill Shaft off. The different models indicate different potential receptors when Red Hill Shaft is not pumping, with maximum number of models showing impact to Hālawa Shaft followed by wells 2252-32, 2255-37, and 2255-39. Figure 5-5 shows the forward migration of groundwater from beneath the tanks for all models when Red Hill Shaft is off and Hālawa Shaft is pumping at 12 mgd. This figure indicates that the path of groundwater from beneath the tanks to the west and the migration paths range from NW to SW, with a larger spread between models farther away from the tanks.

All models are weighted as per the quality of calibration and verification. Table 5-7 shows a summary of the various models' applicability for evaluating capture. Different weighting is provided to the different models using expert judgement, depending on their significance and reasonableness. However, model consideration for addressing risk-management decisions should further consider the objectives. For instance, the conceptual clinker model (Model #55) provides a representation of fast flow pathways that may be critical to objectives at Red Hill Shaft and are not implemented in the other models. Model #54, conversely, is more critical for Hālawa Shaft pumping when Red Hill Shaft is off (e.g., all groundwater migration goes to Hālawa Shaft). Model #53 has a good fit to all the calibration metrics and indicates migration of groundwater from beneath the Facility to other receptors when Red Hill Shaft is not pumping. Therefore, Model #53 may be significant for evaluating impact to these other receptors. The table further indicates whether a model specifically addresses the Regulatory Agencies' top 10 concerns or other regulatory issues.

Table 5-6: Model Travel Times (days) from Tanks to Receptors for Hālawa Shaft Pumping at 12 MGD and Red Hill Shaft Off

		Hālawa Shaft		Kalauao Spring Farm		Well 2255-32		Well 2255-37		Well 2255-39		Well 2355-06		Well 2355-07		Pearl Harbor	
Run ID	Description	Low End	High End	Low End	High End	Low End	High End	Low End	High End	Low End	High End	Low End	High End	Low End	High End	Low End	High End
51	Homogeneous basalt																
51a	Limit horizontal anisotropy (3:1)	374	518	—	—	754	850	724	800	724	800	—	—	—	—	—	—
51b	10:1 anisotropy	259	375	—	—	—	—	—	—	—	—	—	—	—	—	—	—
51c	Zoned along ridges	—	—	—	—	588	652	559	577	559	577	—	—	—	—	688	793
51d	Calibrate on anisotropy	254	382	—	—	—	—	—	—	—	—	—	—	—	—	—	—
51e	Zoned along ridges and within valleys	—	—	883	1,031	—	—	—	—	—	—	—	—	—	—	—	—
52	Alternate saprolite	351	527	—	—	755	852	738	797	738	797	—	—	—	—	—	—
53	Heterogeneous basalt	384	953	1,761	1,831	1,052	1,180	1,020	1,223	1,020	1,223	1,304	1,458	1,304	1,458	—	—
54	Heterogeneous basalt	229	414	—	—	—	—	—	—	—	—	—	—	—	—	—	—
55	Conceptual clinker zone	295	580	1,236	1,252	708	864	685	757	685	757	—	—	—	—	1,938	1,938
56	Structural alterations to tuff cones	137	170	—	—	—	—	—	—	—	—	—	—	—	—	—	—
57	Recharge uncertainty	361	649	—	—	798	932	744	789	744	789	—	—	—	—	—	—
58	Coastal marine discharge variability	366	550	—	—	717	861	691	750	691	750	—	—	—	—	1,494	1,494
59	Lateral inflow from SE	251	463	—	—	539	595	523	590	523	590	—	—	—	—	635	671
60	Low-conductivity material extended partially up valleys	224	466	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 5-7: Summary of Multimodel Applicability for Risk-Based Decision Making

Model #	Description	Significant Features	Weighting	Weighting Considerations
51	Homogeneous basalt with CSM saprolite	Evaluation of regional flow behavior		
51a	Limit horizontal anisotropy (3:1)	Assumed conservative assumption of previous modeling efforts	0.8	Good calibration metrics; fair calibration to water level differences; reasonable conceptual model and water budgets
51b	10:1 anisotropy	Evaluate impact of possible higher horizontal anisotropic conditions	0.9	Good calibration to all metrics; reasonable conceptual model and water budgets
51c	Zoned along ridges	Evaluate impact of possible higher horizontal anisotropic conditions	0.8	Good calibration metrics; fair calibration to water level differences; reasonable conceptual model and water budgets
51d	Calibrate on anisotropy	Evaluate what value of anisotropy best captures regional water level conditions (generally between 17 and 18)	0.9	Same as 51b
51e	Zoned along ridges and within valleys	Evaluate impact of additional zonation since zoned conditions of Model #51c did not adequately distinguish itself from the average conditions of homogeneous Model #51a	0.9	Good calibration to all metrics; reasonable conceptual model and water budgets
52	Alternate saprolite	Test impact of alternate (smaller) saprolite extent and depth below water table	0.8	Same as 51a
53	Heterogeneous basalt	Evaluate impacts of regional- and local-scale heterogeneities using pilot points using random initial parameter distributions	1	Excellent calibration to all metrics; reasonable conceptual model and water budgets
54	Heterogeneous basal	Evaluate alternate impacts of regional- and local-scale heterogeneities using pilot points using initial parameter distributions that block downhill flow from the Facility (tuff cone dam effect)	1	Excellent calibration to all metrics; reasonable conceptual model and water budgets
55	Conceptual clinker zone	Evaluate impact of fast-flow pathway in groundwater beneath the Facility	0.9	Good calibration to all metrics; reasonable conceptual model and water budgets; addresses impact of fast flow pathways
56	Structural alterations to tuff cones	Evaluate impact of a damming effect of tuff cones on flow down Red Hill	0.7	Good calibration to all metrics; reasonable water budgets; unlikely to have barrier as conceptualized
57	Recharge uncertainty	Evaluate impact of applying drought condition recharge inflow	0.8	Good calibration to all metrics; reasonable conceptual model low-end of water budgets
58	Coastal marine discharge variability	Evaluate impact of variability in discharge to ocean and Pearl Harbor	0.8	Good calibration to all metrics; reasonable conceptual model and water budgets
59	Lateral inflow from SE	Evaluate conceptual model of flow across valleys from Kalihi Valley to Pearl Harbor	0.8	Good calibration to all metrics; reasonable conceptual model; plausible water budgets

(green) Addresses Regulatory Agencies' Top 10 issue

(blue) Addresses other regulatory issue

The models were developed and calibrated on several powerful computers including:

- Multiple multi-thread laptops
- Two AMD EPYC 7702P Processor workstations (with 64 CPU cores, 128 threads, max boost clock up to 3.35GHz, base clock 2GHz, 512 GB DDR 4 memory, and 80 TB RAID 6 storage)
- One AMD Ryzen 9 3900X Processor workstation (with 12 CPU cores, 24 threads 24, max boost clock up to 4.6GHz, base clock 3.8GHz, 16 GB DDR 4 memory, and 1 TB NVMe storage)
- Dell Precision T7610, Intel Xeon CPU E5-2697 v2@ 2.7 GHz (2 processors, 48 CPU cores), clock speed 2.7 GHz, turbo speed 3.5 GHz, 128 GB RAM, and 4 TB storage)

5.1 MODEL #51: HOMOGENEOUS MODEL

Model #51 was calibrated for homogeneous basalt properties to note the general flow behavior and understand what the data say about the regional hydrogeologic system. The numerical grid selected for this model considers the first (deeper) representation of saprolite depth and extent beneath South Hālawa Valley, as shown on Figure 4.2-12 and discussed in the geologic CSM (DON 2019). Several evaluations were conducted with this model to note the impact of uncertainties in regional hydrogeologic properties and to try to understand the information content of available data.

5.1.1 Model #51a: Homogeneous Model, 3:1 Anisotropy

Model #51a considered a horizontal anisotropy of 3:1 as a number assumed to be conservative and which was applied in previous modeling efforts. Calibrated model parameter values noted in Table 5-2 are mostly within the expected range for each material type. The significant parameter at the higher end of the expected range was the vertical hydraulic conductivity of the basalt causing a large vertical connectivity through the system. The horizontal and vertical hydraulic conductivity of caprock alluvial sediments were at their upper-bound estimates, while those of the caprock sediments with overlying tuff were at or below their lower-bound estimates, causing the water to exit more toward Pearl Harbor in the alluvium than toward the coast.

Figure 5.1.1-1 shows the simulated versus measured water levels for SP1 (when both Red Hill Shaft and Hālawa Shaft were pumping) and SP3 (when only Hālawa Shaft was pumping). Caprock, valley-fill, and saprolite wells were omitted from the plot to focus on water levels within the basalt. The scatterplot indicates the match between observed and simulated water levels within the basalt. All basalt data were incorporated into the scatterplot, including those that have lower accuracy and lower weighting (shown on Figure 5.1.1-1 with smaller symbols). Monitoring well 2256-12 was given a weight of zero because its head value of 14.95 ft msl, obtained from quarterly monitoring in early 2017, did not match water levels at nearby synoptic study well 2256-10, which ranged from 16.7 to 17 ft msl during the period selected for calibration. Fit to the water level data is generally good except that higher values were simulated low.

Figure 5.1.1-2a shows the simulated versus measured water level differences between RHMW01 and other Red Hill monitoring wells for SP1 and SP3, and Figure 5.1.1-2b shows the simulated versus measured differences between RHMW04 and the other Red Hill monitoring wells for the same condition. Differences at the Facility wells were small and are simulated fairly well. Differences with wells that are to the SE were generally underpredicted, while differences with wells to the NW were generally overpredicted, giving flatter apparent gradients across the valleys. The regression coefficients on Figures 5.1.1-1 and 5.1.1-2 and Table 5-3 indicate that the fit to the differences was better than the fit to the water level values themselves.

Figure 5.1.1-3 shows the simulated and measured drawdown hydrographs for SP2 (when Red Hill Shaft turns off). The “measured” hydrographs were generated by applying a TFN analysis to synoptic observations to create unit step response functions, as further detailed in Appendix A. The simulated response at Red Hill Shaft itself (top row panel) was overpredicted, at non-Facility wells (middle row panels) was mixed, and at Facility wells (bottom row panels) was generally underpredicted (except at wells RHMW08 and RHMW05). This indicates that the hydraulic conductivity (more precisely, the specific capacity) at Red Hill Shaft itself was simulated low (larger drawdown), and that the connectivity of Red Hill Shaft to Facility wells was generally simulated as smaller than observed.

Figure 5.1.1-4 shows the simulated and measured drawdown hydrographs for SP4 (when Hālawa Shaft turns off). The simulated response at Hālawa Shaft itself (top row figure panel) was good, the simulated response at non-Facility wells (middle row panels) was mostly overpredicted, and the simulated response at Facility wells (bottom row panels) was overpredicted. This indicates that the hydraulic conductivity (more precisely the specific capacity) at Hālawa Shaft itself was simulated correctly for the given recharge conditions (appropriate drawdown), in contrast to Red Hill Shaft, where its pumping caused larger drawdown than observed. The connectivity of Hālawa Shaft to non-Facility and Facility wells was simulated larger than observed. The simulated connectivity to Hālawa Deep Monitor Well was high for both Red Hill Shaft and Hālawa Shaft shutdown responses, indicating that the high-end estimate of the vertical hydraulic conductivity may probably be too high for a regional value.

Figure 5.1.1-5 shows the aerial distribution of water level residuals within the basalt. Simulated water level residuals were generally within a foot of observed conditions, being smaller than observed (by about a foot) in wells to the SE of the Facility (TAMC-MW2, Manaiki T24, Moanalua Deep), and larger than observed (by about half a foot) in wells to the NE of the Facility (Hālawa Shaft, Hālawa T45, ‘Aiea Navy, Ka‘amilo Deep).

From Figures 5.1.1-3 and 5.1.1-4, it can be surmised that modeled regional flow behavior could be more toward the NW than field conditions because connectivity in that direction, and vertically, was overpredicted, while the connectivity down Red Hill ridge between the Facility and Red Hill Shaft was generally under-simulated. Alternatively, from the water level distributions across valleys (Figures 5.1.1-1, 5.1.1-2, and 5.1.1-5), the modeled regional flow could be less toward the NW than field conditions because the slopes in water levels across valleys were underpredicted, possibly causing underpredicted regional gradients in that direction.

Figure 5.1.1-6 shows the potentiometric map in Model Layer 5 for when Red Hill Shaft is pumping. The simulated water level gradients underneath the tanks were in the west-NW direction, with a slope of about 1 ft per 6,000 ft (1.14 miles) measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft.

Inflow for Model #51a was lower than for most other models because the recharge factor was allowed to vary during its calibration (Table 5-4). Most of the outflow was via pumping followed by flow to Pearl Harbor Spring. Outflow to Pearl Harbor was about equal to offshore outflow.

Figure 5.1.1-7 shows the results of the numerical verification simulation, indicating that the observed responses to changes in pumping are reflected by the model. To compare observed and simulated fluctuations, because the verification runs do not begin at the same water level value as observed conditions, the simulated drawdown was subtracted from the initial observed water level at each well to provide the simulated curve. Even though the model was calibrated only to the unit step response functions for Red Hill Shaft and Hālawa Shaft shutdown, it matches very well in terms of the responses of turning these pumps on and off, as exhibited in the observations. This verification confirms that the water level changes are well-simulated; however, the hydrographs do not consider verification of water levels themselves or water level gradients. The calibrated model for SP1 and SP3 provide the water level gradients for the respective steady-state pumping conditions. The change in water level gradients through time is little if any, because the hydrographs within each group of wells mostly mirror each other, and thus the water level differences are constant for simulated as well as observed conditions.

Figure 5.1.1-8 shows the results of the TFN verification approach, indicating that the high frequency responses were well-simulated using the unit step response functions derived from the model. This trend is noted for most models of the current study, as further shown in Appendix B. The TFN verification results Appendix B are presented per well on all models, while in this section, these results are presented per model on all wells. The TFN approach evaluates the changes in water levels due to various stresses and does not evaluate water levels or water level changes. Here too, however, the hydrographs of the wells are in synchronicity, and therefore the water level differences are constant.

Figure 5.1.1-9 shows the migration of water from beneath the tanks and the source water zones for Red Hill Shaft pumping at [redacted] mgd, indicating this pumping rate to be sufficient to encompass the entire Facility footprint uphill of the shaft.

Figure 5.1.1-10 shows the migration of water from beneath the Facility and the source water zone of Hālawa Shaft when Red Hill Shaft is off and Hālawa Shaft is pumping at 12 mgd. Water from the water table underneath the tanks migrates in a westerly direction and then turns to the NW underneath the saprolite. Some water migrates toward Hālawa Shaft, while the rest flows toward Pearl Harbor, being intercepted by well 2255-39, ʻAiea Hālawa Shaft, and Kalauao Spring. The simulated source water zone for Hālawa Shaft was mostly from uphill areas to the NE. Source water zones for Hālawa Shaft were not evaluated for when Red Hill Shaft is pumping, because they would be even farther away from the Facility and therefore not of concern.

The water level contours shown on Figure 5.1.1-10 indicate that there was a slope under the Facility down Red Hill ridge that was slightly different from when it was pumping (Figure 5.1.1-6). The simulated head difference between the most uphill Facility well (RHMW04) and the most downhill Facility well (RHMW05) was 0.25 ft (3 inches).

Figure 5.1.1-11 shows the migration of water from underneath the tanks when Red Hill Shaft is off superposed on the capture zone of Red Hill Shaft when it is pumping at [redacted] mgd. This figure helps to evaluate the time that Red Hill Shaft can be off and still capture water that originated from beneath the tanks at the Facility. Figure 5.1.1-12 shows the migration of water from Red Hill Shaft when it is off superposed on the capture zone of Red Hill Shaft when it is pumping at [redacted] mgd. This figure helps to evaluate the time that Red Hill Shaft can be off and still capture water that passed it while it was off. These respective travel times are summarized for each model in Table 5-5.

The current homogeneous model has considerably different results from the homogeneous model of the interim modeling study (DON 2018, Appendix A). That likely results from having a more refined structure within the caprock to include alluvial deposits, marine sediments, and Honolulu Volcanic tuff. In the interim modeling study, calibration and migration behavior was sensitive to addition of a simple zonation of marine sediments and alluvial deposits within the caprock (Model #26 and Model #27). Further zonation within the caprock with lower hydraulic conductivity Honolulu Volcanic tuff probably causes an even greater impact. A higher vertical hydraulic conductivity of the current model may also result in different flow behavior.

5.1.2 Model #51b: Homogeneous Model, 10:1 Anisotropy

Model #51b evaluates the impact of possibly higher horizontal regional anisotropic conditions than for Model #51a by using a 10:1 horizontal anisotropy. Regional anisotropy applied in previous models used a value of 3:1, with the idea that it was conservative and larger numbers would only direct flow more in the SW direction; however, there have been no comprehensive multi-well aquifer tests performed at the site apart from the 2017–2018 synoptic study to determine the anisotropy. Even with such tests, horizontal anisotropy is difficult to quantify using analytical solutions because it depends also on the vertical anisotropy and because the assumption that the well fully penetrates the aquifer is not valid for pumping at the shafts. Thus, since the data suggested larger horizontal anisotropy values, the impact of a 10:1 anisotropy was tested. Calibrated model parameter values are noted in Table 5-2. The recharge factor was fixed at unity in this model, whereas it was calibrated to a lower value in Model #51a. The vertical hydraulic conductivity of caprock alluvial zone was calibrated by PEST to its low-end value in contrast to most other models. The conductance values for the offshore and Pearl Harbor general head boundaries were at their upper prescribed limit, providing little resistance to flow from the caprock layer into the ocean or Pearl Harbor.

For Model #51b, Figures 5.1.2-1 through 5.1.2-8 respectively show the regression plot of water levels, the regression plots of water level differences, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. Fit to the water level data is generally good, with a better fit to higher and lower values across the valleys than for Model #51a (Figure 5.1.2-1). Water level differences were also simulated well, and difference statistics for Model #51b (Figure 5.1.2-2 and Table 5-3) are generally better than those of Model #51a, although the regression coefficients are similar.

Figure 5.1.2-3 shows that the simulated response at Red Hill Shaft itself (top row panel) was overpredicted, at non-Facility wells (middle row panels) was mixed (although larger than for Model #51a), and at Facility wells (bottom row panels) was generally underpredicted (except for RHMW05 and RHMW08) for pumping at Red Hill Shaft. This indicates that the hydraulic conductivity at Red Hill Shaft itself was simulated low (larger drawdown), and that the connectivity of Red Hill Shaft to Facility wells was generally simulated as smaller than observed. Nevertheless, the responses look better than for Model #51a.

Figure 5.1.2-4 shows that the simulated response at Hālawa Shaft itself (top row panel) was good, at non-Facility wells (middle row panels) was mixed but generally overpredicted (although less than for Model #51a), and at Facility wells (bottom row panels) was overpredicted for pumping at Hālawa Shaft. This indicates that the average hydraulic conductivity at Hālawa Shaft itself was appropriate for the given recharge conditions (correct drawdown); however, the connectivity of Hālawa Shaft to Facility and non-Facility wells was simulated larger than observed even with this higher longitudinal anisotropy (although less than for Model #51a). Although not at its maximum, the simulated vertical hydraulic conductivity of basalt was still relatively high, causing a large connectivity for both the shafts to Hālawa Deep Monitor Well.

Simulated water level residuals were generally low but within 1 foot of observed conditions except at Red Hill Shaft itself (Figure 5.1.2-5). The simulated water level gradients underneath the tanks (Figure 5.1.2-6) were in the NW direction, which is more aligned with the regional CSM where heads decreased from SE to NW across the valleys. The water level slope was about 1 ft per 7,000 ft (1.33 miles) measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft. Inflow for Model #51b was larger than for Model #51a because of the recharge factor (Table 5-4). The larger inflow contributed to larger outflow to Pearl Harbor and the offshore boundary. Outflow was still largest due to pumping followed by flow to Pearl Harbor Spring at Kalauao.

Figures 5.1.2-9 through 5.1.2-12 show the particle tracking results as were examined for the other models. When Red Hill Shaft is not pumping, water from underneath the tanks migrates toward the west and turns beneath the saprolite toward Hālawa Shaft (Figure 5.1.2-10).

The larger anisotropy of this model causes a cone of drawdown at Hālawa Shaft that is longer in the principal anisotropy direction, causing its influence to reach out farther and capture water from all particle-seeding locations underneath the tanks when Red Hill Shaft is not pumping. The simulated source water zone for Hālawa Shaft is still mostly from uphill areas to the NE, although its capture area was wider than for Model #51a. For these reasons, Model #51b indicates that a larger anisotropy may actually be more conservative for evaluating capture at Hālawa Shaft when Red Hill Shaft is not pumping. Also, the higher anisotropy fits the regional CSM better than for Model #51a for all metrics considered.

5.1.3 Model #51c: Homogeneous Model, Zoned Along Ridges

Model #51c evaluates the impact of using the 3:1 horizontal anisotropy for basalt but providing flexibility to the calibration by including separate hydraulic conductivity zones for each hill. This is a plausible conceptualization of the hydraulic property distribution considering the nature of lava flows and subsequent erosion, and is corroborated by the different hydraulic responses to pumping at Hālawa Shaft and Red Hill Shaft noted in Section 3.3, which indicates different hydraulic properties in their vicinity. Calibrated model parameter values are noted in Table 5-2. Most values aside from the zoned basalt are similar to those of Model #51a, although the recharge multiplier was fixed at 1.

For Model #51c, Figures 5.1.3-1 through 5.1.3-8 respectively show the regression plot of water levels, the regression plots of water level differences, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. Water levels were generally simulated lower than observed. Residual and RMS statistics were therefore worse than for Model #51a; however, the regression coefficient was better (Figure 5.1.3-1). Water level differences at Facility and non-Facility wells were simulated fairly well (Figure 5.1.3-2), although the larger positive differences were simulated low. The difference statistics for Model #51c (Figure 5.1.3-2 and Table 5-3) are generally better than those of Model #51a and almost as good as the highly anisotropic conditions of Model #51b.

Figure 5.1.3-3 shows that the simulated response at Red Hill Shaft itself (top row panel) was overpredicted, at non-Facility wells (middle row panels) was mixed, and at Facility wells (bottom row panels) was generally good or underpredicted (except for RHMW05 and RHMW08) for pumping at Red Hill Shaft. This indicates that the hydraulic conductivity at Red Hill Shaft itself was simulated low (larger drawdown), and that the connectivity of Red Hill Shaft to Facility wells was generally simulated as good or smaller than observed. Visually, the differences from observed conditions were less than for Model #51a at most wells except Red Hill Shaft itself.

Figure 5.1.3-4 shows that the simulated response at all observation locations was overpredicted for pumping at Hālawa Shaft. This indicates that the hydraulic conductivity at Hālawa Shaft itself was underpredicted (larger drawdown); however, the connectivity of Hālawa Shaft to Facility wells was simulated much larger than observed (although slightly better than Model #51a).

Simulated water level residuals were biased low although generally only within a foot of observed conditions (Figure 5.1.3-5). Simulated water level gradients underneath the Facility (Figure 5.1.3-6) were in the west-NW direction (similar to Model #51a) but with a smaller slope measured down the ridge of about 1 ft per 8,000 ft (1.52 miles) for simulated pumping of [redacted] mgd at Red Hill Shaft. An equal amount of water left the boundary from Pearl Harbor, as at the offshore boundary (Table 5-4).

Figures 5.1.3-9 through 5.1.3-12 show the source water zones and plots of water migration from beneath the tanks, as was examined for the other models. When Red Hill Shaft is not pumping, water from the water table underneath the tanks migrates toward the west with a slight turn to the NW but does not intercept Hālawa Shaft (Figure 5.1.3-10); instead, it is intercepted by wells 2255-39 and ʻAiea Hālawa Shaft as it flows to Pearl Harbor.

The hydraulic conductivity zonation provided for basalt (Layers 4 through 9) in Model #51c above along with the property values of the zones is shown on Figure 5.1.3-13. Calibration metrics for Model #51c were similar to those of Model #51a and Model #51b (some better than others); however, the migration behavior from the Facility was different for all three models when Red Hill Shaft was off.

5.1.4 Model #51d: Calibrate on Anisotropy

Model #51d is a follow-up on the high anisotropy condition of Model #51b. In the various simulations that allowed the regional anisotropy to float as a PEST variable (with different target group weightings or different starting parameter values), it was noticed that simulations gravitated toward a value between 17 and 18, with a vertical hydraulic conductivity between 40 and 70 ft/d to fit the regional data. Since the data suggested larger regional horizontal anisotropy values, because the synoptic data are well suited to determining this parameter, and because analytical solutions are not well suited for these complex evaluations, the model was allowed to be the "aquifer test solution" to quantify what was otherwise only noted as being several times higher in the direction of lava flow than transverse to it. Model #51d presents results of a model where the regional anisotropy was allowed to vary during the PEST calibration process. Calibrated model parameter values are noted in Table 5-2. The simulated horizontal anisotropy for basalt was 17.54.

For Model #51d, Figures 5.1.4-1 through 5.1.4-8 respectively show the regression plot of water levels, the regression plots of water level differences, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. Fit to the water level data is generally good and is similar to Model #51b with a 10:1 anisotropy (Figure 5.1.4-1). Water level differences were also simulated well, with similar difference statistics to Model #51b (Table 5-3). Simulated responses to Red Hill Shaft pumping and Hālawa Shaft pumping were also similar to Model #51b (Figures 5.1.4-3 and 5.1.4-4). Simulated water level residuals were generally low but within a foot of observed conditions (Figure 5.1.4-5). The simulated water level gradients underneath the Facility were in the NW direction, with a slope of about 1 ft per 6,500 ft (1.23 miles) measured down the ridge, and were only slightly smaller than Model #51b for simulated pumping of [redacted] mgd at Red Hill Shaft (Figure 5.1.4-6).

Figures 5.1.4-9 through 5.1.4-12 show the particle tracking results as were examined for the other models. When Red Hill Shaft is not pumping, water from underneath the tanks migrates toward the west and turns beneath the saprolite toward Hālawa Shaft (Figure 5.1.4-10). The capture zone for Hālawa Shaft is slightly wider than in Model #51b with a 10:1 anisotropy.

Thus, Model #51d with a horizontal anisotropy of about 17:1 gives similar calibrated conditions to Model #51b with a 10:1 horizontal anisotropy. The capture zones of Hālawa Shaft were slightly wider than those of Model #51d, indicating a larger capture area with greater anisotropy. The migration behavior of water from beneath the Facility is also similar; however, travel times were typically slightly shorter for Model #51d, indicating that in this regard too, higher anisotropy may be a more conservative analysis for capture of water from the Facility at Hālawa Shaft when Red Hill Shaft is not pumping.

5.1.5 Model #51e: Zoned Along Ridges and Within Valleys

Model #51e is a follow-up on the zoned basalt condition of Model #51c. Since the simple hydraulic conductivity zonation of Model #51c had only a small impact on the calibration metrics from Model #51a, additional zonation was considered under the valleys to note if that could be a significant factor. Therefore, Model #51e included hydraulic conductivity zonation beneath the valleys in addition to that along the ridges, considering that basalt under the valleys may also be hydrogeologically different (perhaps due to weathering). In addition, the model included zonation of the specific storage of the basalt material beneath each ridge. Calibrated model parameter values are noted in Table 5-2. Most values aside from the zoned basalt are similar to those of Model #51c. The conductance values for general heads along the ocean boundary and in Pearl Harbor and for the drains were calibrated differently, however, to match the data.

For Model #51e, Figures 5.1.5-1 through 5.1.5-8 respectively show the regression plot of water levels, the regression plots of water level differences, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. Residual and RMS statistics for water levels were better than for all previous models (Figure 5.1.5-1). Water level differences at Facility and non-Facility wells were also well-simulated (Figure 5.1.5-2).

The simulated response at Red Hill Shaft itself (top row panel) was overpredicted, but the simulated response at non-Facility and Facility wells (middle and bottom row panels) was good, for pumping at Red Hill Shaft (Figure 5.1.5-3). This indicates that the hydraulic conductivity at Red Hill Shaft itself was simulated low (larger drawdown); however, the connectivity of Red Hill Shaft to non-Facility and Facility wells was simulated well.

Figure 5.1.5-4 shows that the simulated response at all observation locations was good for pumping at Hālawa Shaft. This indicates that the hydraulic conductivity at Hālawa Shaft itself was good (appropriate drawdown), and that the connectivity of Hālawa Shaft to non-Facility and Facility wells was also generally simulated well.

Simulated water level residuals were generally good and within half a foot of observed conditions (Figure 5.1.5-5). Simulated water level gradients underneath the Facility (Figure 5.1.5-6) were in the west-NW direction, with a slope measured down the ridge of about 1 ft per 6,000 ft (1.14 miles). Very little water left the boundary from Pearl Harbor when compared to offshore discharge (Table 5-4).

Figures 5.1.5-9 through 5.1.5-12 show the source water zones and plots of water migration from beneath the tanks as was examined for the other models. Red Hill Shaft captures all water from beneath the tanks when it was pumping at [redacted] mgd and the capture zone of Hālawa Shaft is only from uphill regions. When Red Hill Shaft was not pumping, water from the water table underneath the tanks migrated in the SW direction from the Facility, turning to the west and NW, ultimately discharging into Pearl Harbor Springs (Figure 5.1.5-10).

The hydraulic conductivity zonation provided for basalt (Layers 4 through 9) in Model #51e above, along with the property values of the zones, is shown on Figure 5.1.5-13. A zone was not included for basalt beneath South Hālawa Valley on the figure because preliminary PEST simulations with such a zone tended to create higher water levels between South and North Hālawa Valleys, causing a simulated flow barrier between the Facility and Hālawa Shaft. Even though no data exist to indicate otherwise, this simulated condition was not conservative to Hālawa Shaft; therefore, a basalt zone beneath South Hālawa Valley was not simulated in the final Model #51e presented herein.

5.1.6 Summary of Homogeneous Models

Model #51a through Model #51e test different hypotheses regarding regional material properties of basalt. Model #51a with lower regional horizontal anisotropy and models with higher anisotropy (Model #51b and Model #51d) have similar calibration statistics but show different migration pathways, specifically when Red Hill Shaft is not pumping. Model #51e with similar calibration statistics shows even different migration pathways when Red Hill Shaft is not pumping. Thus, the information content of available data is not able to further resolve between the models. The regional-scale parameters of these models are not unreasonable, yet their uncertainties are technically challenging to resolve. The main set of models that are distinct from these are Model #51a, which has a 3:1 anisotropy; Model #51b with a 10:1 anisotropy; and Model #51e with zones of basalt hydraulic parameters across the ridges and valleys and underneath the caprock. Therefore, these models should be used further to evaluate their impact on migration of water from beneath the Facility and contaminant transport simulations unless these parameter and conceptual issues can be better resolved.

5.2 MODEL #52: ALTERNATE SAPROLITE

Model #52 had the same material parameter values as Model #51a; however, the numerical grid selected for this model considered the second (shallower) representation of saprolite depth and extent beneath South Hālawa Valley, as shown on Figure 4.2-13 and discussed in the geologic CSM (DON 2019). This model therefore evaluates the impact of a shallower, less-extensive representation of the saprolite structure and provides a comparison with the first saprolite representation with regard to its impact as a barrier to flow through or beneath it.

Figures 5.2-1 through 5.2-12 show the various calibration statistics, water level maps, and model application simulation results for Model #52. The calibration statistics, water budgets, groundwater flow paths from underneath the tanks, and source water zones of Red Hill Shaft and Hālawa Shaft are all very similar to those of Model #51a, indicating that differences in the modeled saprolite structure did not result in significant impact to groundwater flow. Only a slight difference was noted in terms of the particle migration and travel time durations. During the interim modeling study, the presence of saprolite was noted to cause a moderate sensitivity to calibration and application results (Model #8) (DON 2018, Appendix A). Therefore, saprolite depth and extent were evaluated further for the current study to better define the possible barrier effect caused by saprolite beneath the valleys. However, within the range of uncertainty of saprolite depth and extent simulated for South Hālawa Valley, the impact was small. This is because the difference in saprolite depth of 10–40 ft between the models causes little change to the transmissivity of the basalt considering its large hydraulic conductivity and vertical freshwater thickness of 600–800 ft. Due to this insensitivity to calibration and to the results, the shallower, less-extensive saprolite structure was used in all further models, as was agreed to by the SMEs.

5.3 Model #53: Heterogeneous Model

Model #53 had heterogeneous parameter values in an attempt to capture more localized variations in the data and evaluate if greater model flexibility can provide resolution at finer scales at the Facility and across the valleys.

An overparameterized approach was invoked whereby pilot points were generated throughout the domain to represent locations for computing hydraulic parameter values, which were then geostatistically interpolated to generate the modeled parameter field. The density of pilot points was highest where information was highest at the Facility, with less density outside the immediate region of the Facility and Hālawa Shaft. Also, a shallower basalt zone consisting of Layers 4 through 6 was treated separately and with a higher pilot point density than a deeper basalt zone consisting of Layers 7 through 9, so as to focus calibration efforts on flow closer to the water table, which is of interest. A homogenous regularization condition was applied between the pilot points within each of these zones to provide heterogeneity only as needed. Model #51e was used as initial conditions for the PEST calibration simulation.

Inclusion of inflow from the SE boundary was also considered during calibration of Model #53. However, this process was subsequently removed during calibration because that resulted in better calibration statistics.

For Model #53, Figures 5.3-1 through 5.3-8 respectively show the water level regression plot, the water level difference regression plots, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. The simulated water levels and water level differences are good, with better statistics than any of the homogeneous models. The connectivity of Red Hill Shaft to the Facility monitoring wells is good, and the connectivity of Hālawa Shaft to the Facility monitoring wells is also good. Water level gradients underneath the Facility were in the west-NW direction, with a slope of about 1 ft per 5,500 ft (greater than 1 mile) measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft.

Figures 5.3-9 through 5.3-12 show the various source water zones and plots of water migration from beneath the Facility, as was examined for the other models. Preliminary simulations with a constant 1% porosity indicated that the travel times were unrealistic for such high hydraulic conductivities as occur in the model. The porosity of basalt was therefore varied with the hydraulic conductivity to represent the higher voids of the fast flow pathways such as lava tunes or clinker zones as compared to the bulk basalt. Table 5-8 shows the relationship of porosity with hydraulic conductivity used for this model for particle tracking, indicating that porosity ranged from 0.8% for the low hydraulic conductivity regions in the basalt up to 15% for the highly permeable regions representing fast flow pathways. This is a conservative range that adds a safety factor of about 4 to the travel time calculations; previous studies from literature have suggested 4% as a bulk value for basalt and 50% for the high permeable clinker zones. Migration speeds are related to porosity, which could not be estimated via calibration to available data; therefore, these timing estimates are subject to greater uncertainty.

Table 5-8: Porosity Values of Heterogeneous Models for Particle Tracking

Hydraulic Conductivity(ft/d)			
From	To	Porosity	Notes
< 244.44	244.44	0.008	Lower limit of 0.8% on anything smaller than K of 244 ft/d

244.45	1000.00	0.01	Porosity of 1% has base K of 1,000 ft/d
1000.01	2888.89	0.015	—
2888.90	4777.78	0.02	—
4777.79	8555.56	0.03	—
8555.57	16111.11	0.05	—
16111.12	23666.67	0.07	—
23666.68	35000.00	0.1	Porosity of 10% has a K value of 35,000 ft/d
35000.01	42555.56	0.12	Upper limit of 12 % on anything higher than K of 42,500 ft/d
42555.57	>42555.57	0.15	—

Note: Table assumes linear interpolation between 1,000 ft/d and 35,000 ft/d values.

Water from the Facility was all captured by Red Hill Shaft when it was pumping at [redacted] mgd (Figure 5.3-9) and took 47-150 days to reach Red Hill Shaft. When Red Hill Shaft was not pumping, some water from the Facility migrates toward Hālawa Shaft while the rest flows toward Pearl Harbor Spring, being also intercepted by well 2255-39 and ʻAiea Hālawa Shaft.

5.4 MODEL #54: HETEROGENEOUS MODEL

Model #54 was an alternate heterogeneous parameter model for capturing localized variations in the data and evaluating if greater model flexibility can provide resolution at finer scales at the Facility and across the valleys.

The overparameterized approach of Model #53 was also used for Model #54; however, a different starting condition and target weights were used for running PEST. Specifically, while a random starting parameter value was used for the PEST simulations in Model #53, starting parameter values of Model #54 were selected to attempt NW flow directions from the Facility toward Hālawa Shaft, as discussed with SMEs (this was not observed with a random initial parameter condition). The intent was to see what it would take parameter-wise to make such a situation happen; therefore, initial parameter values were created to block flow down-valley, making it turn northwestward. Regularization was then applied to the initial parameter distribution values at pilot points, such that parameters could move by 5% of their value in log space toward the mean value. Therefore, development of Model #54 tried to induce the NW movement of water from beneath the Facility, as discussed by SMEs, which could not be created by the other homogeneous models or the heterogeneous model (Model #53), which was initiated with uniform parameter values over zones and valleys.

For Model #54, Figures 5.4-1 through 5.4-8 respectively show the water level regression plot, the water level difference regression plots, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. Water levels, water level differences, and drawdown impacts for Red Hill Shaft and Hālawa Shaft shutdown were all well-simulated. Even though water level gradients (Figure 5.4-6) appear visually different from those of Model #53, slope measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft was similar (about 1 ft per 5,500 ft).

Figures 5.4-9 through 5.4-12 show the various source water zones and plots of water migration from beneath the Facility, as was examined for the other models. The porosity of basalt was varied with the hydraulic conductivity for particle tracking simulations in a manner similar to the previous heterogeneous model (Model #53), as shown in Table 5-8. Water from the Facility was all captured by Red Hill Shaft when it was pumping at [redacted] mgd (Figure 5.4-9) and took 56–228 days to reach Red Hill Shaft; however, the path was significantly more convoluted than in other models. Water from the Facility migrated in the NW direction when Red Hill Shaft was not pumping (Figure 5.4-10) and was captured at Hālawa Shaft. Therefore, starting the parameterization with forced parameter values created a model that indicated travel to the NW from the Facility. The simulated travel times from the Facility to Hālawa Shaft ranged from 229 to 414 days.

The hydraulic conductivity distribution of basalt in Layers 4 through 6 is shown on Figure 5.4-13, and the hydraulic conductivity distribution of basalt in Layers 7 through 9 is shown on Figure 5.4-14. The density of pilot points was the same as that of Model #53. The starting hydraulic conductivity distribution for basalt before PEST runs was as shown on Figure 5.4-15 and is constructed to create a block to down-valley flow at Red Hill with a high conceptual clinker zone in the upper basalt layers (Layers 4–6). The calibrated hydraulic conductivity patterns were similar to those of Model #53, specifically in the shallow layers at the Facility. Thus, both models (Model #53 and Model #54) gravitated toward similar PEST results in this region where data density was greatest, even though they had different starting conditions. Also, there is a general pattern of higher basalt hydraulic conductivity in the NE and lower basalt hydraulic conductivity to the west of the model domain, which was noted in both models for shallow and deep basalt layers. However, Model #54 indicates a lower hydraulic conductivity of shallow basalt underneath the caprock slowing down or restricting flow into that area, thus causing different migration patterns for groundwater from the Facility when Red Hill Shaft is not pumping relative to Model #53, even though hydraulic properties in the vicinity of the Facility are similar between the models. As a result, collecting more hydrogeologic data in the vicinity of the Facility to use in a model will not help resolve this uncertainty in flow behavior resulting from parameterization farther to the SW.

5.5 MODEL #55: CONCEPTUAL CLINKER ZONE

Model #55 was developed to evaluate the impact of a fast-flow pathway in groundwater beneath the Facility. Such fast-flow pathways occur in the basalt in the form of clinker zones or lava tubes that are generally aligned with the direction of lava flow and can impact the migration of water from beneath the Facility. Since the homogeneous basalt model reflects average conditions for flow, simulated travel times may not reflect the impact of a fast-flow pathway possibly existing beneath the Facility and connecting to Red Hill Shaft. Since the geology beneath the site is complex, a clinker zone was conceptually included beneath the site in Layers 5 and 6 as the extreme case of a fast-flow pathway. The hydraulic conductivity of the clinker zone was calibrated as a PEST parameter. The porosity value was 0.1 within the clinker zone for particle tracking computations.

For Model #55, Figures 5.5-1 through 5.5-8 respectively show the water level regression plot, the water level difference regression plots, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. Water levels and water level differences at Facility and non-Facility wells (Figures 5.5-1 and 5.5-2) were simulated fairly well, with better overall statistics than for Model #51a, which did not simulate a clinker zone. Simulated drawdown hydrographs for Red Hill Shaft shutdown and Hālawa Shaft shutdown (Figures 5.5-3 and 5.5-4) were good for many of the wells and were significantly improved compared to the homogeneous model, indicating that the respective connectivities were also simulated better. The hydraulic conductivity at Red Hill Shaft itself was under-simulated (larger drawdown at the shaft itself shown on the top panel of Figure 5.5-3), while the connectivity of Hālawa Shaft to Facility wells was still over-simulated (larger drawdown at monitoring wells shown on the bottom panels of Figure 5.5-4). Simulated water level gradients underneath the Facility (Figure 5.5-6) are in the west-SW direction but curve to the NW toward the simulated clinker zone from the south. The slope of the water level is about 1 ft per 6,000 ft (1.1 miles) measured down the ridge (similar to that of the homogenous model, Model #51a) for simulated pumping of [redacted] mgd at Red Hill Shaft.

Figures 5.5-9 through 5.5-12 show the various source water zones and plots of water migration from beneath the Facility, as were examined for the other models. Water from the Facility was all captured by Red Hill Shaft and it took 21–69 days to reach Red Hill Shaft when it was pumping at [redacted] mgd (Figure 5.5-9). This is faster than for the homogeneous model (Model #51a); however, travel times are related to porosity, which cannot be calibrated from the observations. The clinker porosity value of 0.1 was conservative, and travel times are probably larger with longer travel times. Travel toward potential downgradient receptors was similar to that of the homogeneous model (Model #51a) when Red Hill Shaft was not pumping (Figure 5.5-10 and 5.5-11) except that some water was also captured at Pearl Harbor Spring at Kalauao.

The hydraulic conductivity distribution provided for basalt (Layers 4 through 9) in Model #55 above is shown on Figure 5.5-13. Although the clinker zone has a high hydraulic conductivity value, the basalt hydraulic conductivity was lower than that of that of the homogeneous model (Model #51a). The conclusion of interest from this model is that a fast-flow pathway underneath the Facility can cause larger Darcy flux through it, but ultimately the modeled recharge and lateral inflow determines flow rates. Also, the pore velocity may not be much larger for a clinker zone than for average basalt conditions due to its larger porosity. Since porosity is a significant parameter in computing migration speeds, and because it cannot be calibrated from available observations, values were used in the model were conservative.

5.6 MODEL #56: STRUCTURAL ALTERATIONS TO TUFF CONES

Model #56 was developed to evaluate the impact of an alternate structural conceptualization for the tuff cones. The consideration here was to provide a damming effect by the tuff cones on flow down Red Hill ridge, an additional conceptualization discussed by SMEs, which would then divert the flow northward. The tuff cones, as implemented in the other models, did not provide such a damming effect, even with very low hydraulic conductivity values, and water would flow around them and down Red Hill ridge. Therefore, instead of conducting a sensitivity to the hydraulic conductivity values of the cones as was originally envisioned, its conceptualization was changed by merging the cones and enlarging their extent to try and create a barrier to the south of Red Hill ridge.

In preliminary calibration simulations, extending the tuff cone extents did not create a barrier nor did it create NE water level gradients as was conceptualized. To further this conceptualization, the simulation also included inflow from the SE boundary. This was facilitated in the model by releasing the SE general head boundary conductance to a higher value and allowing its value to vary in PEST such that around 10 mgd of inflow can occur from the SE boundary as well. Table 5-4 shows that the model ultimately included 9 mgd of inflow from the SE boundary.

For Model #56, Figures 5.6-1 through 5.6-8 respectively show the water level regression plot, the water level difference regression plots, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. The regression to water levels (Figure 5.6-1) and to water level differences (Figure 5.6-2) is comparable to that of other models. The connectivity of Facility and non-Facility wells to Red Hill Shaft was mixed (Figure 5.6-3), with a larger connectivity to Facility wells and smaller connectivity to non-Facility wells than for Model #51a. Connectivity to Hālawa Shaft was good (Figure 5.6-4) and an improvement connectivity-wise over Model #51a. Water level gradients underneath the Facility were in the west-NW direction, with a slope of about 1 ft per 5,000 ft (1 mile) measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft.

Figures 5.6-9 through 5.6-12 show the various source water zones and plots of water migration from beneath the Facility, as were examined for the other models. The source water zone of Red Hill Shaft was more to the east than for Model #51a (Figure 5.6-9), resulting from the barrier effect as well as the SE inflow condition. Water from the Facility moved in a NW direction and was captured at Hālawa Shaft when Red Hill Shaft was not pumping.

The hydraulic conductivity distribution provided for basalt (Layers 4 through 9) in Model #56 is shown on Figure 5.6-13. The tuff cones are not likely to be connected in this manner; however, the model did create a wall along the SW regions of Red Hill ridge but could not create flat water table conditions or reverse flow gradients behind it, as was anticipated.

5.7 MODEL #57: RECHARGE

Model #57 was developed to evaluate the impact of recharge uncertainty by using the drought condition for areal recharge, which was a factor of 0.75 less than for current conditions, as noted in Table 3-3. The material parameter values of Table 5-2 indicate that basalt horizontal hydraulic conductivity was reduced as a result, although the vertical hydraulic conductivity remained at its maximum.

For Model #57, Figures 5.7-1 through 5.7-8 respectively show the water level regression plot, the water level difference regression plots, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. The regression to water levels (Figure 5.7-1) and to water level differences (Figure 5.7-2) is good and comparable to that of other models. The connectivity of Facility and non-Facility wells to Red Hill Shaft was similar to that of Model #51a (Figure 5.7-3). Connectivity to Hālawa Shaft was less for Facility and non-Facility wells than in Model #51a (Figure 5.7-4) and is an improvement connectivity-wise between the Facility wells and Hālawa Shaft over that of Model #51a. Water level gradients underneath the Facility were in the west-NW direction, with a slope of about 1 ft per 5,000 ft (less than 1 mile) measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft.

Figures 5.7-9 through 5.7-12 show the various source water zones and plots of water migration from beneath the Facility, as were examined for the other models. The various source water zones and migration pathways were similar to those of Model #51a, indicating that uncertainty in recharge magnitudes could impact the associated model parameterization but may not have a significant impact on migration of water or source water zones of Hālawa Shaft and Red Hill Shaft. Thus, having different recharge factors does not impact migration; however, the impact of spatial uncertainties in recharge distribution have not been evaluated.

5.8 MODEL #58: COASTAL MARINE DISCHARGE VARIABILITY

Model #58 was developed to evaluate the impact of variability in discharge to the coast versus to Pearl Harbor. This is because there is uncertainty in this distribution of the water budget outflow term, with concerns expressed by SMEs that it could impact direction of flow from the Facility. Since the potential concerns were to the NW of the Facility, this model considered little to no flow toward the ocean boundary, with all the remaining outflow budget (after pumping and flow to the springs) being diverted to Pearl Harbor. To facilitate this in the model, the general head boundary conductance at the ocean boundary was set to a low value with a high value beneath Pearl Harbor, as indicated in Table 5-2.

For Model #58, Figures 5.8-1 through 5.8-8 respectively show the water level regression plot, the water level difference regression plots, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. The regression to water levels (Figure 5.8-1) and to water level differences (Figure 5.8-2) is good and comparable to that of other models. The connectivity of Facility and non-Facility wells to Red Hill Shaft was similar to that of Model #51a (Figure 5.8-3). Connectivity to Hālawa Shaft was less for Facility and non-Facility wells than in Model #51a (Figure 5.8-4). This model's lower hydraulic conductivity values for basalt causes the lower connectivity. Water level gradients underneath the Facility were in the west-NW direction, with a slope of about 1 ft per 5,500 ft (greater than 1 mile) measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft.

Figures 5.8-9 through 5.8-12 show the various source water zones and plots of water migration from beneath the Facility, as were examined for the other models. The various source water zones and migration pathways were similar to those of Model #51a, indicating that uncertainty in coastal marine discharge does not have a significant impact on migration of water or source water zones of Hālawa Shaft and Red Hill Shaft. The water budgets in Table 5-4 indicate that only about 10% of the discharge is to the ocean boundary and Pearl Harbor, with most of it going to pumping and the springs; therefore, diverting this small amount of water one way or the other did not significantly impact the migration behavior of interest.

5.9 MODEL #59: LATERAL INFLOW FROM SOUTHEAST BOUNDARY

Model #59 was developed to evaluate the impact of inflow from the SE boundary of the model. It is likely that the thick low-permeability caprock to the east of the model domain causes some of this water to be diverted westward underneath the valleys instead of flowing to the overlying marine sediments and subsequently to the ocean. This conceptualization had been put forth by Mink (1980), and the SMEs suggested that it be tested. Preliminary calibration simulations had indicated that calibration was not sensitive to this condition, and the model may be as well-calibrated as some of the other models. Therefore, further simulations provided a target inflow of 10 mgd from the SE boundary as a reasonable number, considering the magnitude of the other water budget inflow terms. To facilitate this in the model, the general head boundary conductance at the SE boundary was set to a higher value and then calibrated as a PEST parameter such that the target inflow was generally achieved.

For Model #59, Figures 5.9-1 through 5.9-8 respectively show the water level regression plot, the water level difference regression plots, the drawdown hydrographs for SP2 and SP4, a map of water level residuals, the potentiometric surface map in the basalt for when Red Hill Shaft and Hālawa Shaft were pumping (SP1 of the calibration simulation), the numerical verification hydrographs, and the TFN verification hydrographs. The regression to water levels (Figure 5.9-1) and to water level differences (Figure 5.9-2) is good and comparable to that of other models. The connectivity of Facility and non-Facility wells to Red Hill Shaft was generally well-simulated (Figure 5.9-3). Connectivity to Hālawa Shaft for Facility and non-Facility wells was simulated high (Figure 5.9-4). Water level gradients underneath the Facility were in the west-NW direction, with a slope of about 1 ft per 5,500 ft (greater than 1 mile) measured down the ridge for simulated pumping of [redacted] mgd at Red Hill Shaft.

Figures 5.9-9 through 5.9-12 show the various source water zones and plots of water migration from beneath the Facility, as were examined for the other models. The various source water zones and migration pathways were shifted more to the east than for Model #51a. However, migration behavior from the Facility was similar to Model #51a, with water being captured by Hālawa Shaft, well 2255-39, and ʻAiea Hālawa Shaft on its way to Pearl Harbor.

This model demonstrates that the Mink (1980) conceptualization is considered valid as it provided a reasonable calibration to the available information. The model indicates that source water zones of wells may be shifted eastward as a result, but the migration behavior of water from the Facility was not impacted.

5.10 Summary and Conclusions

The models have indicated the general flow and migration behavior of water from beneath the Facility and evaluated some key impacts of uncertainties of concern regarding conceptualization and parameterization. Some general and significant observations made during calibration of these models include:

- The models were generally well-calibrated to regional water levels and water level differences.
- Most models overpredicted the response of Hālawa Shaft at the Facility, indicating a larger simulated connectivity between the Facility and Hālawa Shaft (conservative); however, the heterogeneous models (Model #53 and Model #54), and the model with barriers (Model #51e) performed fairly well in terms of the simulated connectivity between the Facility and Hālawa Shaft.
- Summary statistics in Table 5-3 for water levels and water level differences were useful in comparing the performance of the various models for slope and water level determination. All models performed well, with the best statistics shown for the heterogeneous models (Model #53 and Model #54) and for the model with zones beneath the valleys (Model #51e).
- Summary statistics in Table 5-3 for responses to Hālawa Shaft or Red Hill Shaft shutdown did not provide useful information on the connectivity of groundwater between Red Hill Shaft or Hālawa Shaft and the Facility. That is because larger drawdown at the pumping shaft itself indicates a lower connectivity, while larger drawdown at other monitoring wells indicates a higher connectivity. The related drawdown figures were, however, useful in determining the connectivities within the basalt, for the various models. It was noted that the connectivity to Hālawa Shaft was overpredicted in most models, with the best connectivity between the Facility and the water supply shafts (Red Hill Shaft and Hālawa Shaft) displayed by the heterogeneous models (Model #53 and Model #54) and the model with zones beneath the valleys (Model #51e).
- Hālawa Deep response indicated that the vertical connectivity of basalt may have been simulated too high. However, this well is close to the deeper zones of well RHMW11, which indicated that the vertical connectivity was appropriate for many models. The RHMW11 response was considered more reliable because Hālawa Deep has issues including its construction as a long open borehole. Also, having a deeper connectivity in the model adds a safety factor to the analyses in terms of Hālawa Shaft connection allowing for water to dive easier beneath the saprolite that is in the travel path of water from the Facility.
- The connection between Hālawa Shaft and the Facility was high in most models, which also indicates a safety factor in terms of its pumping impact on migration from the Facility toward Hālawa Shaft.
- It took about 3 years to achieve steady state after shutting off pumping at Hālawa Shaft or Red Hill Shaft.

- When Red Hill Shaft is not pumping, the low hydraulic conductivity of tuff along with higher hydraulic conductivity of alluvium within the caprock caused a greater preference for water from the Facility to flow toward the alluvium, which is located near Pearl Harbor, rather than through the overlying tuff immediately downhill of Red Hill and toward the ocean. The low hydraulic conductivity value for tuff was discussed with the SMEs, and impacts depicted in the interim modeling effort (whereby migration is more westward and less to the north) may also be valid, as the hydraulic properties of these materials are largely unknown.
- Larger specific storage terms gave smaller drawdown responses for both Hālawa Shaft and Red Hill Shaft shutdown.
- Larger vertical hydraulic conductivity values gave smaller drawdowns for Hālawa Shaft shutdown and more so for Red Hill Shaft shutdown.
- Larger horizontal anisotropy gave more NW-facing water level gradients compared to smaller horizontal anisotropy.
- Larger anisotropy may be more conservative toward Hālawa Shaft when Red Hill Shaft is not pumping, since it causes a larger capture area for it due to a more elongated drawdown cone.

Significant observations of the particle tracking analyses with the models include:

- All models indicated capture of water from beneath the tanks by Red Hill Shaft when it is pumping at [redacted] mgd.
- All models indicated that the source water zone of Red Hill Shaft encompasses the Facility footprint uphill of the shaft.
- Depending on the uncertainty addressed by a model, water from beneath the tanks migrated toward Hālawa Shaft or Pearl Harbor (or both) when Red Hill Shaft is not pumping and Hālawa Shaft is pumping at 12 mgd.
- Discharge to the ocean boundary was a small component of outflow when recharge in the model was limited (recharge multiplying factor less than 1); therefore, most water flows toward the discharge locations at wells and springs or to Pearl Harbor for such conditions. However, during prolonged drought conditions, pumping from these shafts may need to be curtailed for other reasons, which may induce different travel paths.

A comparison of the various models indicates that when Red Hill Shaft is pumping, the uncertainty in travel paths near the Facility is small (Figure 5-4). All models indicate that groundwater from beneath the Facility is captured by Red Hill Shaft pumping at [redacted] mgd. However, when Red Hill Shaft is not pumping, various models show different travel paths depending on modeled conditions, as shown on Figure 5-5. A larger regional anisotropy (Model #51b) causes the capture zone of Hālawa Shaft to reach out farther downhill to intercept water from the Facility. Future modeling may also consider using the 17:1 anisotropy rather than 10:1 based on calibration results. Less anisotropy causes capture at Hālawa Shaft as well as at well 2355-39, 'Aiea Hālawa Shaft, and Kalauao Spring (Model #51a). However, if the bulk basalt properties were different beneath the ridges and valleys (Model #51e), migration of groundwater from the Facility is more southward, discharging in Pearl Harbor Springs. Also, the heterogeneous models Model #53 and Model #54 have good calibration statistics and similar parameter values around the Facility, but different migration patterns. It would be technically challenging to resolve these data uncertainties. Therefore, these models should be retained in further evaluations and for model applications addressing transport of potential solutes. Model #55 depicting a conceptual clinker zone should also be retained because it addresses the fast flow pathway. On the other hand, impact of saprolite depth and extent is negligible for groundwater flow (Model #52 and

Model #51a); recharge uncertainty does not translate to uncertainty in migration of groundwater with or without Red Hill Shaft pumping (Model #57), neither does coastal marine discharge variability (Model #58) or lateral inflow from the southeast (Model #59). Also, there is no geologic basis for low-conductivity structures at the downhill end of Red Hill ridge as in Model #56. Therefore, results of these models should be documented for future reference, and the models should be removed from further consideration unless deemed otherwise at a later date.

The significant conclusions from these simulations include:

- All models indicated that Red Hill Shaft captures water from the water table beneath the tanks and that its source water zone encompasses the Facility footprint uphill of the shaft when pumping at [redacted] mgd.
- The migration behavior depicted by the particle tracking figures of the various models and the travel times of interest indicated in Table 5-5 show that the variability tested by these models caused little to no change in the outcome when Red Hill Shaft is pumping at [redacted] mgd.
- There was considerable variability in outcome for migration of water from the Facility when Red Hill Shaft is not pumping, with larger variability between models as water migrates farther away from the Facility. The information content of available data is not able to discern this uncertainty in flow directions among the models farther away from the Facility.
- When Red Hill Shaft is not pumping, flow was generally to the west nearer to the Facility but then turned to the NW underneath the saprolite, possibly affecting Hālawa Shaft, well 2255-39, ʻAiea Hālawa Shaft, Kalauao Spring, Pearl Harbor Spring at Kalauao, or Pearl Harbor.
- Saprolite does not form a barrier to groundwater flow causing groundwater to flow around it; instead, flow occurs within the basalt beneath the saprolite as the path of least resistance.
- A heterogeneous model (Model #54) was calibrated so that it did have migration from the Facility in the NW direction when Red Hill Shaft was not pumping. However, the parameter field for this model was developed purposefully to induce this condition. The PEST model provided heterogeneity to improve calibration but retained the migration properties of the initial parameter set.
- The main difference between Model #53 and Model #54 is the basalt hydraulic conductivity underneath the caprock that resulted due to the models' different starting parameter values. Otherwise, both heterogeneous models (Model #53 and Model #54) displayed similar calibrated properties in the vicinity of Red Hill ridge where the synoptic study data for calibration were available. Therefore, additional hydrogeologic data at the Facility will not resolve the noted differences in groundwater migration from the Facility between these two models.
- As a fast path evaluation approach, utilization of a conceptual clinker zone at the water table connecting the Facility to Red Hill Shaft showed that the migration times were 1.2–2.2 times quicker than for homogeneous conditions. This can vary considerably considering the uncertainty in porosity of basalt and clinker material, and therefore conservative porosity values were used for the models to provide a safety factor.
- Heterogeneous models used a porosity range of 0.8% to 15% to represent the basalt. A linear interpolation between conservative estimates for bulk basalt and for a clinker zone was used to provide the larger pore space required to accommodate large volumes of flow in the highly conductive clinker zones. Porosity cannot be calibrated with available observations; therefore,

the travel times may have larger uncertainty, and other means would be necessary to define porosity regionally in the domain and locally at the Facility, to better estimate travel times.

- A regional horizontal anisotropy of about 17:1 better fits the regional water level and water level difference data.
- Zonation of the basalt properties along ridges and within valleys provides a better fit to regional water level data, water level difference data, and connectivity of Red Hill Shaft and Hālawa Shaft to Facility monitoring wells.
- There is no damming impact of tuff cones to downhill flow from the Facility within the basalt as expressed by current geological interpretations. A lower-permeability structure within the basalt all across the south of the Facility caused a northward deflection in the flow from the Facility. However, the existence of these connected subsurface structures (tuff cones) is highly unlikely.
- There was almost no impact of variability in discharge to Pearl Harbor and the ocean boundary (Model #58 compared to Model #51a) on migration behavior from the Facility or on source water zones of Red Hill Shaft and Hālawa Shaft. Considering the water budget of these models, this quantity is small and therefore does not impact the flow behavior.
- There was almost no impact of recharge uncertainty to simulated migration behavior from the Facility whether Red Hill Shaft is pumping or not. Models calibrated to different recharge factors indicated similar flow behavior; however, recharge distribution uncertainty impacts have not been evaluated.
- A reasonable amount of inflow from the SE boundary can still calibrate a groundwater flow model to the calibration metrics and available data but did not significantly impact the migration behavior from the Facility.
- The multimodel approach provides a means for evaluation of various models relative to different risk-management decisions. Table 5-9 summarizes the models relative to groundwater travel times to key receptors and highlights potential models that may be important in addressing key risk-management decisions. Considerations for selecting models for addressing risk-management decisions may include factors such as reasonableness of the model scenario, weighting, travel times, and potential flux issues relative to receptors. Travel times and flow paths are relative to groundwater flow and are thus very conservative in nature. Potential migration of chemicals of concern will be evaluated as part of the contaminant fate and transport modeling effort.

Table 5-9: Summary of Multimodel Applicability for Risk-Based Decision Making

Model #	Description	Effective Capture Zone with Red Hill Shaft Pumping	Groundwater Flow Times to: (days)		
			Red Hill Shaft (Red Hill Shaft and Hālawa Shaft Pumping)	Hālawa Shaft (Red Hill Shaft Not Pumping)	Other Receptors (Red Hill Shaft Not Pumping)
51	Homogeneous basalt with CSM saprolite				
51a	Limit horizontal anisotropy (3:1)	✓	25–121	374–518	724–850
51b	10:1 anisotropy	✓	19–118	259–375	N/A
51c	Zoned along ridges	✓	17–94	N/A	559–793
51d	Calibrate on anisotropy	✓	9–118	254–382	N/A
51e	Zoned along ridges and within valleys	✓	41–135	N/A	883–1,031
52	Alternate saprolite	✓	28–121	351–527	738–852
53	Heterogeneous basalt	✓	47–150	384–953	1,020–1,831
54	Heterogeneous basal	✓	56–228	229–414	N/A
55	Conceptual clinker zone	✓	21–69	295–580	685–1,938
56	Structural alterations to tuff cones	✓	16–83	137–170	N/A
57	Recharge uncertainty	✓	33–129	361–649	744–932
58	Coastal marine discharge variability	✓	31–122	366–550	691–1,494
59	Lateral inflow from SE	✓	24–101	251–463	523–671

Suggested for risk consideration (yellow highlight)

N/A not applicable

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Figures

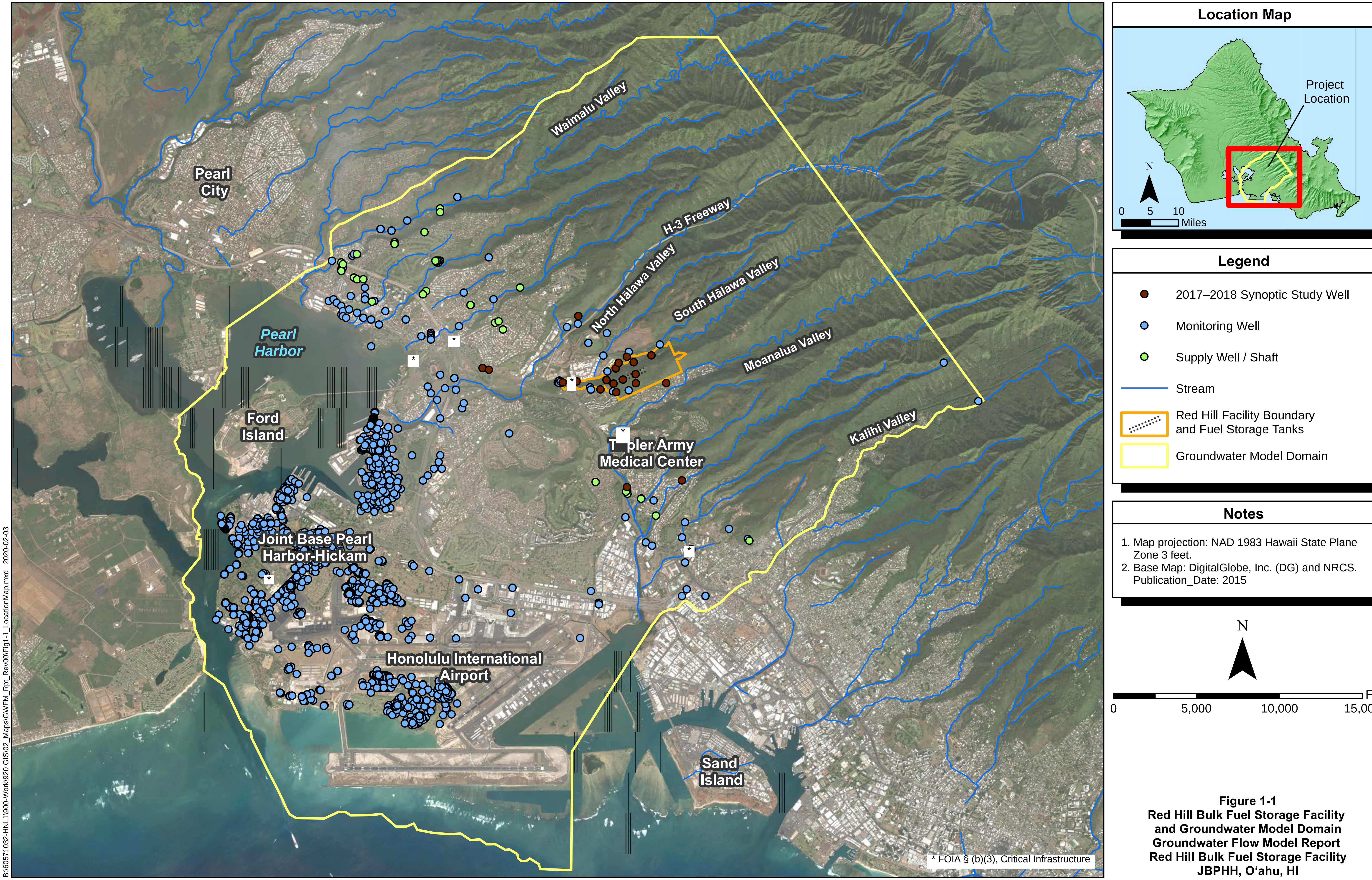

Figure 1-1
Red Hill Bulk Fuel Storage Facility and Groundwater Model Domain
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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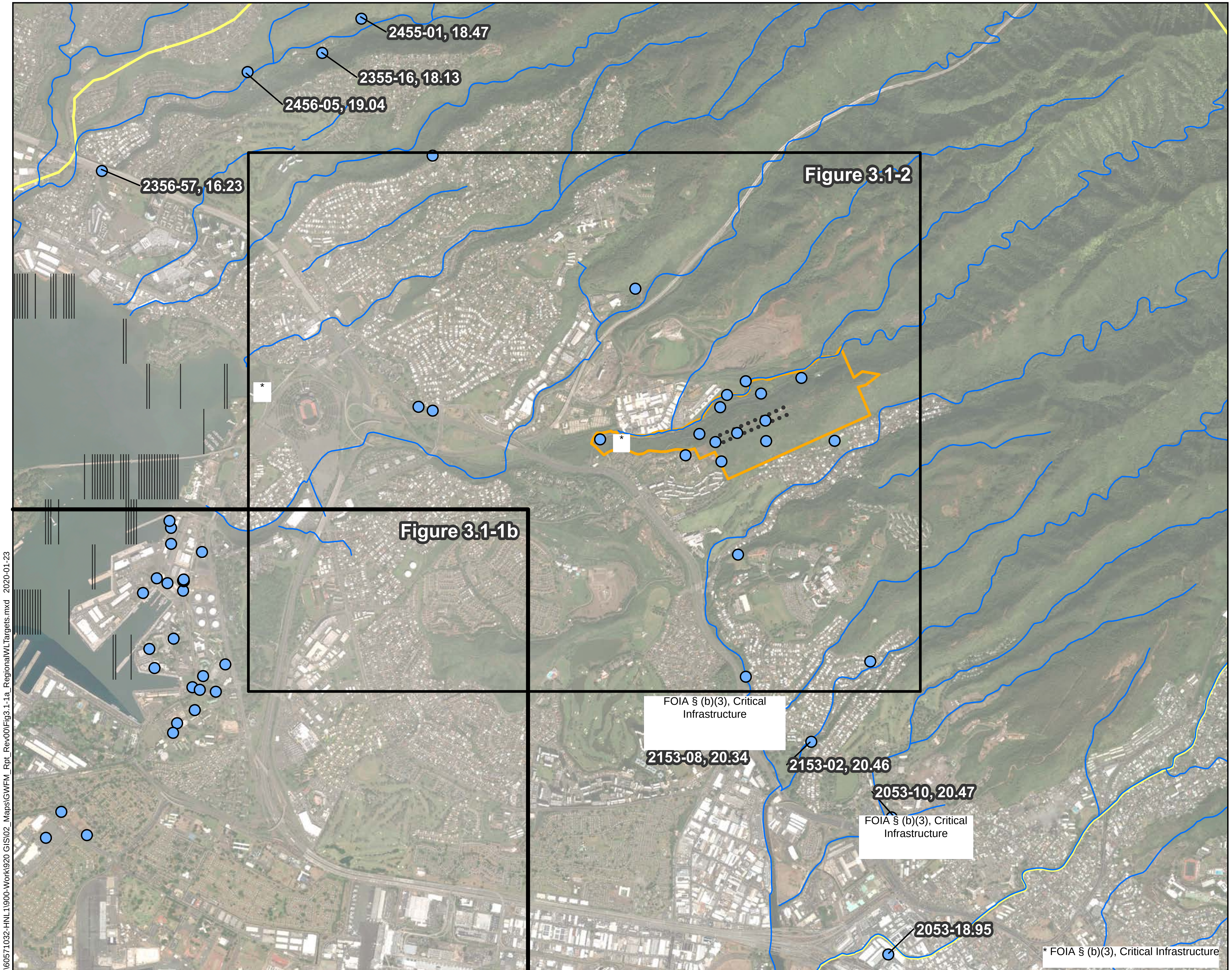

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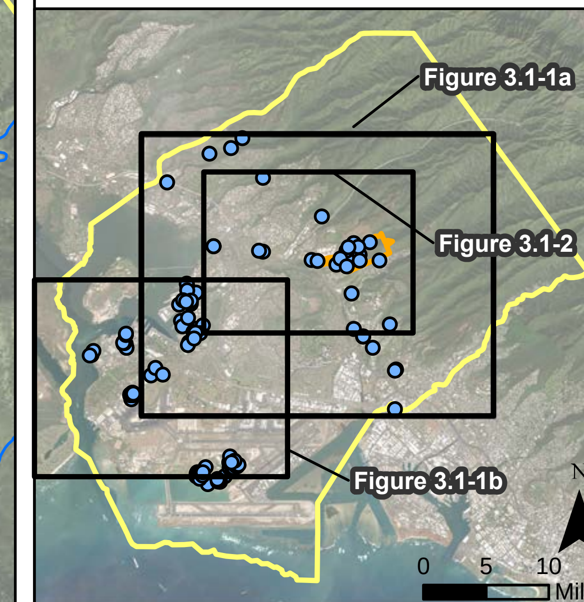


Legend

- Stress Period 1 Calibration Target Wells
- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

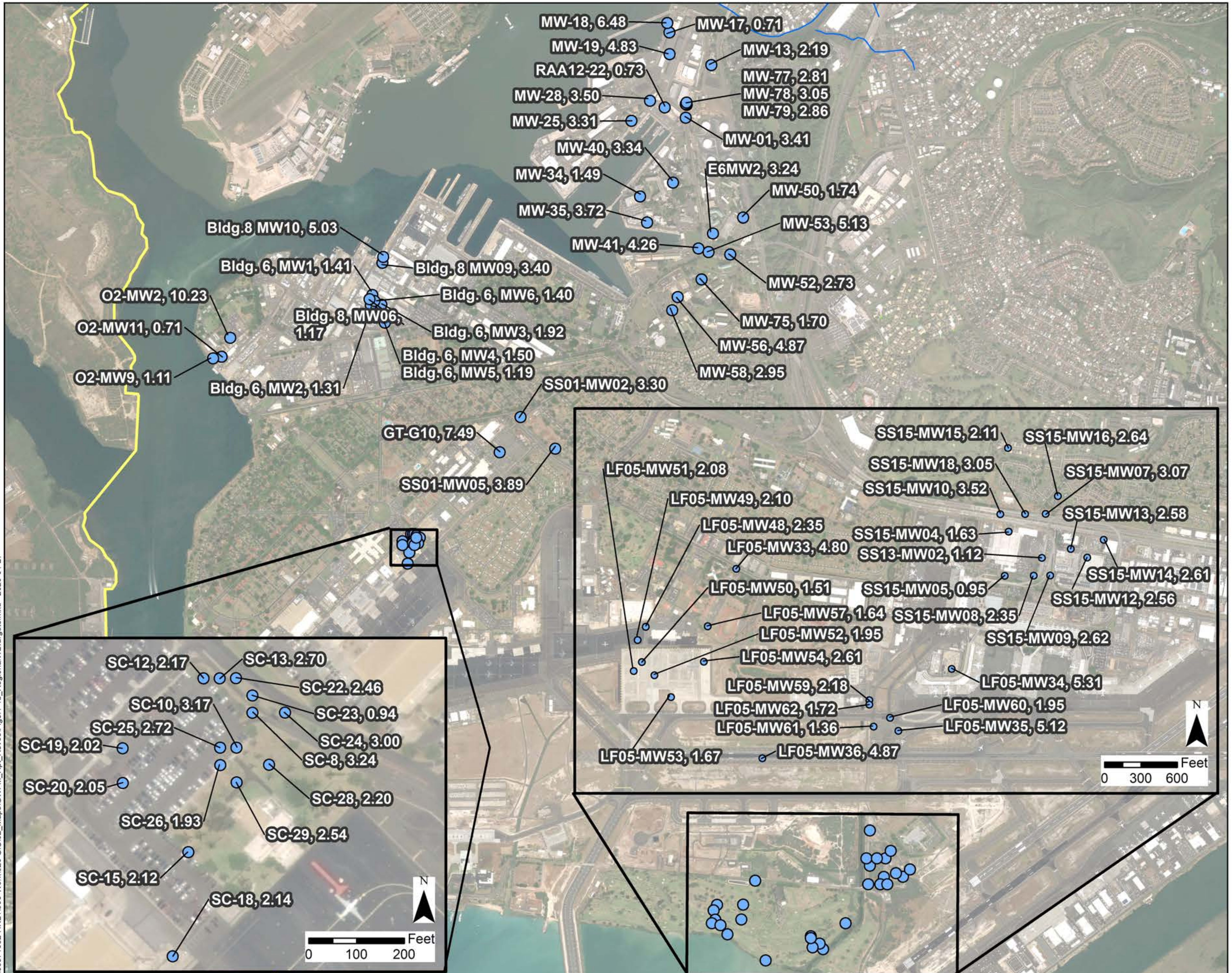
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. 2153-09, 19.43 Well ID, Water level elevation in feet above mean sea level

N

0 1,000 2,000 3,000 4,000 Feet

Figure 3.1-1a
Regional Water Level Targets When Red Hill Shaft and Hālawa Shaft Are Pumping at Average Conditions
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



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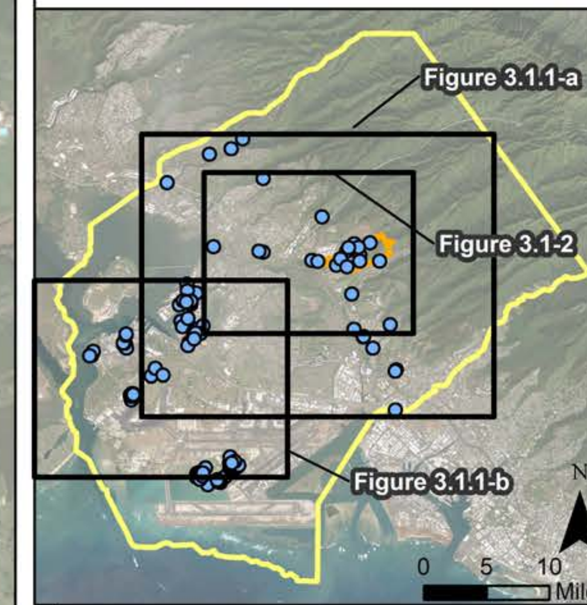


Legend

- Stress Period 1 Calibration Target Well
- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

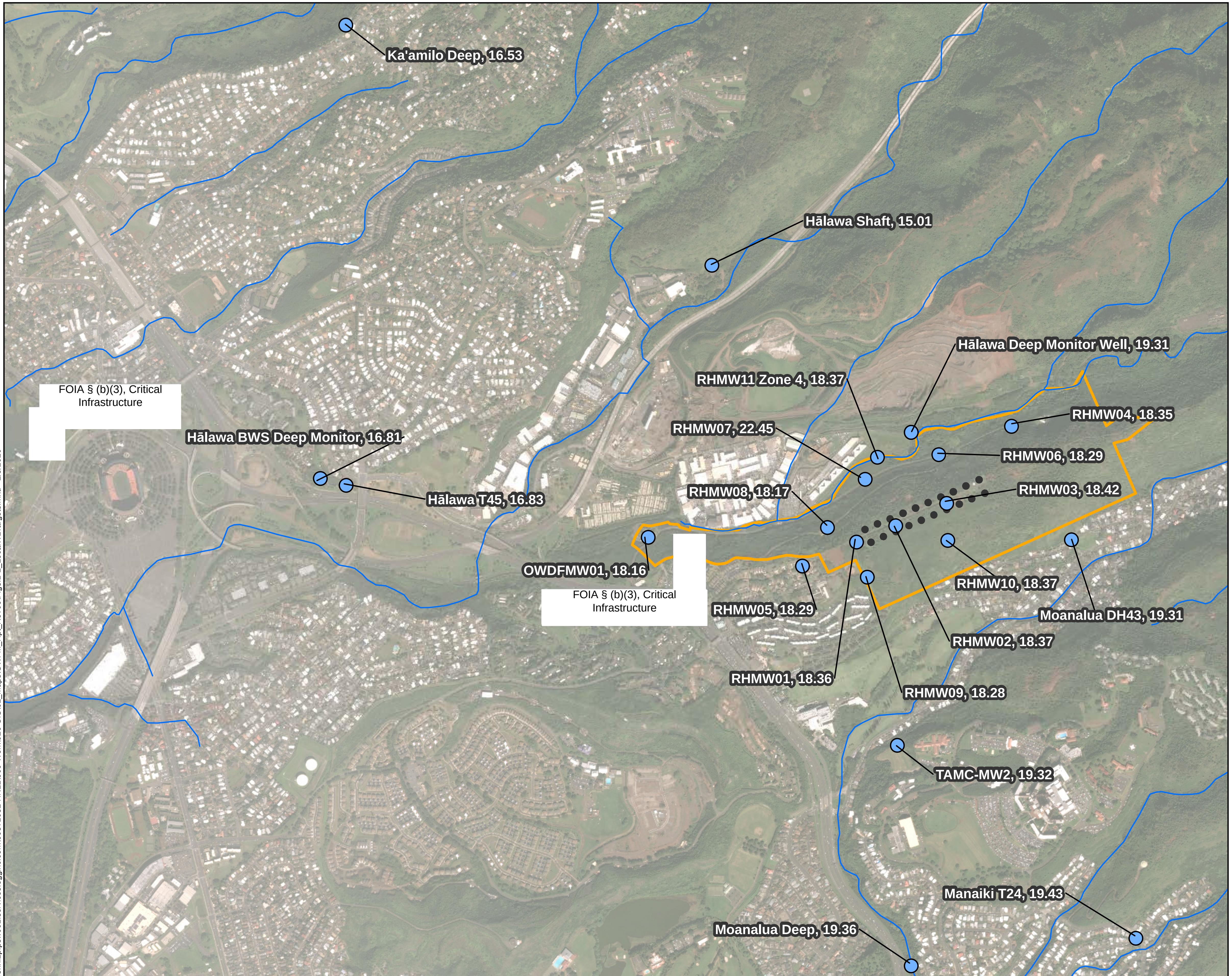
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. 2153-09, 19.43 Well ID, Water level elevation in feet above mean sea level

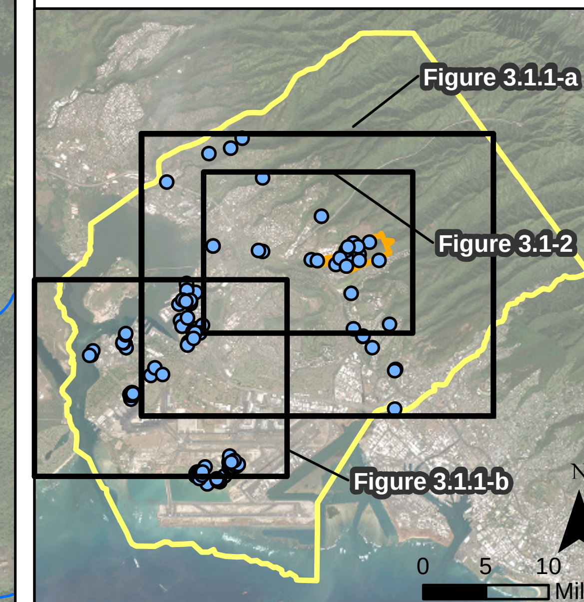
N

Feet
0 1,000 2,000 3,000 4,000

Figure 3.1-1b
Regional Water Level Targets When Red Hill Shaft and Hālawa Shaft Are Pumping at Average Conditions
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

- Stress Period 1 Calibration Target Well
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

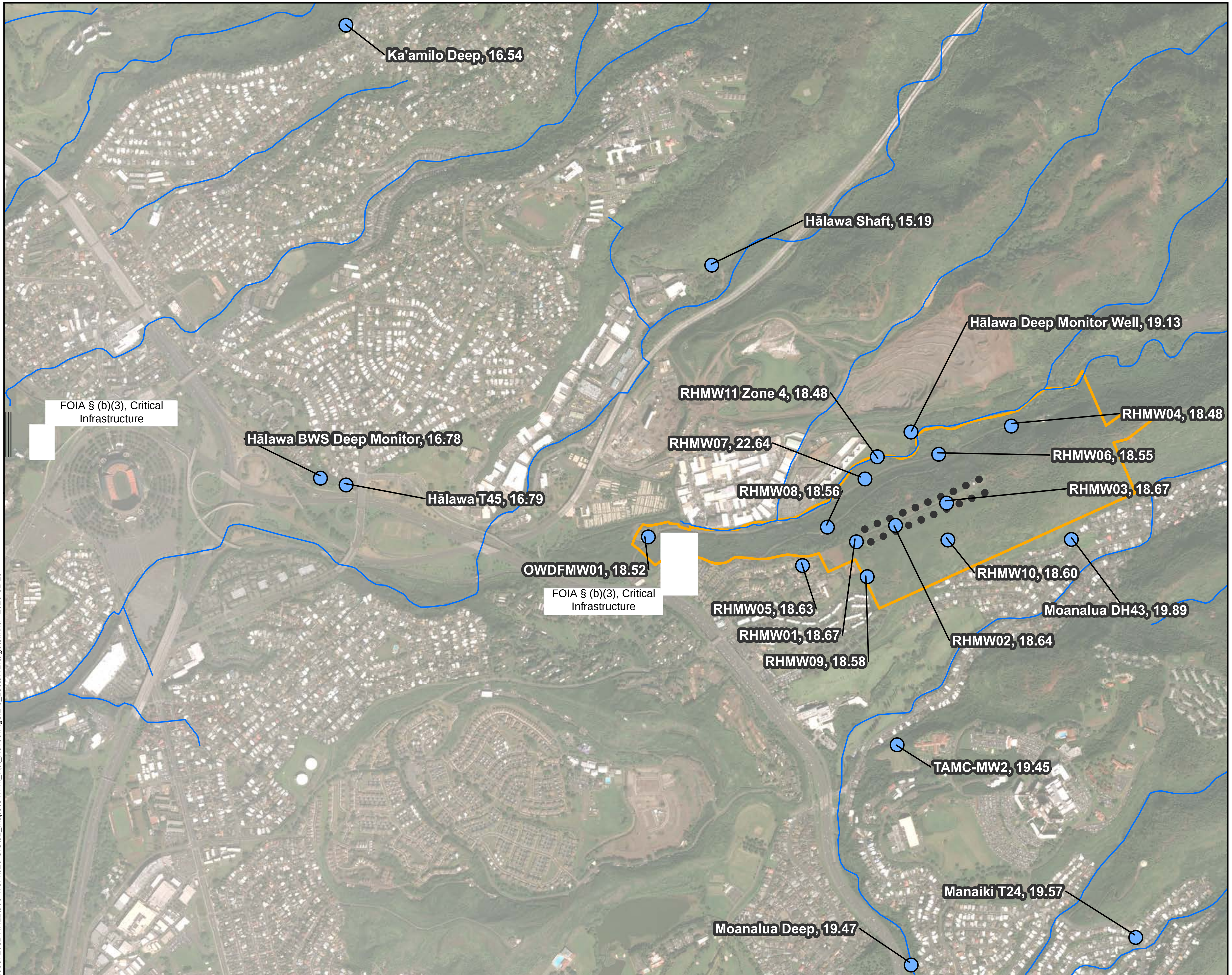
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. 2153-09, 19.43 Well ID, Water level elevation in feet above mean sea level
4. 2256-12 was not part of the synoptic study.

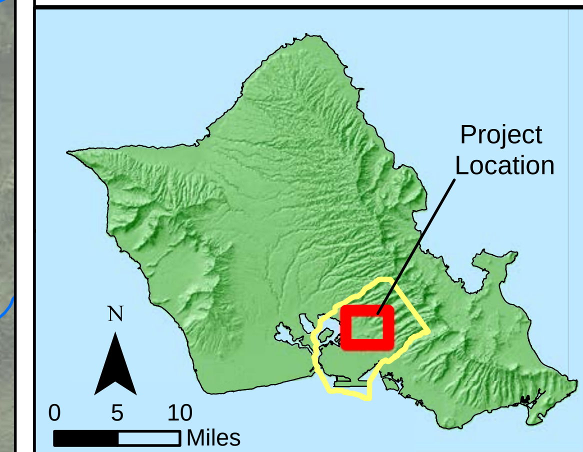
N

0 1,000 2,000 3,000 4,000 Feet

Figure 3.1-2
Local Synoptic Study Well Targets When Red Hill Shaft and Hālawa Shaft Are Pumping at Maximum Rates
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



Location Map



Legend

- Stress Period 3 Calibration Target Well
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. 2153-09, 19.43 Well ID, Water level elevation in feet above mean sea level

N

0 1,000 2,000 3,000 4,000 Feet

Figure 3.1-3
Local Synoptic Study Well Targets When Red Hill Shaft Is Not Pumping and Hālawa Shaft Is Pumping at Average Conditions
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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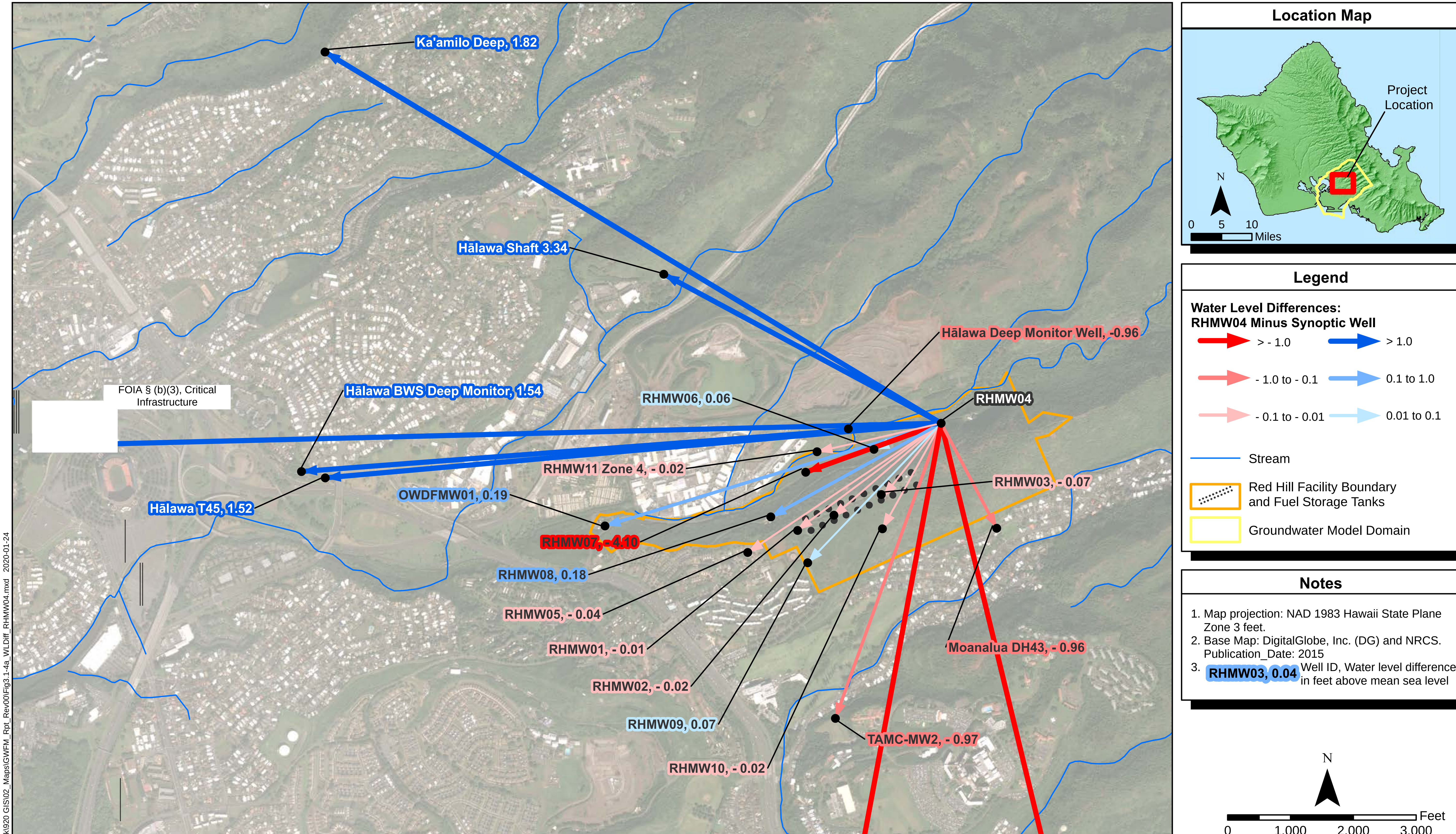

Figure 3.1-4a
Water Level Differences Compared to RHMW04 When Red Hill Shaft Is Pumping
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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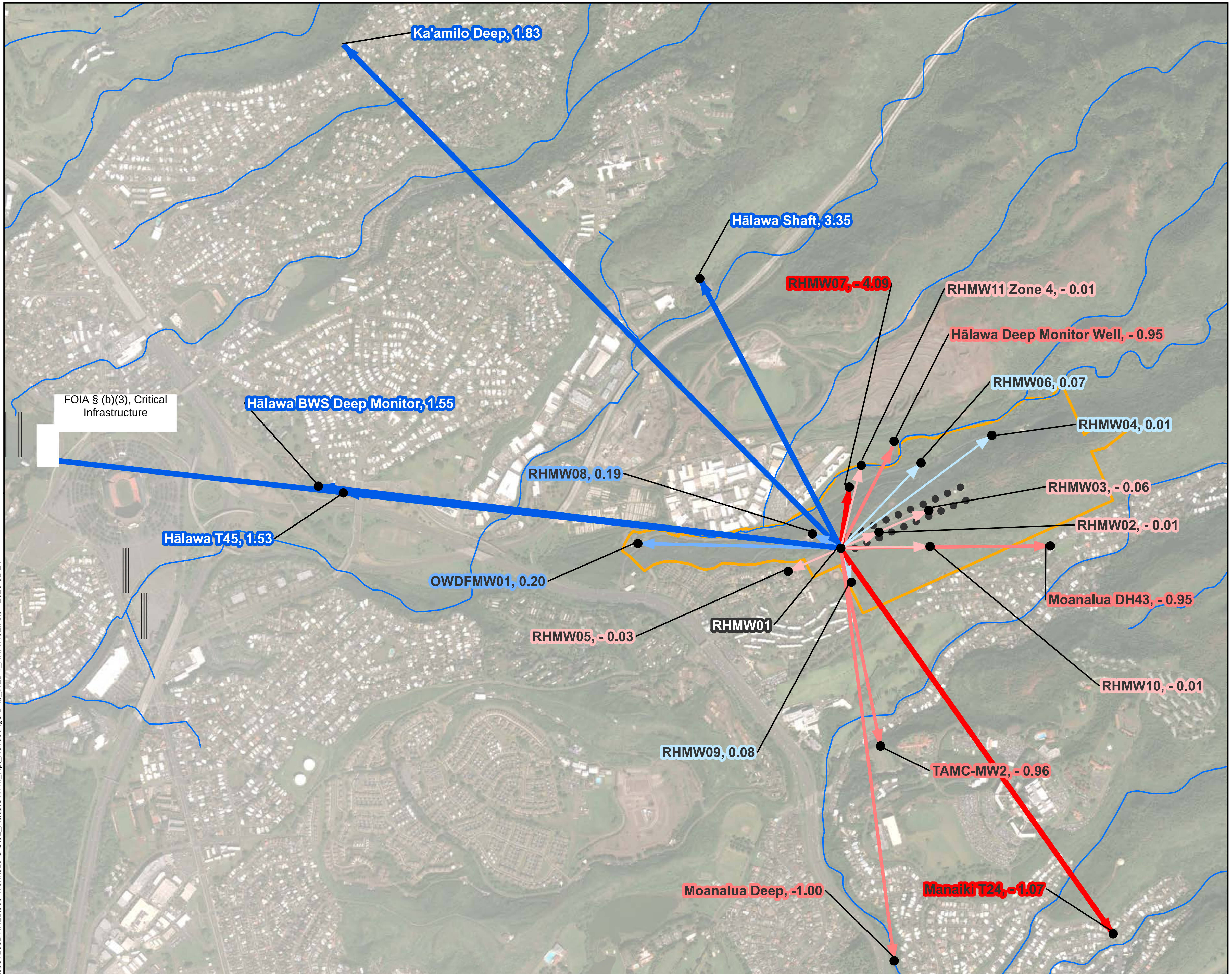
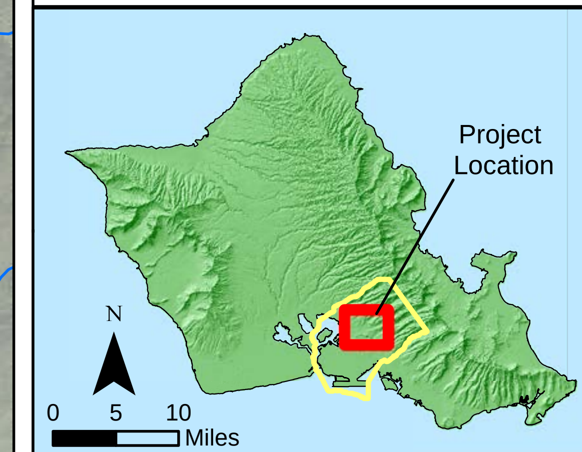


Location Map



Legend

Water Level Differences: RHMW01 Minus Synoptic Well

- > - 1.0
- - 1.0 to - 0.1
- - 0.1 to - 0.01
- > 1.0
- 0.1 to 1.0
- 0.01 to 0.1

Stream

Red Hill Facility Boundary and Fuel Storage Tanks

Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. RHMW03, 0.04 Well ID, Water level difference in feet above mean sea level

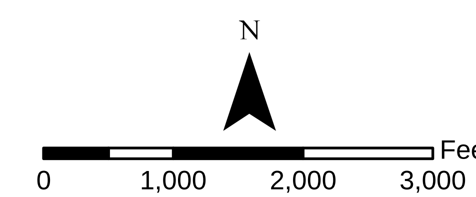
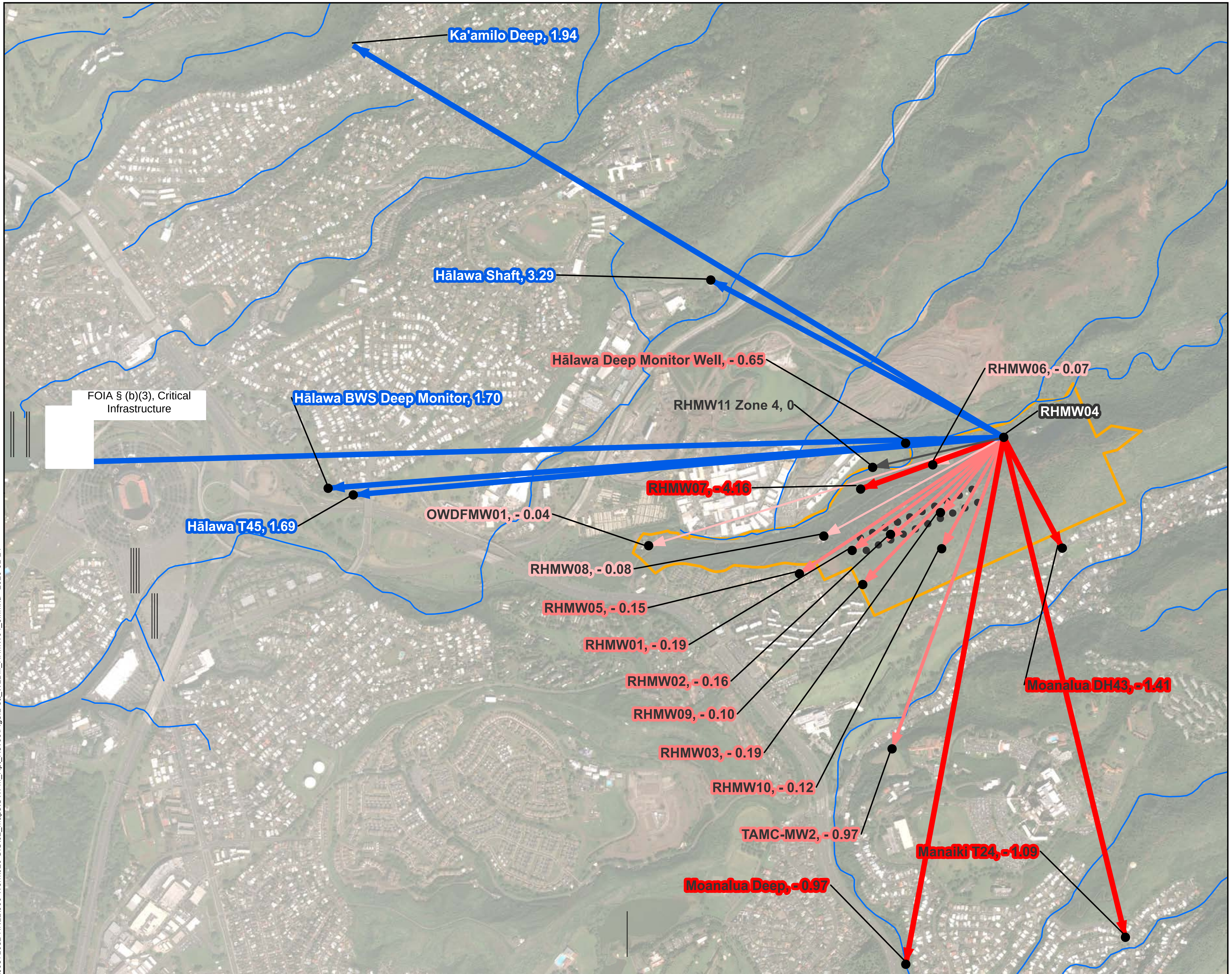
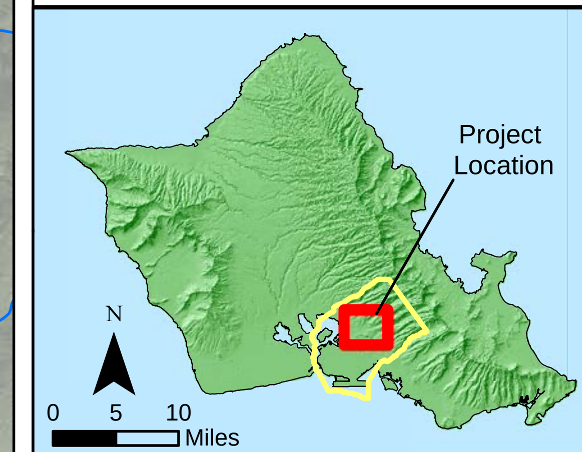


Figure 3.1-4b
Water Level Differences Compared to RHMW01 When Red Hill Shaft Is Pumping
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

B:\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.1-4b_WLDiff_RHMW01.mxd 2020-01-24



Location Map



Legend

Water Level Differences: RHMW04 Minus Synoptic Well

- > - 1.0
- - 1.0 to - 0.1
- - 0.1 to - 0.01
- 0
- > 1.0
- 0.1 to 1.0
- 0.01 to 0.1
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

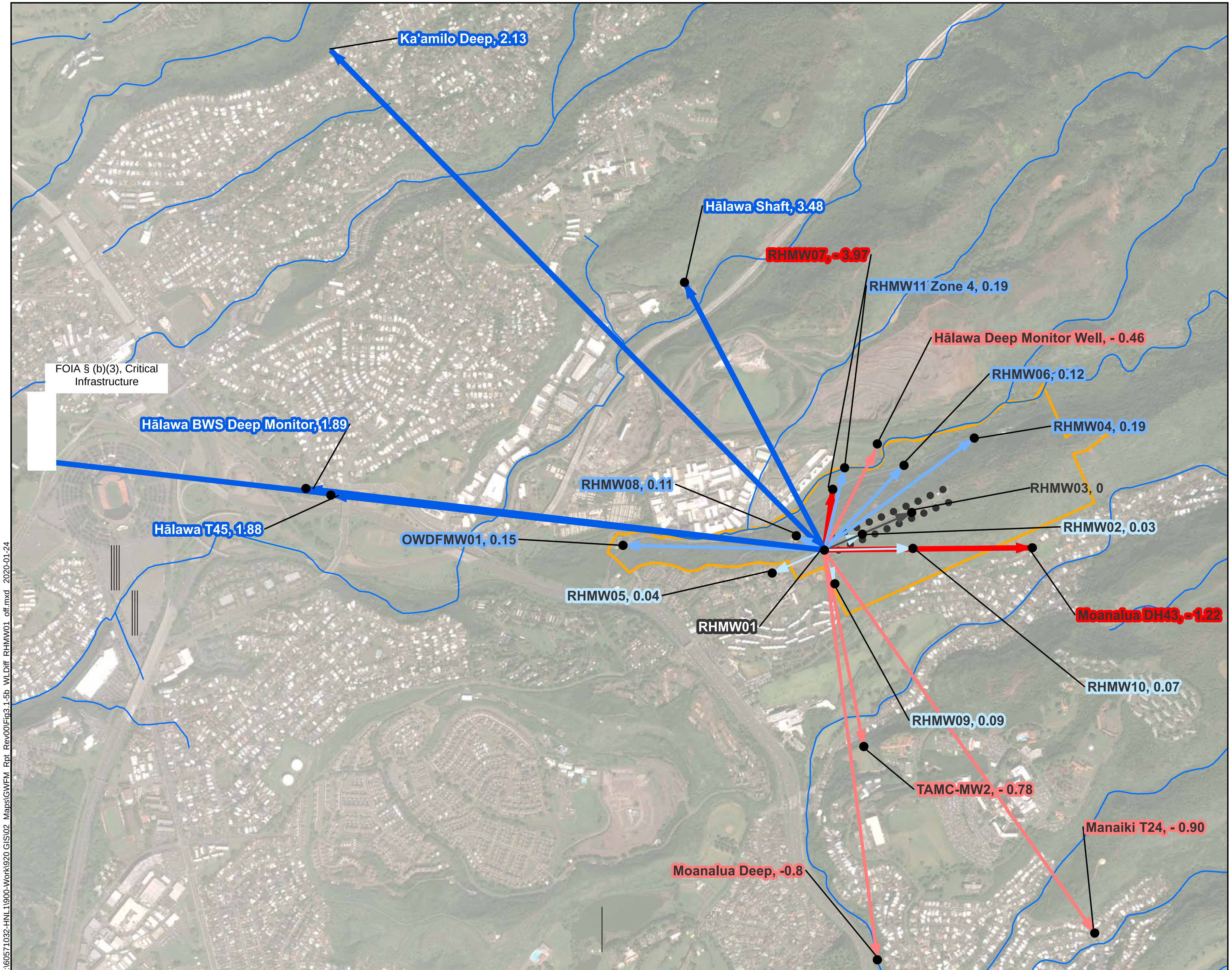
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. RHMW03, 0.04 Well ID, Water level difference in feet above mean sea level

N

0 1,000 2,000 3,000 Feet

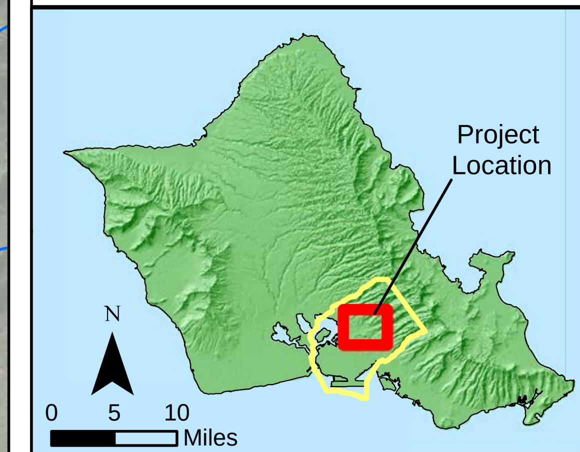
Figure 3.1-5a
Water Level Differences Compared to RHMW04 When Red Hill Shaft Is Not Pumping
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

B:\60571032-HNL\1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.1-5a_WLDiff_RHMW04_off.mxd 2020-01-24



B:\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.1-5b_WLDiff_RHMW01_off.mxd 2020-01-24

Location Map



Legend

Water Level Differences: RHMW01 Minus Synoptic Well

- > - 1.0
- > 1.0
- - 1.0 to - 0.1
- 0.1 to 1.0
- - 0.1 to - 0.01
- 0.01 to 0.1
- 0
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

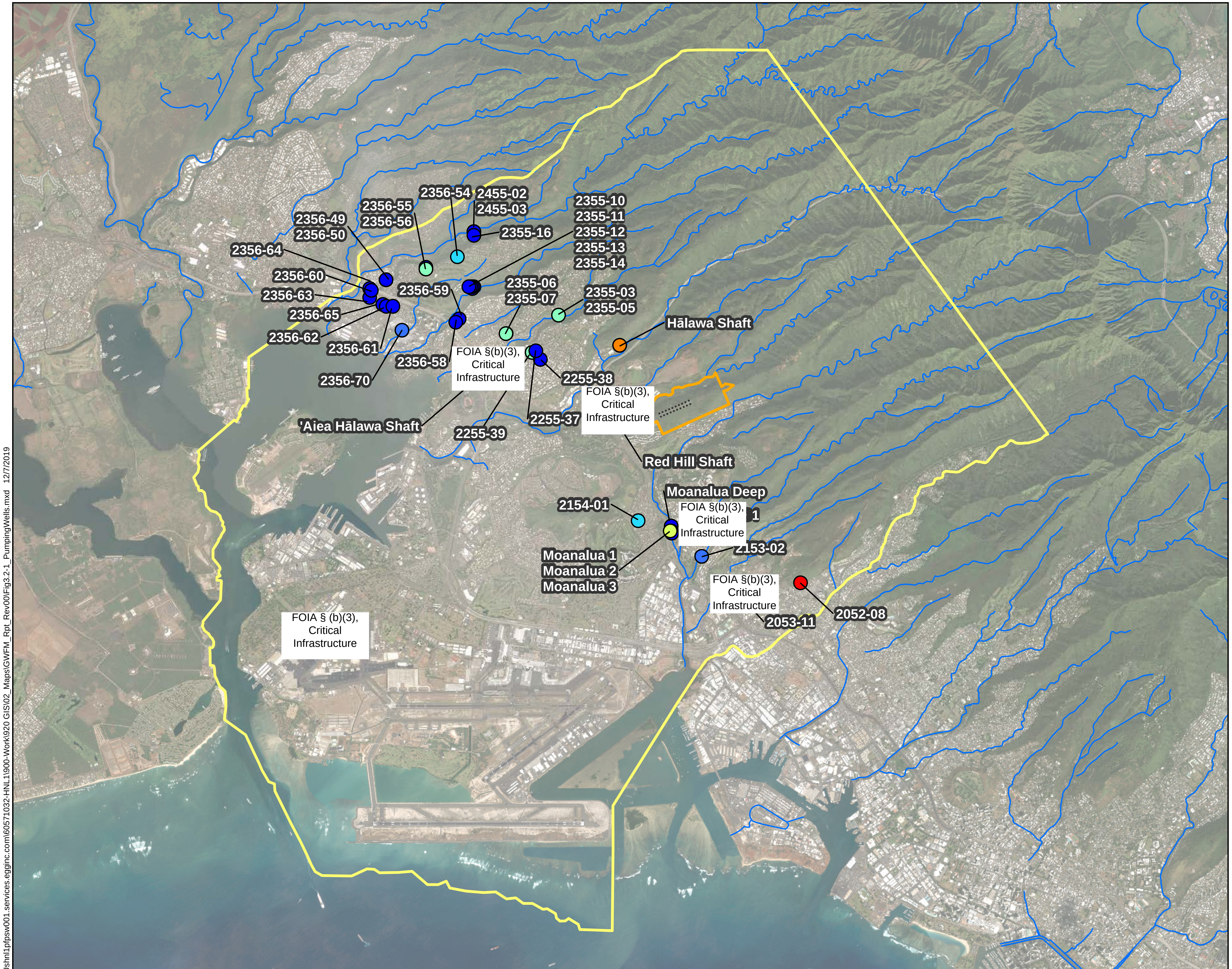
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. RHMW03, 0.04 Well ID, Water level difference in feet above mean sea level

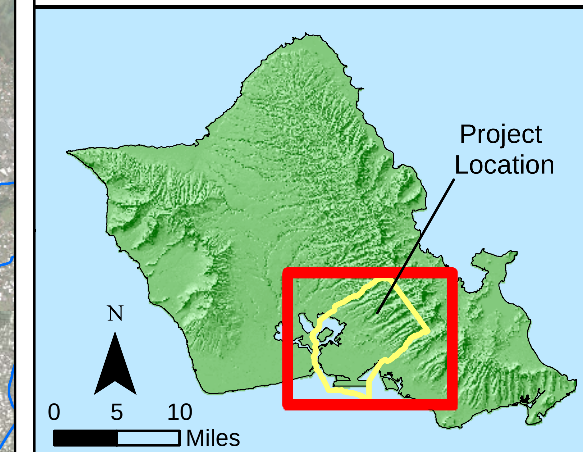
N

0 1,000 2,000 3,000 Feet

Figure 3.1-5b
Water Level Differences Compared to RHMW01 When Red Hill Shaft Is Not Pumping
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Pumping Rates (million gallons per day)

- 0
- 0.01 - 0.05
- 0.05 - 0.50
- 0.50 - 1.00
- 1.00 - 5.00
- 5.00 - 6.00
- 6.00 - 7.00
- > 7.00
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Red Hilll Shaft and Hālawa Shaft observed pumping rates are for the pumping periods of the synoptic study. All other puming wells and shafts depict average observed pumping rates for 2017.

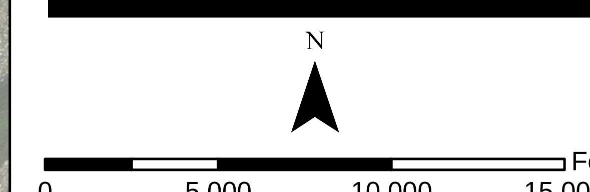


Figure 3.2-1
Pumping Well/Shaft Locations
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL1\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.2-1_PumpingWells.mxd 12/7/2019

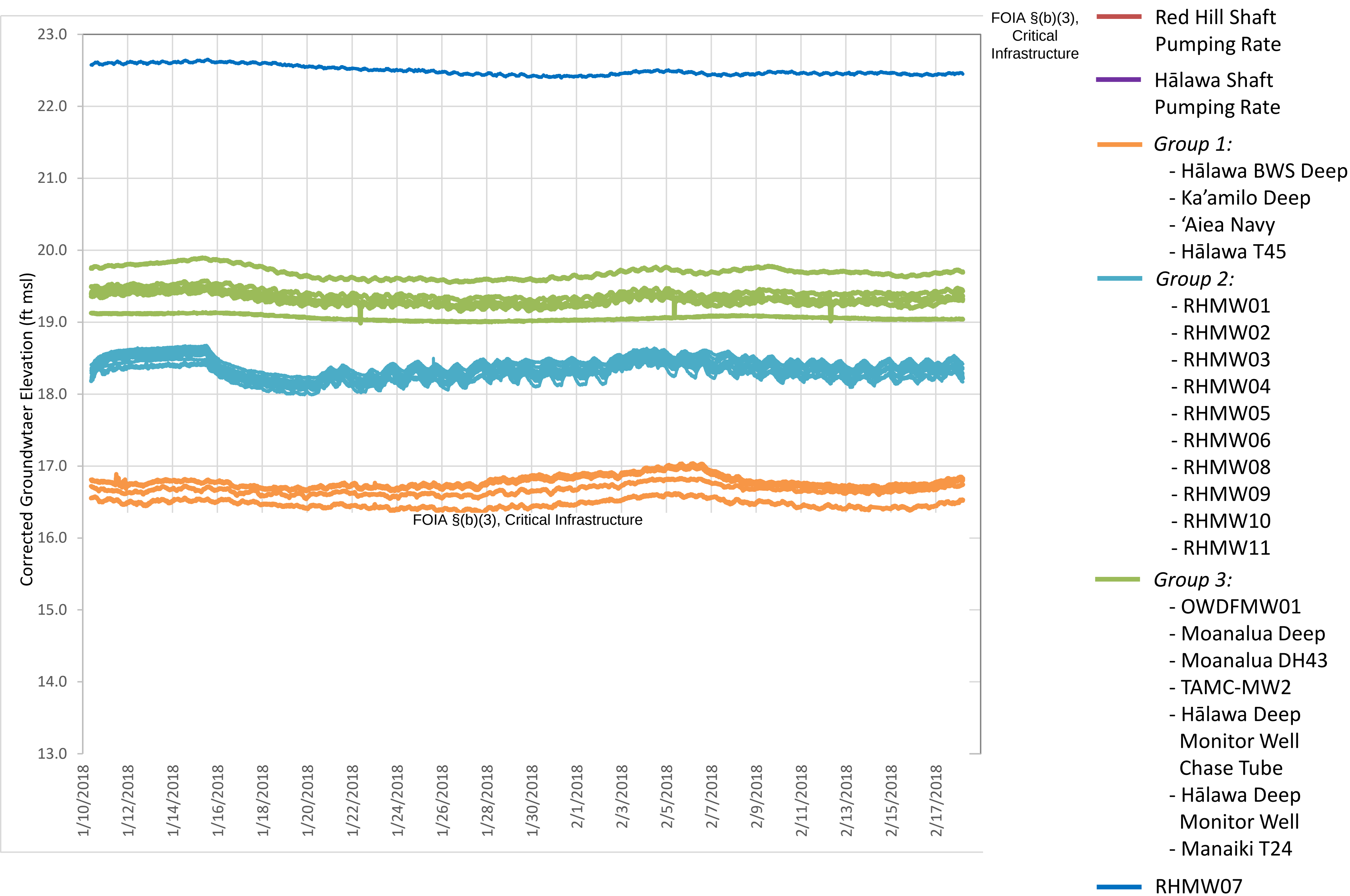


Figure 3.3-1
Water Level Response at Select Monitoring Wells Between January 10 and February 18, 2018
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

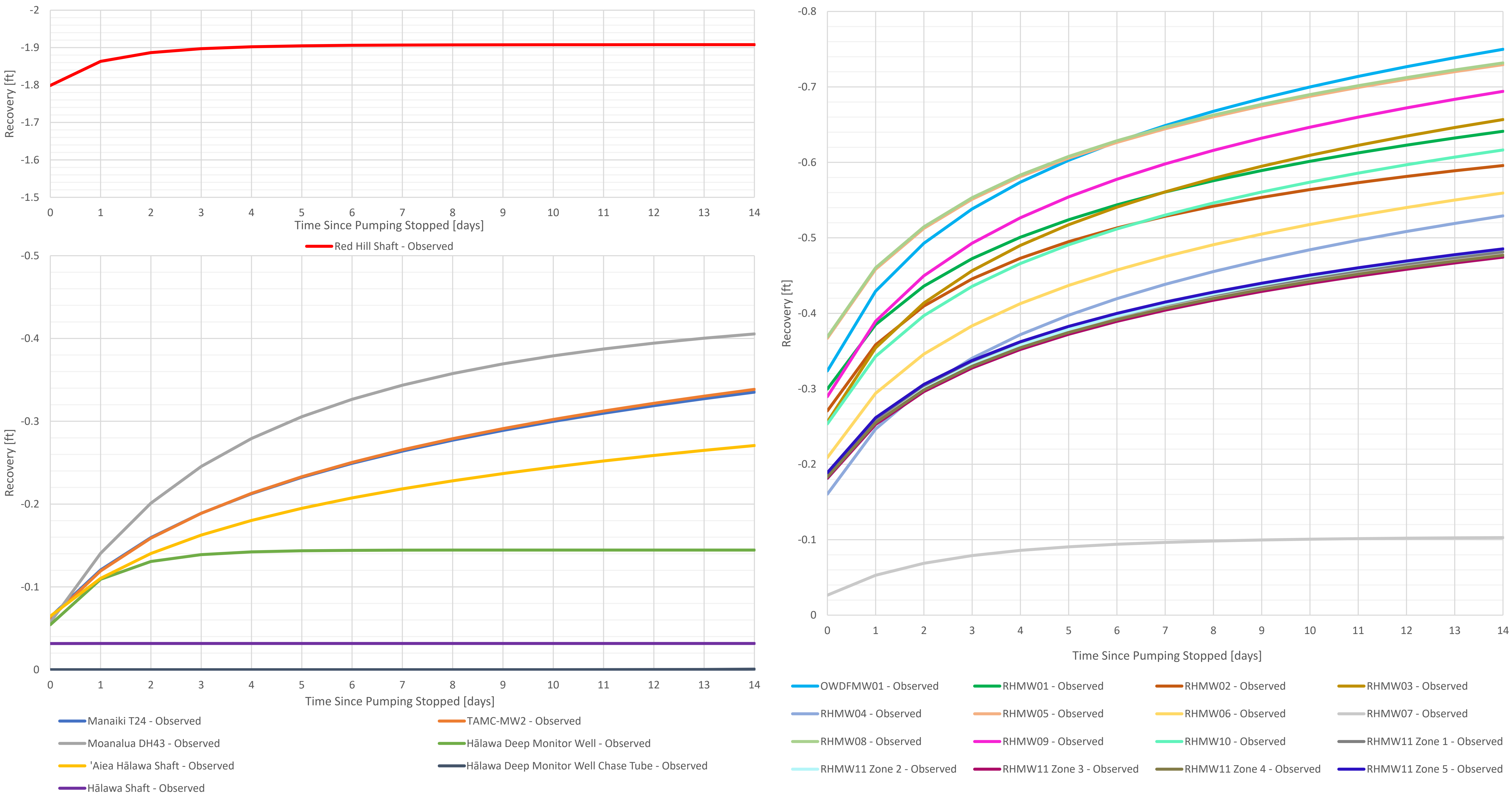


Figure 3.4-1
Unit Step Response Function for Recovery at
Red Hill Shaft Pumping [redacted] MGD Starting at February 18, 2018 7:10
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

FOIA §(b)(3), Critical Infrastructure

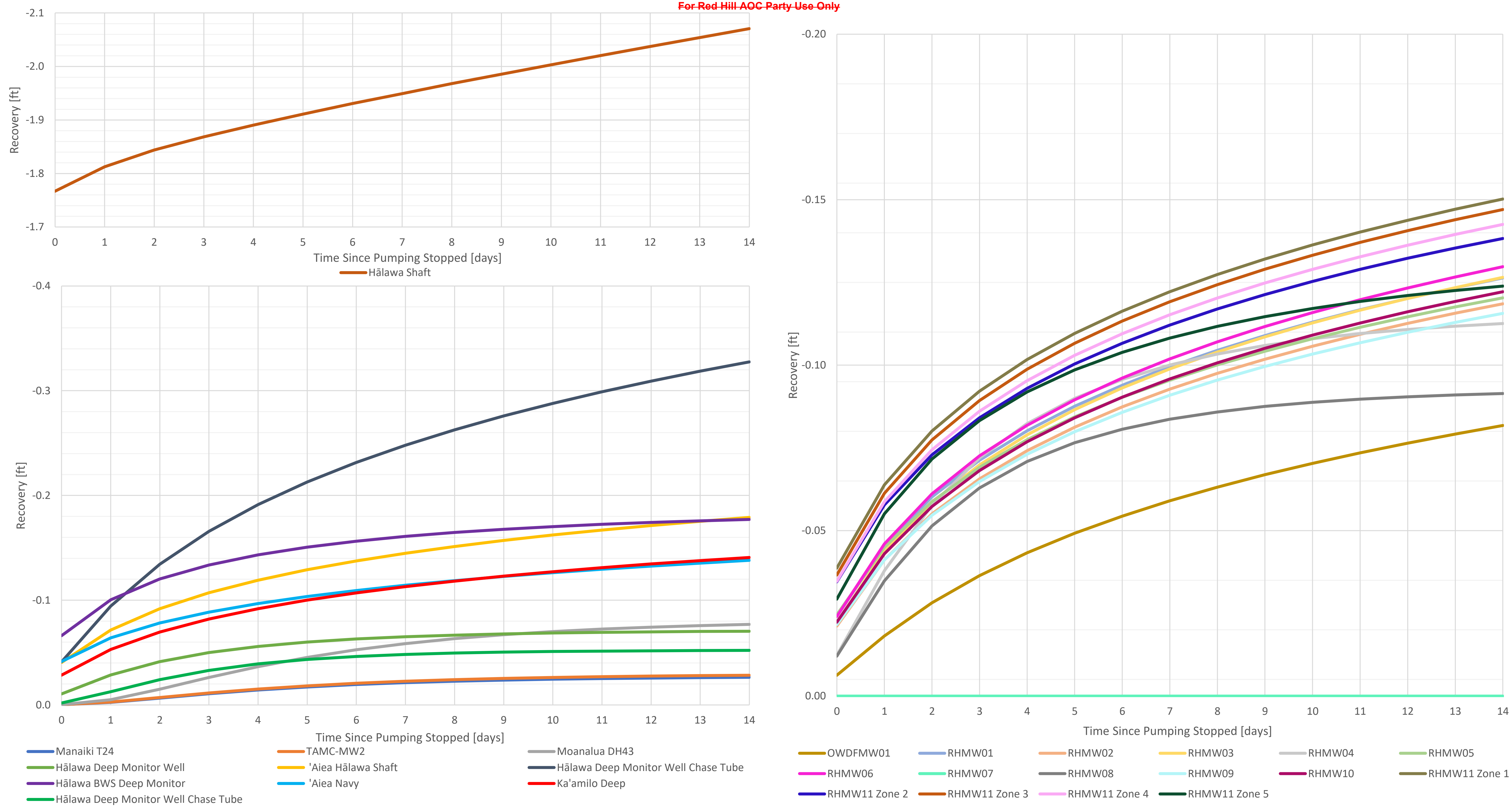
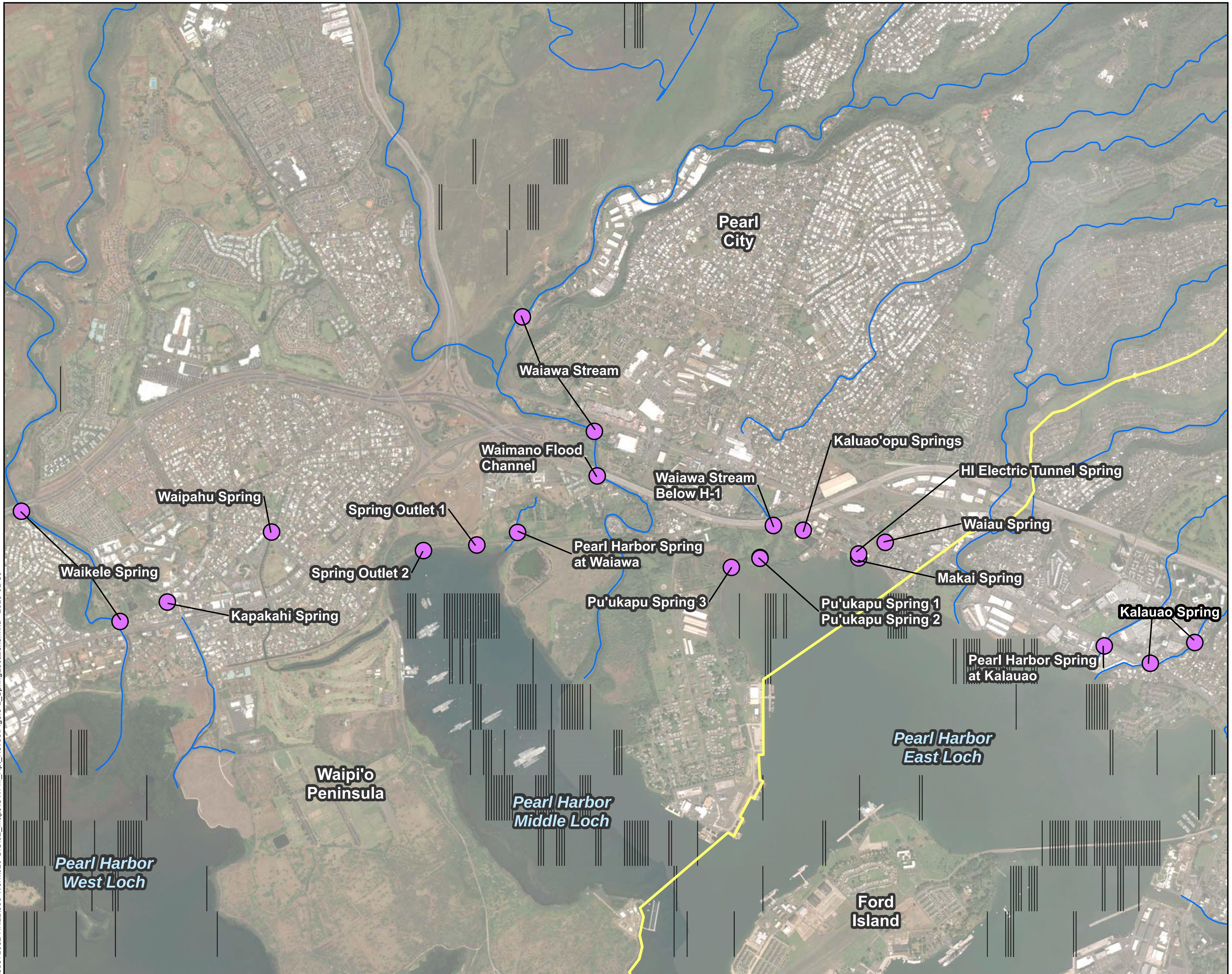
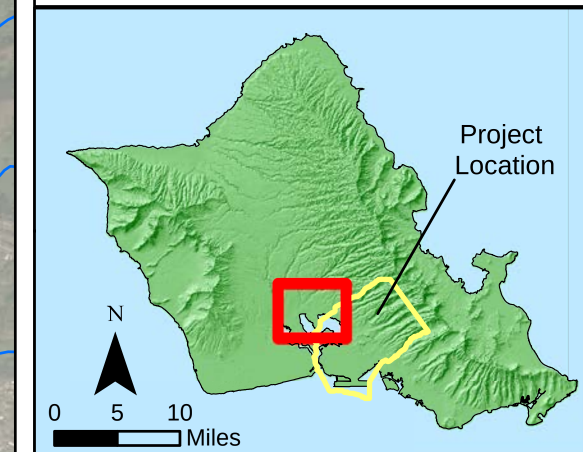


Figure 3.4-2
Unit Step Response Function for Recovery at
Hālawa Shaft Pumping 6.33 MGD Starting at March 6, 2018 6:10
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Location Map



Legend

- United States Geological Survey Spring Monitoring Location
- Stream
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

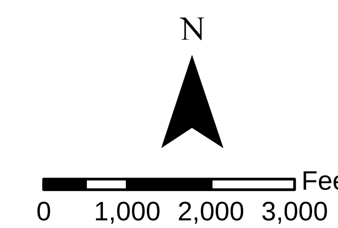
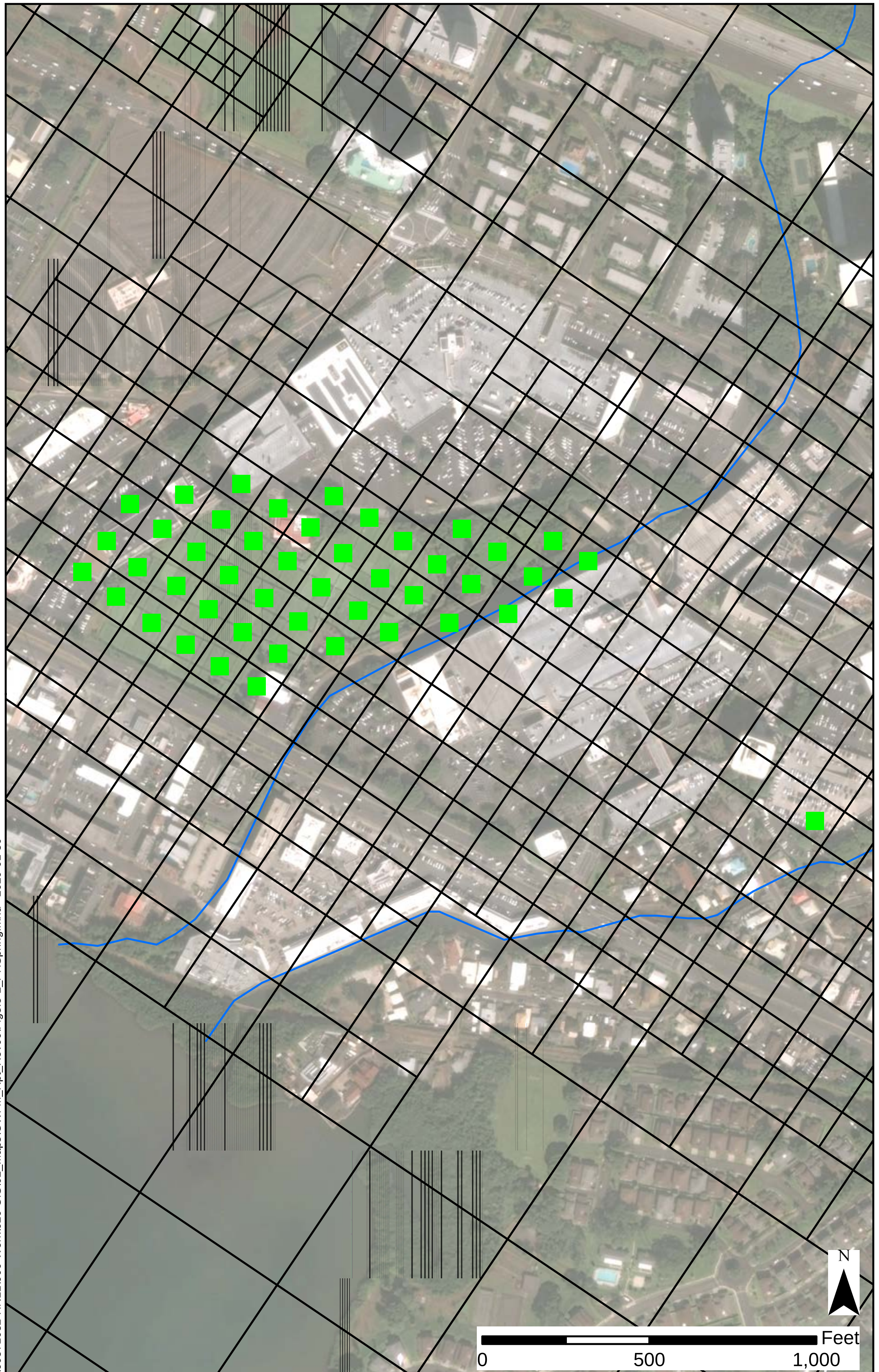
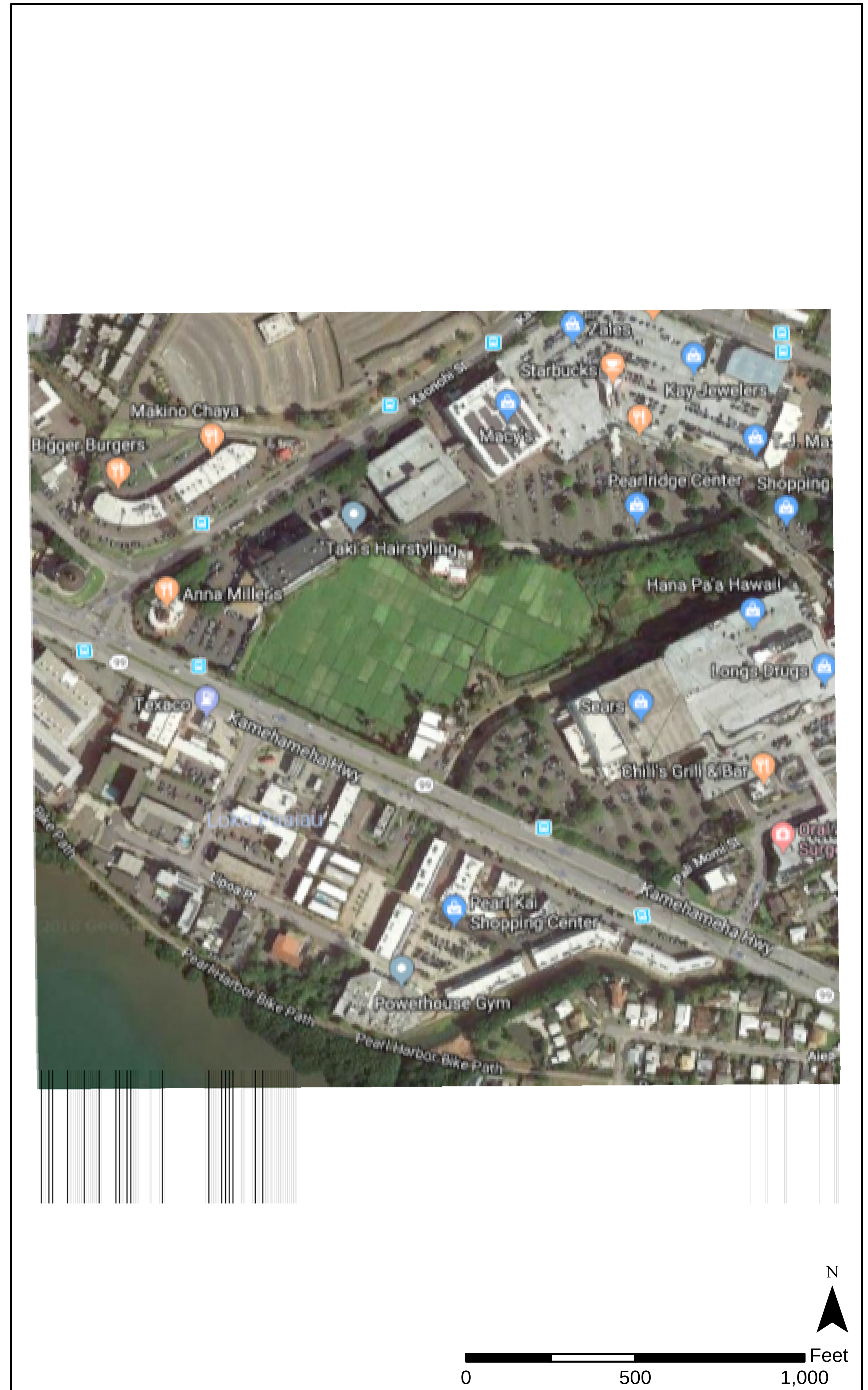


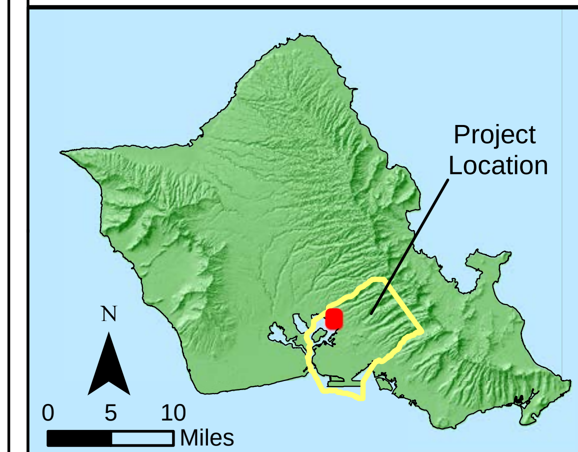
Figure 3.5-1
Spring Locations
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

B:\60571032-HNL\1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.5-1_SpringLocations.mxd 2020-01-30





Location Map



Legend

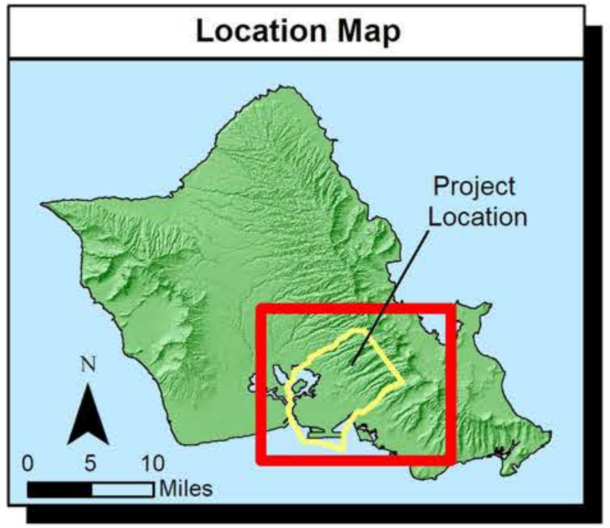
- Model Drain Cell
- Stream
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 3.5-2
Pearl Harbor Spring at
Kalauao (Watercress Farm) Drainage Area
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

B:\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.5-2_PHSpring.mxd 2020-01-30



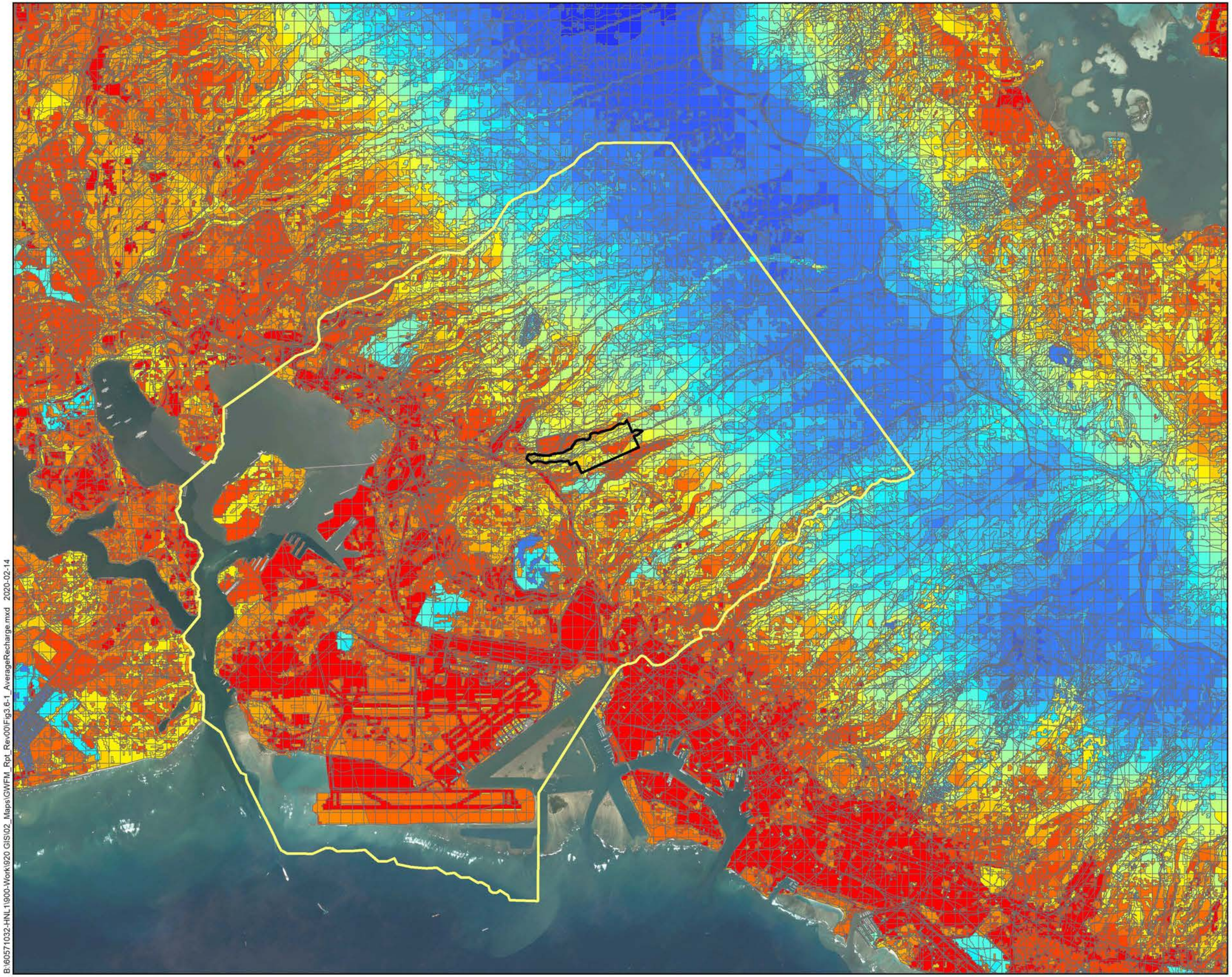
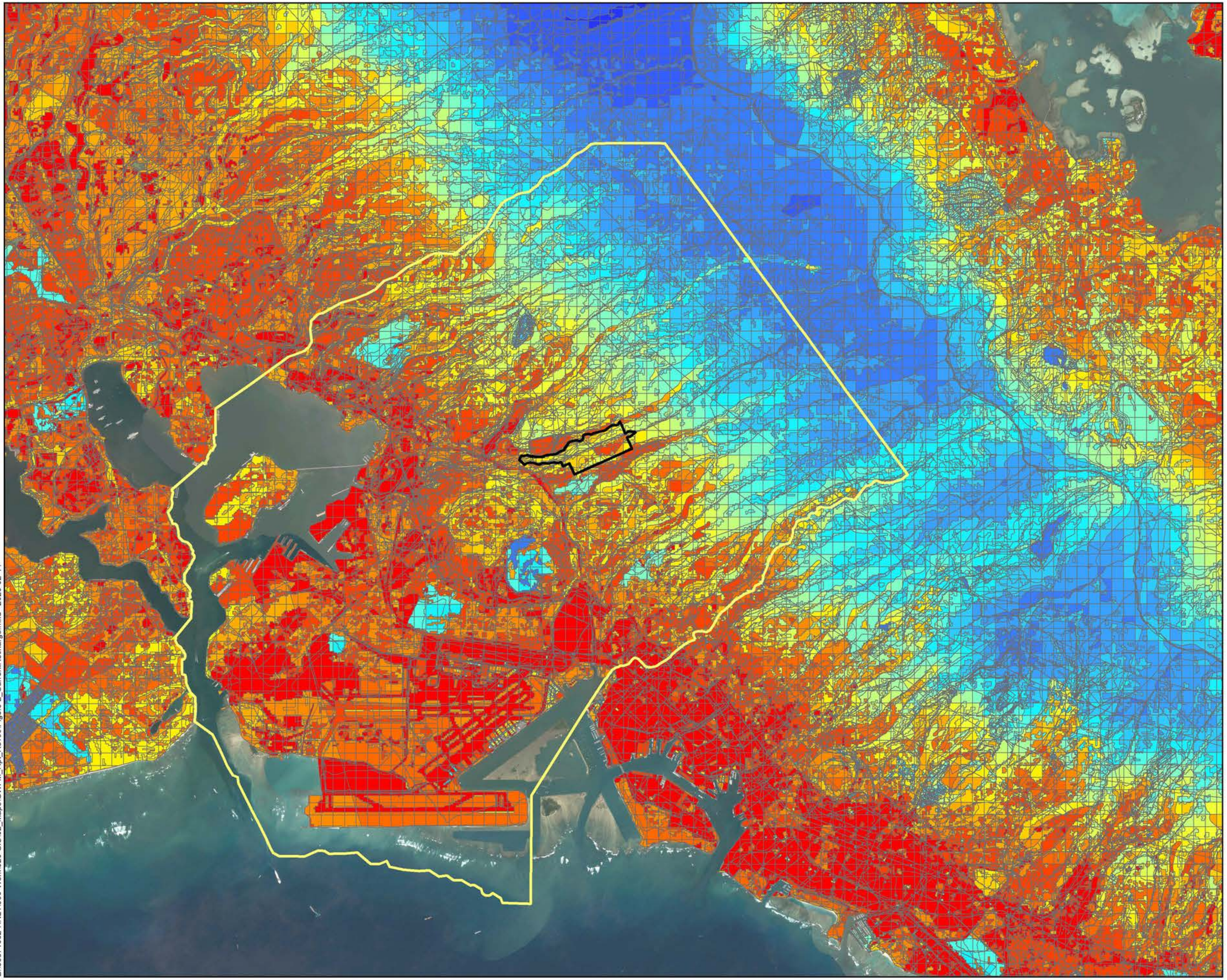
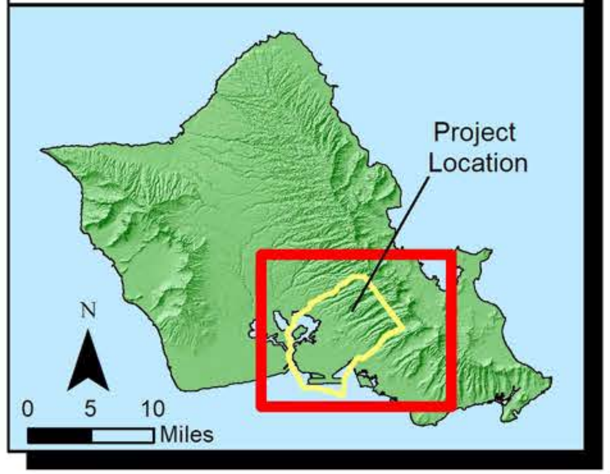


Figure 3.6-1
Average Recharge
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

B:\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.6-1_AverageRecharge.mxd 2020-02-14



Location Map



Legend

Current Conditions (inches per year)

- 0.0 - 1.007
- 1.0071 - 2.833
- 2.8331 - 4.757
- 4.7571 - 6.424
- 6.4241 - 8.134
- 8.1341 - 9.699
- 9.6991 - 11.342
- 11.3421 - 13.168
- 13.1681 - 15.363
- 15.3631 - 18.096
- 18.0961 - 21.500
- 21.5001 - 25.947
- 25.9471 - 31.158
- 31.1581 - 38.603
- 38.6031 - 48.178
- 48.178 - 59.381
- 59.3811 - 75.330
- 75.3301 - 100.996
- 100.9961 - 143.092
- 143.0921 - 245.942

Red Hill Facility Boundary and Fuel Storage Tanks

Groundwater Model Domain

Notes

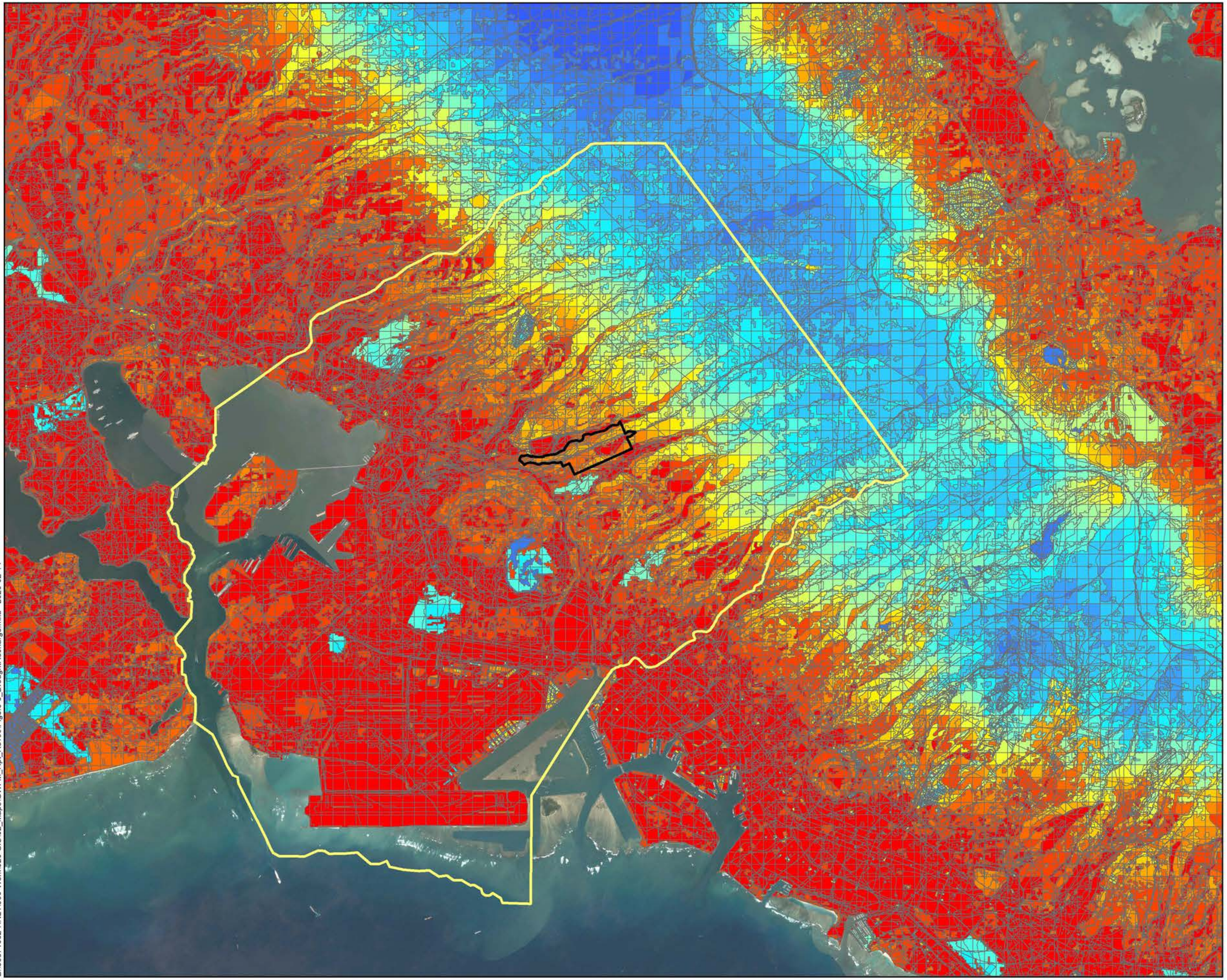
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N
0 5,000 10,000 15,000 Feet

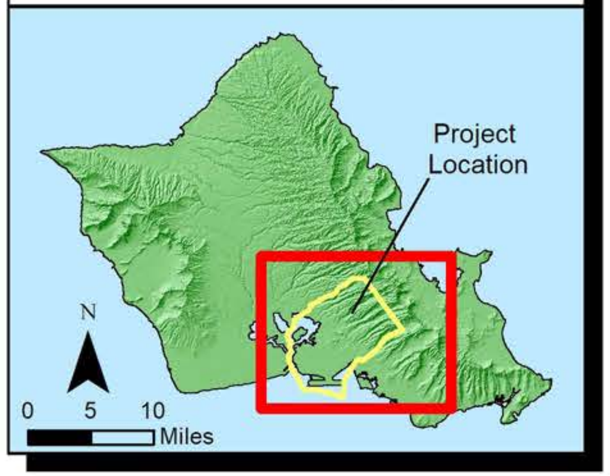
Figure 3.6-2
Current Recharge
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

B:\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.6-2_CurrentRecharge.mxd 2020-02-14

~~For Red Hill AOC Party Use Only~~



Location Map



Legend

Drought Conditions (inches per year)

- 0.0 - 1.007
- 1.0071 - 2.833
- 2.8331 - 4.757
- 4.7571 - 6.424
- 6.4241 - 8.134
- 8.1341 - 9.699
- 9.6991 - 11.342
- 11.3421 - 13.168
- 13.1681 - 15.363
- 15.3631 - 18.096
- 18.0961 - 21.500
- 21.5001 - 25.947
- 25.9471 - 31.158
- 31.1581 - 38.603
- 38.6031 - 48.178
- 48.178 - 59.381
- 59.3811 - 75.330
- 75.3301 - 100.996
- 100.9961 - 143.092
- 143.0921 - 245.942

Red Hill Facility Boundary and Fuel Storage Tanks

Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

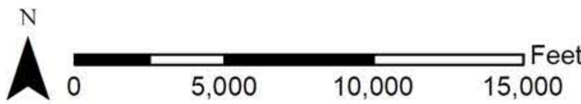
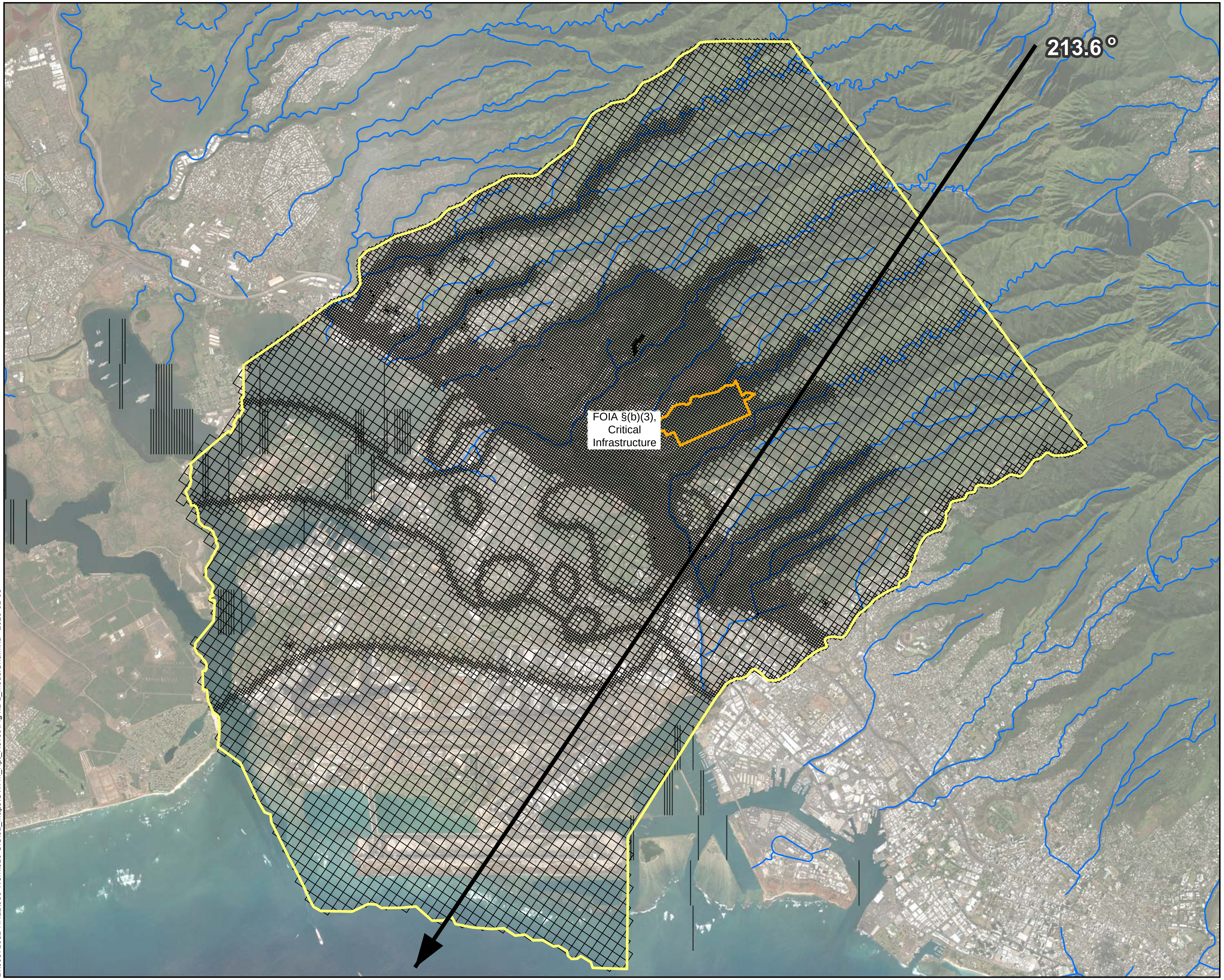
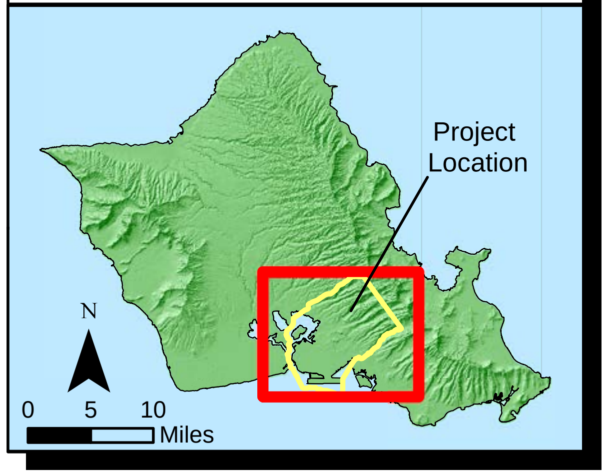


Figure 3.6-3
Drought Conditions
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

B:\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig3.6-3_DroughtRecharge.mxd 2020-02-14



Location Map



Legend

- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

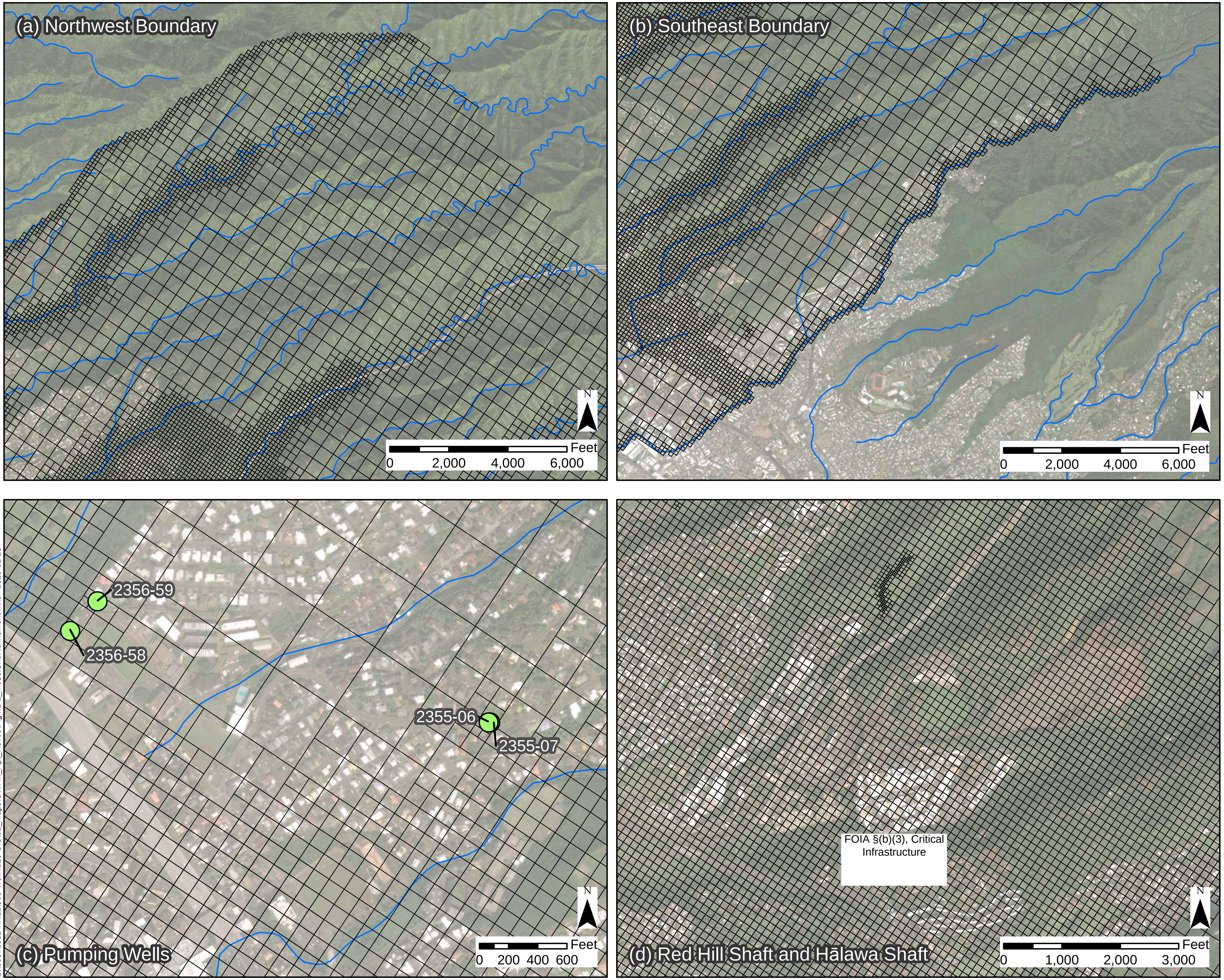
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

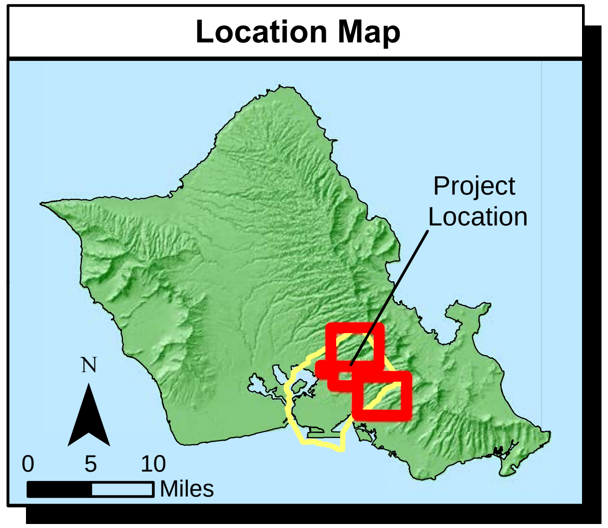
N

0 5,000 10,000 15,000 Feet

Figure 4.1-1
Model Grid
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

B:\60571032-HNL\1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig4.1-1_ModelGrid.mxd 2020-02-03





Legend

- Supply Well
- Stream
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

B:\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig4.1-2_ModelGridRefinement.mxd 2020-01-23

Figure 4.1-2
Model Grid Refinement
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

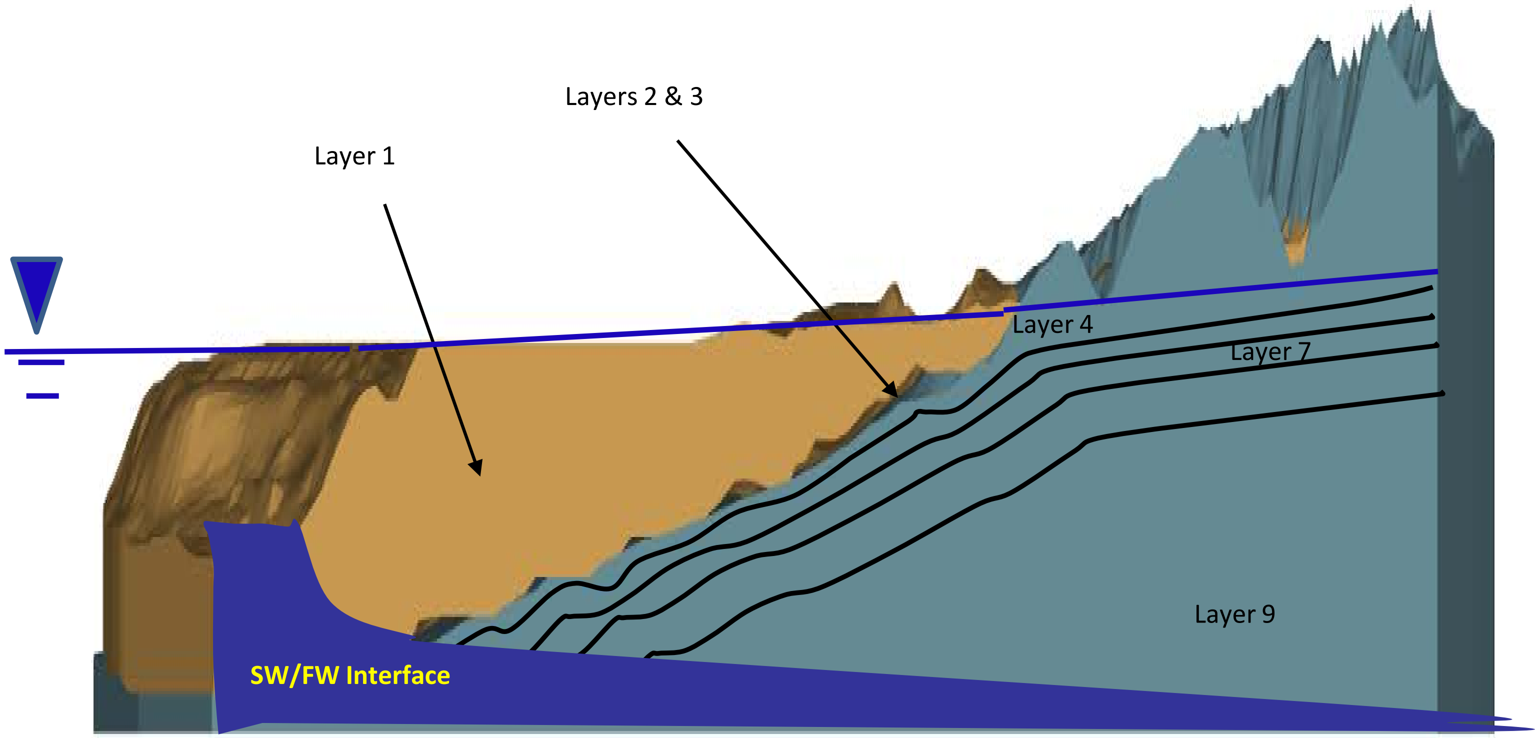
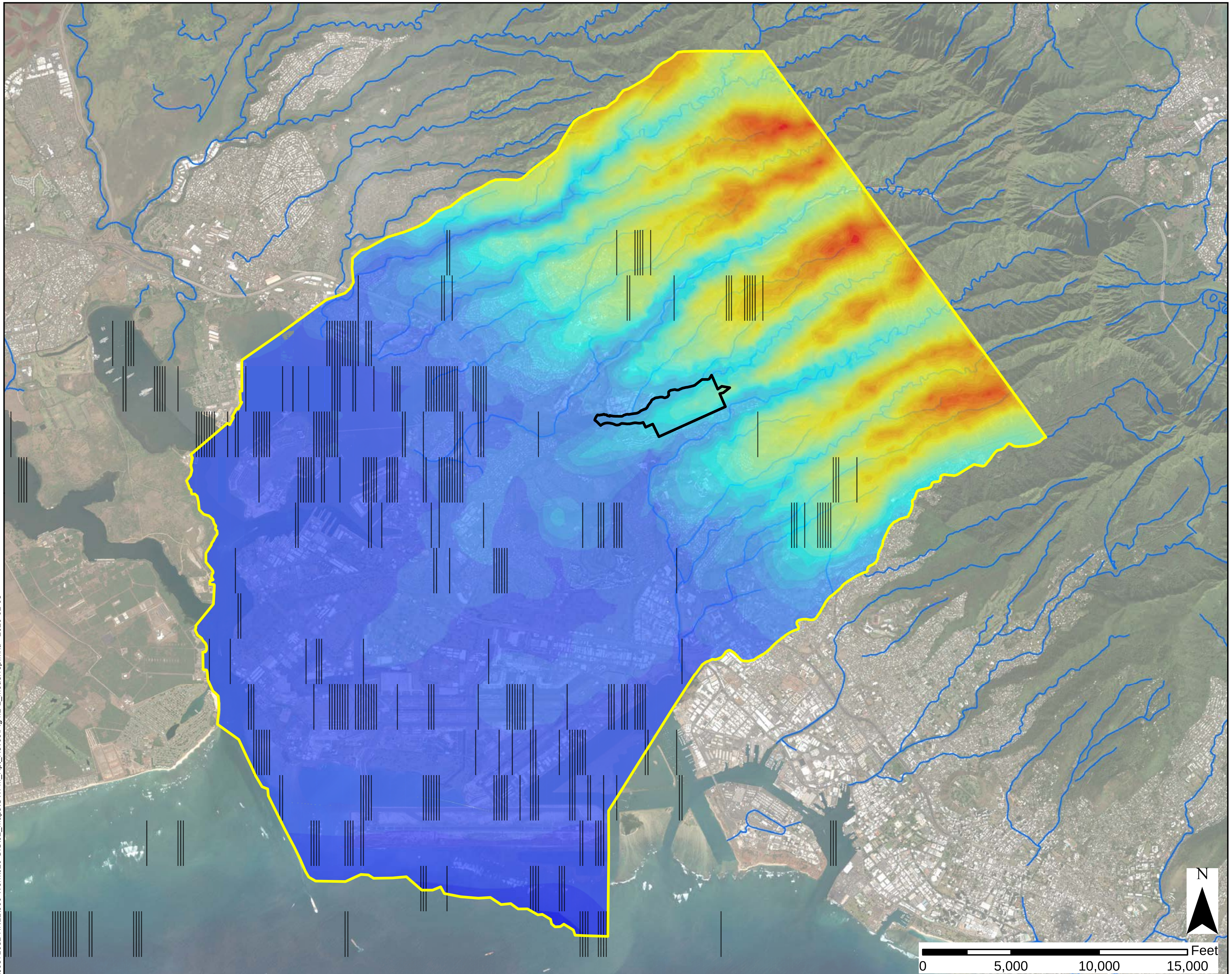
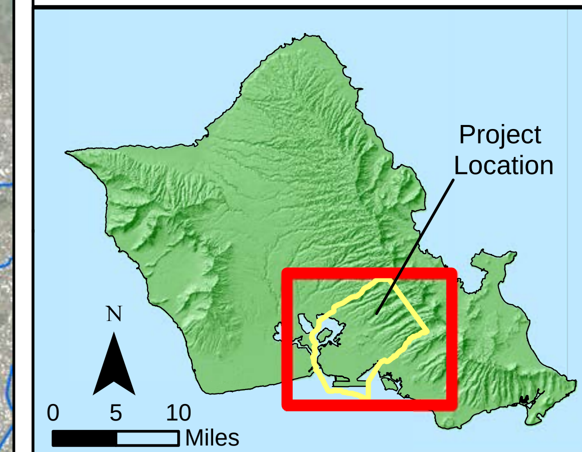


Figure 4.2-1
Schematic of Model Layering
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



Location Map



Legend

ModelTop Contour (ft msl)

- 240 to - 200	740 to 819
- 199 to - 140	820 to 879
- 199 to - 60	879 to 939
- 59 to 0	940 to 999
1 to 59	1,000 to 1,079
60 to 119	1,80 to 1,139
120 to 179	1,140 to 1,199
180 to 239	1,200 to 1,259
240 to 320	1,250 to 1,339
320 to 379	1,340 to 1,399
380 to 439	1,400 to 1,459
439 to 499	1,460 to 1,519
500 to 559	1,520 to 1,579
560 to 619	1,580 to 1,639
620 to 679	1,640 to 1,699
680 to 739	1,700 to 1,780

Stream

Red Hill Facility Boundary

Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 4.2-2
Model Top: Land Surface Elevation
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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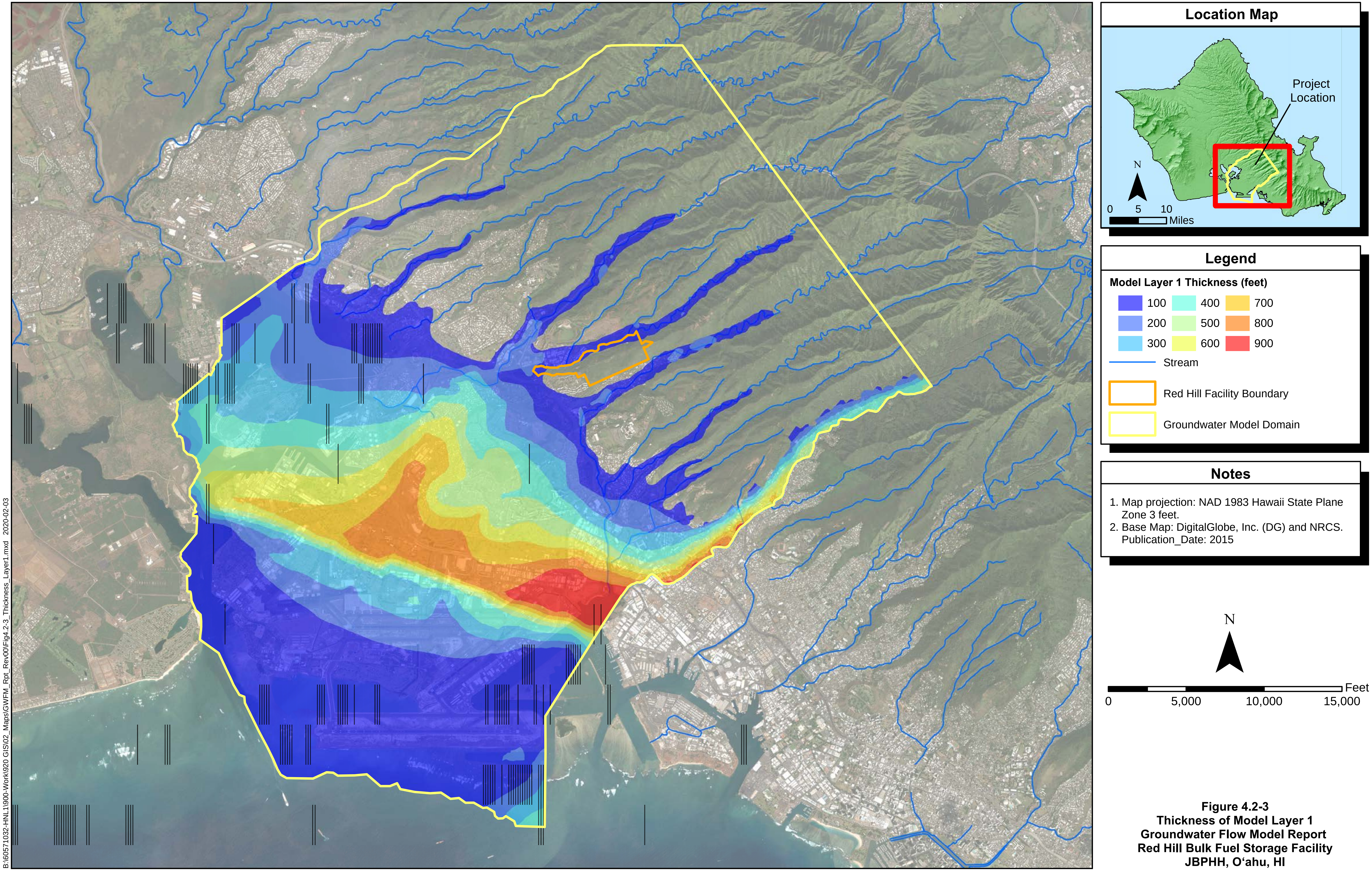
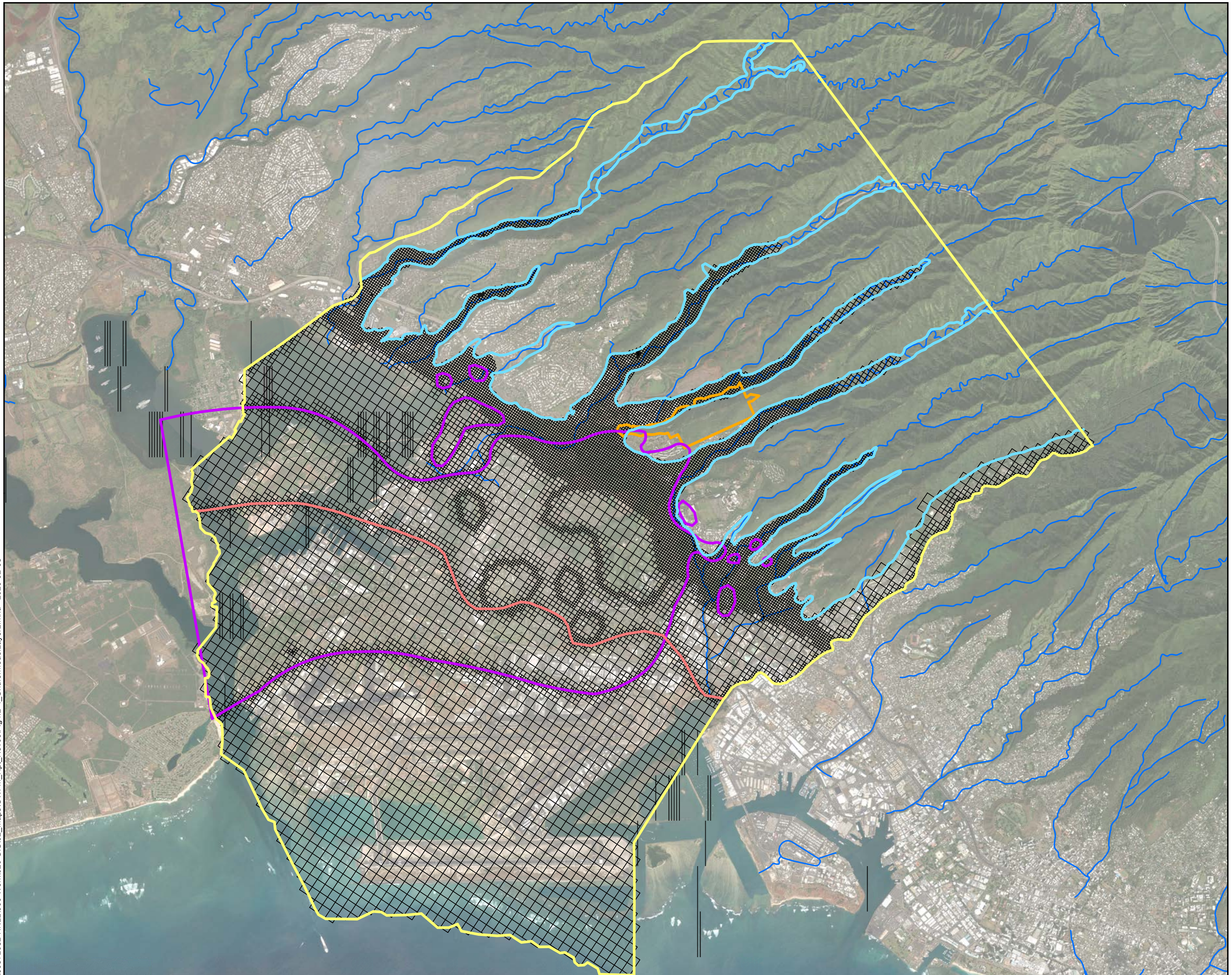
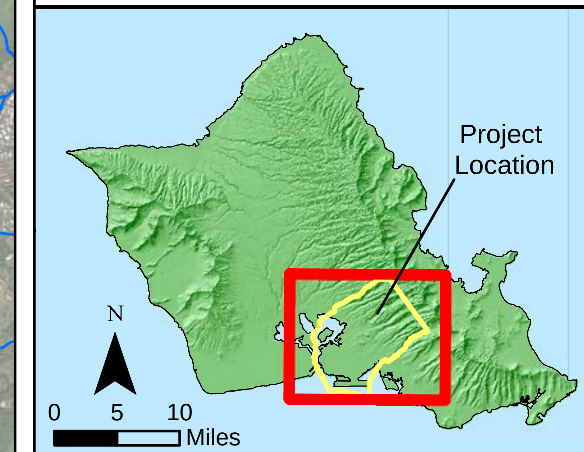


Figure 4.2-3
Thickness of Model Layer 1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

- Marine Sediments Extent
- Alluvial Sediments Extent
- Tuff Extent
- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 4.2-4
Grid for Model Layer 1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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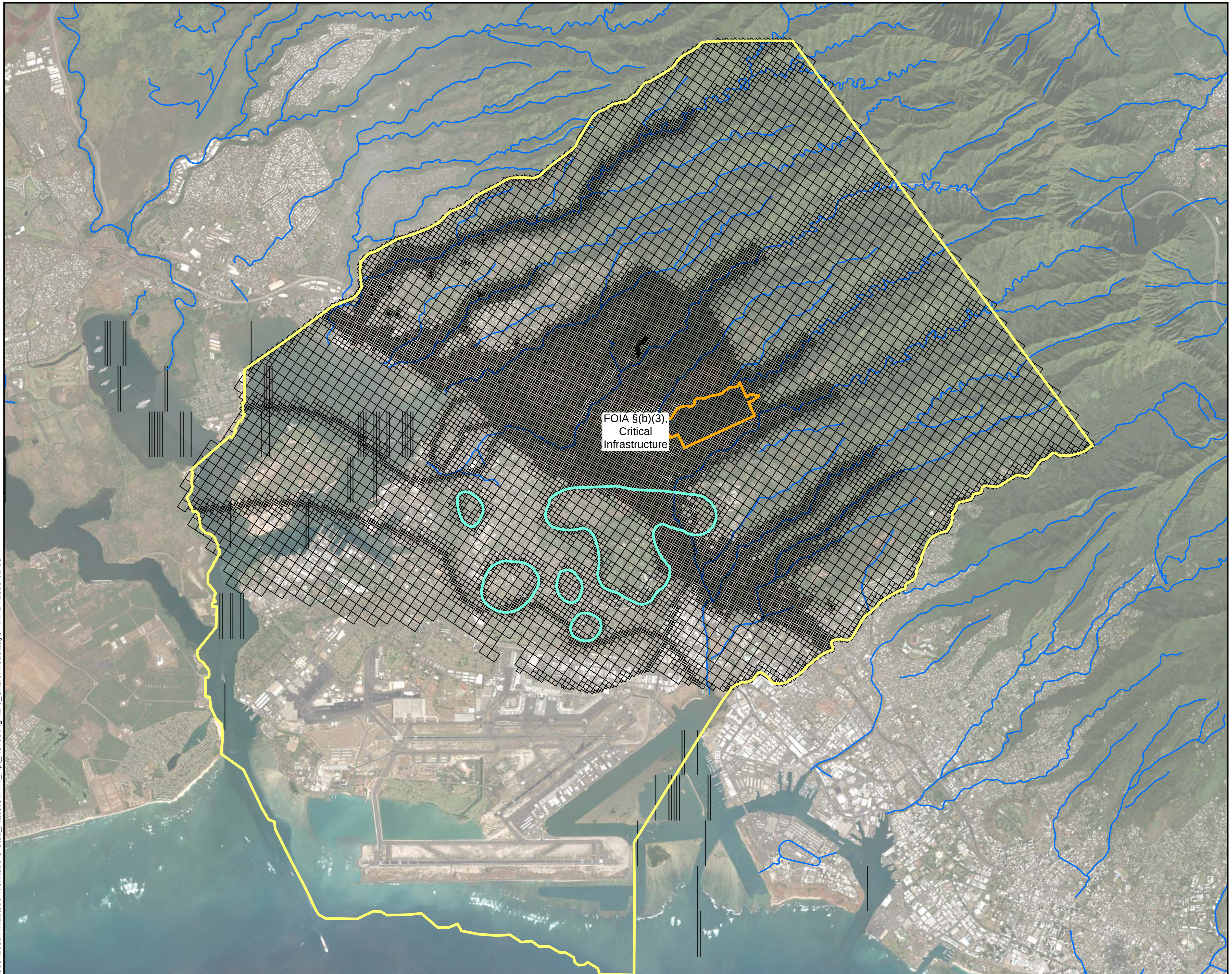
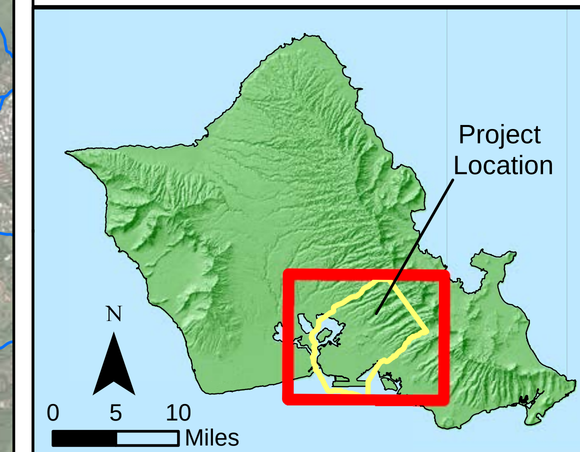


Location Map



Legend

- Tuff Cone
- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

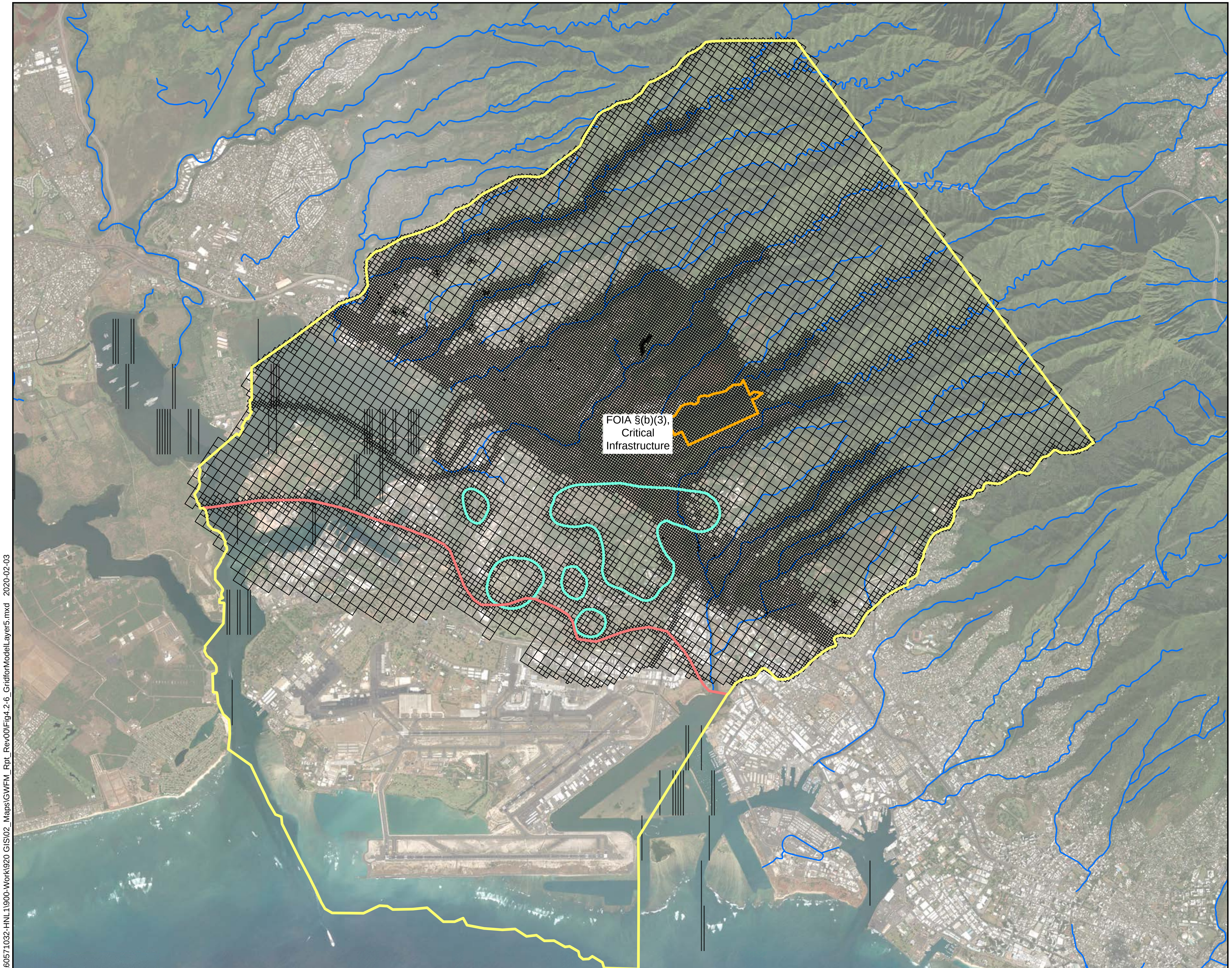
Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

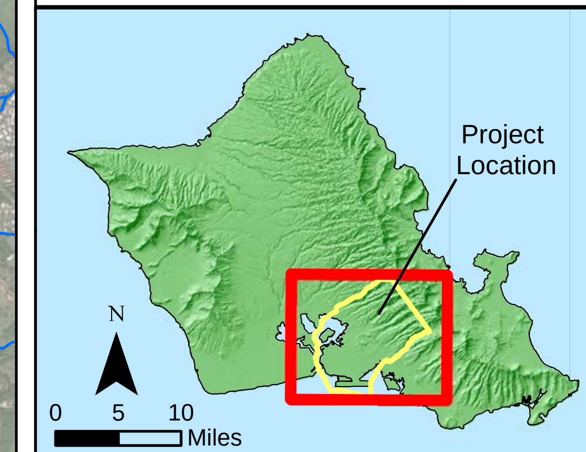
N

0 5,000 10,000 15,000 Feet

Figure 4.2-5
Grid for Model Layer 4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

- Marine Sediments Extent
- Tuff Cone
- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 4.2-6
Grid for Model Layer 5
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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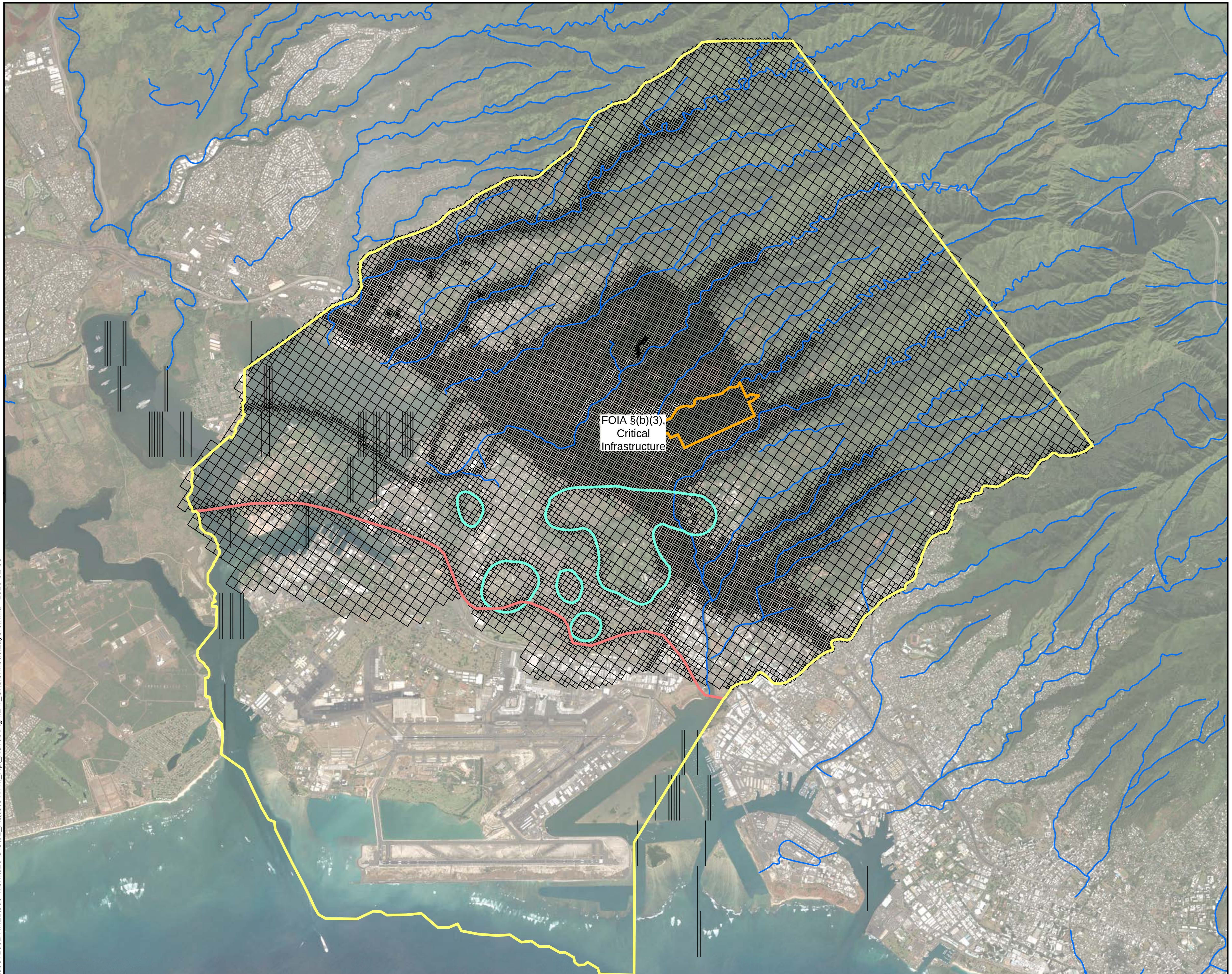

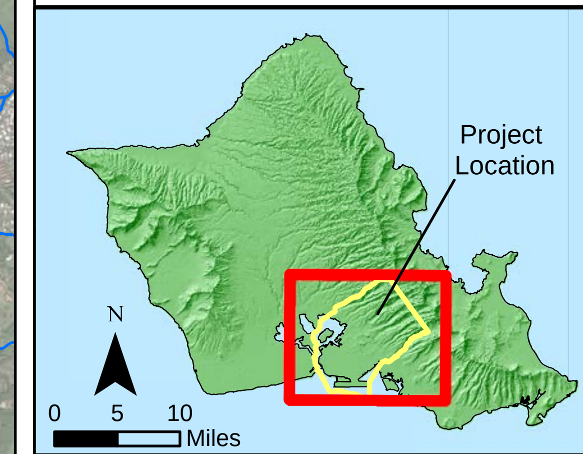

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 4.2-7
Grid for Model Layer 6
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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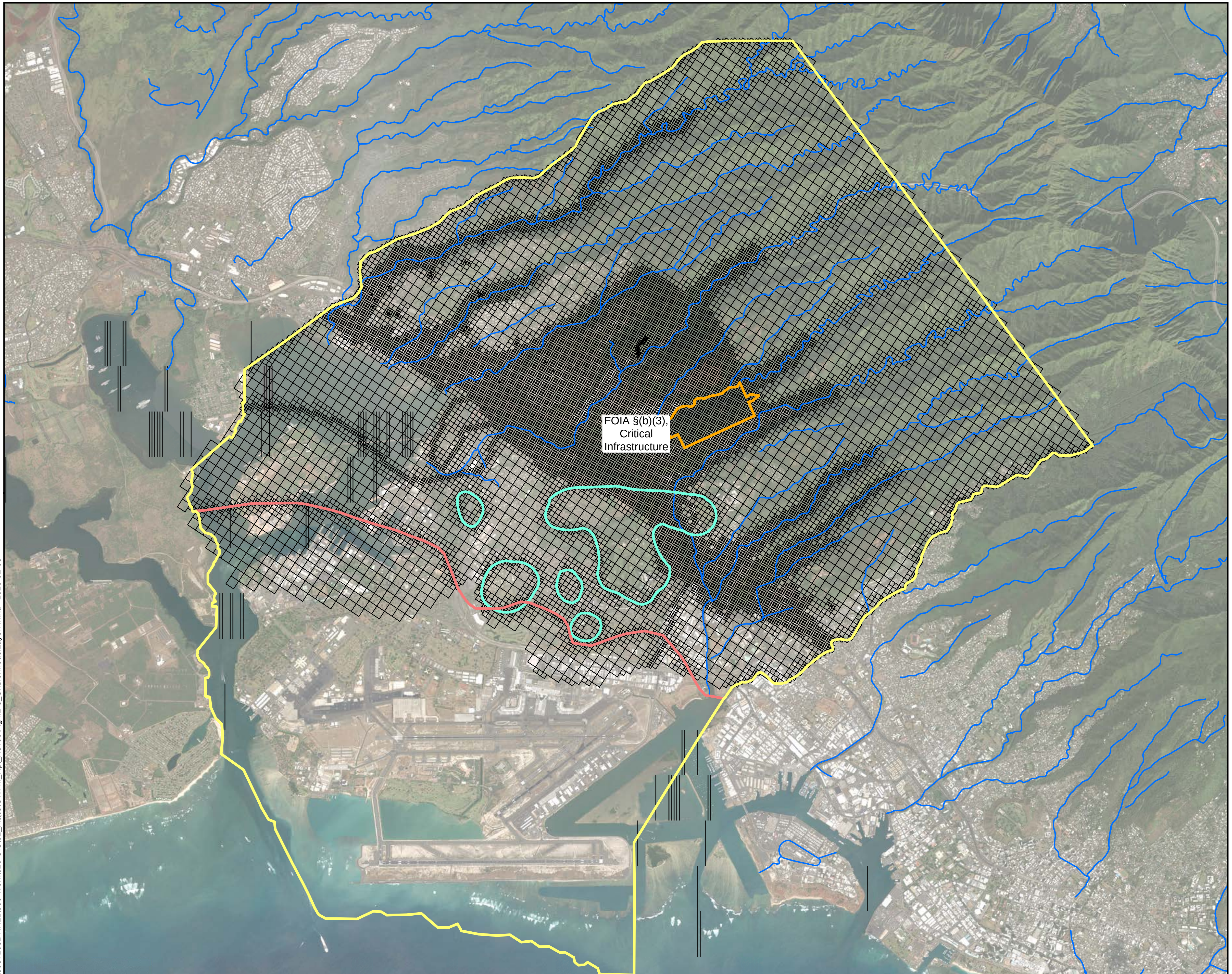
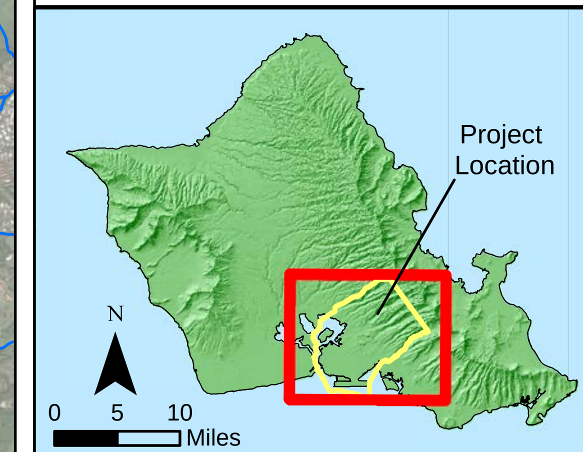


Location Map



Legend

- Marine Sediments Extent
- Tuff Cone
- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 4.2-8
Grid for Model Layer 7
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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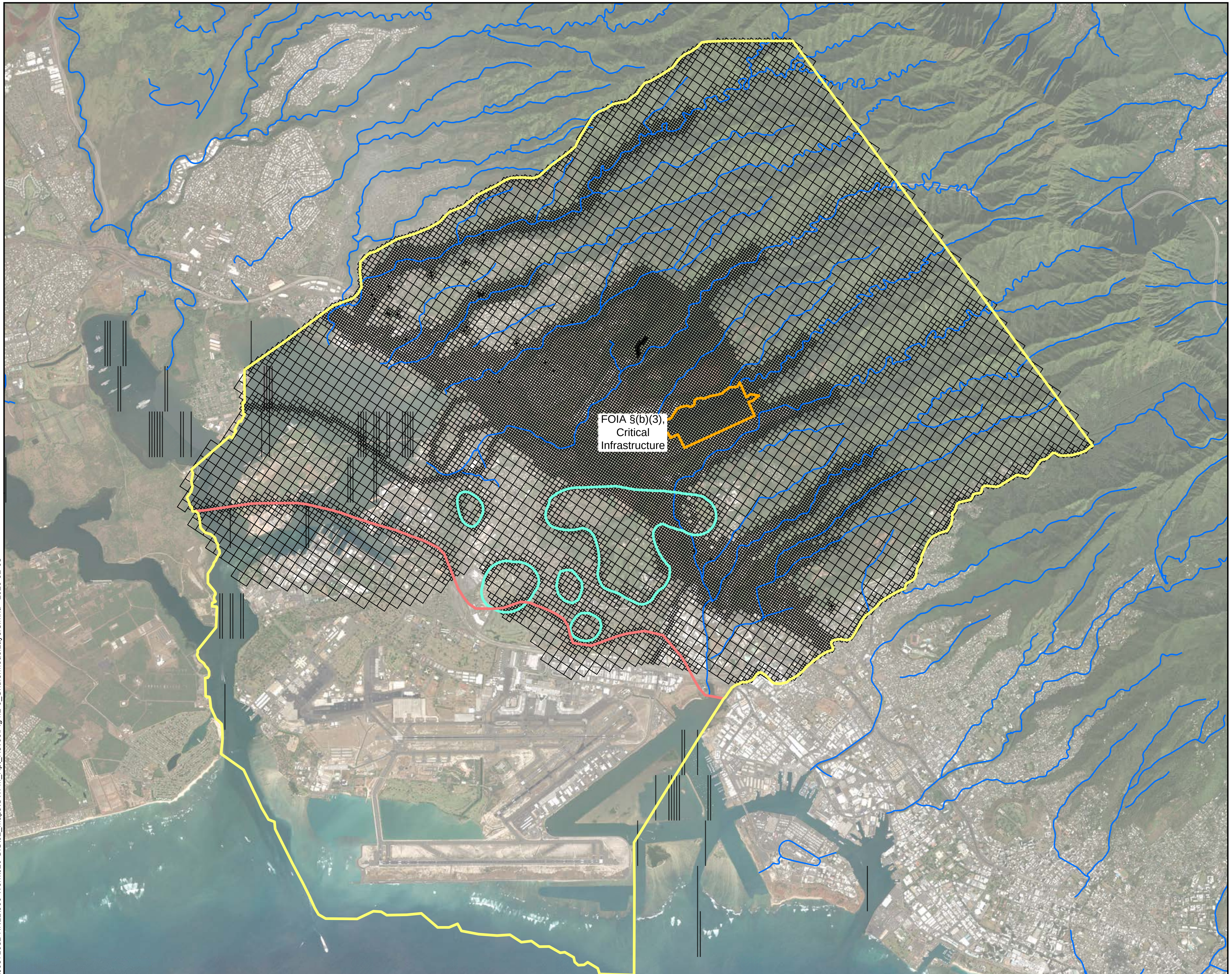
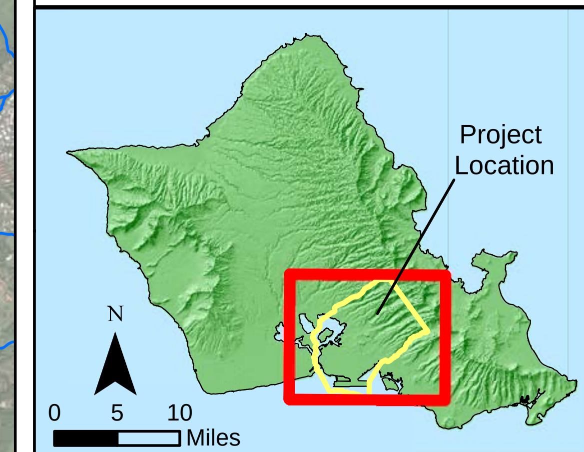


Location Map



Legend

- Marine Sediments Extent
- Tuff Cone
- Stream
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

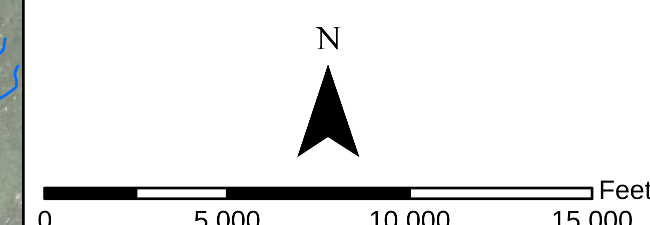


Figure 4.2-9
Grid for Model Layer 8
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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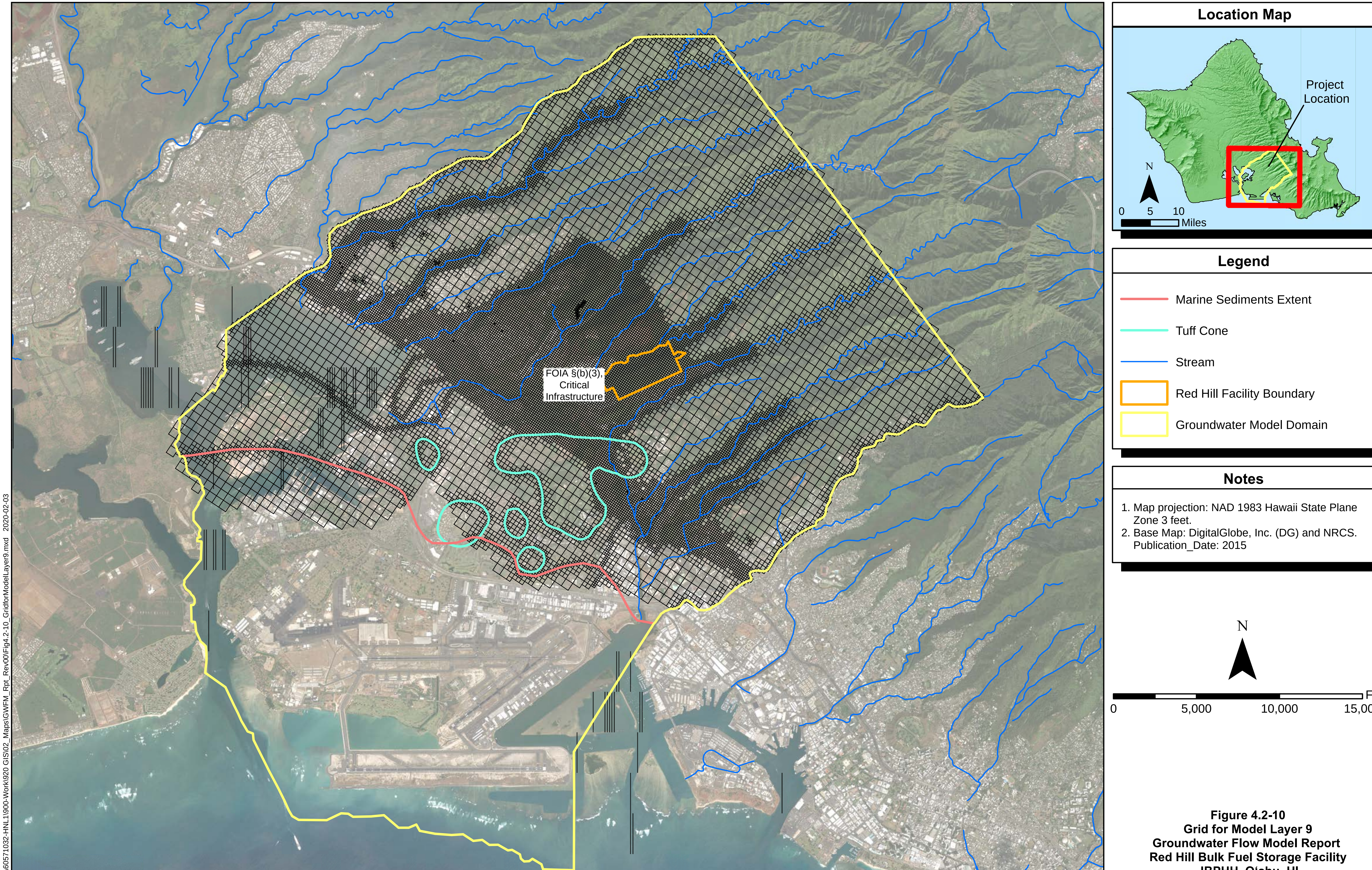

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 4.2-10
Grid for Model Layer 9
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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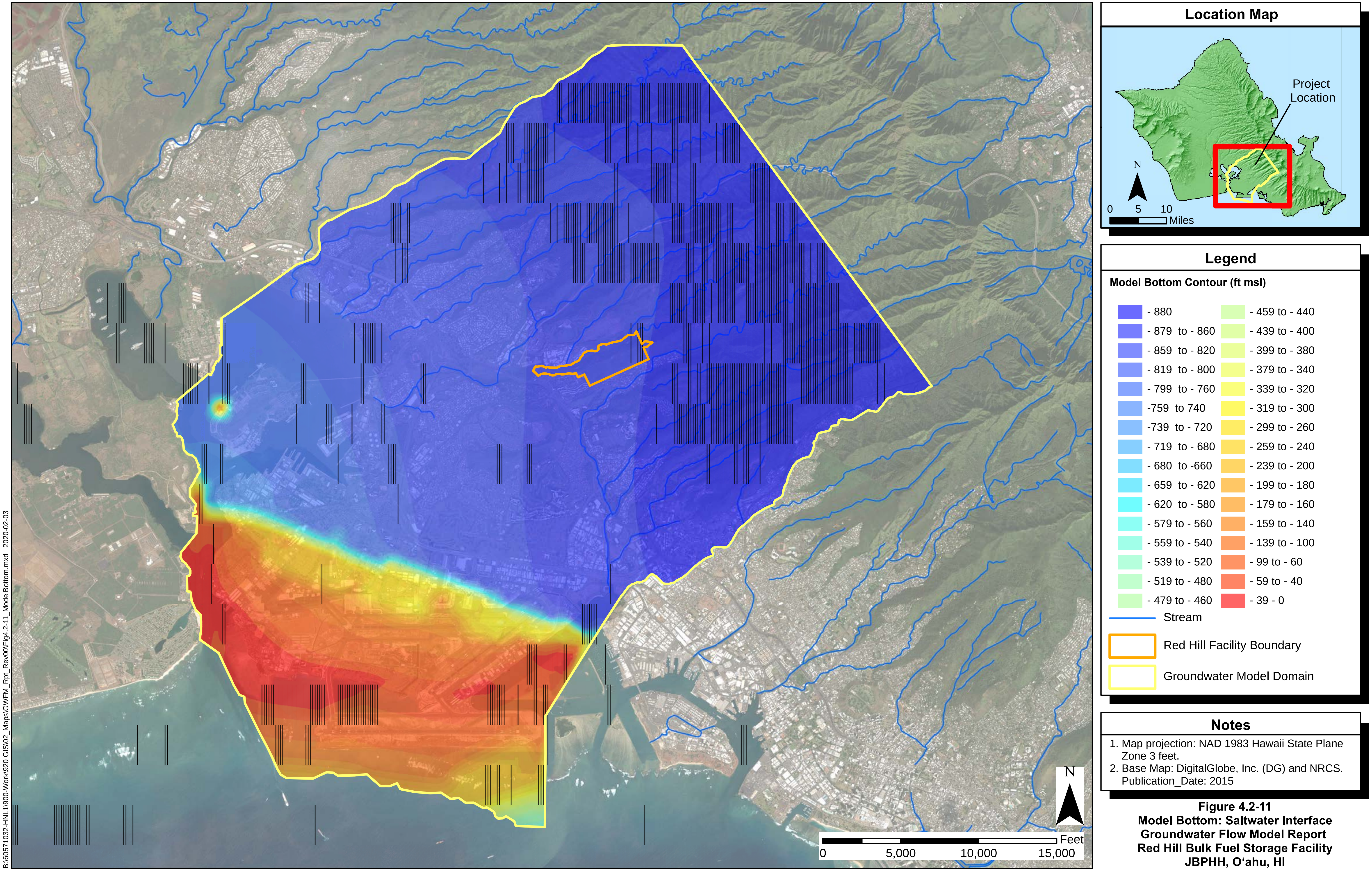
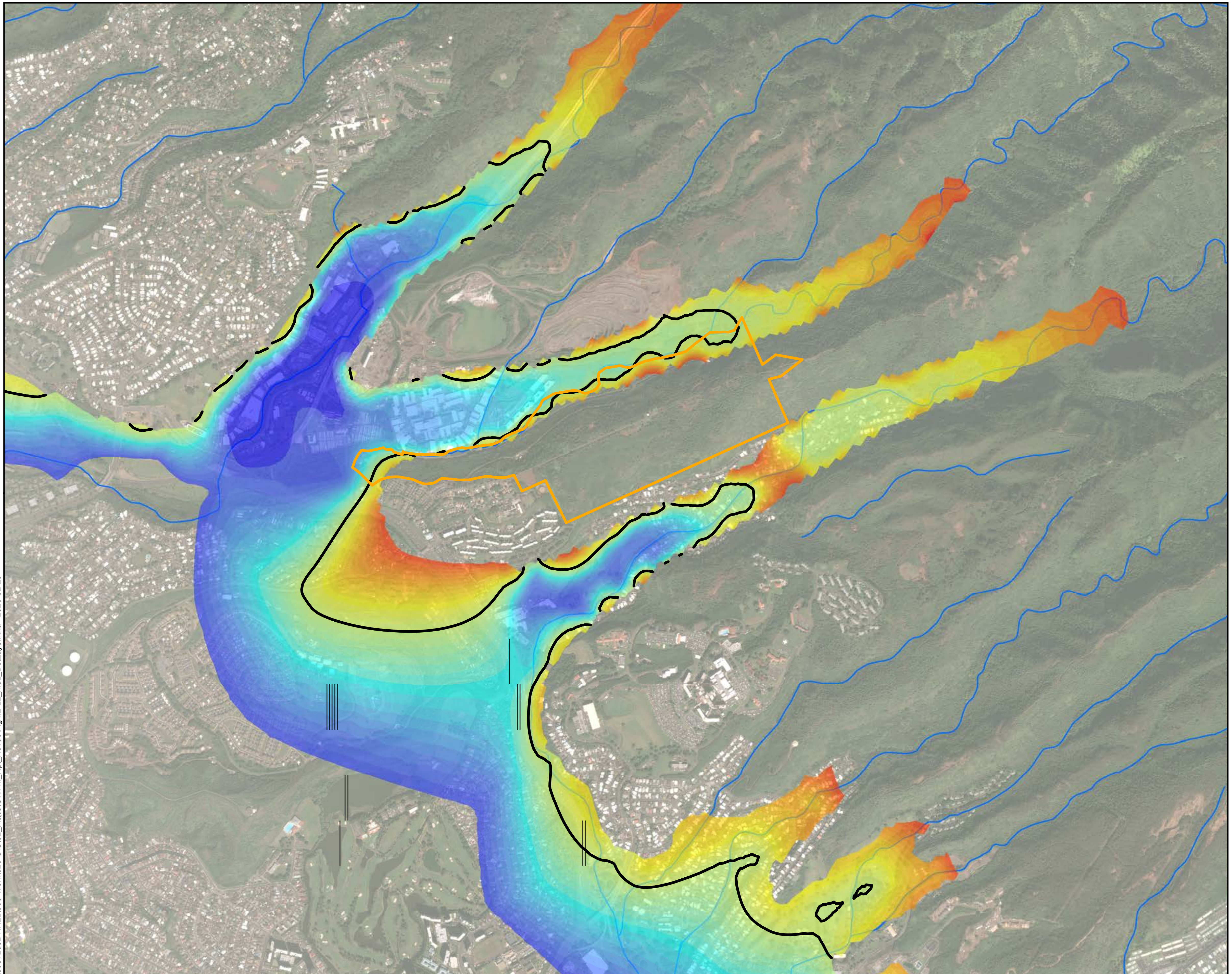
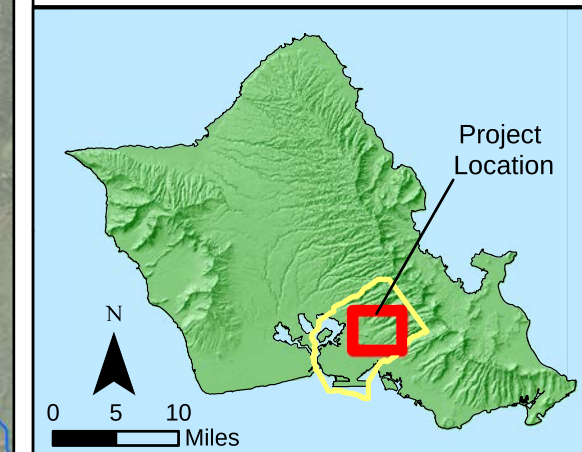


Figure 4.2-11
Model Bottom: Saltwater Interface
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Model Bottom Contour (ft msl)

- -250
- -225
- -210
- -195
- -180
- -165
- -150
- -135
- -120
- -105
- -90
- -75
- -60
- -45
- -30
- -15
- 0
- 15
- 30
- 45
- 60
- 75
- 90
- 105
- 120
- 135
- 150
- 165
- 180
- 195
- 210

15 ft msl contour

Stream

Red Hill Facility Boundary

Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. ft msl = feet above mean sea level

N

0 1,000 2,000 3,000 Feet

Figure 4.2-12
Bottom Elevation of Saprolite in North and South Hālawa Valley – Representation 1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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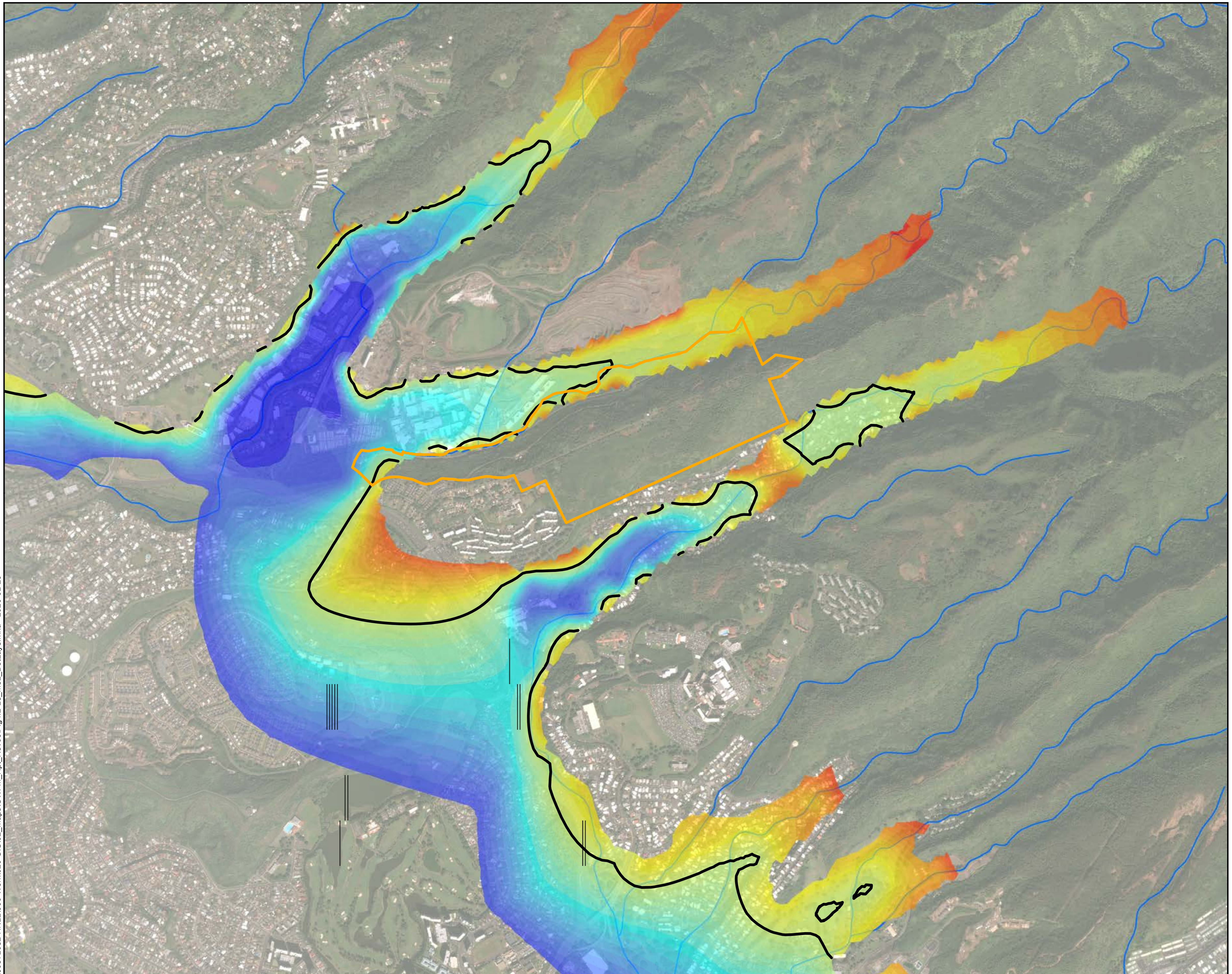

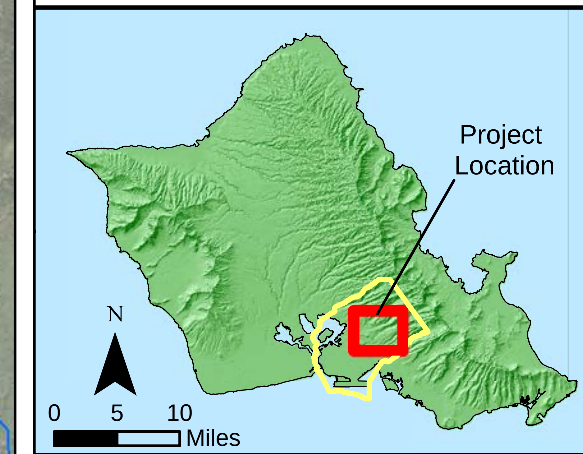

Legend

Model Bottom Contour (ft msl)

- 250	- 120	0	120
- 225	- 105	15	135
- 210	- 90	30	150
- 195	- 75	45	165
- 180	- 60	60	180
- 165	- 45	75	195
- 150	- 30	90	210
- 135	- 15	105	

15 ft msl contour

Stream

Red Hill Facility Boundary

Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. ft msl = feet above mean sea level

N

0 1,000 2,000 3,000 Feet

Figure 4.2-13
Bottom Elevation of Saprolite in North and South Hālawa Valley – Representation 2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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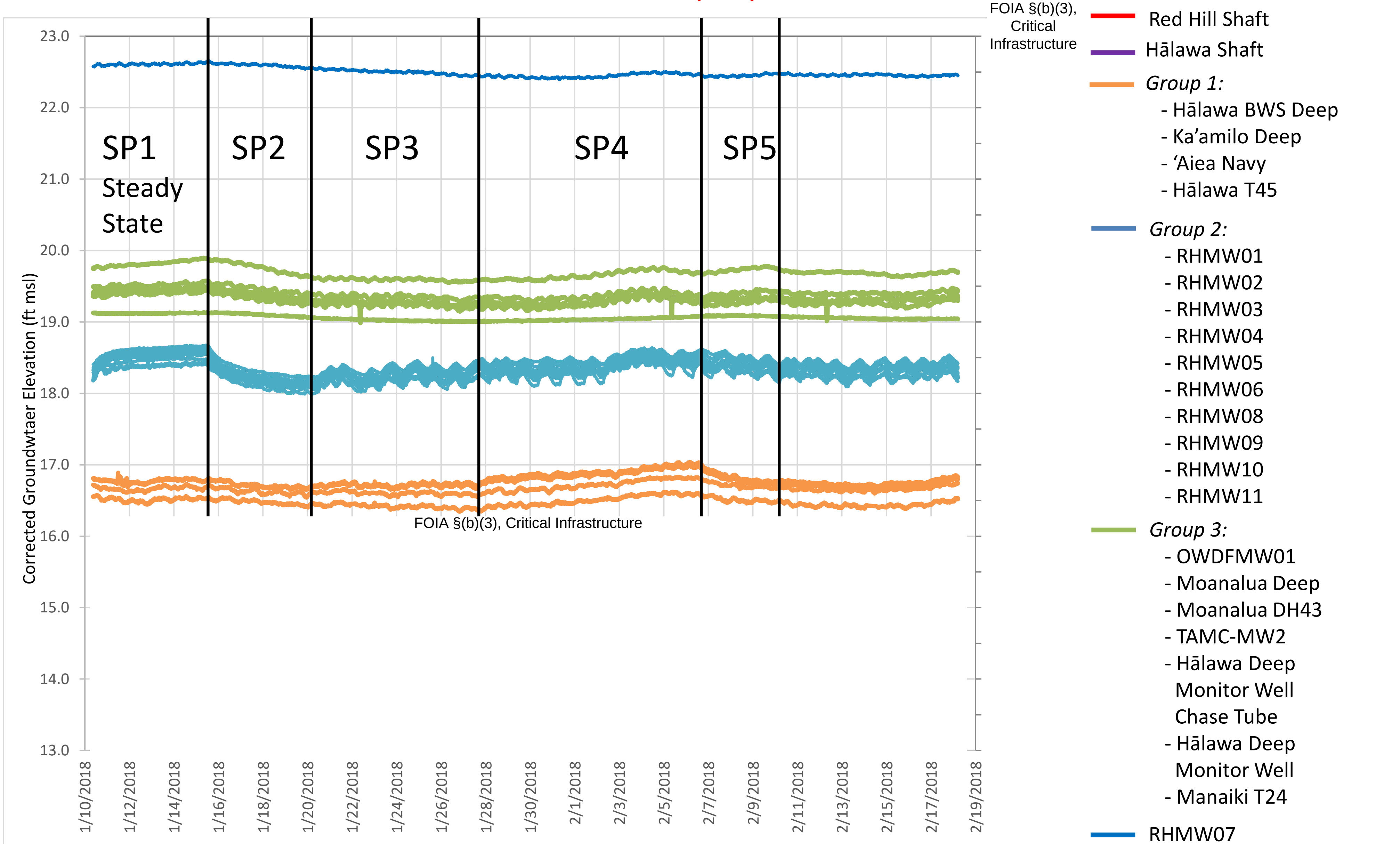
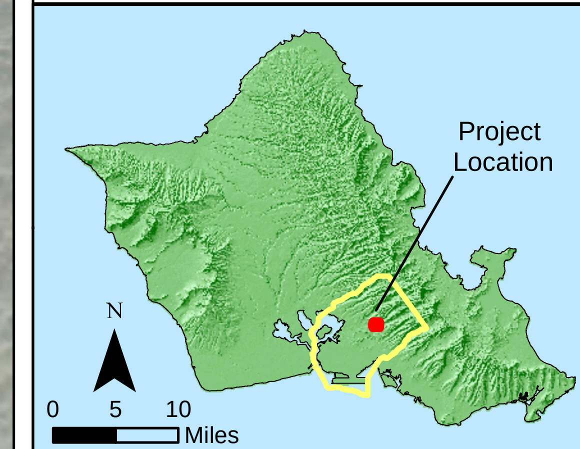


Figure 4.6-1
Stress Period Setup for Verification Simulation
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

~~For Red Hill AOC Party Use Only~~

Location Map



Legend

- Particle Location
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility foward pathline arrows = 1 year.

N

0 100 200 300 400 Feet

Figure 4.7-1
Starting Location of Forward Particle Tracks from Beneath the Facility
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL1\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig4.7-1_ParticleLocation.mxd 1/1/2020

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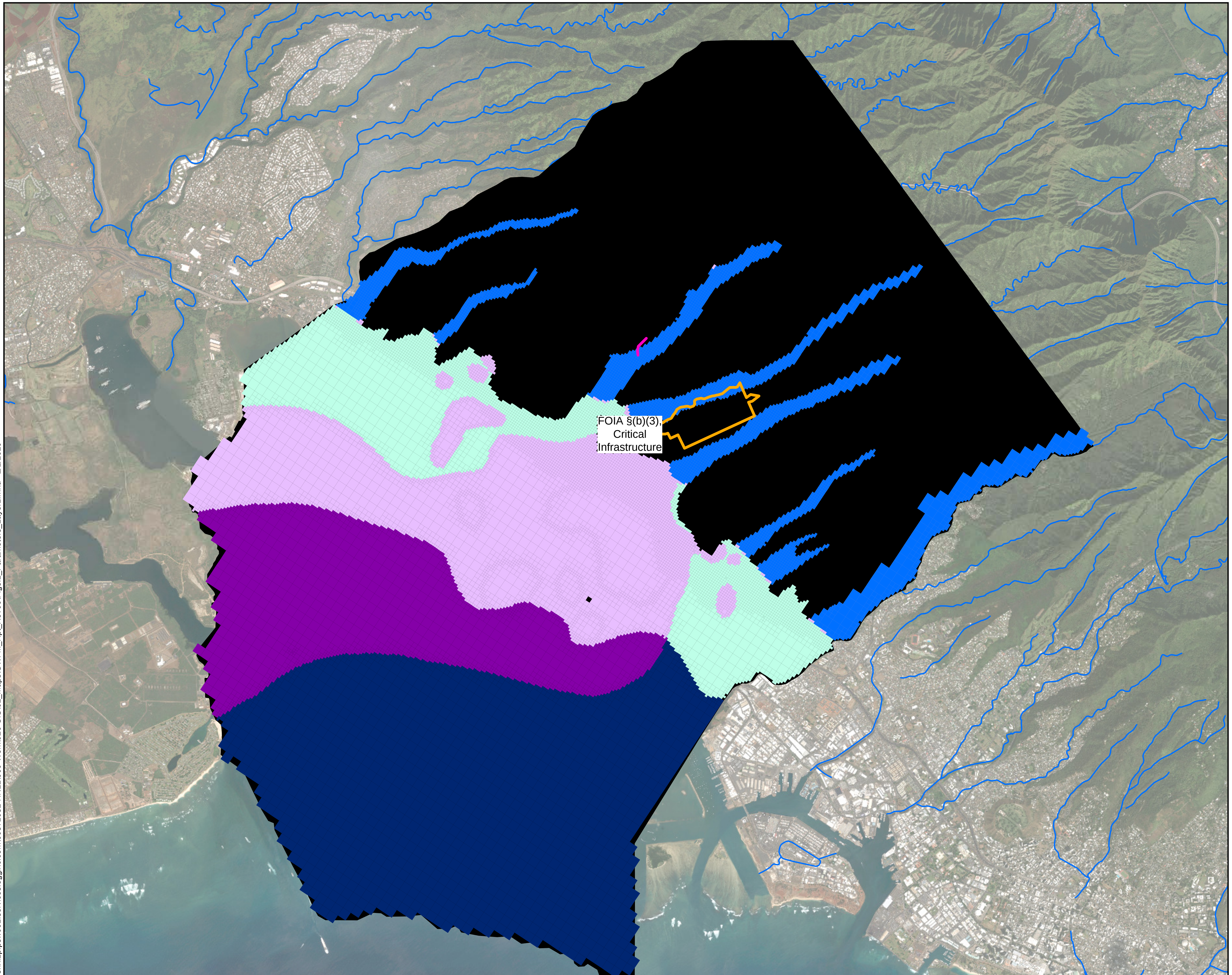
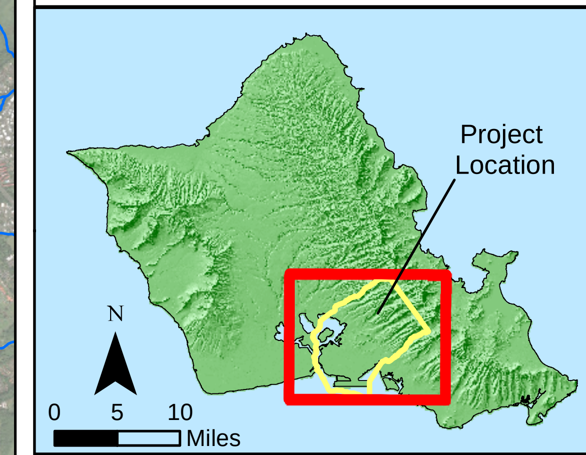


Location Map



Legend

- Caprock Alluvial Sediments
- Caprock Tuff Overlying Alluvial Sediments
- Caprock Tuff Overlying Marine Sediments
- Caprock Marine Sediments
- Saprolite Under Valley Fill
- Inactive Model Cells
- Shaft
- Red Hill Facility Boundary
- Stream

Notes

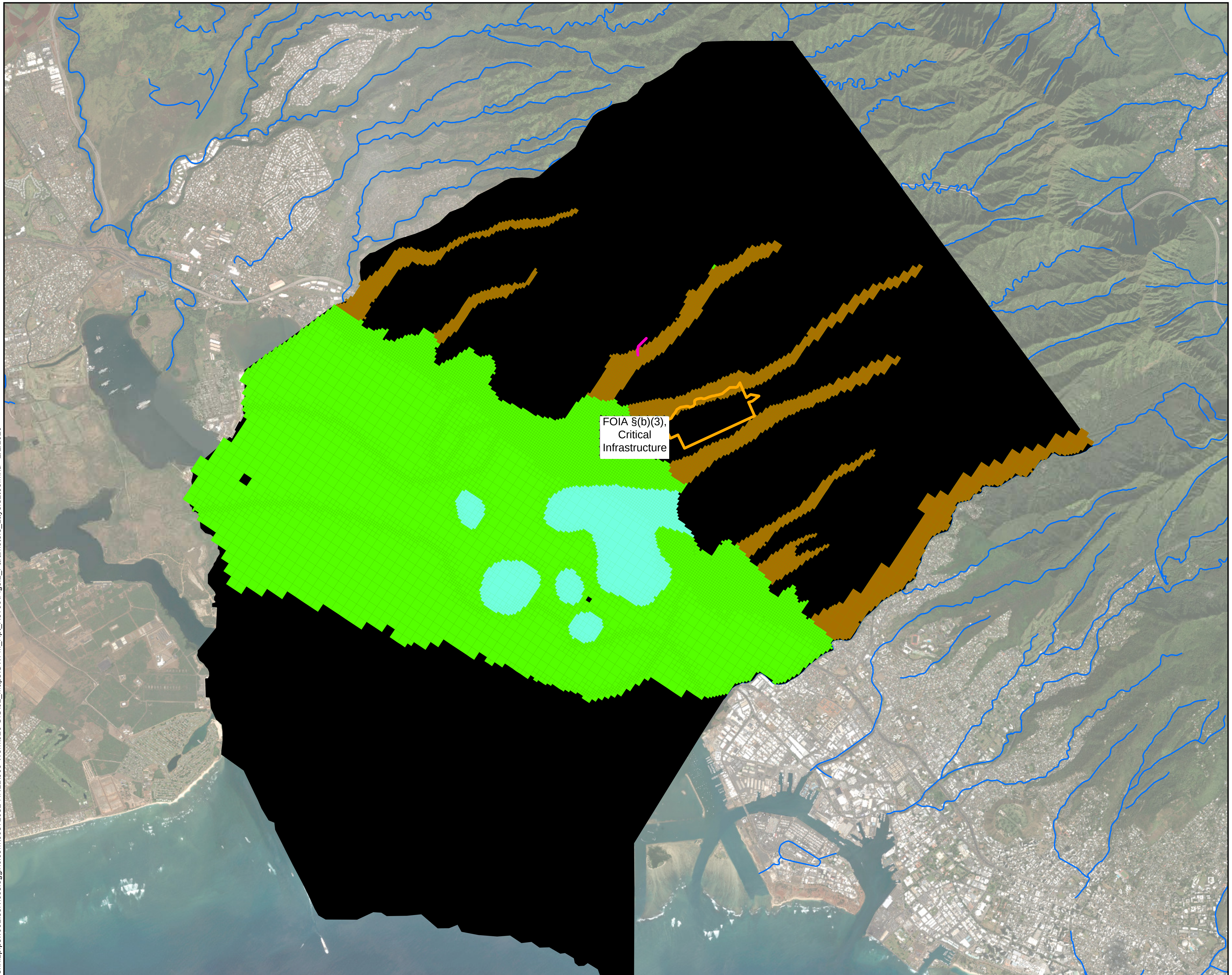
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

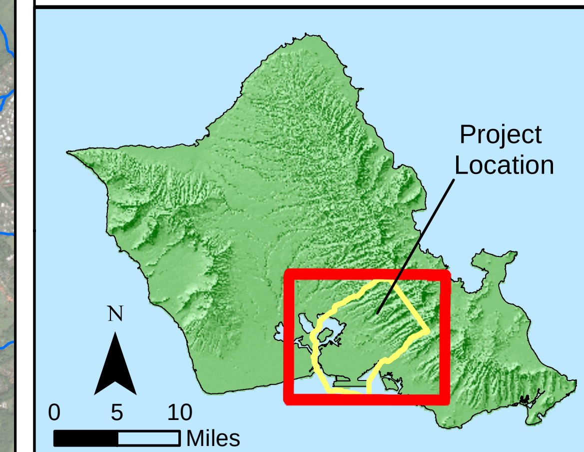
0 5,000 10,000 15,000 Feet

Figure 5-1
Material Parameter Distribution Map for Model Layer 1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.1_Parameters_Layer1.mxd 2/1/2020



Location Map



Legend

- Tuff Cone
- Saprolite Under Valley Fill
- Saprolite Underneath Caprock
- Inactive Model Cells
- Shaft
- Red Hill Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 5-2
Material Parameter Distribution Map for Model Layers 2 and 3
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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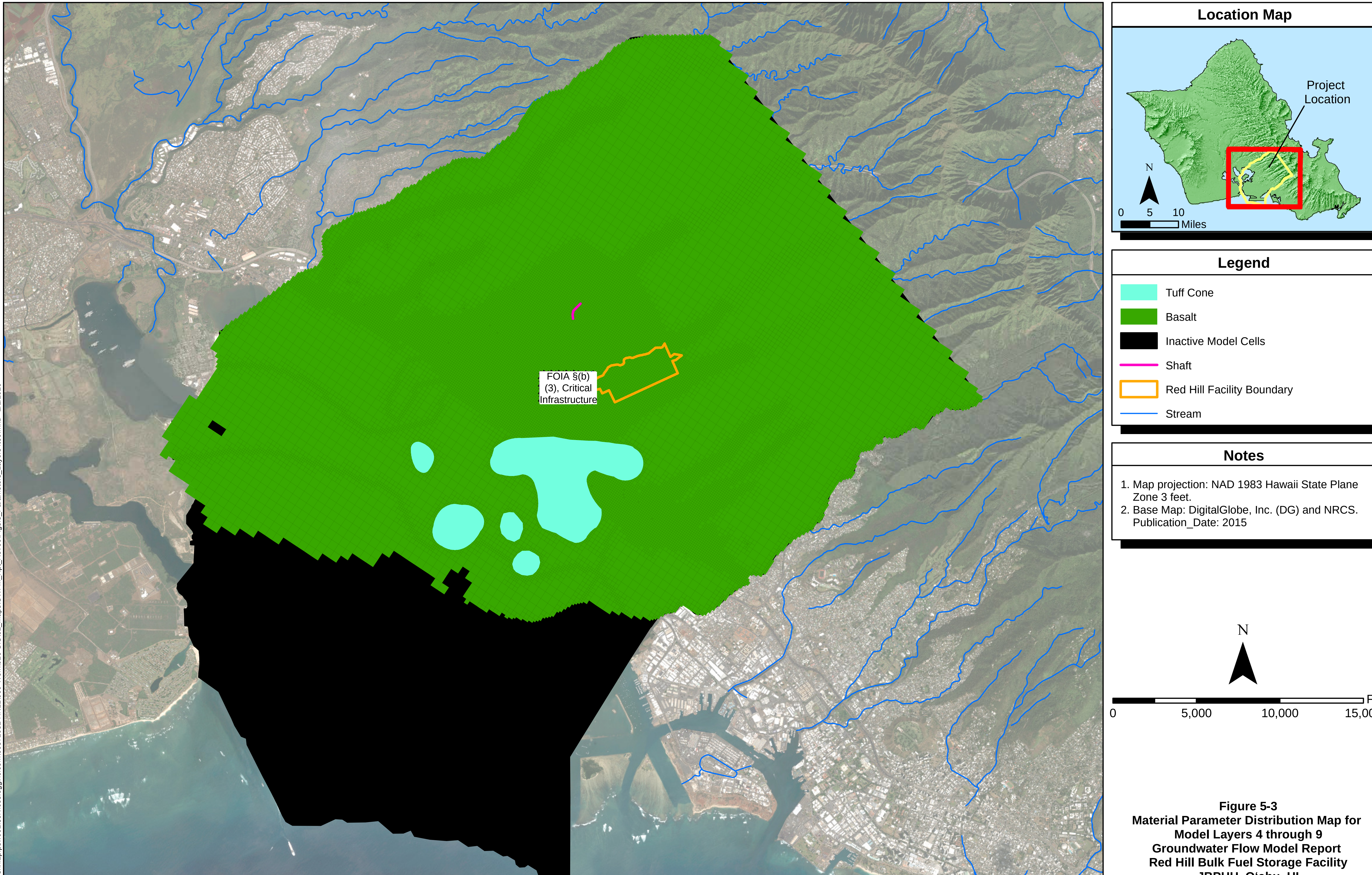

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5-3
Material Parameter Distribution Map for Model Layers 4 through 9
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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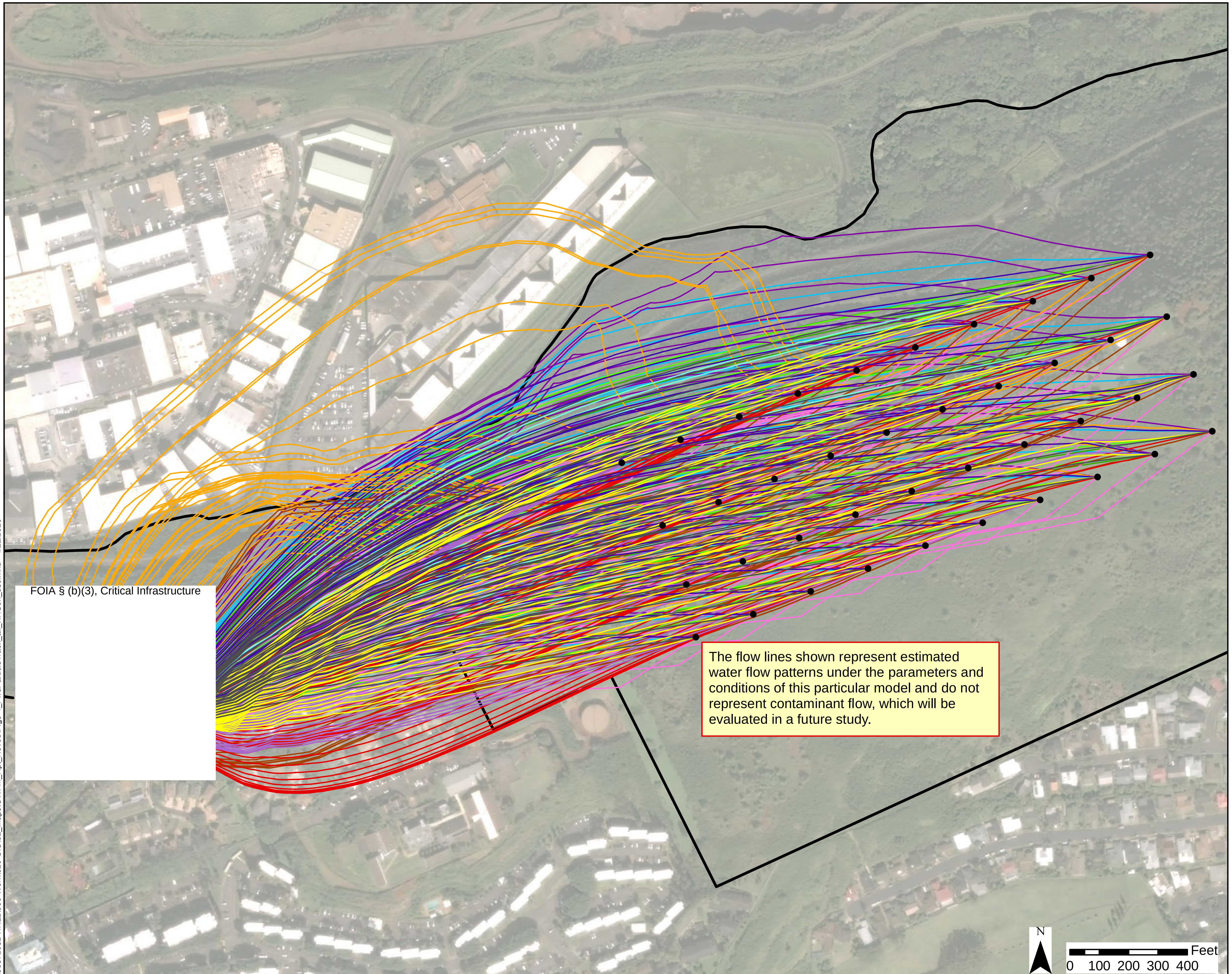
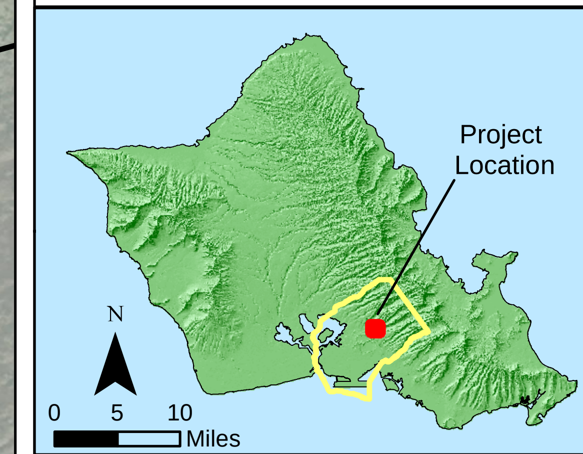


Location Map



Legend

- Particle Location
- Model #51a
- Model #51b
- Model #51c
- Model #51d
- Model #51e
- Model #52
- Model #53
- Model #54
- Model #55
- Model #56
- Model #57
- Model #58
- Model #59
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5-4
Forward Particle Tracking from All Models for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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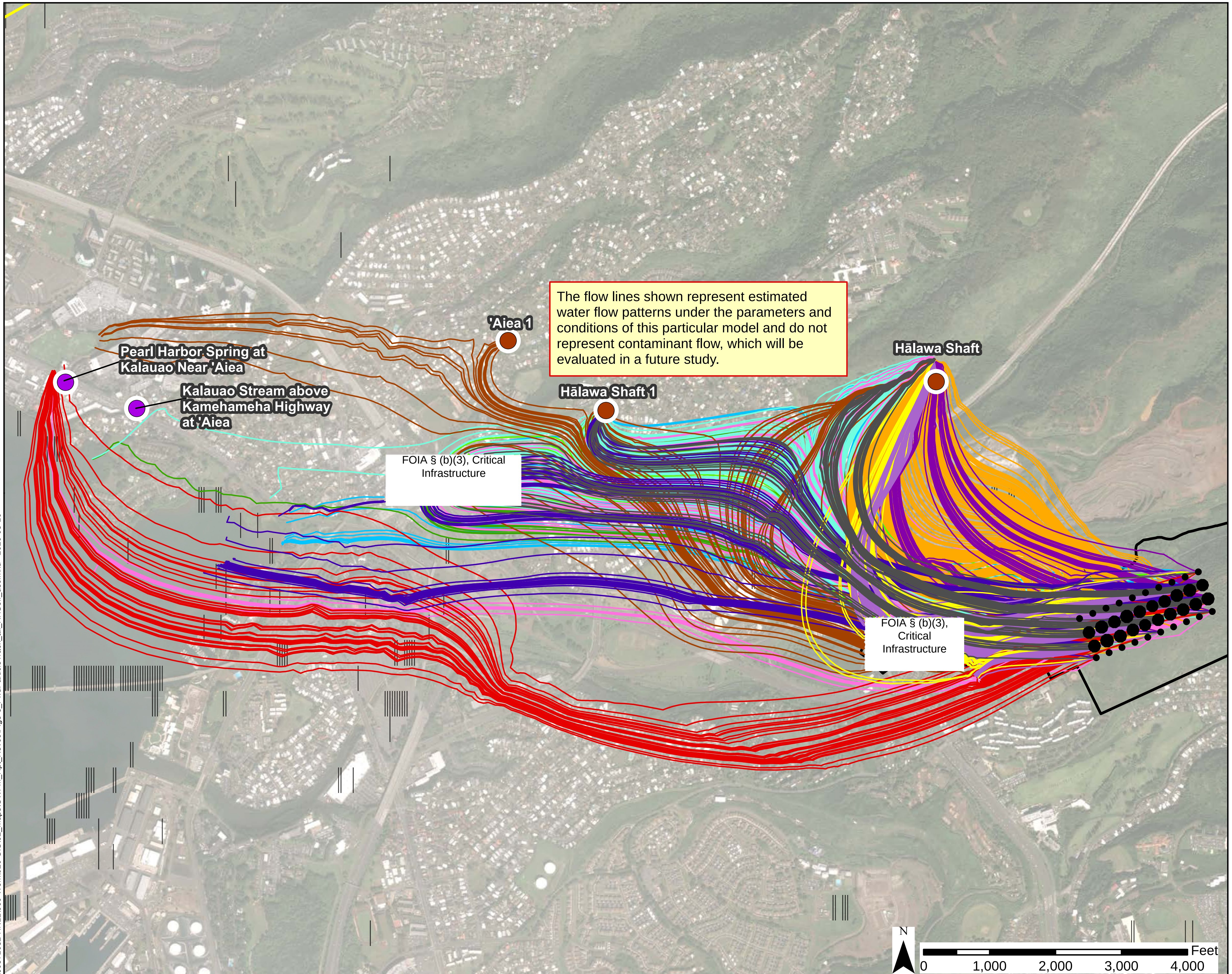
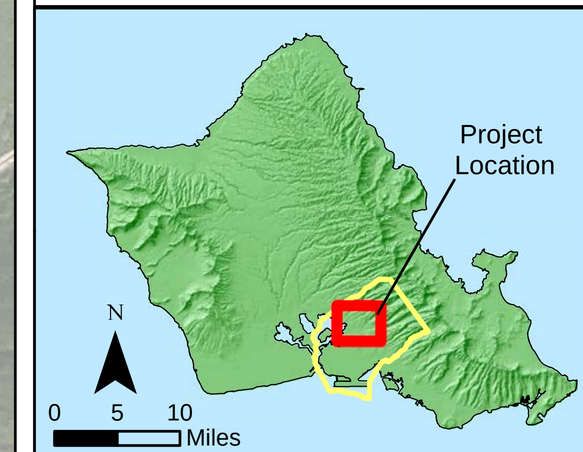


Location Map



Legend

- Spring
- Pumping Well
- Model #51a
- Model #54
- Model #51b
- Model #55
- Model #51c
- Model #56
- Model #51d
- Model #57
- Model #51e
- Model #58
- Model #52
- Model #59
- Model #53
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5-5
Forward Particle Tracking from All Models for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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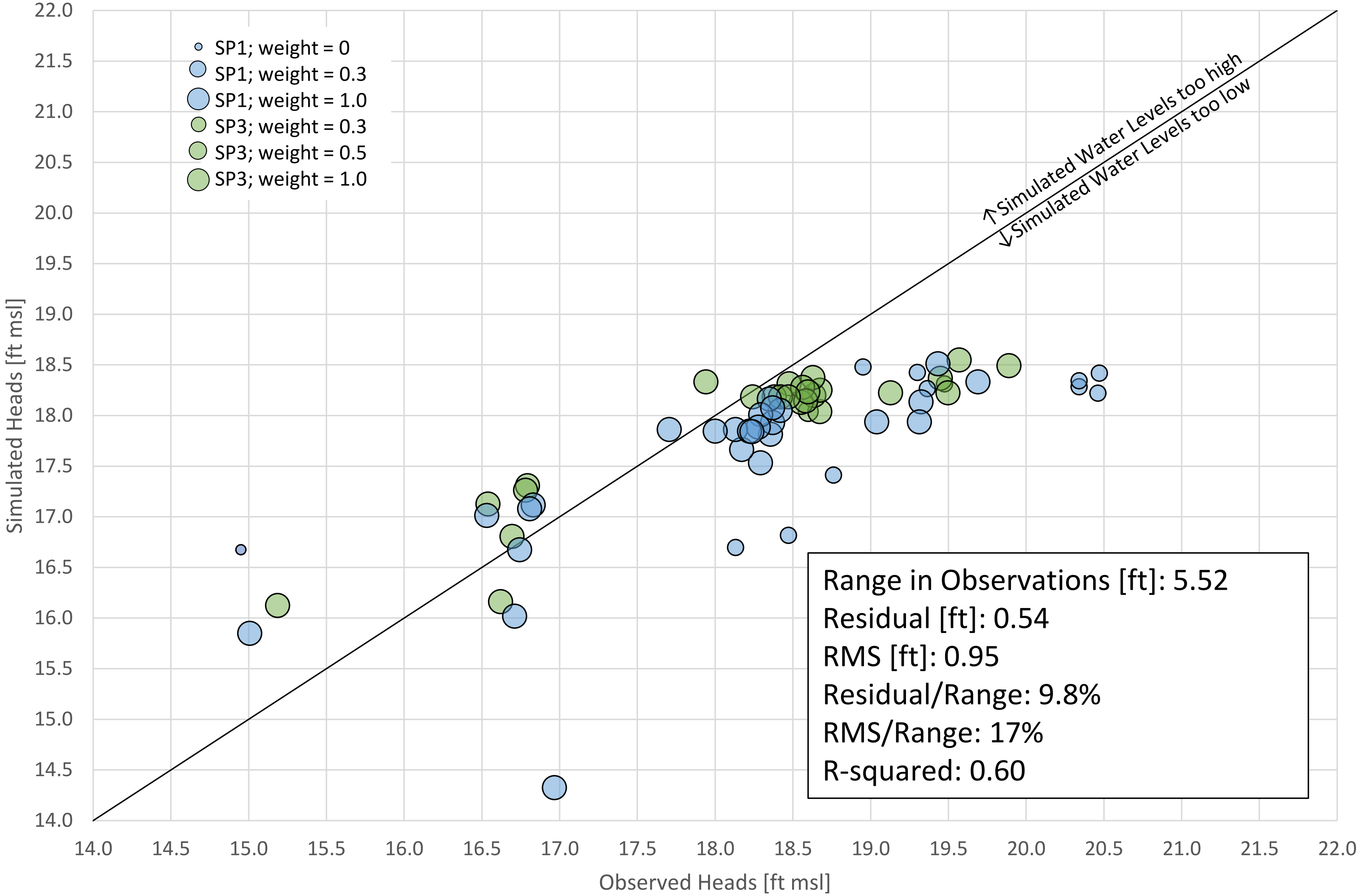

Figure 5.1.1-1
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

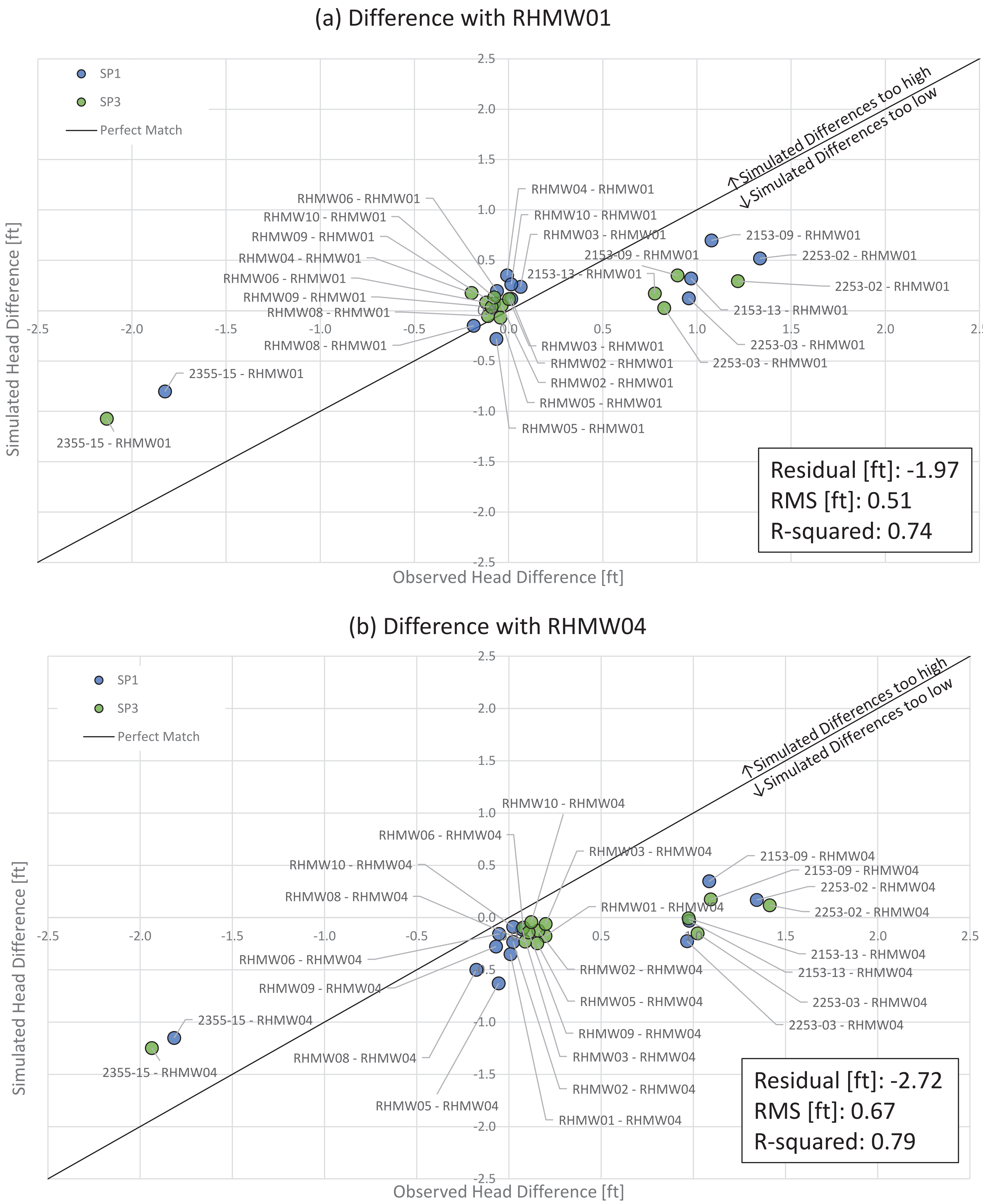

Figure 5.1.1-2
Model #51a: Homogeneous Basalt with 3:1 Anisotropy –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

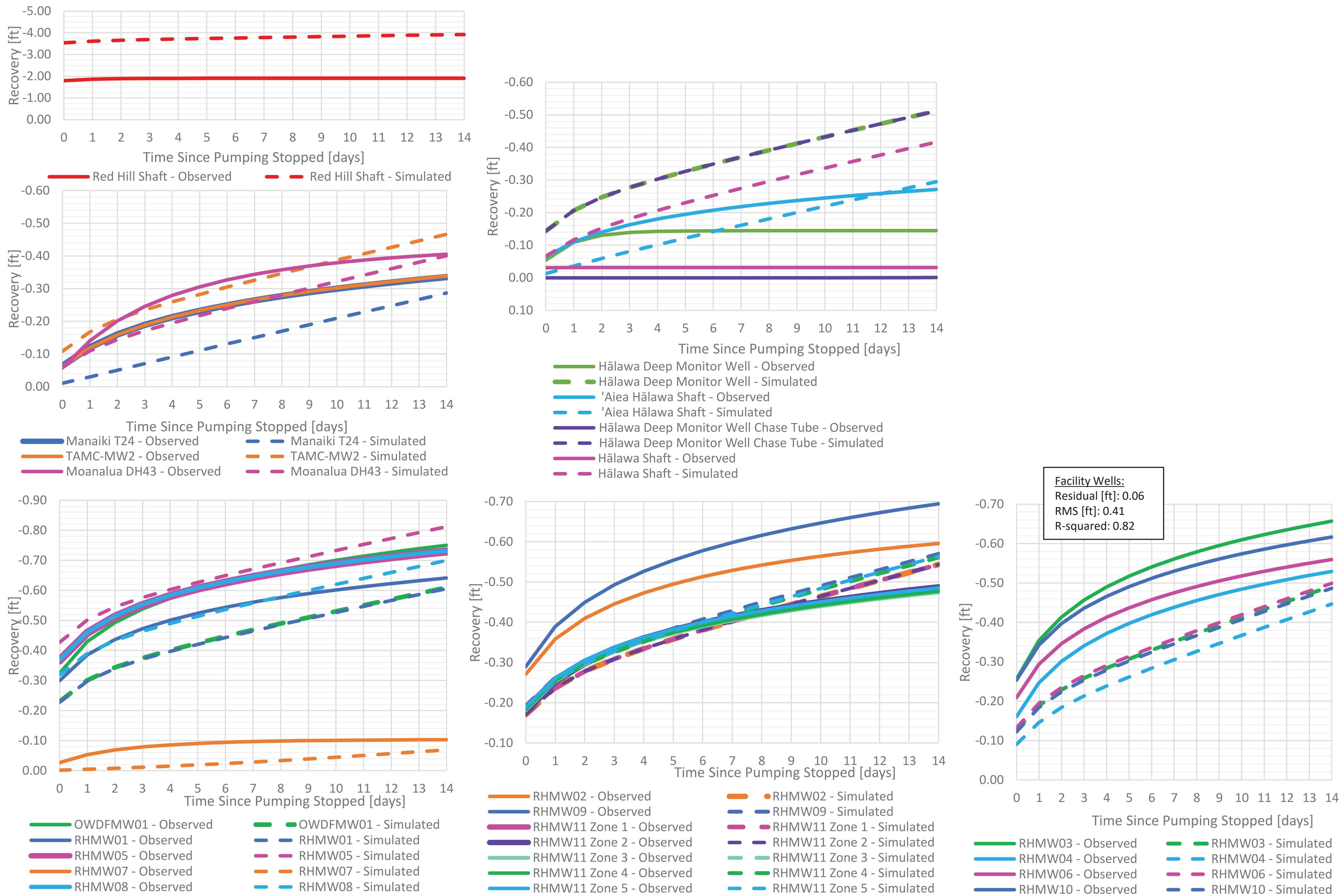

Figure 5.1.1-3
Model #51a: Homogeneous Basalt with 3:1 Anisotropy –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

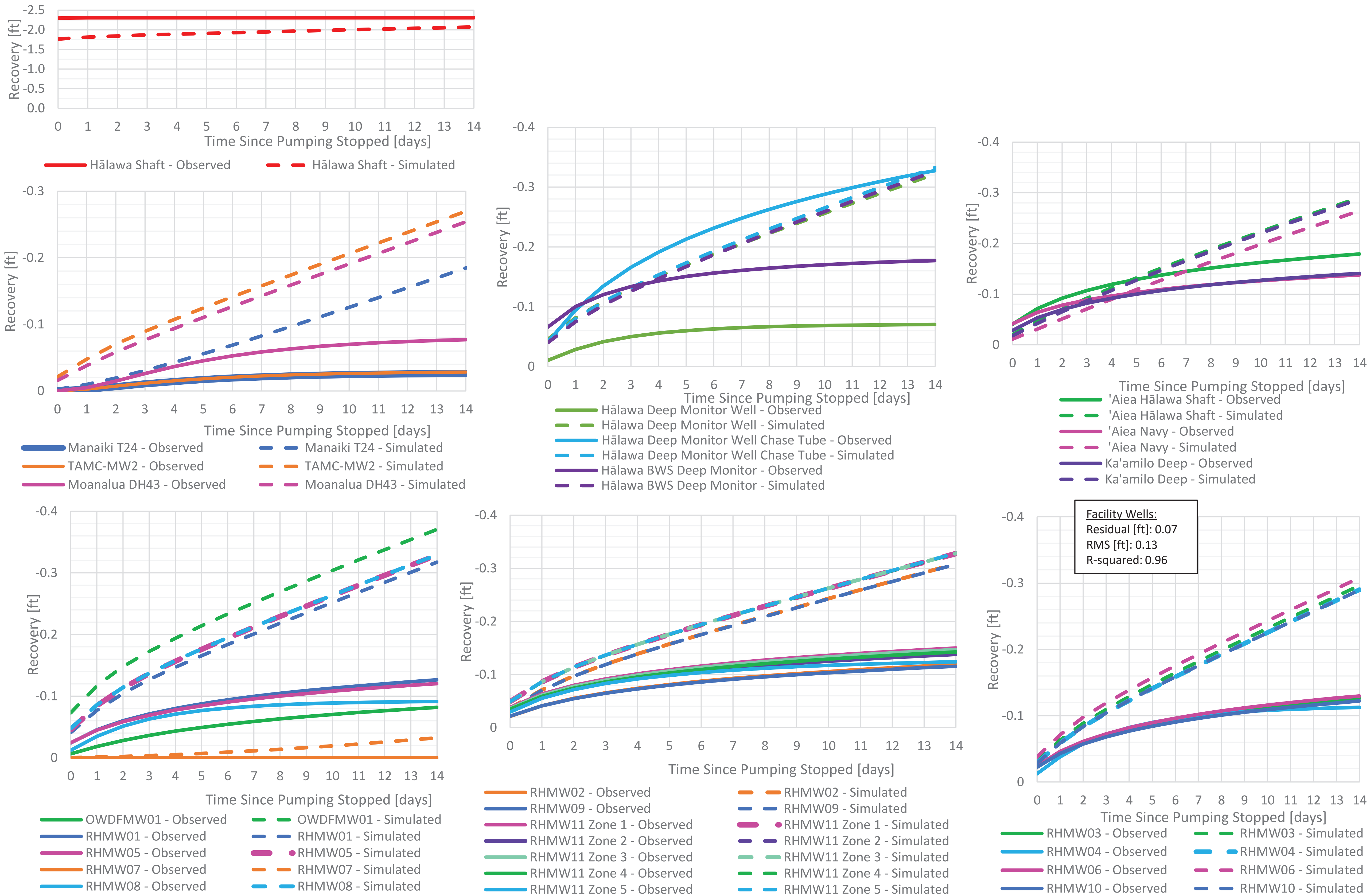

Figure 5.1.1-4
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

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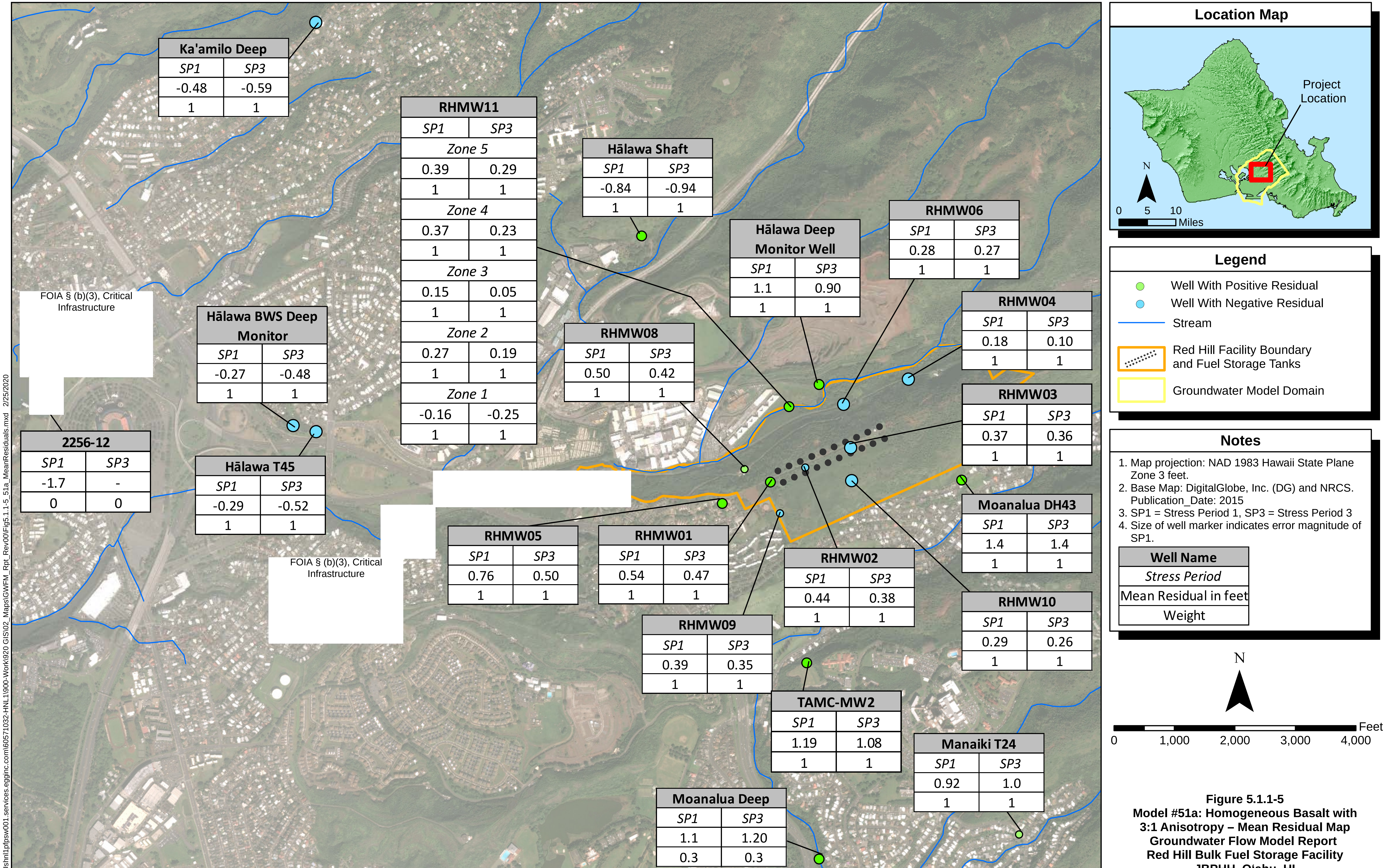

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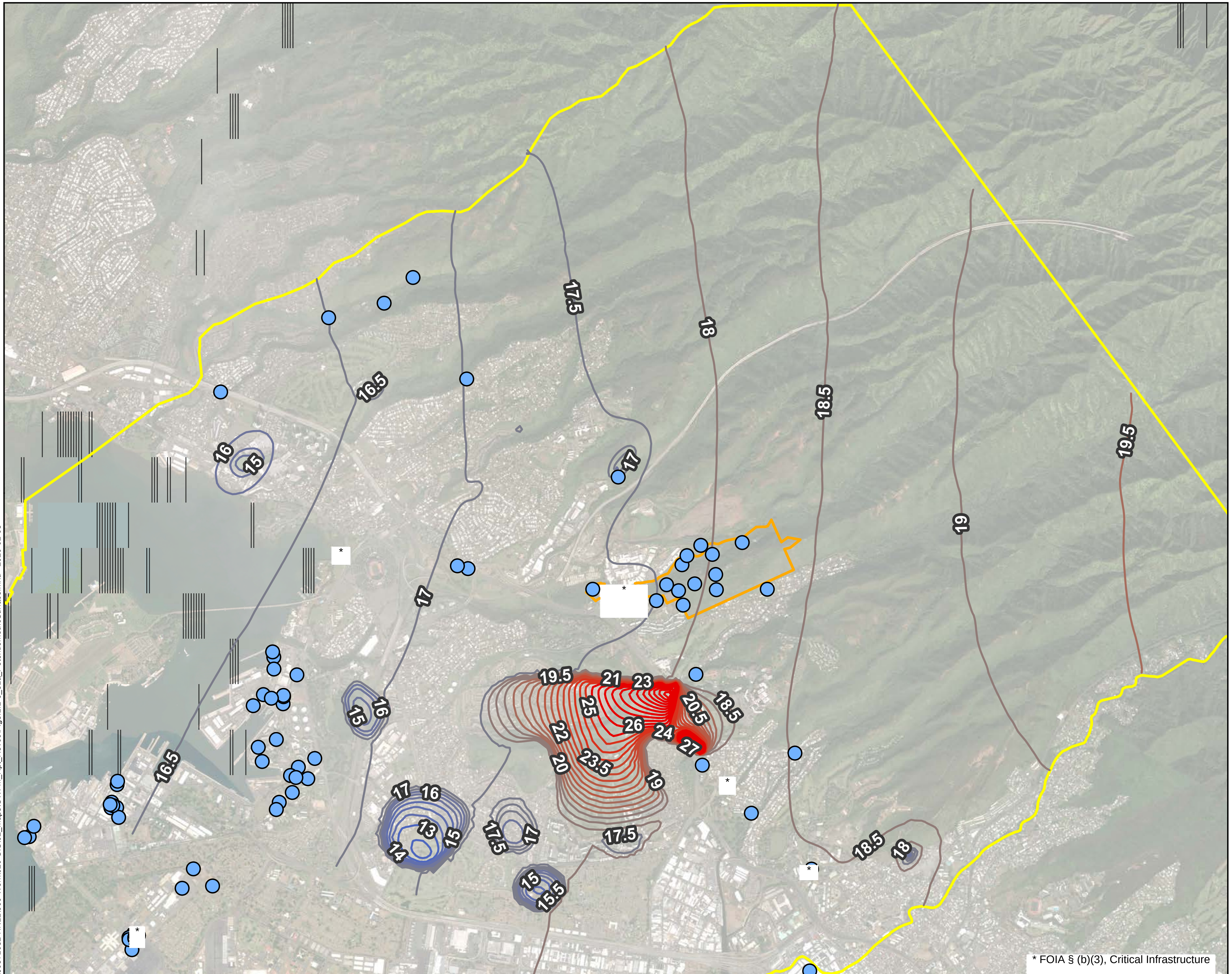
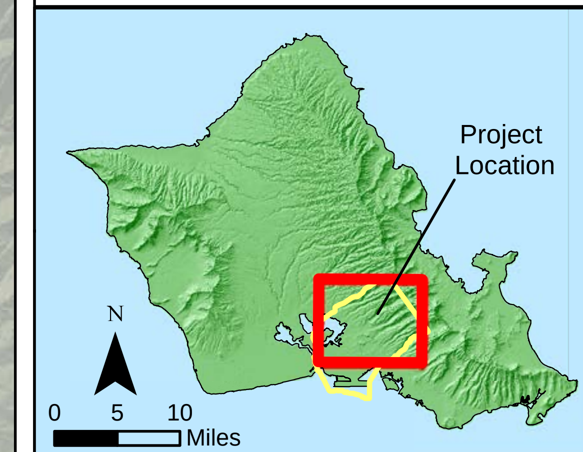
Figure 5.1.1-5
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Red Hill Facility Boundary

Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.1.1-6
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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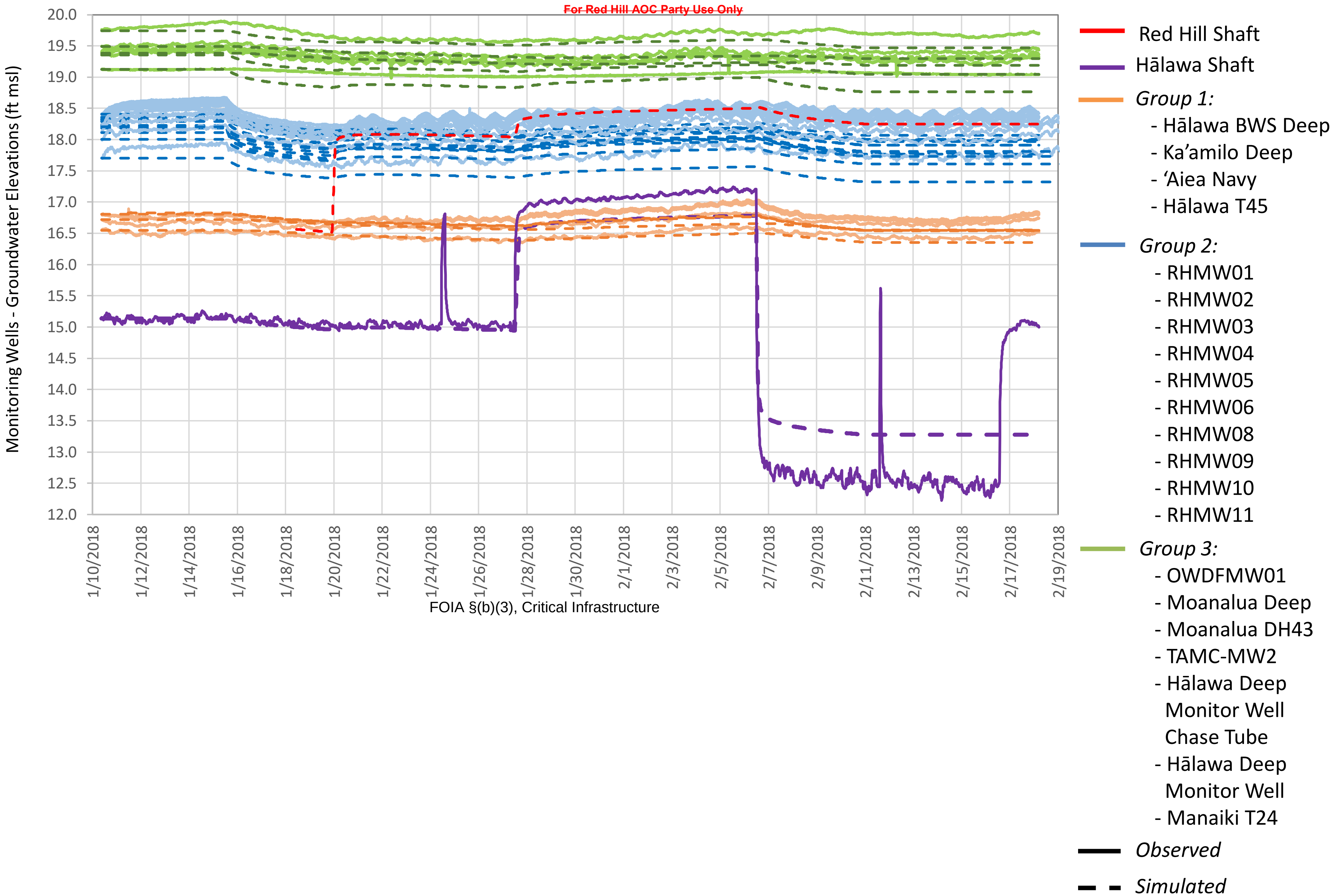


Figure 5.1.1-7
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

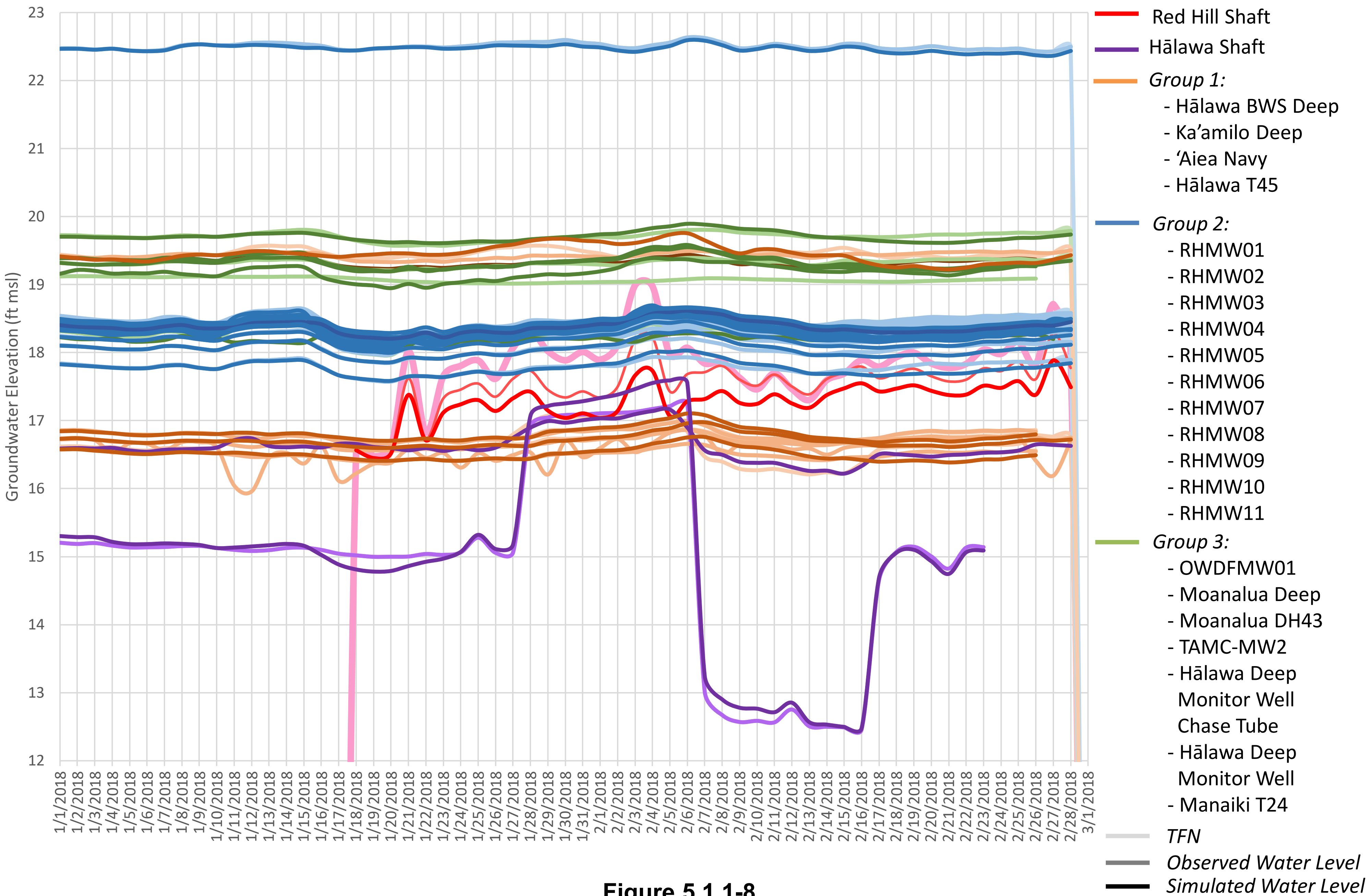


Figure 5.1.1-8
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

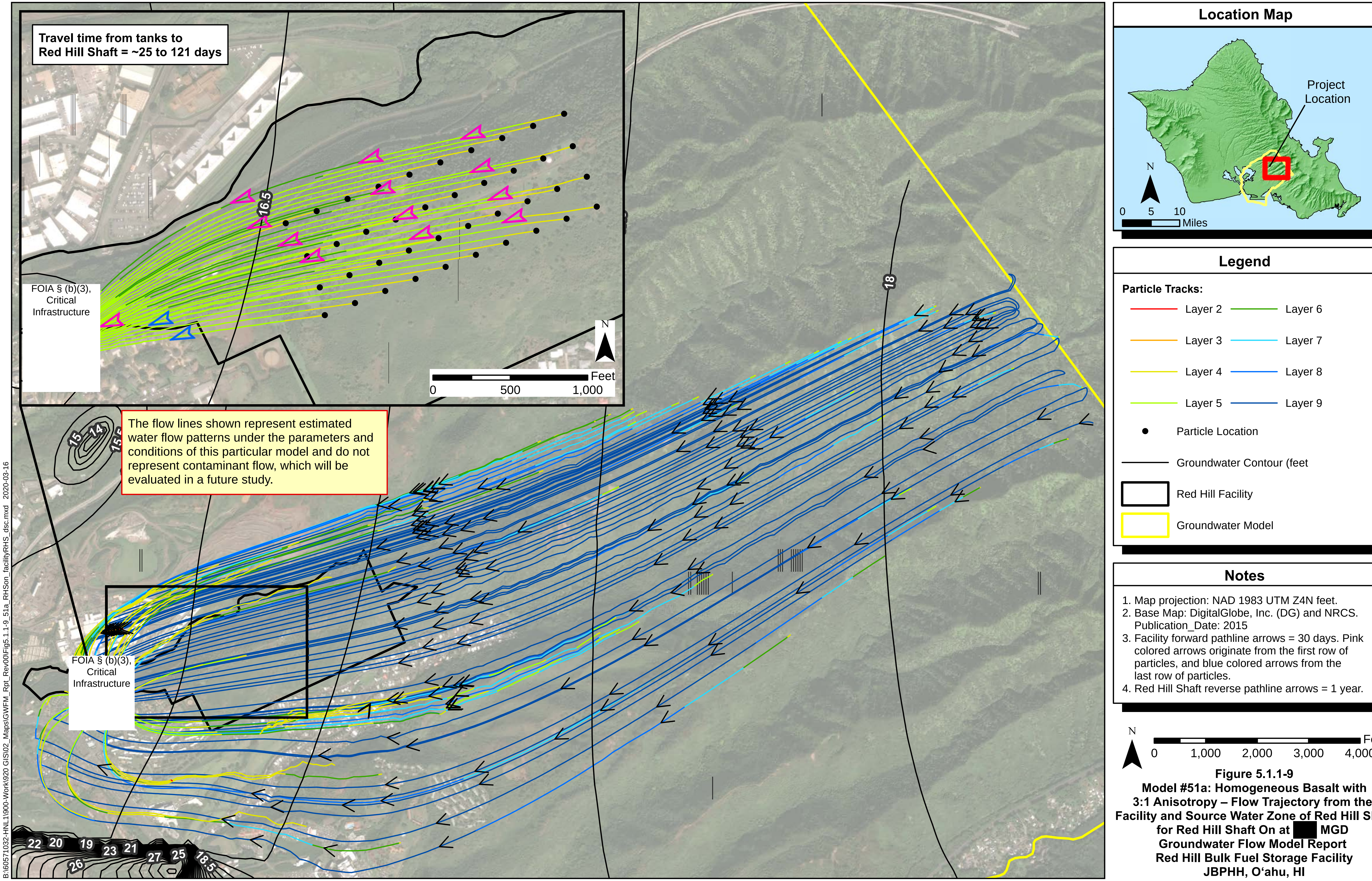
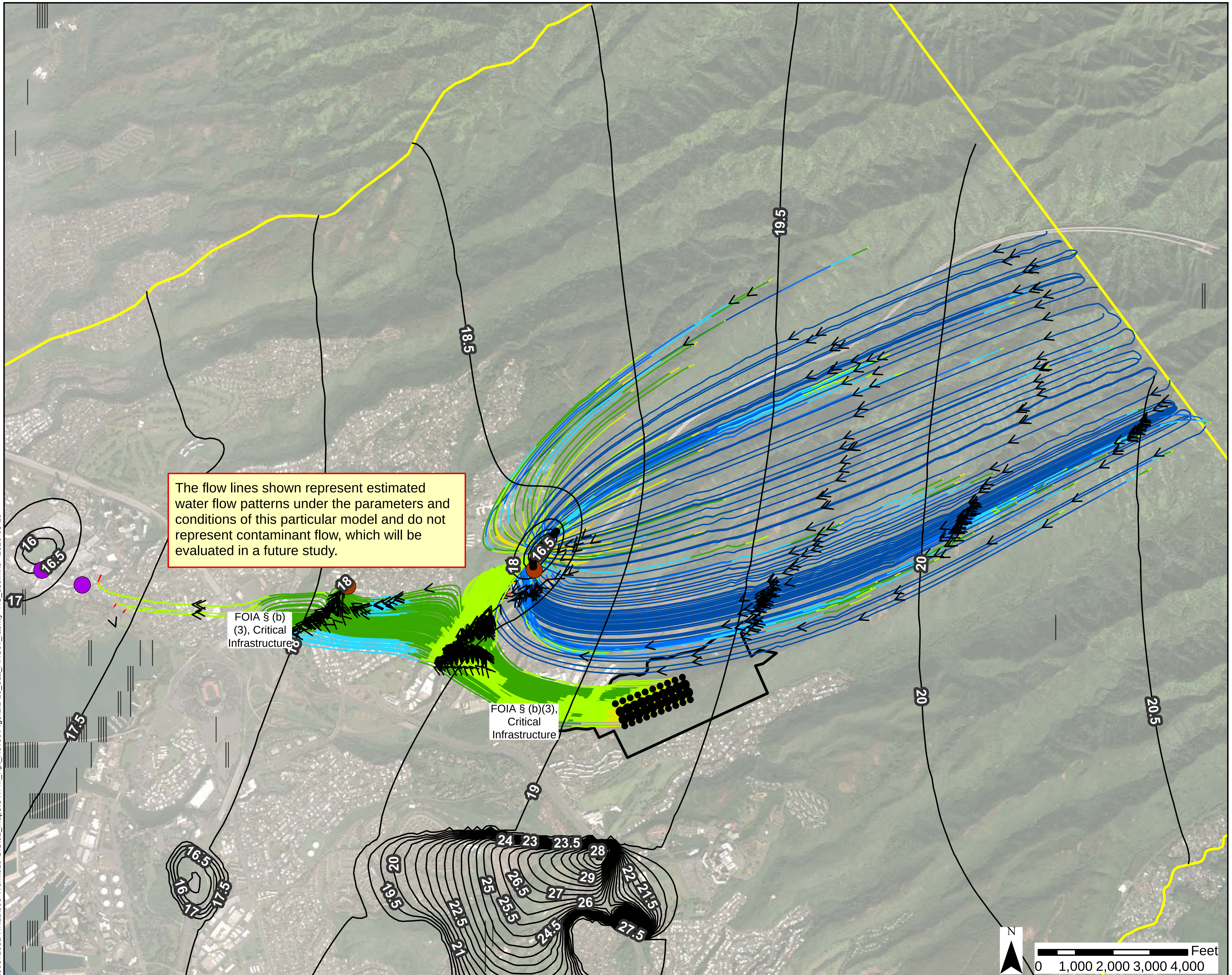
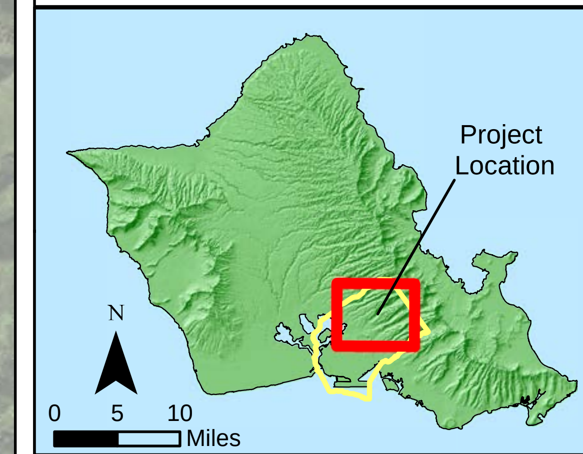


Figure 5.1.1-9
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet above mean sea level)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 1 year.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.1.1-10
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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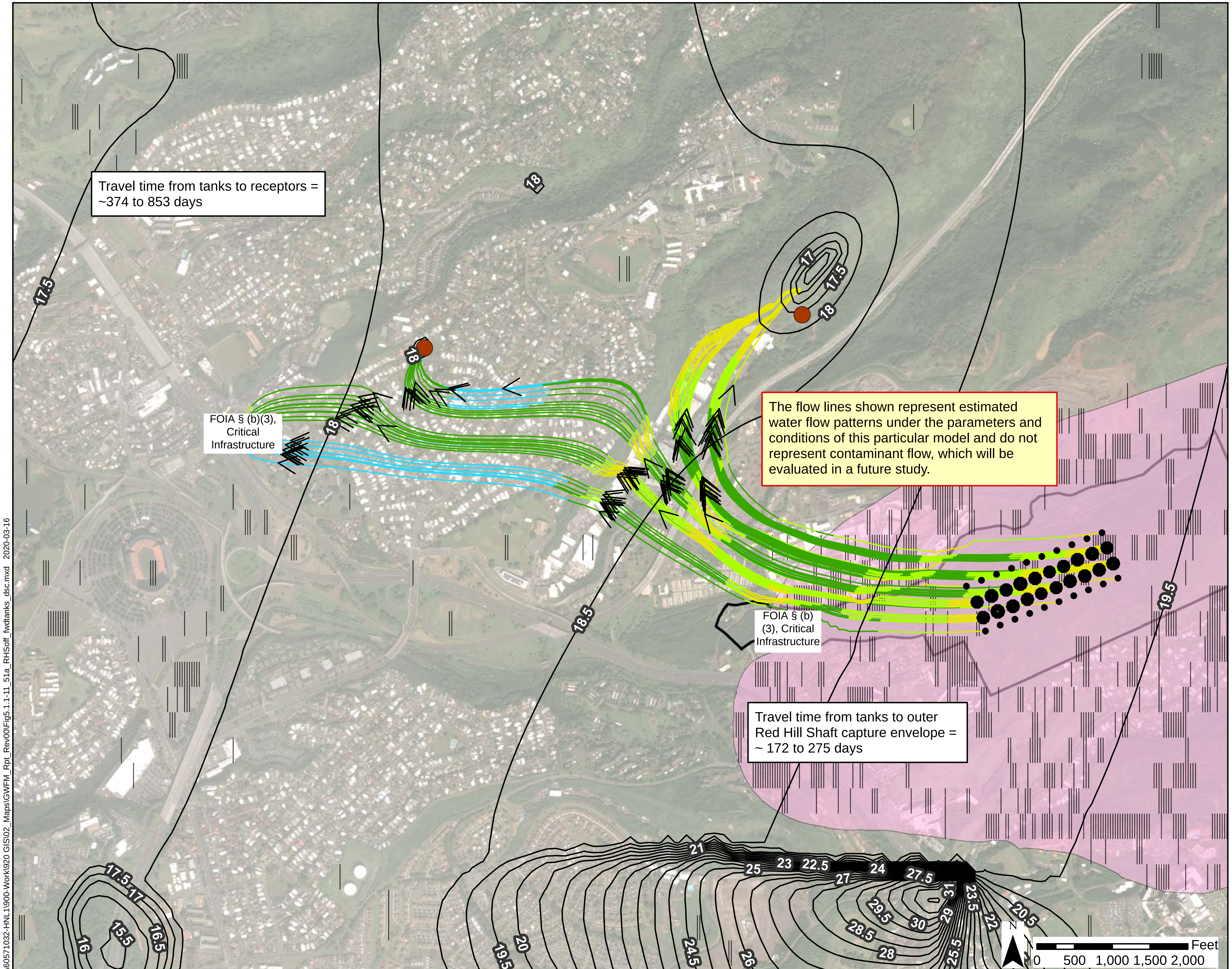
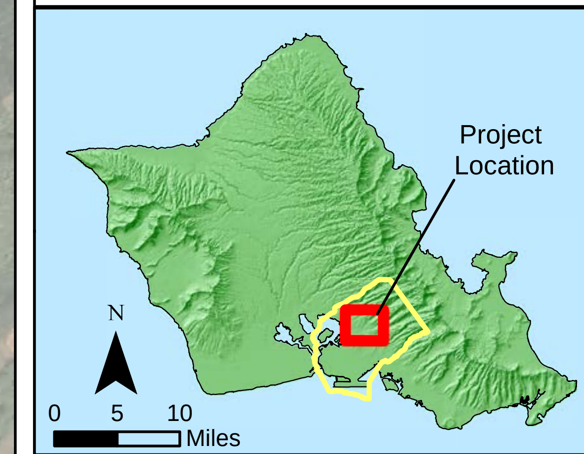


Location Map



Legend

Particle Tracks:

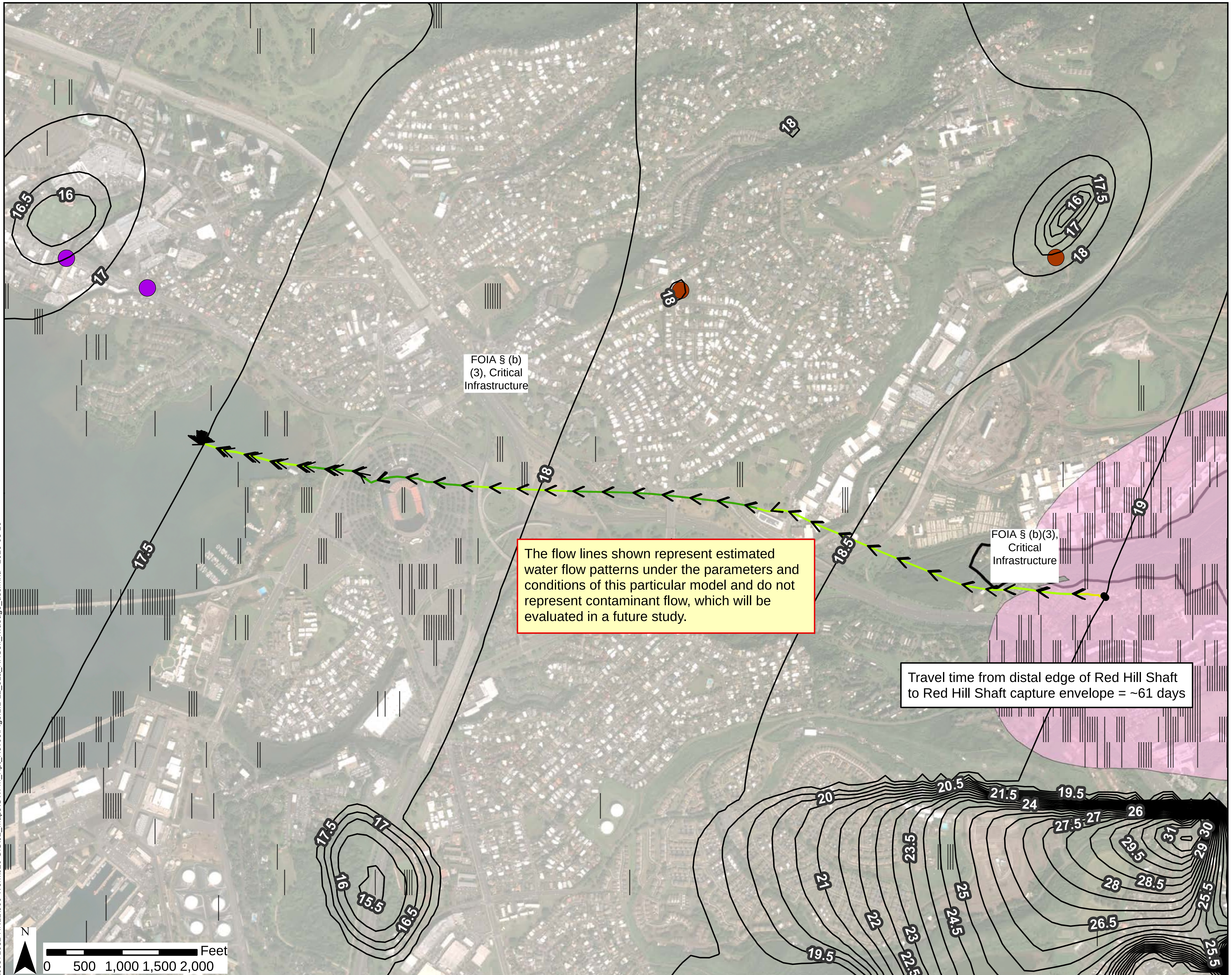
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Pumping Well
- Groundwater Contour (feet above mean sea level)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

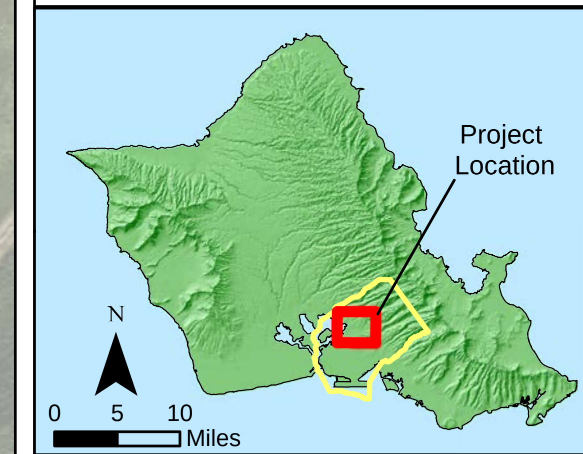
1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 1 year.

Figure 5.1.1-11
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

B:\60571032-HNL11900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.1.1-11_51a_RHSoff_fwdtanks_dsc.mxd 2020-03-16



Location Map



Legend

Particle Tracks:
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet above mean sea level)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 1 year.

Figure 5.1.1-12
Model #51a: Homogeneous Basalt with 3:1 Anisotropy – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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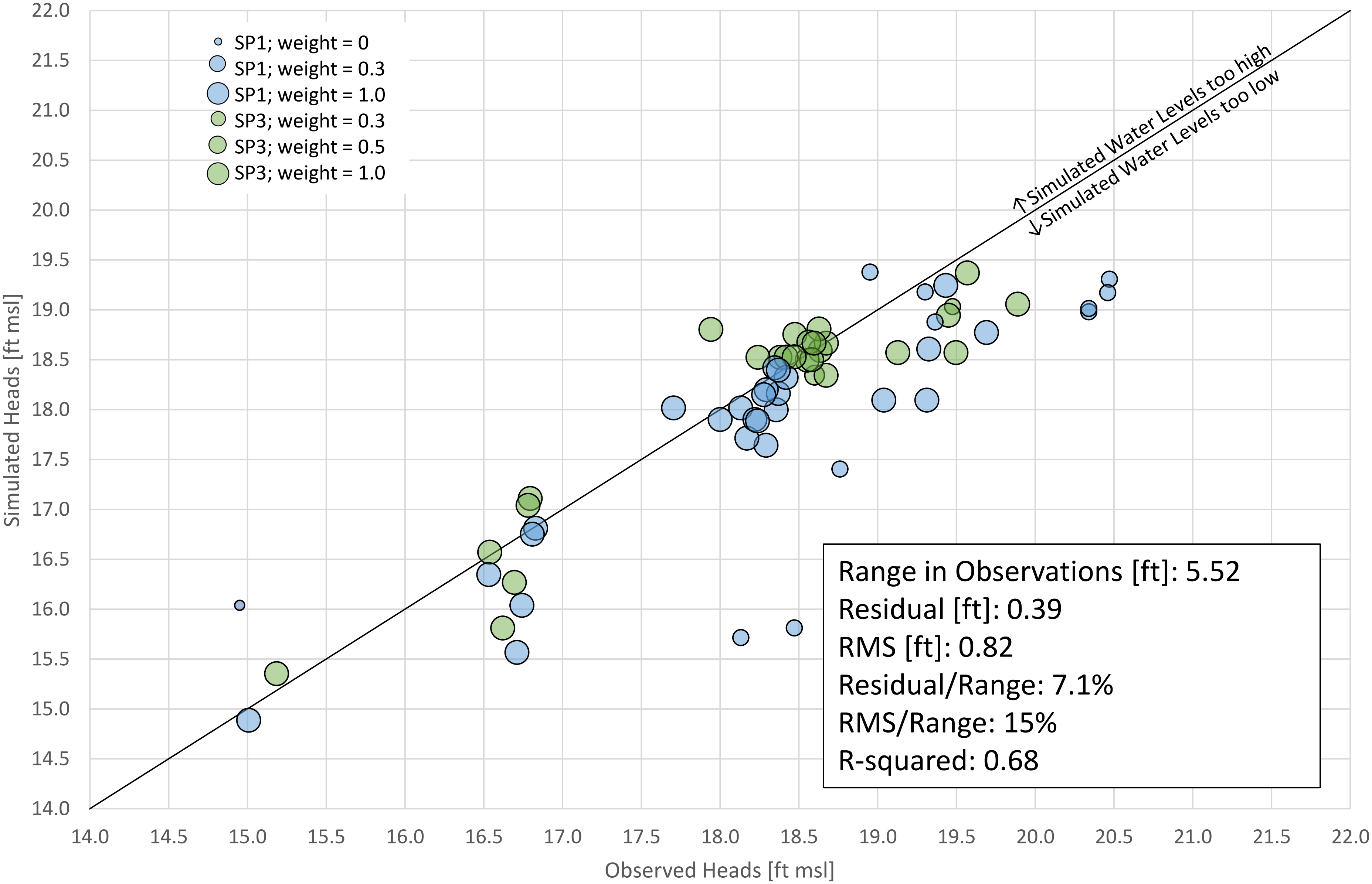
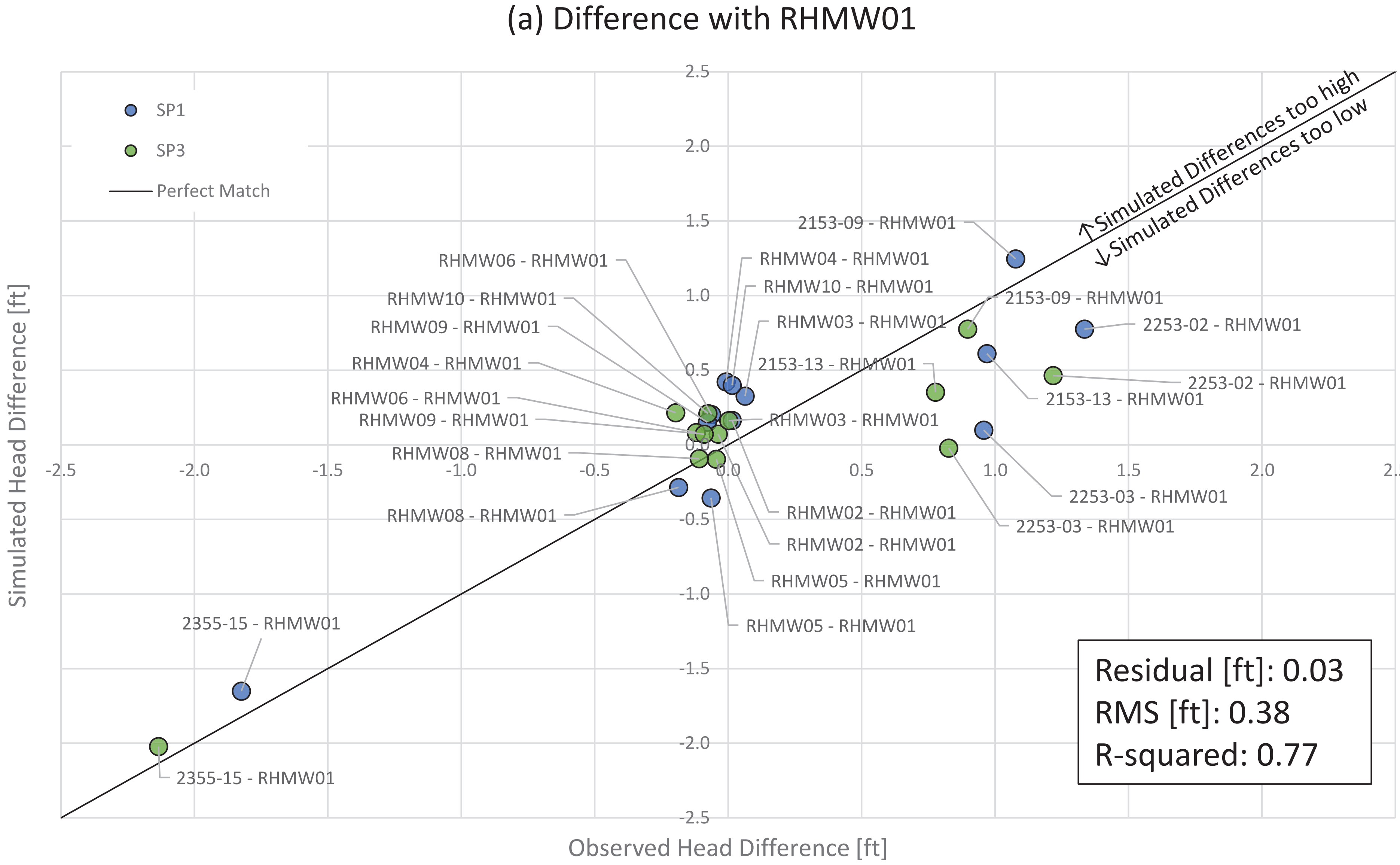


Figure 5.1.2-1
Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



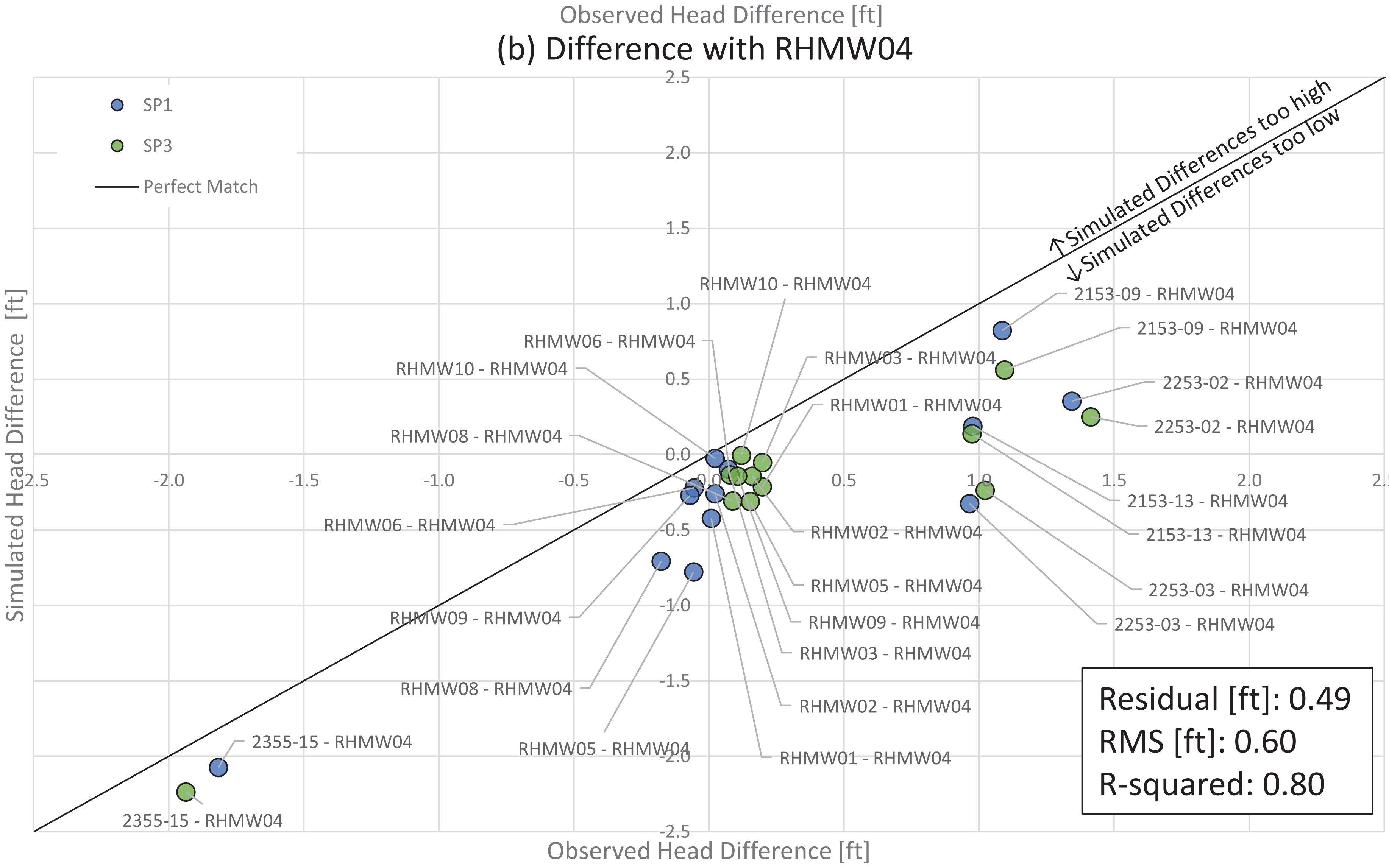


Figure 5.1.2-2
Model #51b: Homogeneous Basalt with 10:1 Anisotropy –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

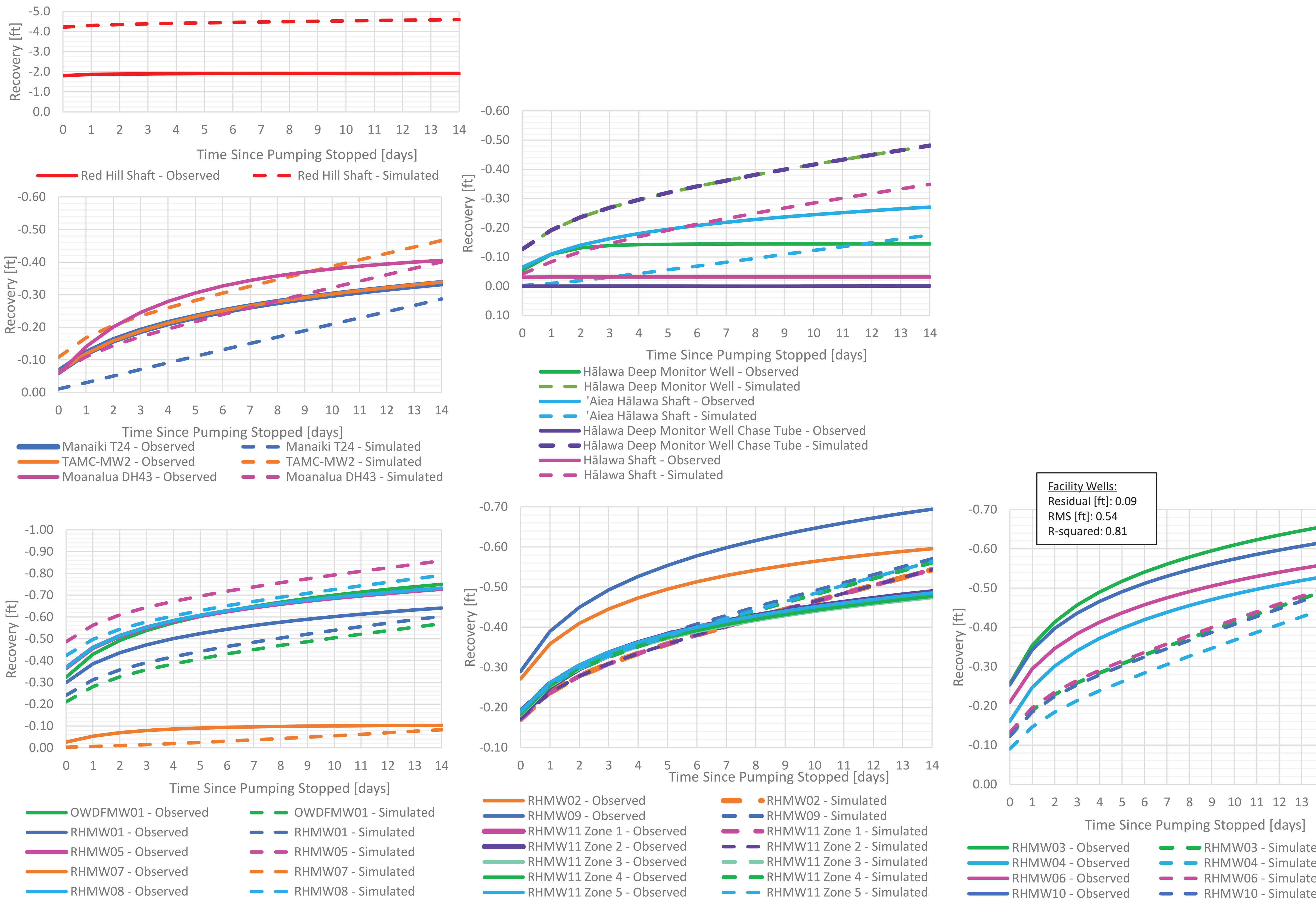


Figure 5.1.2-3
Model #51b: Homogeneous Basalt with 3:1 Anisotropy – Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

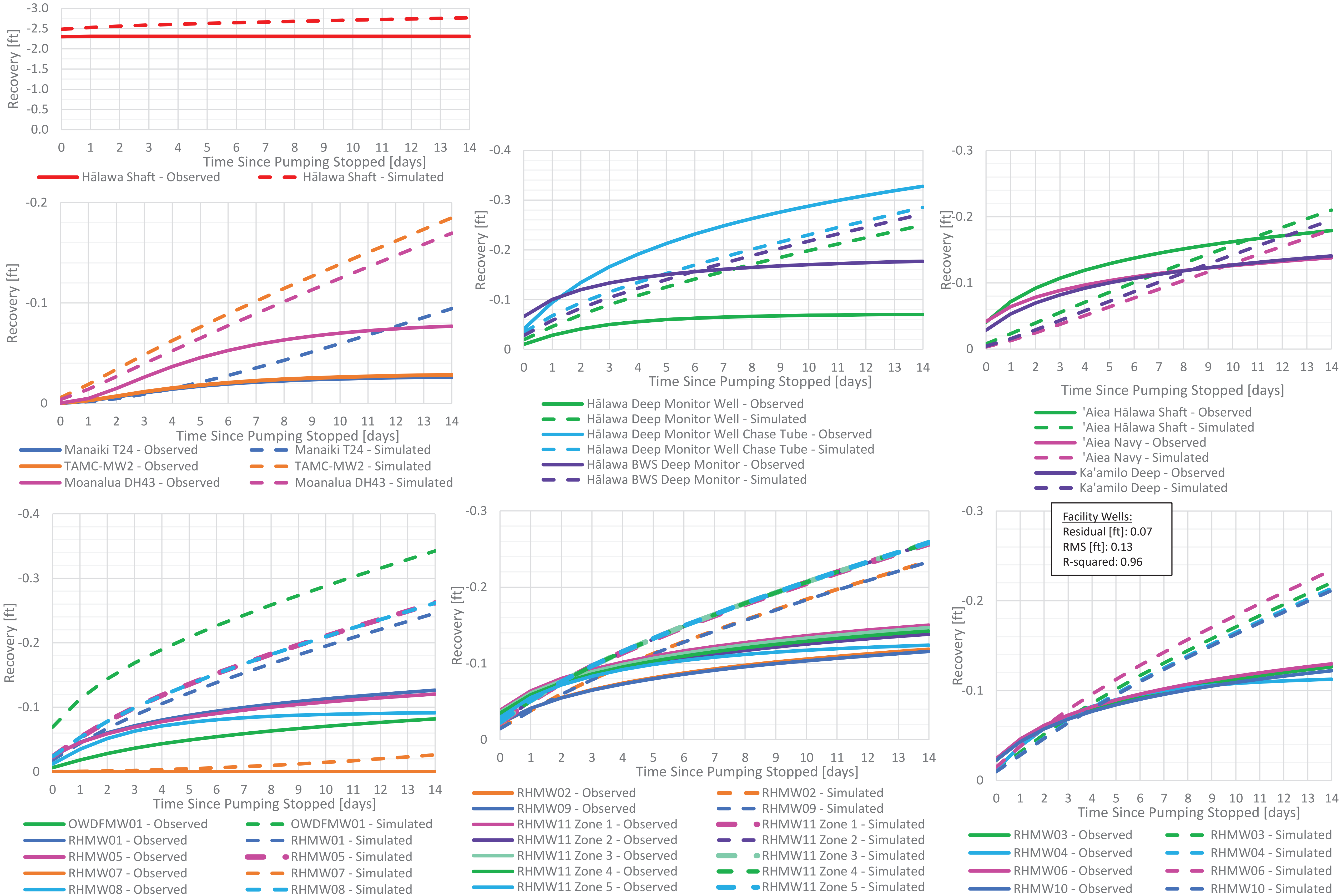
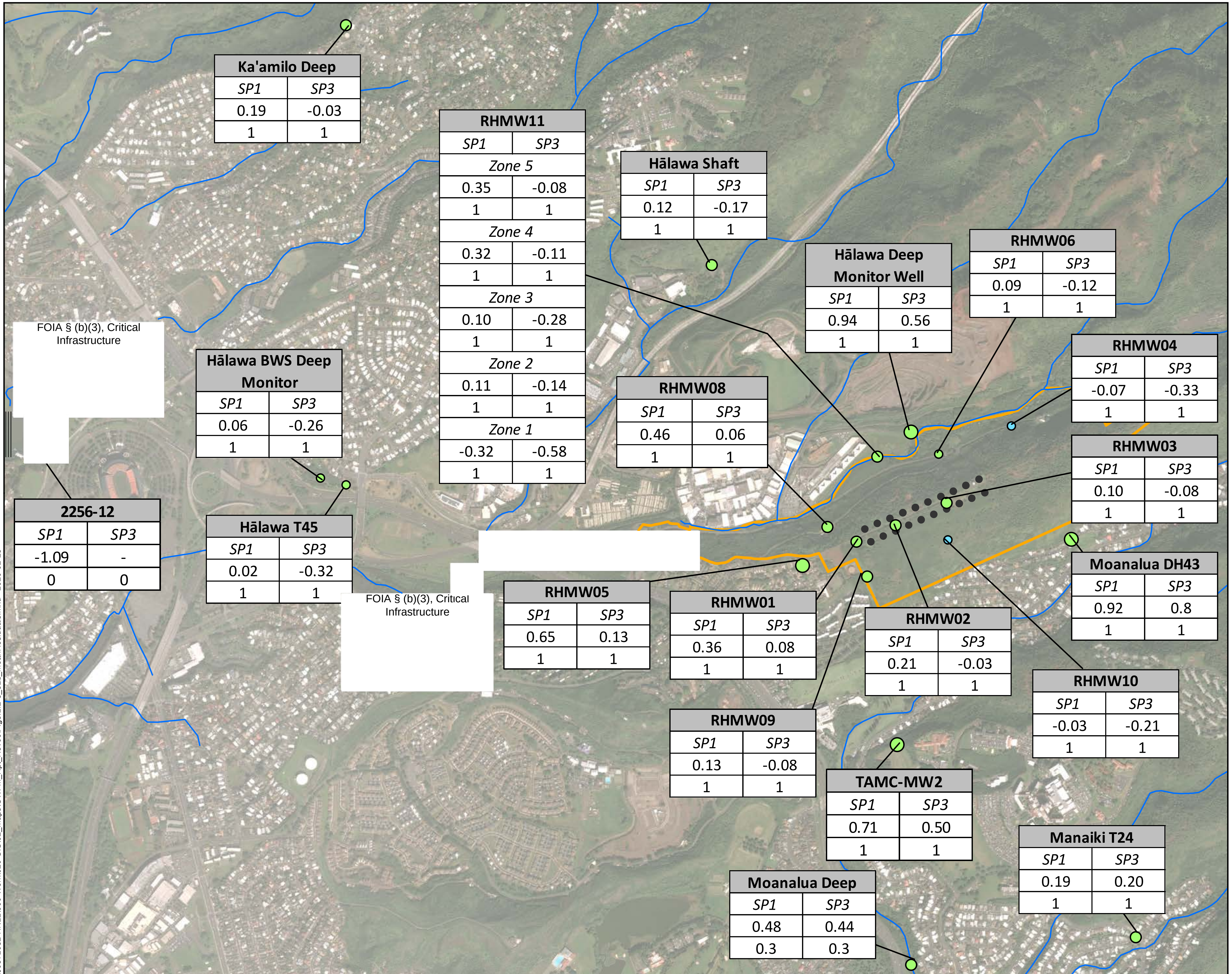


Figure 5.1.2-4
Model #51b: Homogeneous Basalt with 10:1 Anisotropy –
Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



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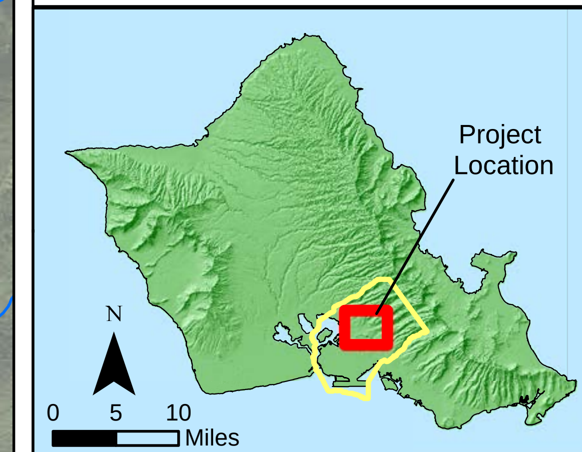
Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

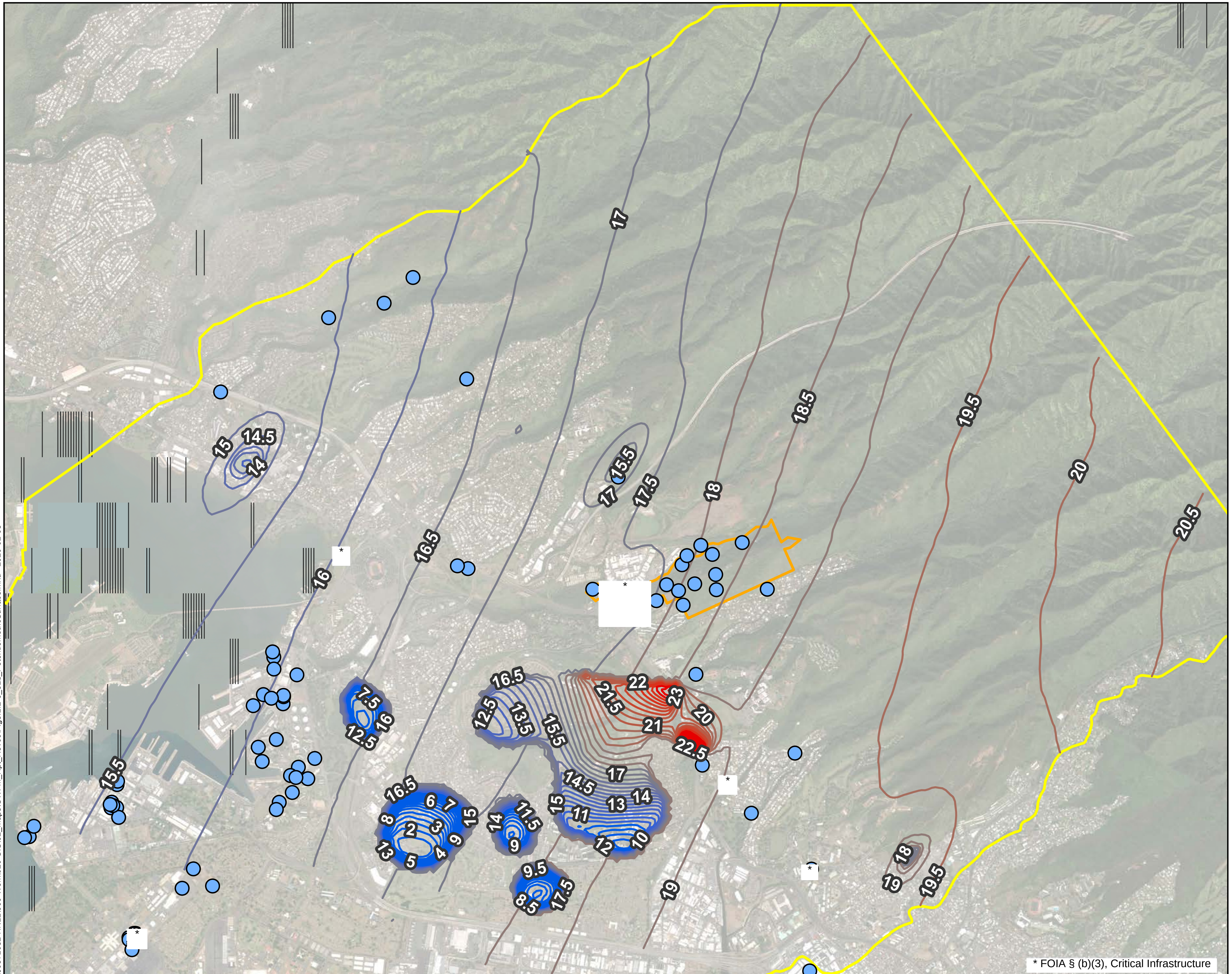
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

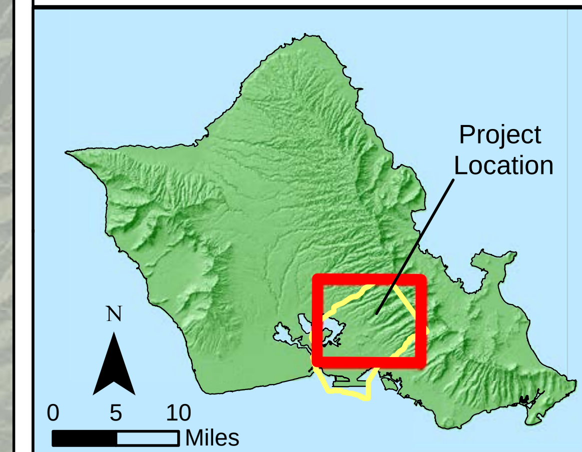
N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.1.2-5
Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.1.2-6
Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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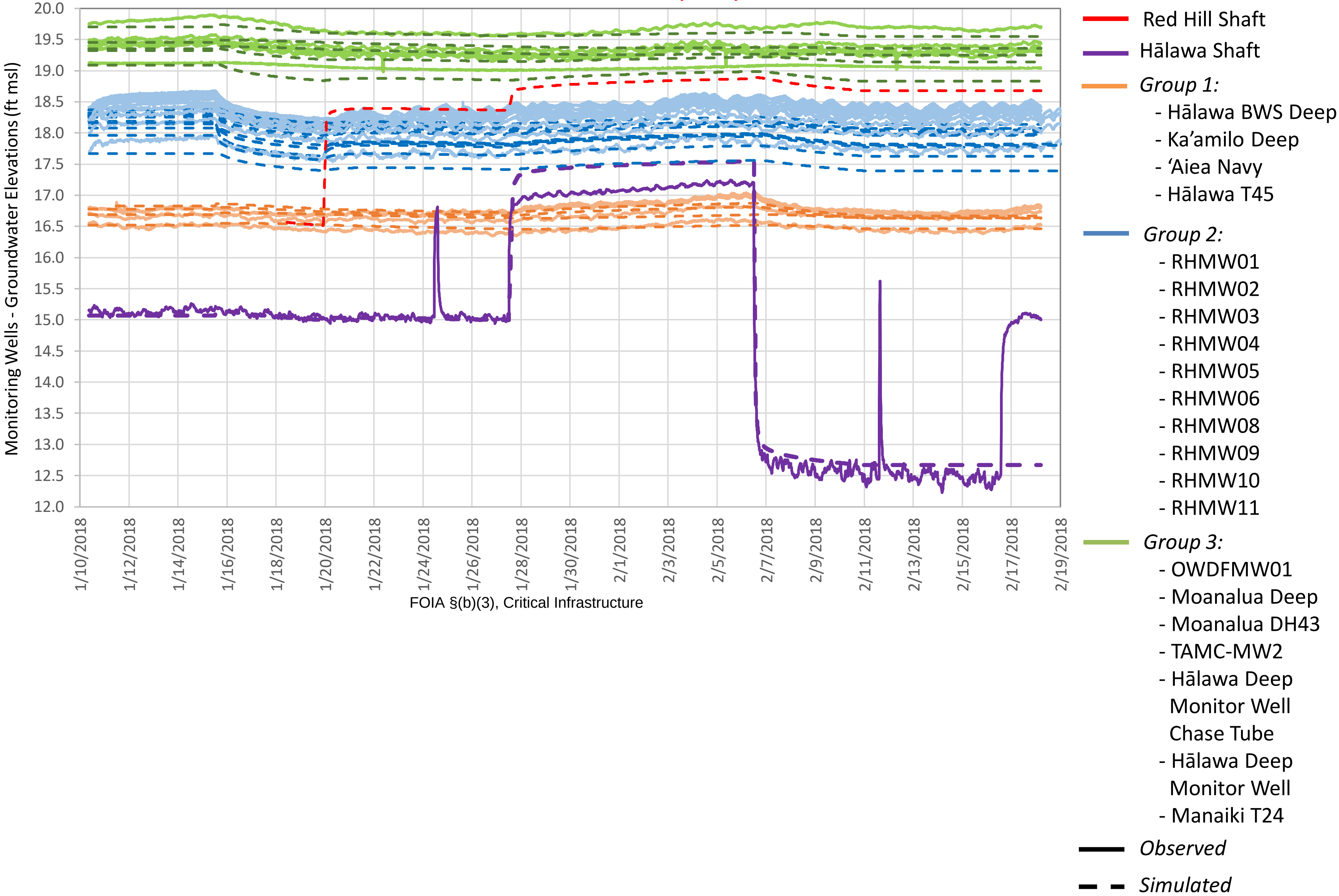


FOIA §(b)(3), Critical Infrastructure

Figure 5.1.2-7
Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

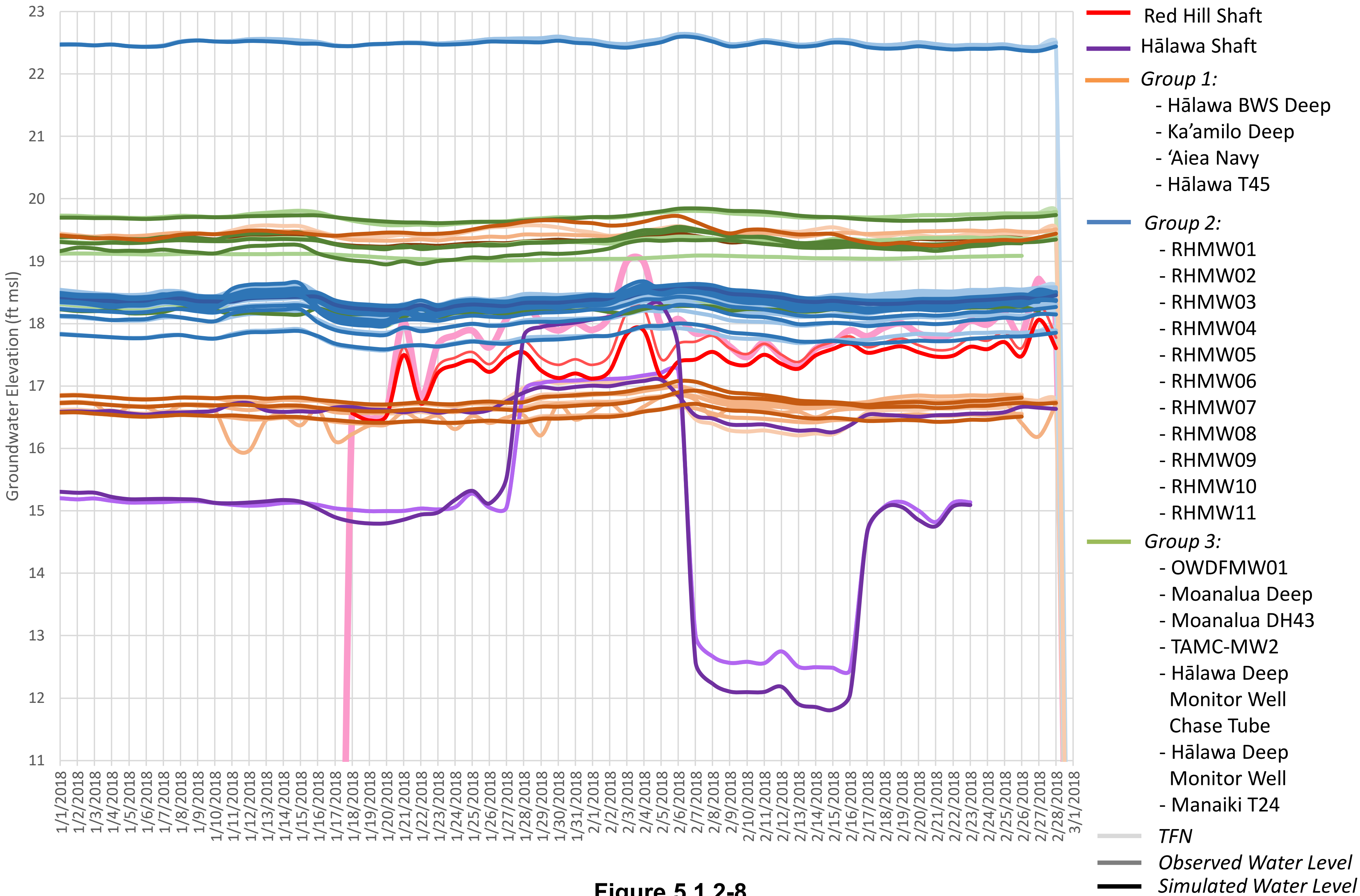


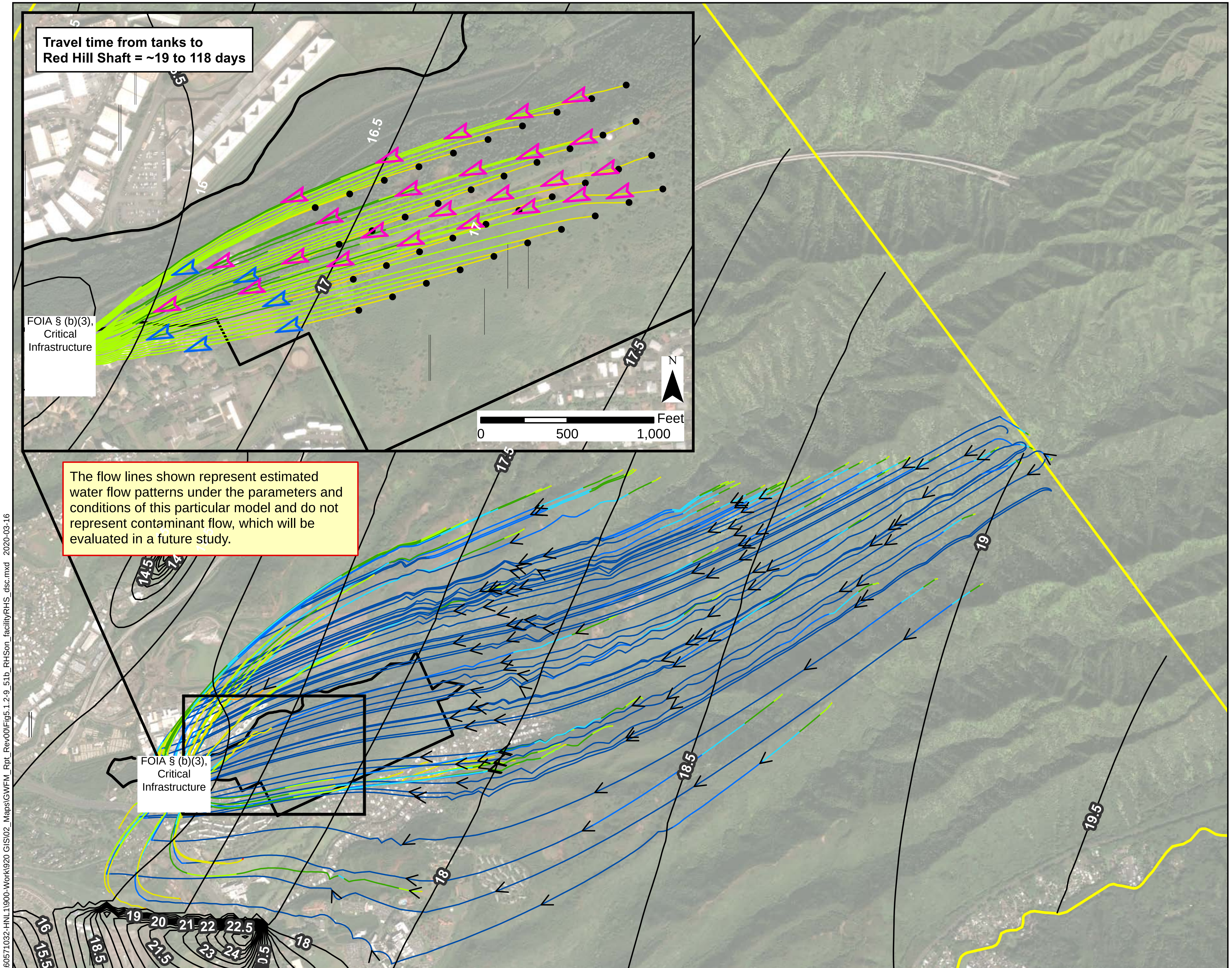
Figure 5.1.2-8

Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Verification Data Transfer Function-Noise Analysis

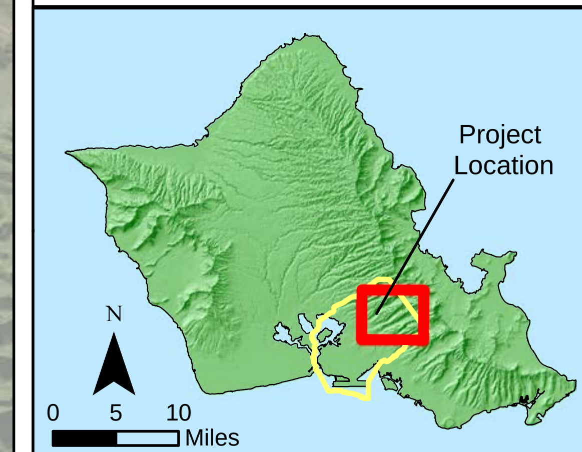
Groundwater Flow Model Report

Red Hill Bulk Fuel Storage Facility

JBPHH, O'ahu, Hawai'i



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet
- Red Hill Facility Boundary
- Groundwater Model

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 15 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.1.2-9
Model #51b: Homogeneous Basalt with 10:1 Anisotropy –
Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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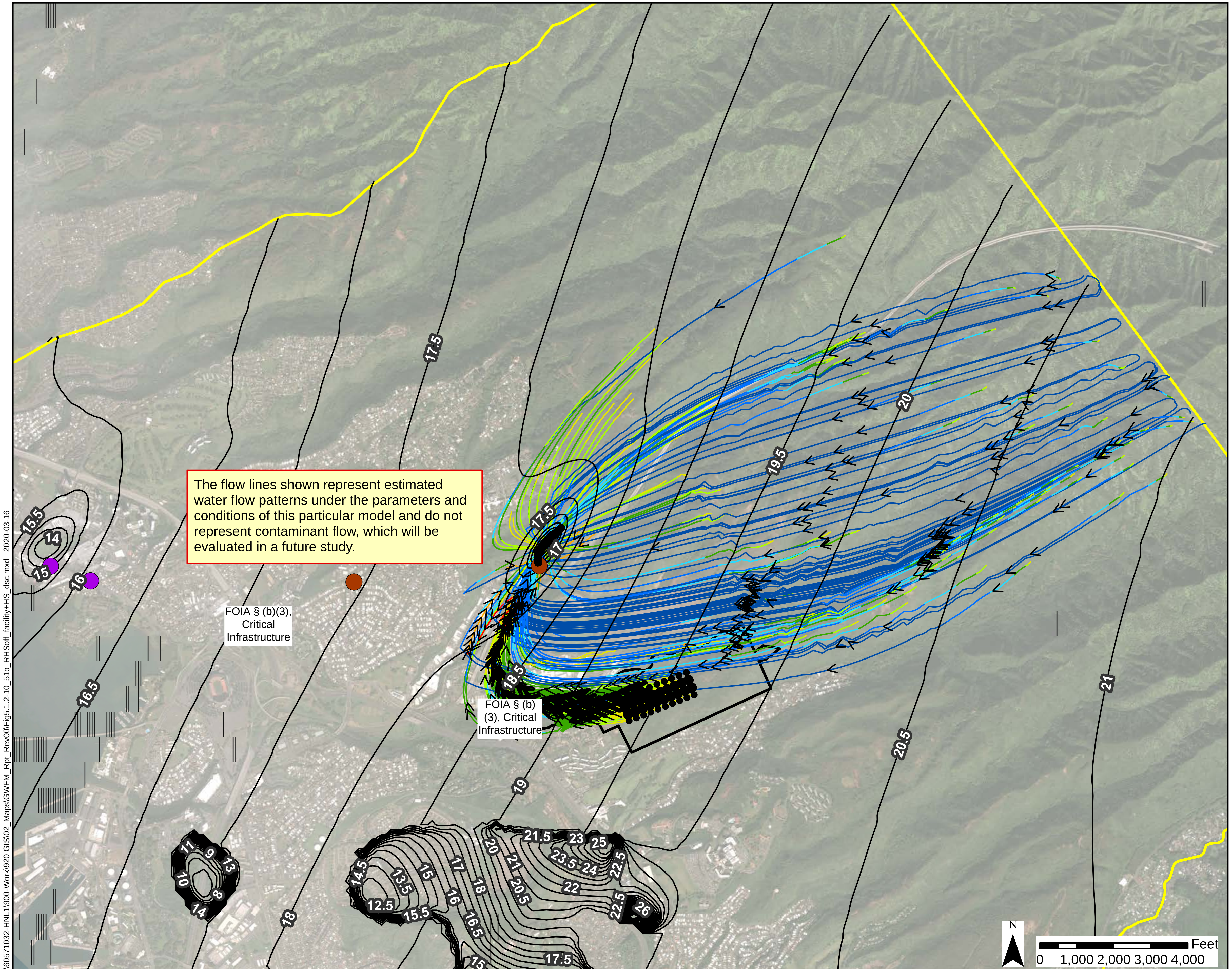

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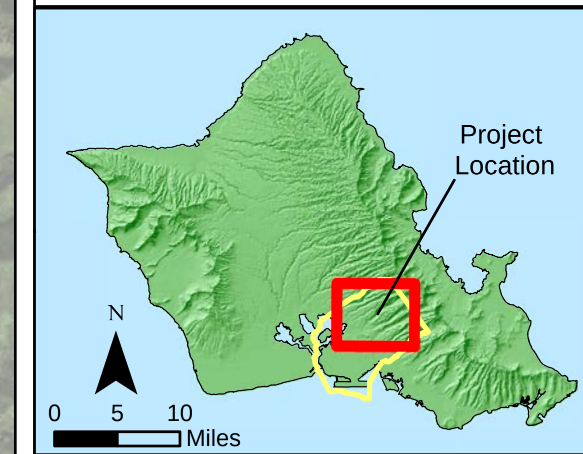
Location Map



Legend

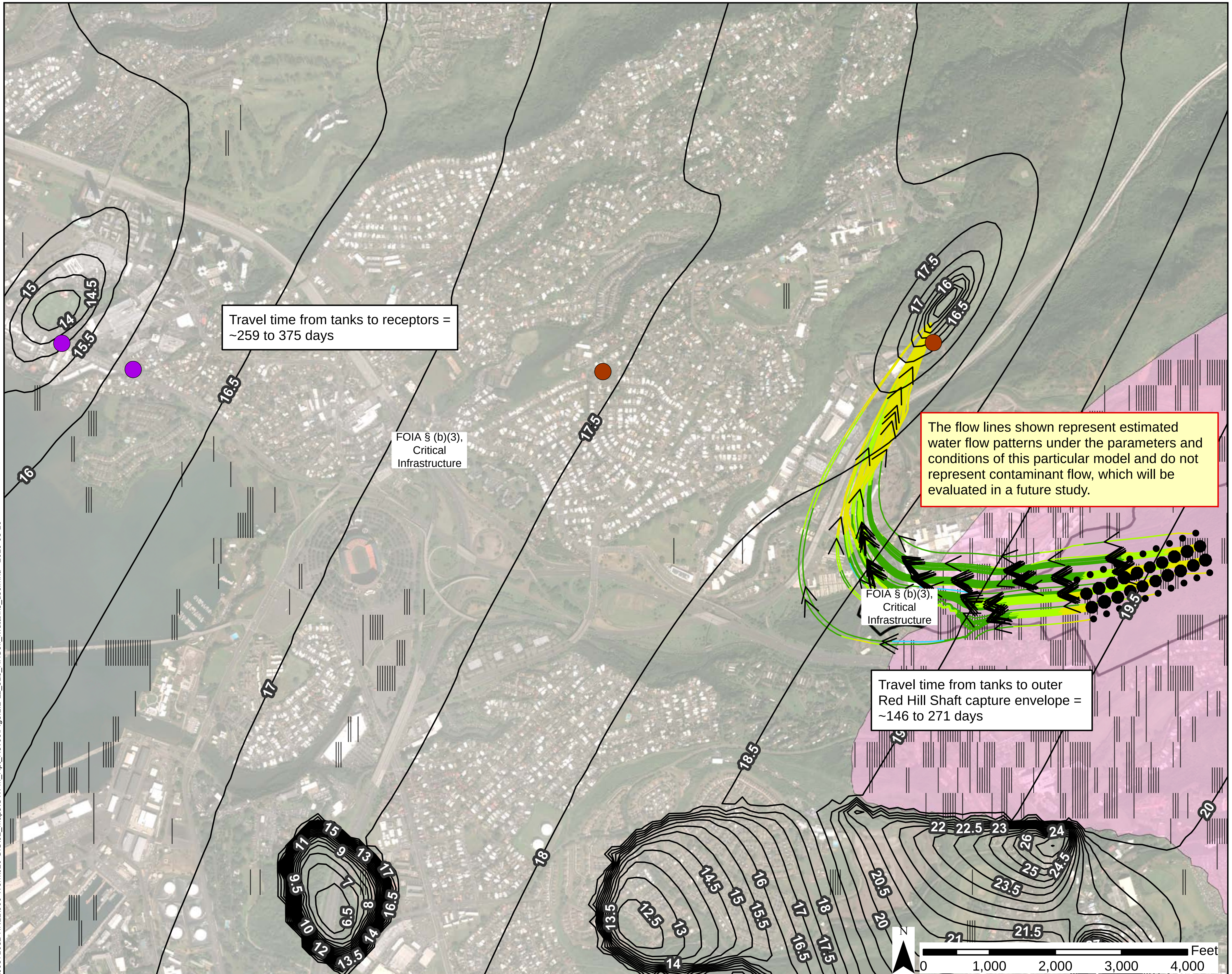
Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

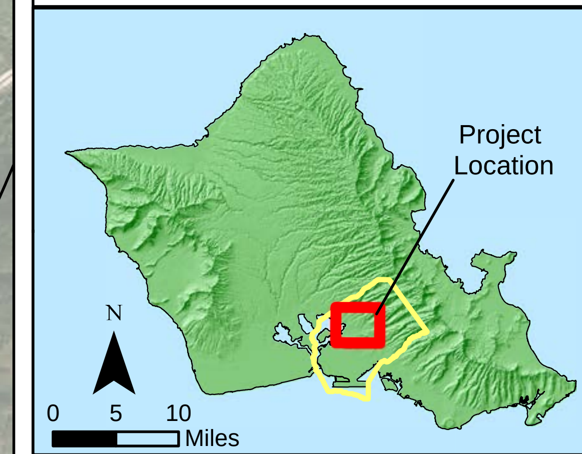
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.1.2-10
Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

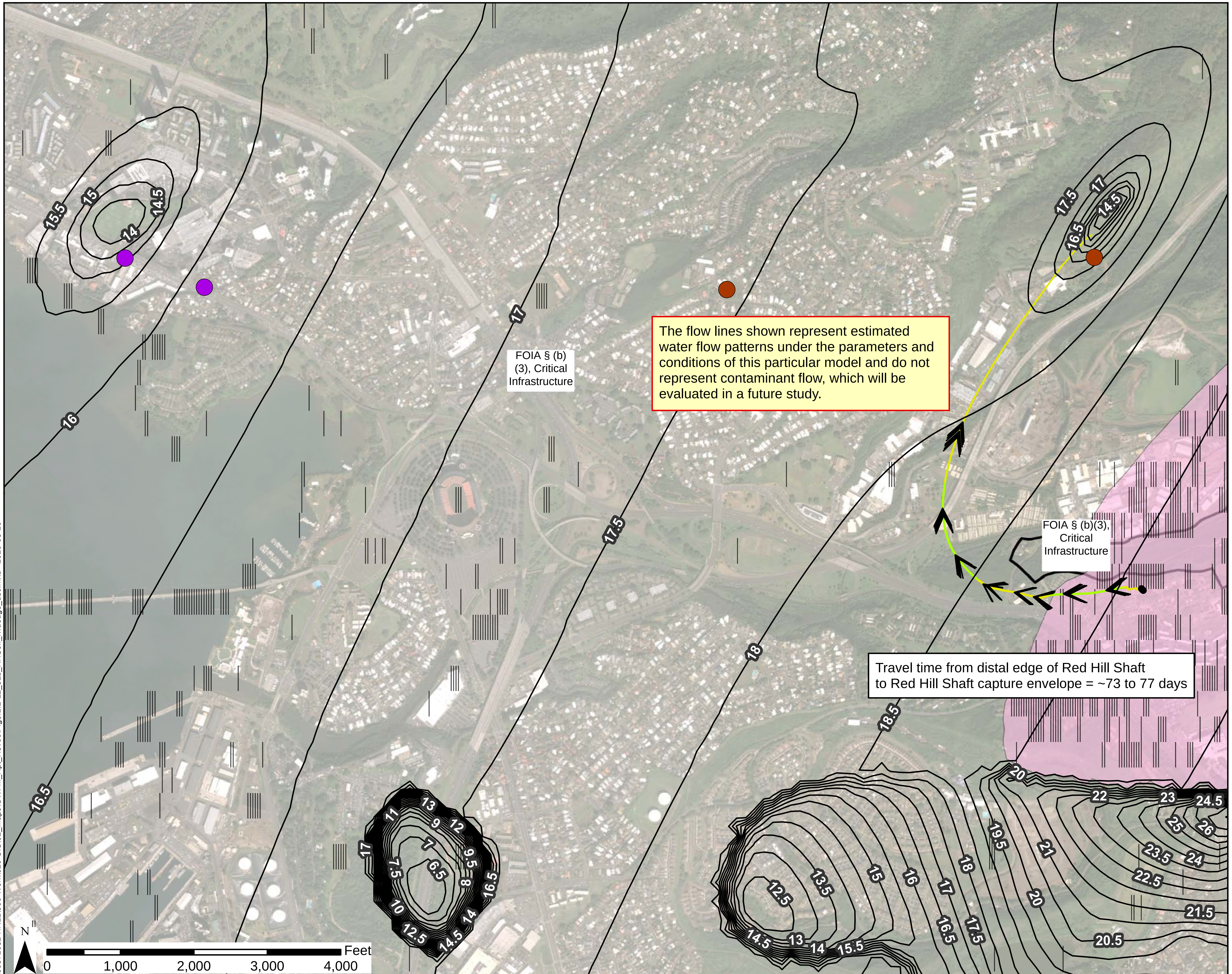
Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

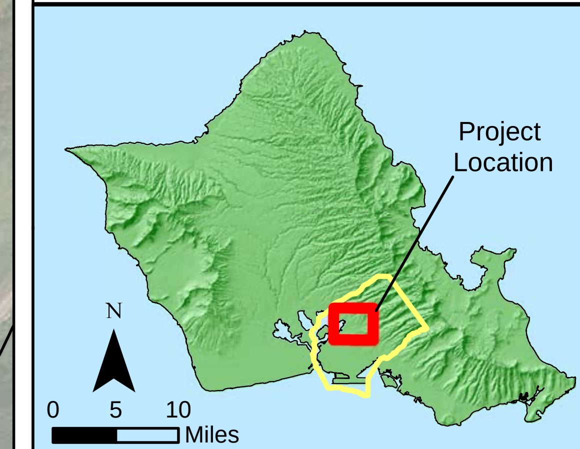
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.1.2-11
Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days.

Figure 5.1.2-12
Model #51b: Homogeneous Basalt with 10:1 Anisotropy – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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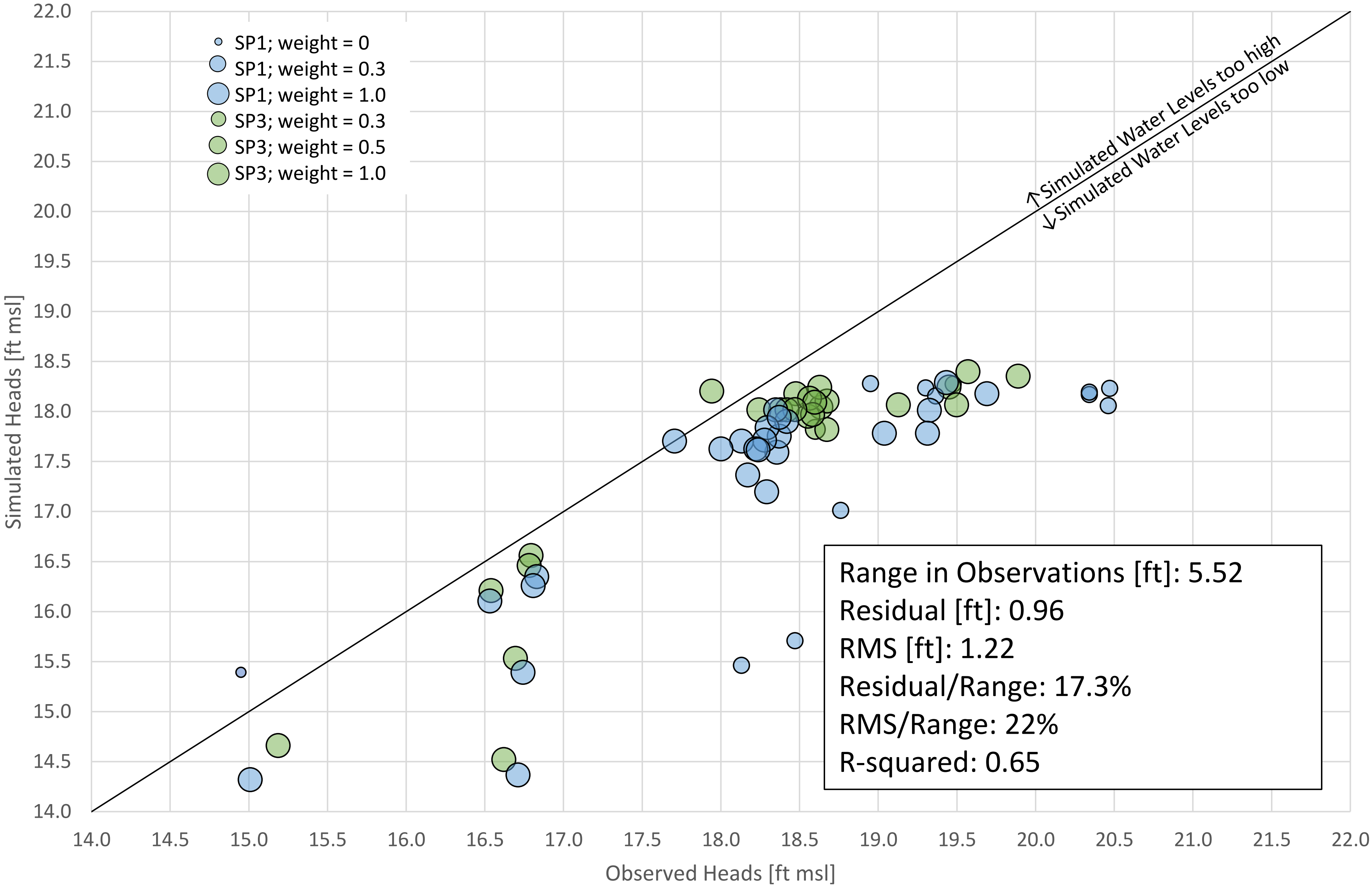


Figure 5.1.3-1
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

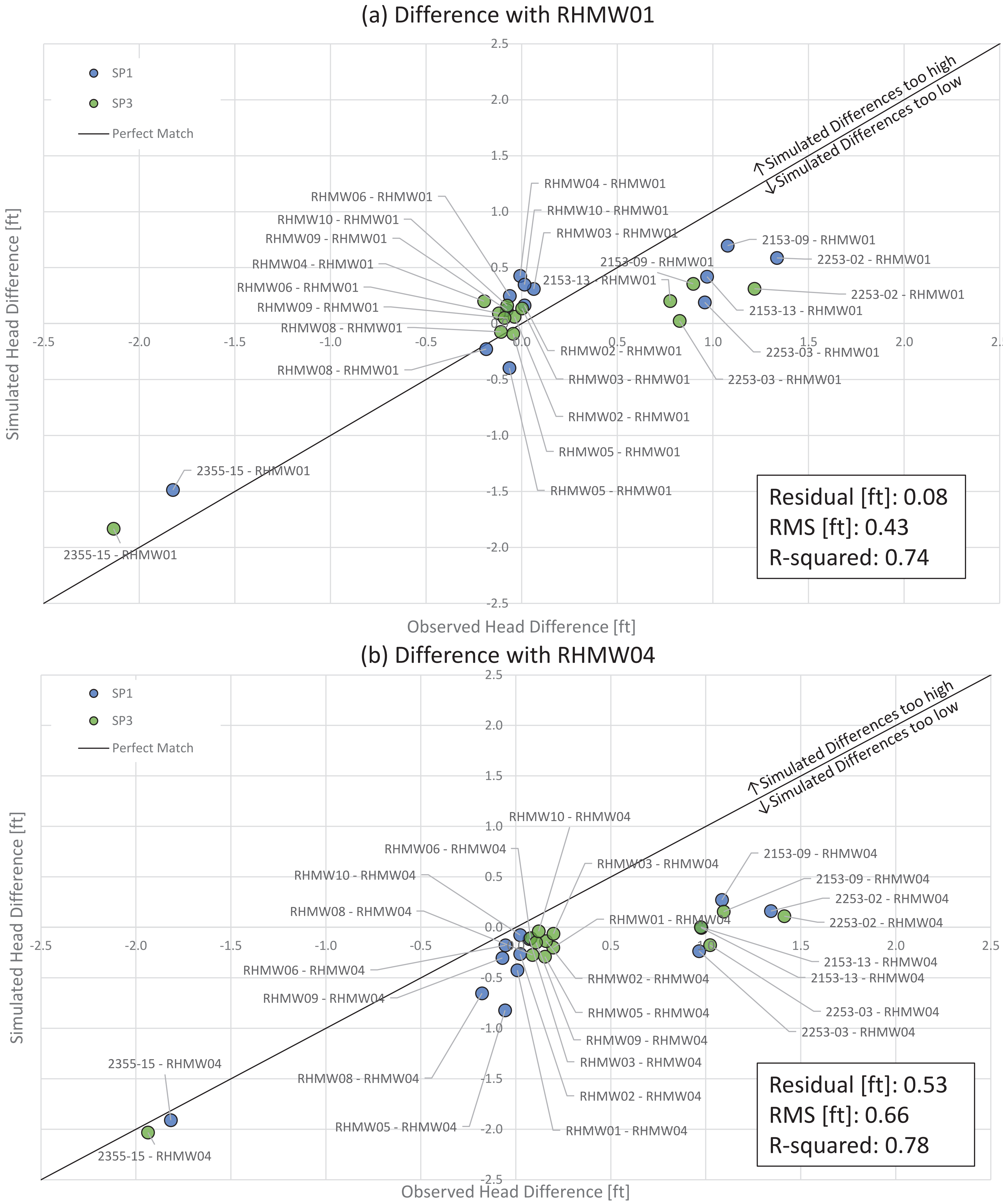


Figure 5.1.3-2
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

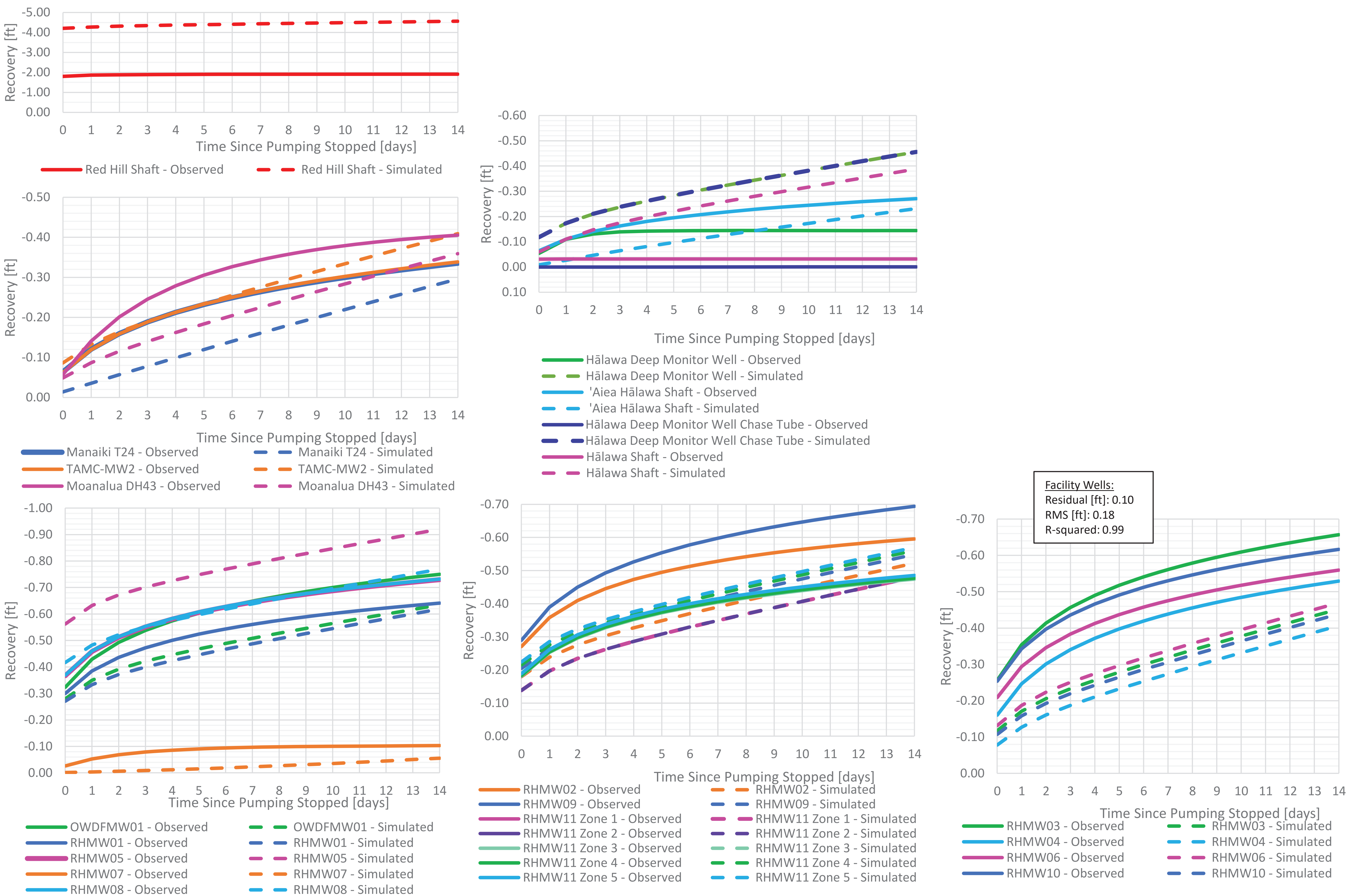


Figure 5.1.3-3
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

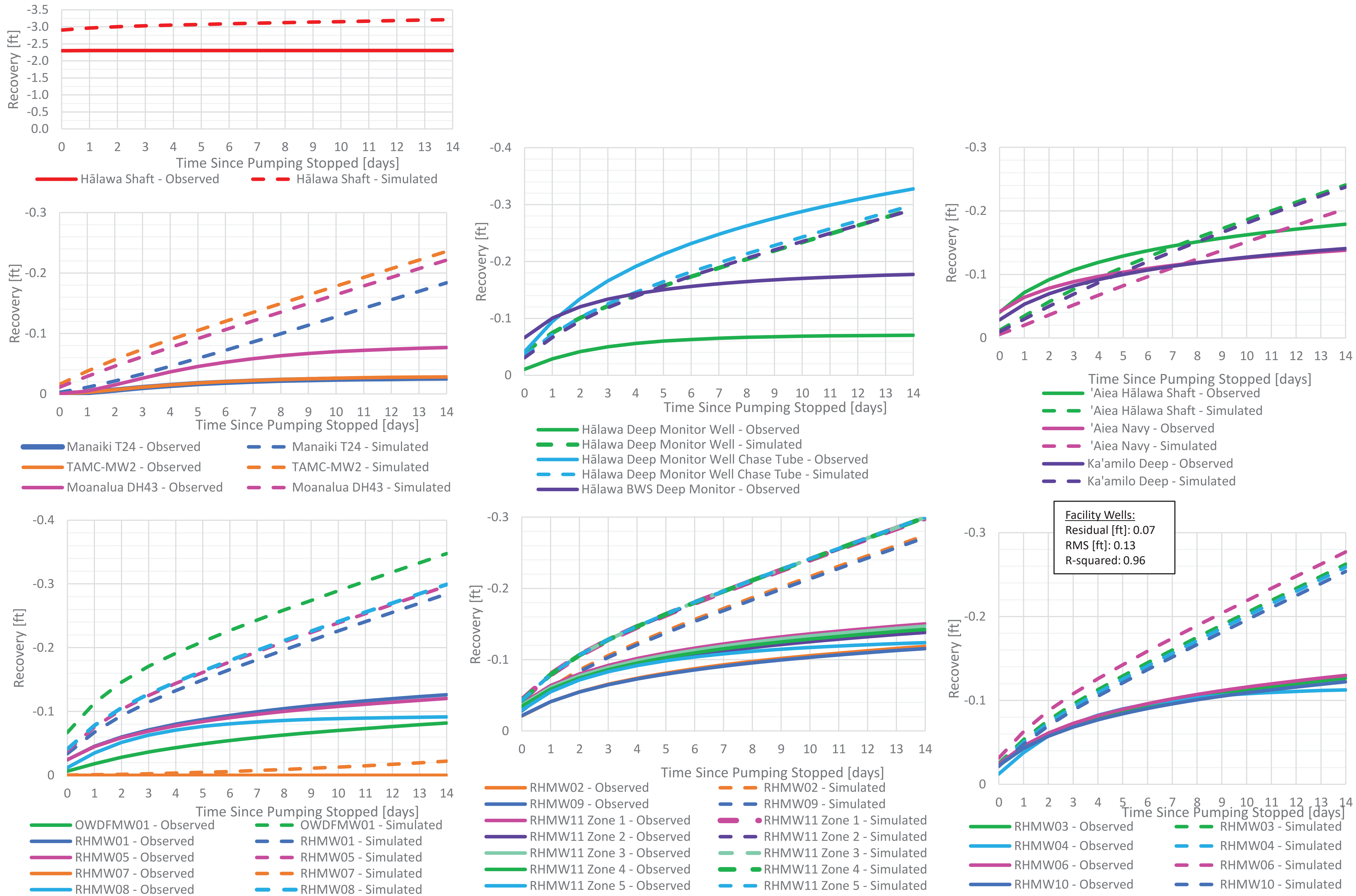
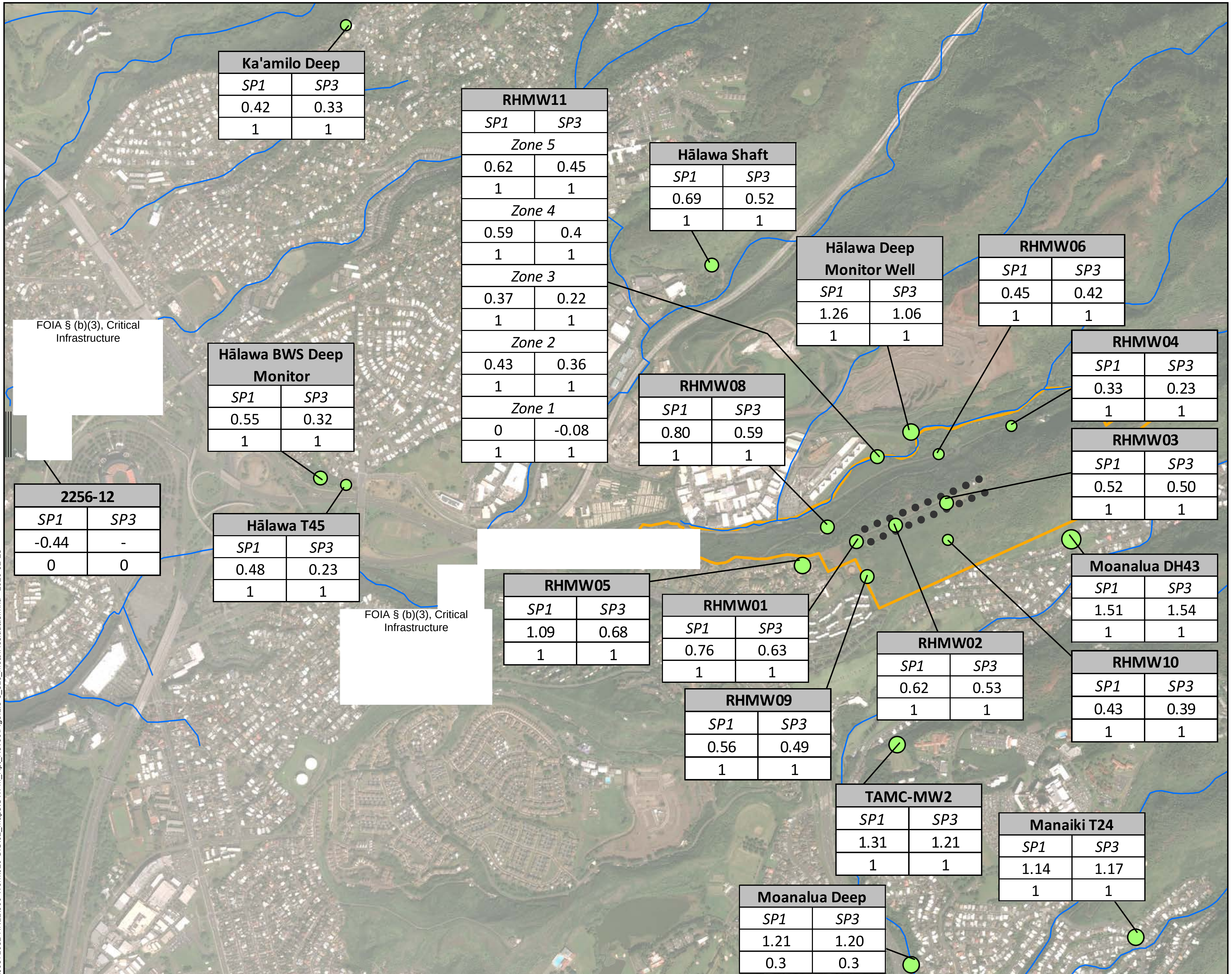
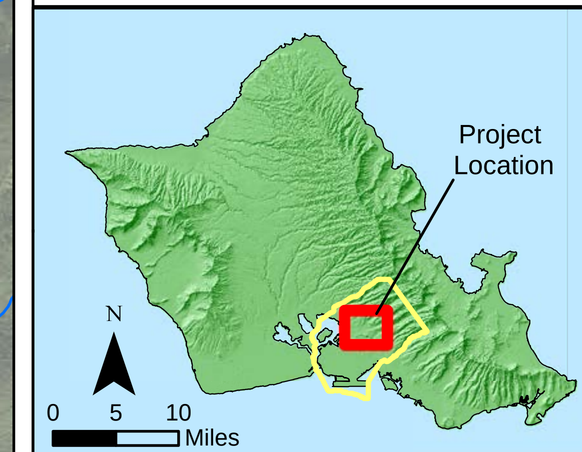


Figure 5.1.3-4
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

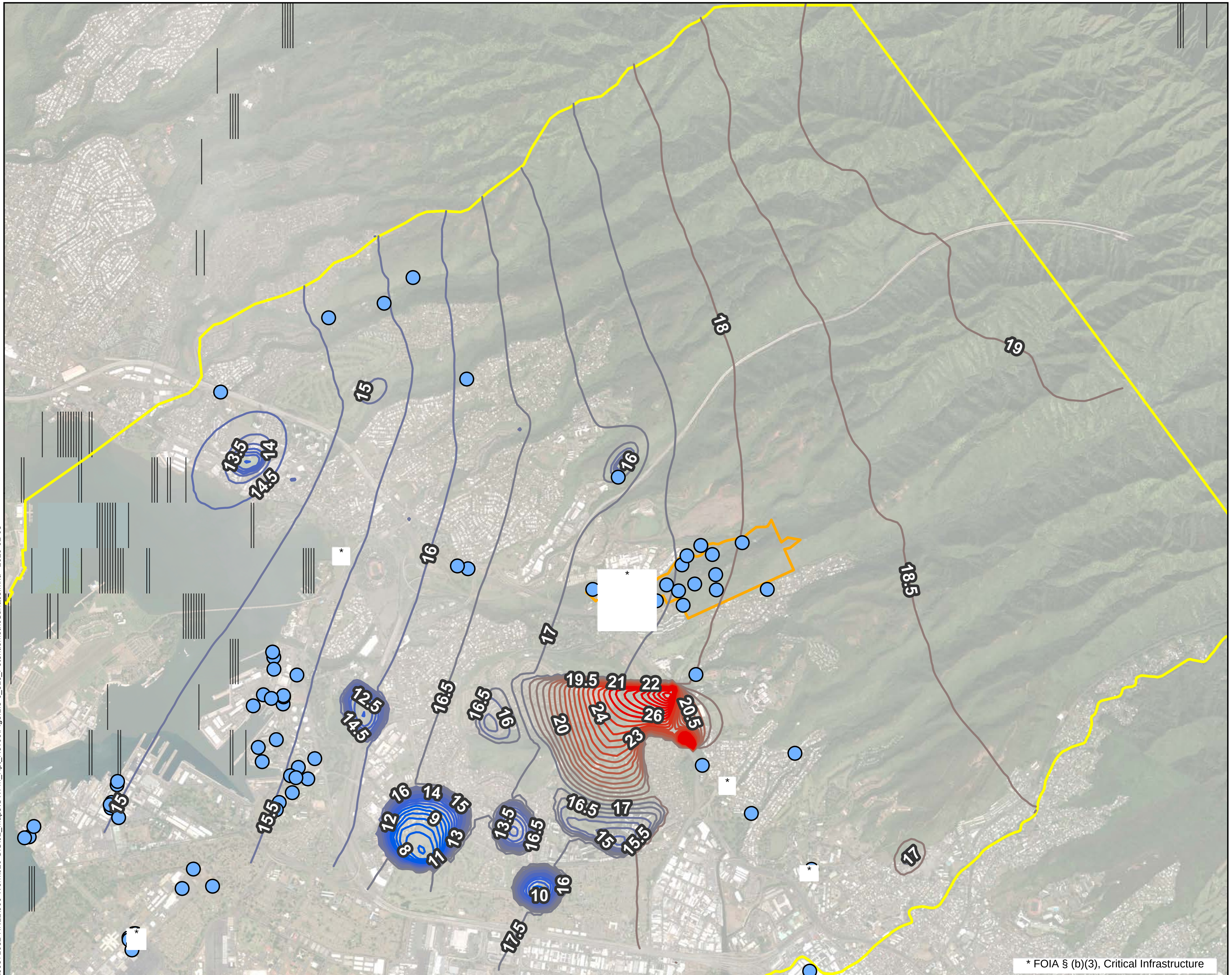
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

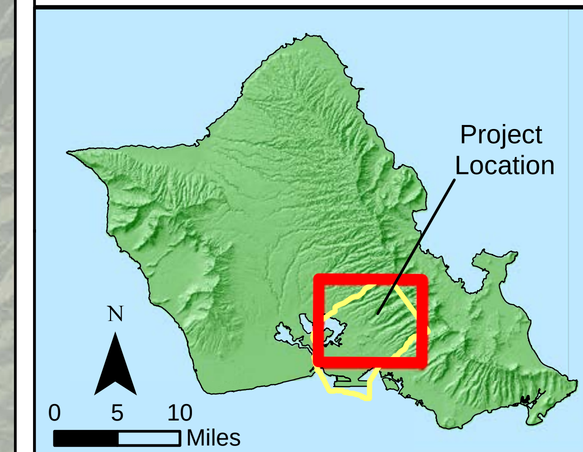
N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.1.3-5
Model #51c: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.1.3-6
Model #51c: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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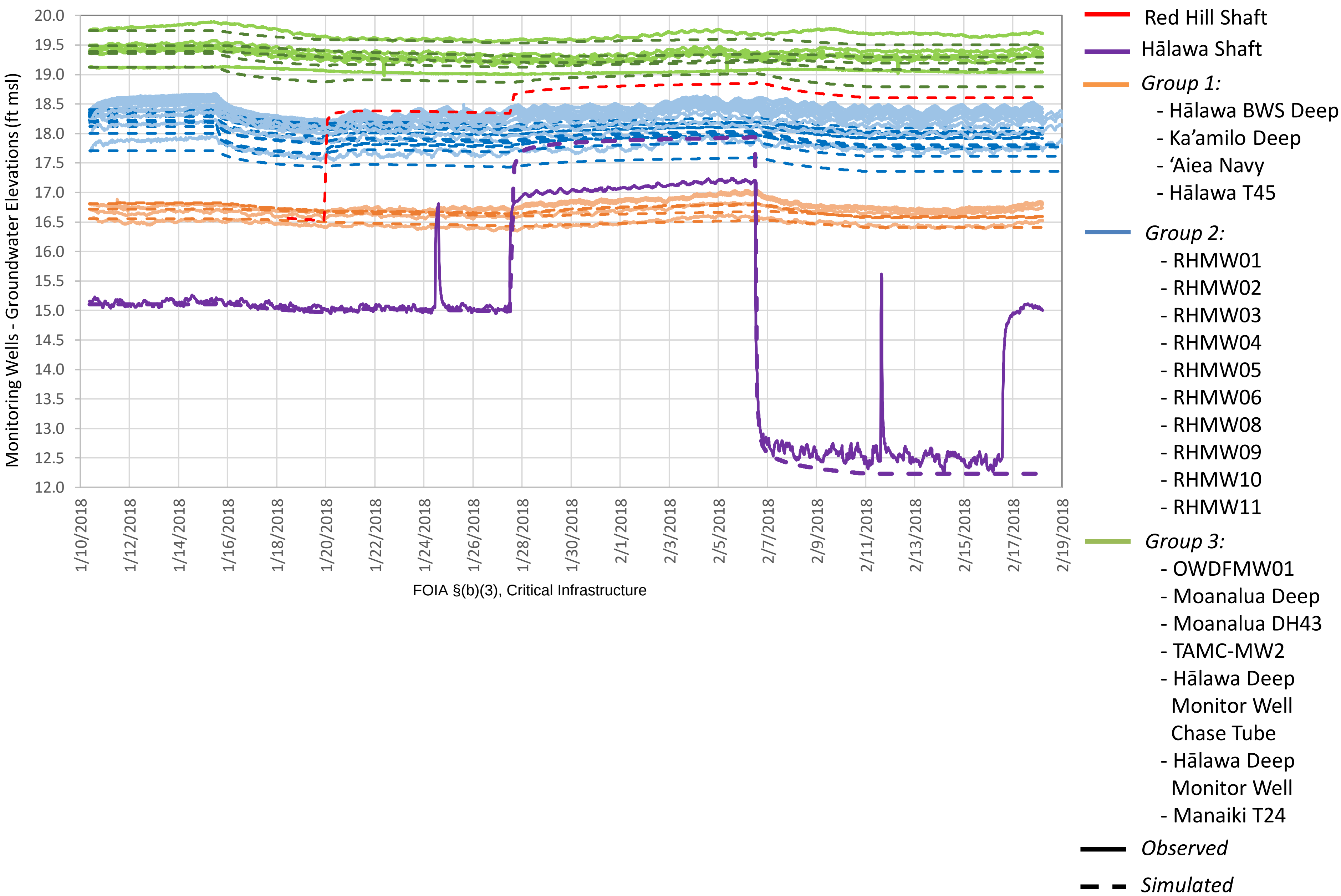


FOIA §(b)(3), Critical Infrastructure

Figure 5.1.3-7
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

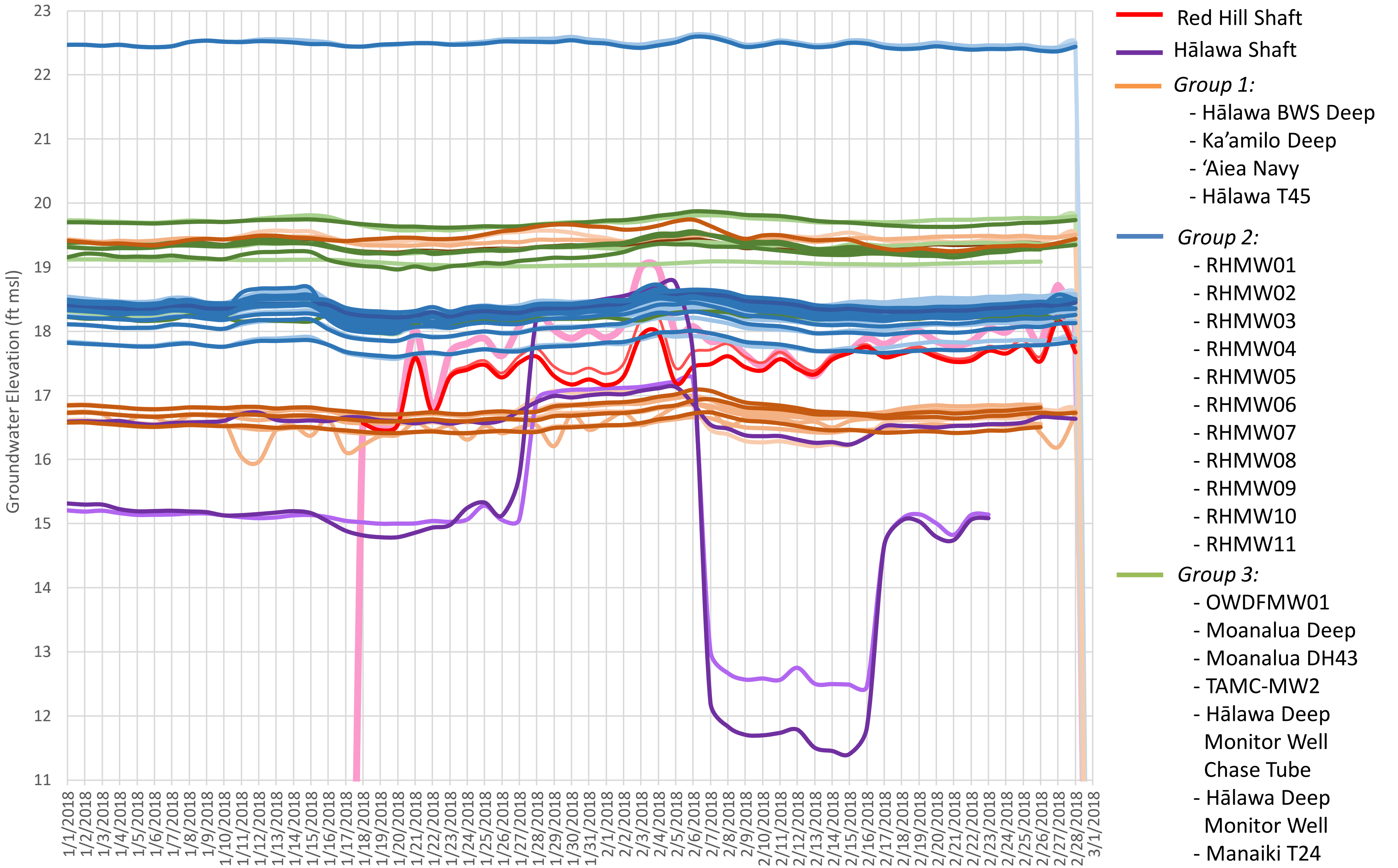
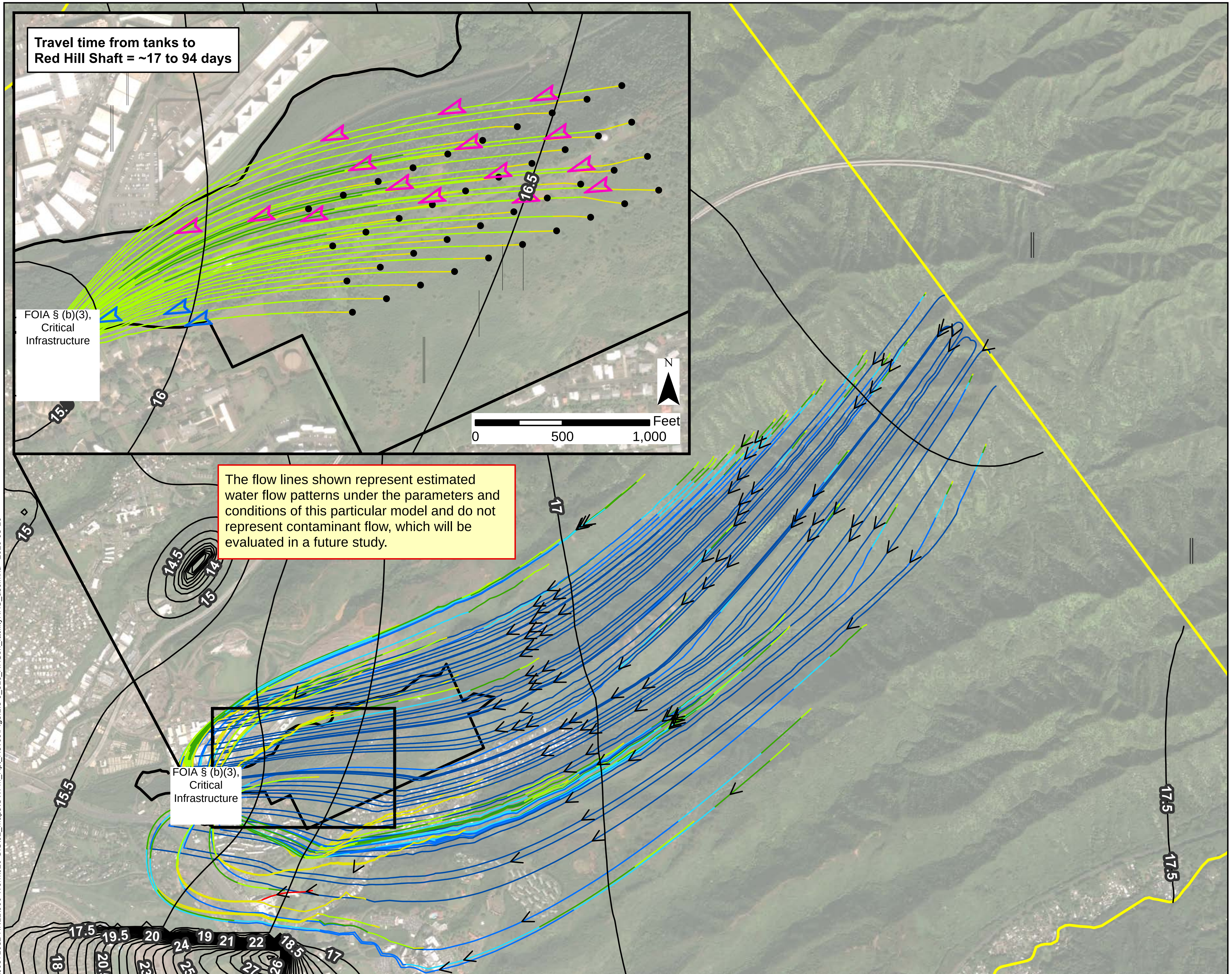
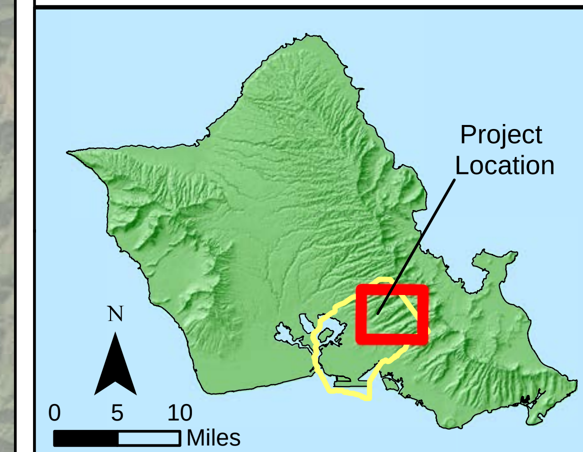


Figure 5.1.3-8
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet
- Red Hill Facility Boundary
- Groundwater Model

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 20 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.1.3-9
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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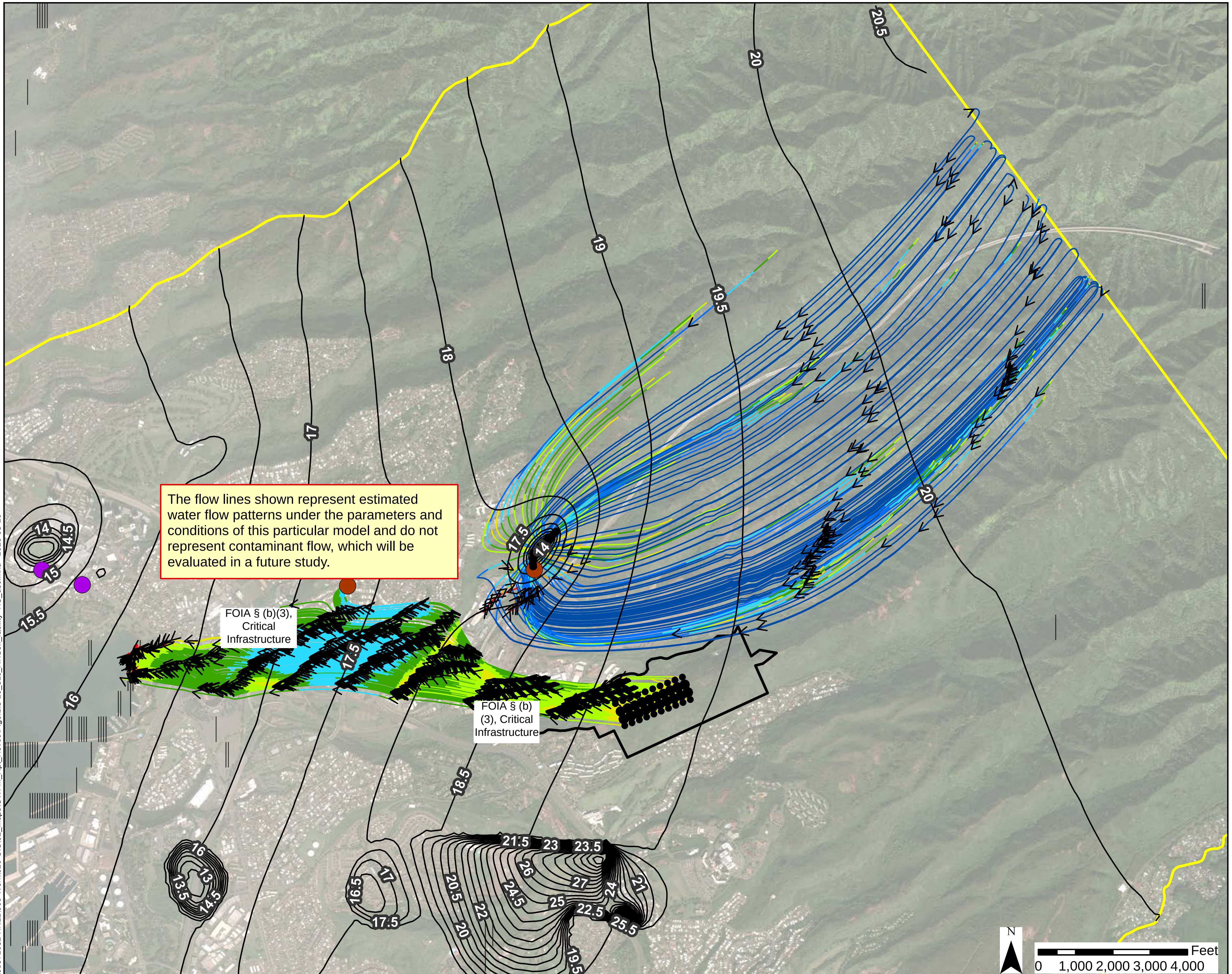
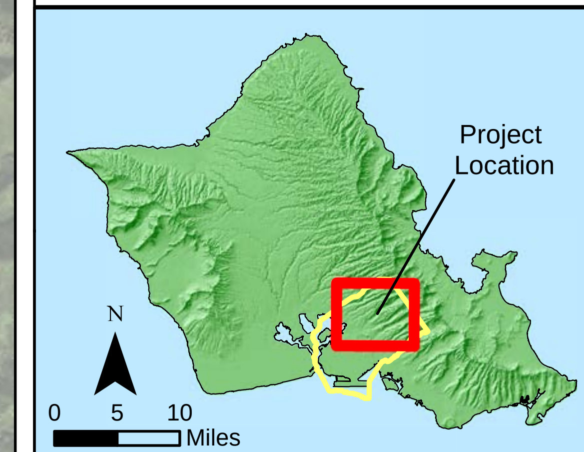


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.1.3-10
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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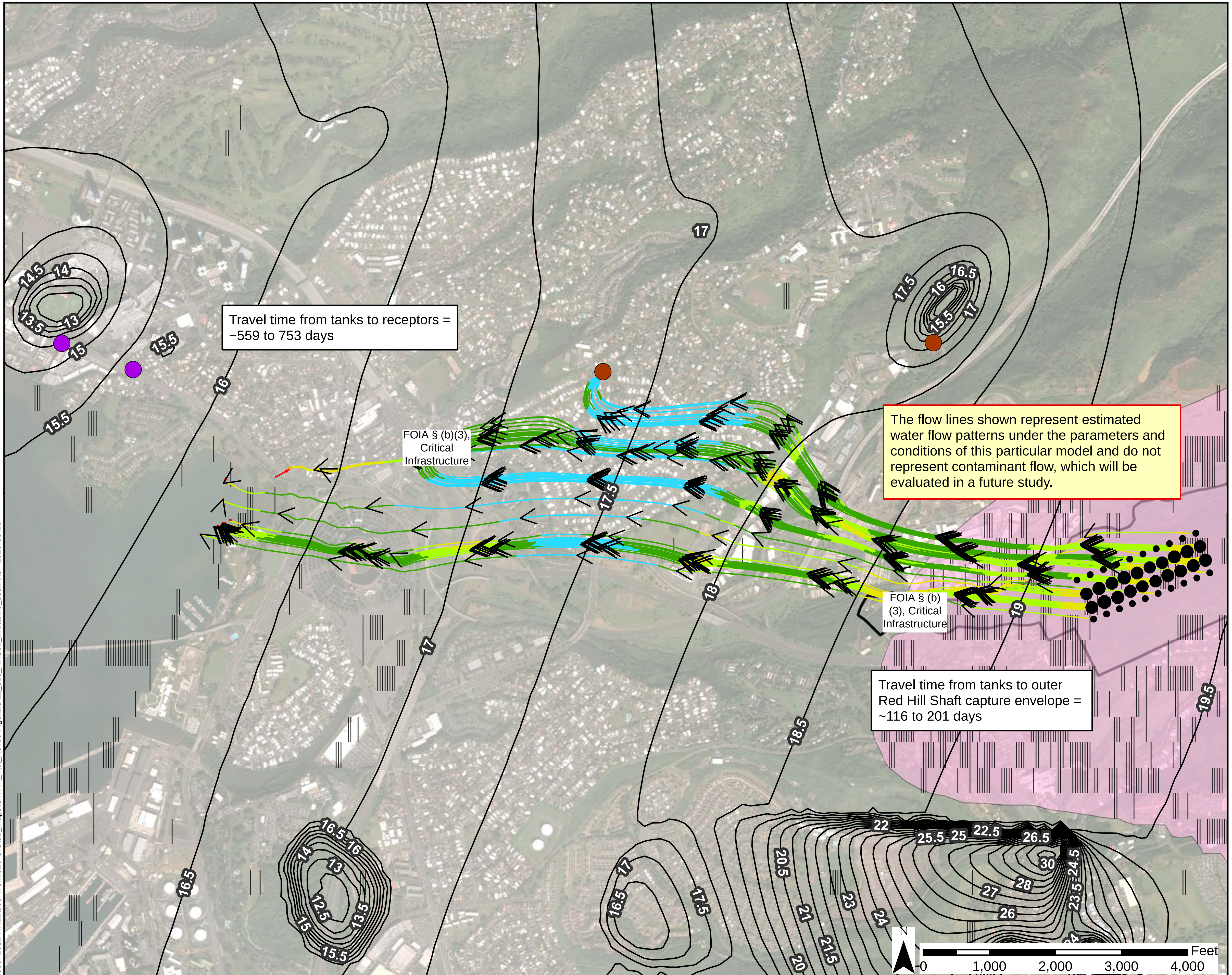
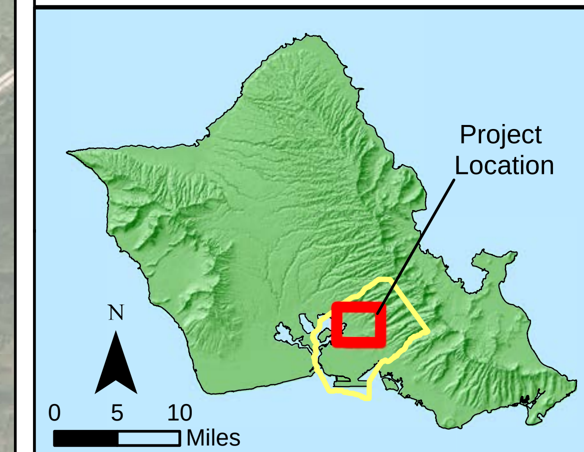


Location Map



Legend

Particle Tracks:

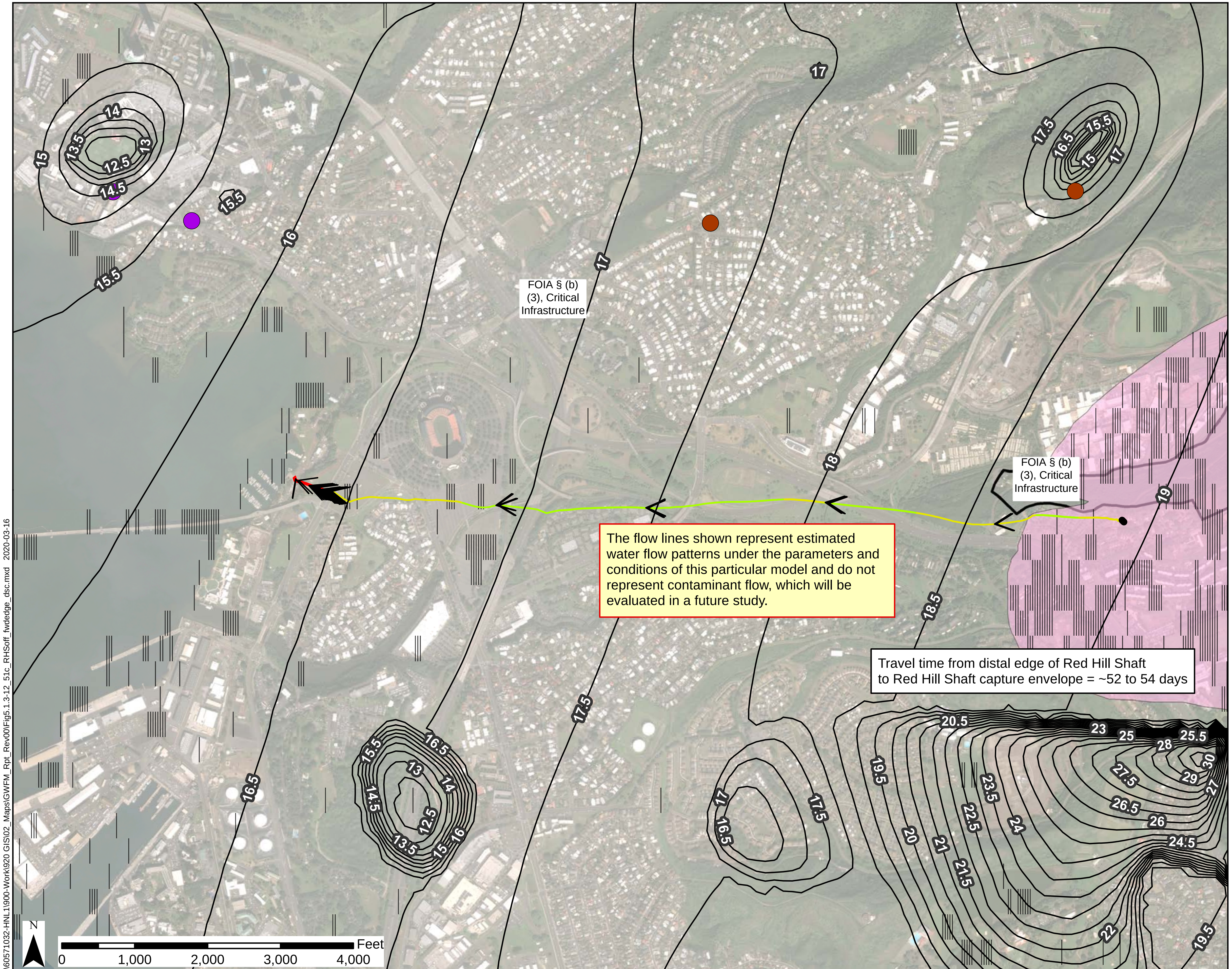
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.1.3-11
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

B:\60571032-HNL11900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.1.3-11_51c_RHSoff_fwdtanks_dsc.mxd 2020-03-16



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet
- Red Hill Shaft Capture
- Red Hill Facility
- Groundwater Model

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.1.3-12
Model #51c: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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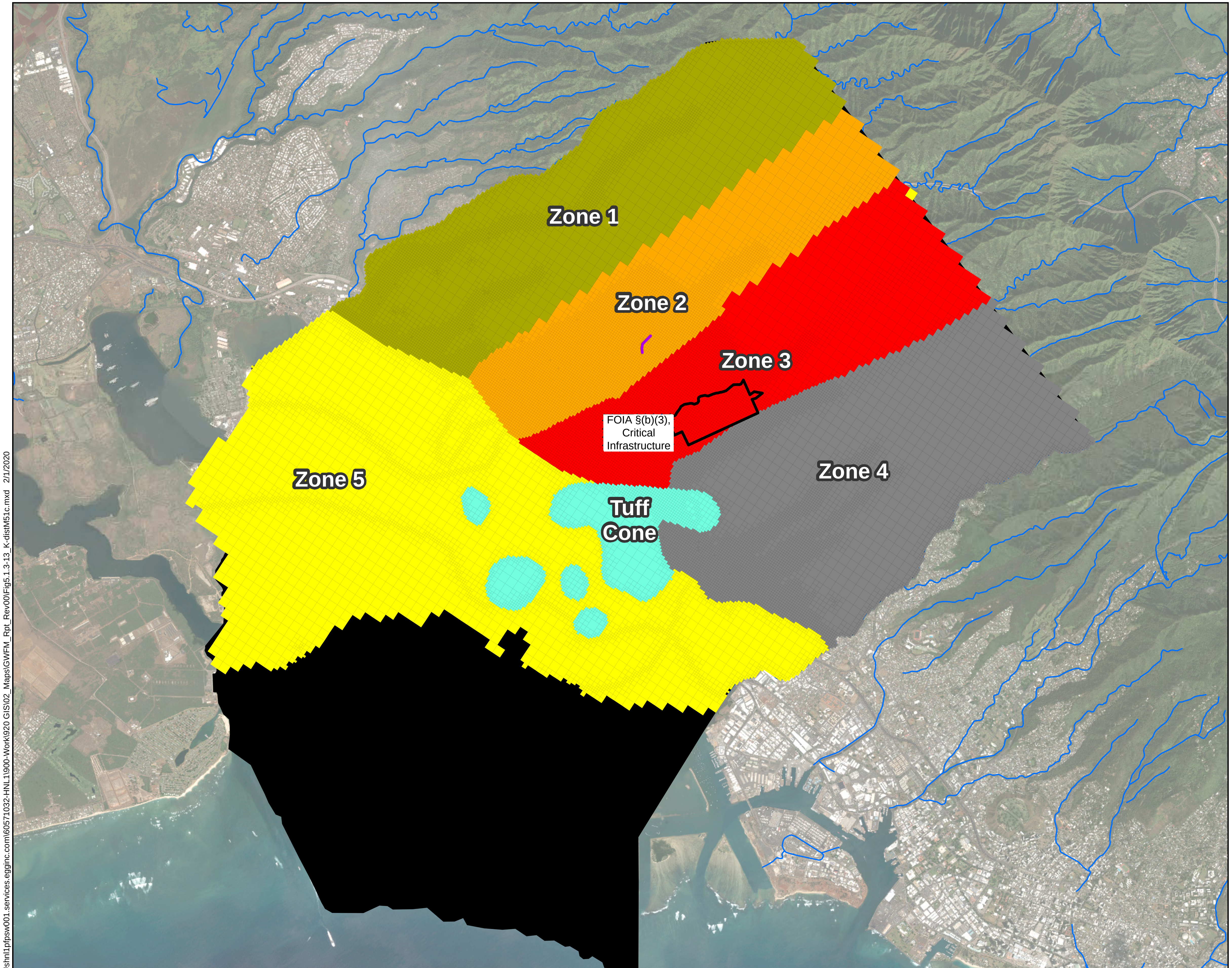
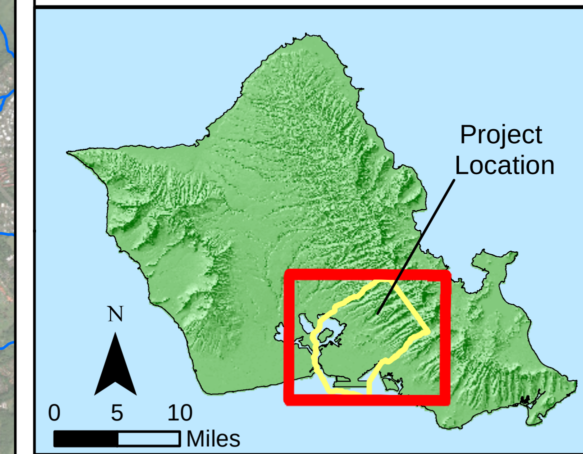


Location Map



Legend

	Kx (ft/day)	Kv (ft/day)
Zone 1	1,000	67
Zone 2	1,700	113
Zone 3	3,000	200
Zone 4	7,000	467
Zone 5	6,000	400
Tuff Cone		
Inactive Model Cells		
Shaft		
Red Hill Facility Boundary		
Stream		

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

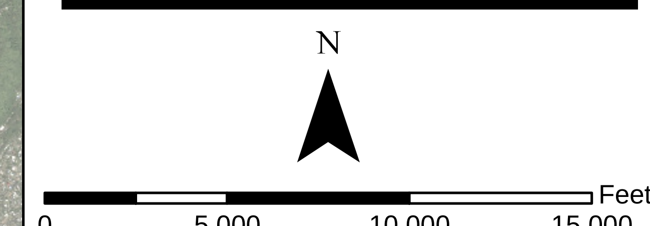


Figure 5.1.3-13
Hydraulic Conductivity Zonation in Basalt for Model #51c
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.1.3-13_K-distM51c.mxd 2/1/2020

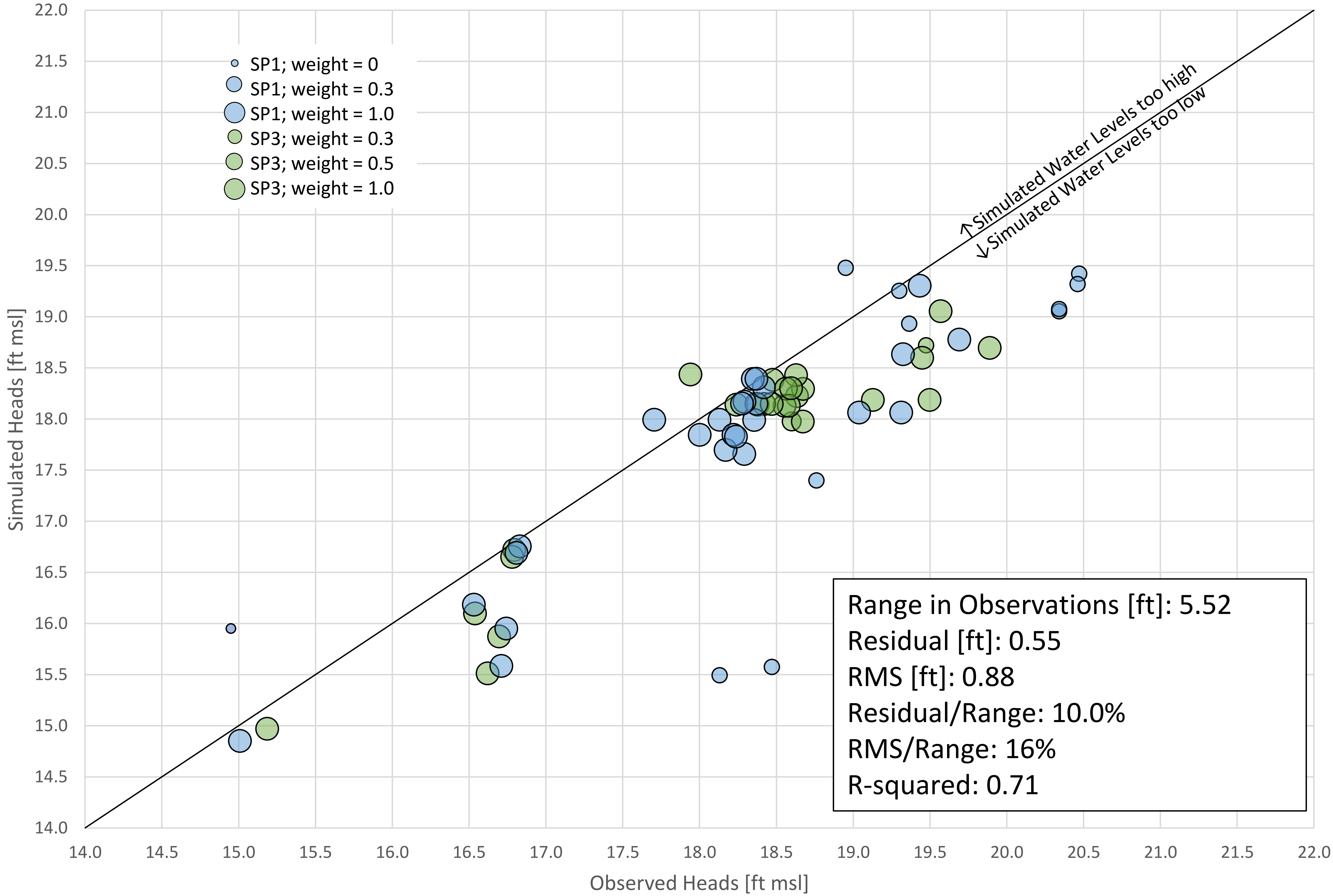
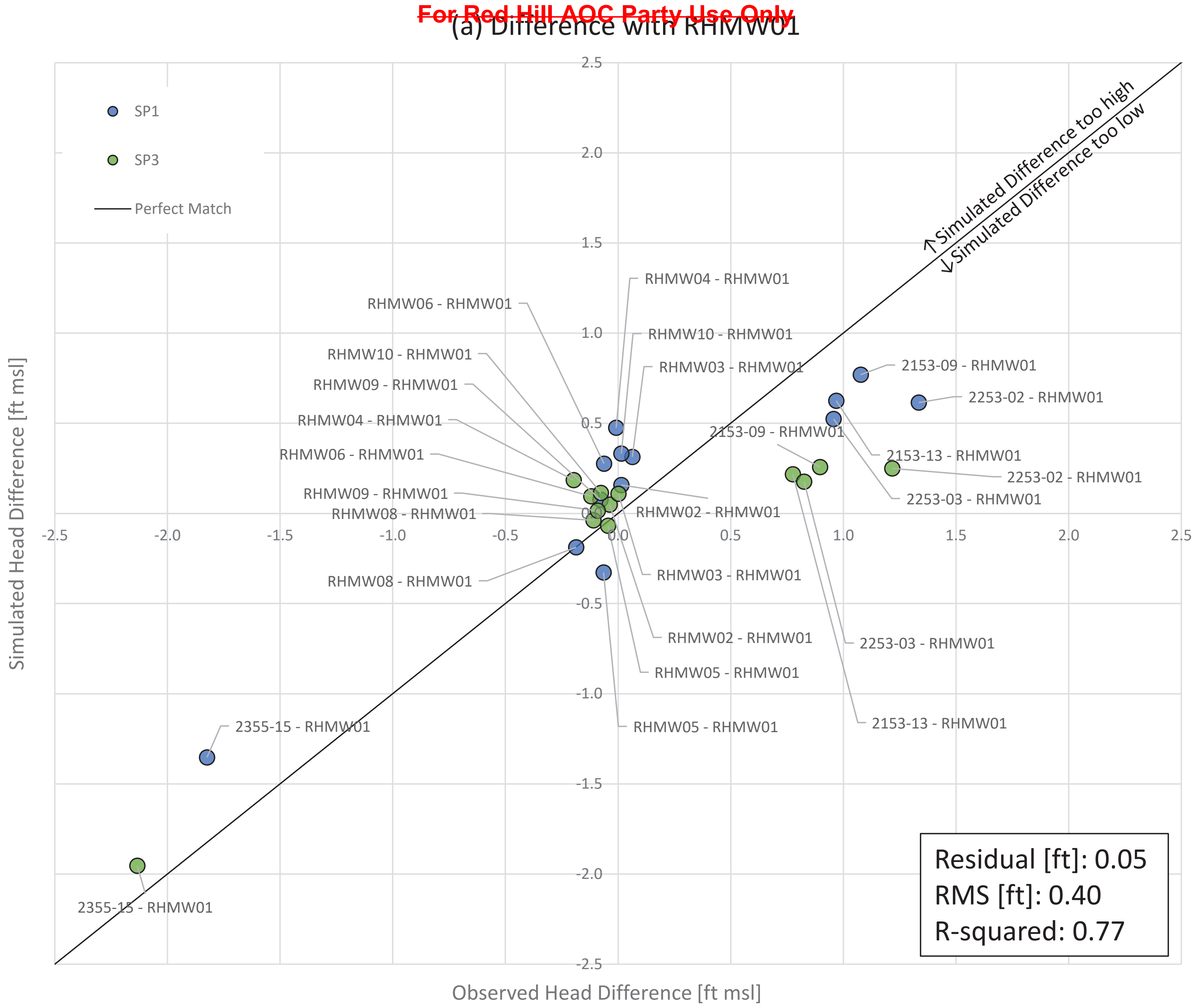


Figure 5.1.4-1
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



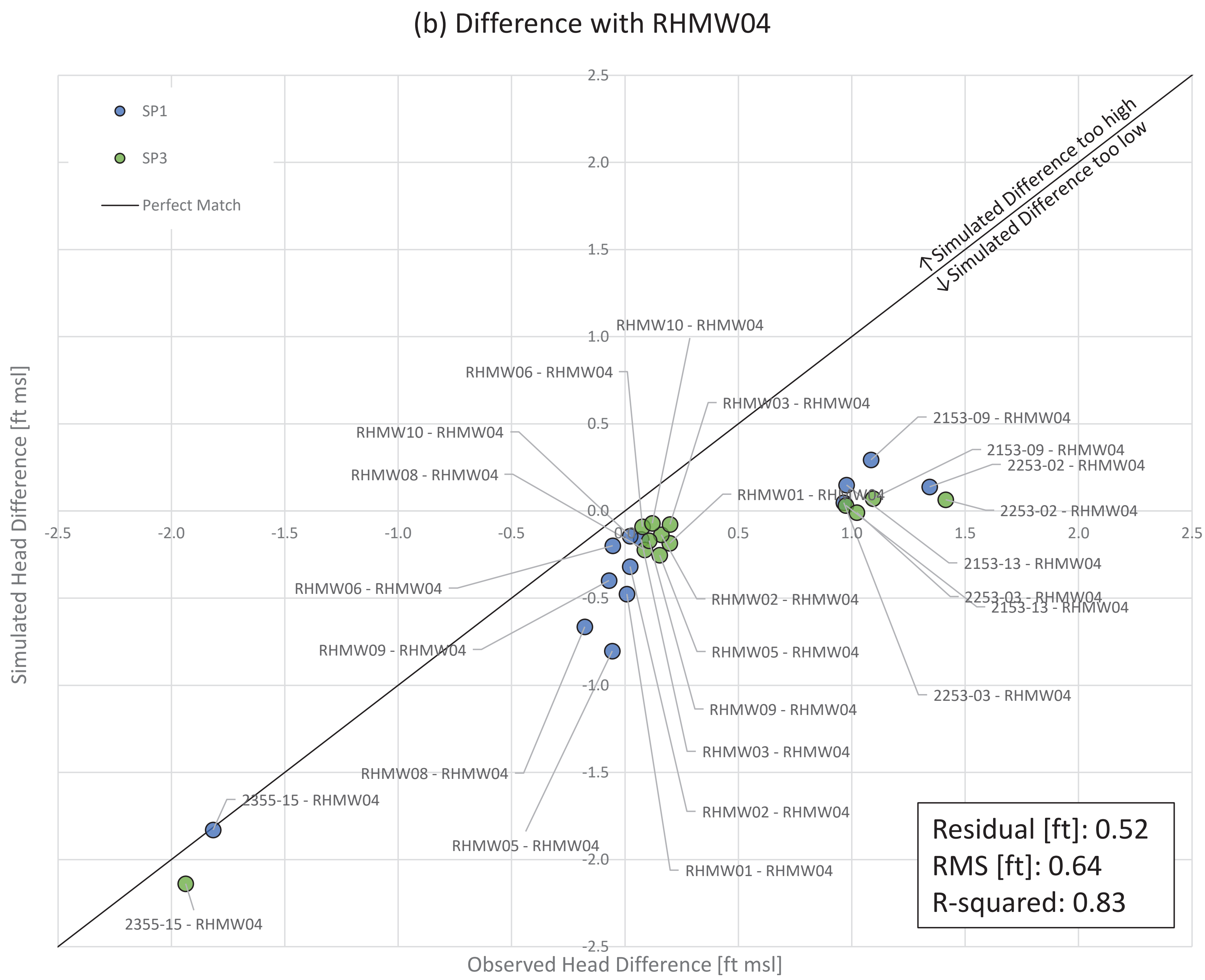


Figure 5.1.4-2
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

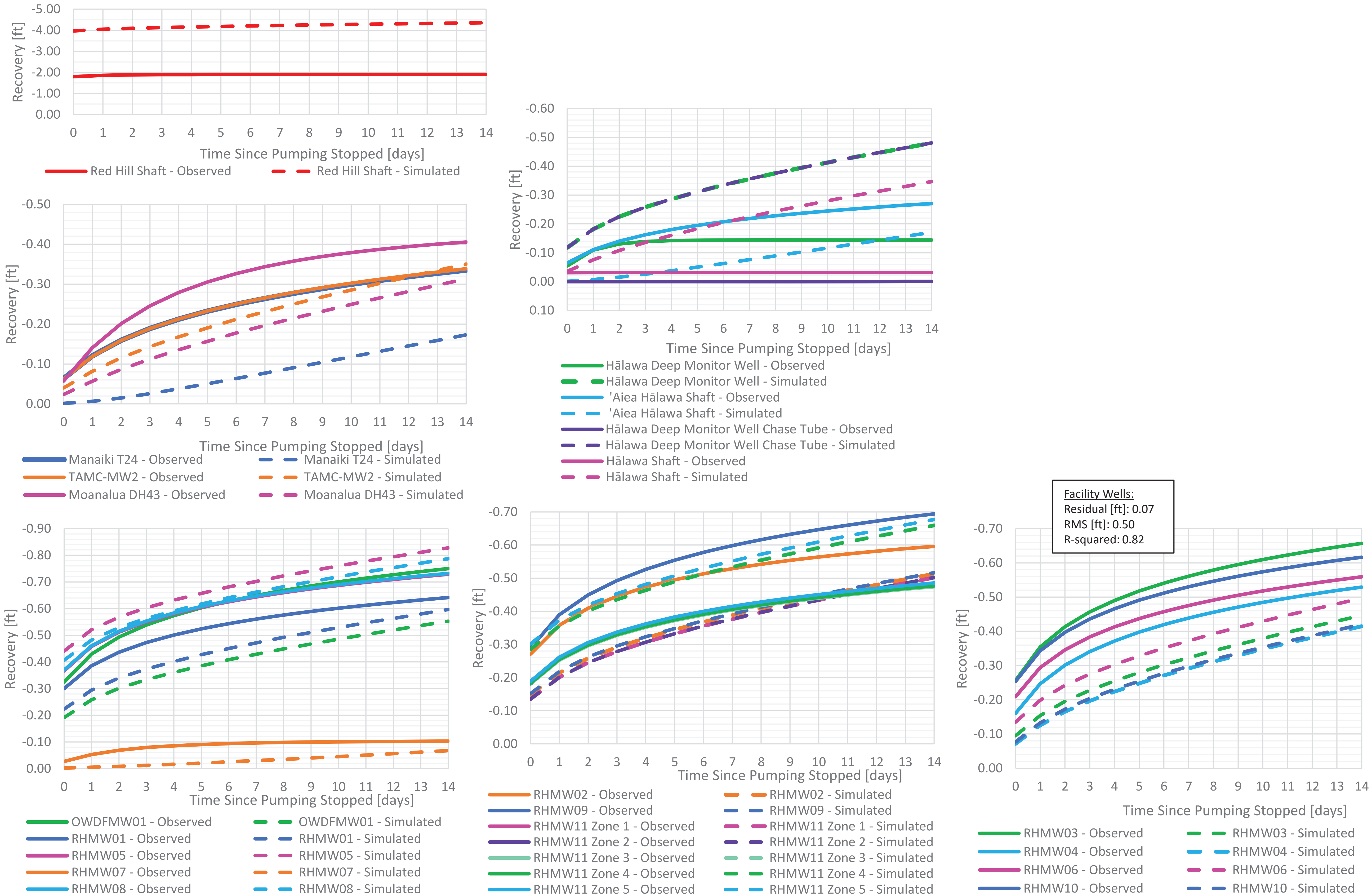


Figure 5.1.4-3
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

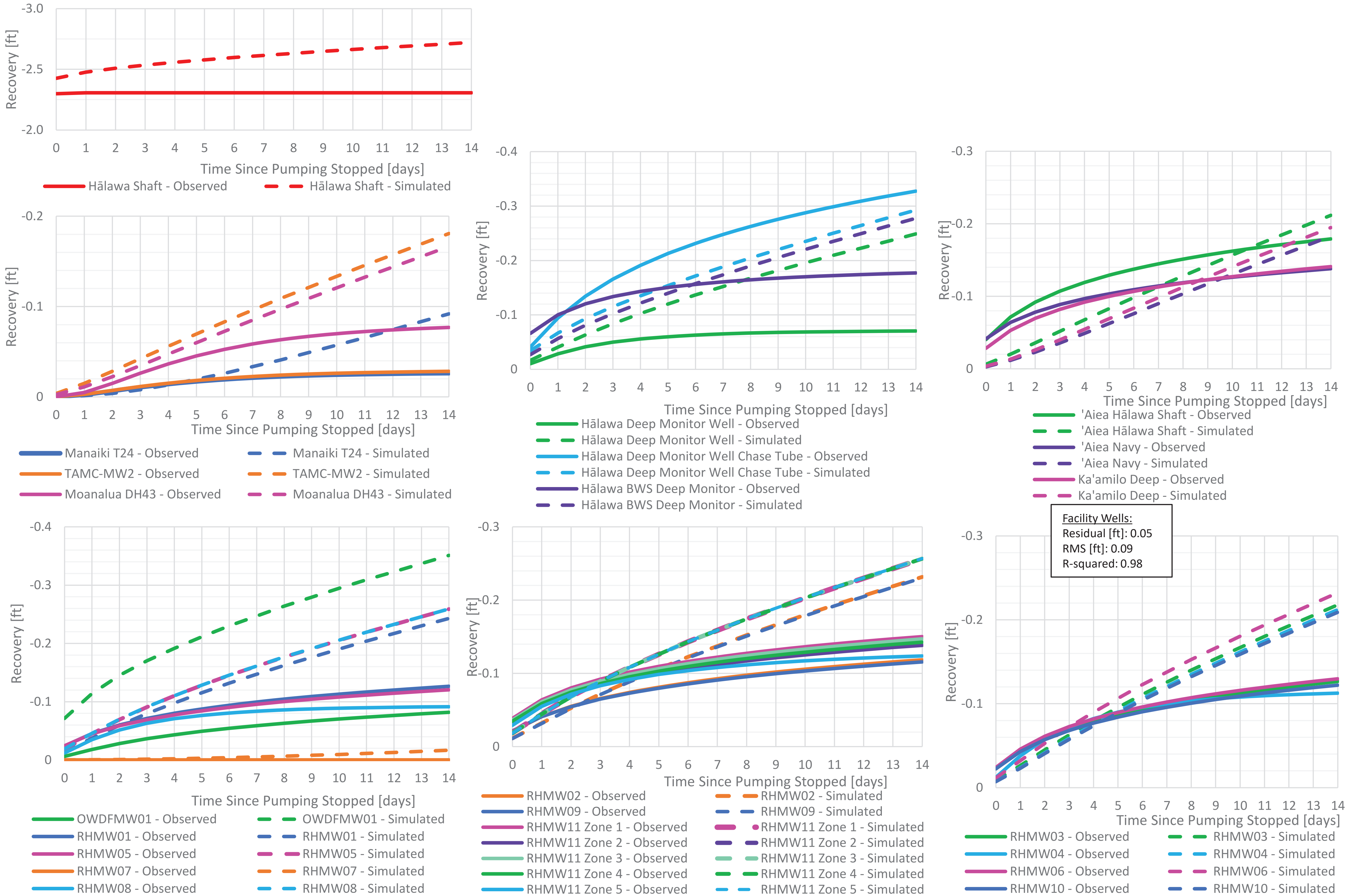
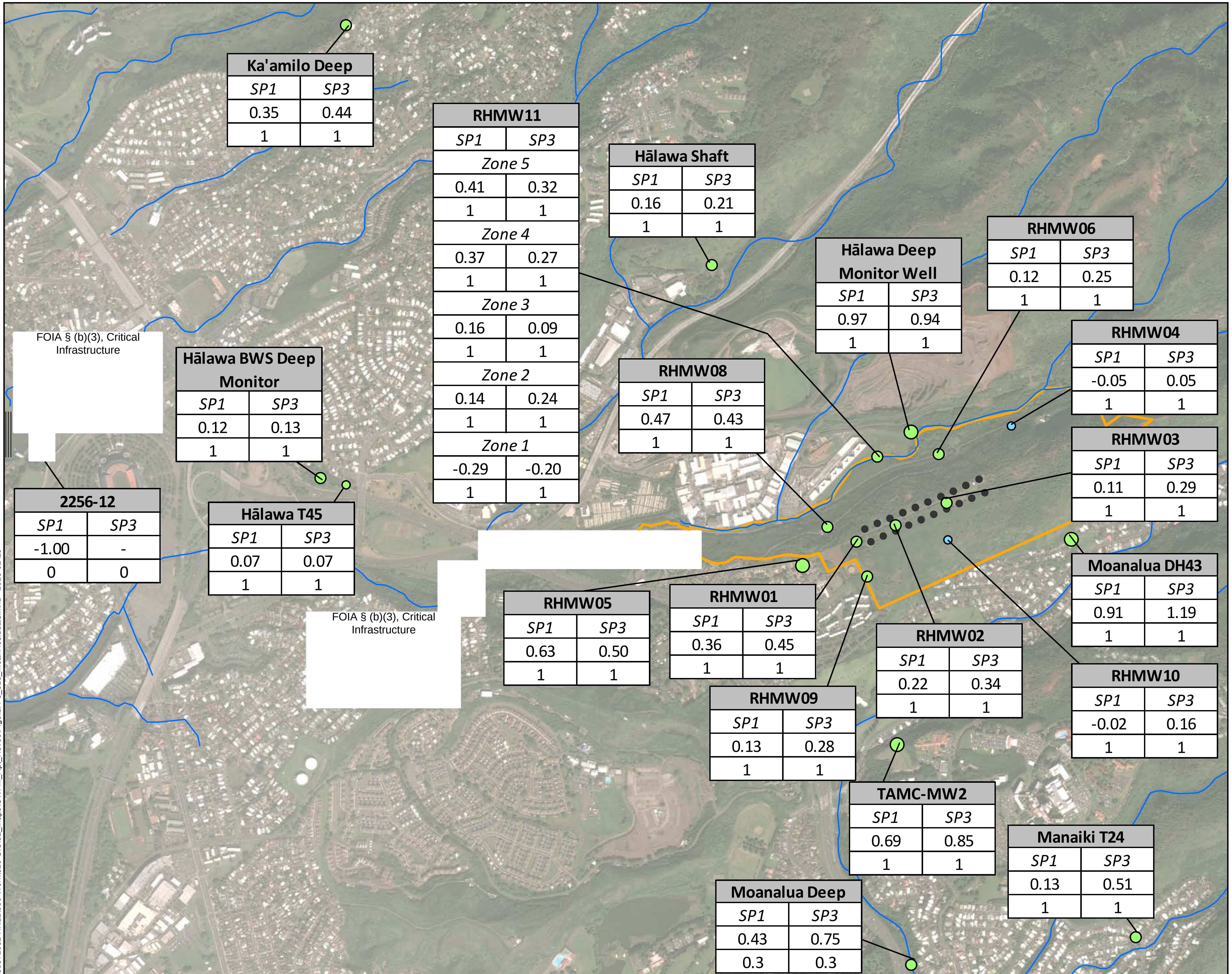
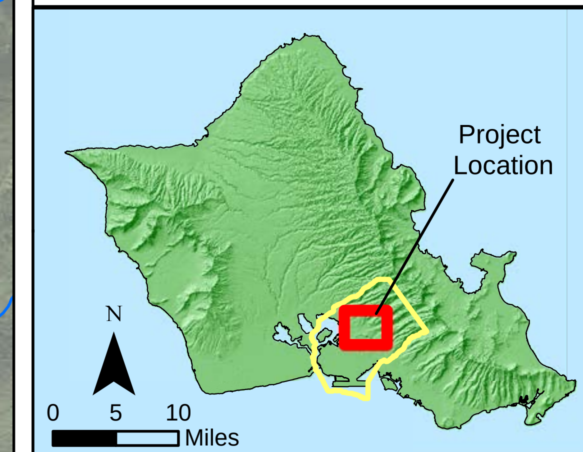


Figure 5.1.4-4
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy – Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.1.4-5
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy with Basalt Zonation – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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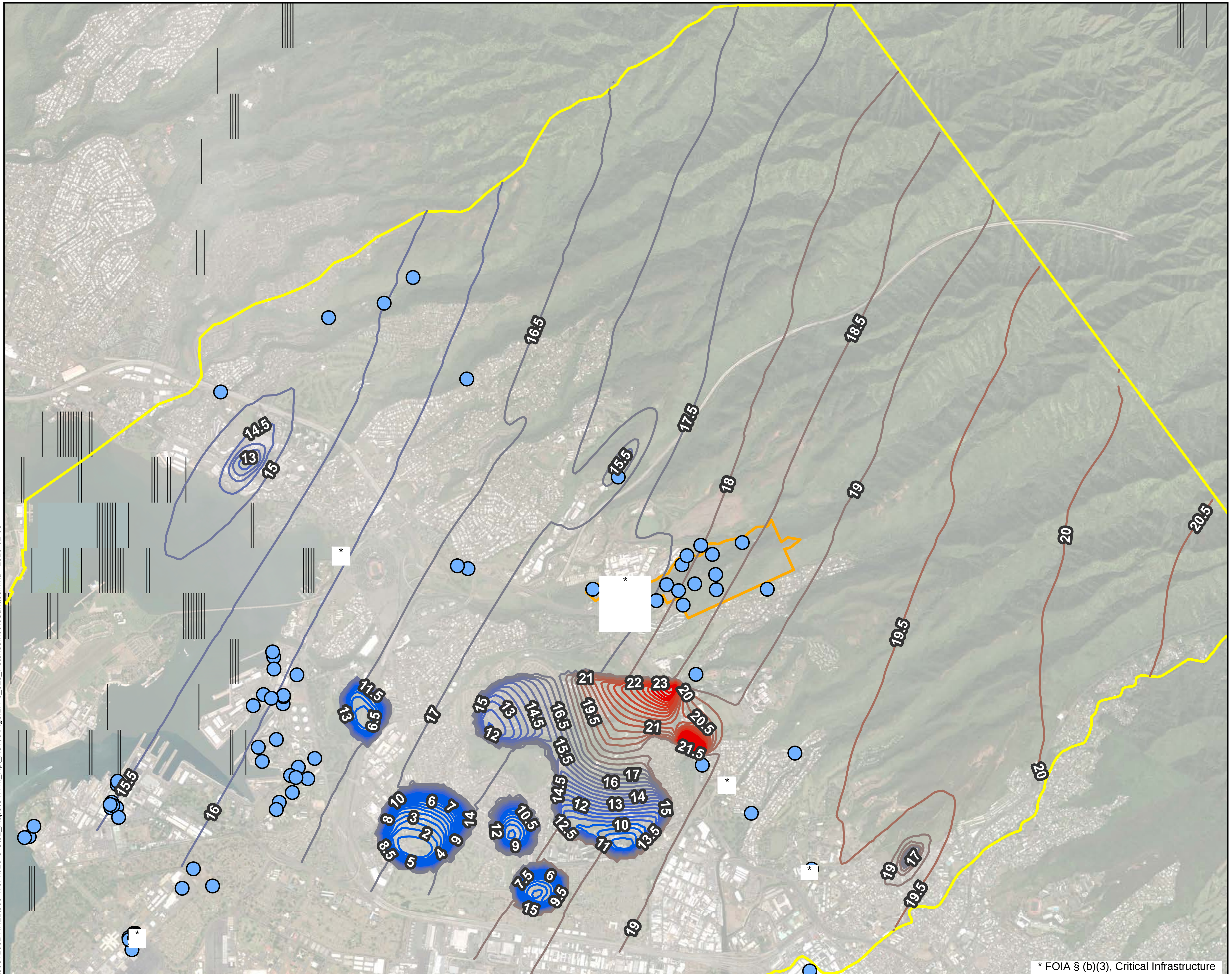
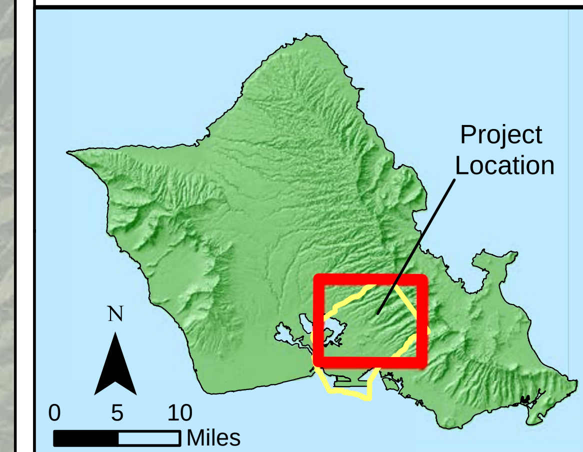


Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.1.4-6
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy and Basalt Zonation – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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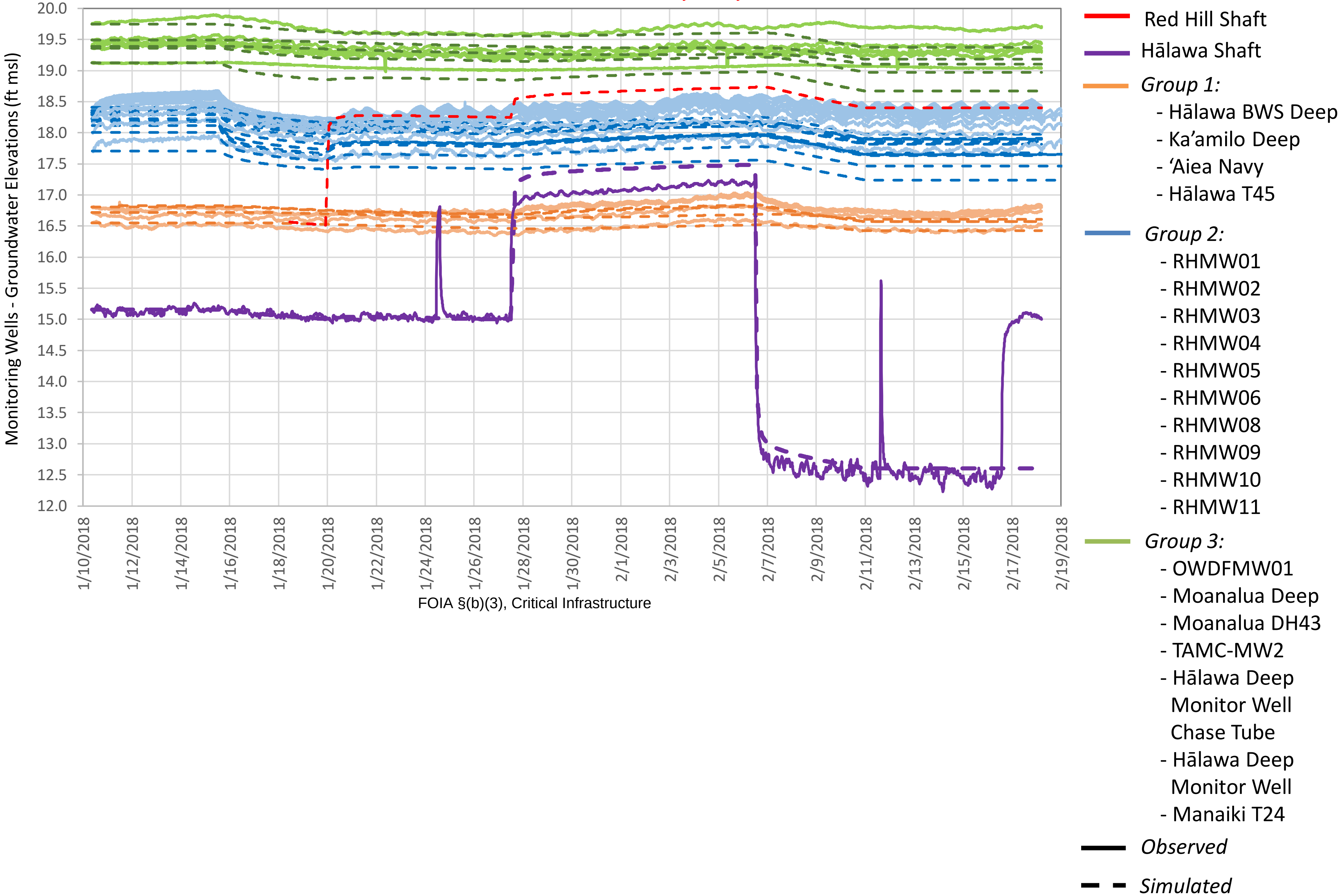


Figure 5.1.4-7
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

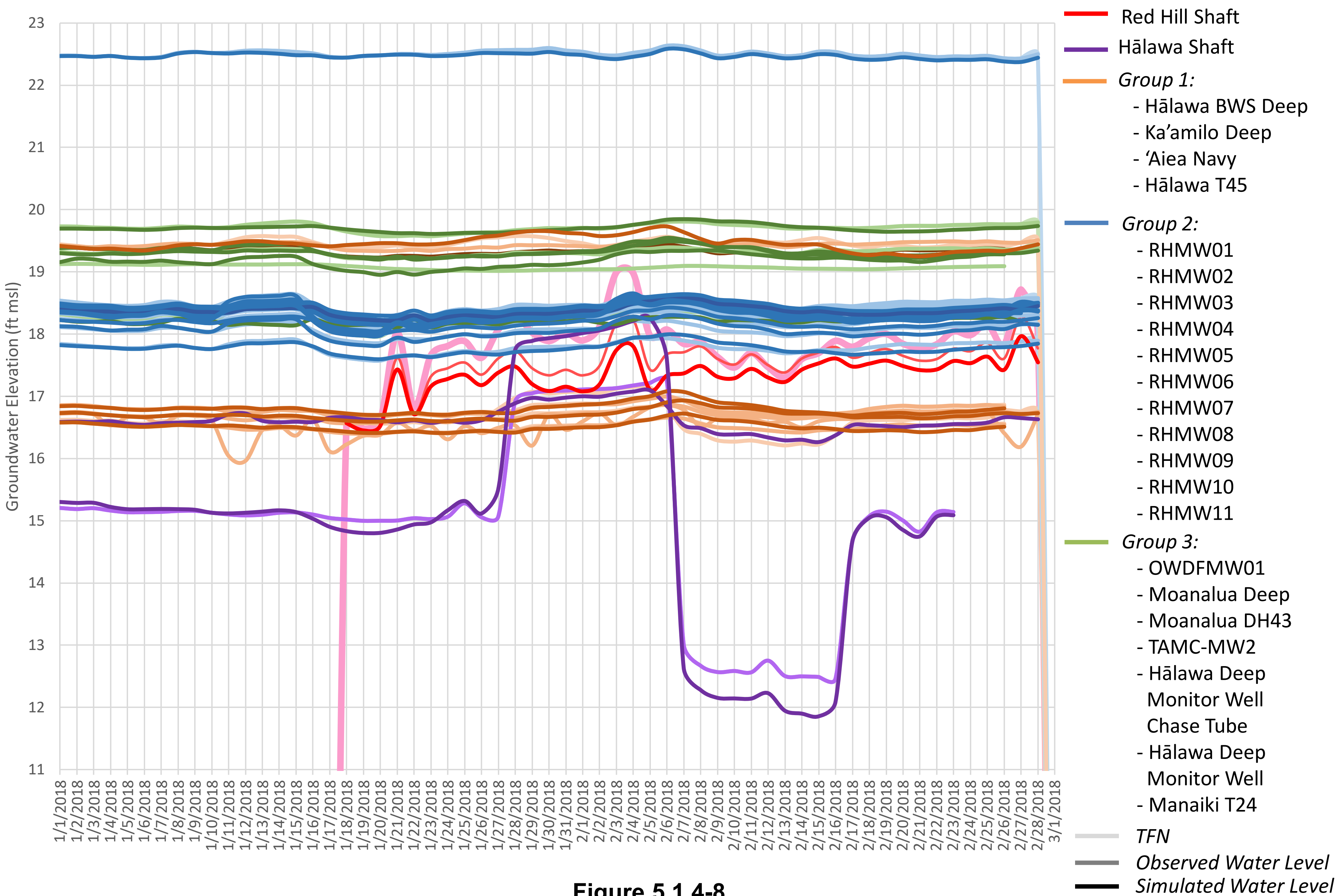
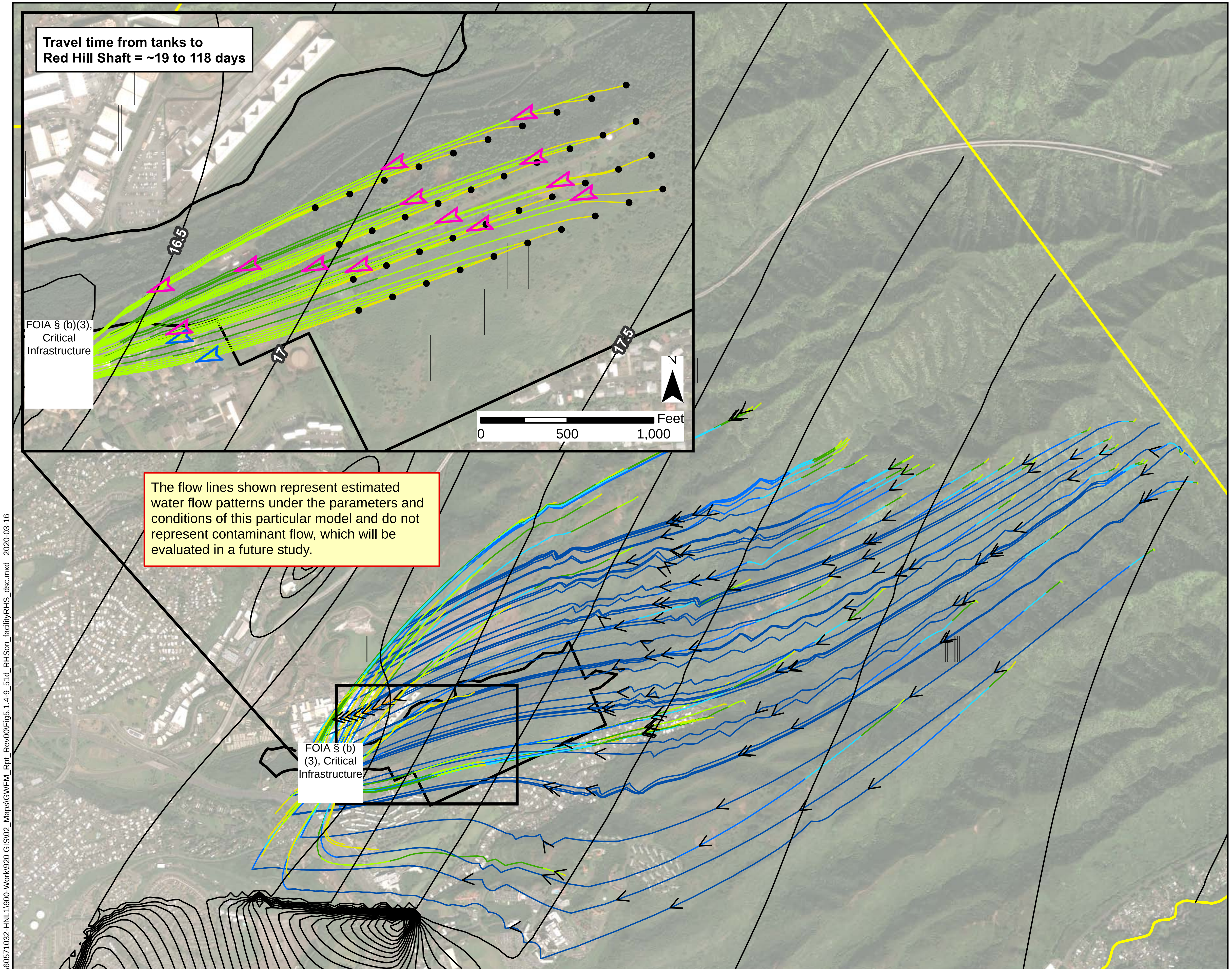
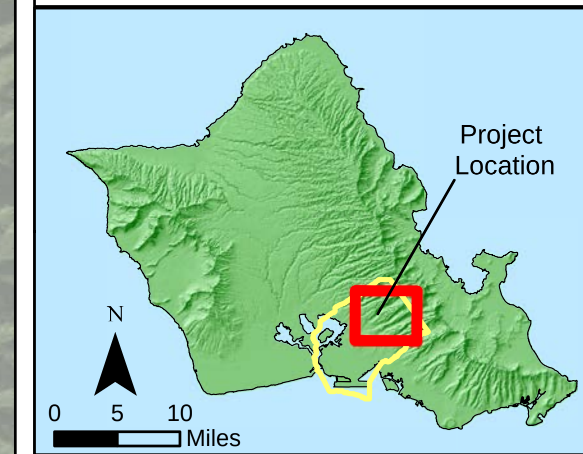


Figure 5.1.4-8
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, Hawaiʻi



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.1.4-9
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy and Basalt Zonation – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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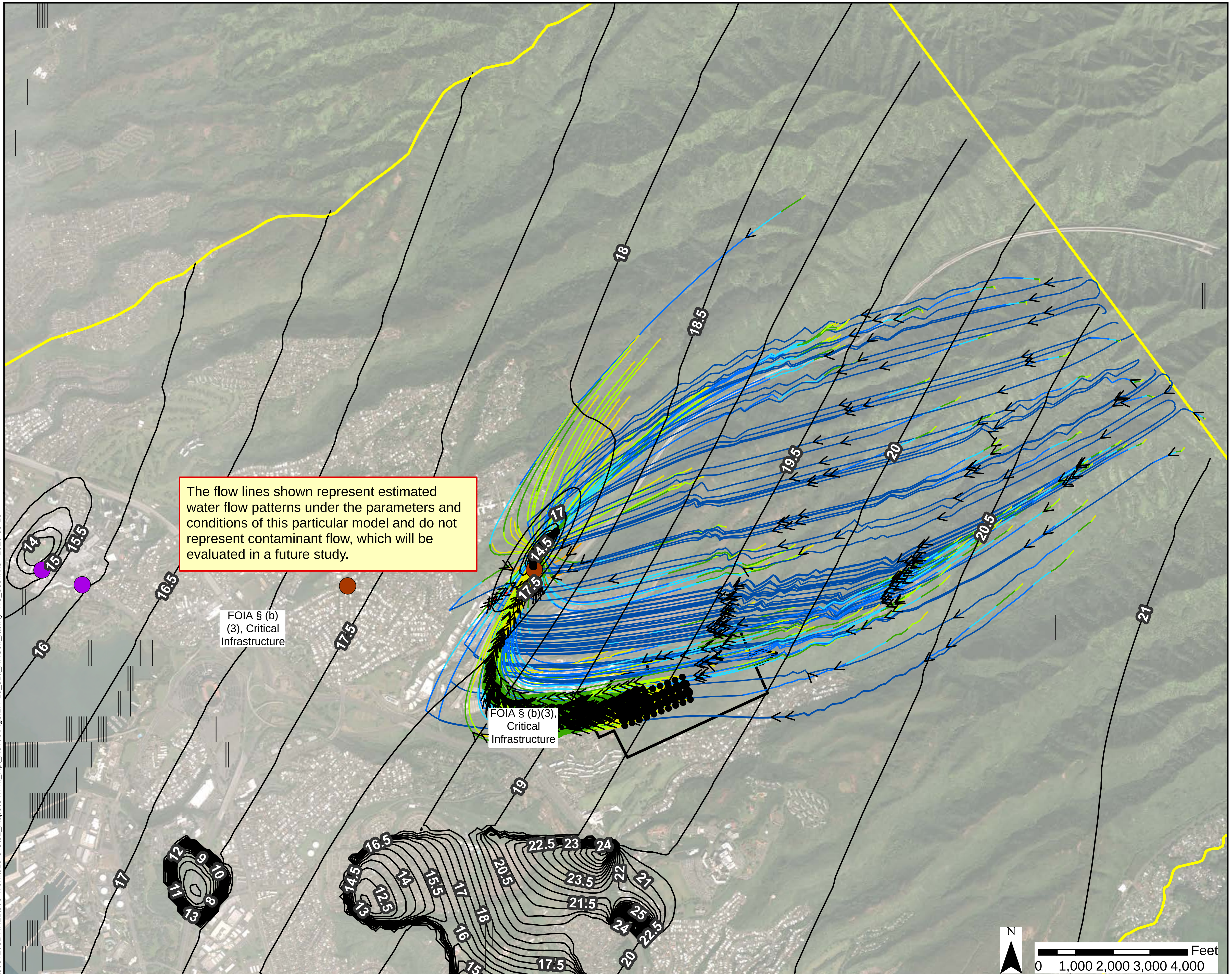
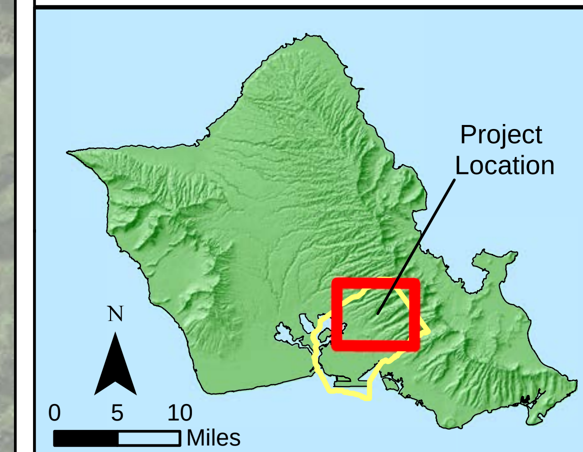


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.1.4-10
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy and Basalt Zonation – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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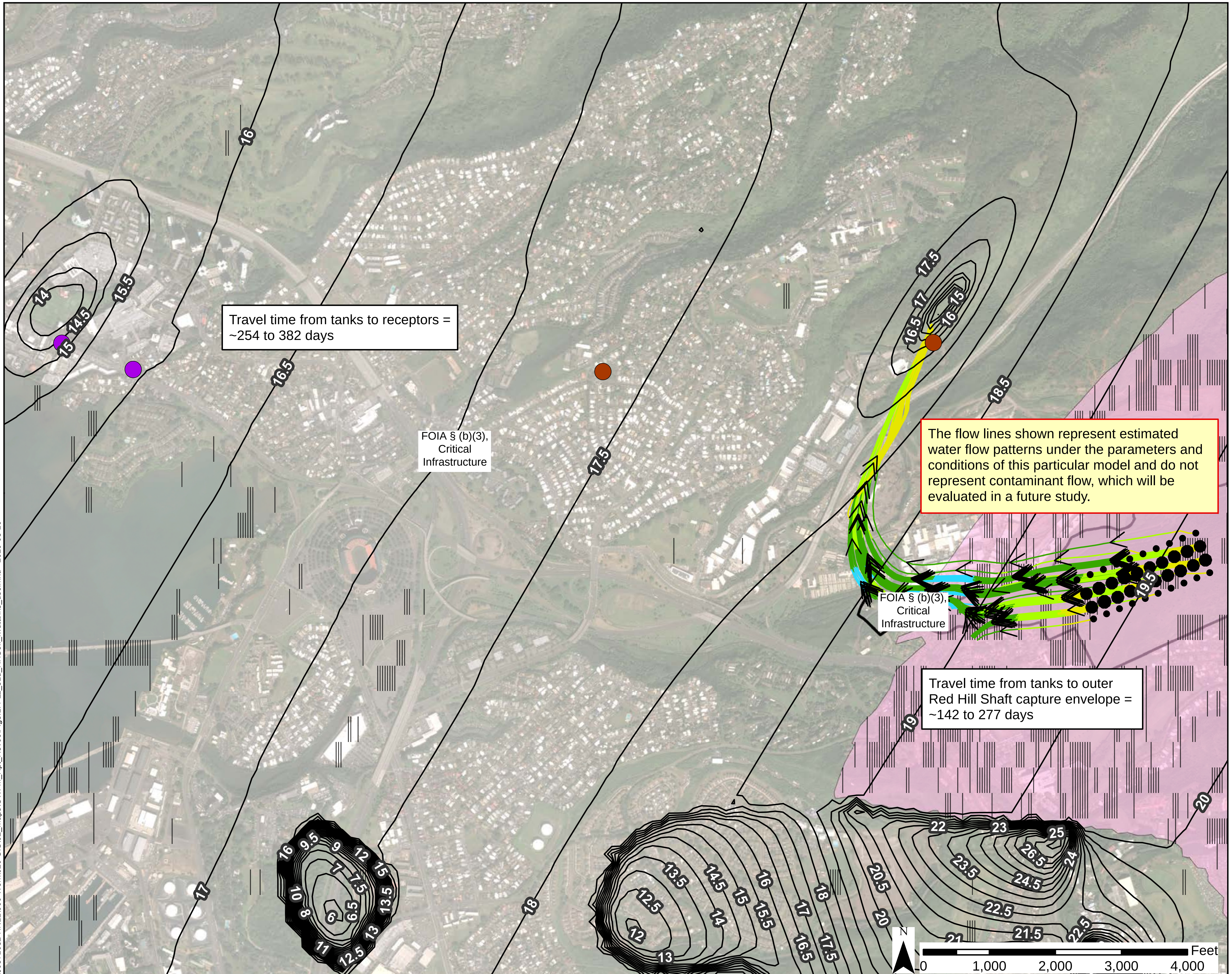
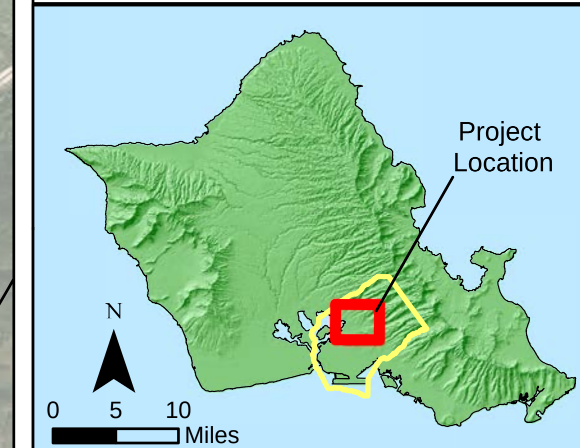


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet
- Red Hill Shaft Capture
- Red Hill Facility
- Groundwater Model

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.1.4-11
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy and Basalt Zonation – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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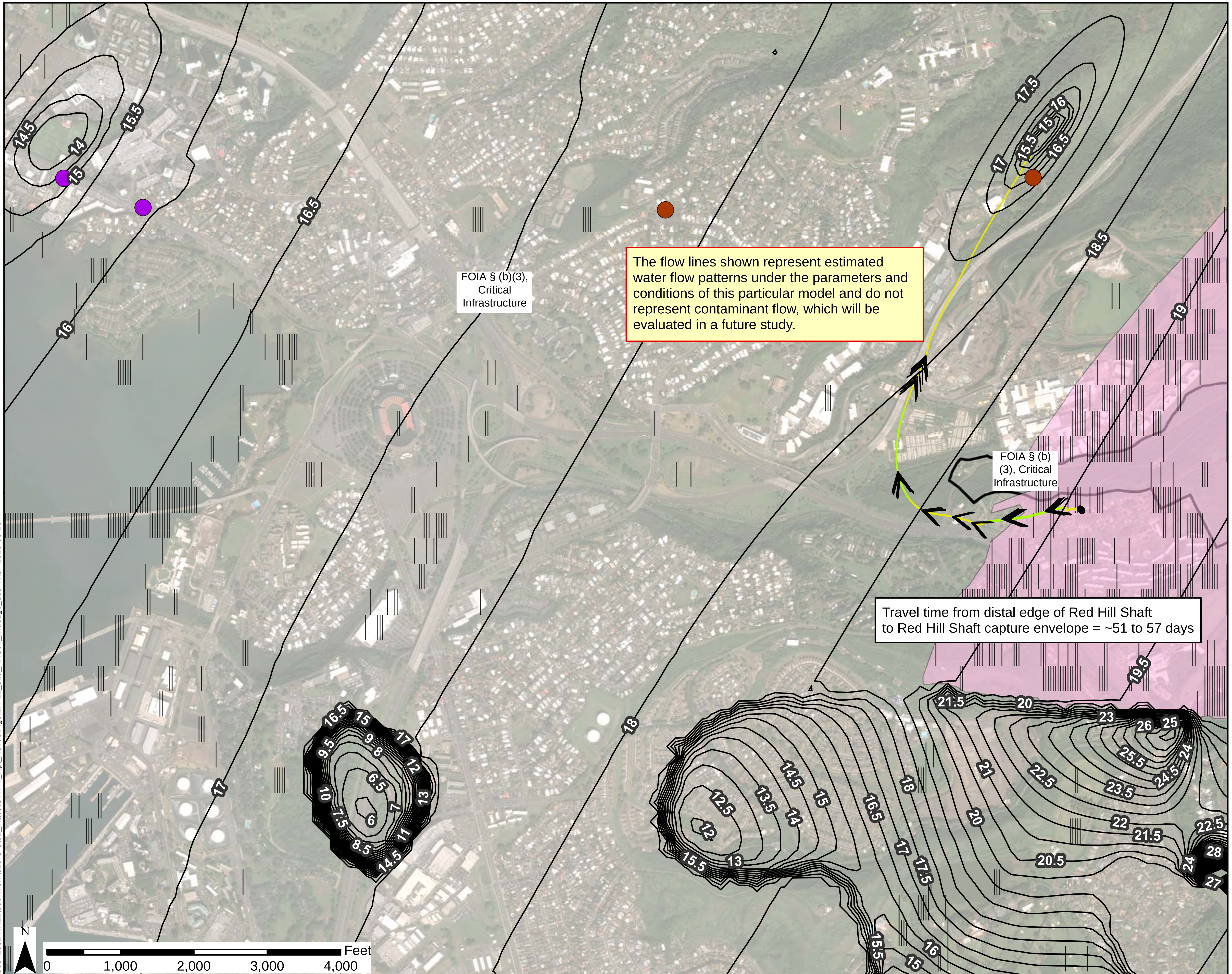
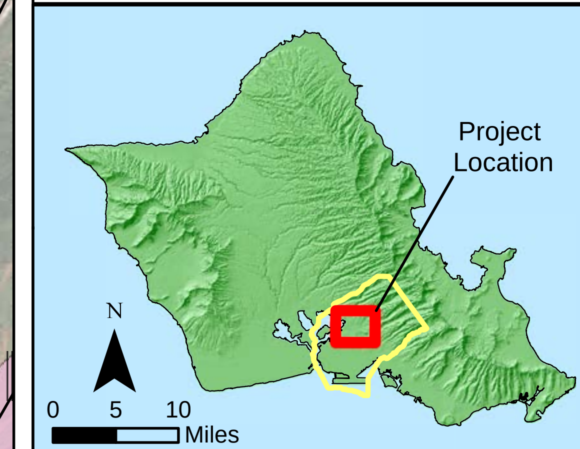


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days.

Figure 5.1.4-12
Model #51d: Homogeneous Basalt with 17.5:1 Anisotropy and Basalt Zonation – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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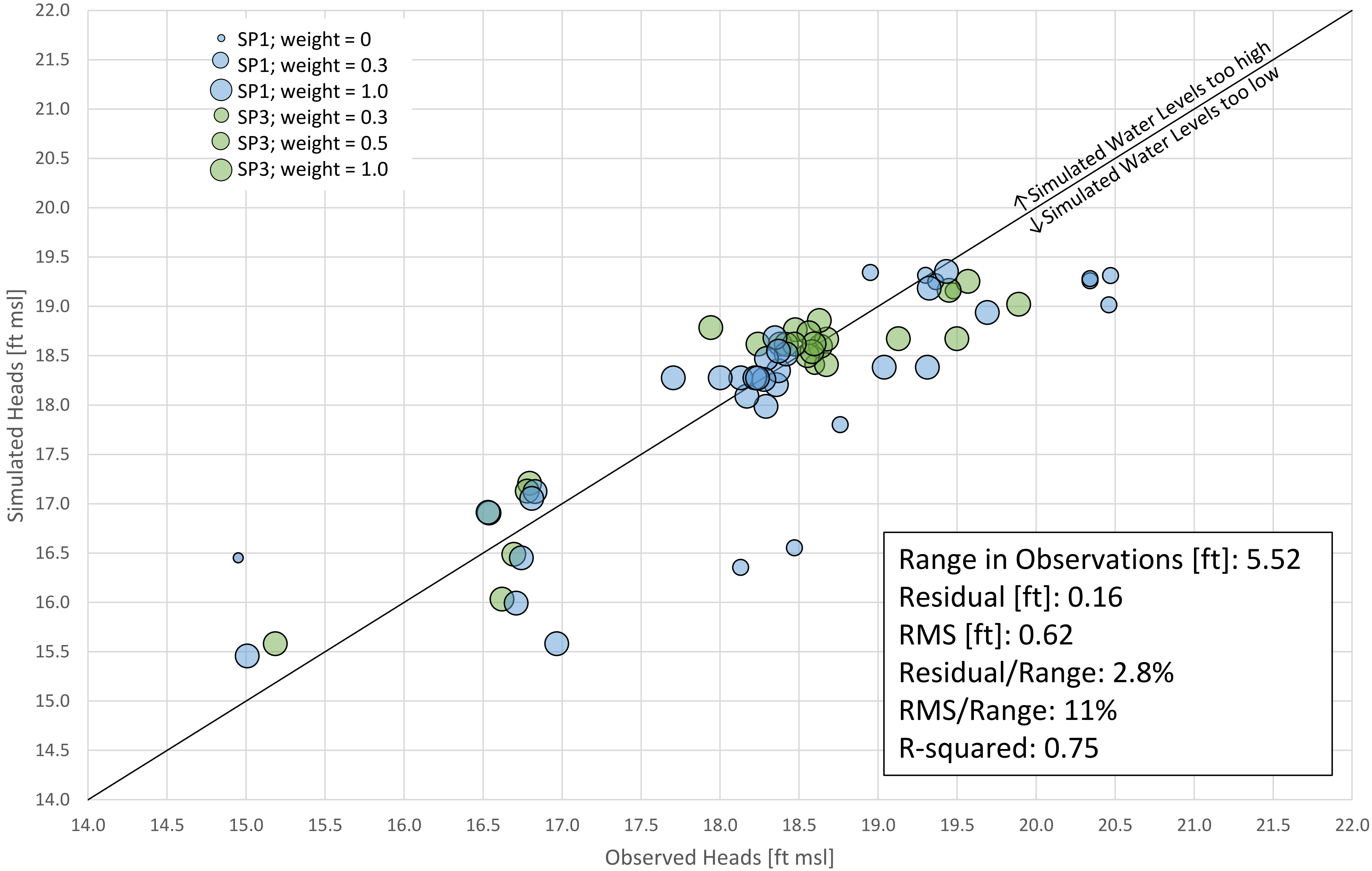
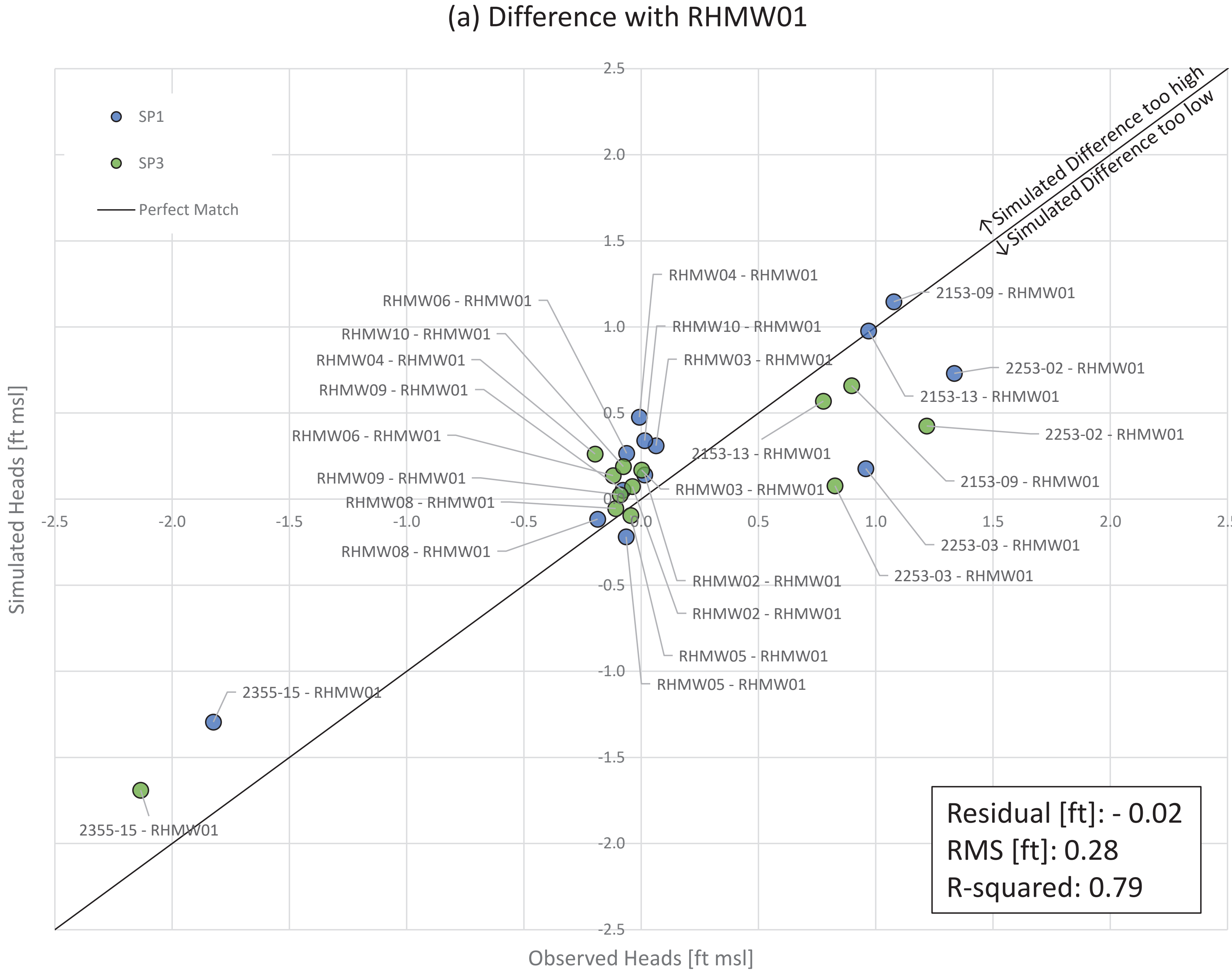


Figure 5.1.5-1
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

For Red Hill AOC Party Use Only



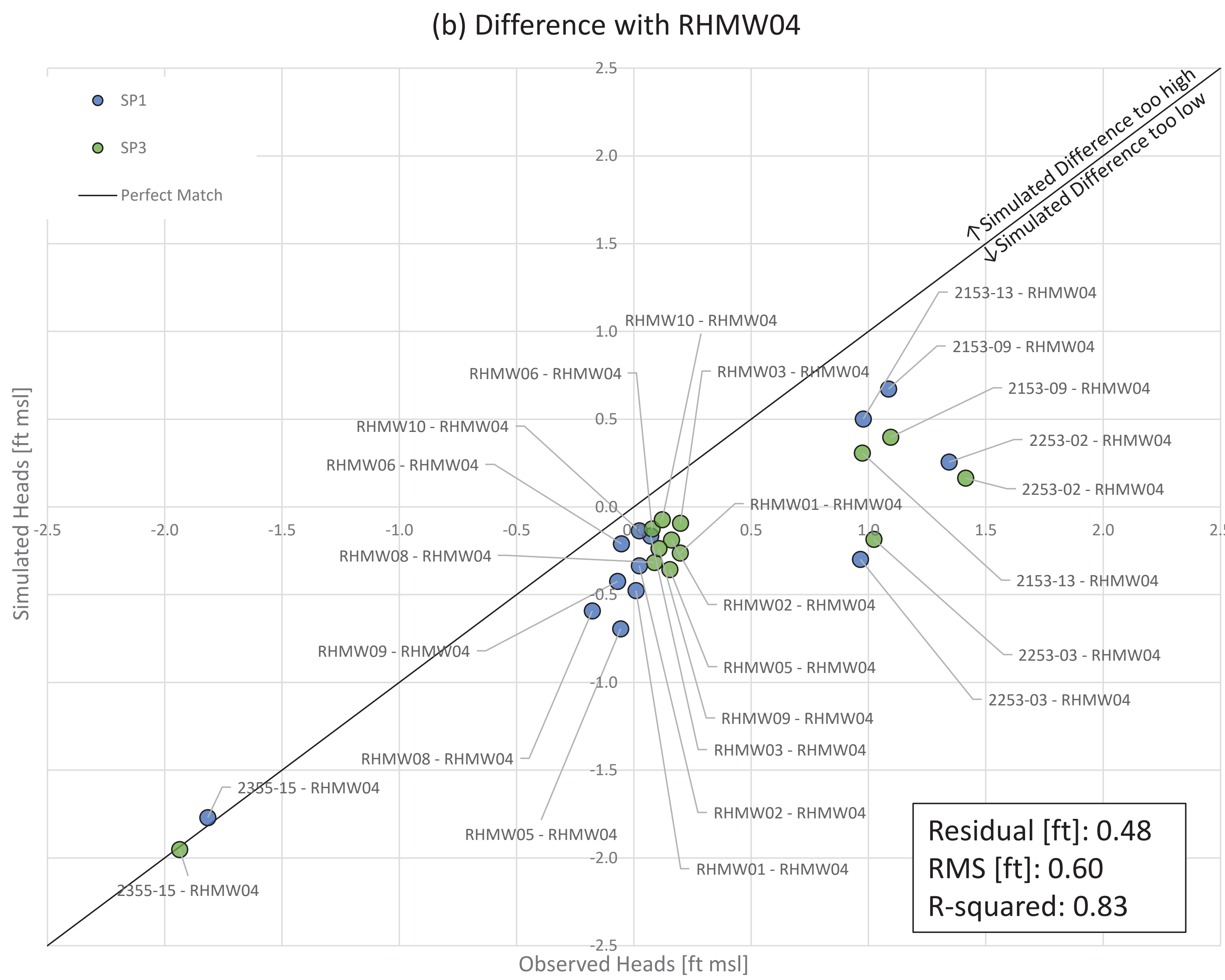


Figure 5.1.5-2
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys –
Scatterplot of Water Level Differences Between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

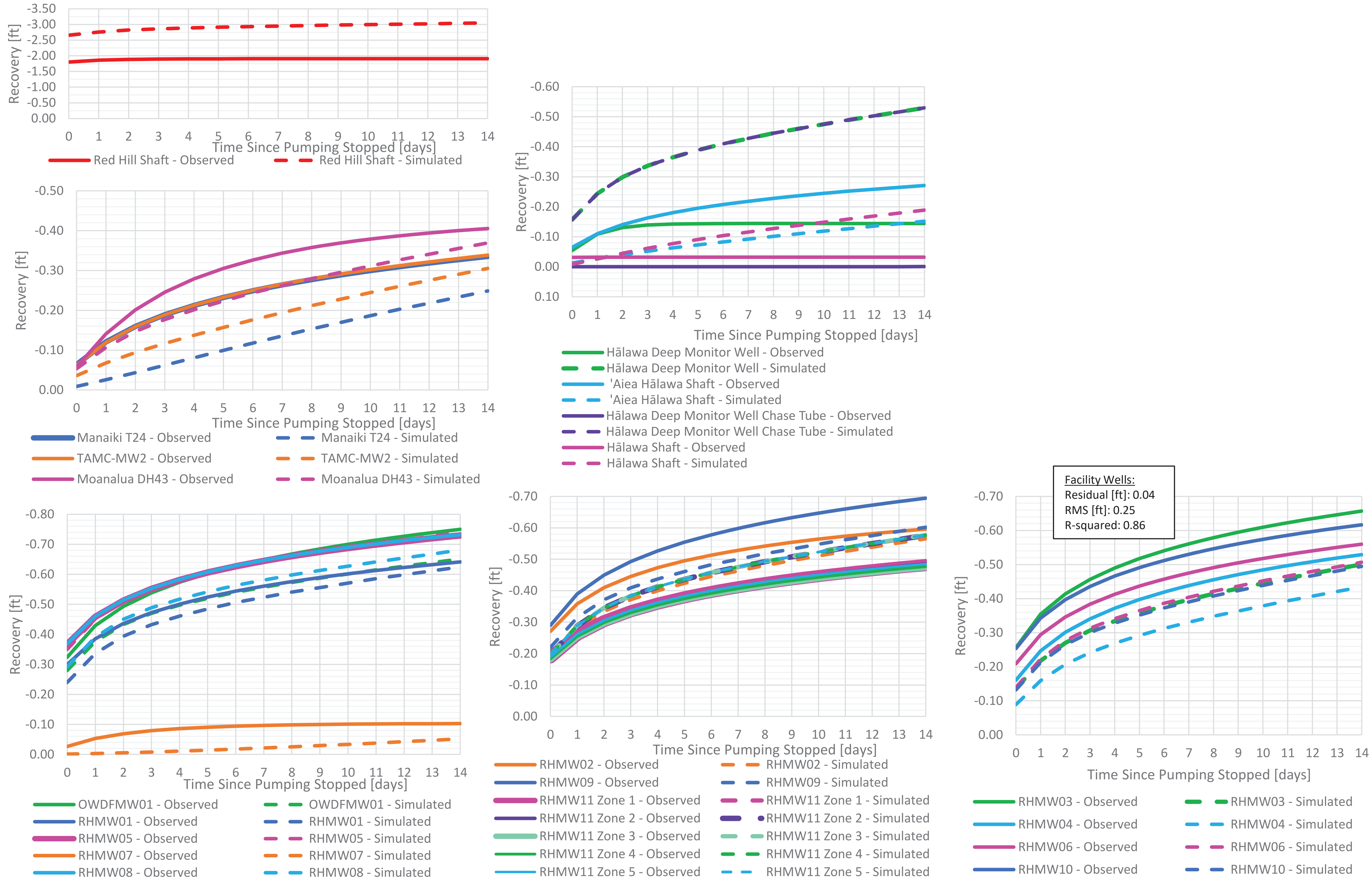


Figure 5.1.5-3
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

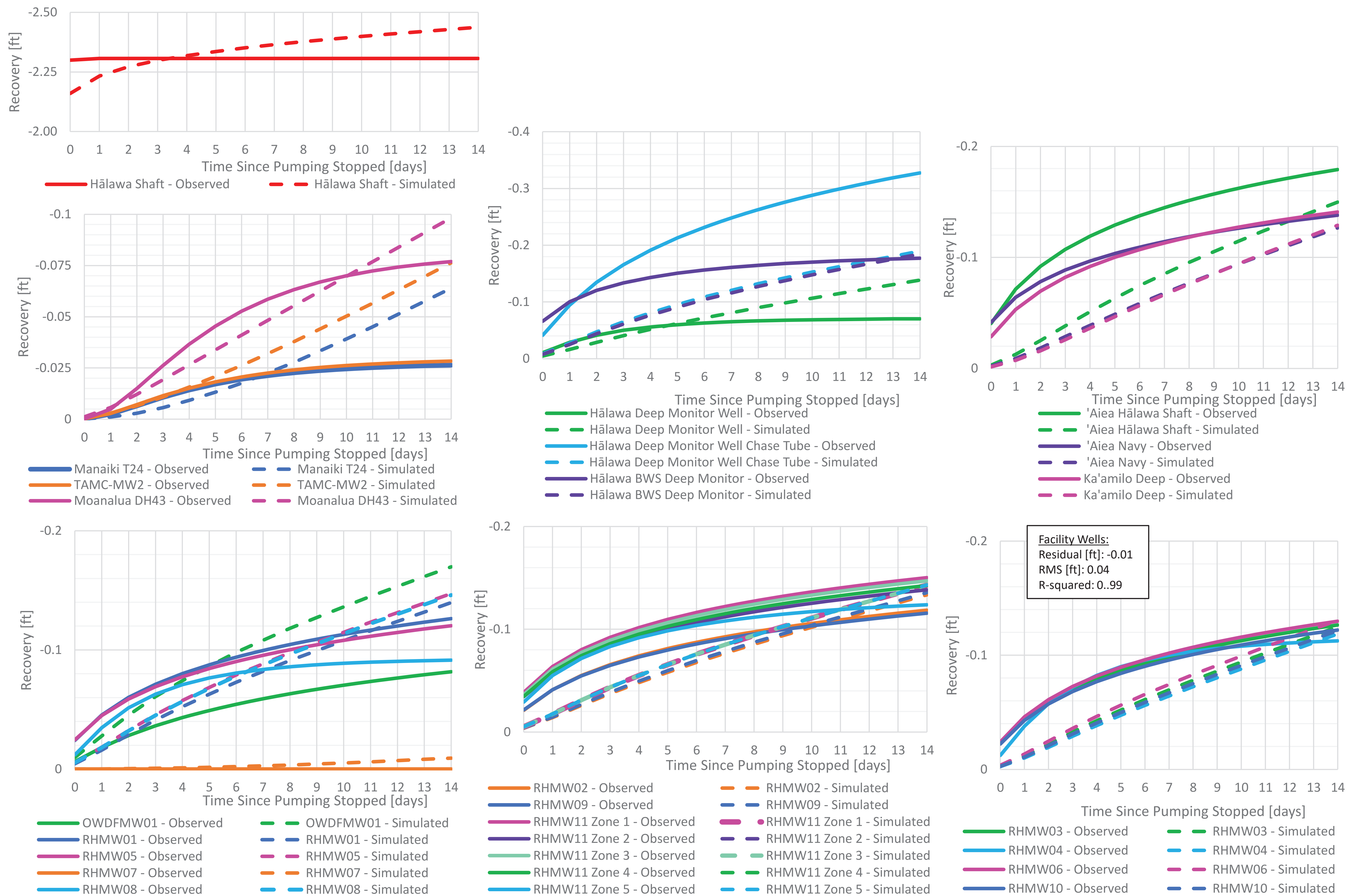
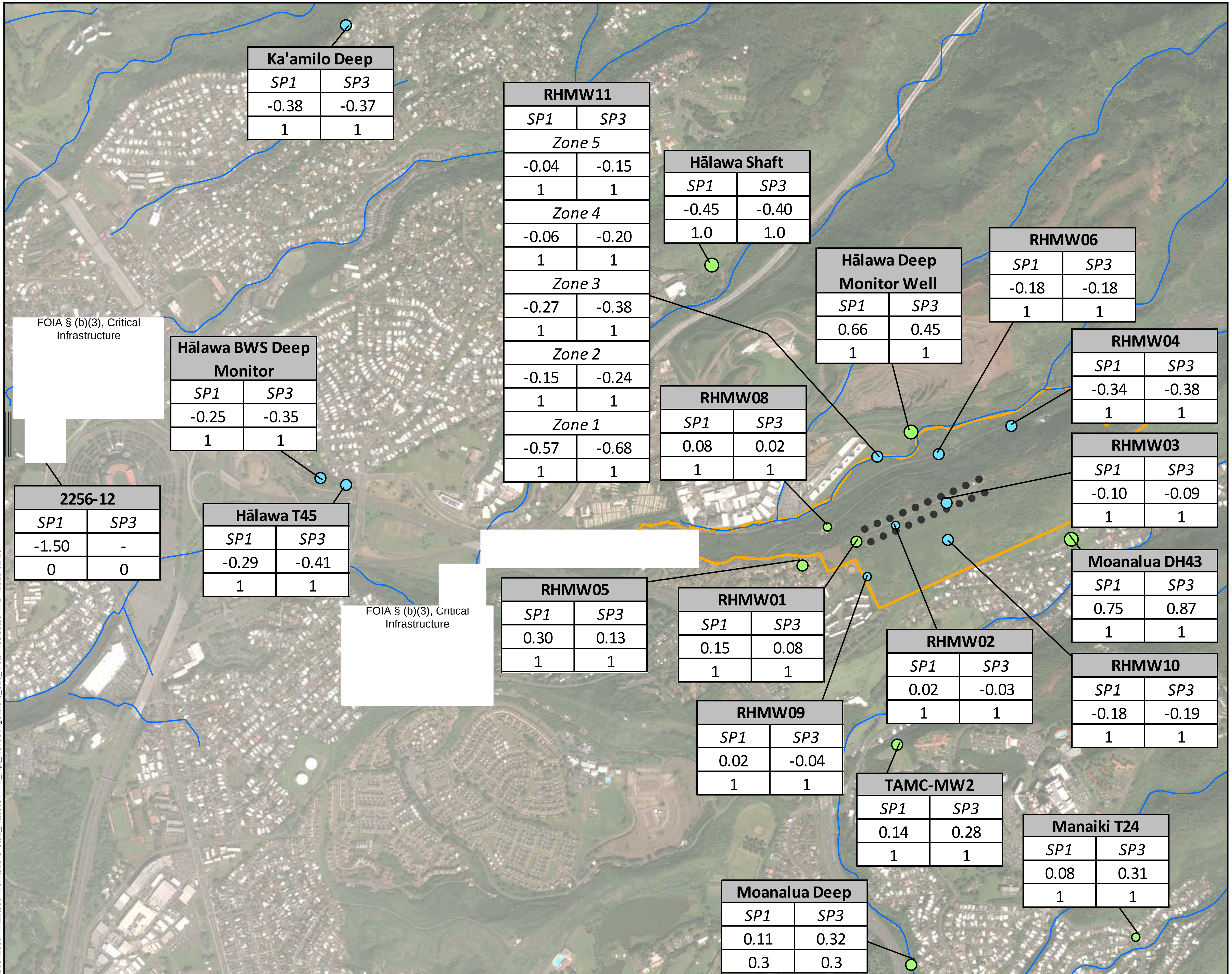


Figure 5.1.5-4
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



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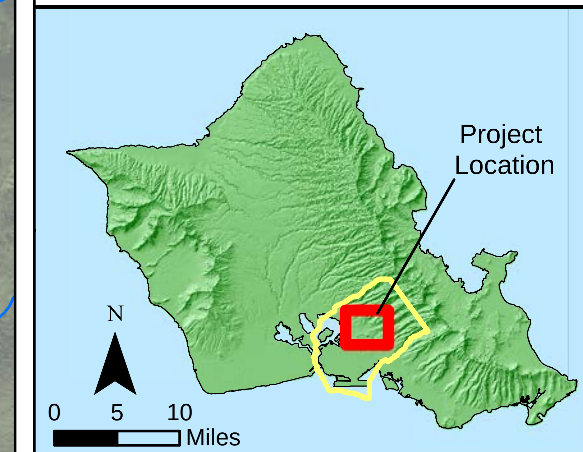
Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

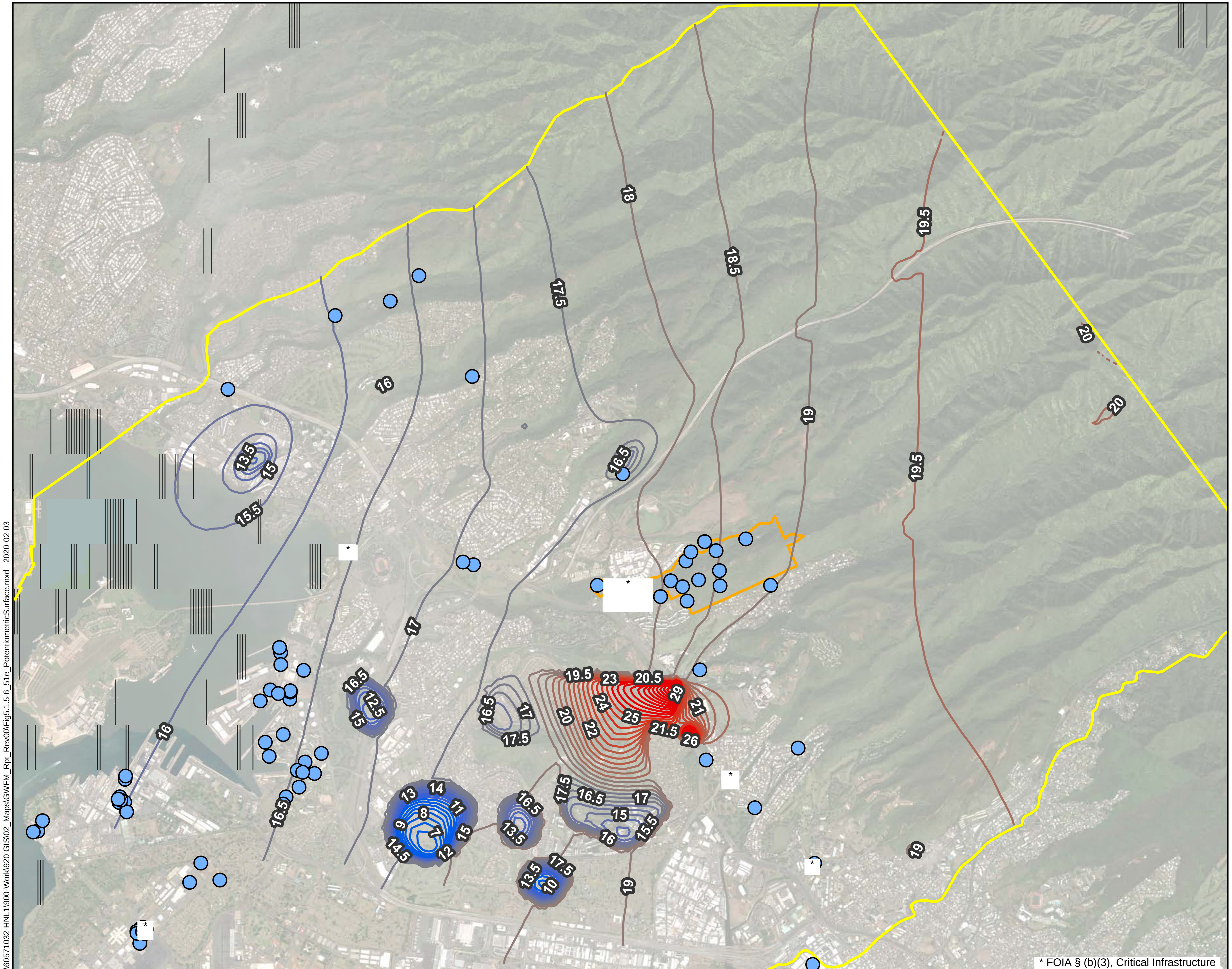
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

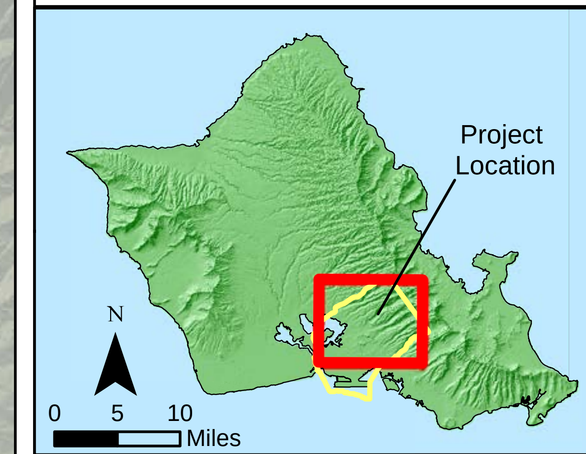
N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.1.5-5
Model #51e: Homogeneous Basalt with 3:1 Anisotropy with Basalt Zonation Over Hills and Valleys –
Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N
0 2,000 4,000 6,000 Feet

Figure 5.1.5-6
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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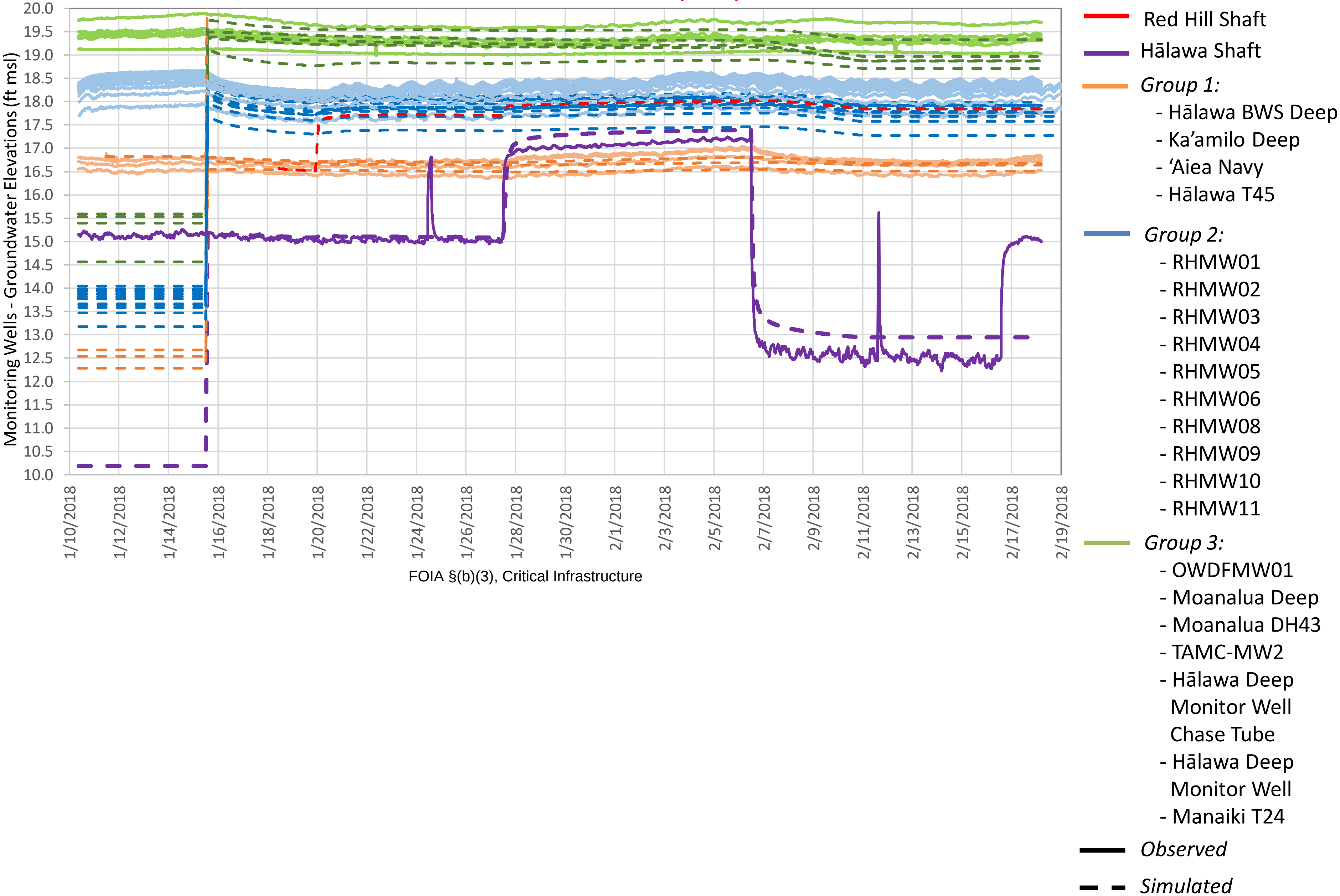


FOIA §(b)(3), Critical Infrastructure

Figure 5.1.5-7
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

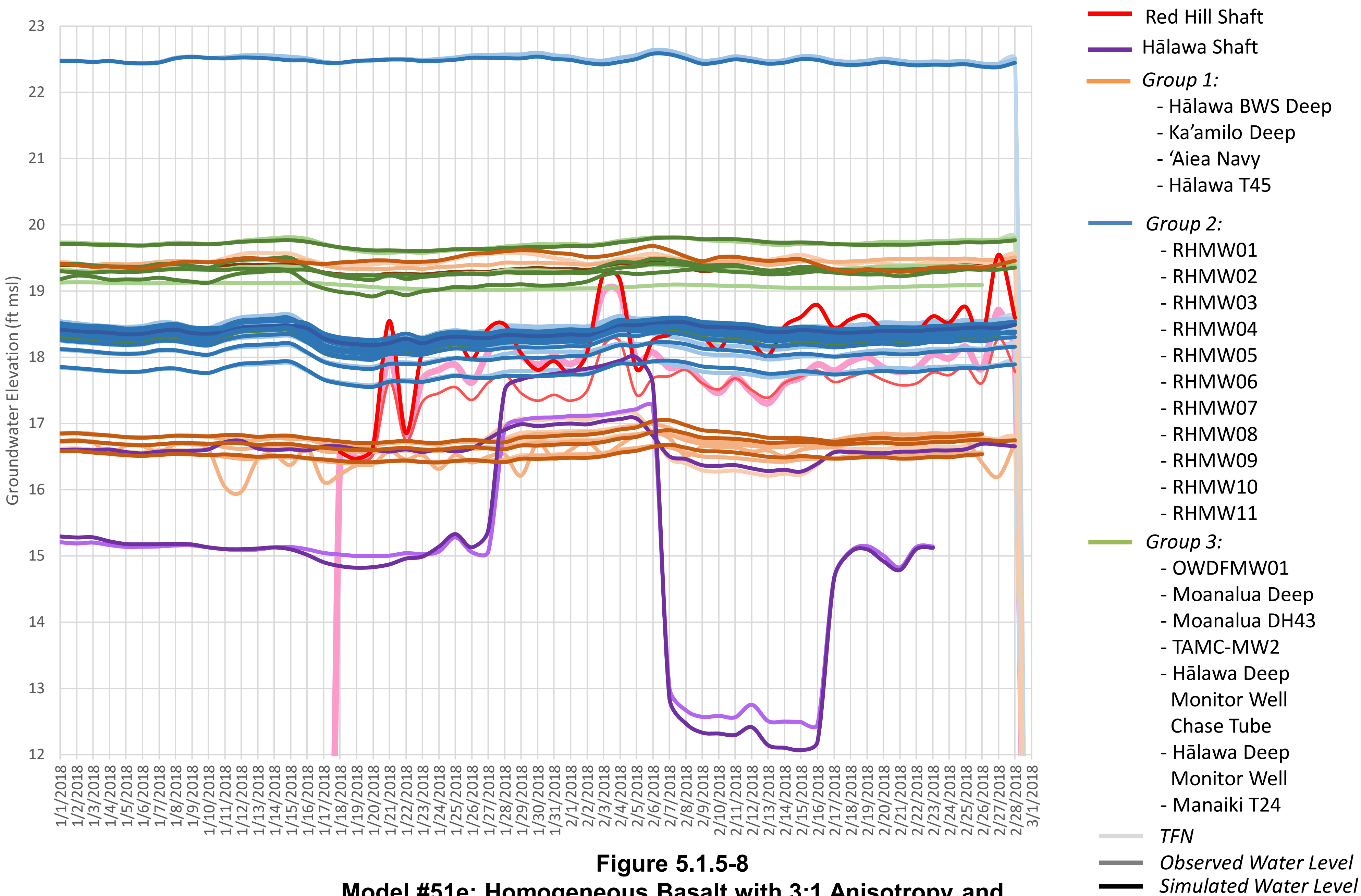
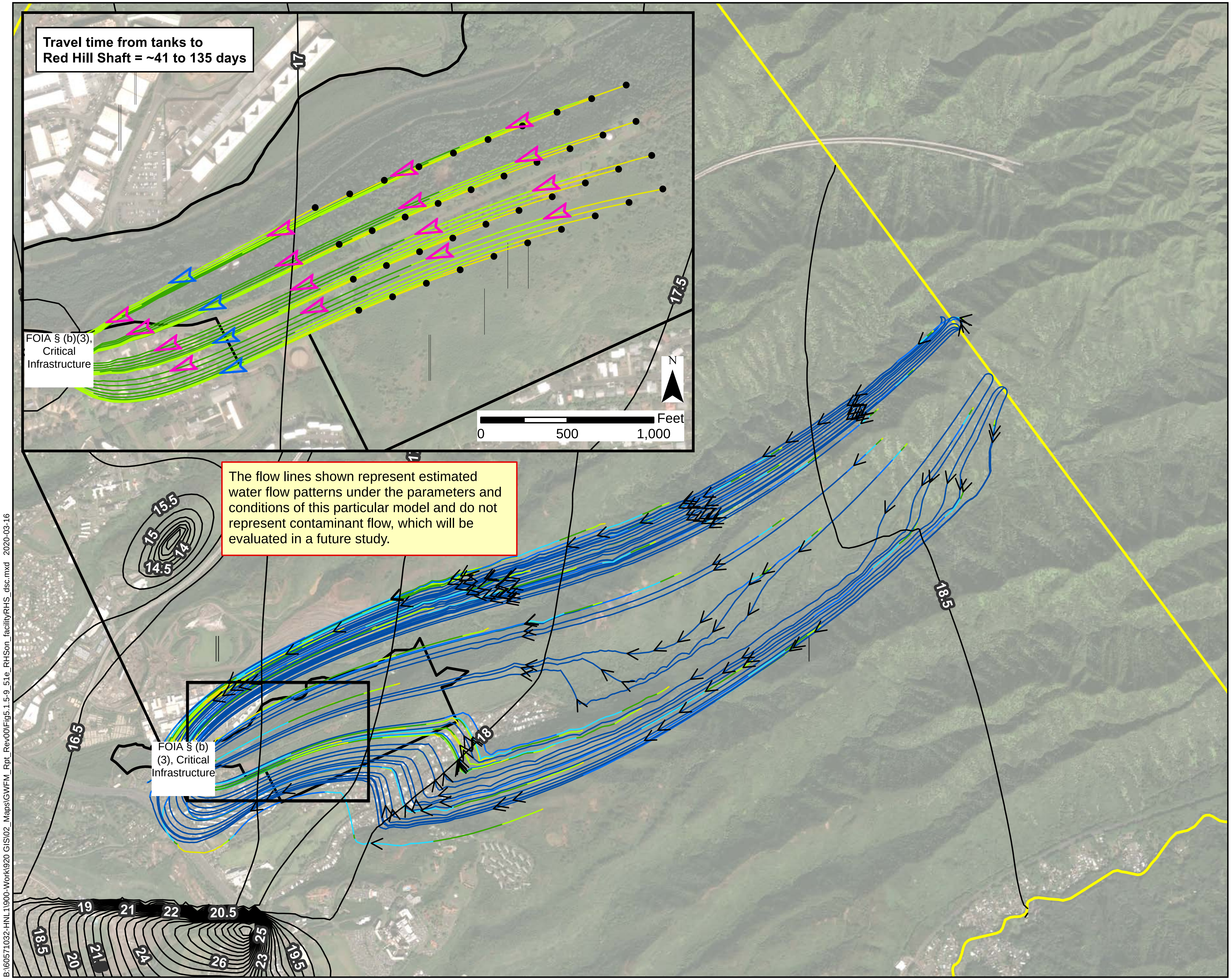
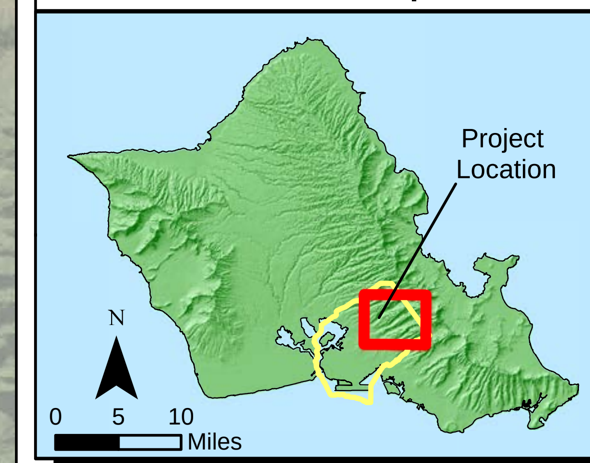


Figure 5.1.5-8
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.1.5-9
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys –
Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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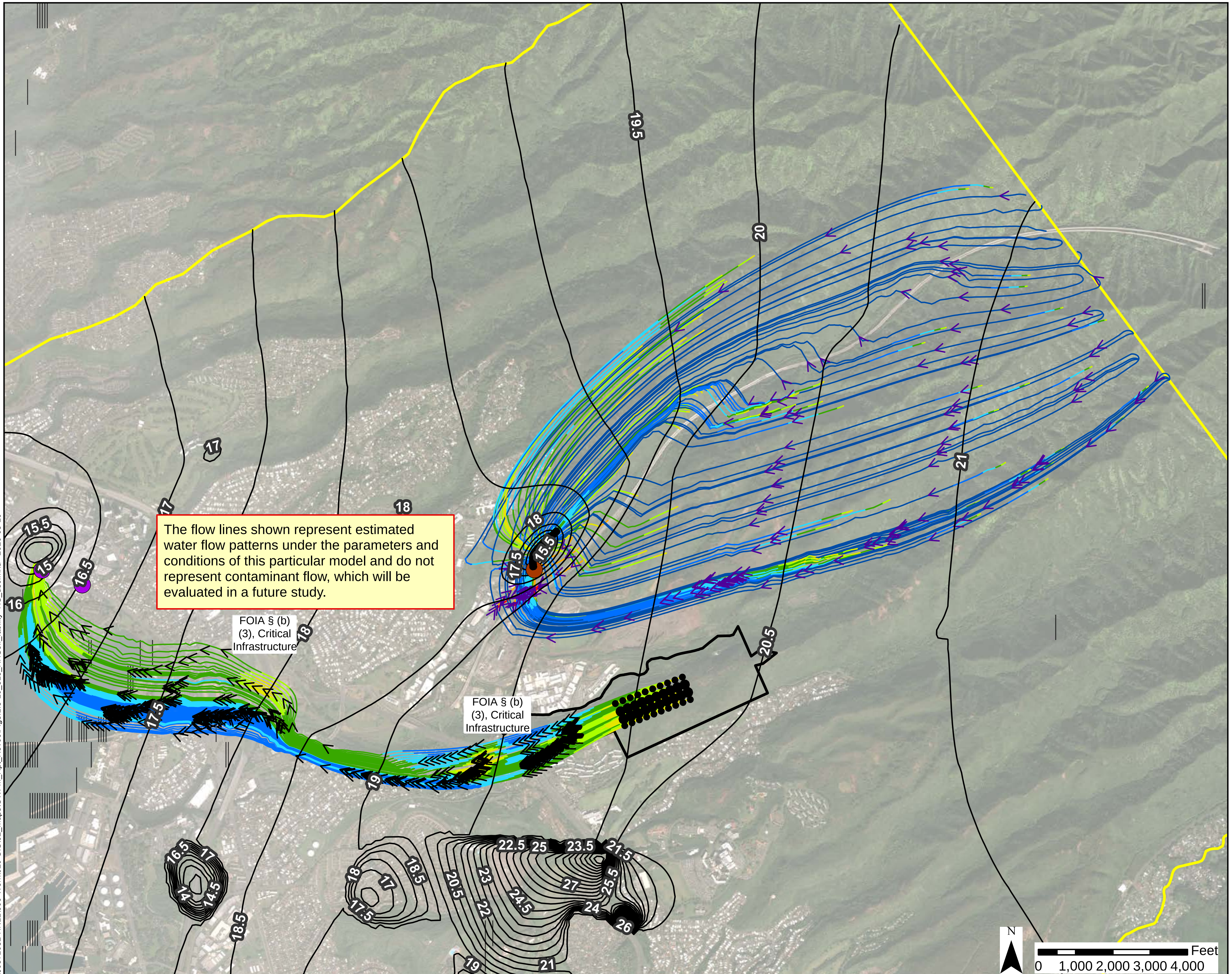
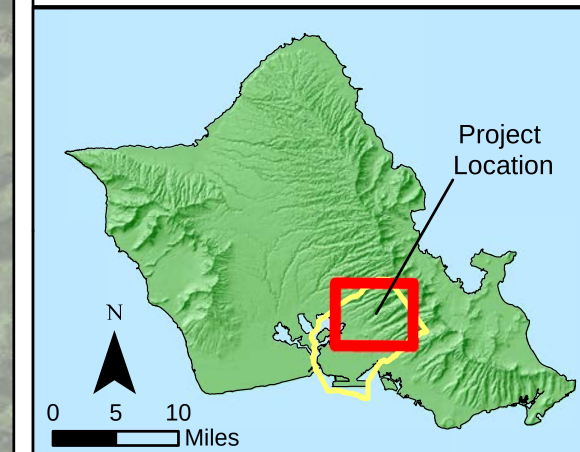


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 180 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.1.5-10
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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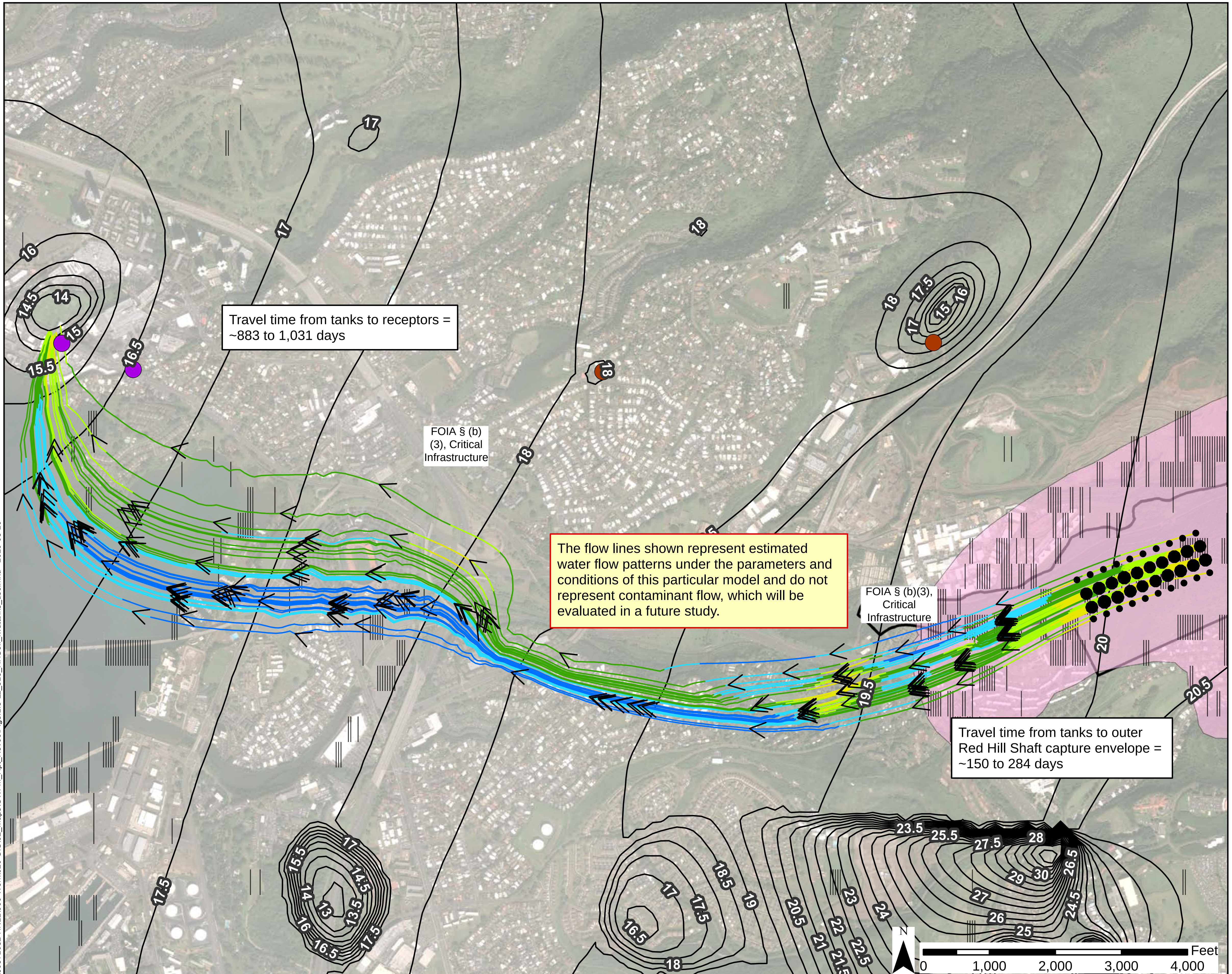
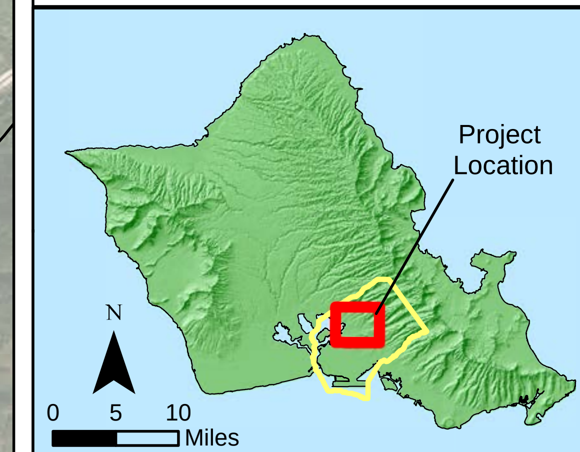


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.1.5-11
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys –
Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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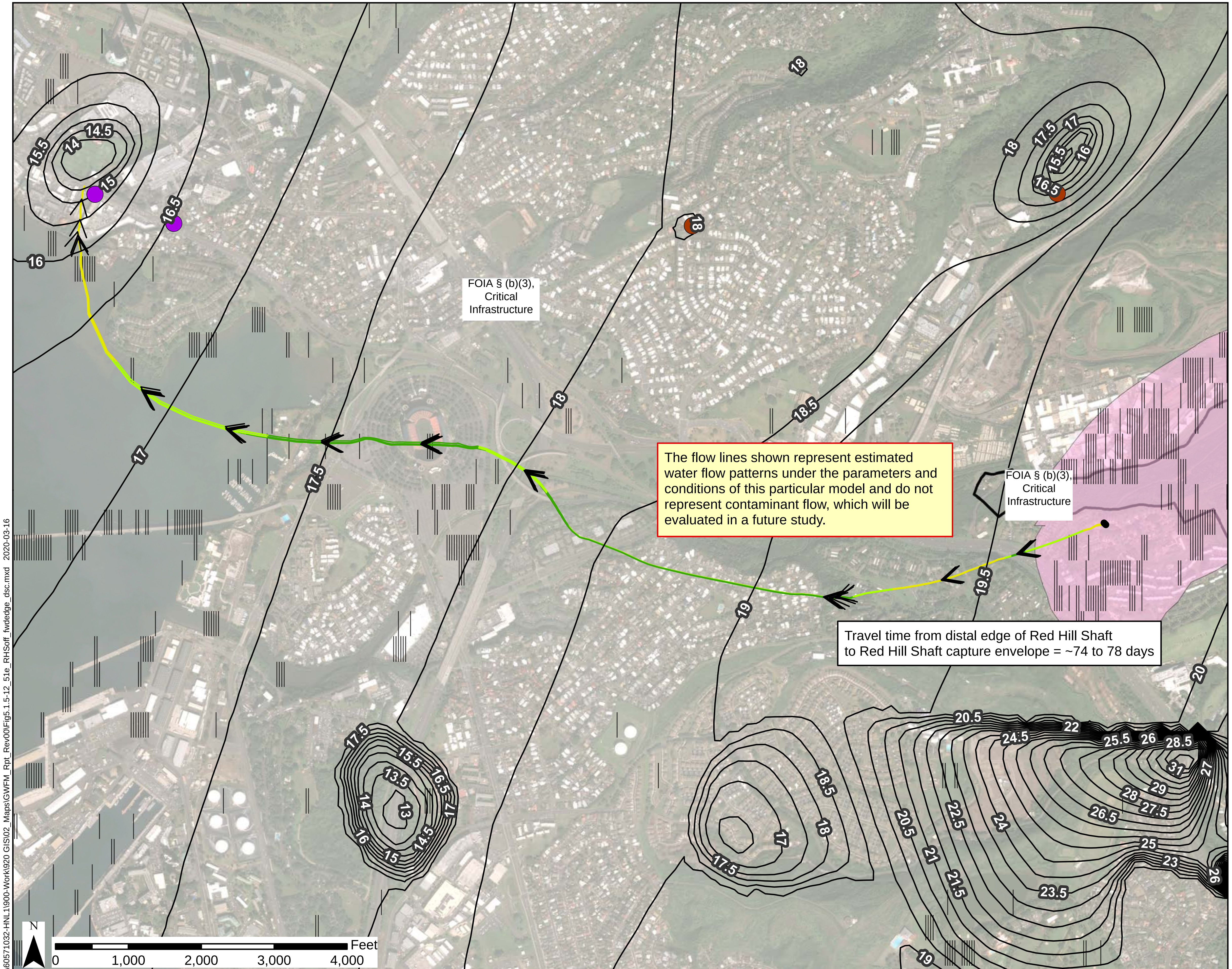
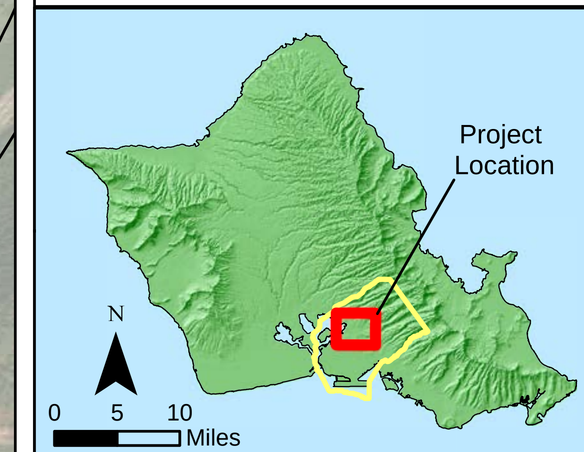


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days.

Figure 5.1.5-12
Model #51e: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation Over Hills and Valleys – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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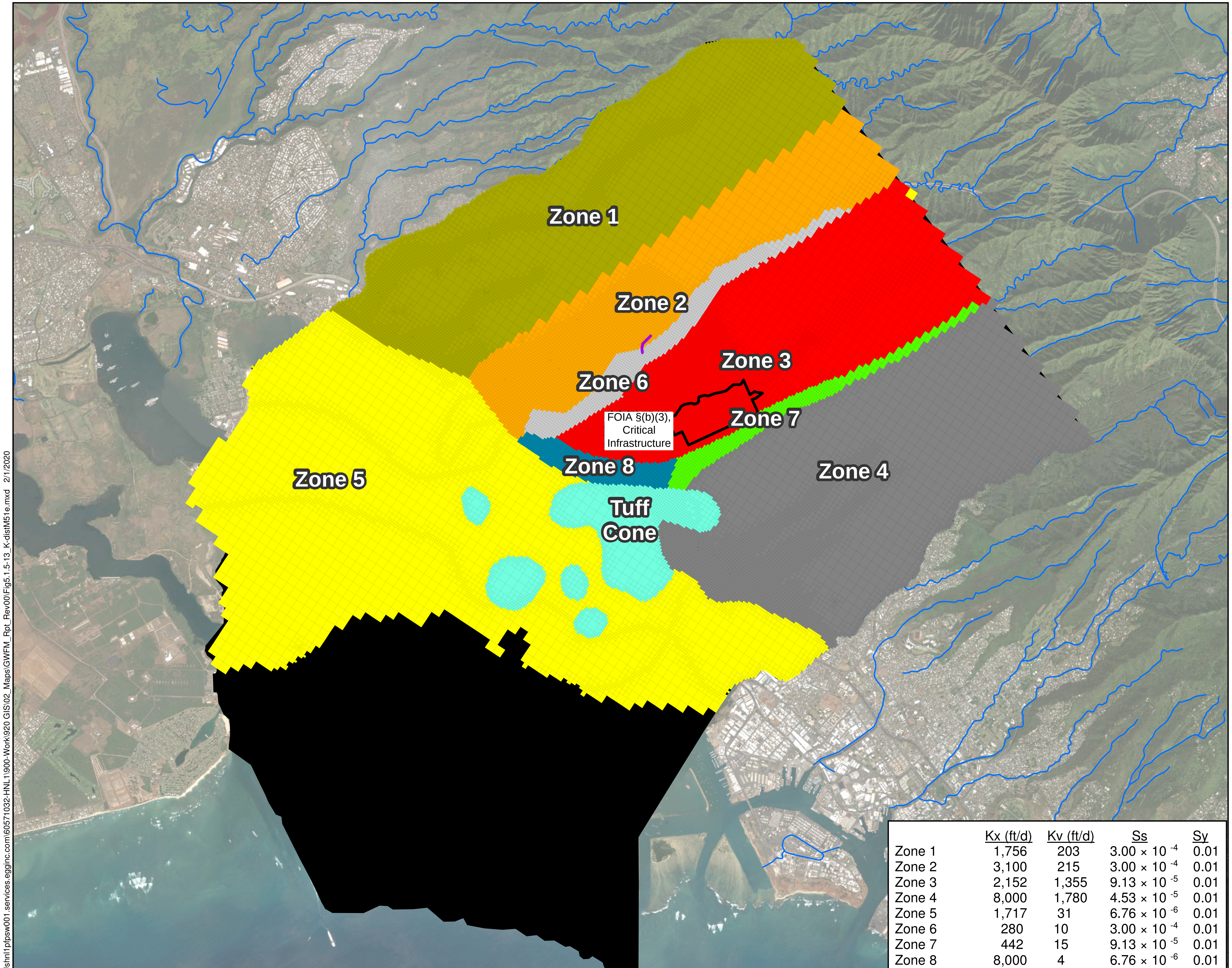
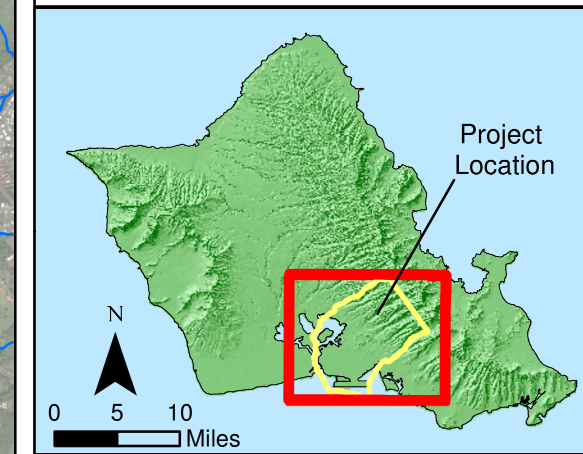


	Kx (ft/d)	Kv (ft/d)	Ss	Sy
Zone 1	1,756	203	3.00×10^{-4}	0.01
Zone 2	3,100	215	3.00×10^{-4}	0.01
Zone 3	2,152	1,355	9.13×10^{-5}	0.01
Zone 4	8,000	1,780	4.53×10^{-5}	0.01
Zone 5	1,717	31	6.76×10^{-6}	0.01
Zone 6	280	10	3.00×10^{-4}	0.01
Zone 7	442	15	9.13×10^{-5}	0.01
Zone 8	8,000	4	6.76×10^{-6}	0.01

Location Map



Legend

- Zone 1
- Zone 2
- Zone 3
- Zone 4
- Zone 5
- Zone 6
- Zone 7
- Zone 8
- Tuff Cone
- Inactive Model Cells
- Shaft
- Red Hill Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

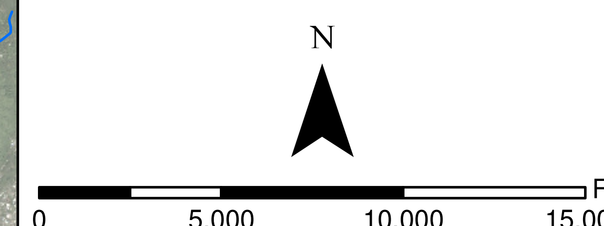


Figure 5.1.5-13
Hydraulic Conductivity Zonation in Basalt for Model #51e
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

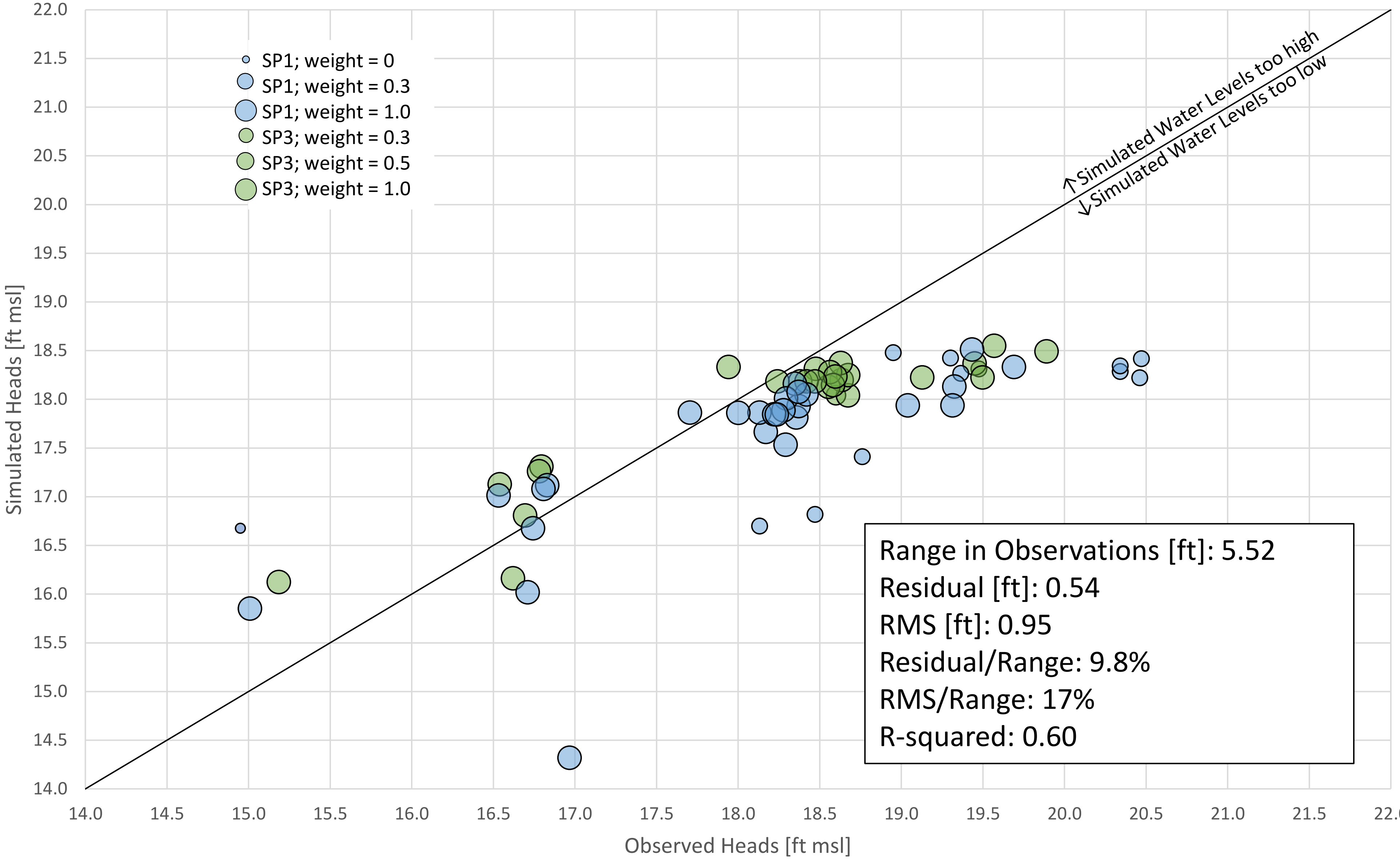
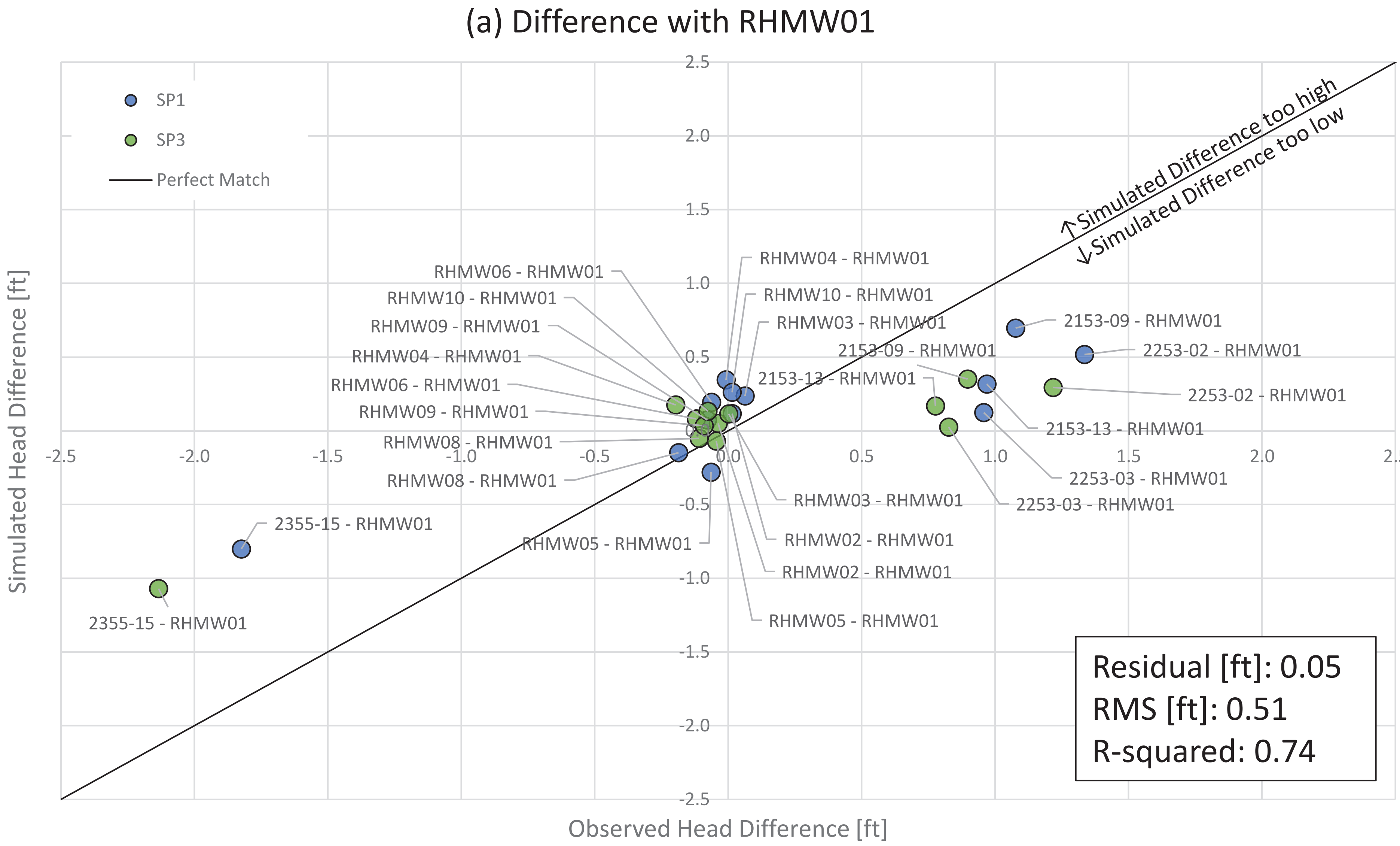


Figure 5.2-1
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



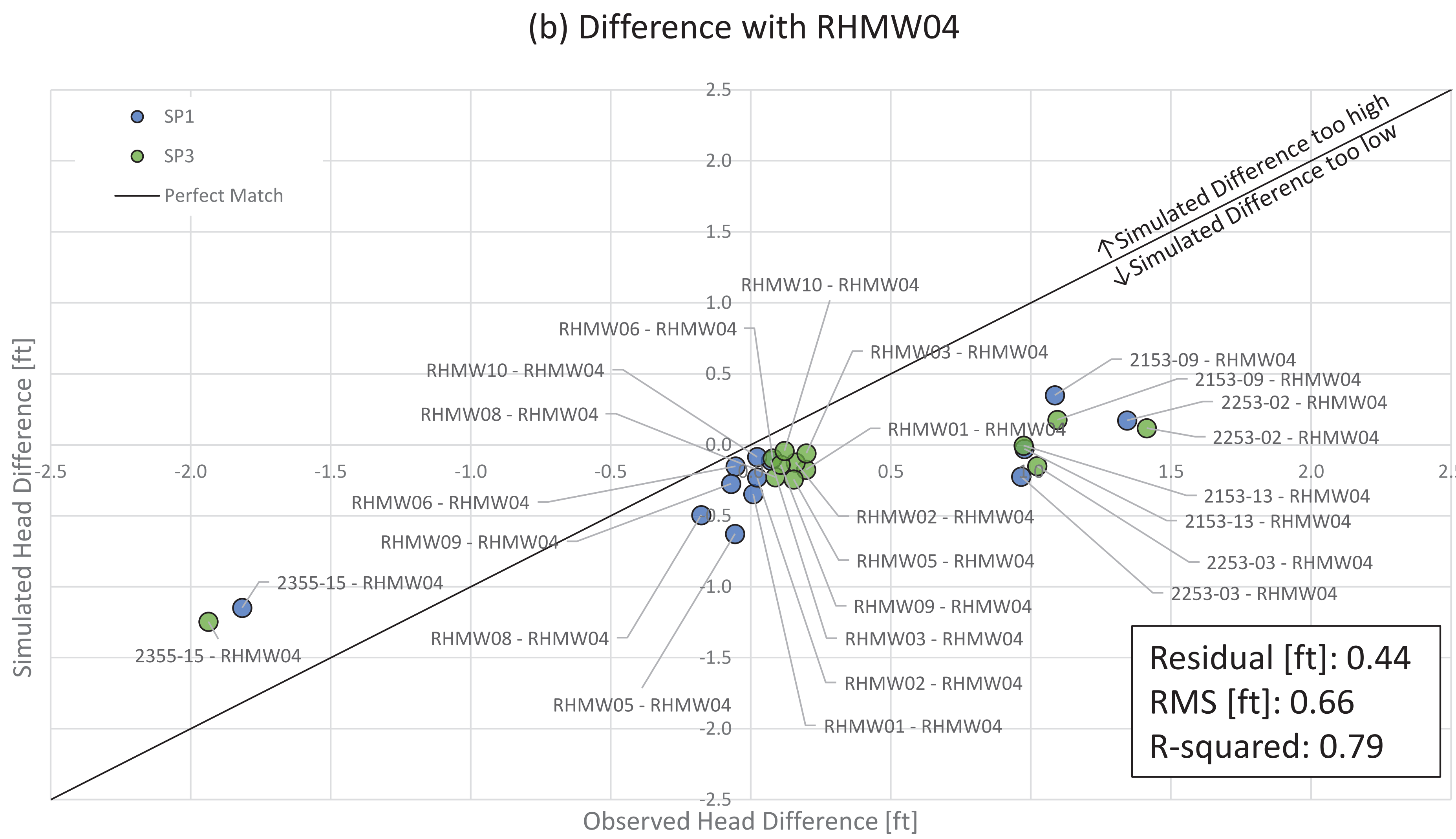


Figure 5.2-2
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

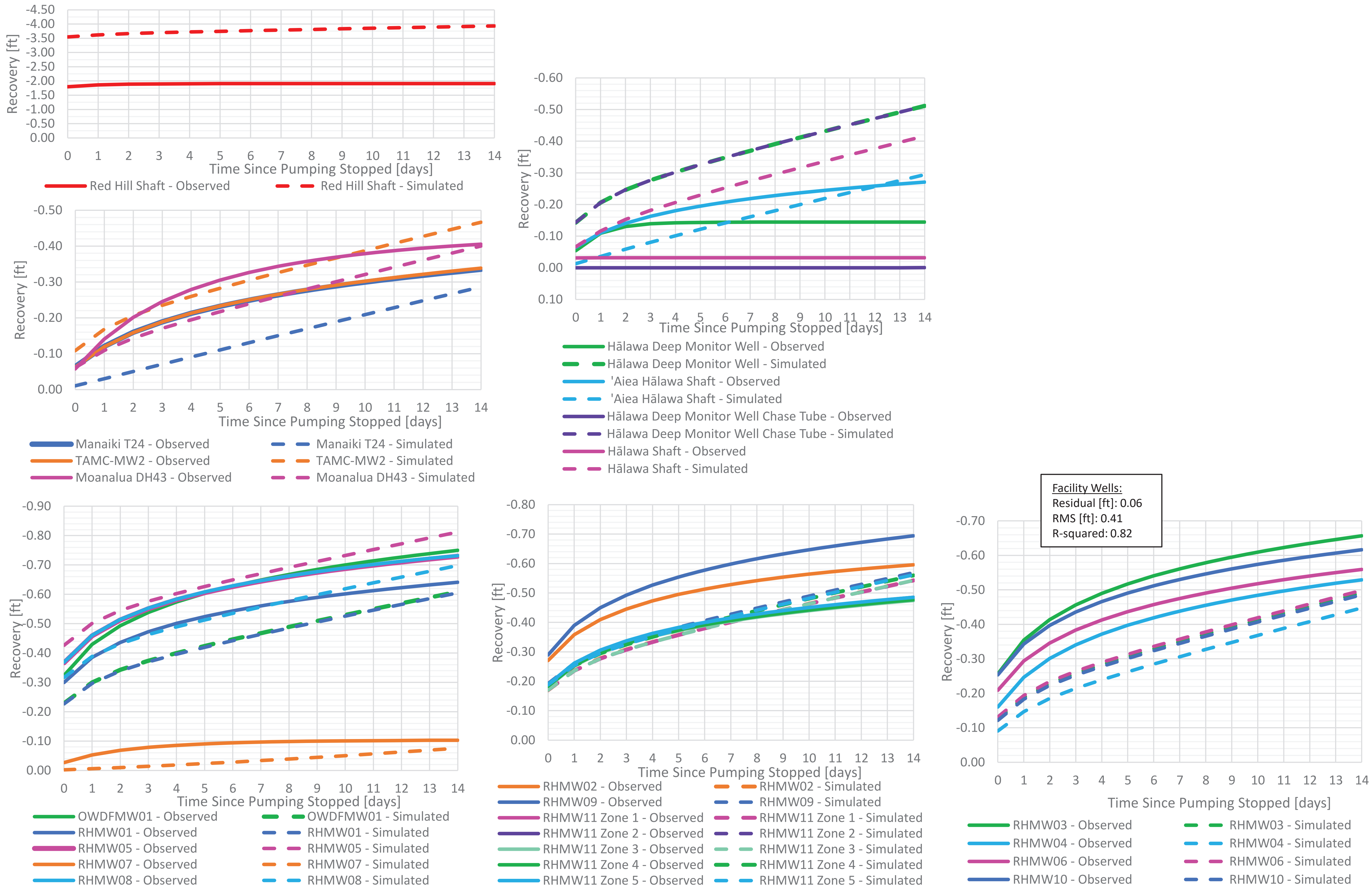


Figure 5.2-3
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

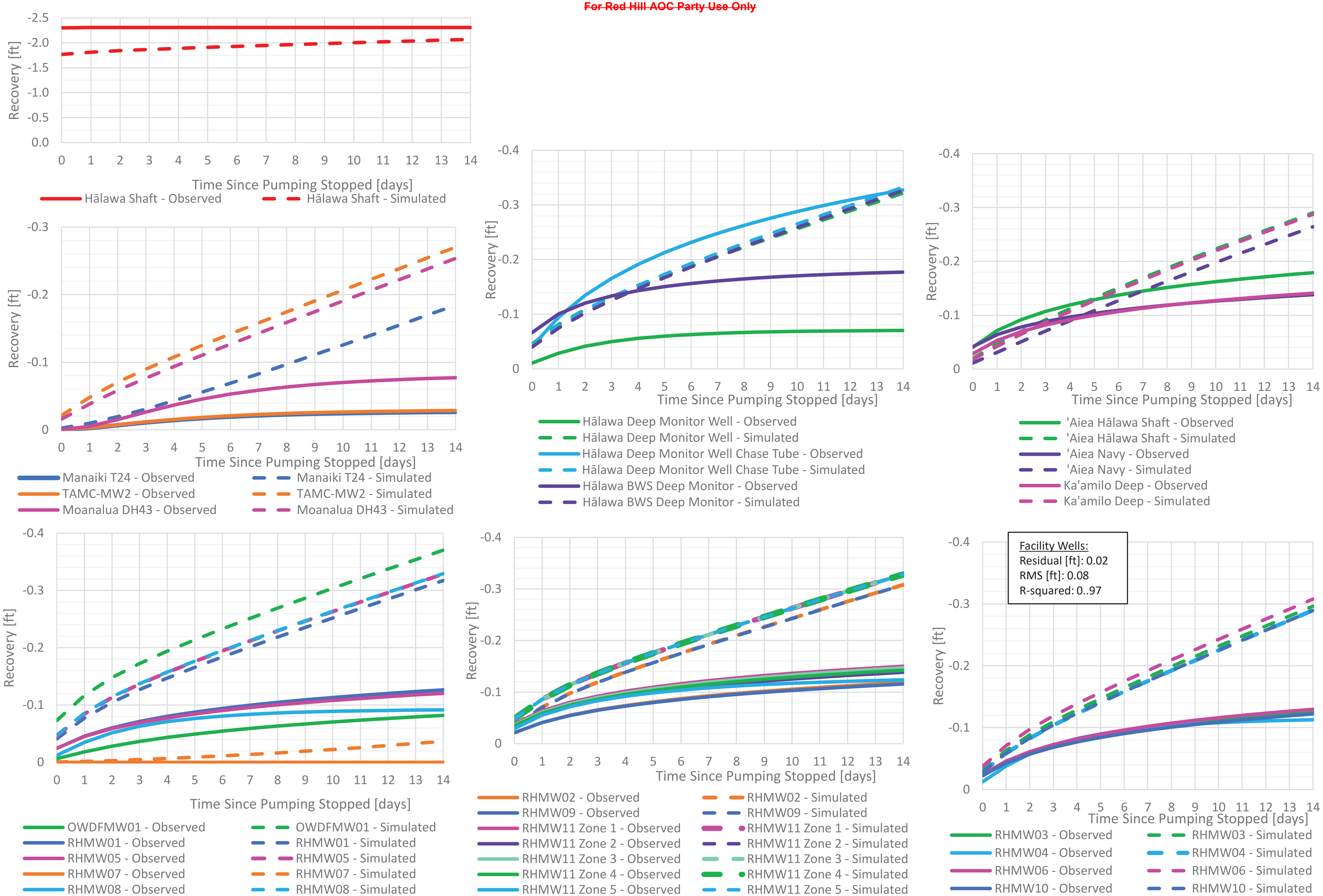
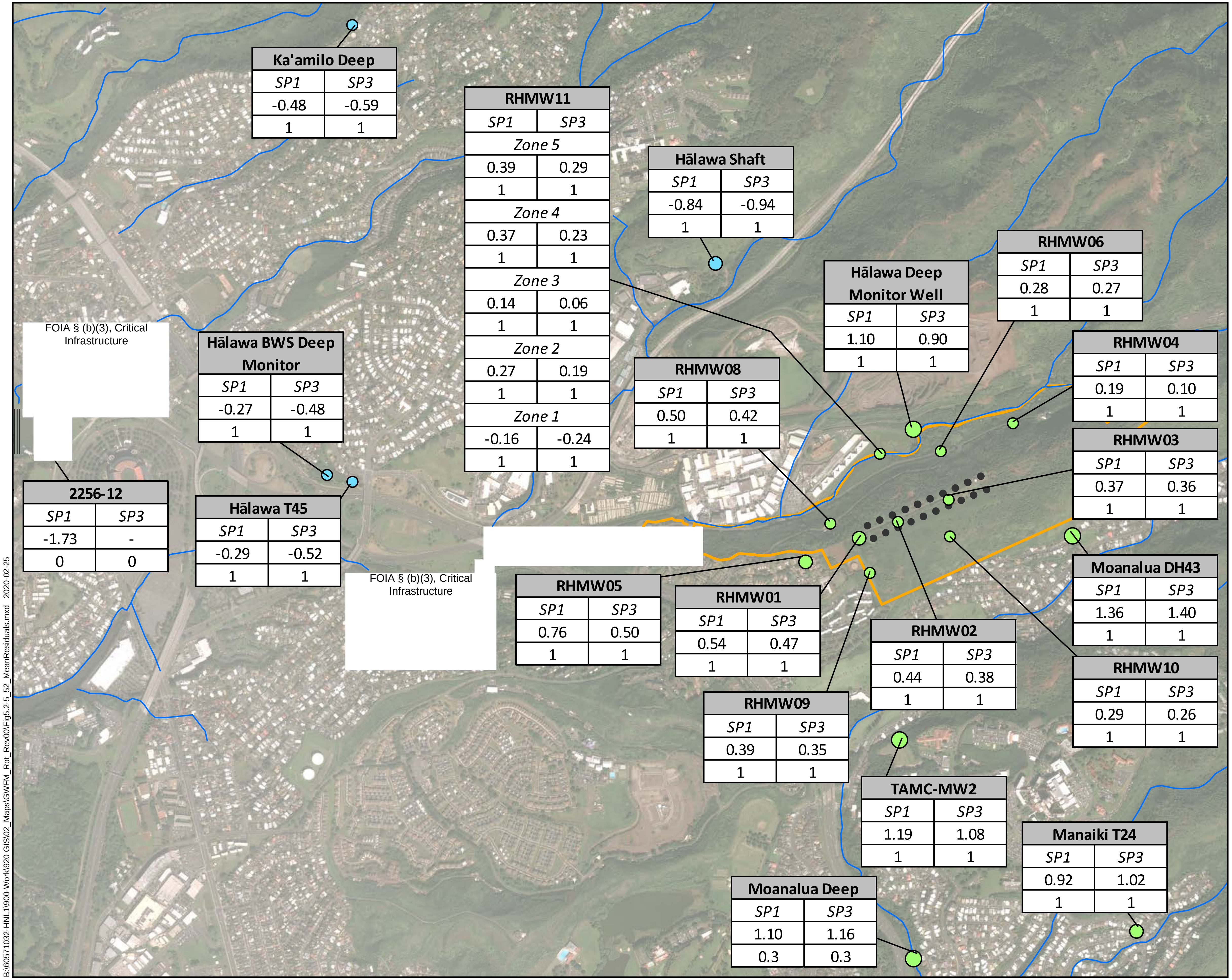


Figure 5.2-4
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



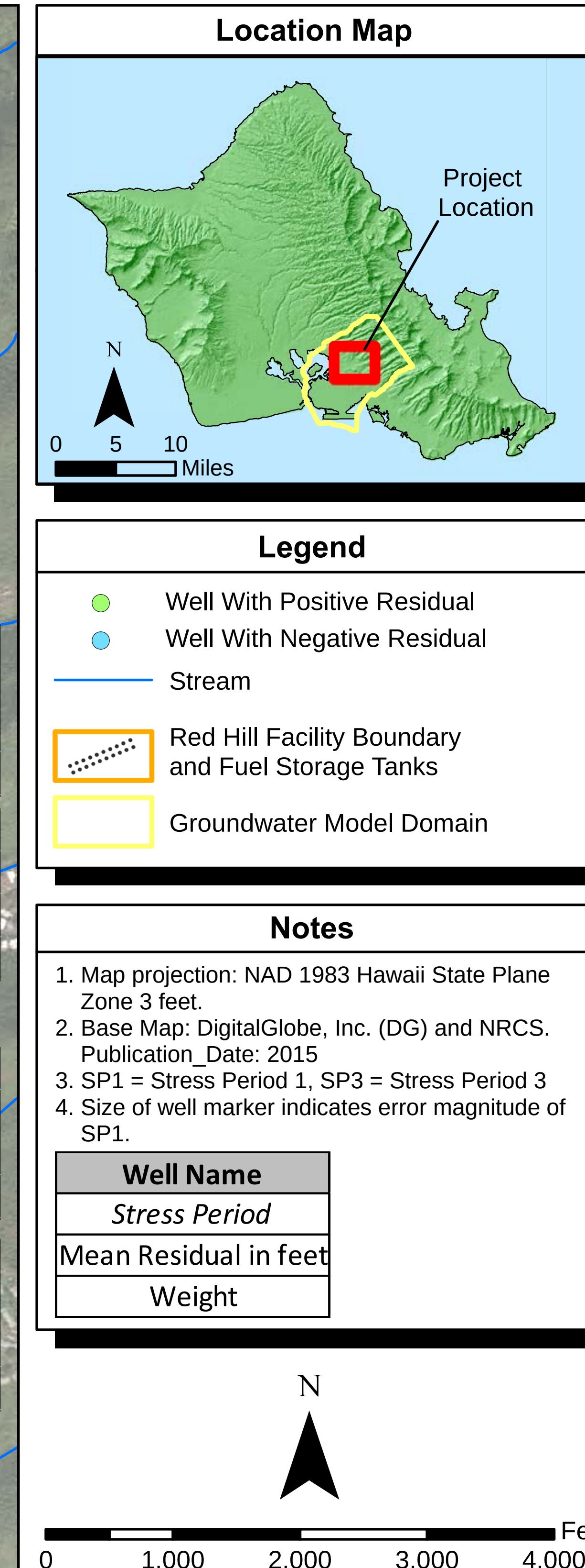


Figure 5.2-5
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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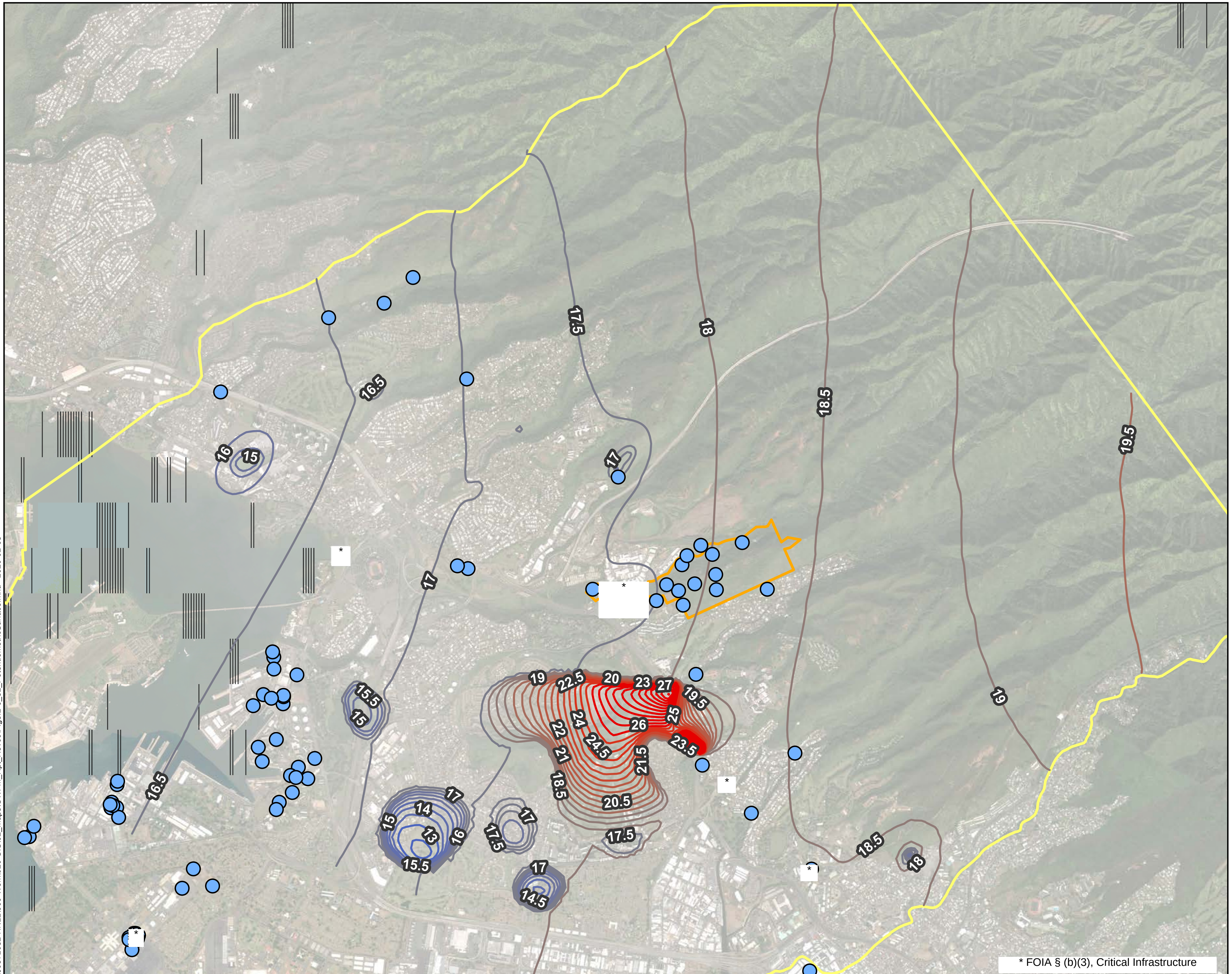
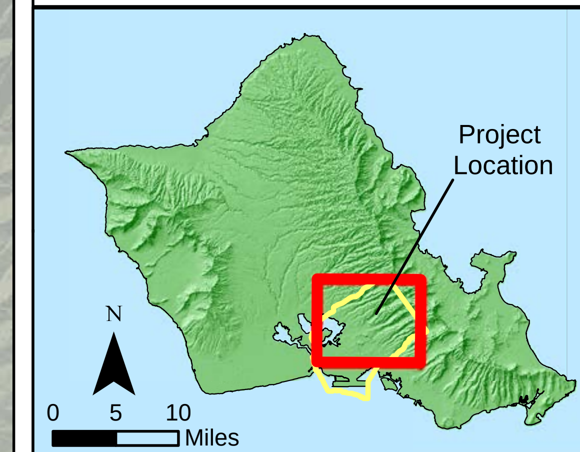


Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.2-6
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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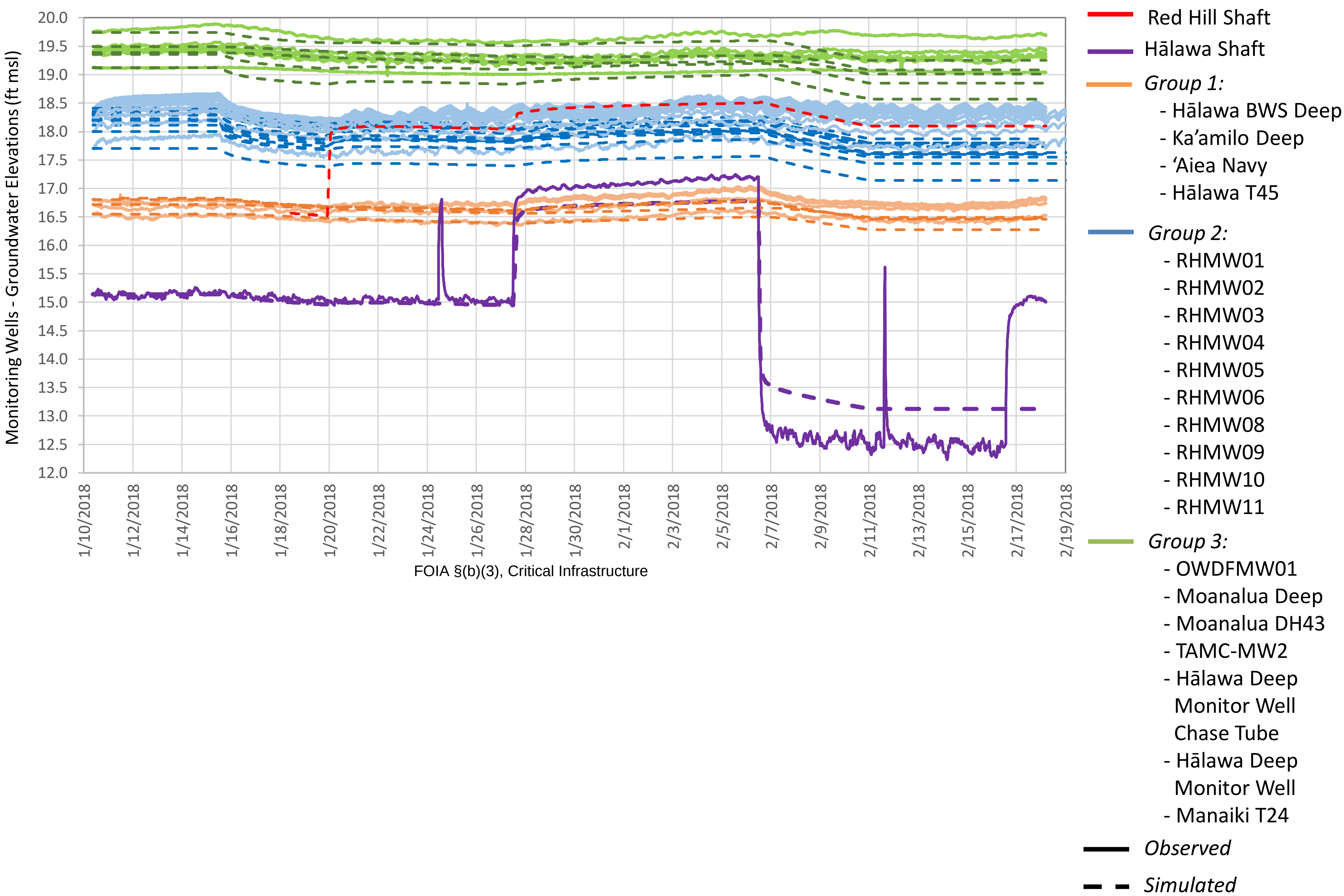


Figure 5.2-7
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

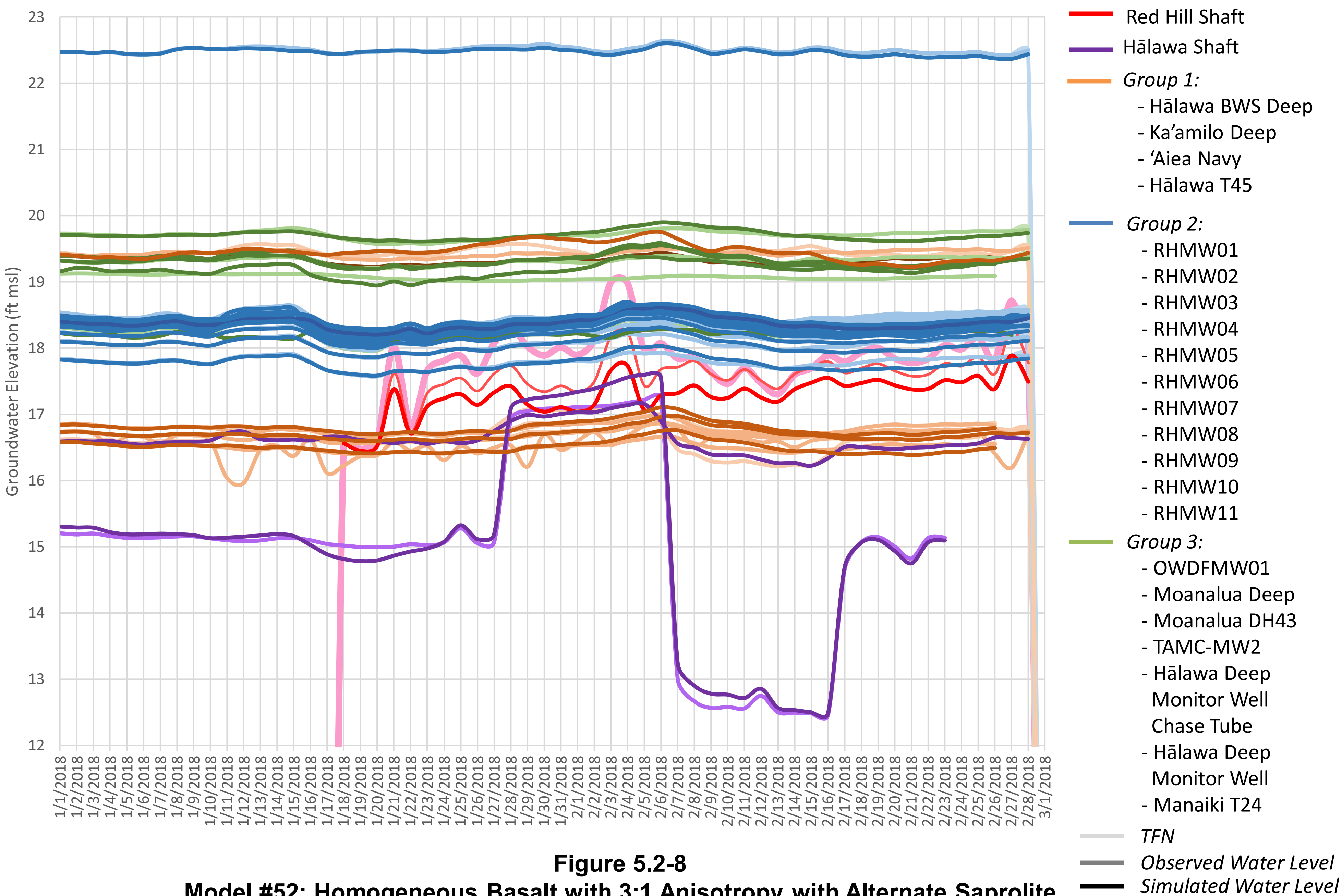
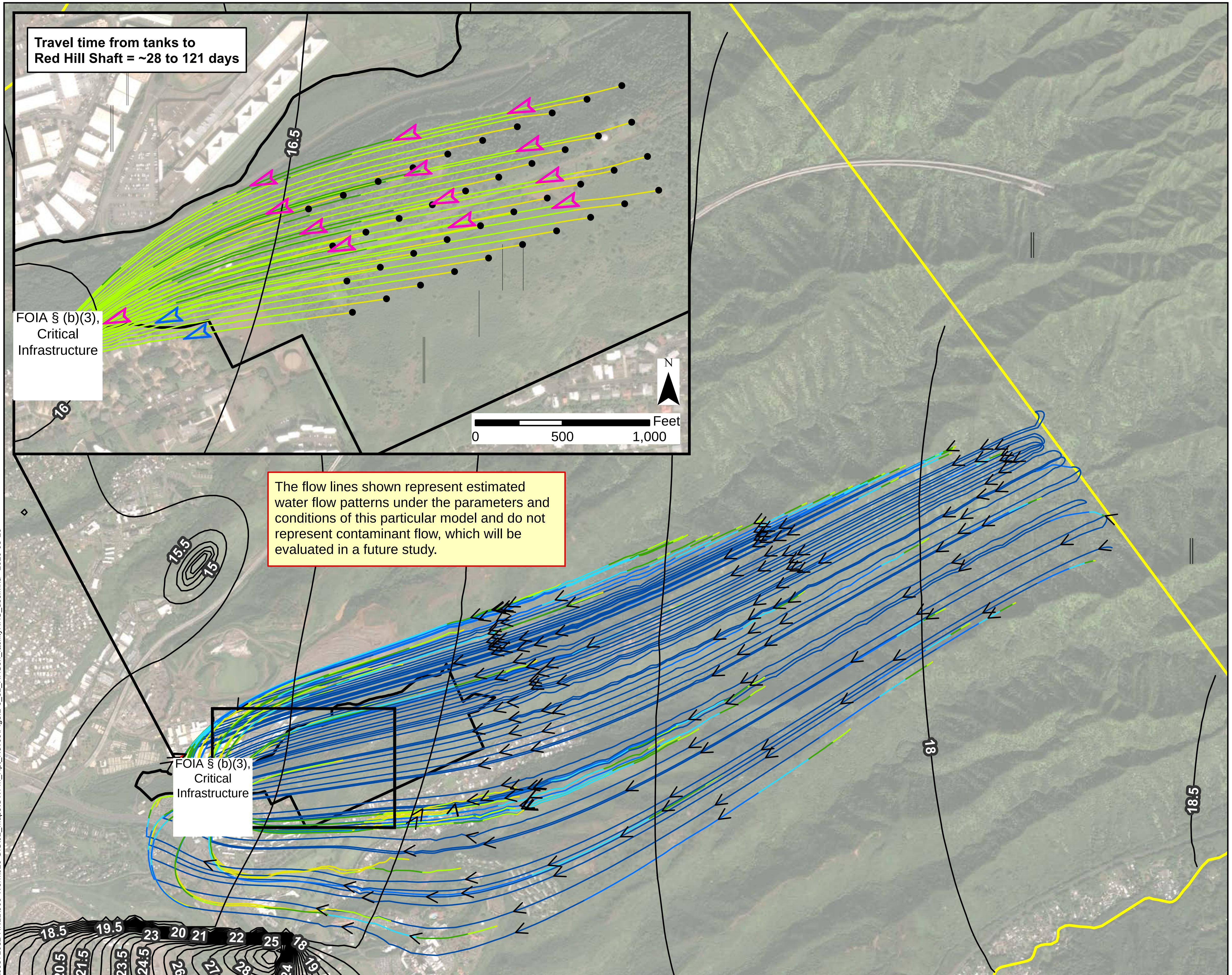
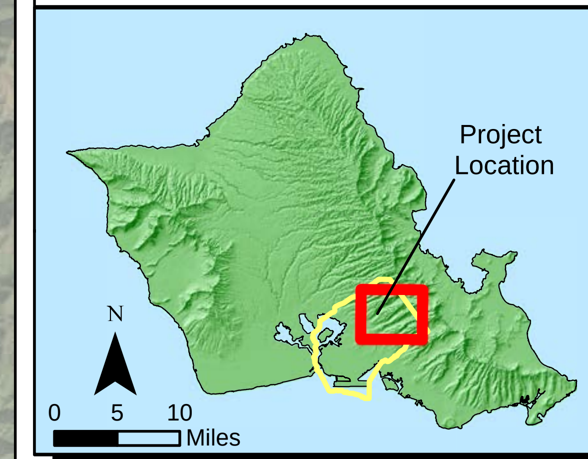


Figure 5.2-8
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.2-9
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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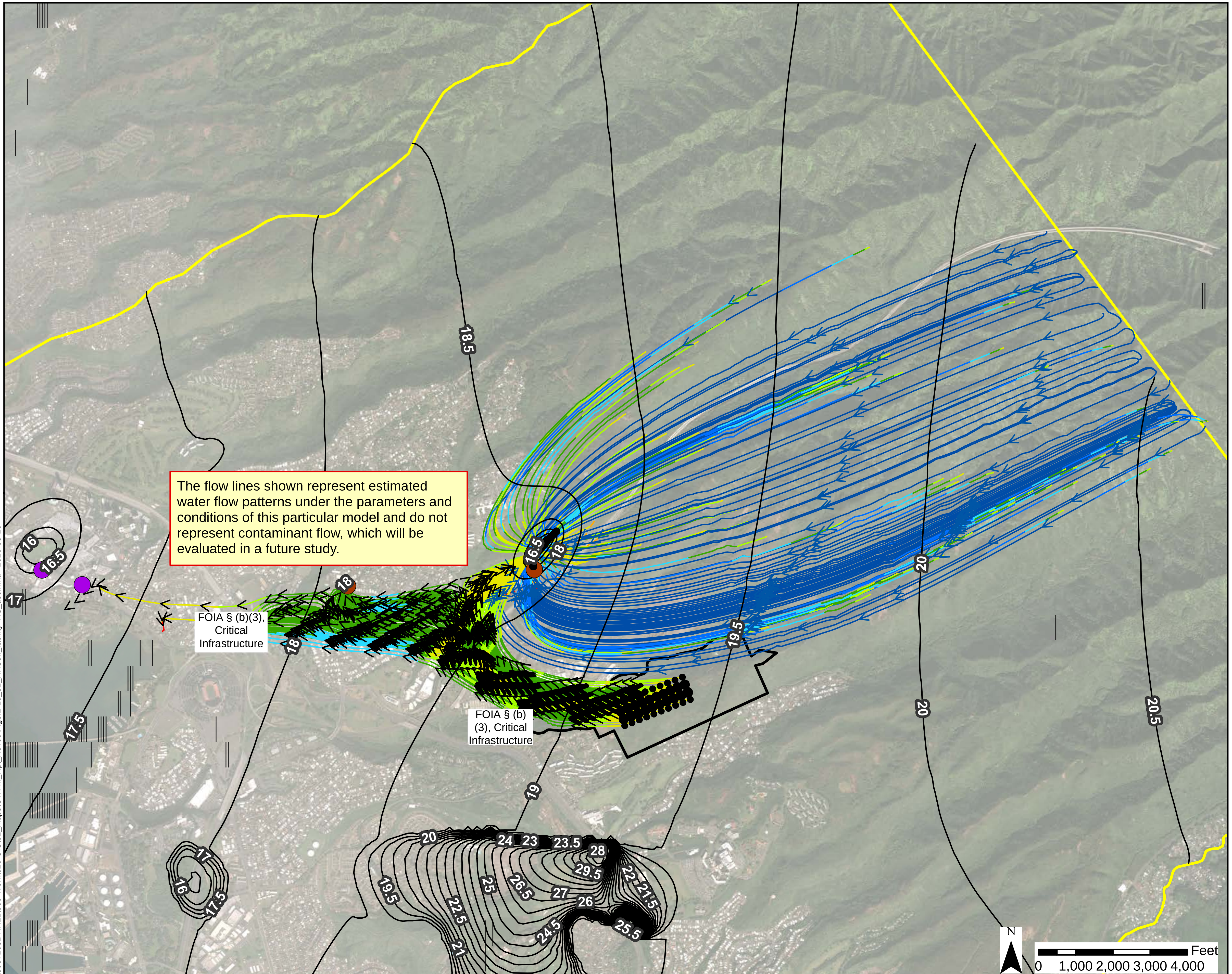
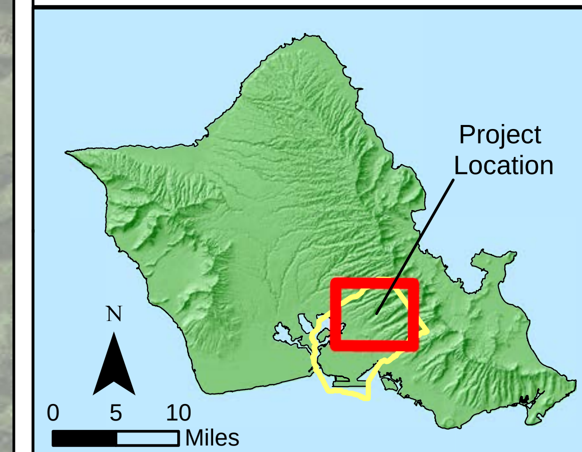


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.2-10
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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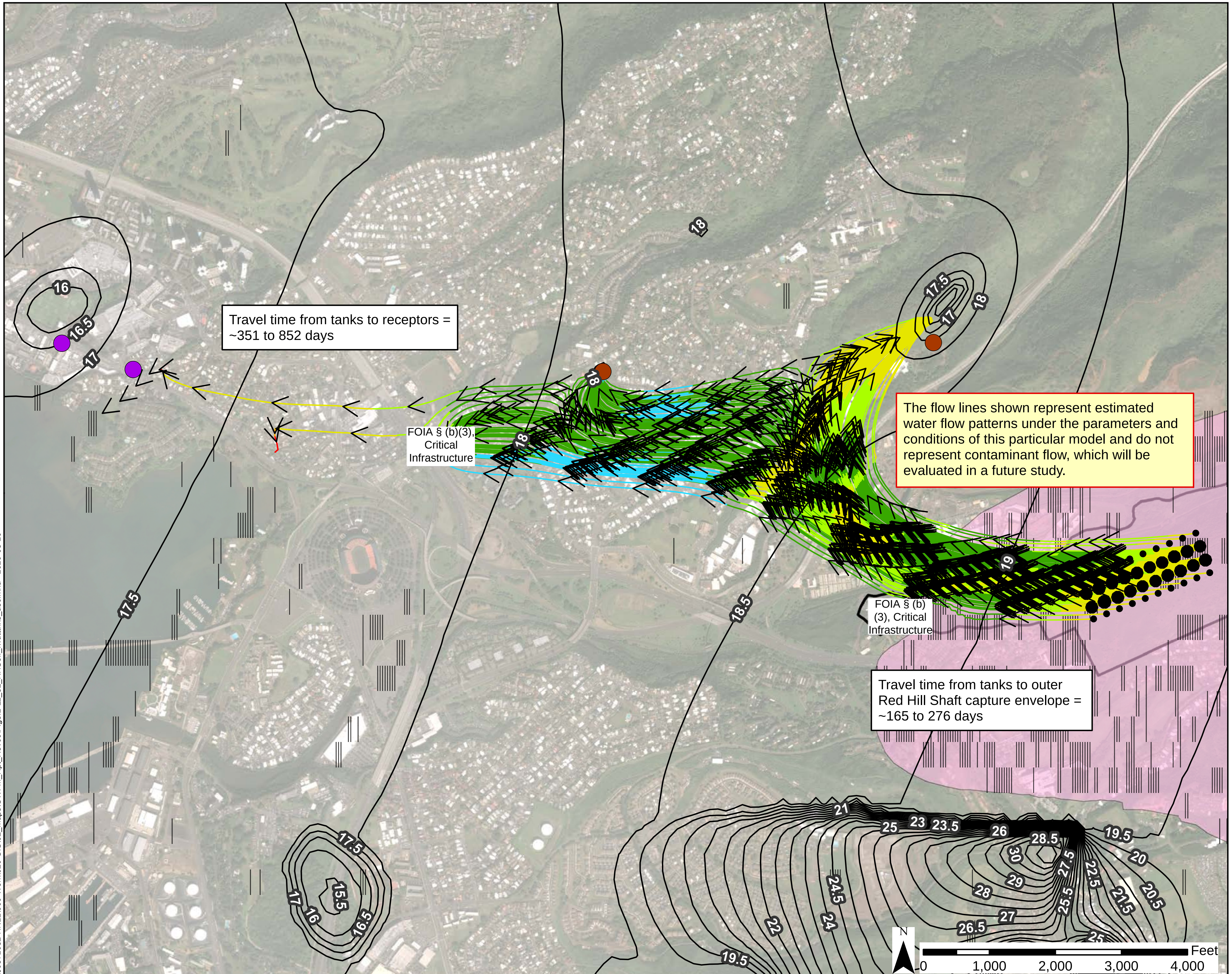
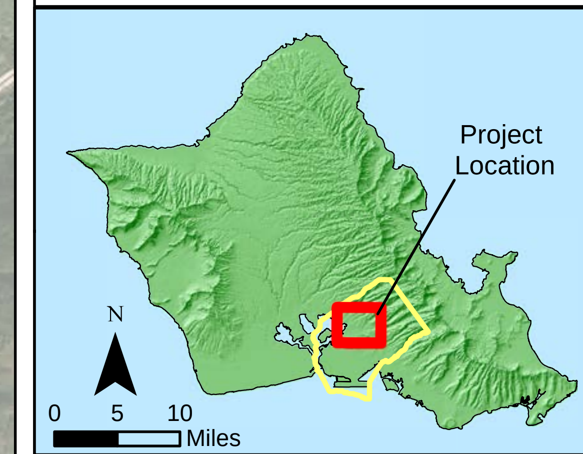


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.2-11
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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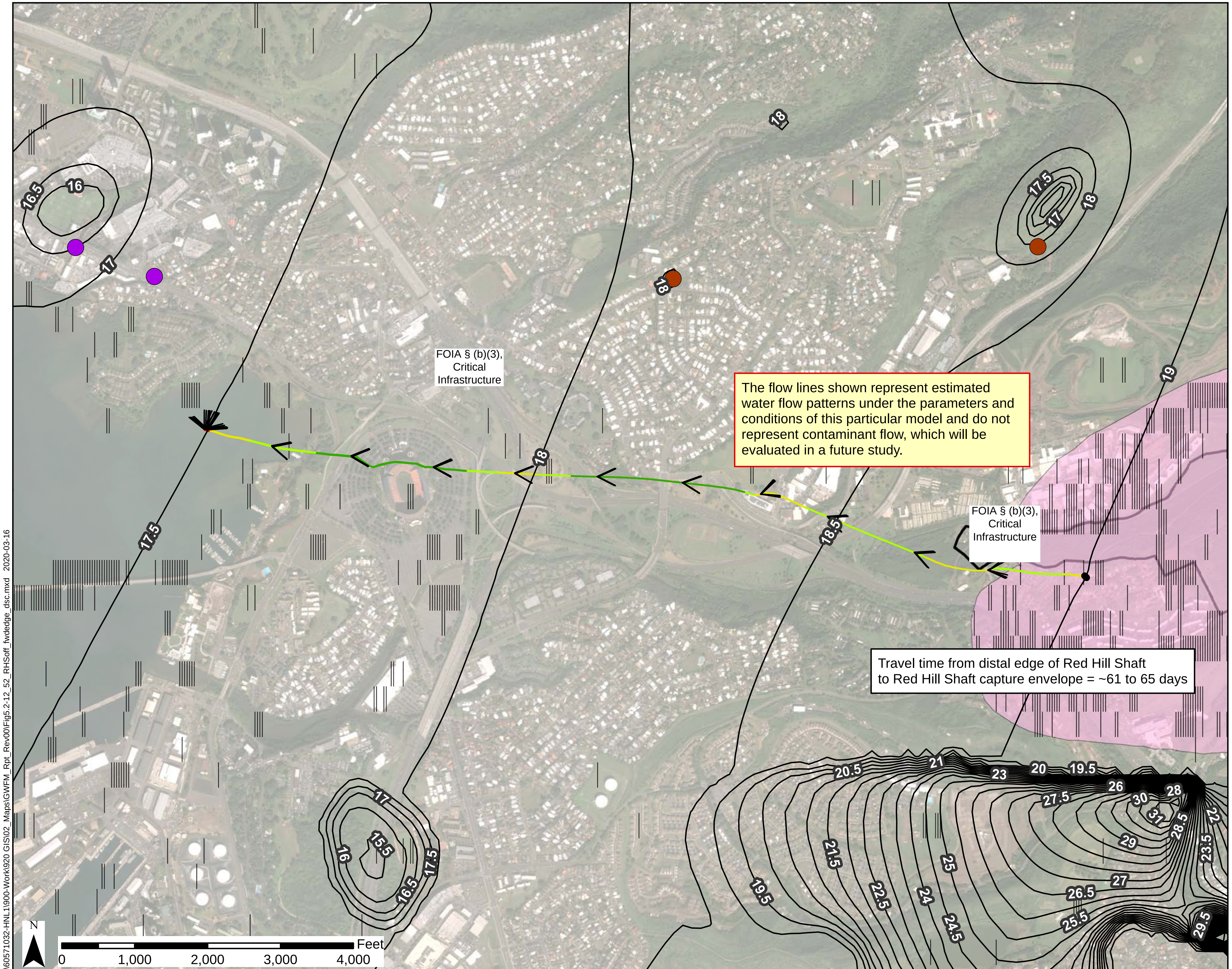
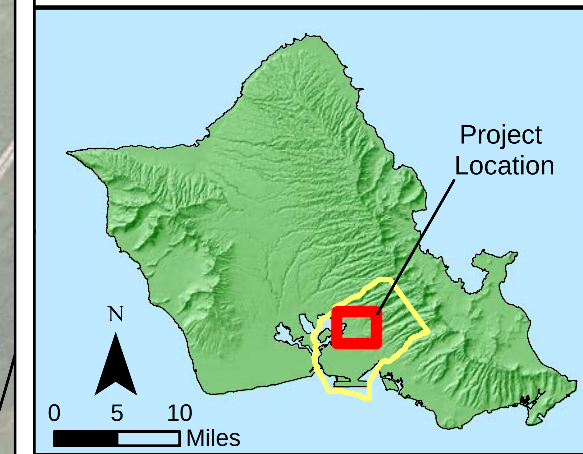


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9

- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.2-12
Model #52: Homogeneous Basalt with 3:1 Anisotropy with Alternate Saprolite – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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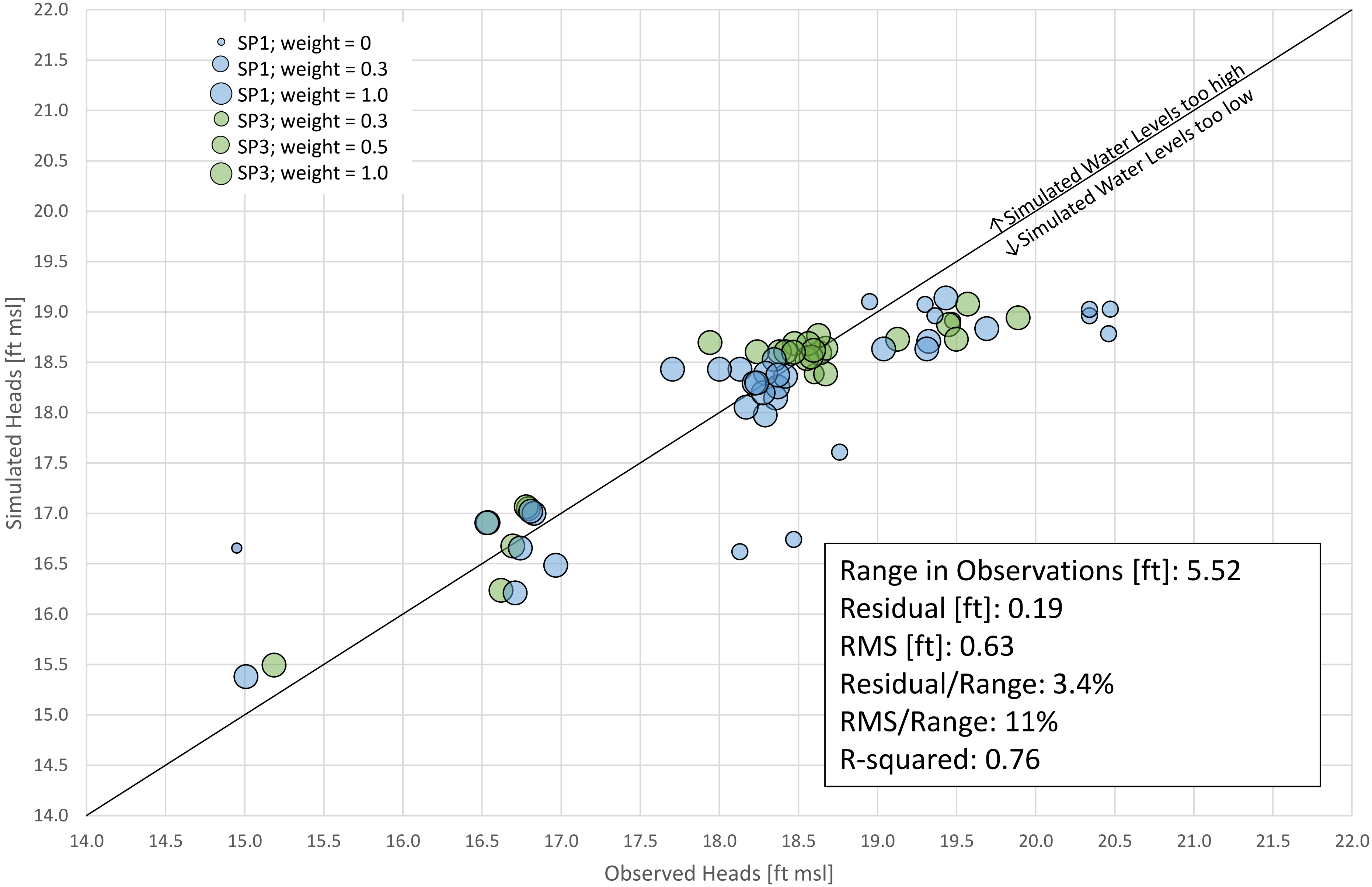
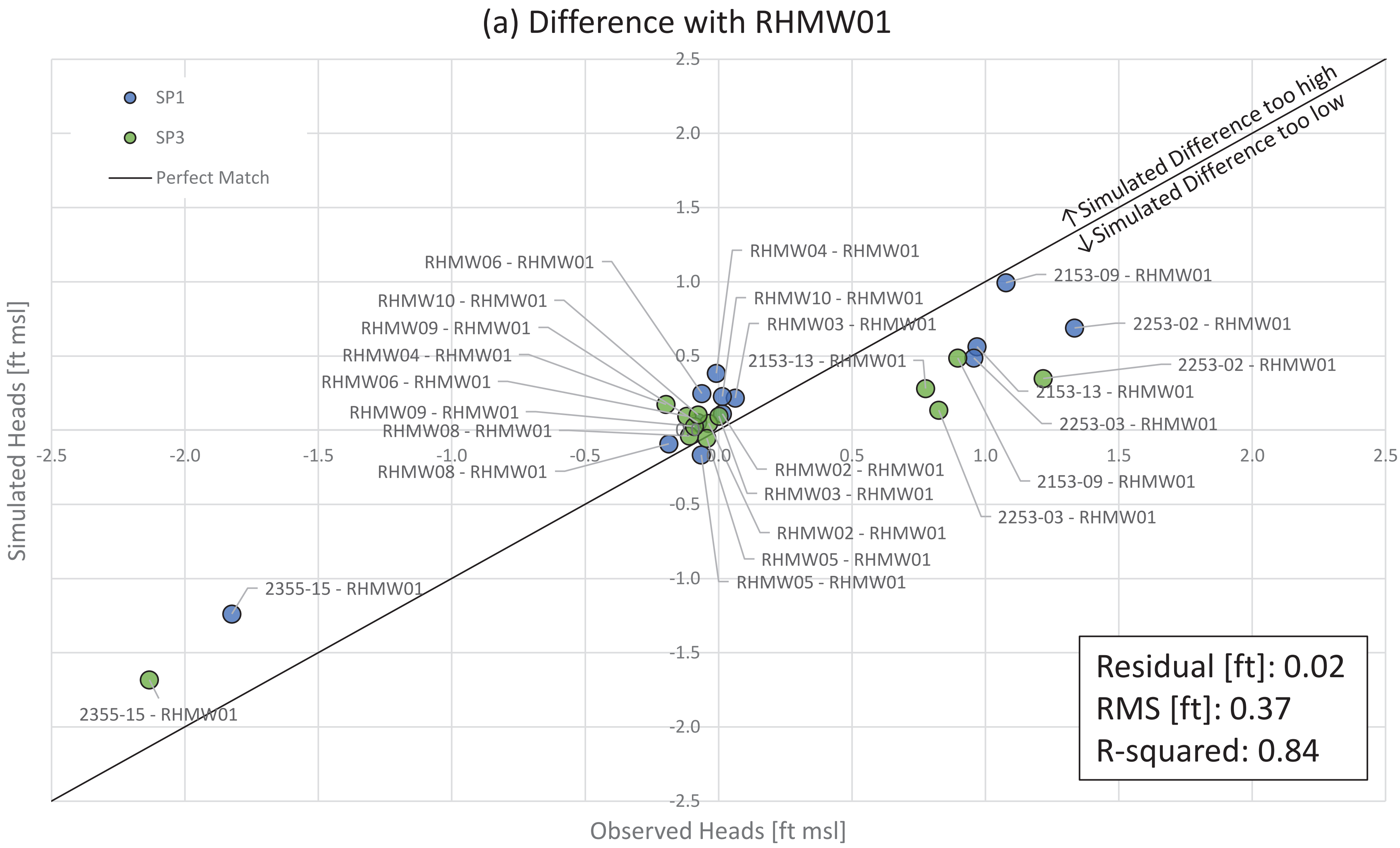


Figure 5.3-1
Model #53: Heterogeneous Basalt – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



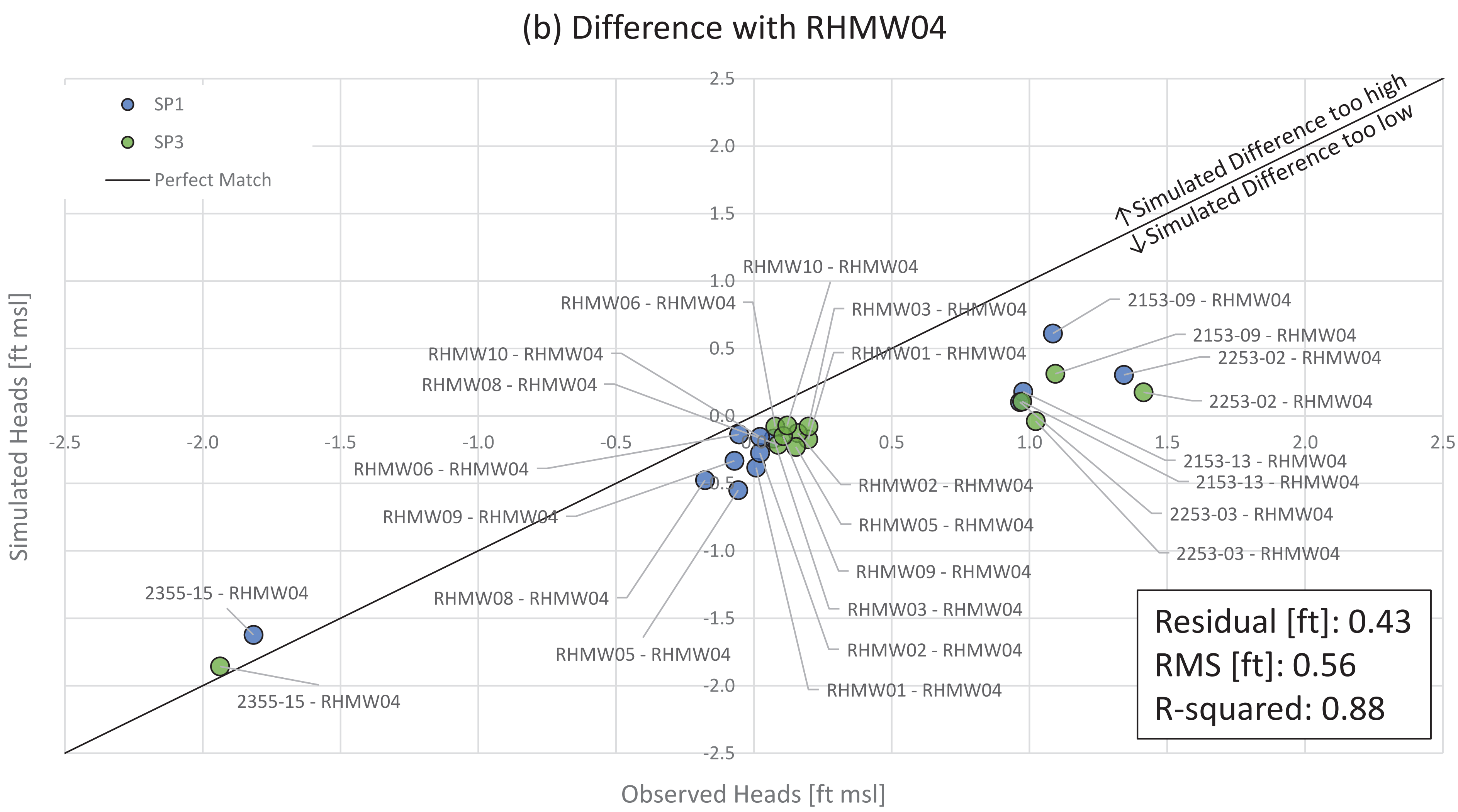


Figure 5.3-2
Model #53: Heterogeneous Basalt –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

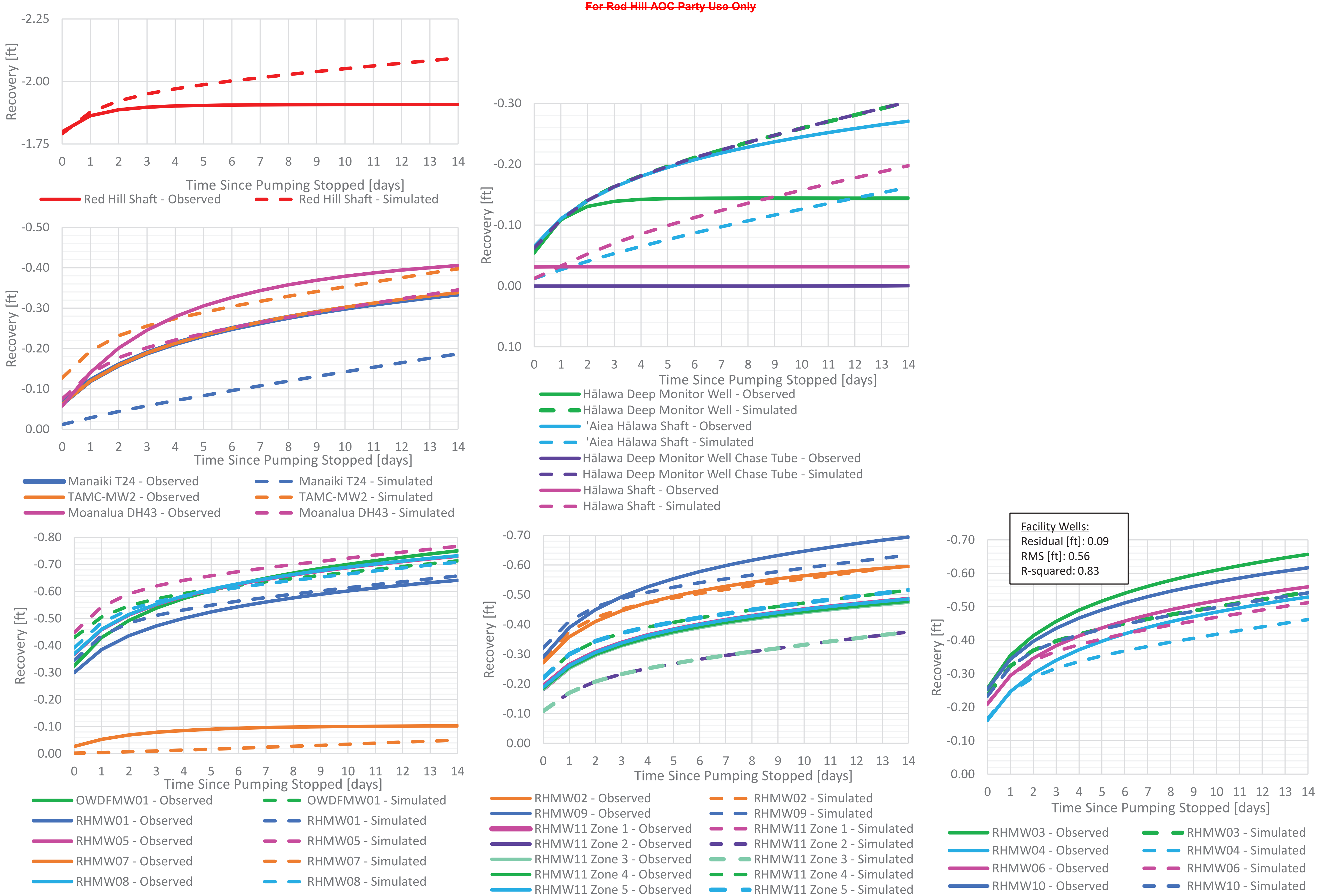


Figure 5.3-3
Model #53: Heterogeneous Basalt –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

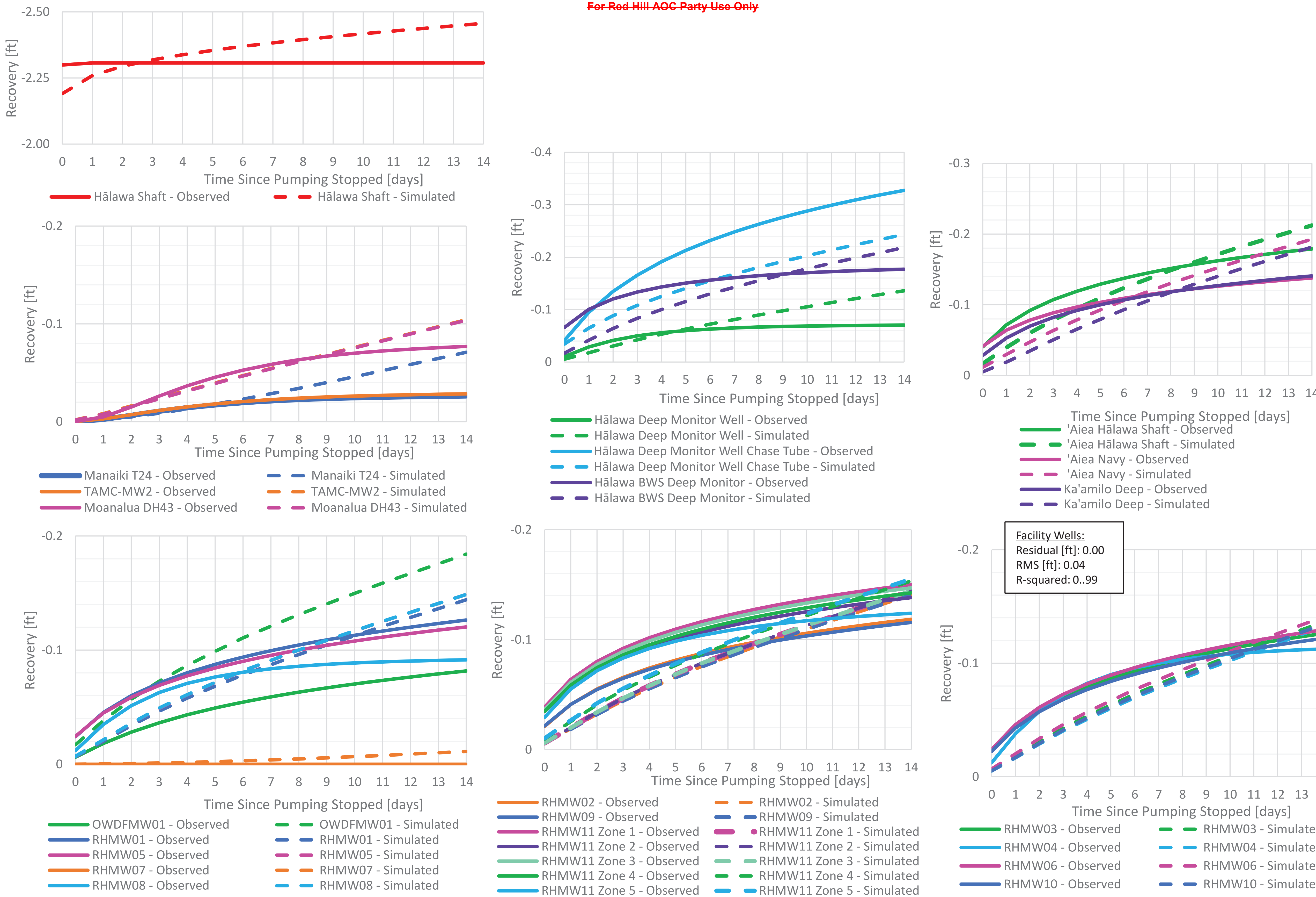
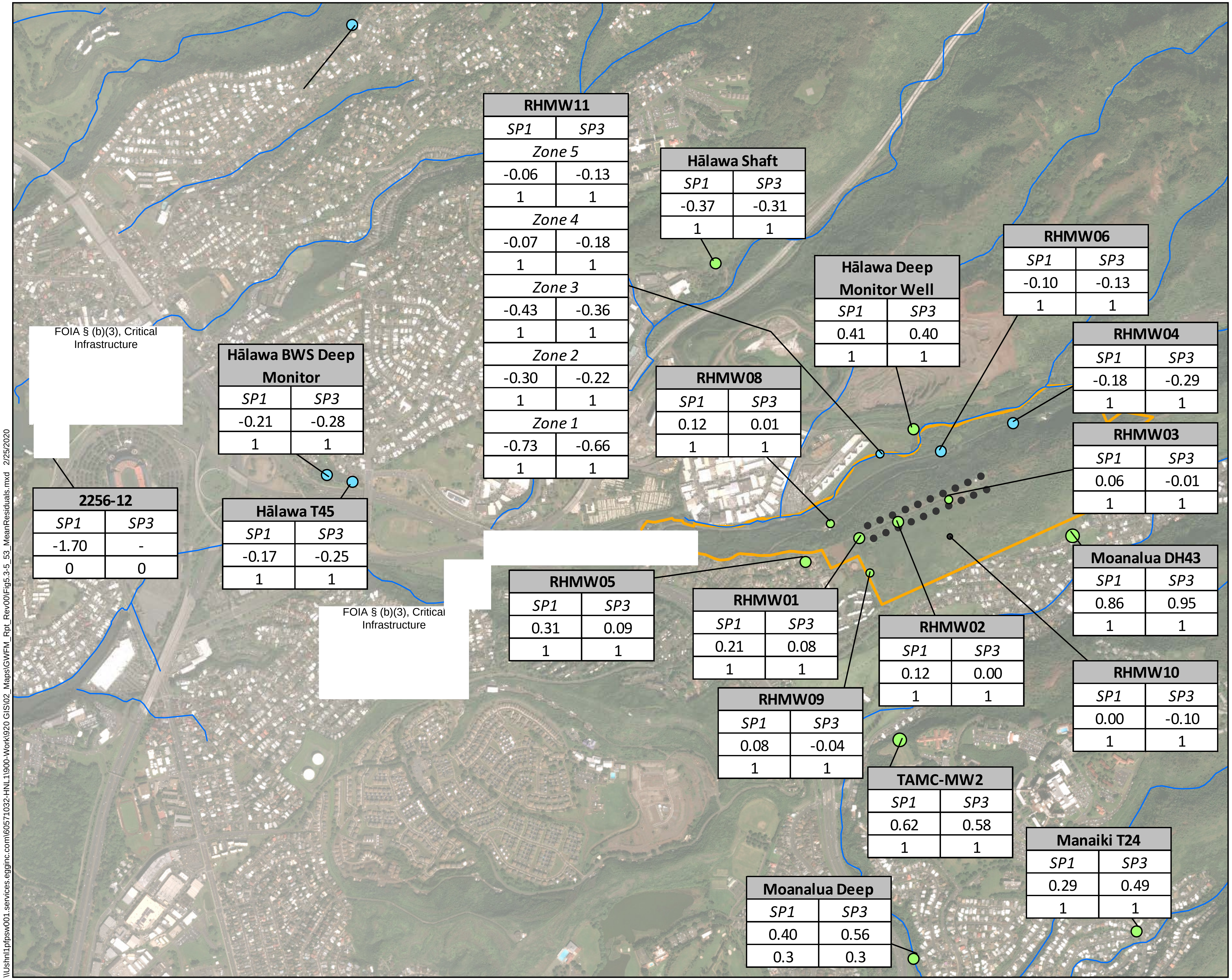


Figure 5.3-4
Model #53: Heterogeneous Basalt –
Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



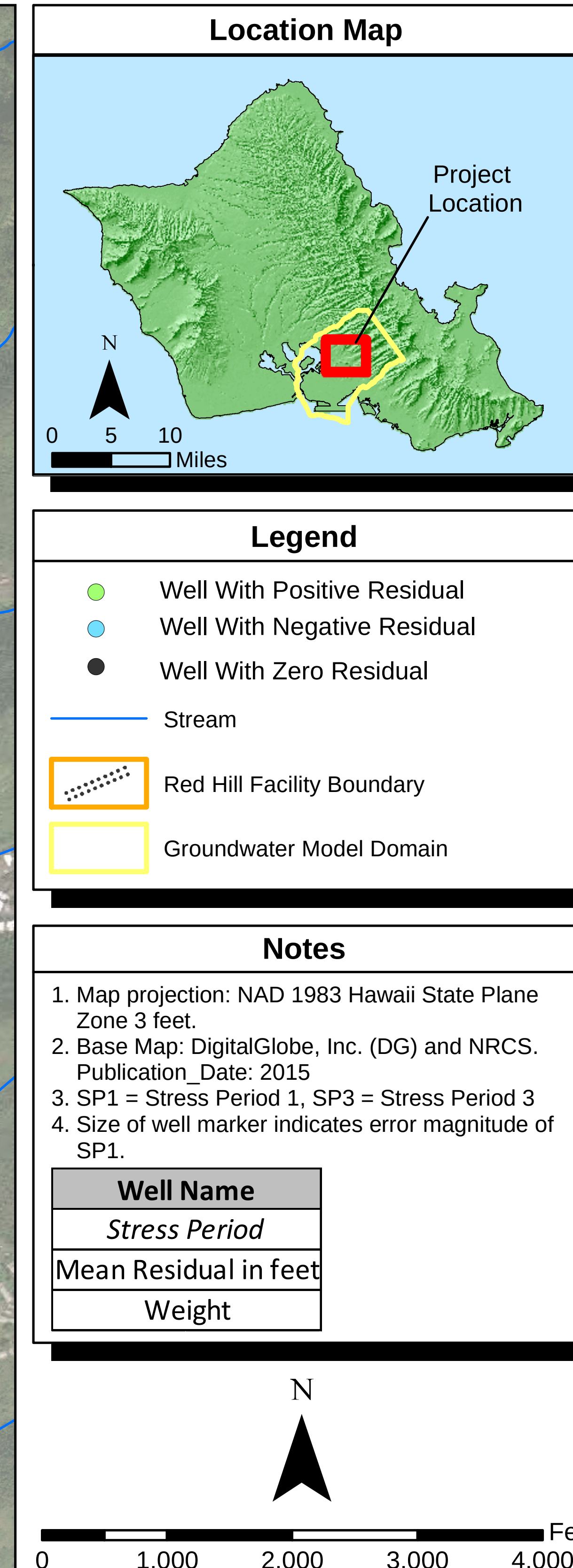
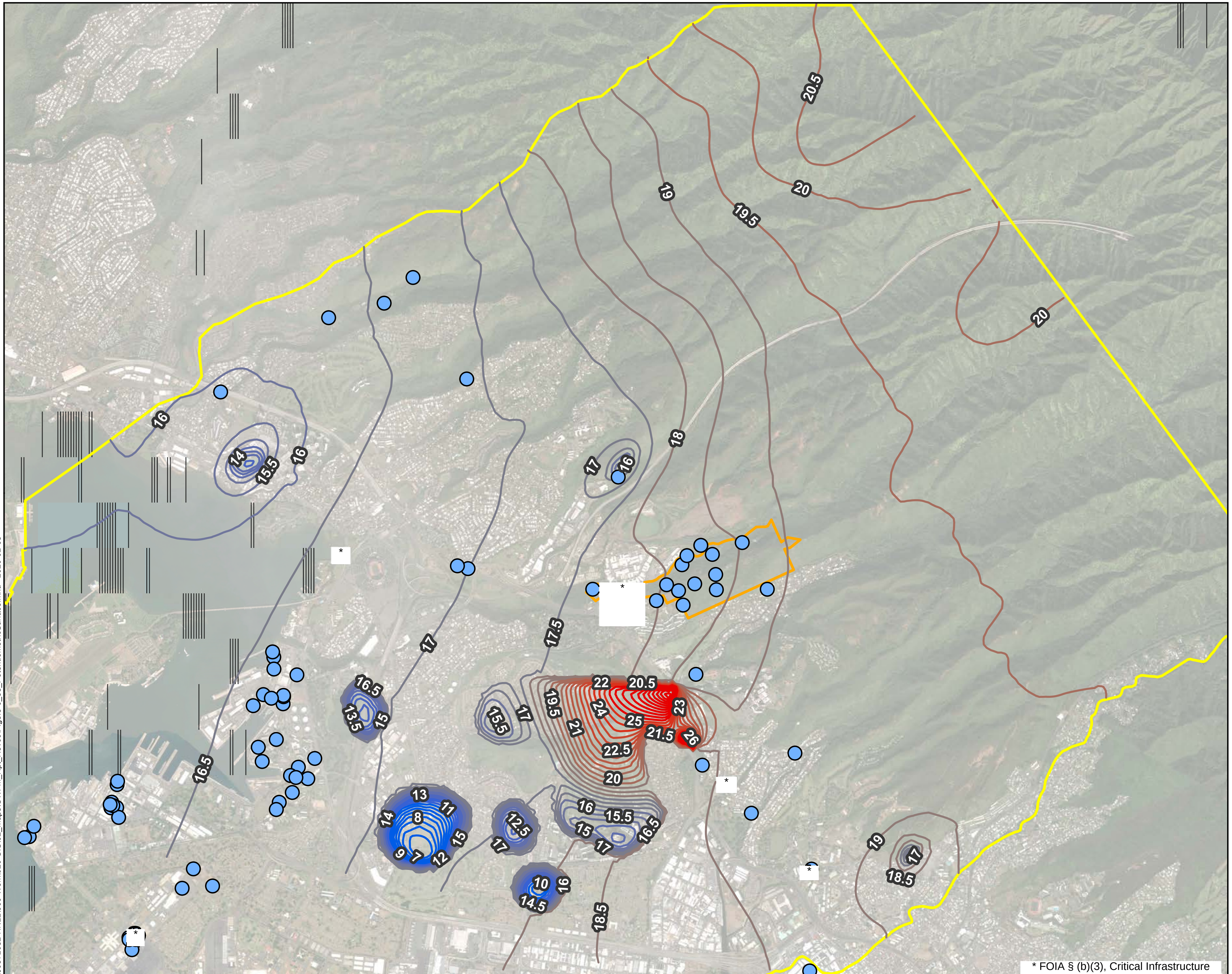
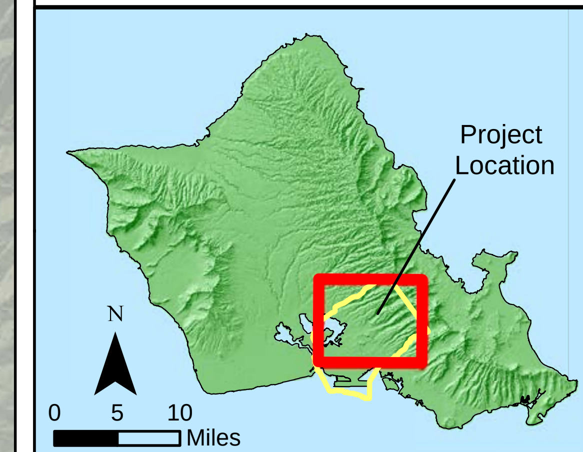


Figure 5.3-5
Model #53: Heterogeneous Basalt – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL1\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.3-5_53_MeanResiduals.mxd 2/25/2020



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.3-6
Model #53: Heterogeneous Basalt – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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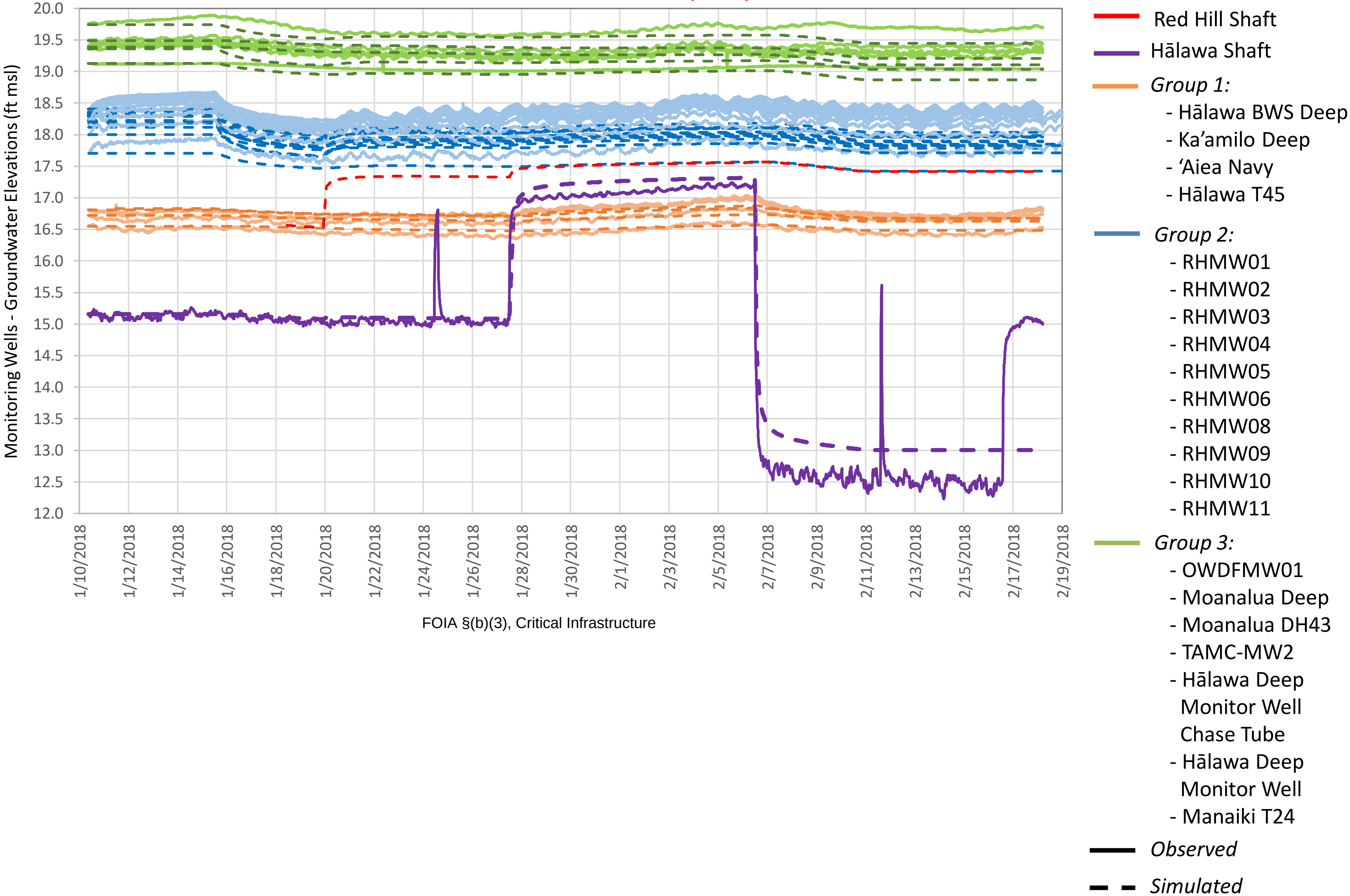


FOIA §(b)(3), Critical Infrastructure

Figure 5.3-7
Model #53: Heterogeneous Basalt – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

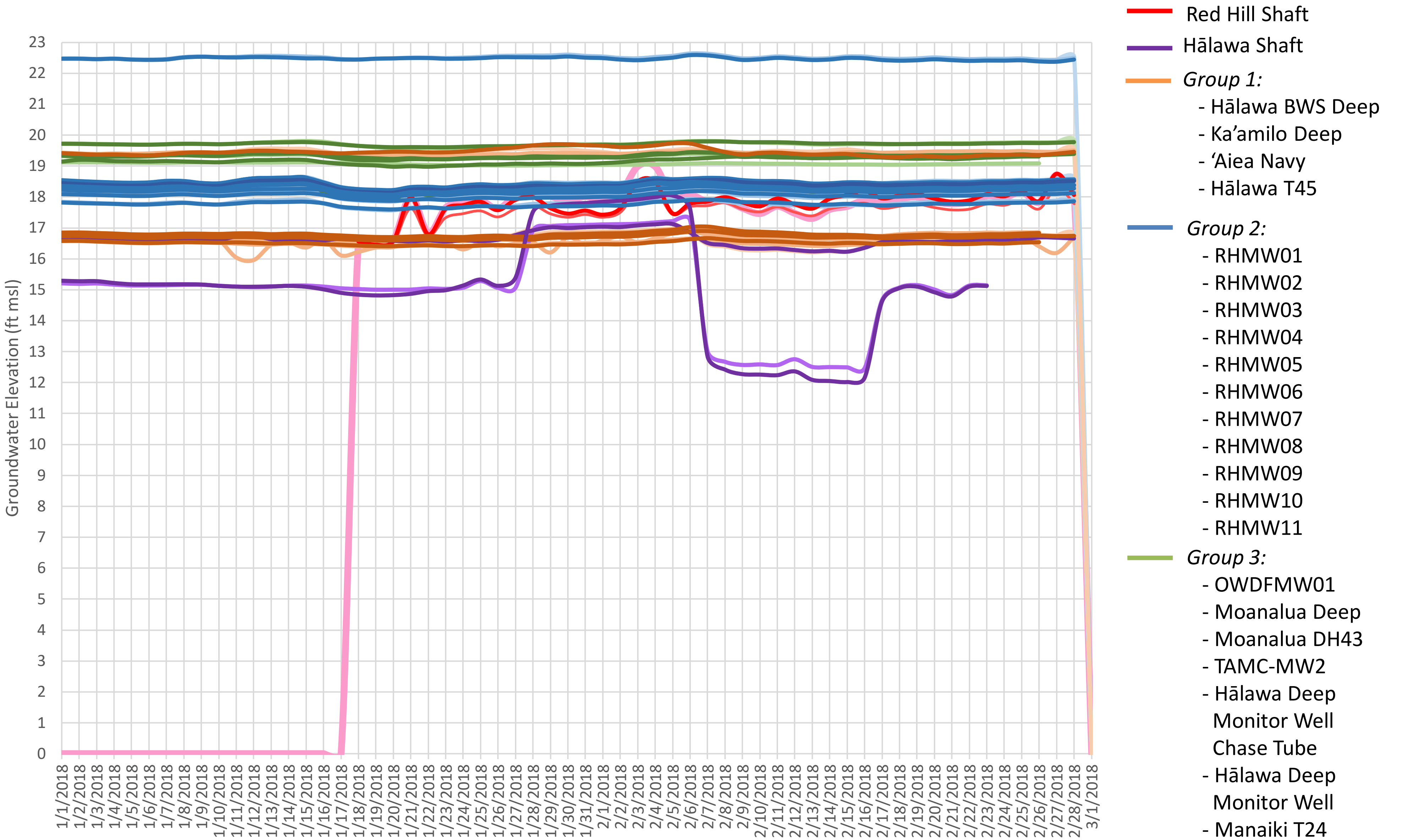
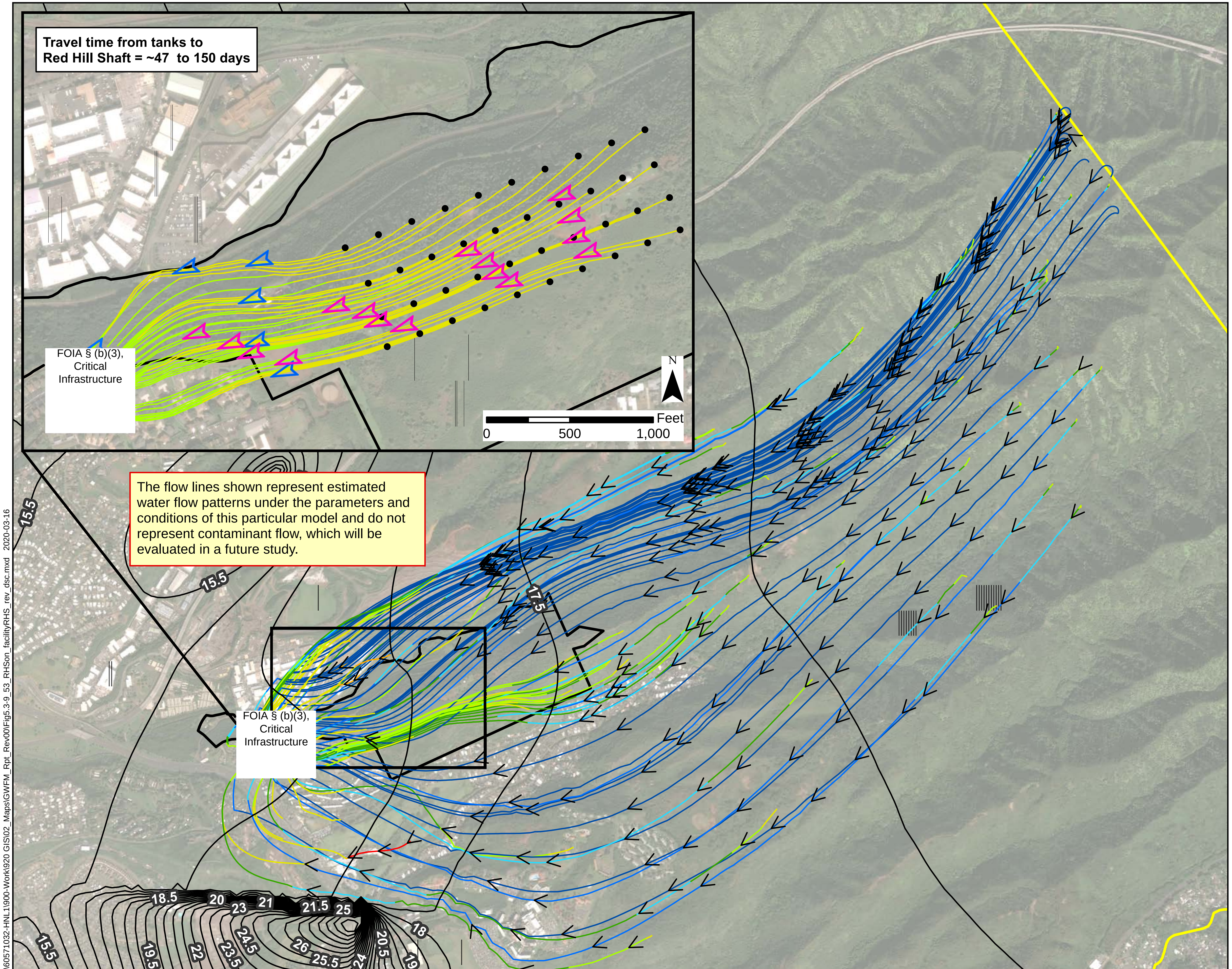


Figure 5.3-8
Model #53: Heterogeneous Basalt –
Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



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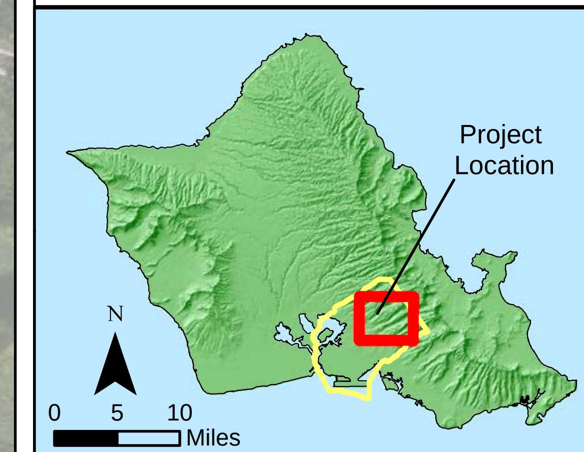
Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9

- Particle Location
- Groundwater Contour (ft
- Red Hill Facility
- Groundwater Model

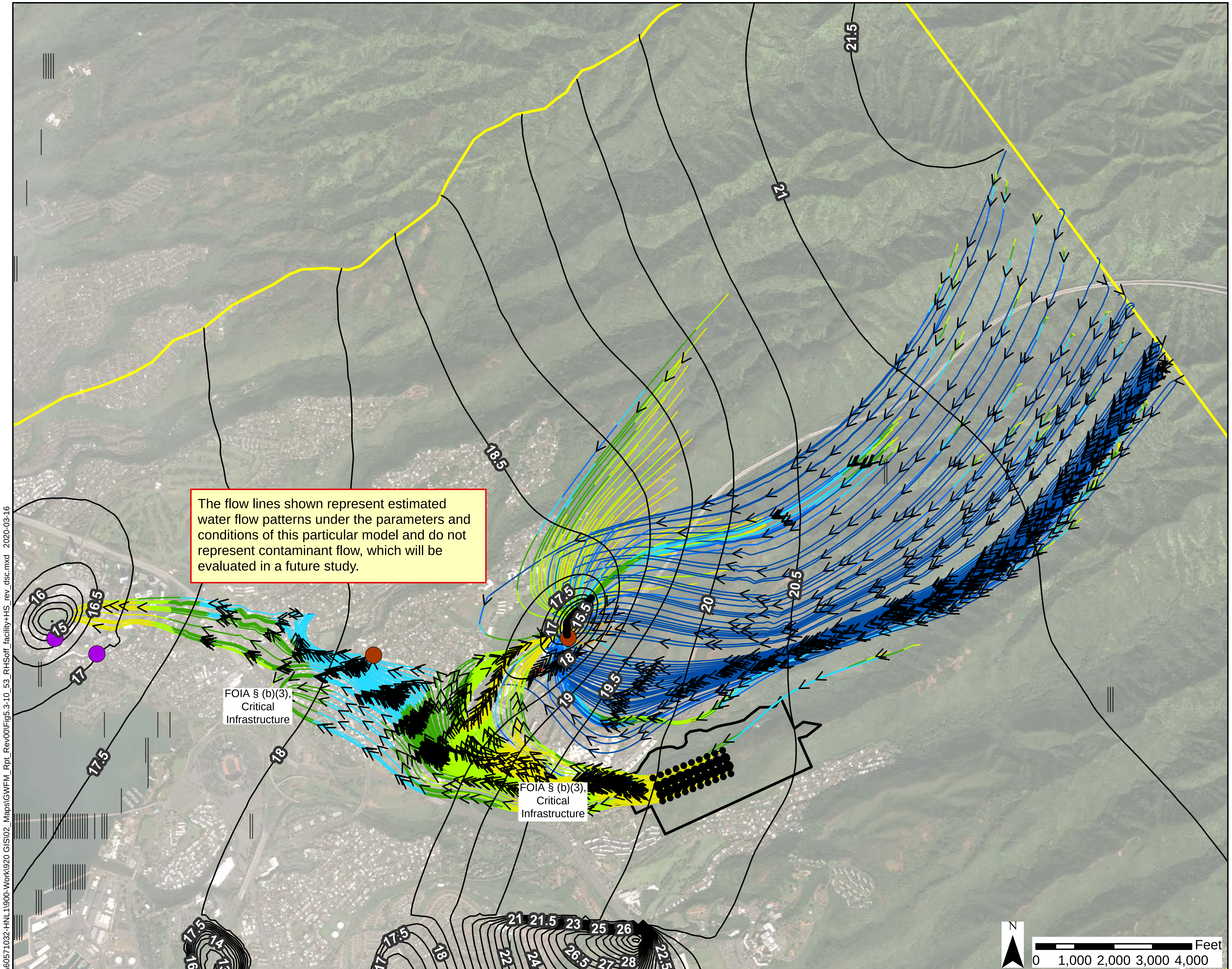
Notes

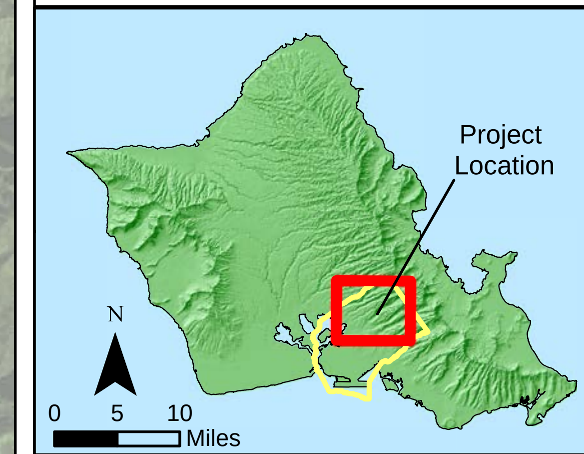
1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.3-9
Model #53: Heterogeneous Basalt – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI





Legend

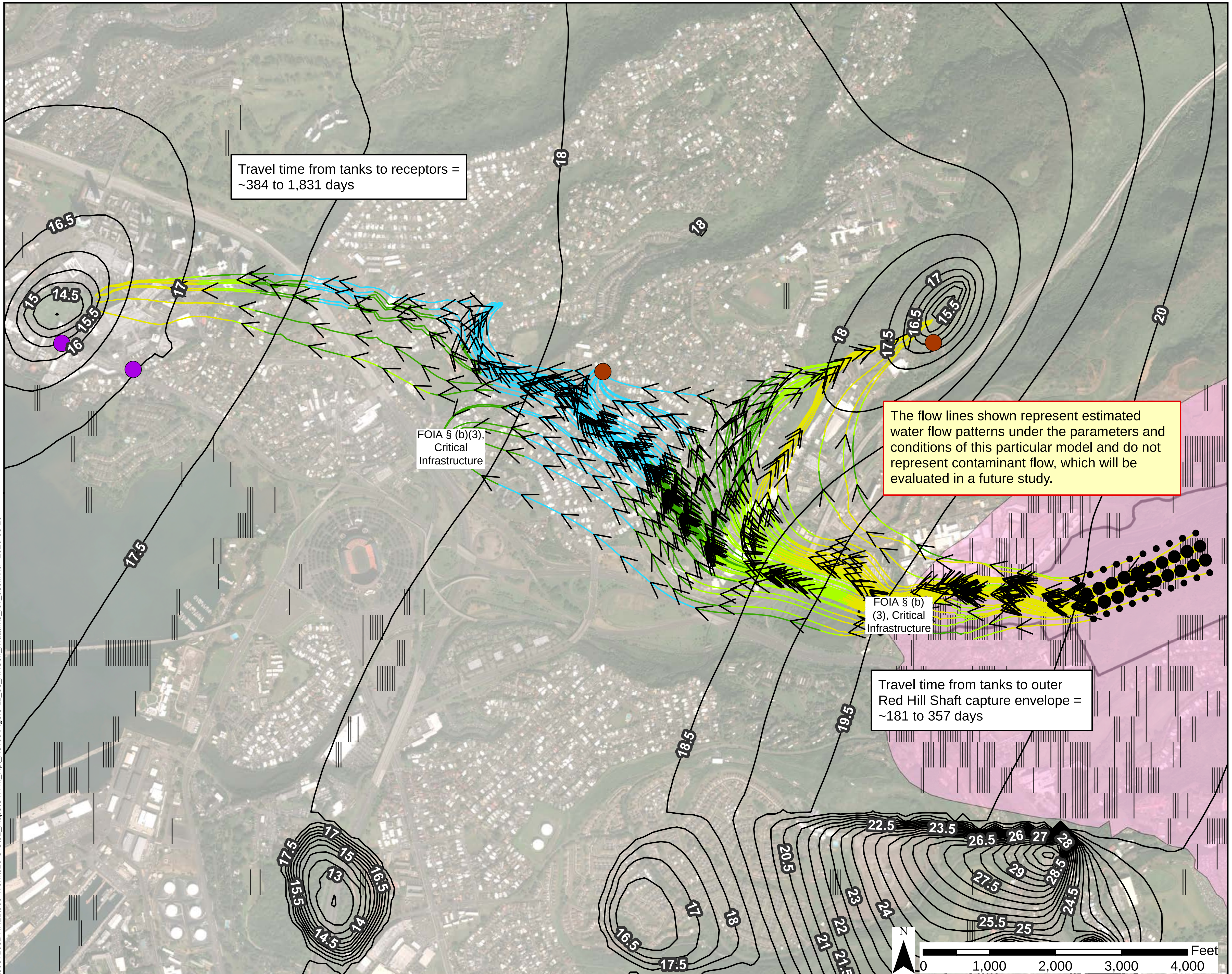
Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (ft msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

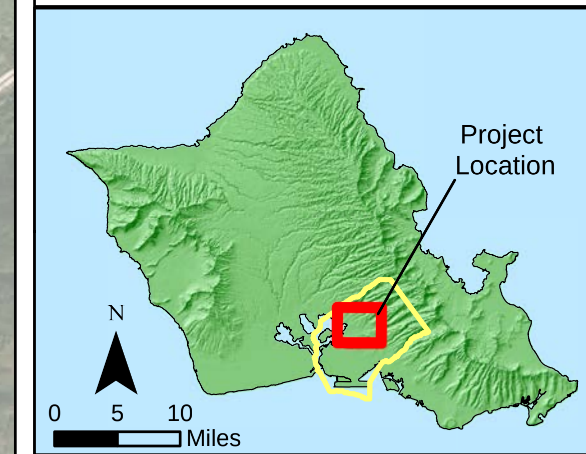
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 180 days.
4. Hālawa Shaft reverse pathline arrows = 180 days.

Figure 5.3-10
Model #53: Heterogeneous Basalt – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location (220)
- Spring
- Pumping Well
- Groundwater Contour (ft msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.3-11
Model #53: Heterogeneous Basalt – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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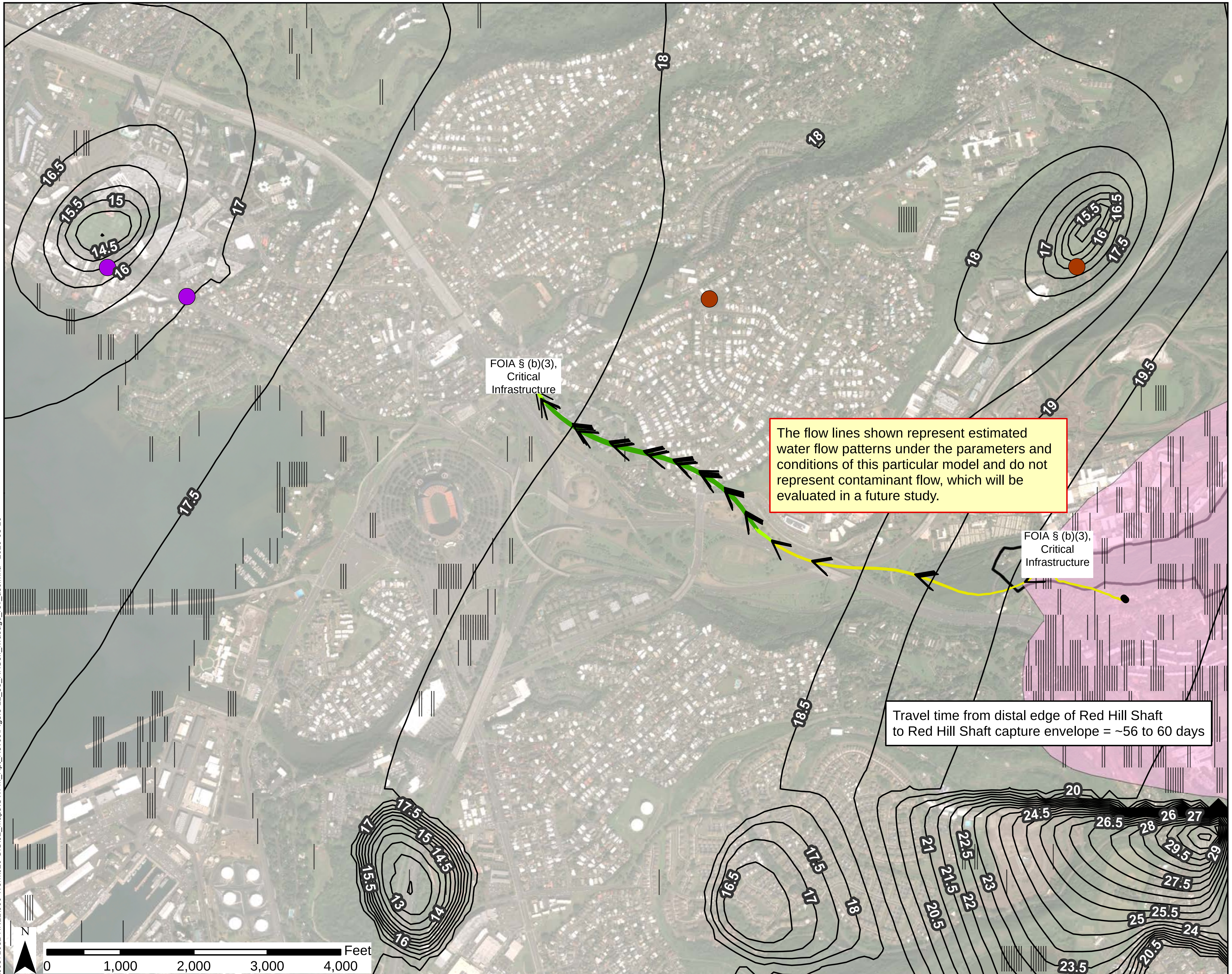
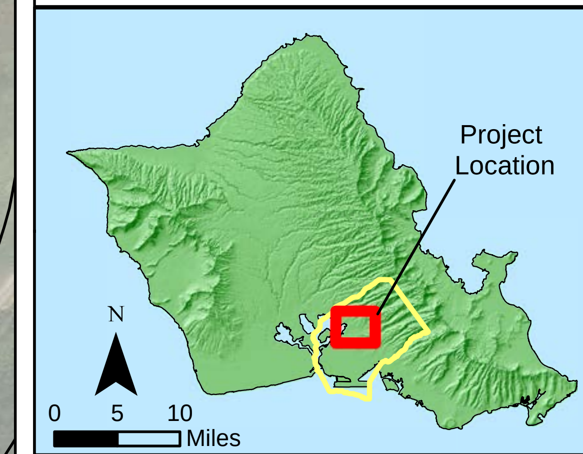


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (ft
- Red Hill Shaft Capture
- Red Hill Facility
- Groundwater Model

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.3-12
Model #53: Heterogeneous Basalt – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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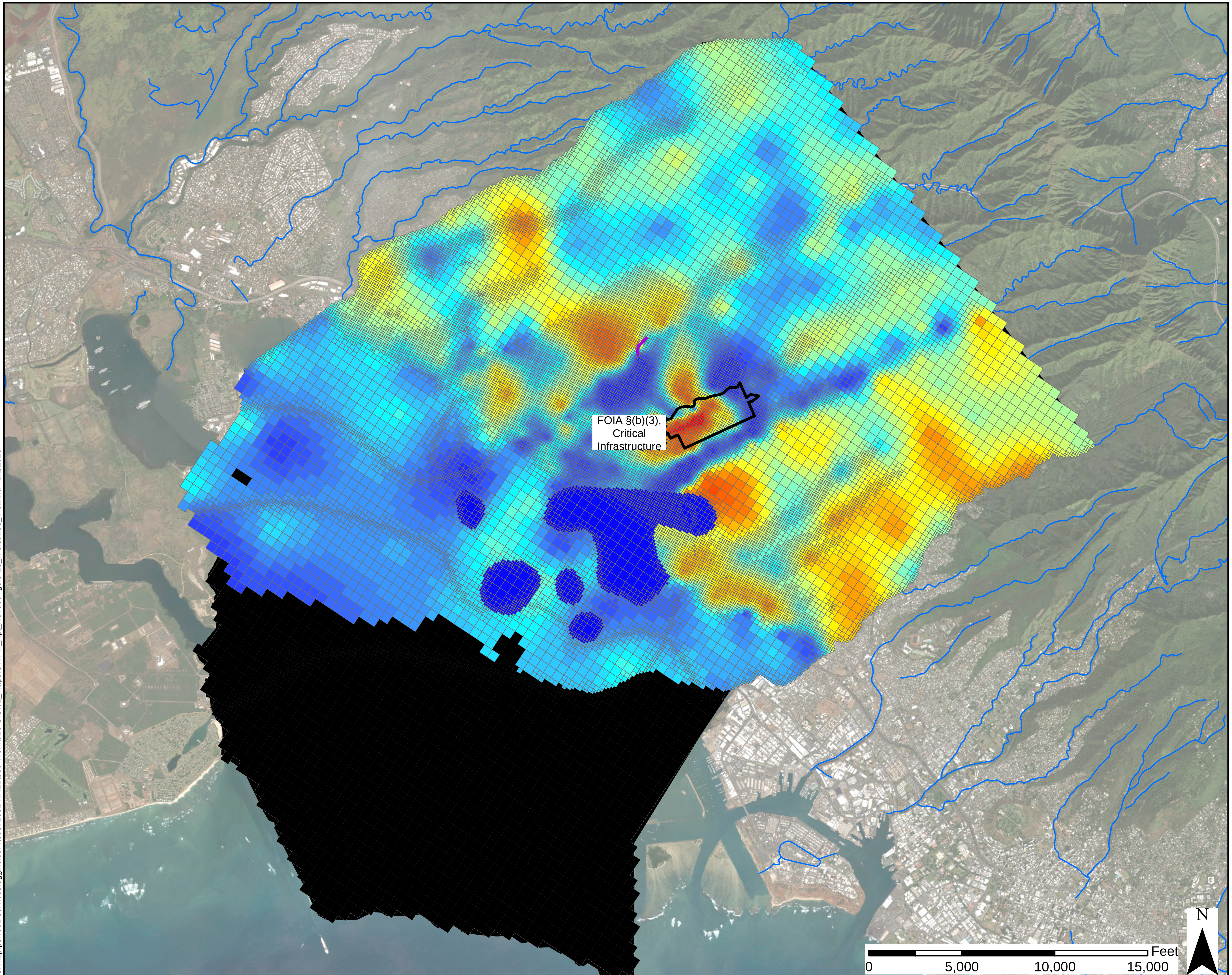
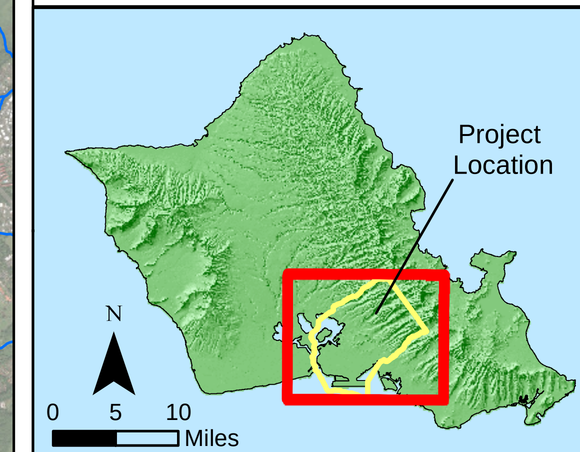


Location Map



Legend

Hydraulic Conductivity (ft/day)

0	4230 - 4592
1 - 727	4593 - 4993
728 - 939	4994 - 5448
940 - 1132	5449 - 5963
1133 - 1307	5964 - 6526
1308 - 1483	6527 - 7100
1484 - 1657	7101 - 7723
1658 - 1817	7724 - 8406
1818 - 2014	8407 - 9246
2015 - 2296	9247 - 10539
2297 - 2618	10540 - 12755
2619 - 2932	12756 - 16005
2933 - 3245	16006 - 19873
3246 - 3572	19874 - 25505
3573 - 3897	25506 - 31970
3898 - 4229	31971 - 40103
Inactive Model Cells	Shaft
Red Hill Facility Boundary	Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.3-13
Hydraulic Conductivity Distribution in Layers 4 to 6 for Model #53
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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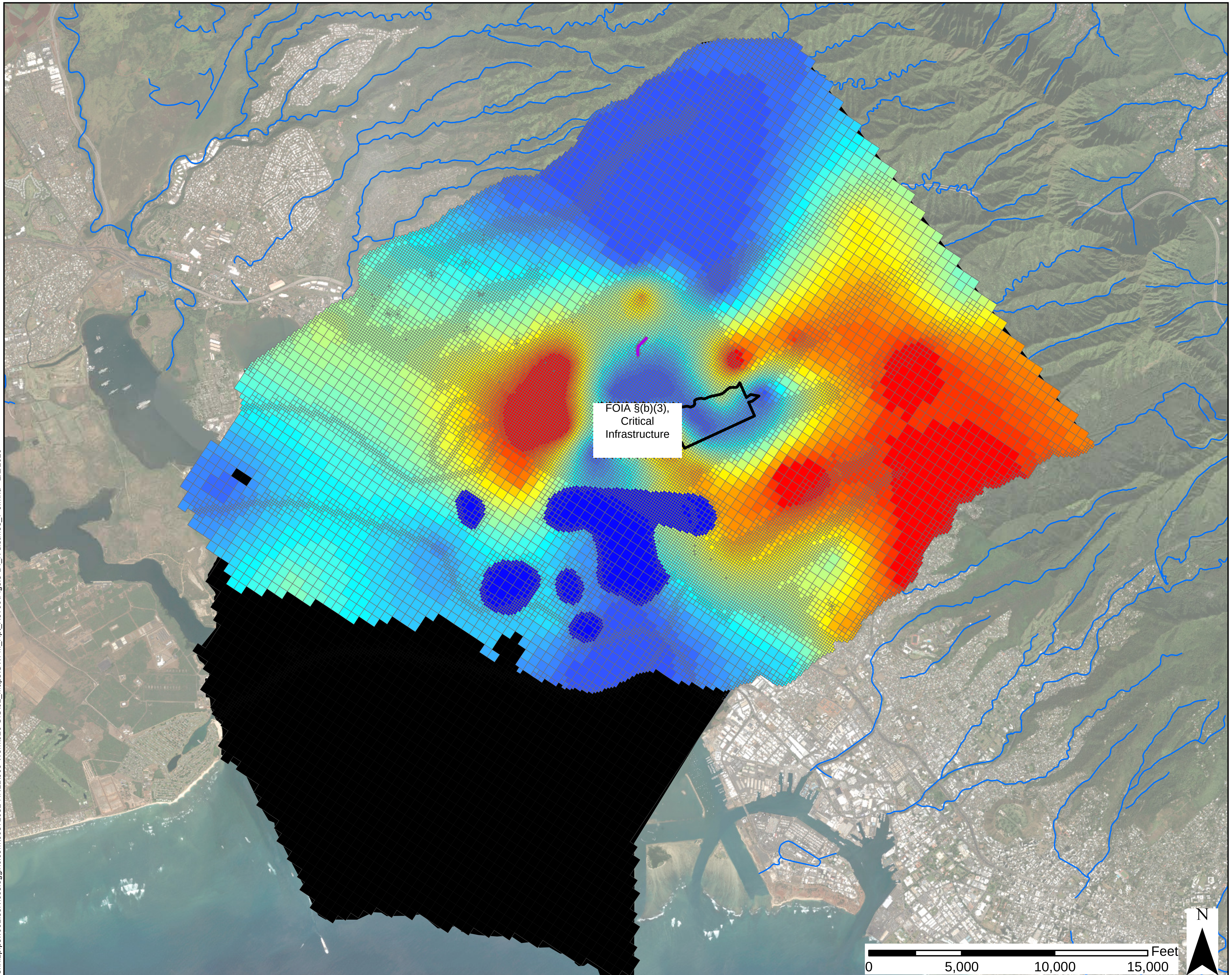
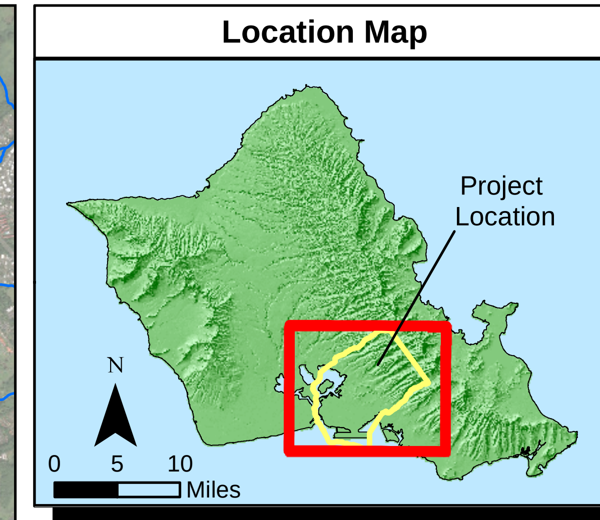




Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.3-14
Hydraulic Conductivity Distribution in Layers 7 to 9 for Model #53
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

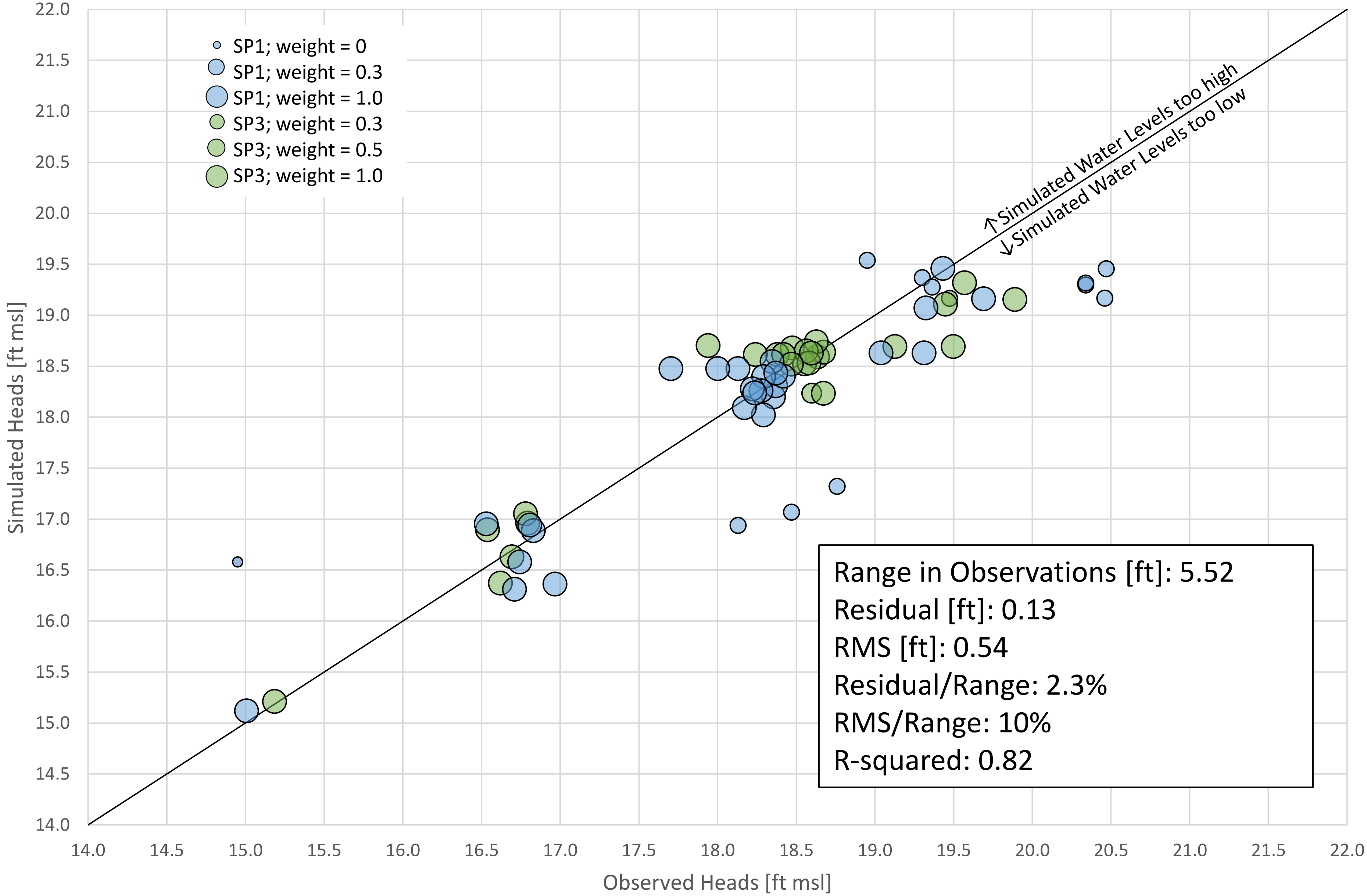


Figure 5.4-1
Model #54: Heterogeneous Basalt – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

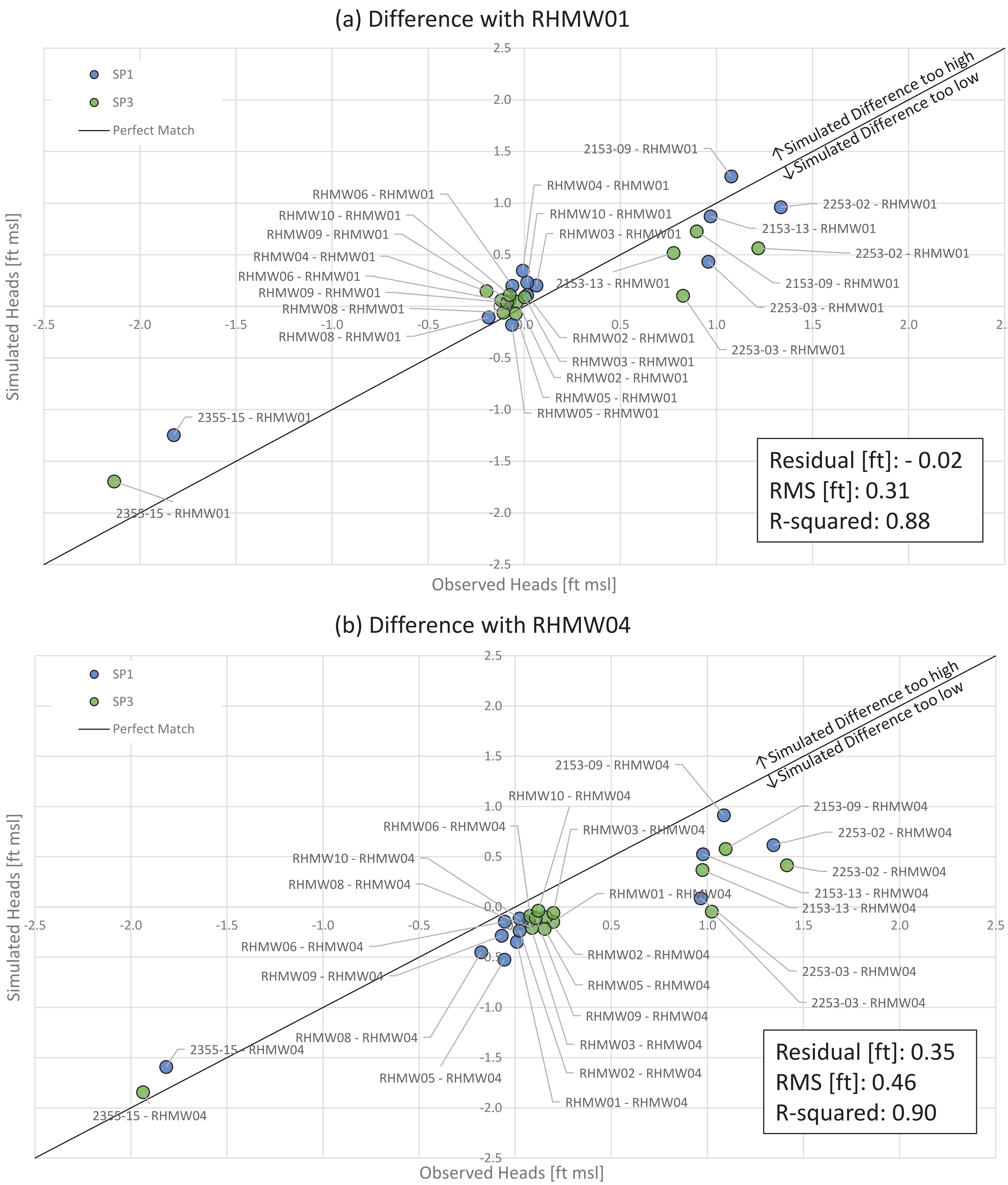


Figure 5.4-2
Model #54: Heterogeneous Basalt –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

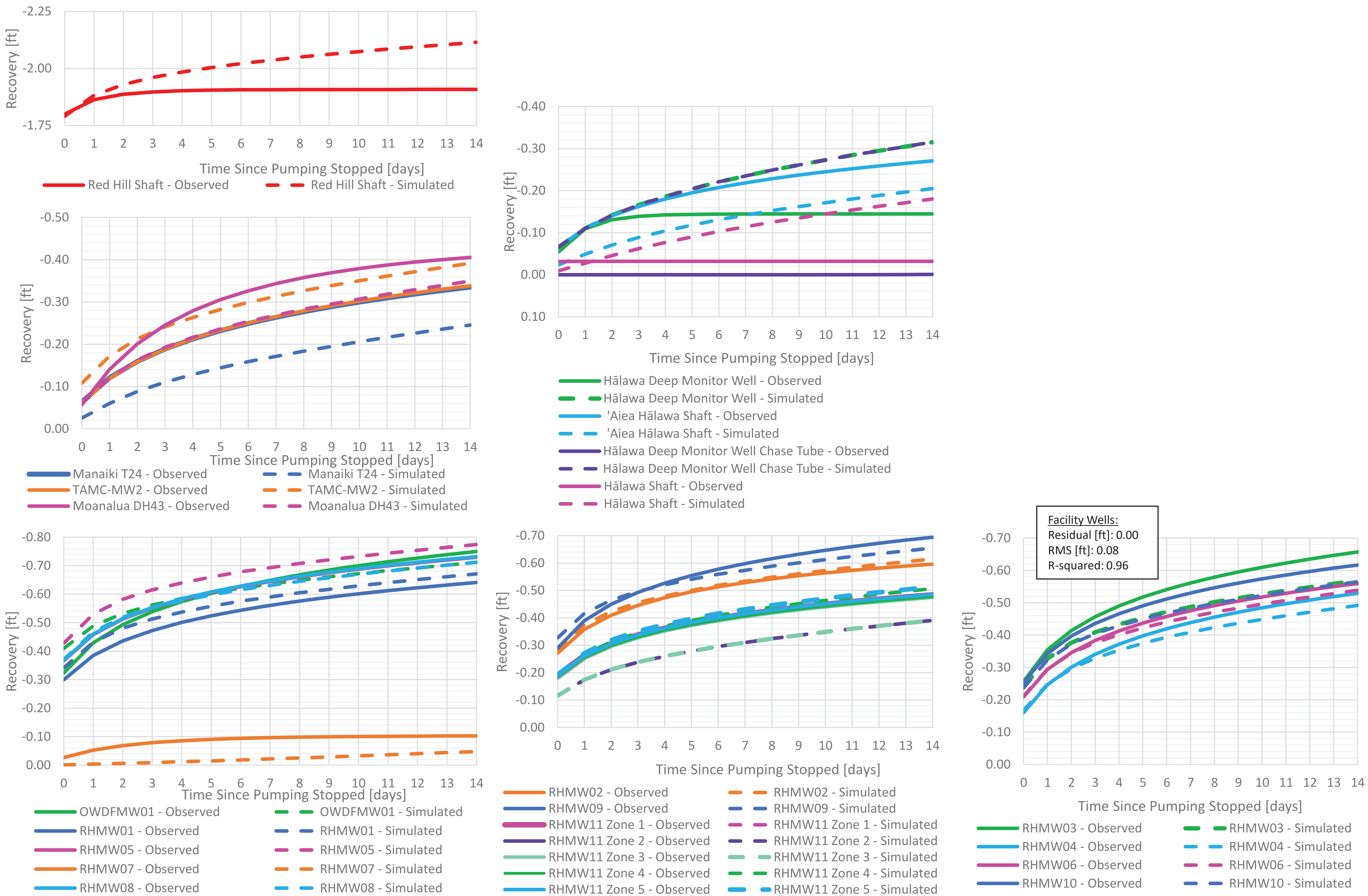


Figure 5.4-3
Model #54: Heterogeneous Basalt –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

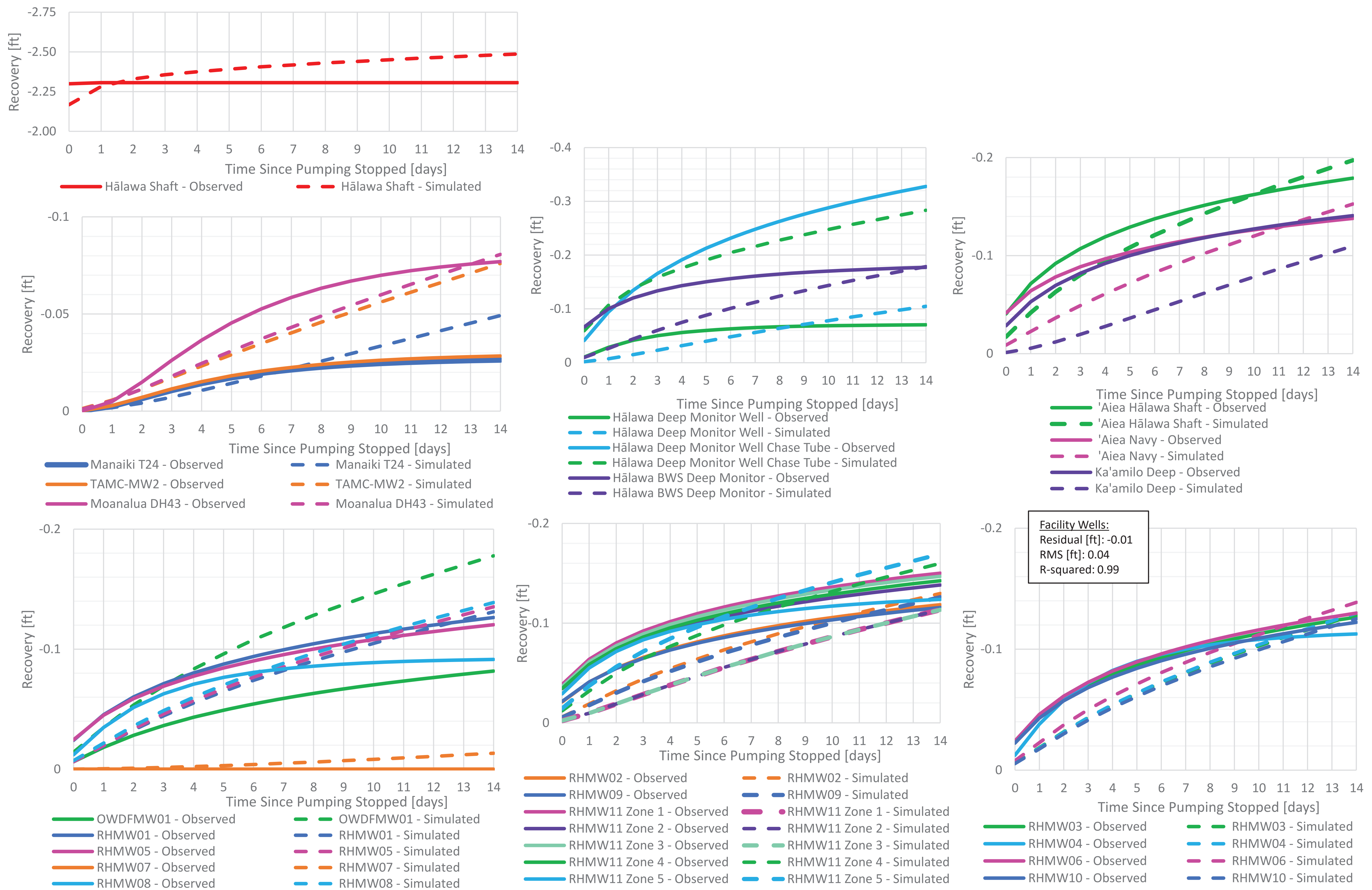
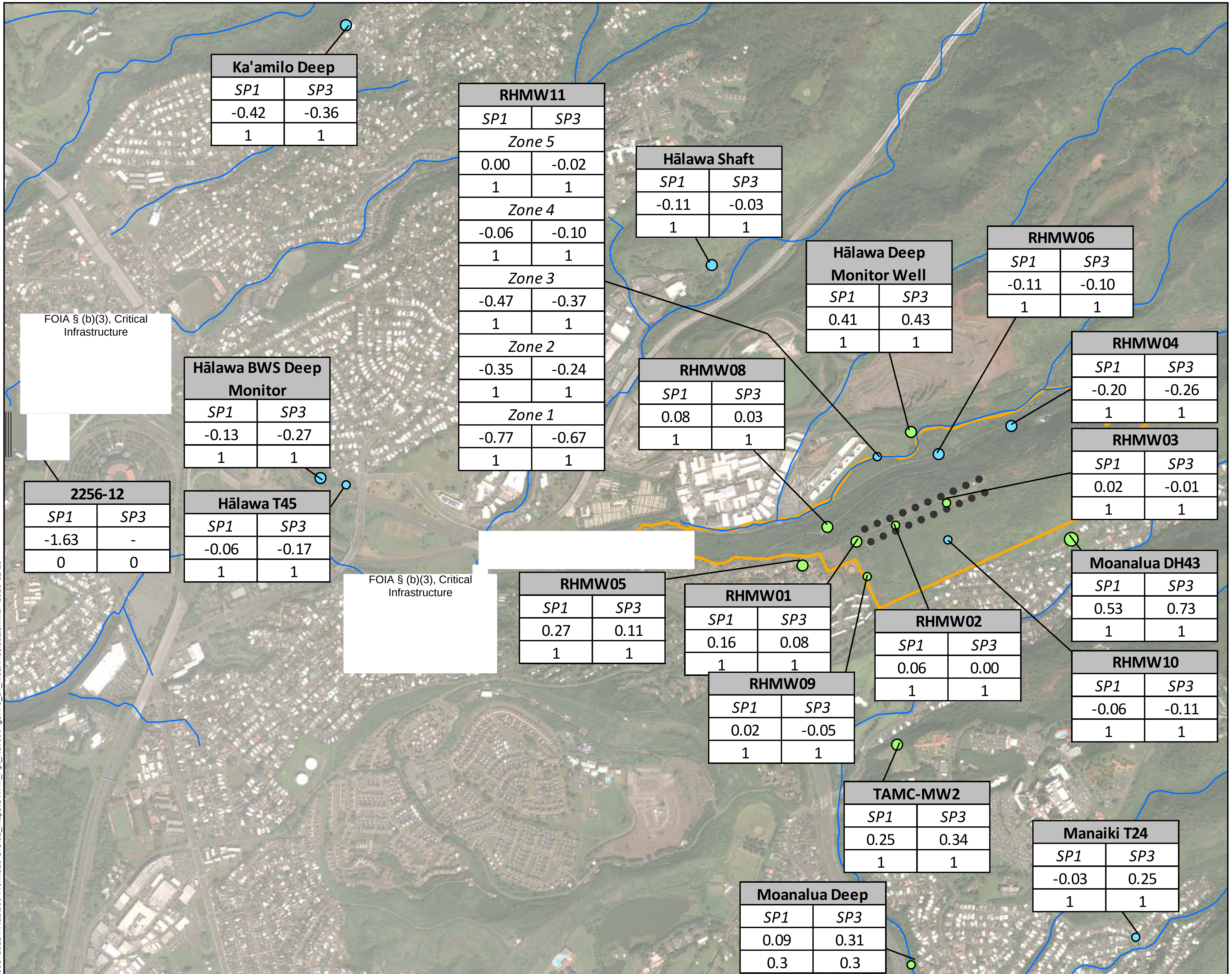
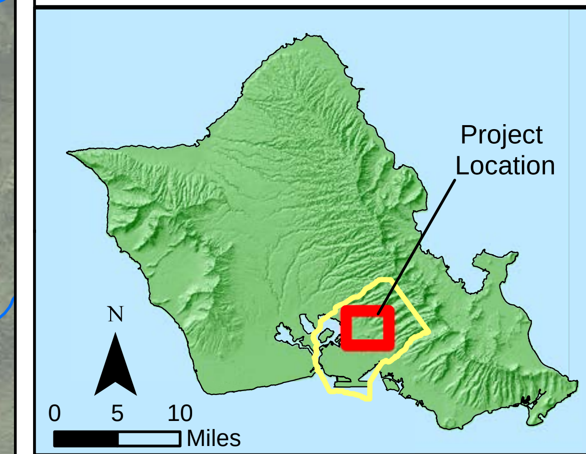


Figure 5.4-4
Model #54: Heterogeneous Basalt – Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.4-5
Model #54: Heterogeneous Basalt – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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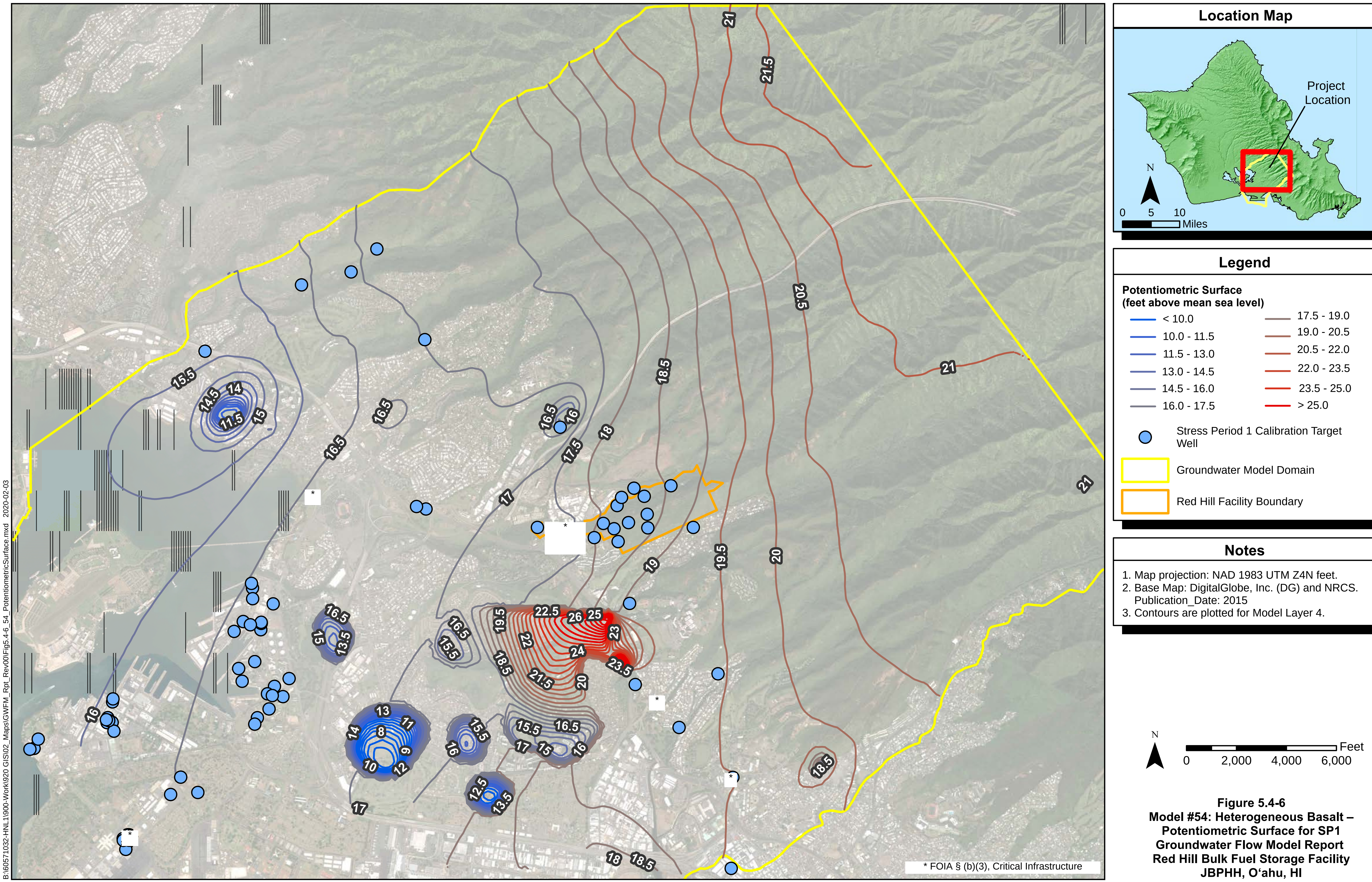
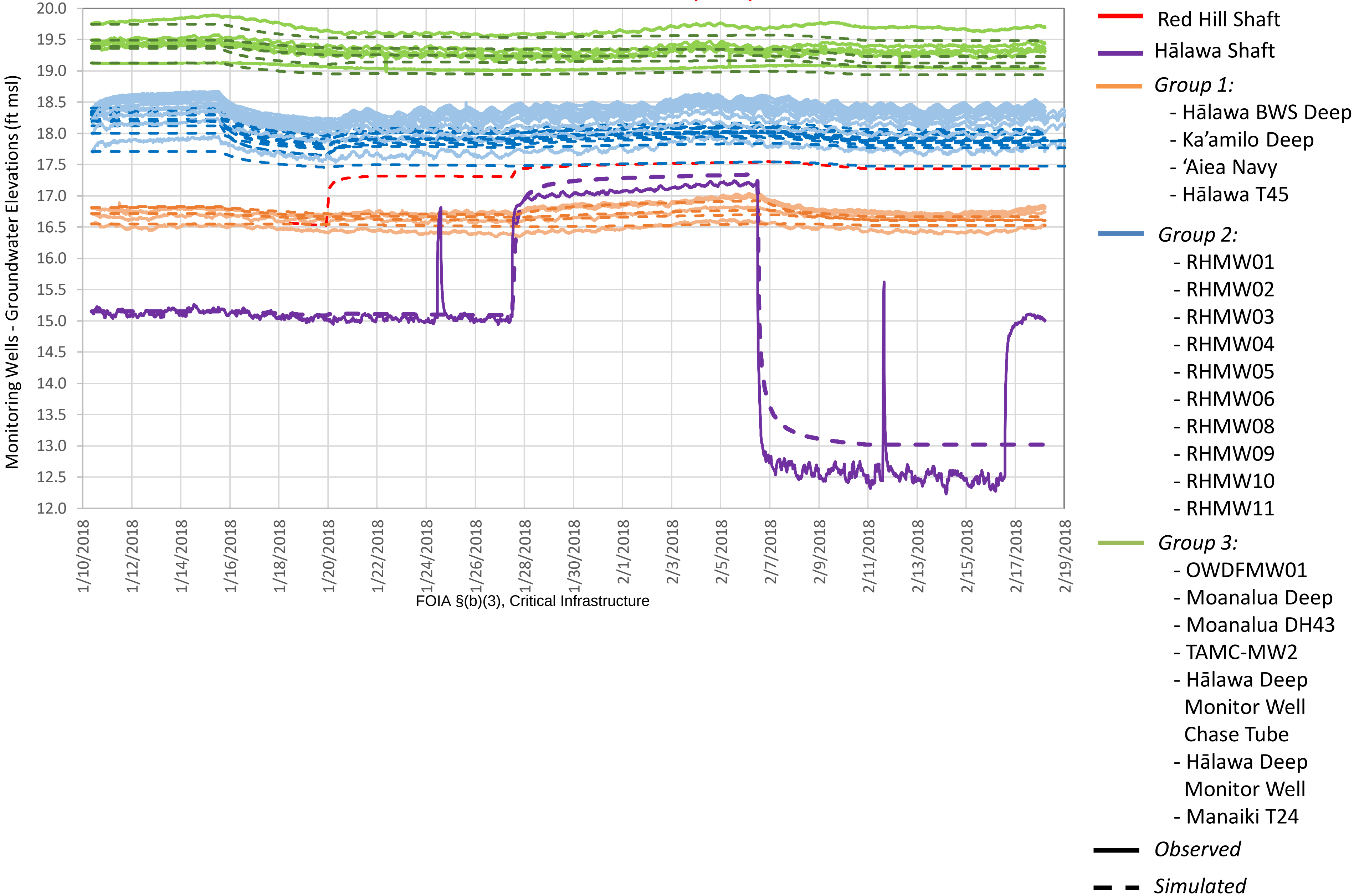


Figure 5.4-6
Model #54: Heterogeneous Basalt – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



FOIA §(b)(3), Critical Infrastructure

Figure 5.4-7
Model #54: Heterogeneous Basalt – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

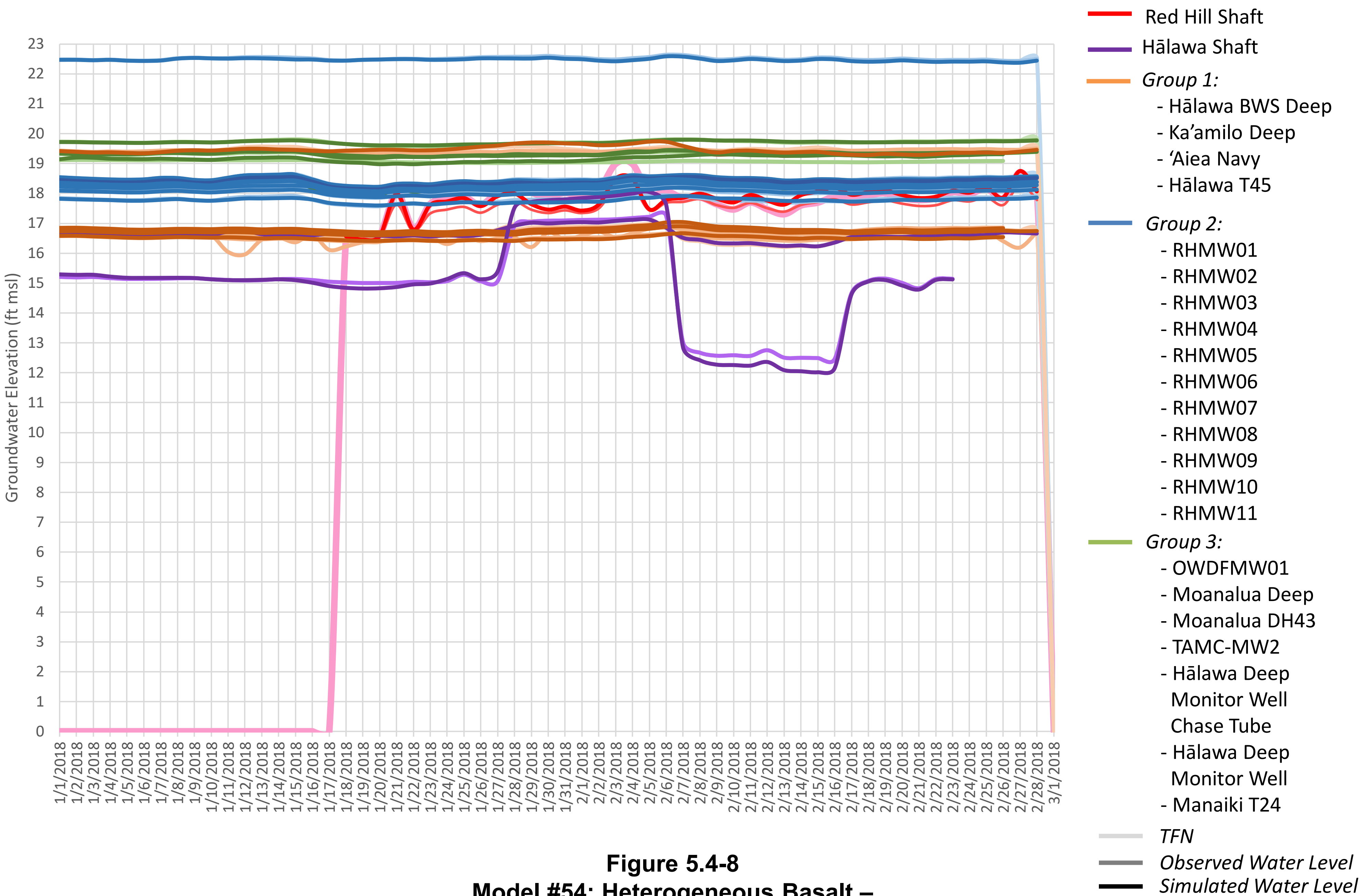
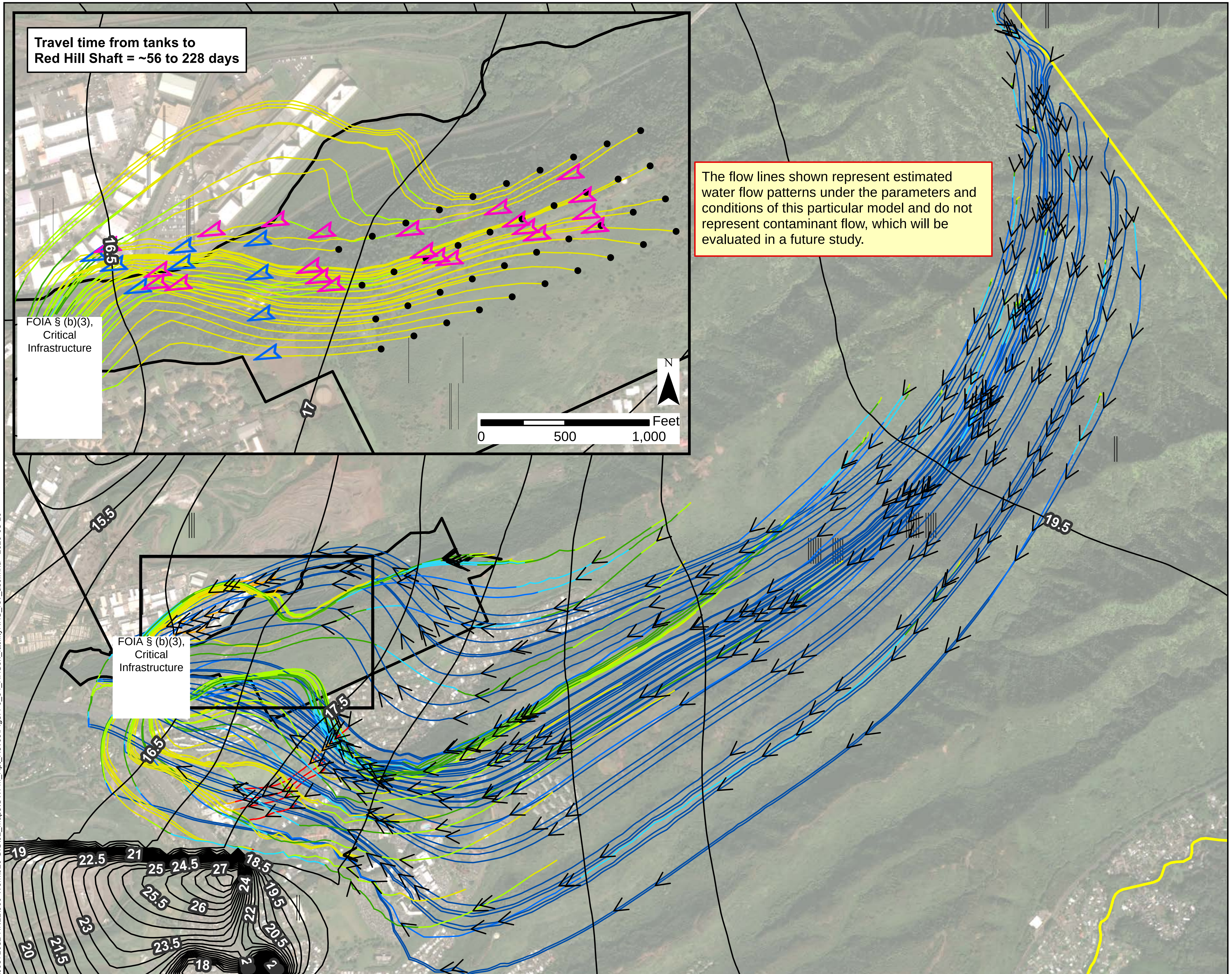
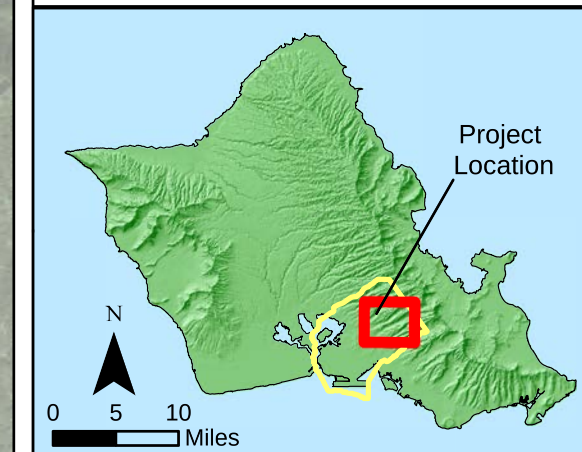


Figure 5.4-8
Model #54: Heterogeneous Basalt –
Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (ft msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.4-9
Model #54: Heterogeneous Basalt – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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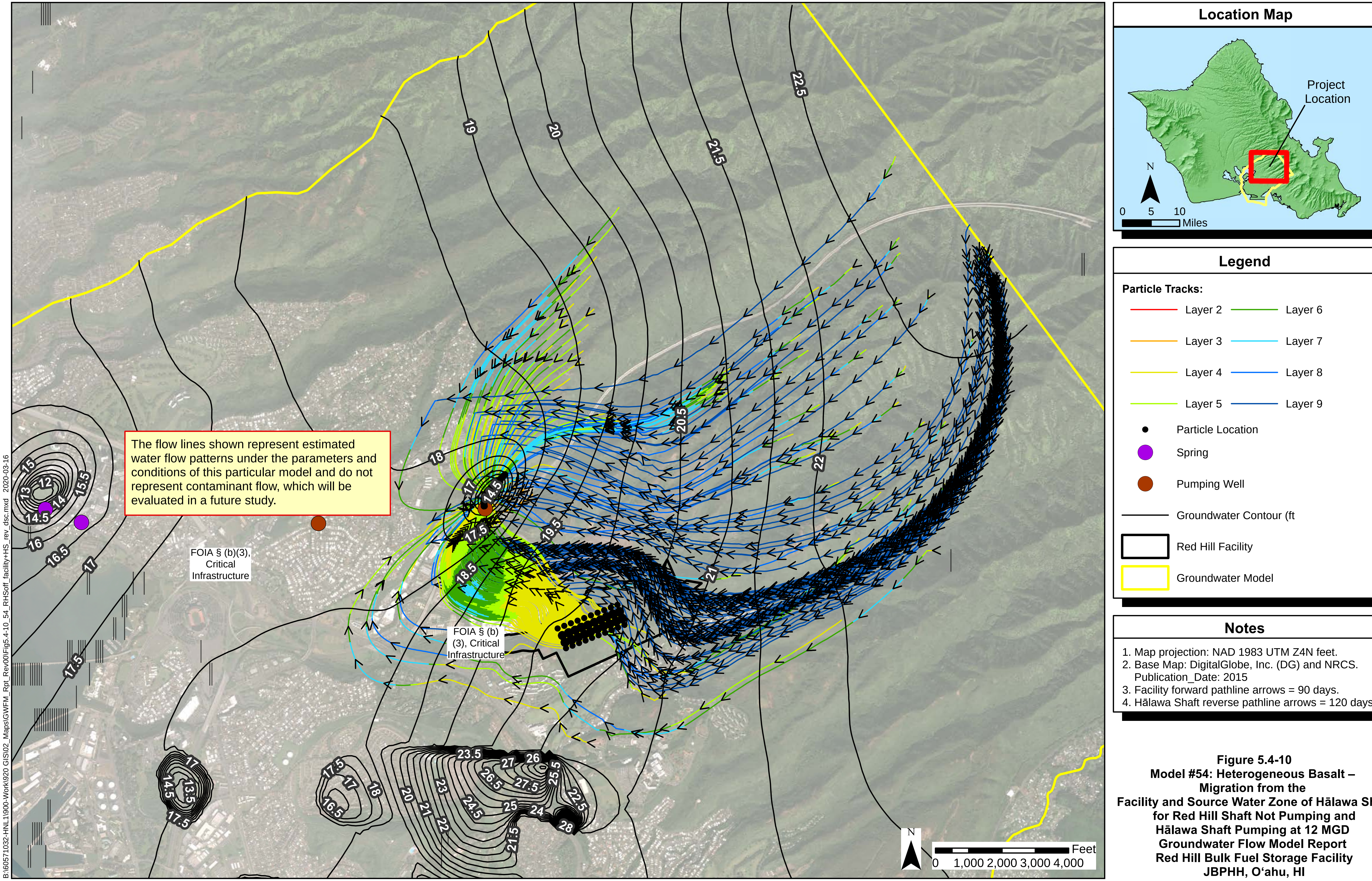

Figure 5.4-10
Model #54: Heterogeneous Basalt – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

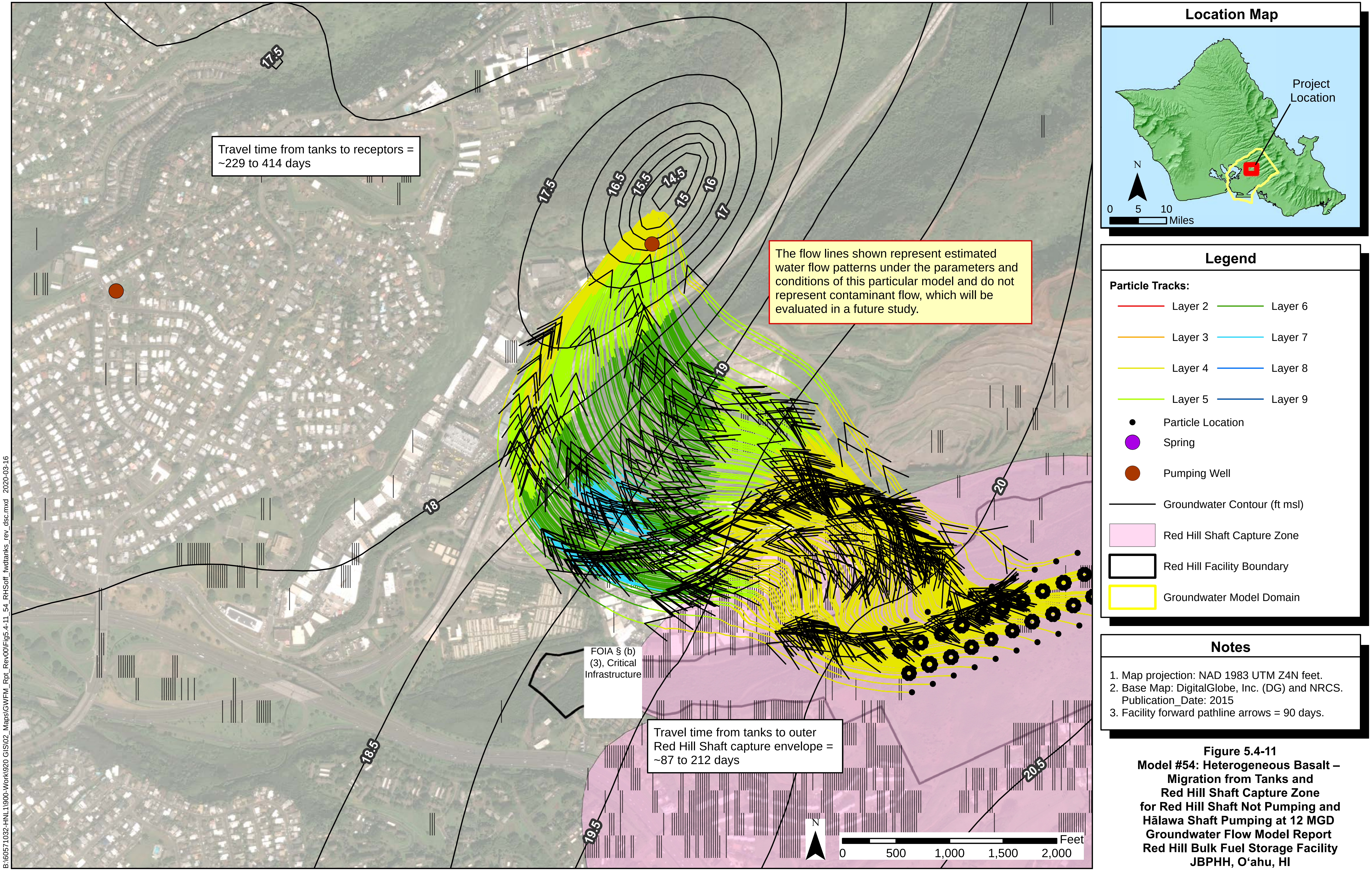

Figure 5.4-11
Model #54: Heterogeneous Basalt – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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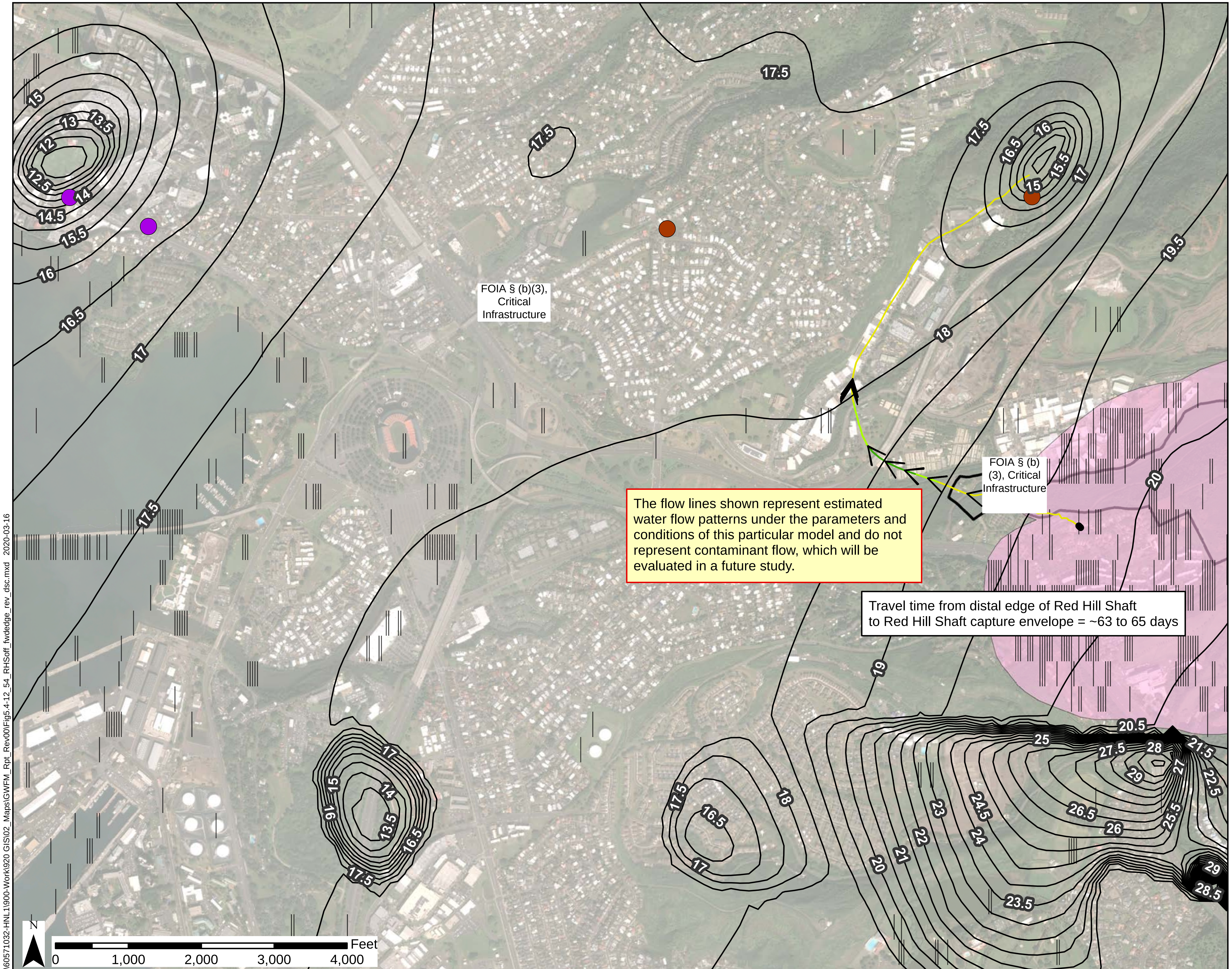
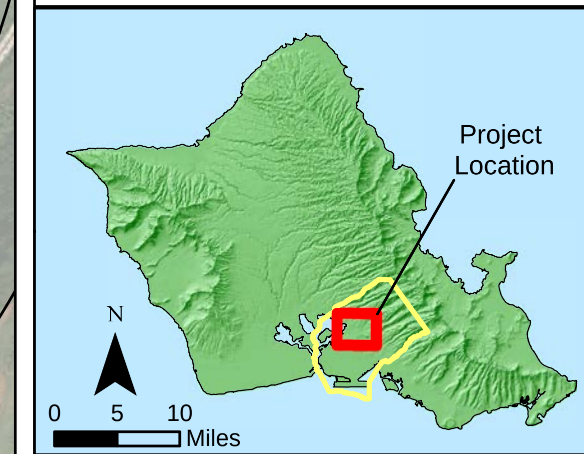


Location Map



Legend

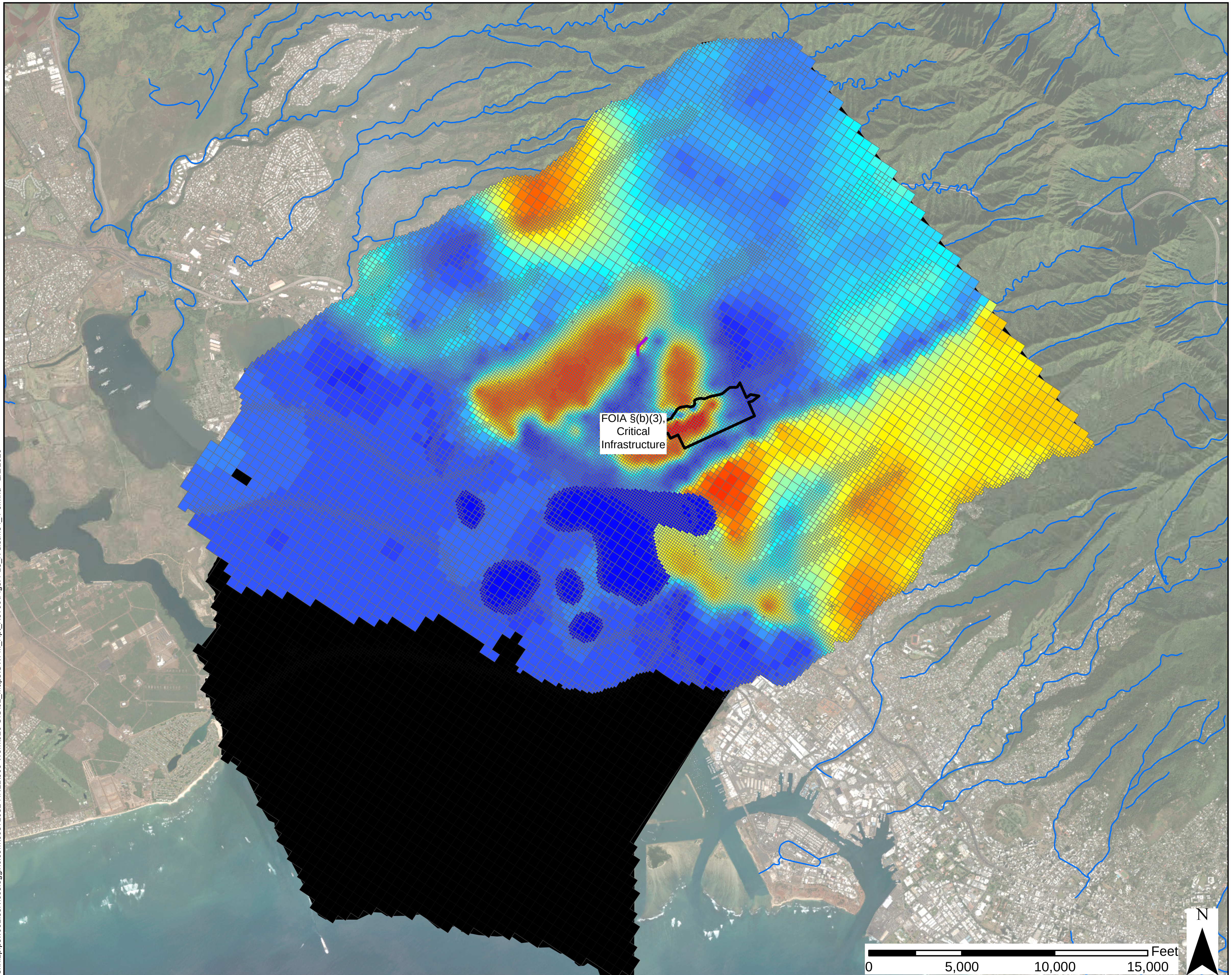
Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (ft msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

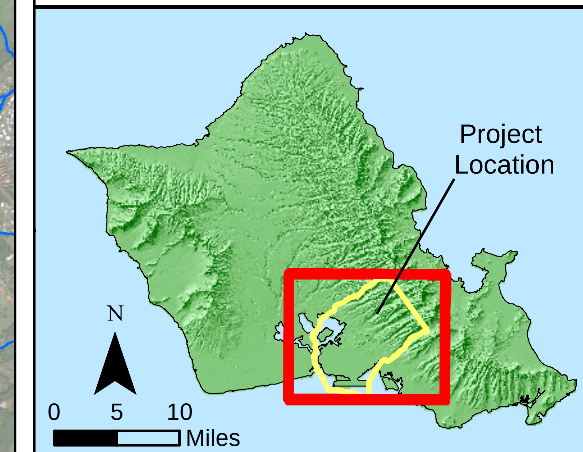
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days.

Figure 5.4-12
Model #54: Heterogeneous Basalt – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



Location Map



Legend

Hydraulic Conductivity (ft/day)

0	3782 - 4235
1 - 491	4236 - 4723
492 - 546	4724 - 5296
547 - 617	5297 - 5920
618 - 723	5921 - 6581
724 - 868	6582 - 7264
869 - 1044	7265 - 8045
1045 - 1243	8046 - 9027
1244 - 1481	9028 - 10204
1482 - 1752	10205 - 11629
1753 - 2012	11630 - 13601
2013 - 2272	13602 - 16124
2273 - 2563	16125 - 18976
2564 - 2919	18977 - 22795
2920 - 3334	22796 - 29636
3335 - 3781	29637 - 47000

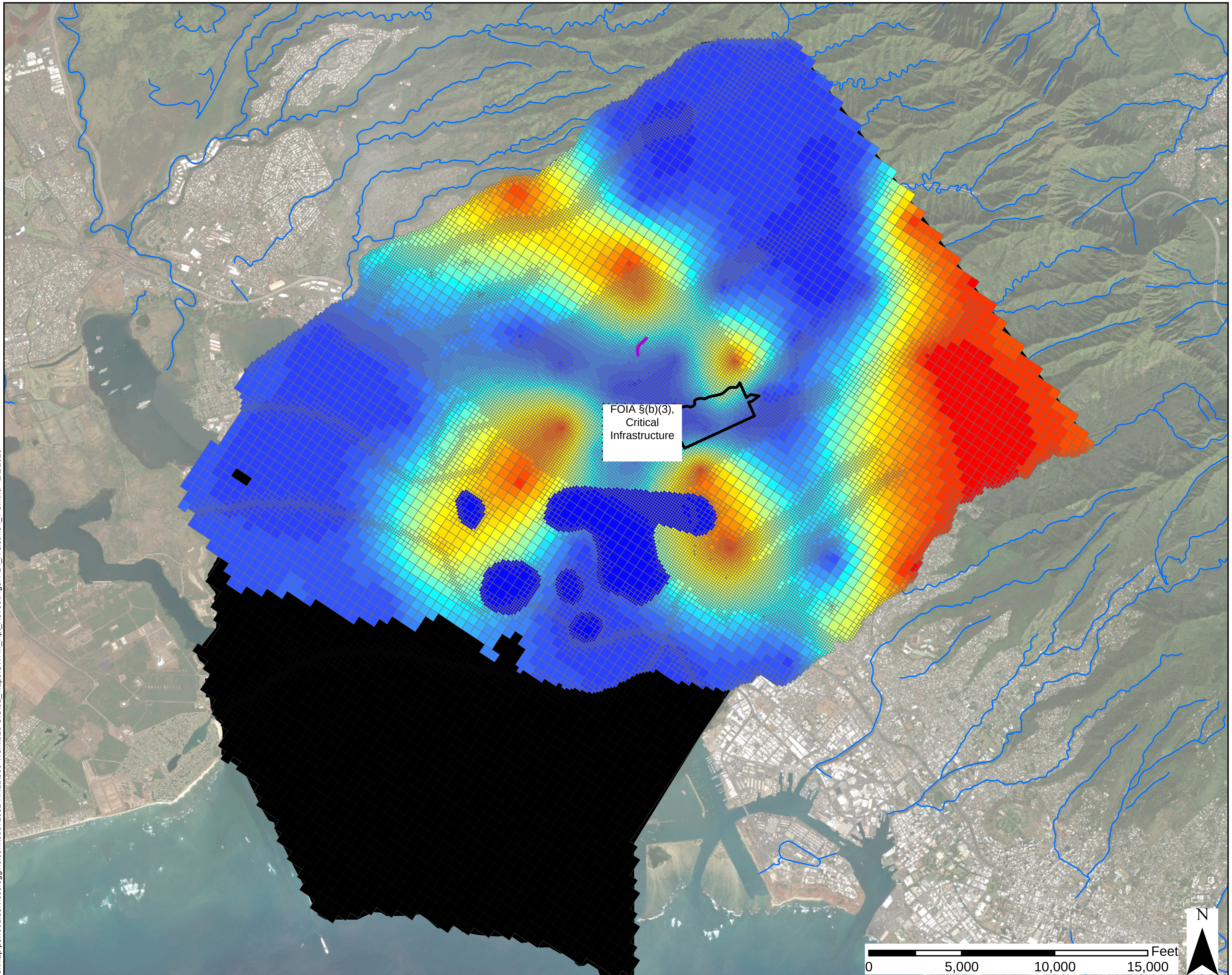
Inactive Model Cells
Shaft
Red Hill Facility Boundary
Stream

Notes

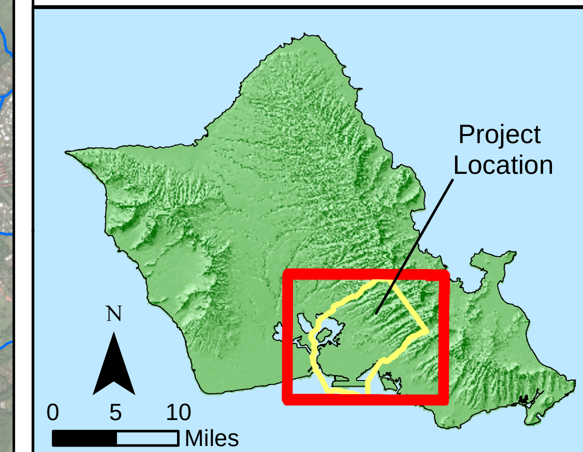
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

Figure 5.4-13
Hydraulic Conductivity Distribution in Layers 4 to 6 for Model #54
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL1\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.4-13_K-distM54_4-6.mxd 2/1/2020



Location Map



Legend

Hydraulic Conductivity (ft/day)

- 0
- 1 - 475
- 476 - 555
- 556 - 640
- 641 - 743
- 744 - 860
- 861 - 994
- 995 - 1145
- 1146 - 1296
- 1297 - 1461
- 1462 - 1659
- 1660 - 1881
- 1882 - 2130
- 2131 - 2405
- 2406 - 2701
- 2702 - 3036
- 3037 - 3417
- 3418 - 3841
- 3842 - 4301
- 4302 - 4835
- 4836 - 5463
- 5464 - 6248
- 6249 - 7174
- 7175 - 8224
- 8225 - 9420
- 9421 - 10671
- 10672 - 12020
- 12021 - 13526
- 13527 - 15105
- 15106 - 16447
- 16448 - 17627
- 17628 - 19315

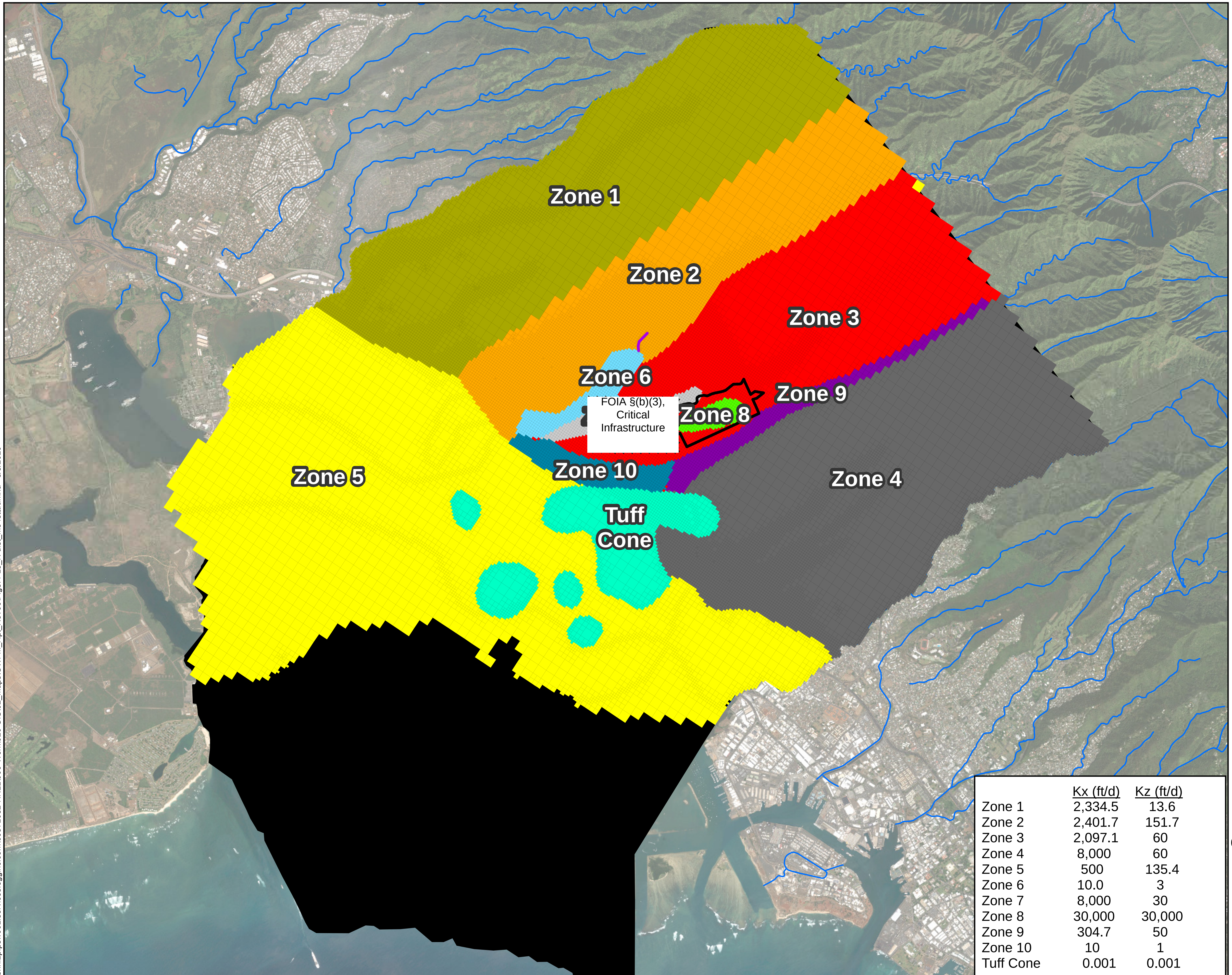
Inactive Model Cells
Shaft
Red Hill Facility Boundary
Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

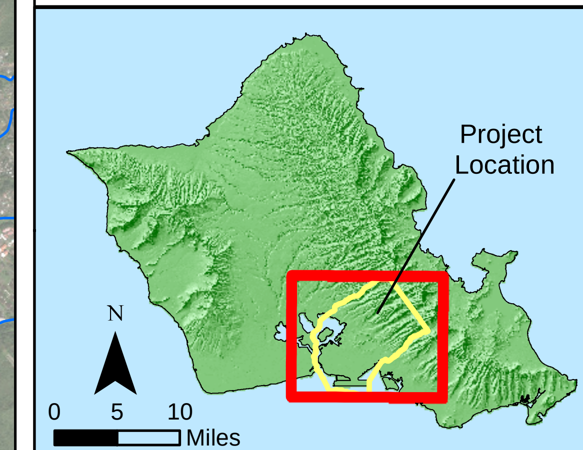
Figure 5.4-14
Hydraulic Conductivity Distribution in Layers 7 to 9 for Model #54
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL1900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.4-14_K-distM54_7-9.mxd 2/1/2020



	Kx (ft/d)	Kz (ft/d)
Zone 1	2,334.5	13.6
Zone 2	2,401.7	151.7
Zone 3	2,097.1	60
Zone 4	8,000	60
Zone 5	500	135.4
Zone 6	10.0	3
Zone 7	8,000	30
Zone 8	30,000	30,000
Zone 9	304.7	50
Zone 10	10	1
Tuff Cone	0.001	0.001

Location Map



Legend

- Zone 1
- Zone 2
- Zone 3
- Zone 4
- Zone 5
- Zone 6
- Zone 7
- Zone 8
- Zone 9
- Zone 10
- Tuff Cone
- Inactive Model Cells
- Shaft
- Red Hill Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 5.4-15
Starting Parameter Distribution in Basalt for PEST Simulations of Model #54
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

\\ushnl1pfpsw001.services.egginc.com\60571032-HNL1\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.4-15_K-dist_M54start.mxd 3/8/2020

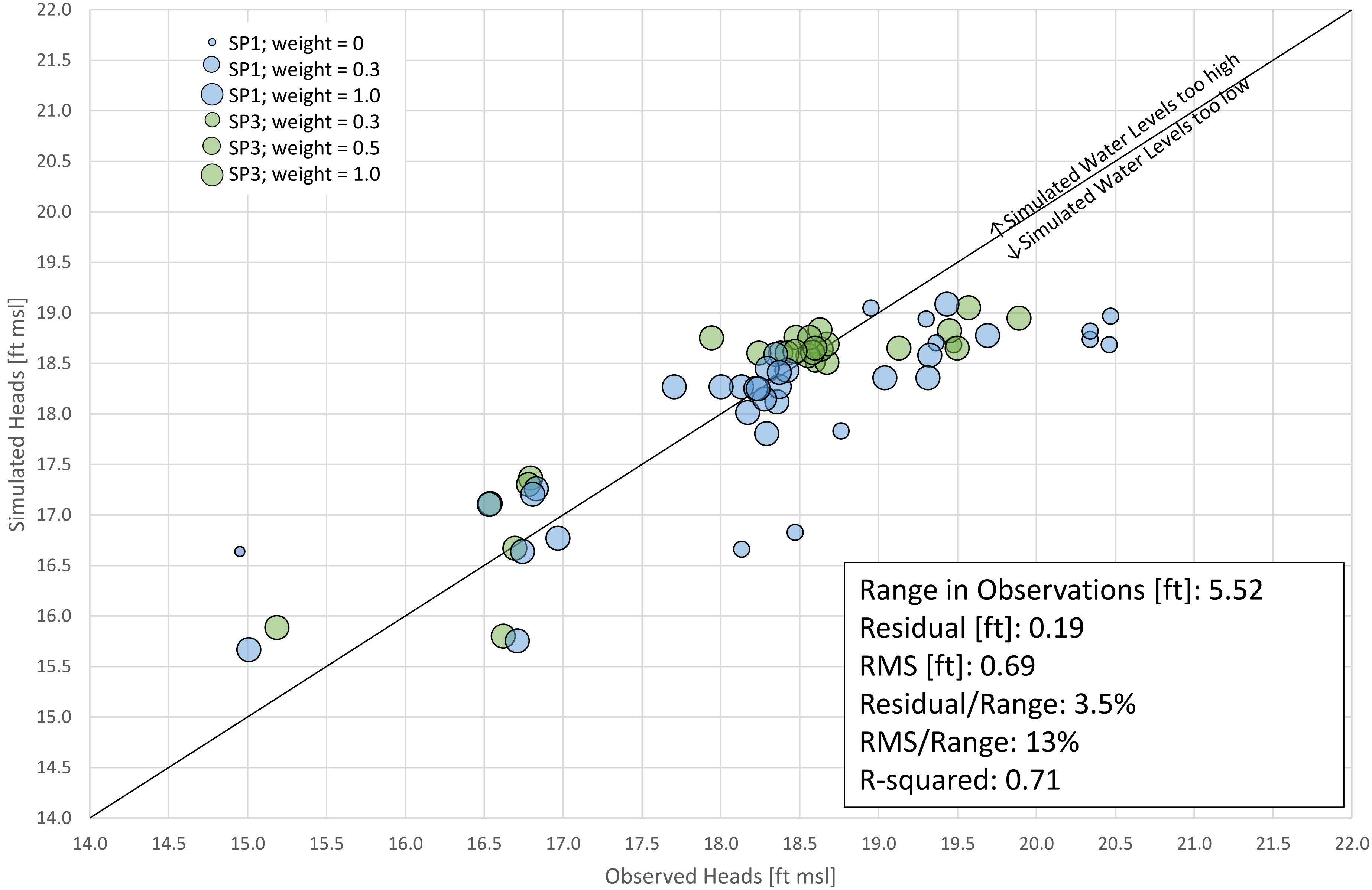
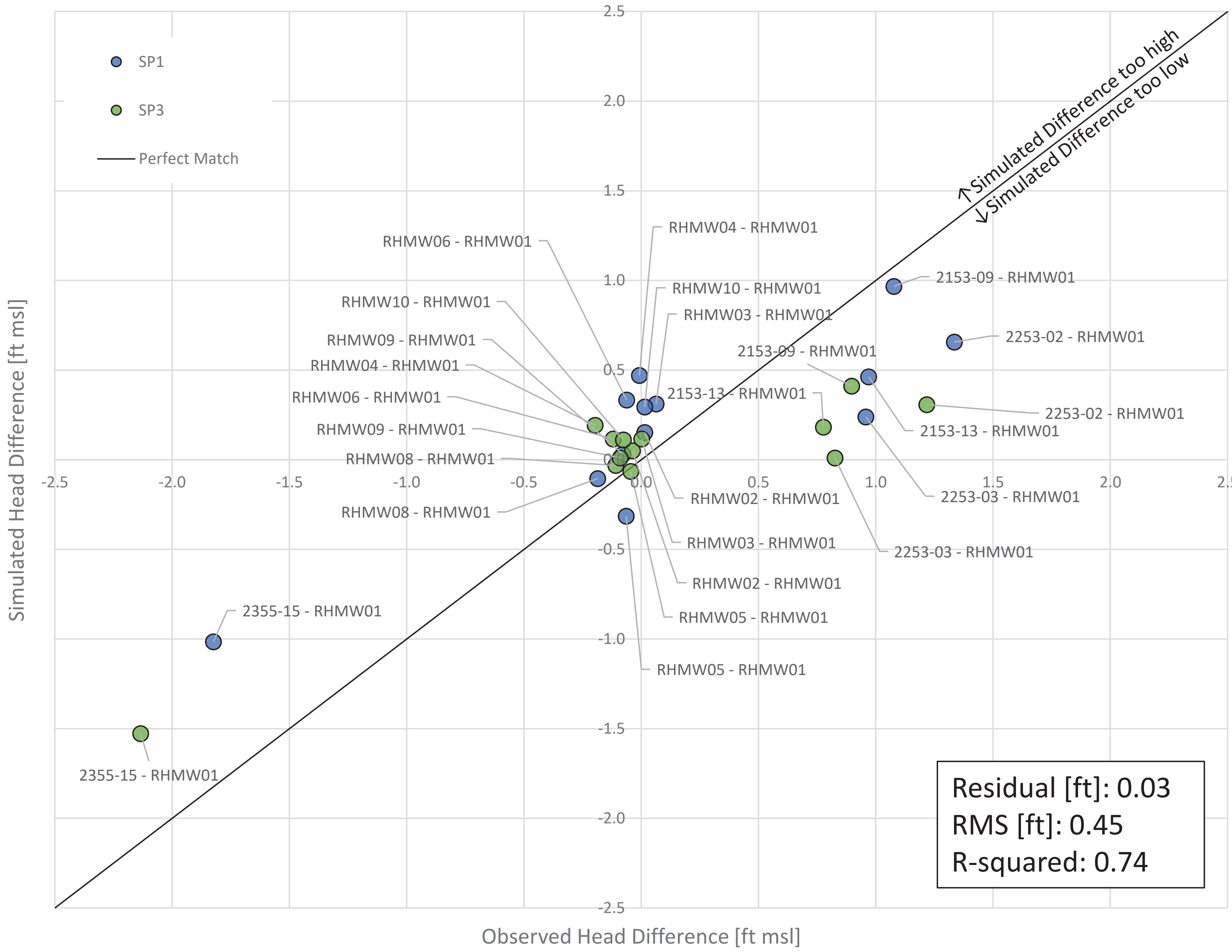


Figure 5.5-1
Model #55: Conceptual Clinker Zones – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

(a) Difference with RHMW01



(b) Difference with RHMW04

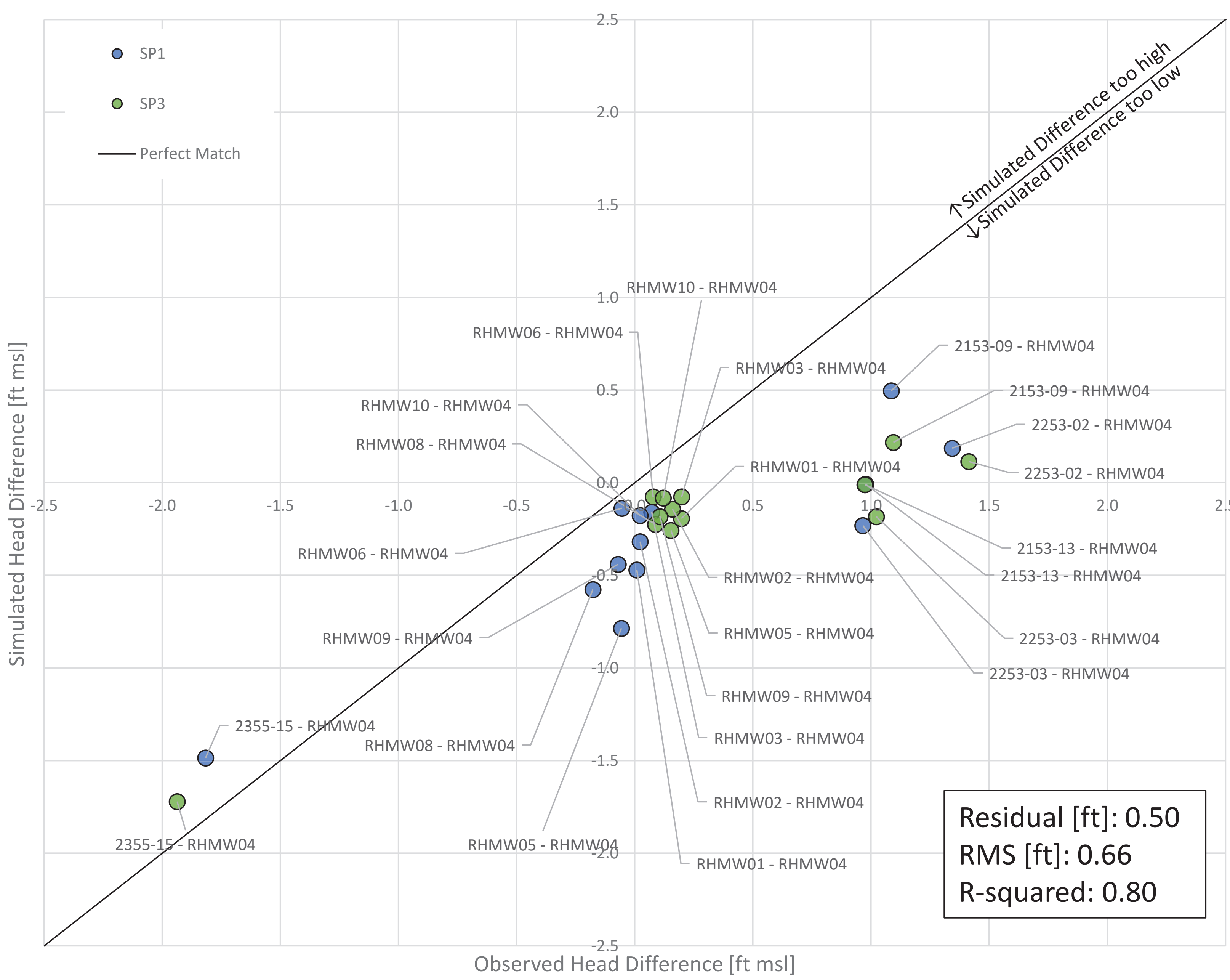


Figure 5.5-2
Model #55: Conceptual Clinker Zones –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

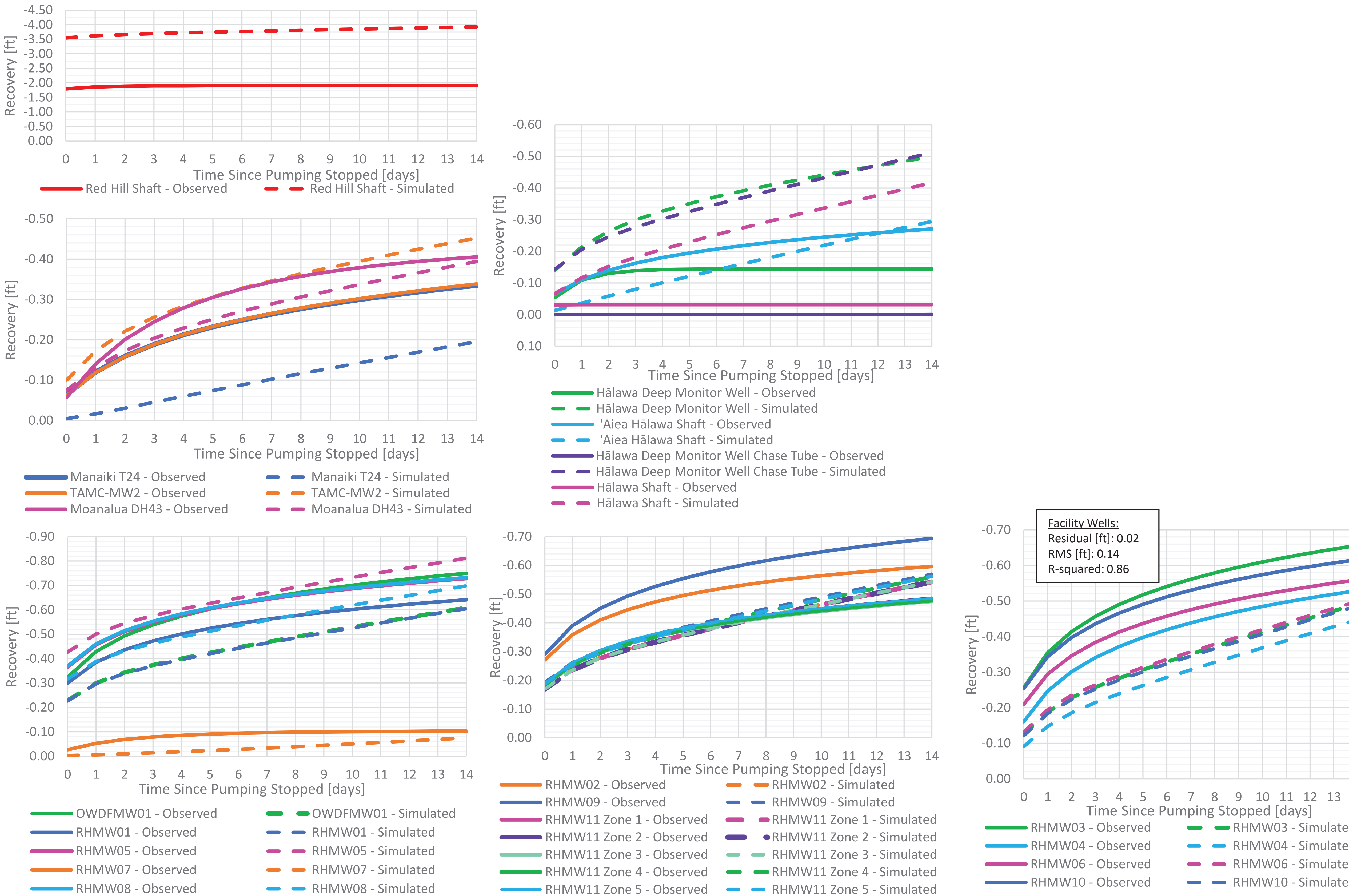


Figure 5.5-3
Model #55: Conceptual Clinker Zones –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

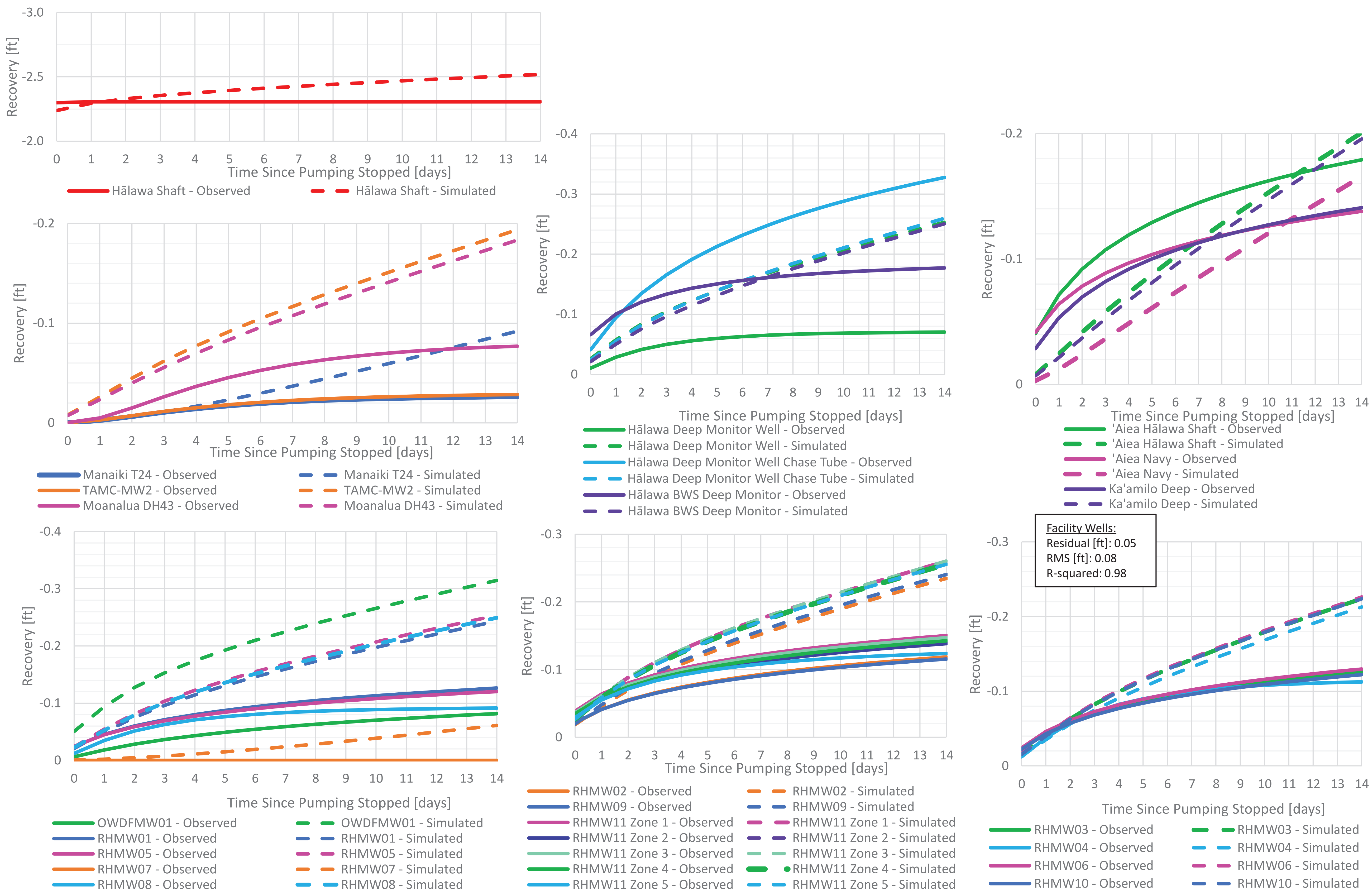
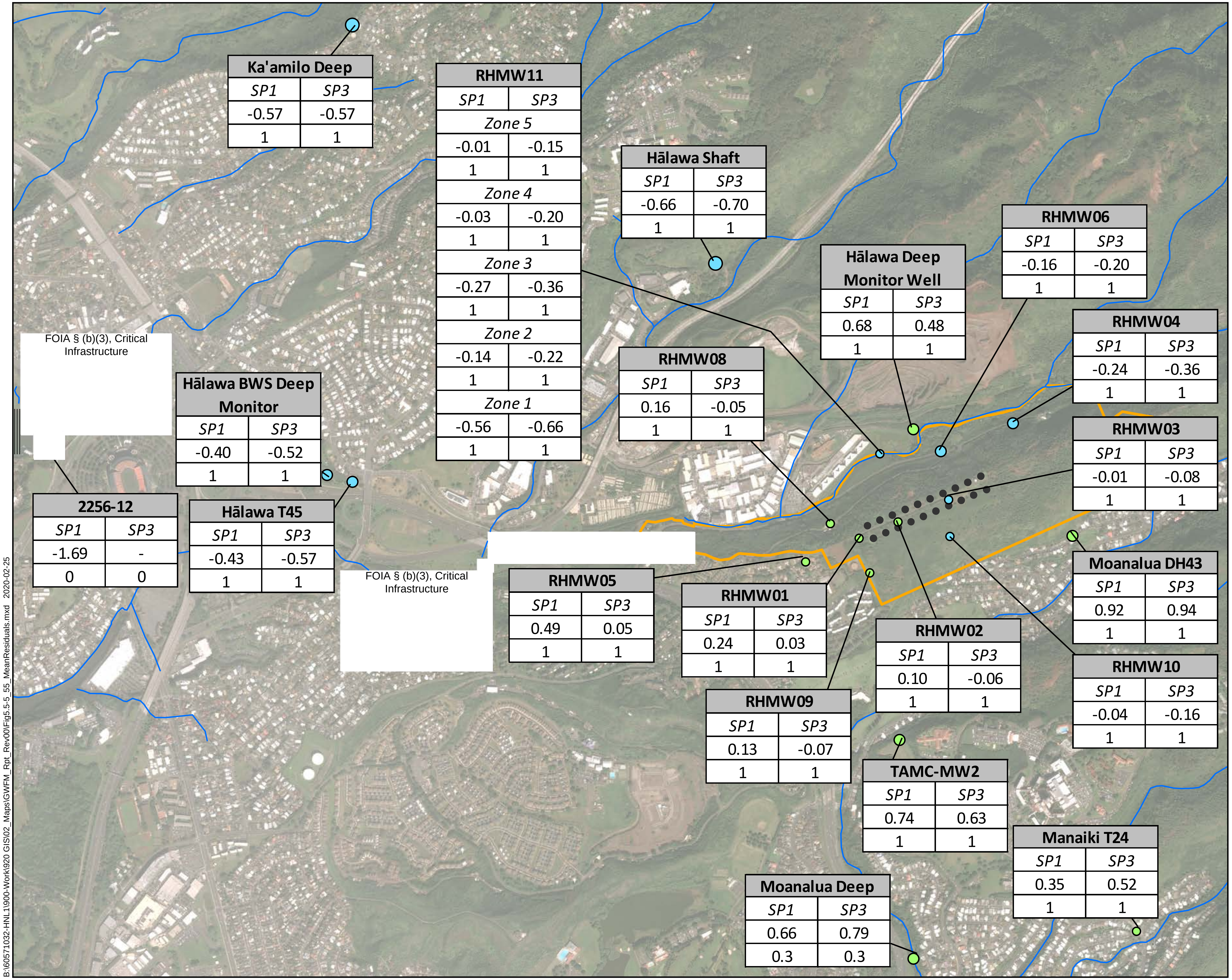


Figure 5.5-4
Model #55: Conceptual Clinker Zones –
Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



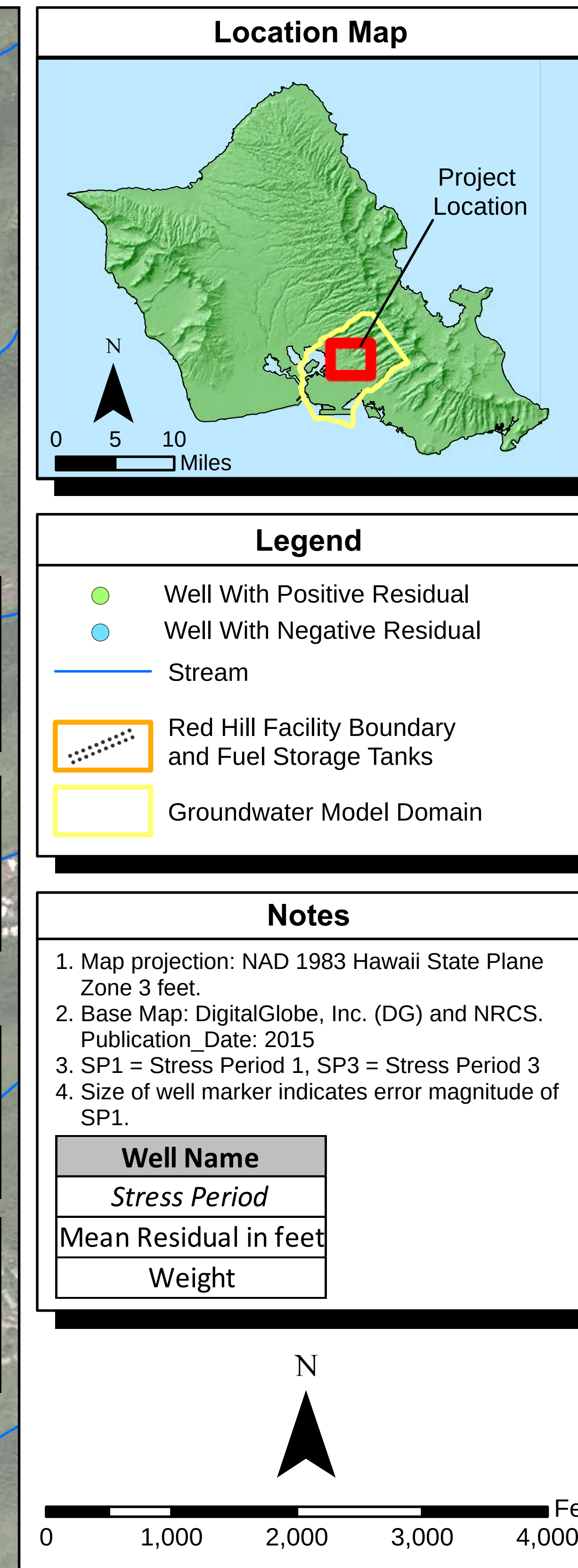


Figure 5.5-5
Model #55: Conceptual Clinker Zones – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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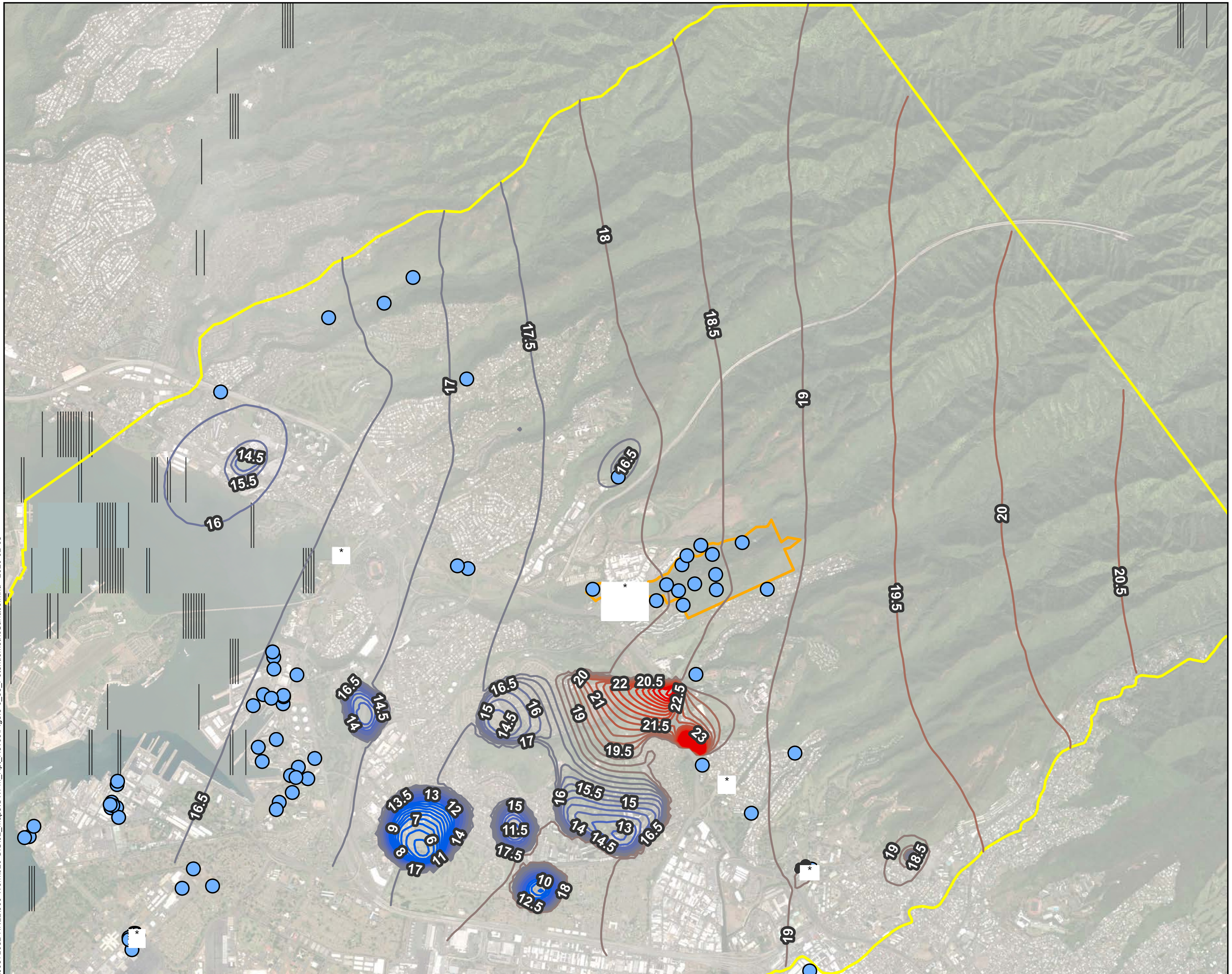
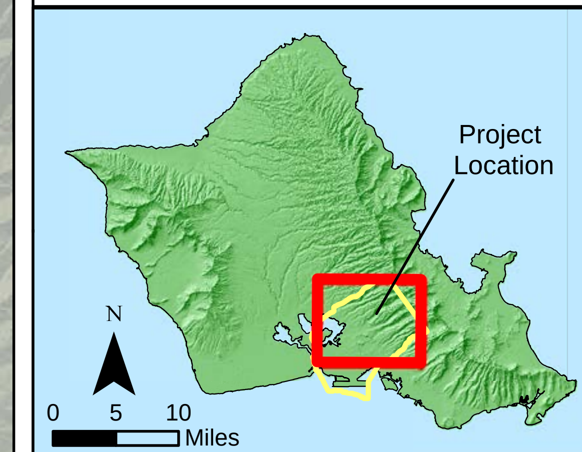
~~For Red Hill AOC Party Use Only~~



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.5-6
Model #55: Homogeneous Basalt with 3:1 Anisotropy and Basalt Zonation – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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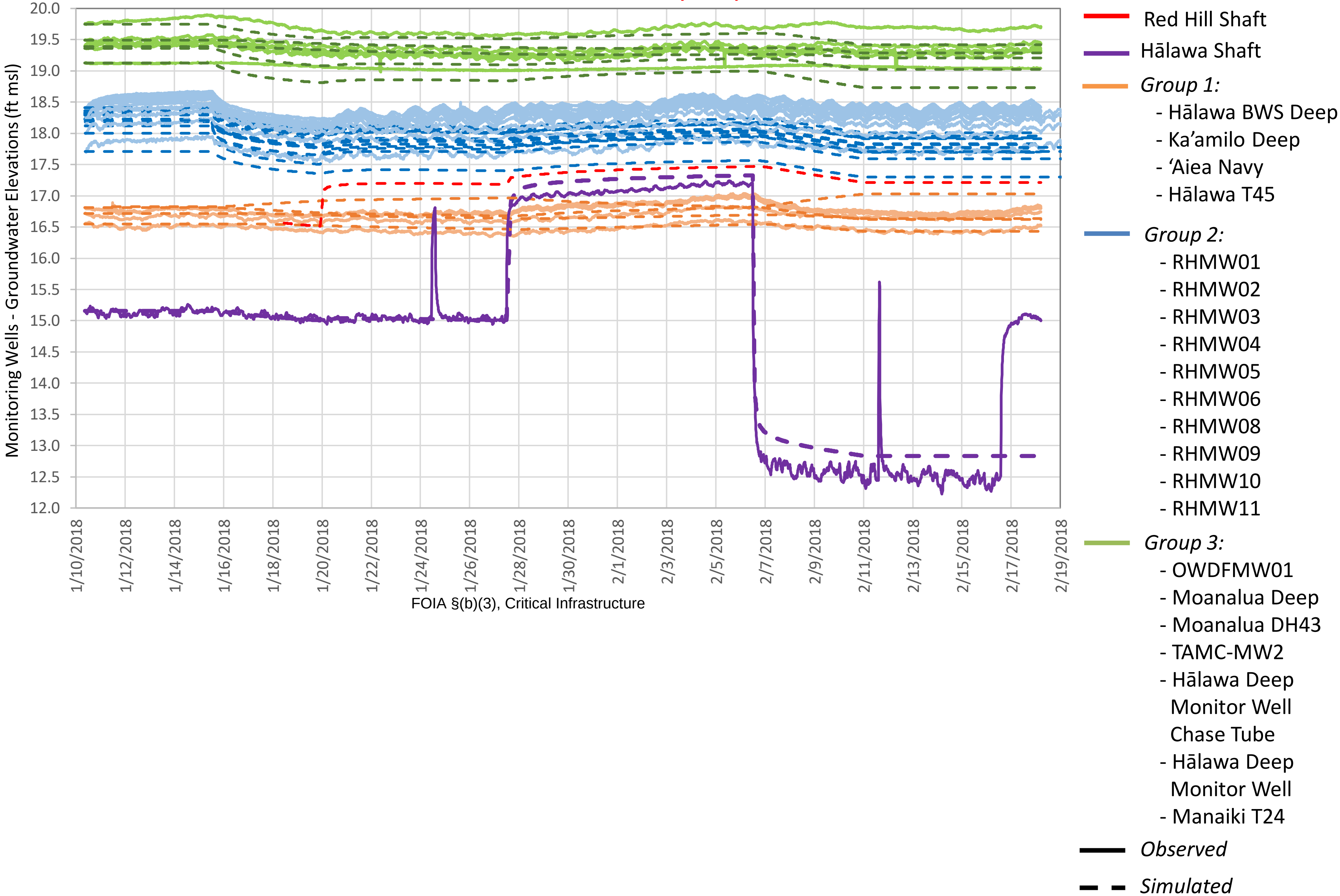


FOIA §(b)(3), Critical Infrastructure

Figure 5.5-7
Model #55: Conceptual Clinker Zones – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

~~For Red Hill AOC Party Use Only~~

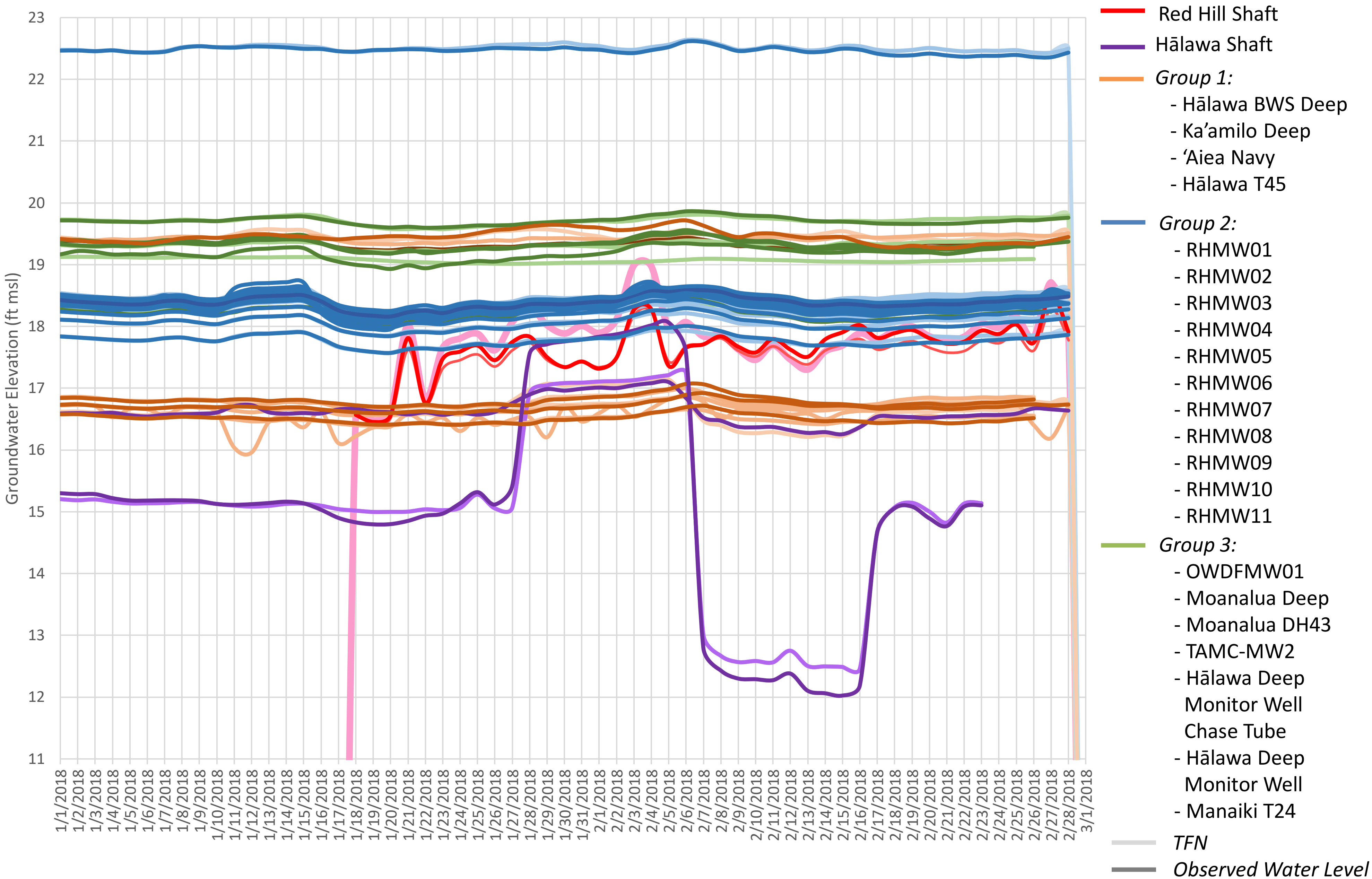
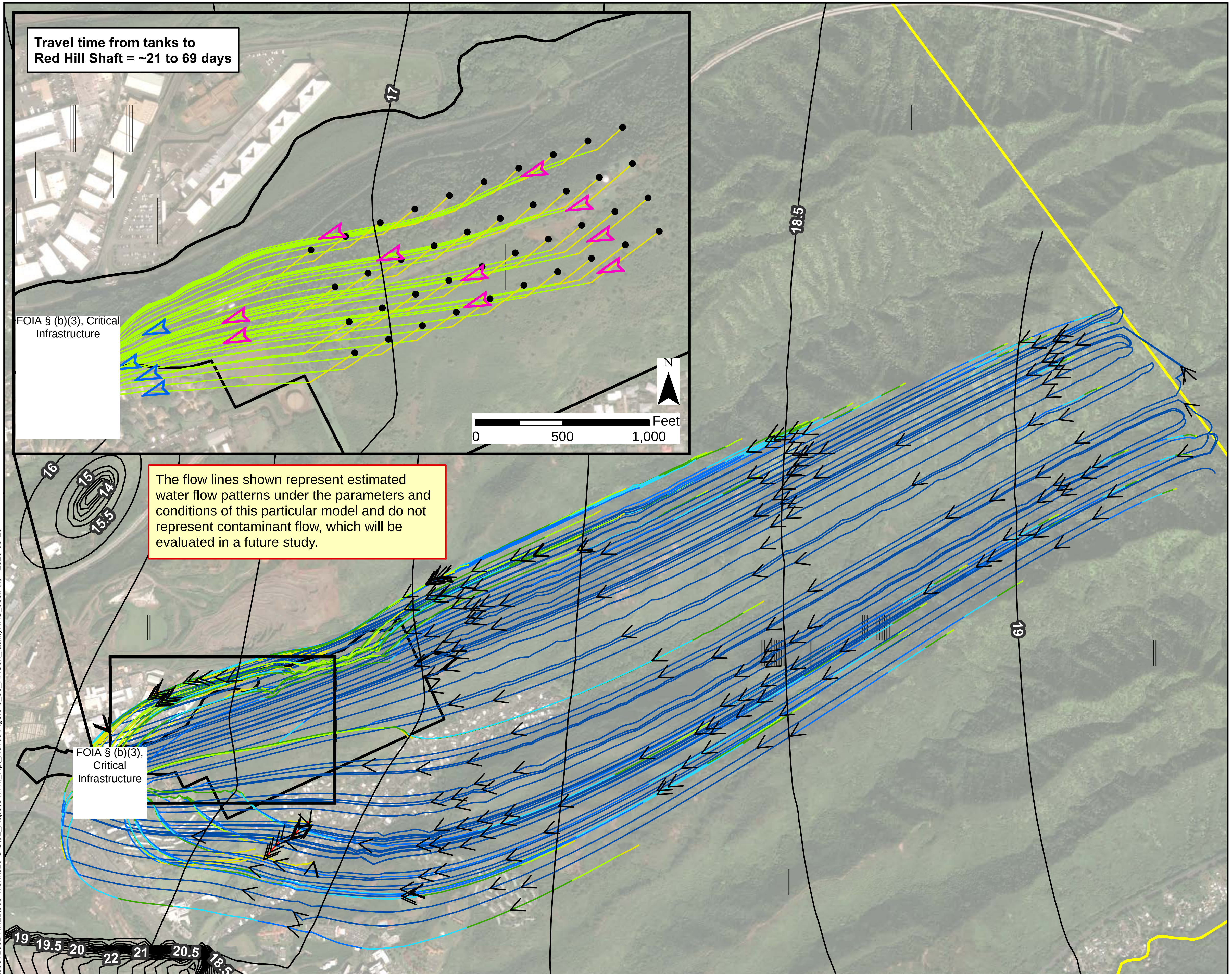
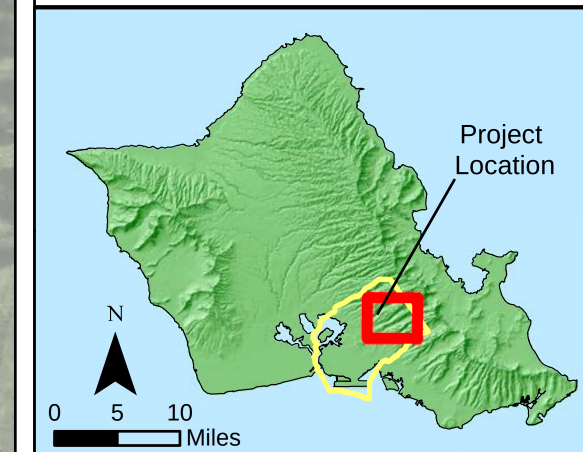


Figure 5.5-8
Model #55: Conceptual Clinker Zones – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet
- Red Hill Facility
- Groundwater Model

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 20 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N
Feet
0 1,000 2,000 3,000 4,000

Figure 5.5-9
Model #55: Conceptual Clinker Zones – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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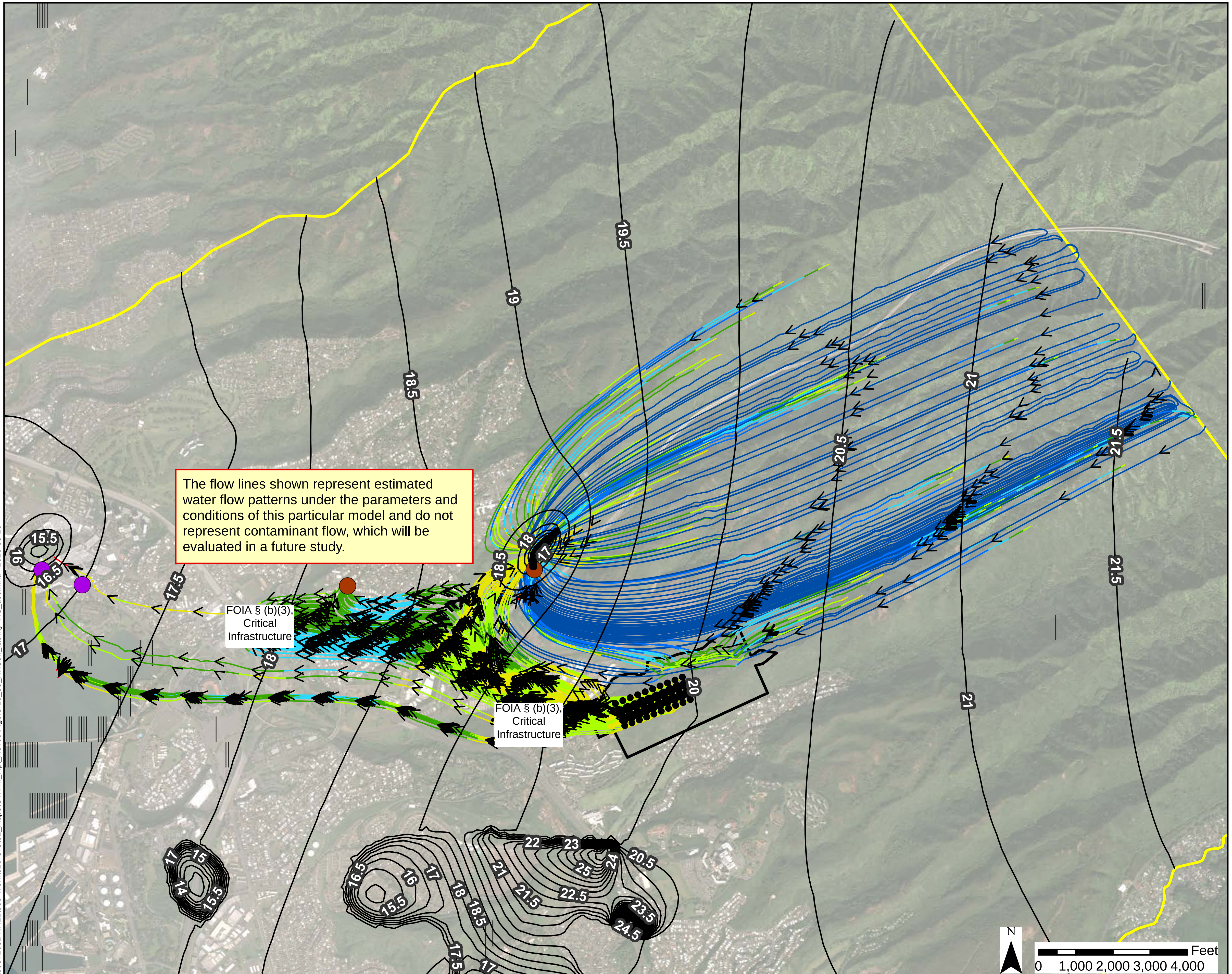

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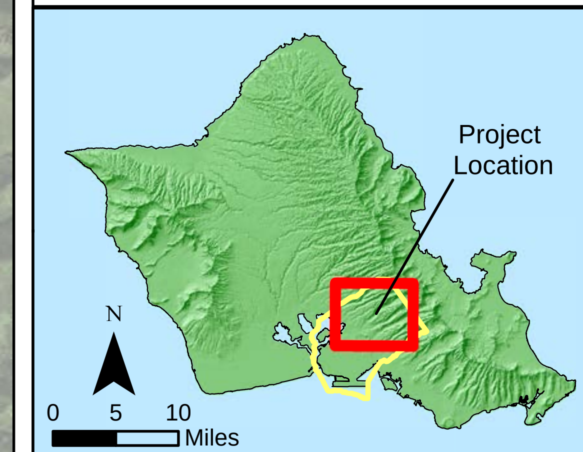
Location Map



Legend

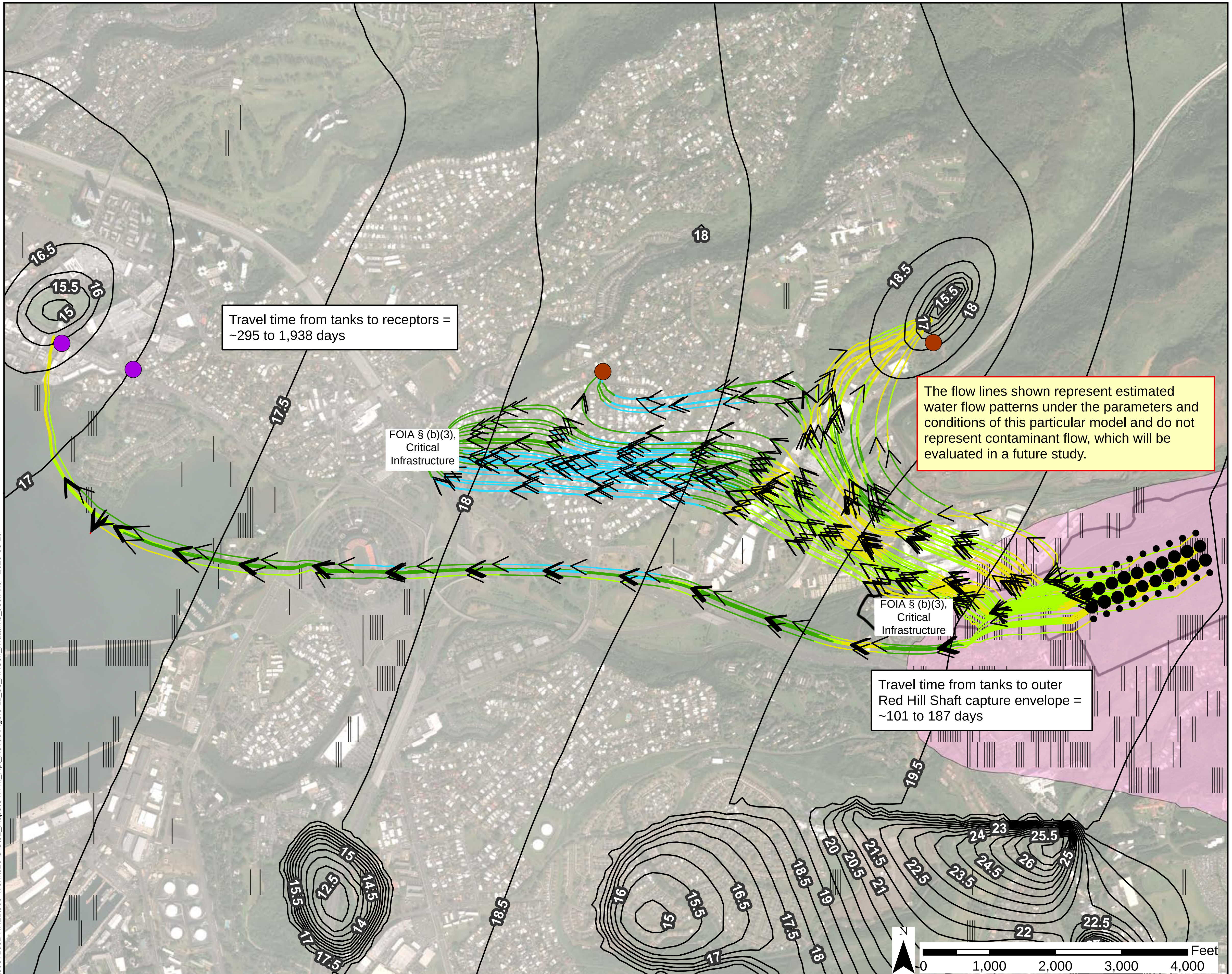
Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

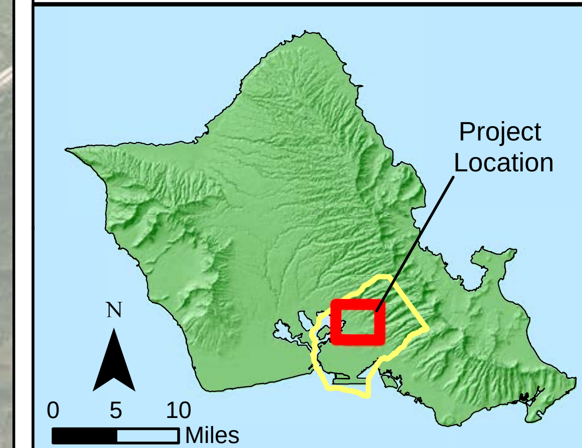
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.5-10
Model #55: Conceptual Clinker Zones – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Locatior
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.5-11
Model #55: Conceptual Clinker Zones – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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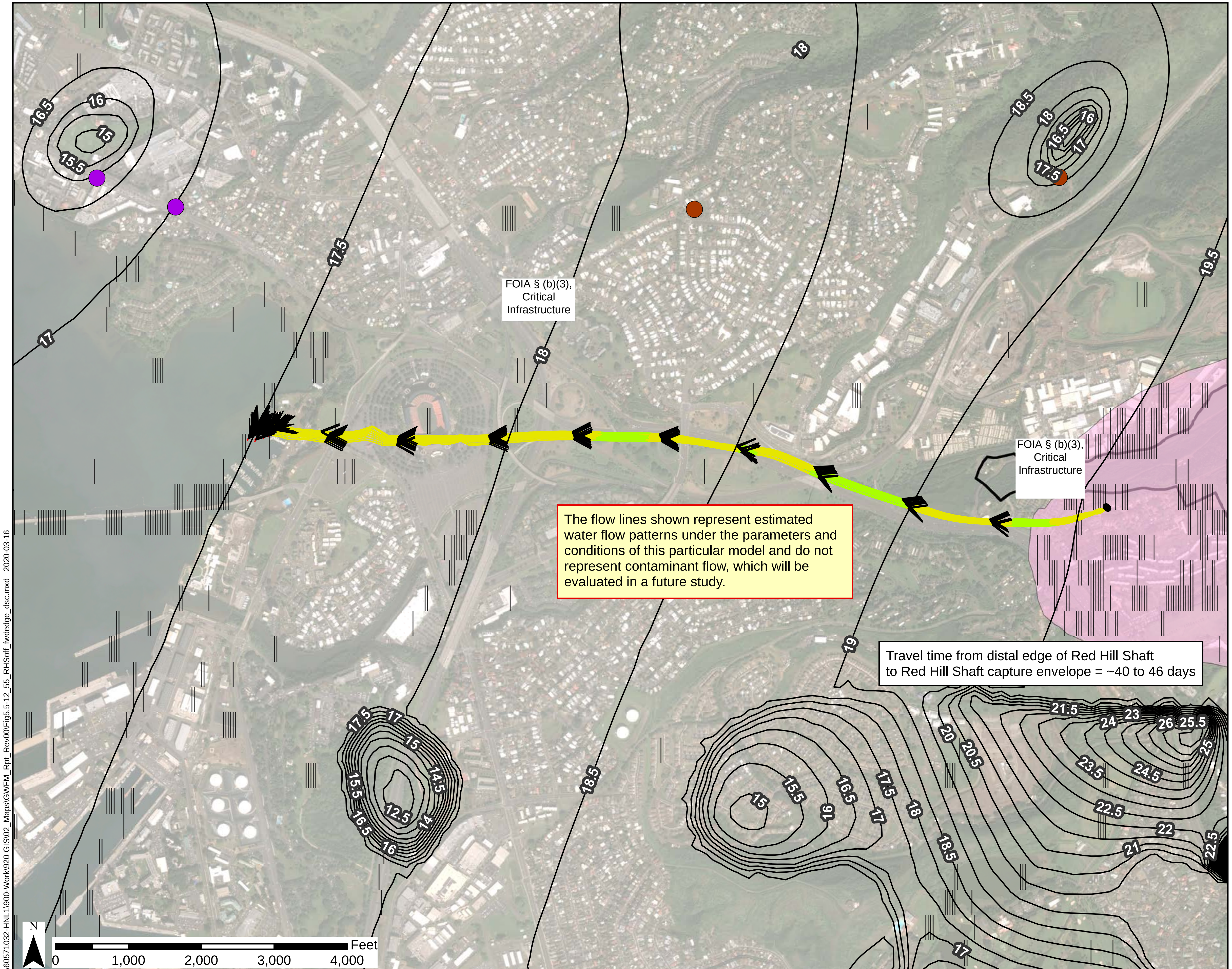
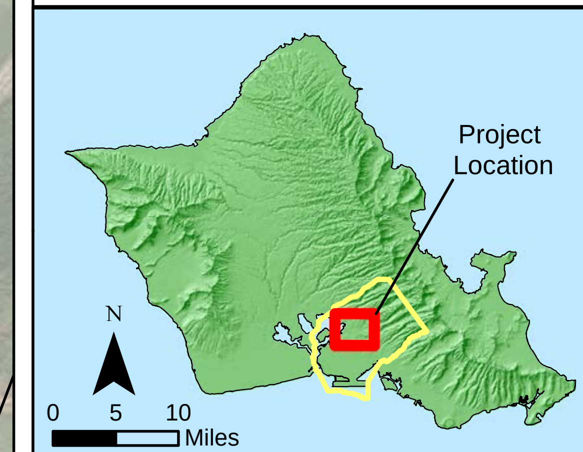


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.5-12
Model #55: Conceptual Clinker Zones – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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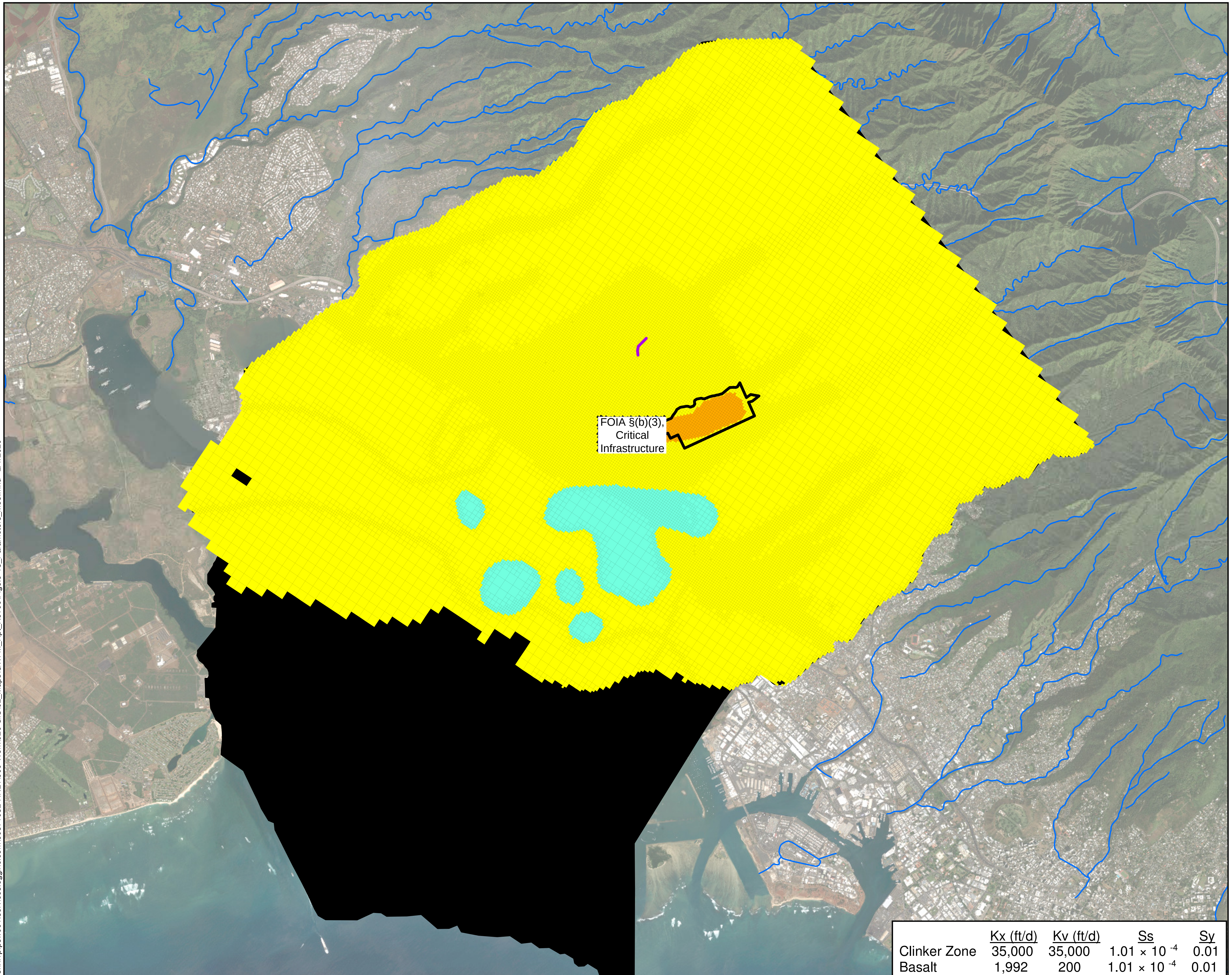
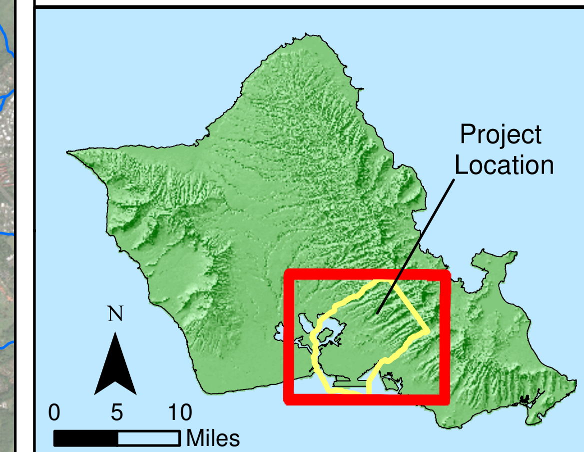


	Kx (ft/d)	Kv (ft/d)	Ss	Sy
Clinker Zone	35,000	35,000	1.01×10^{-4}	0.01
Basalt	1,992	200	1.01×10^{-4}	0.01

Location Map



Legend

- Clinker Zone
- Basalt
- Tuff Cone
- Inactive Model Cells
- Shaft
- Red Hill Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

N

0 5,000 10,000 15,000 Feet

Figure 5.5-13
Hydraulic Parameter Zonation in Basalt for Model #55
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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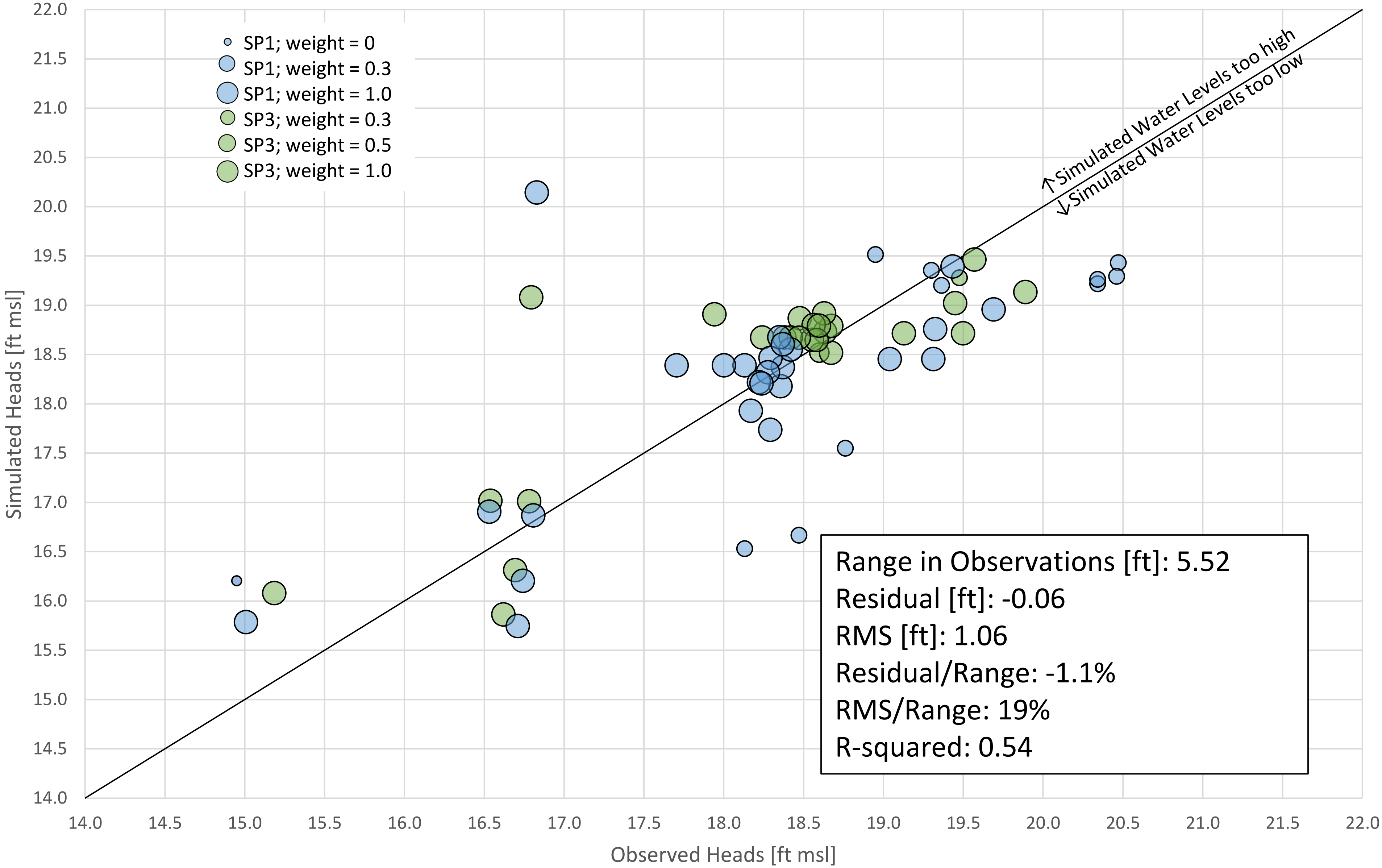
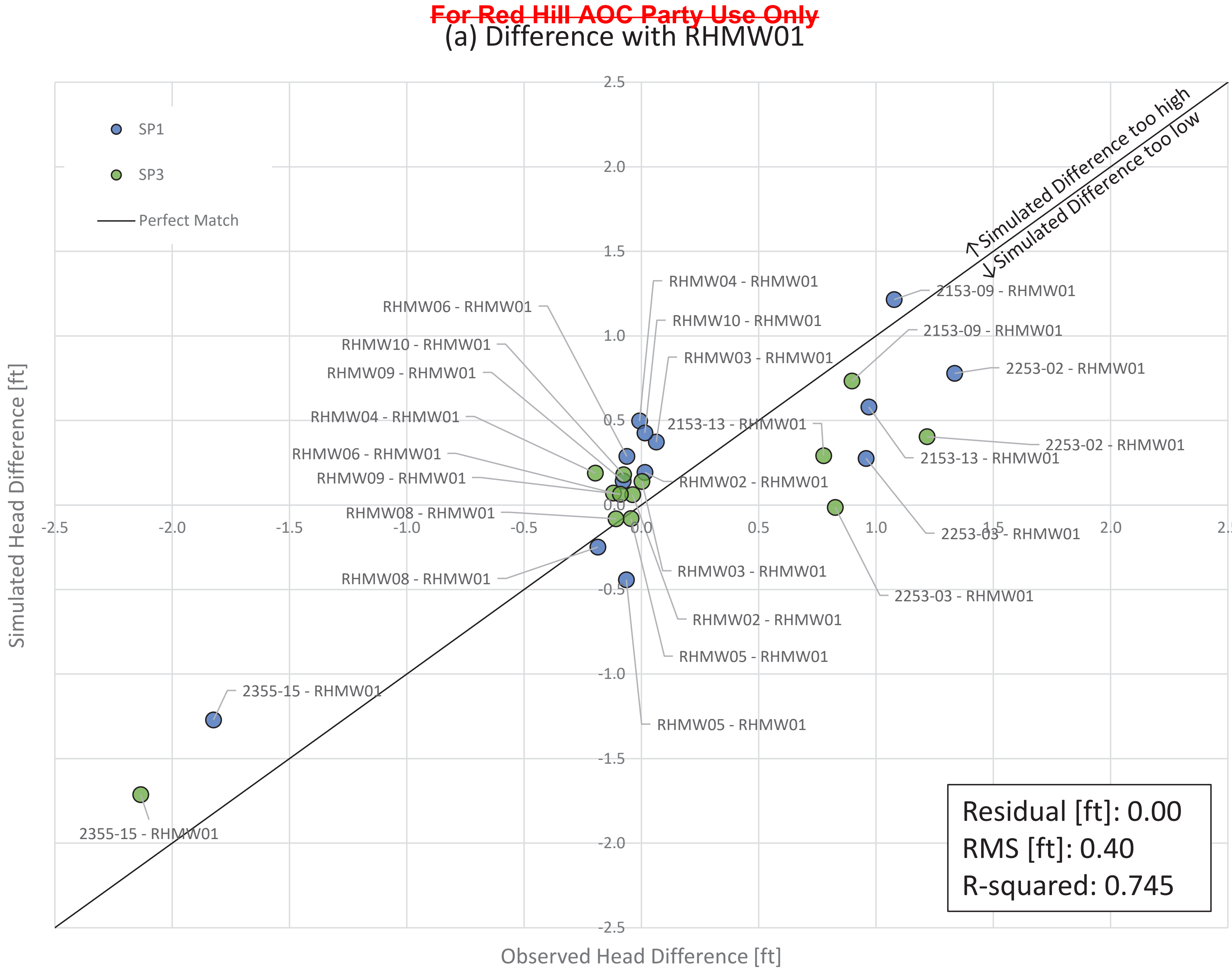


Figure 5.6-1
Model #56: Structural Alterations of Tuff Cones – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



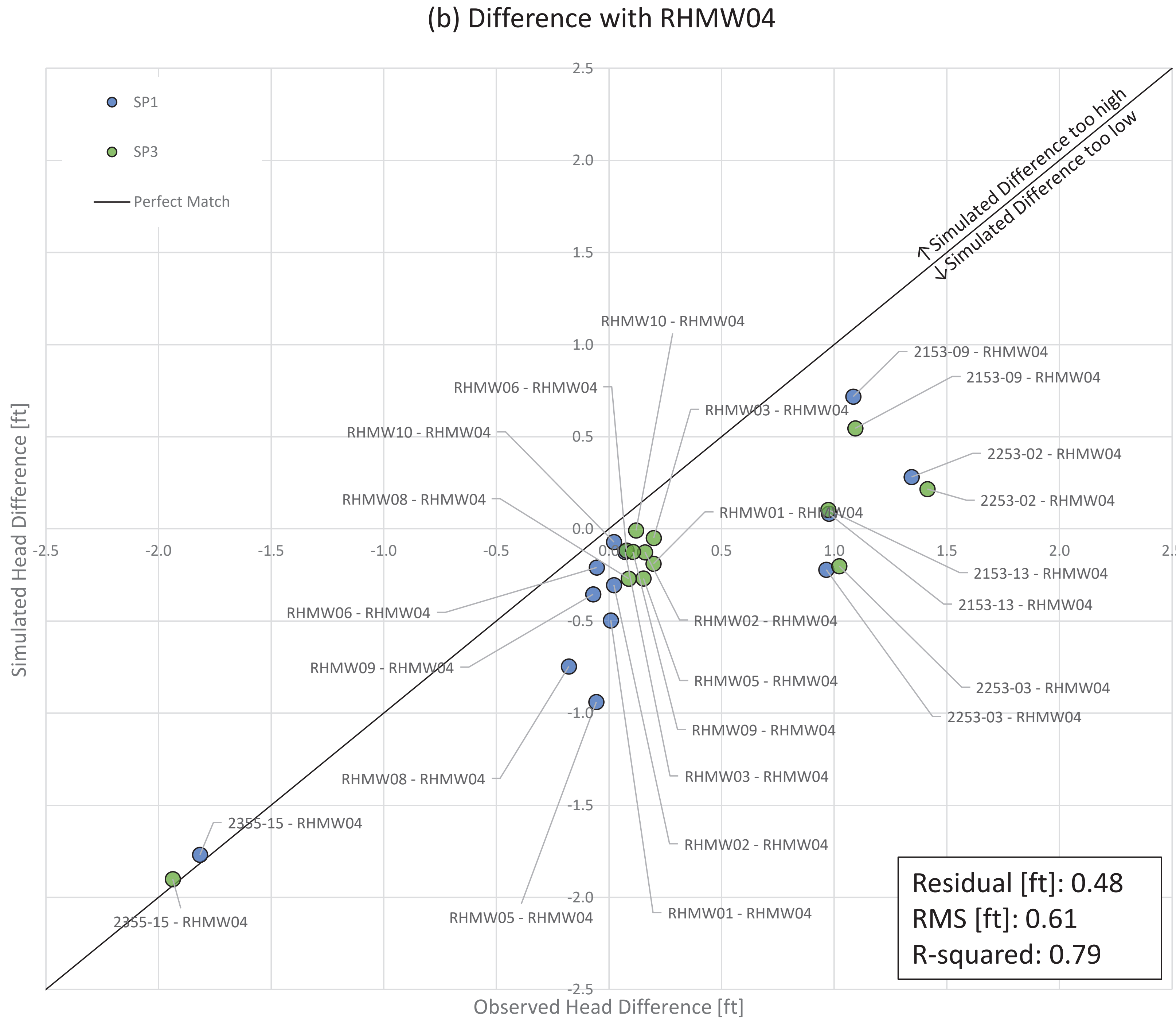


Figure 5.6-2
Model #56: Structural Alterations of Tuff Cones –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

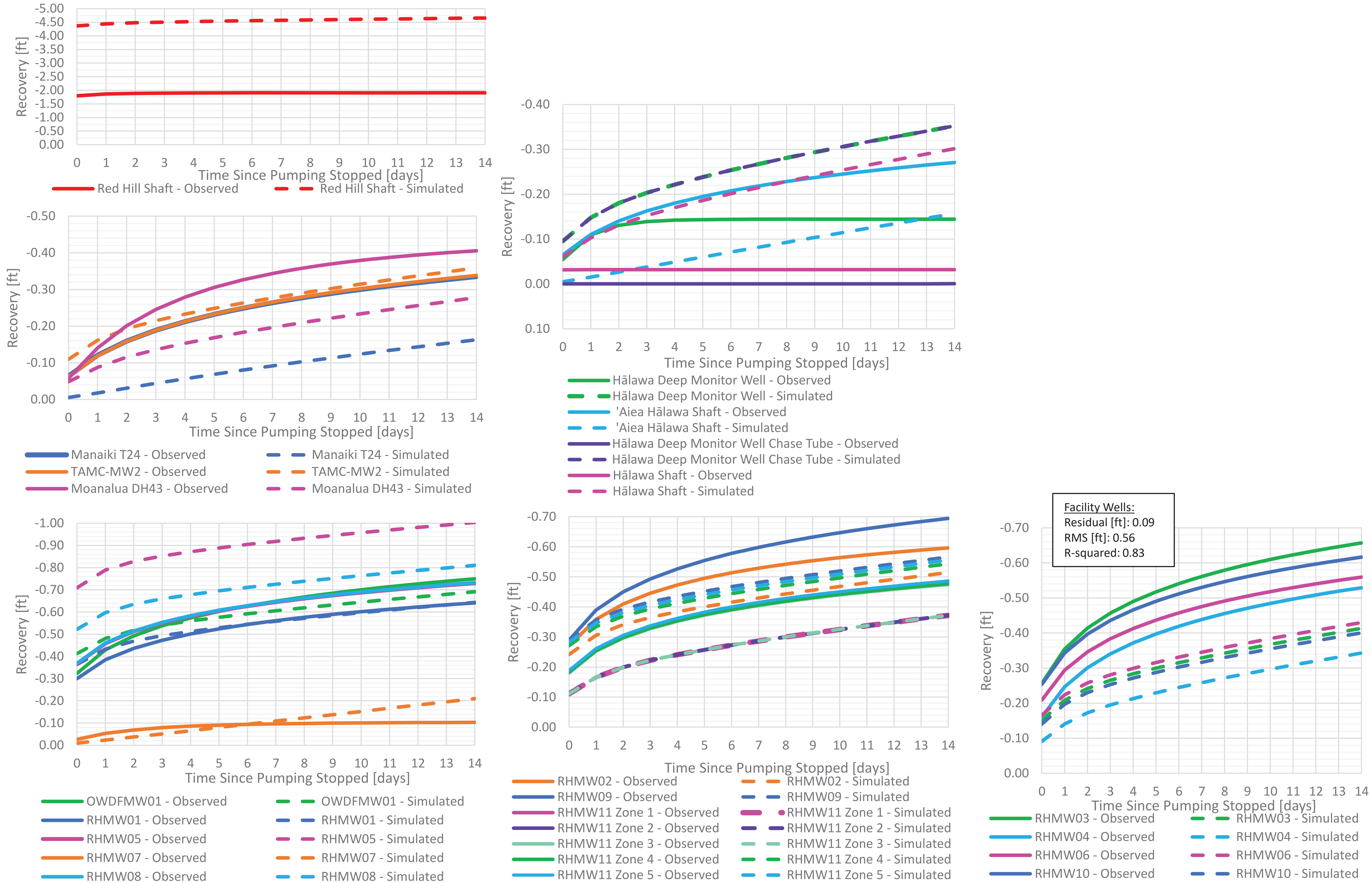


Figure 5.6-3
Model #56: Structural Alterations of Tuff Cones –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

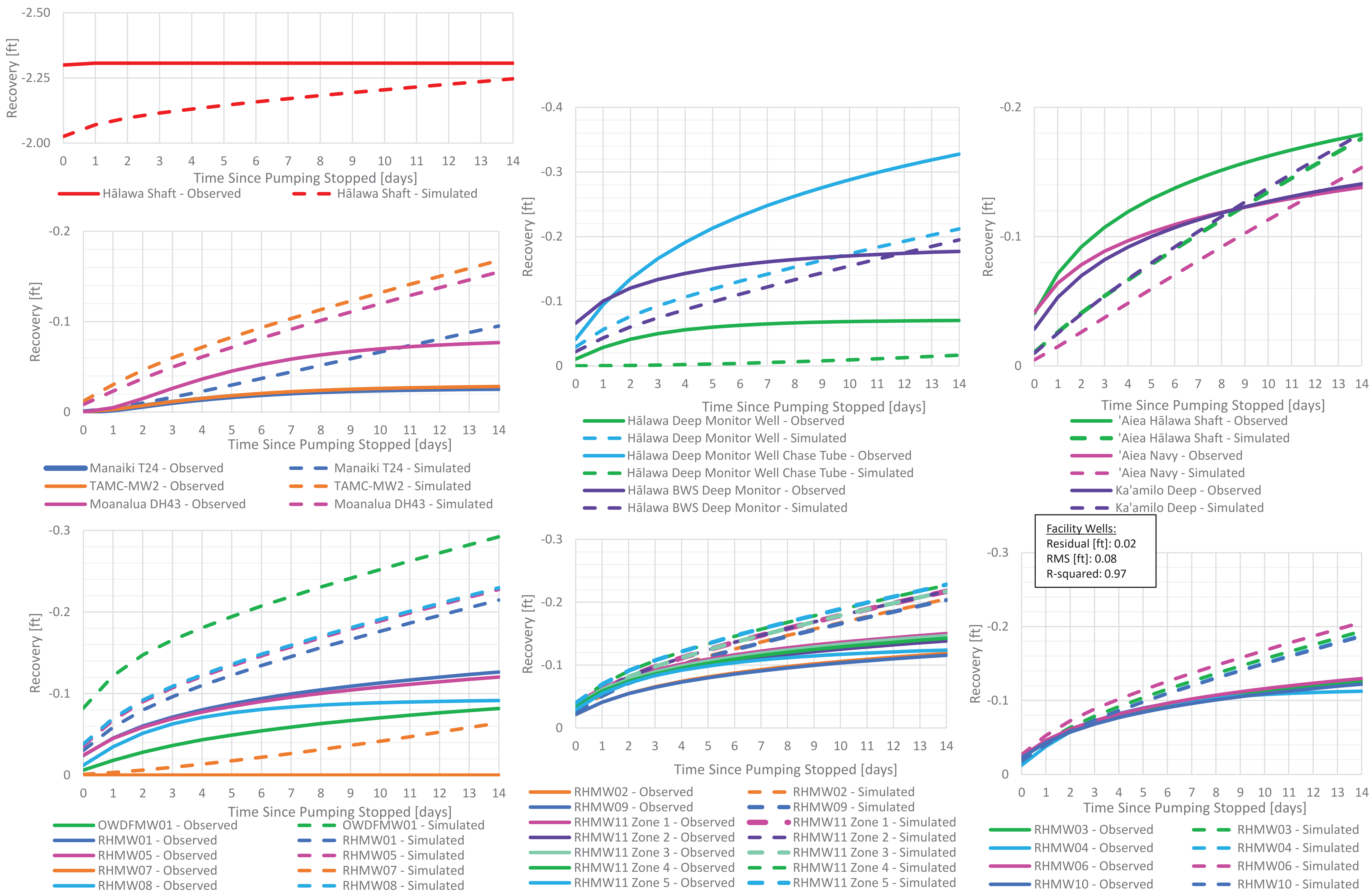
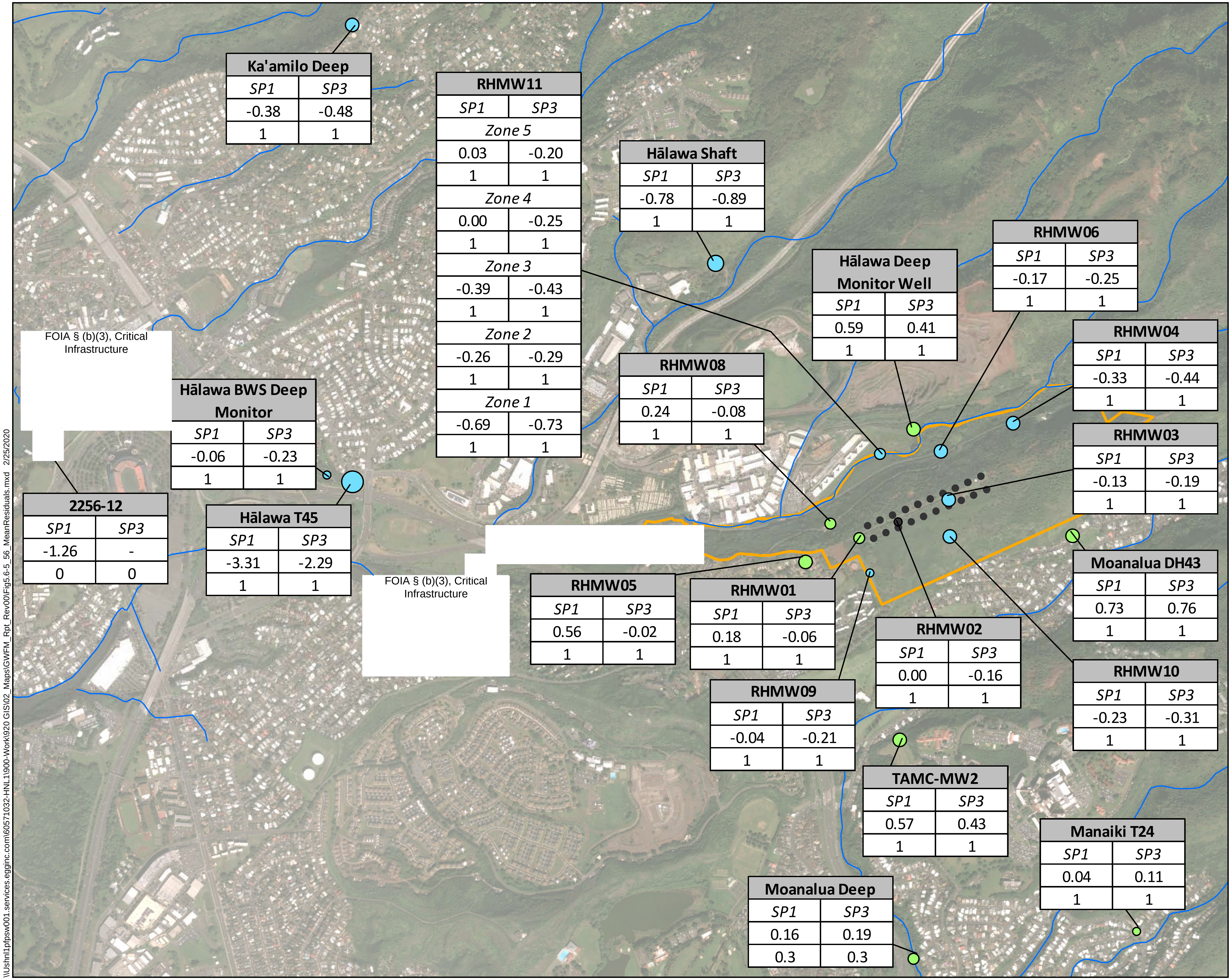


Figure 5.6-4
Model #56: Structural Alterations of Tuff Cones –
Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



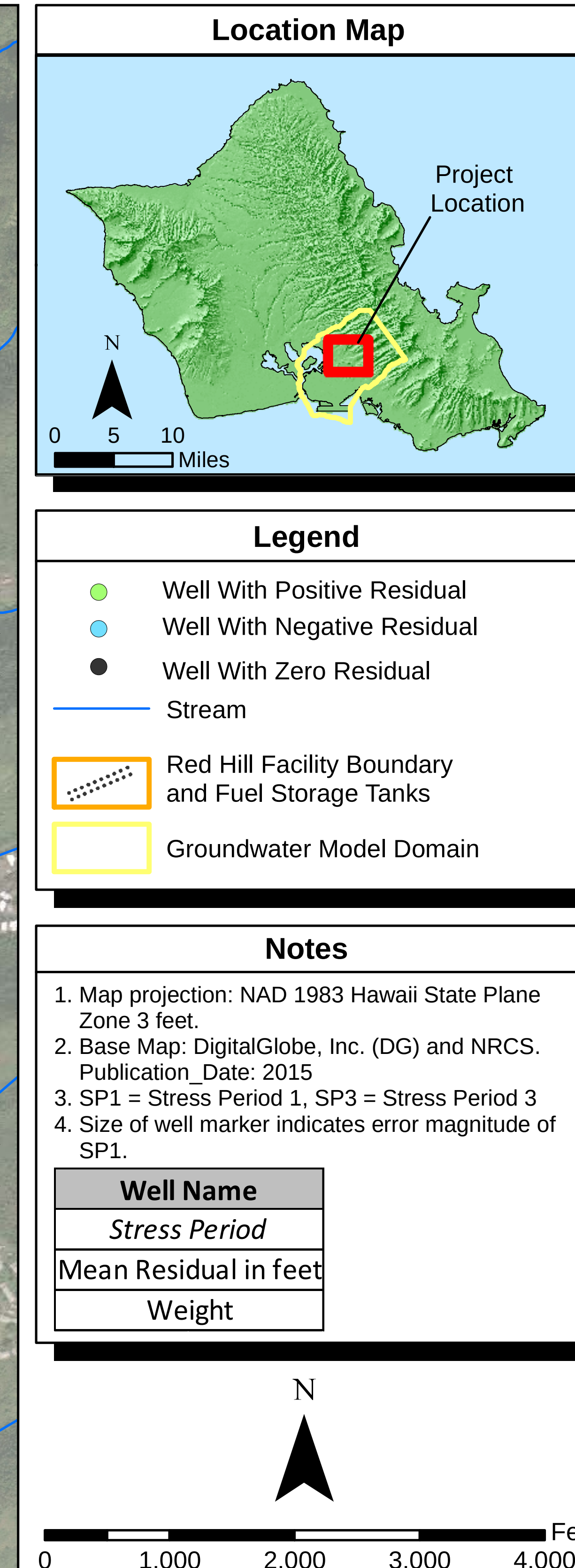
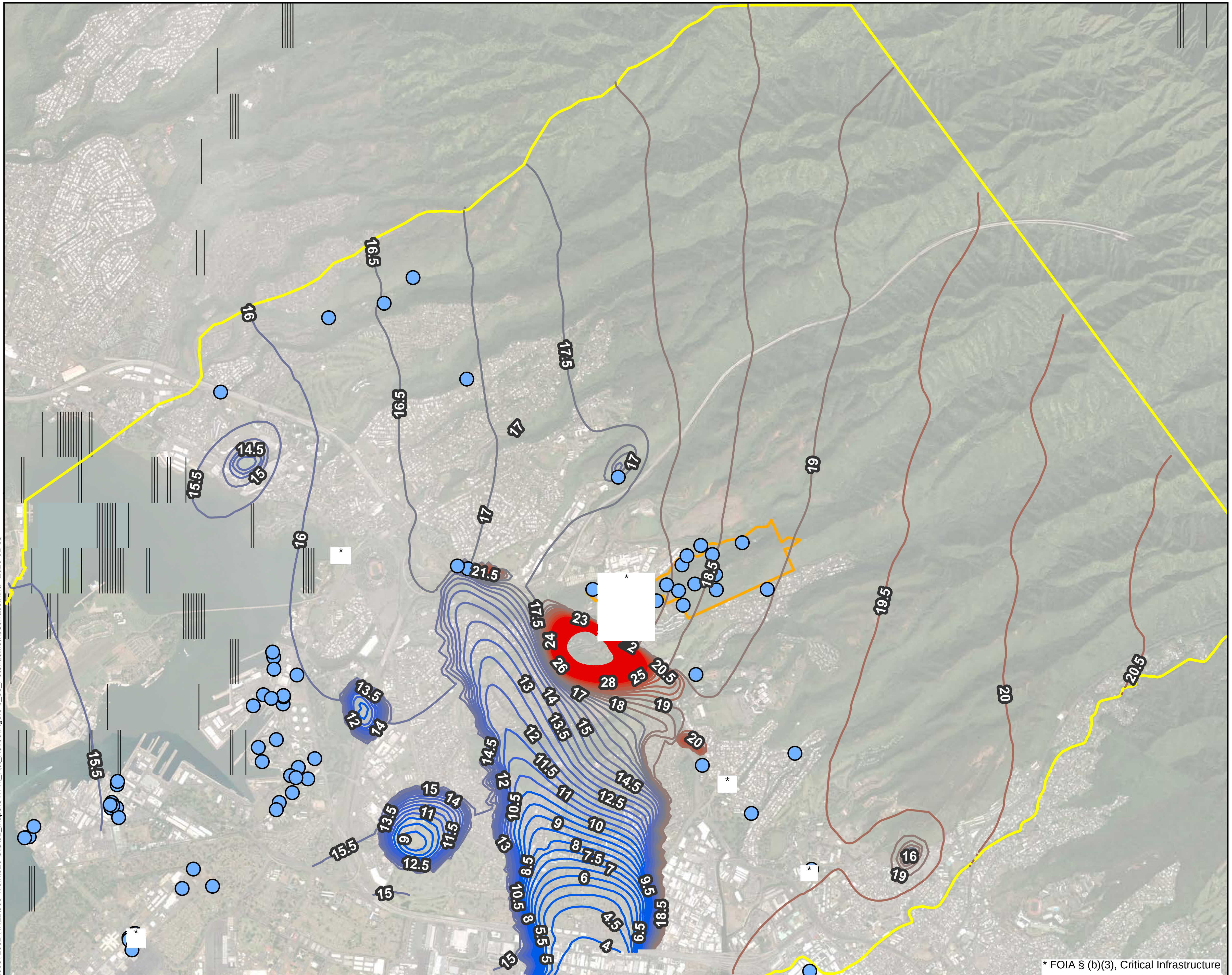
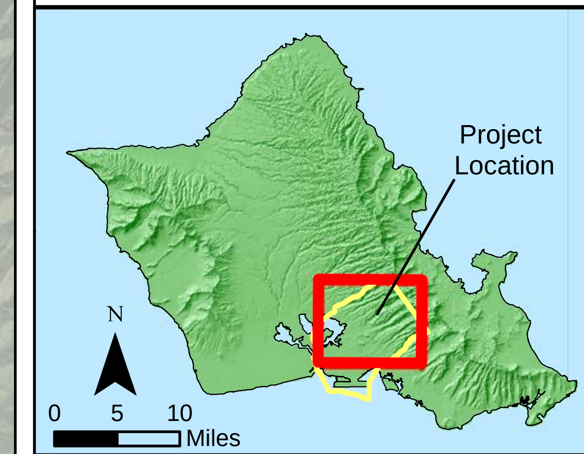


Figure 5.6-5
Model #56: Structural Alterations of Tuff Cones – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Potentiometric Surface
(feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N
0 2,000 4,000 6,000 Feet

Figure 5.6-6
Model #56: Caprock Heterogeneity –
Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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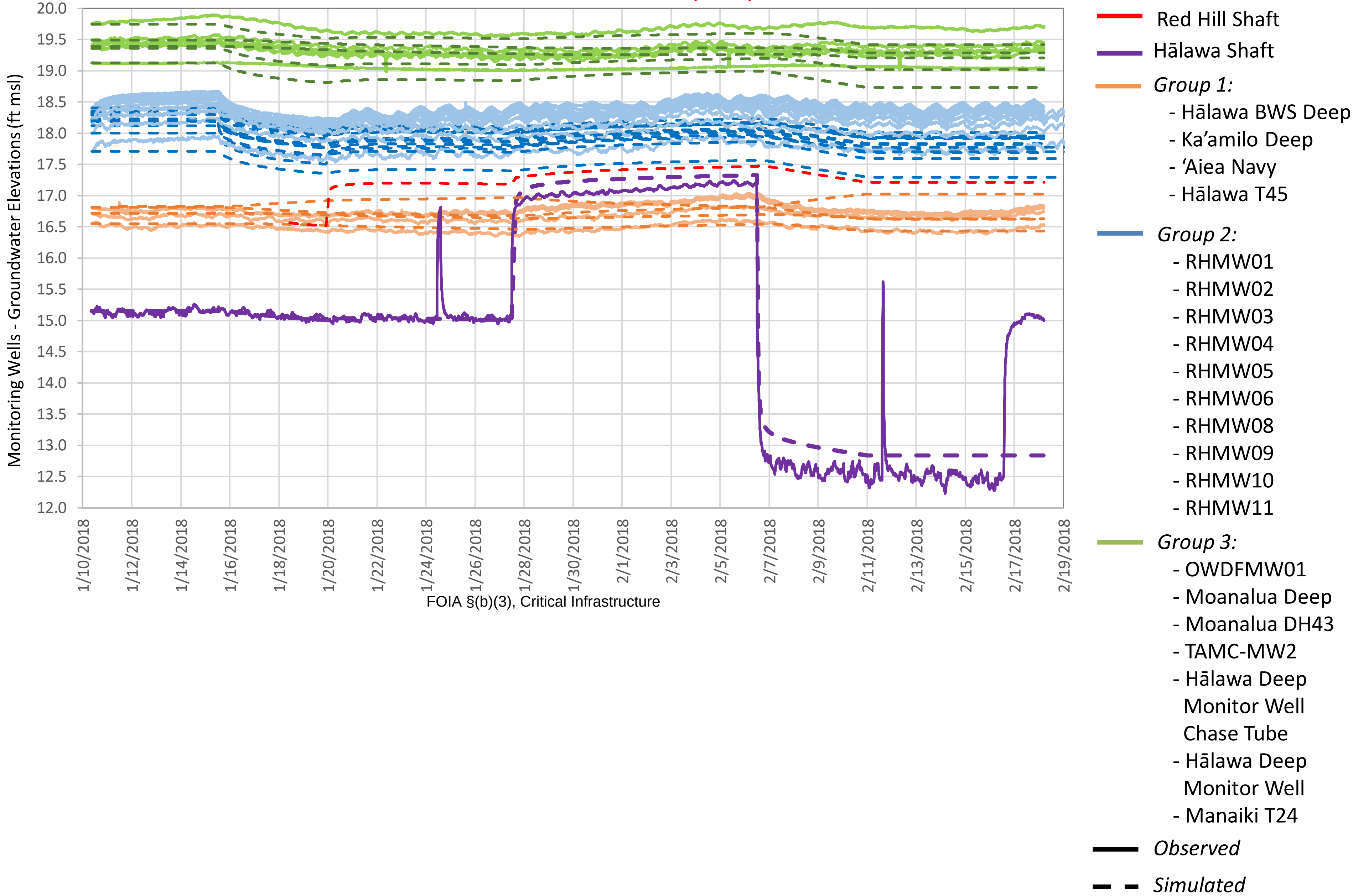


FOIA §(b)(3), Critical Infrastructure

Figure 5.6-7
Model #56: Structural Alterations of Tuff Cones – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

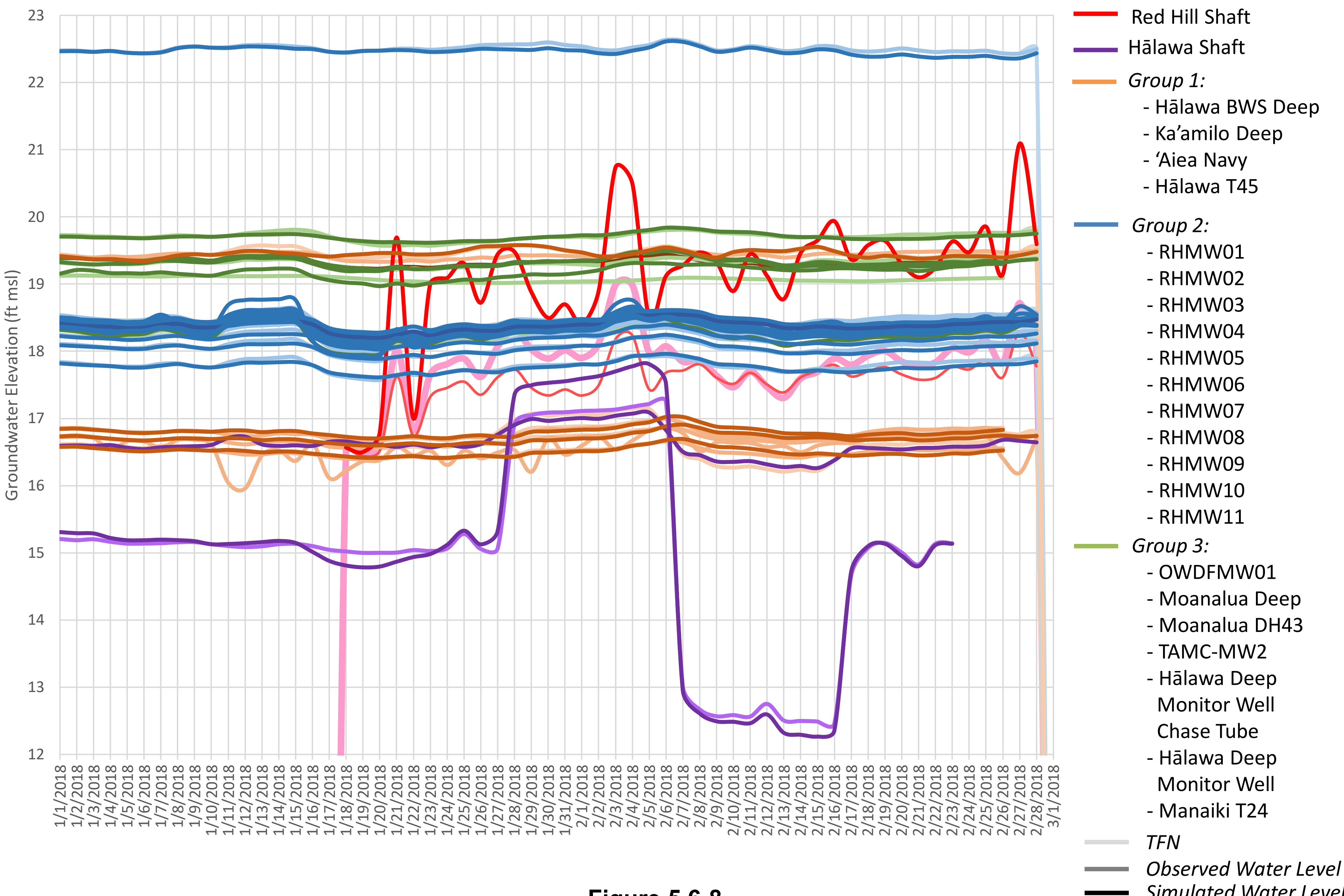


Figure 5.6-8
Model #56: Structural Alterations of Tuff Cones – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

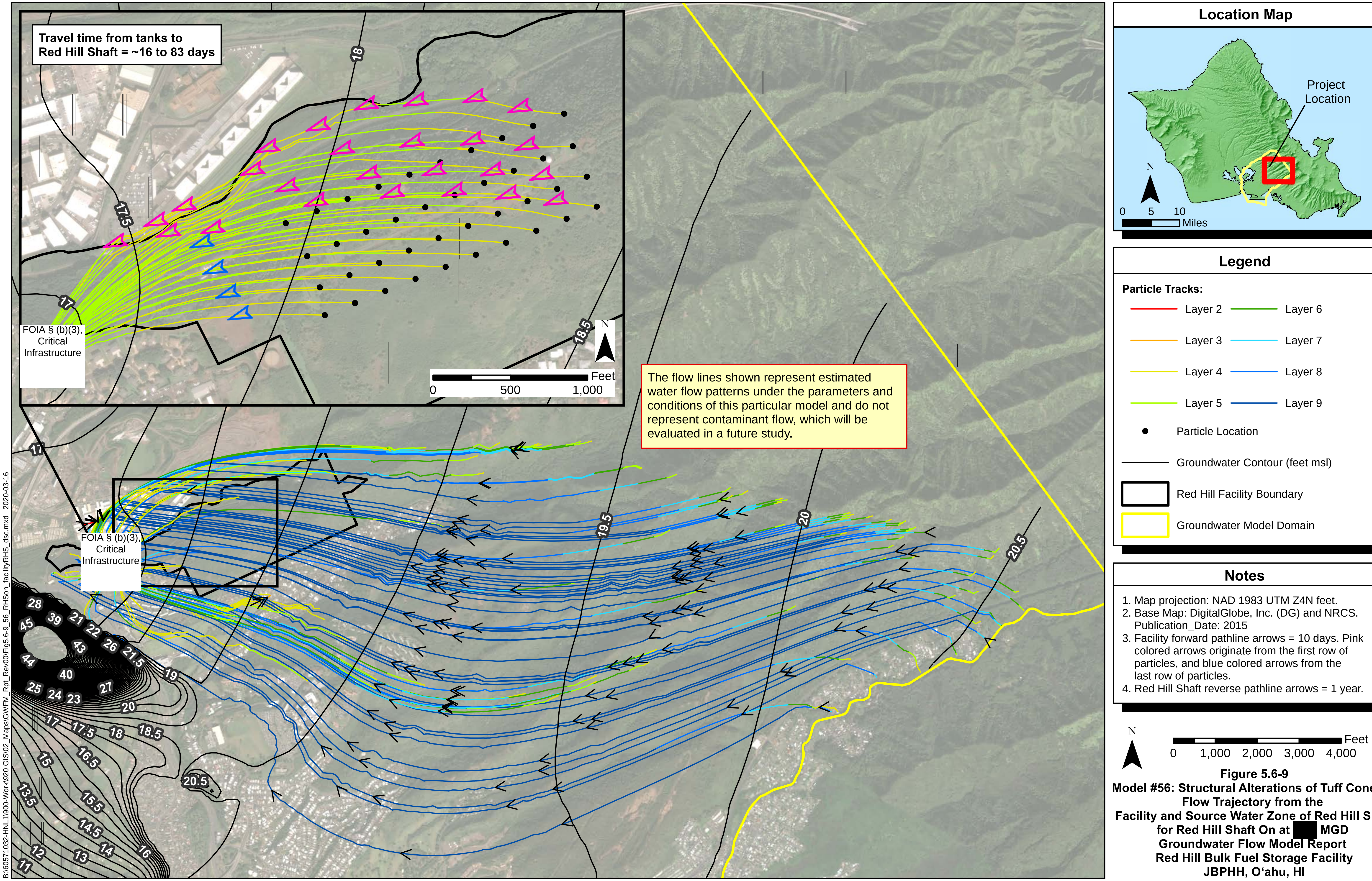
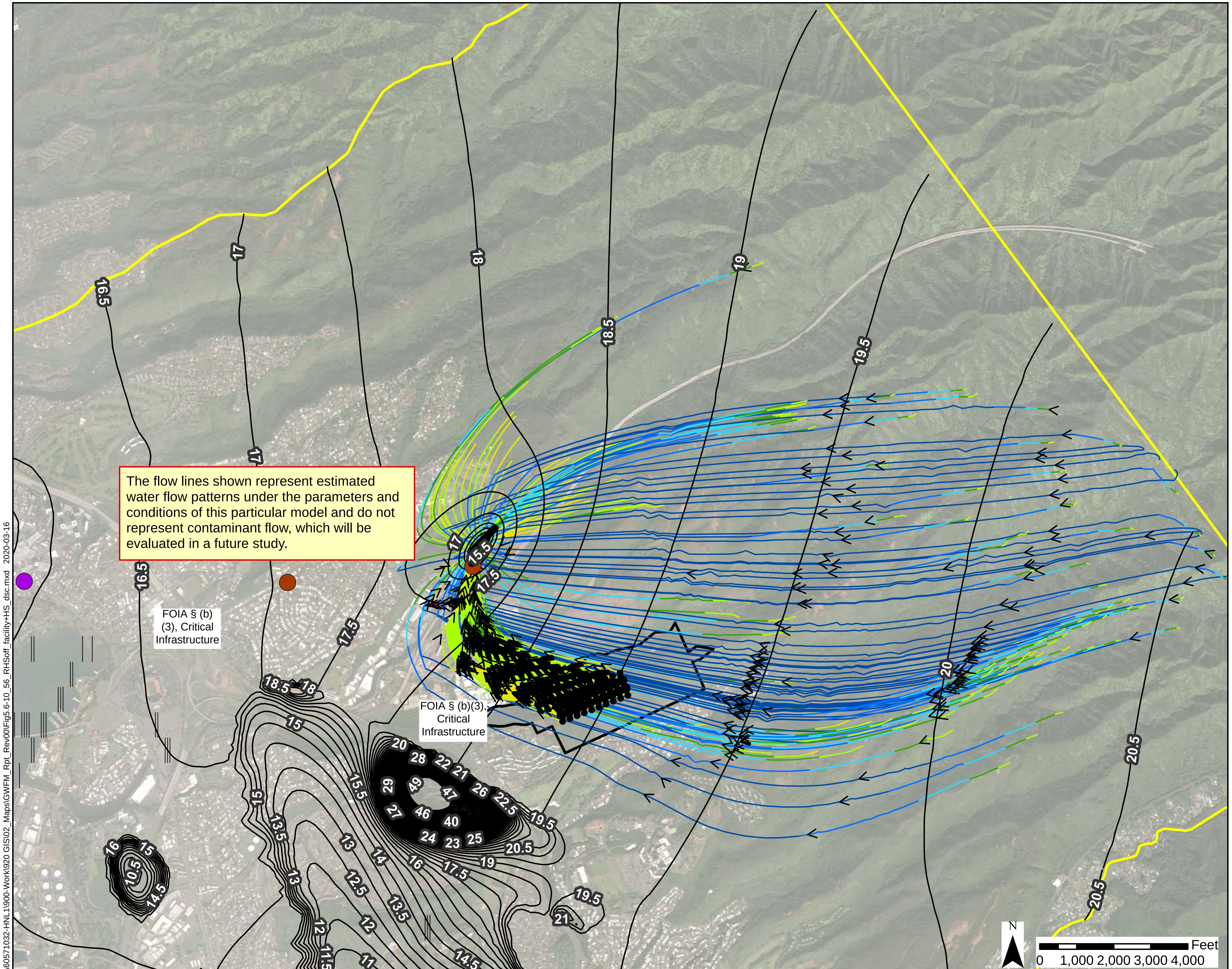
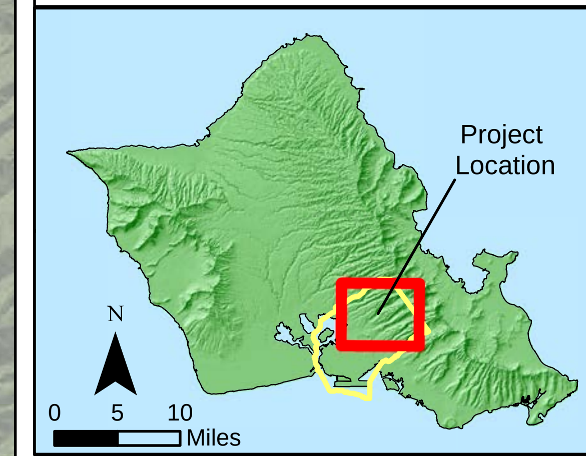


Figure 5.6-9
Model #56: Structural Alterations of Tuff Cones – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows =30 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.6-10
Model #56: Structural Alterations of Tuff Cones – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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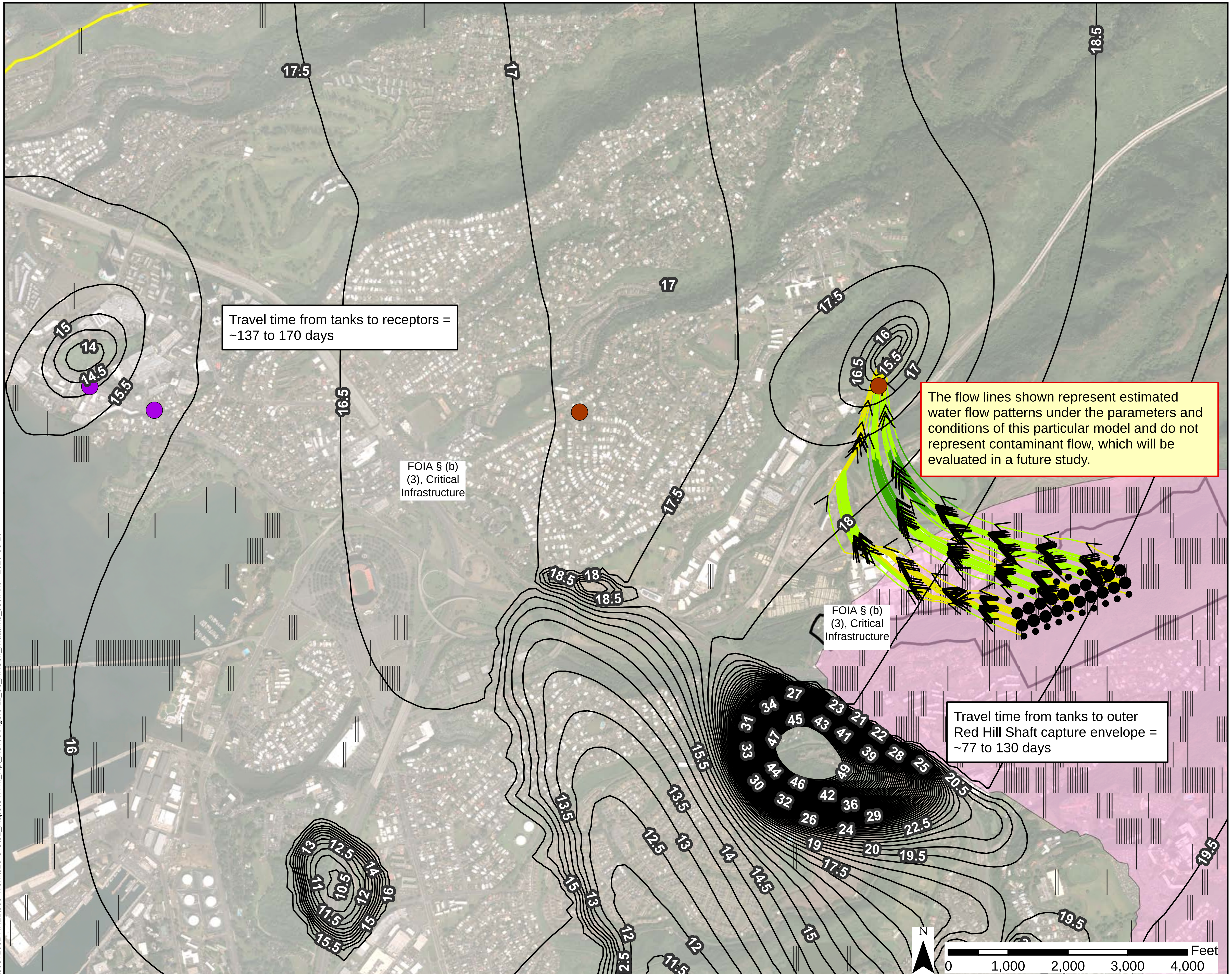
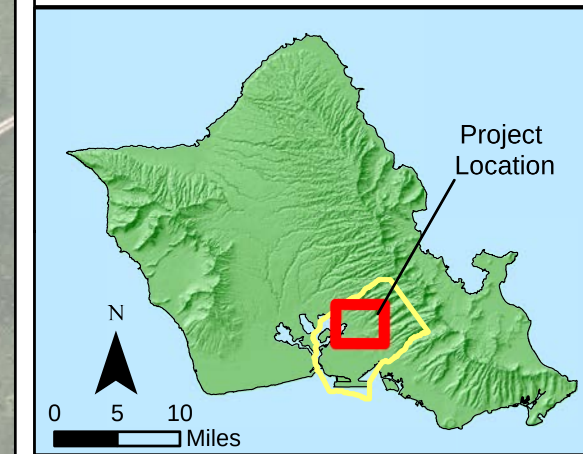


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days.

Figure 5.6-11
Model #56: Structural Alterations of Tuff Cones – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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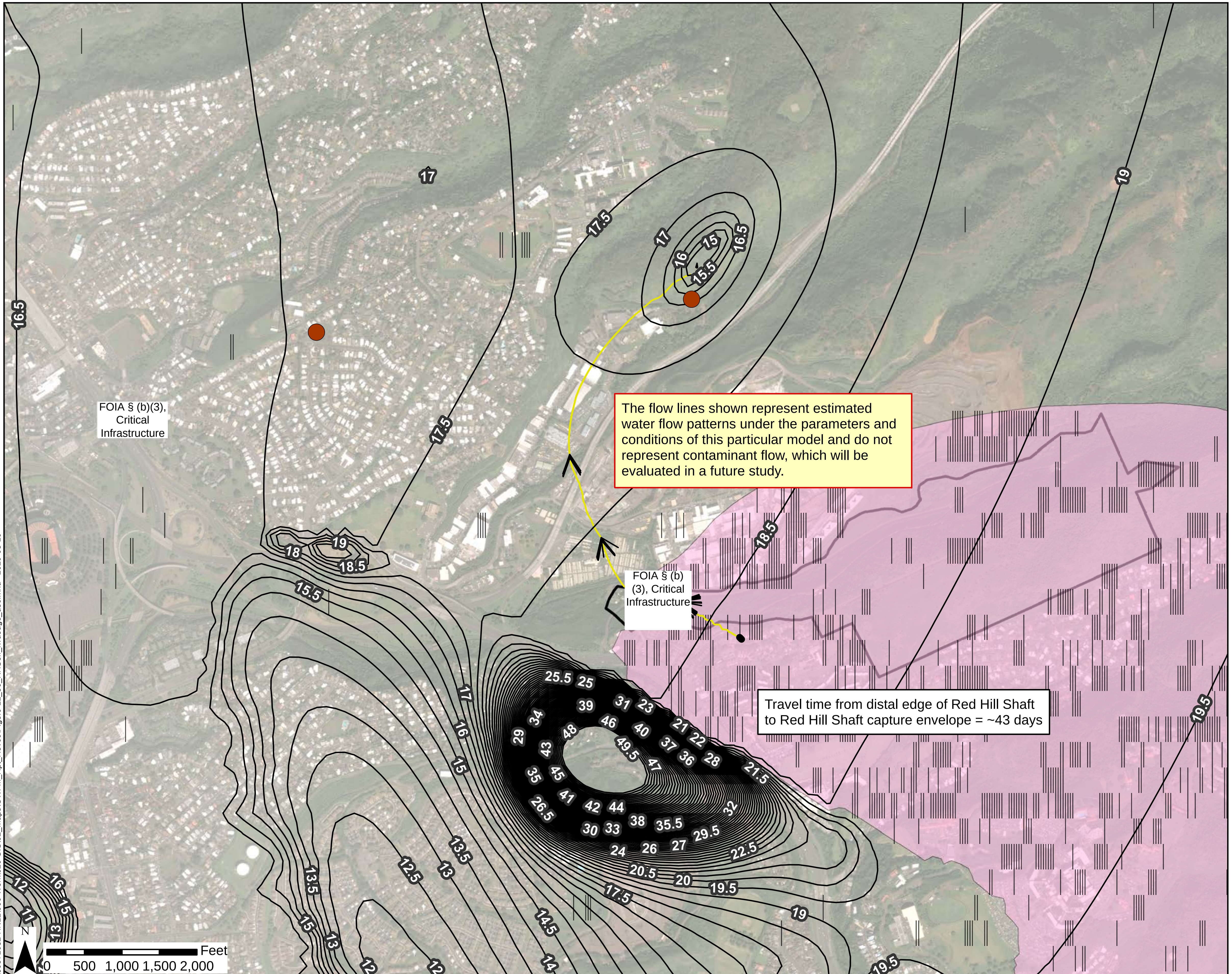

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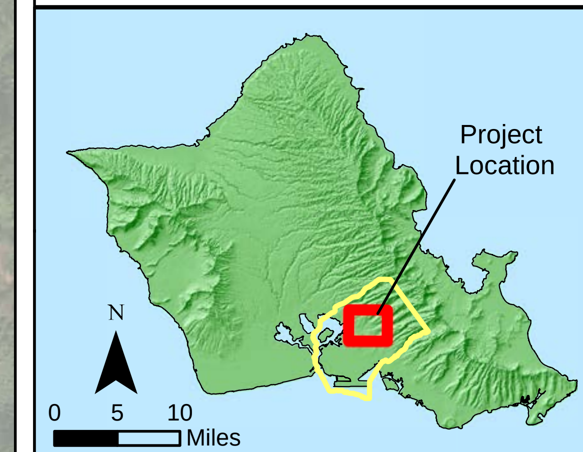
Location Map



Legend

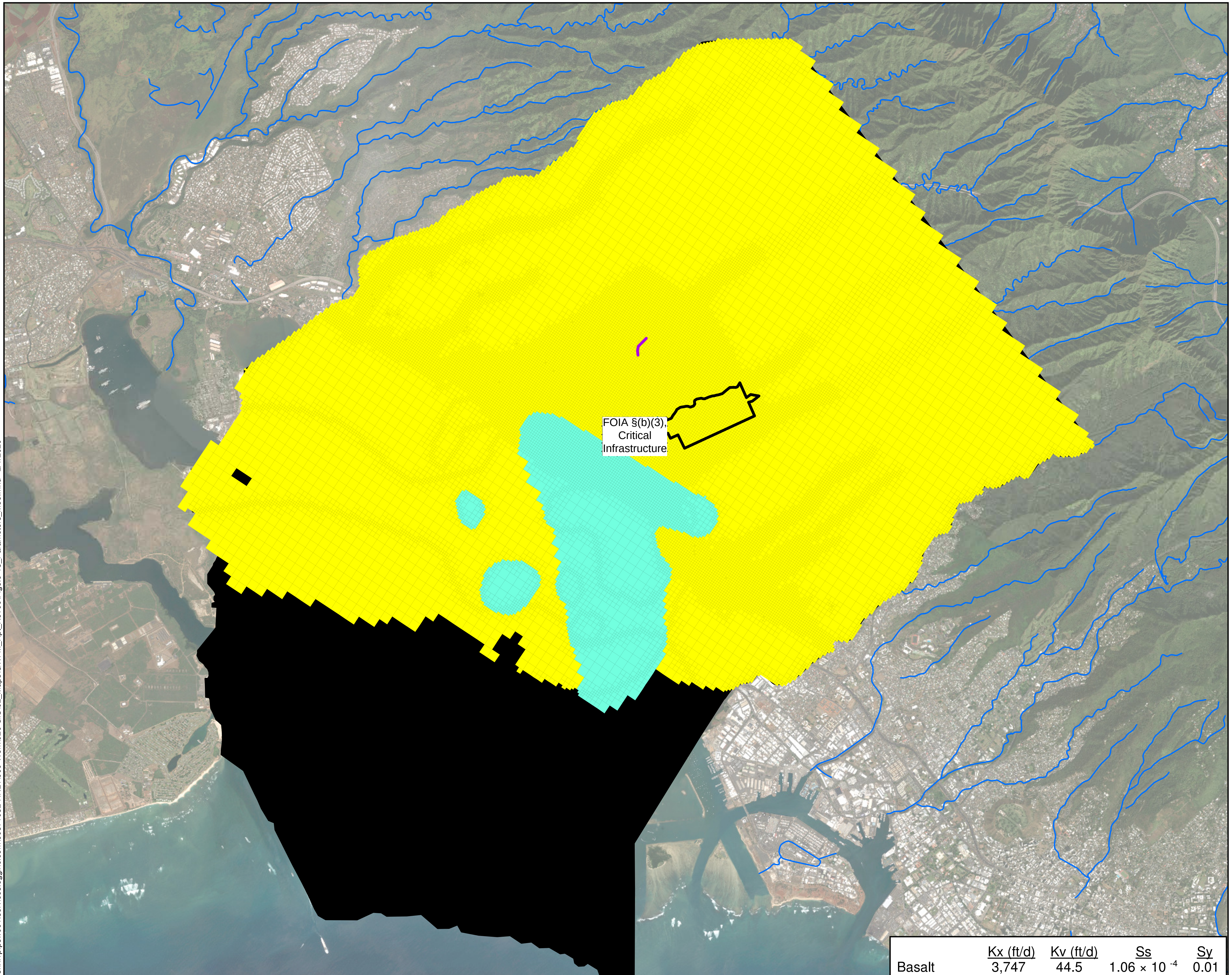
Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

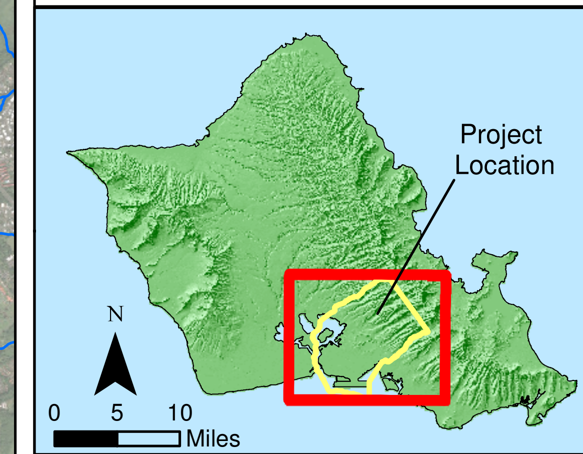
1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility foward pathline arrows = 30 days.

Figure 5.6-12
Model #56:Structural Alterations of Tuff Cones – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



	Kx (ft/d)	Kv (ft/d)	Ss	Sy
Basalt	3,747	44.5	1.06×10^{-4}	0.01

Location Map



Legend

- Basalt
- Tuff Cone
- Inactive Model Cells
- Shaft
- Red Hill Facility Boundary
- Stream

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015

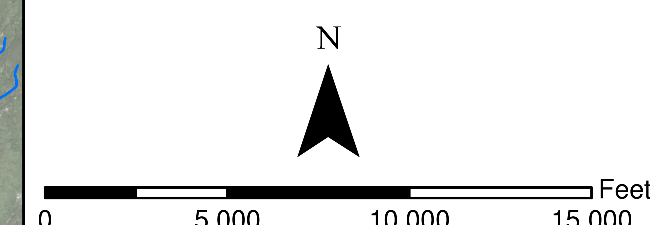


Figure 5.6-13
Hydraulic Parameter Zonation in Basalt for Model #56
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

\\Ushnl1pfpsw001.services.egginc.com\60571032-HNL1\900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.6-13_Parameters_M56.mxd 2/1/2020

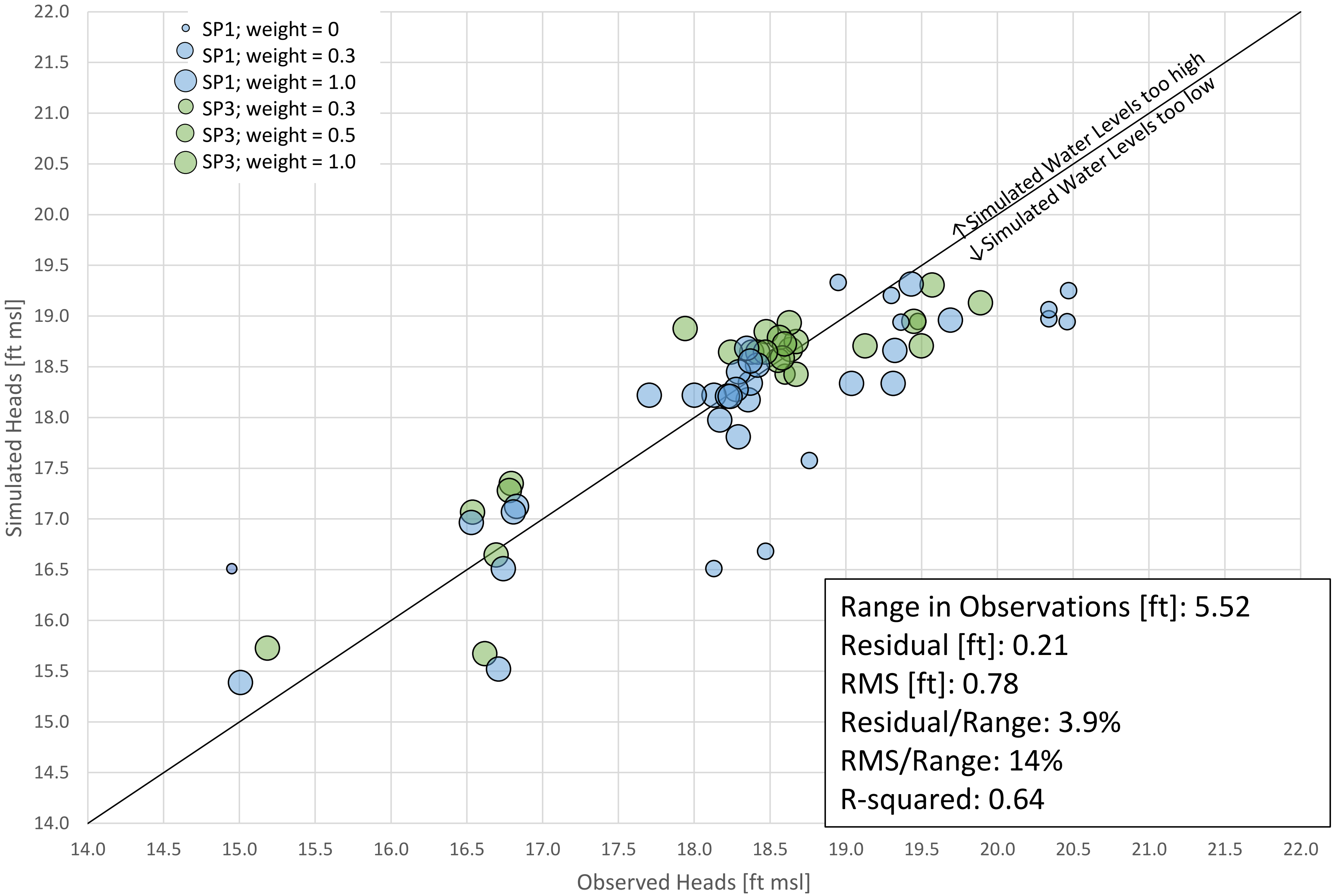


Figure 5.7-1
Model #57: Recharge and Lateral Inflow – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

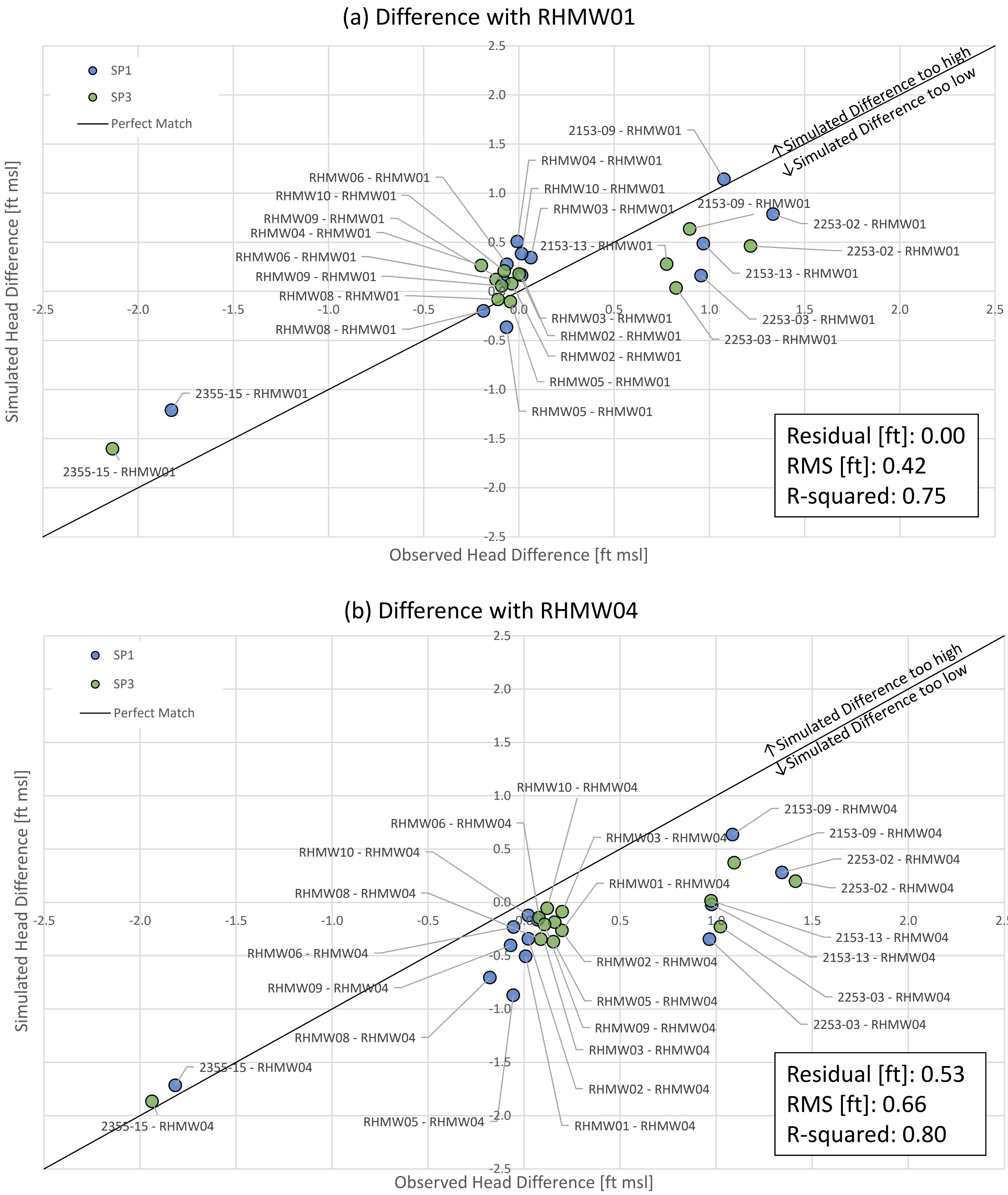


Figure 5.7-2
Model #57: Recharge and Lateral Inflow –
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

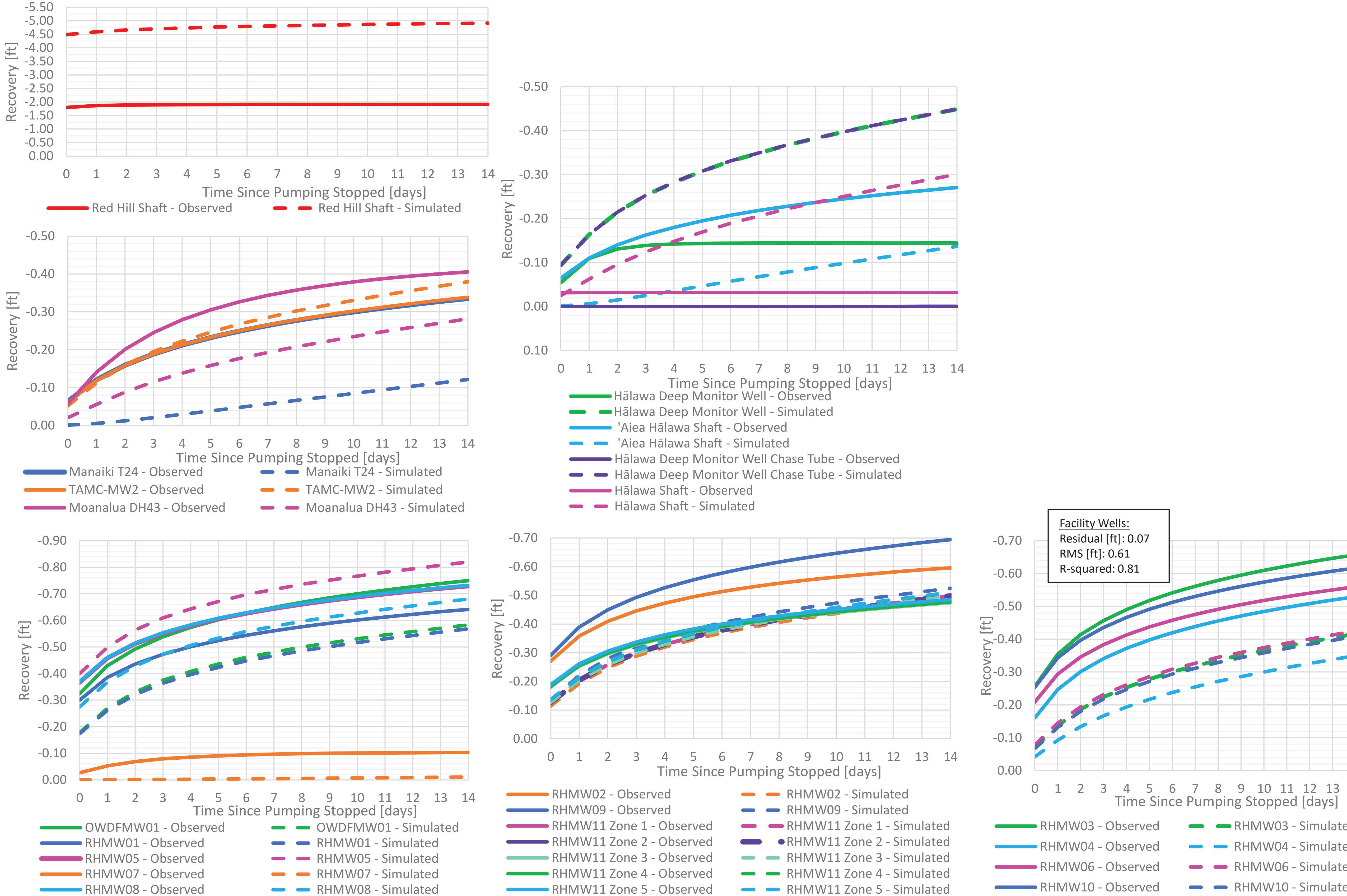


Figure 5.7-3
Model #57: Recharge and Lateral Inflow –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

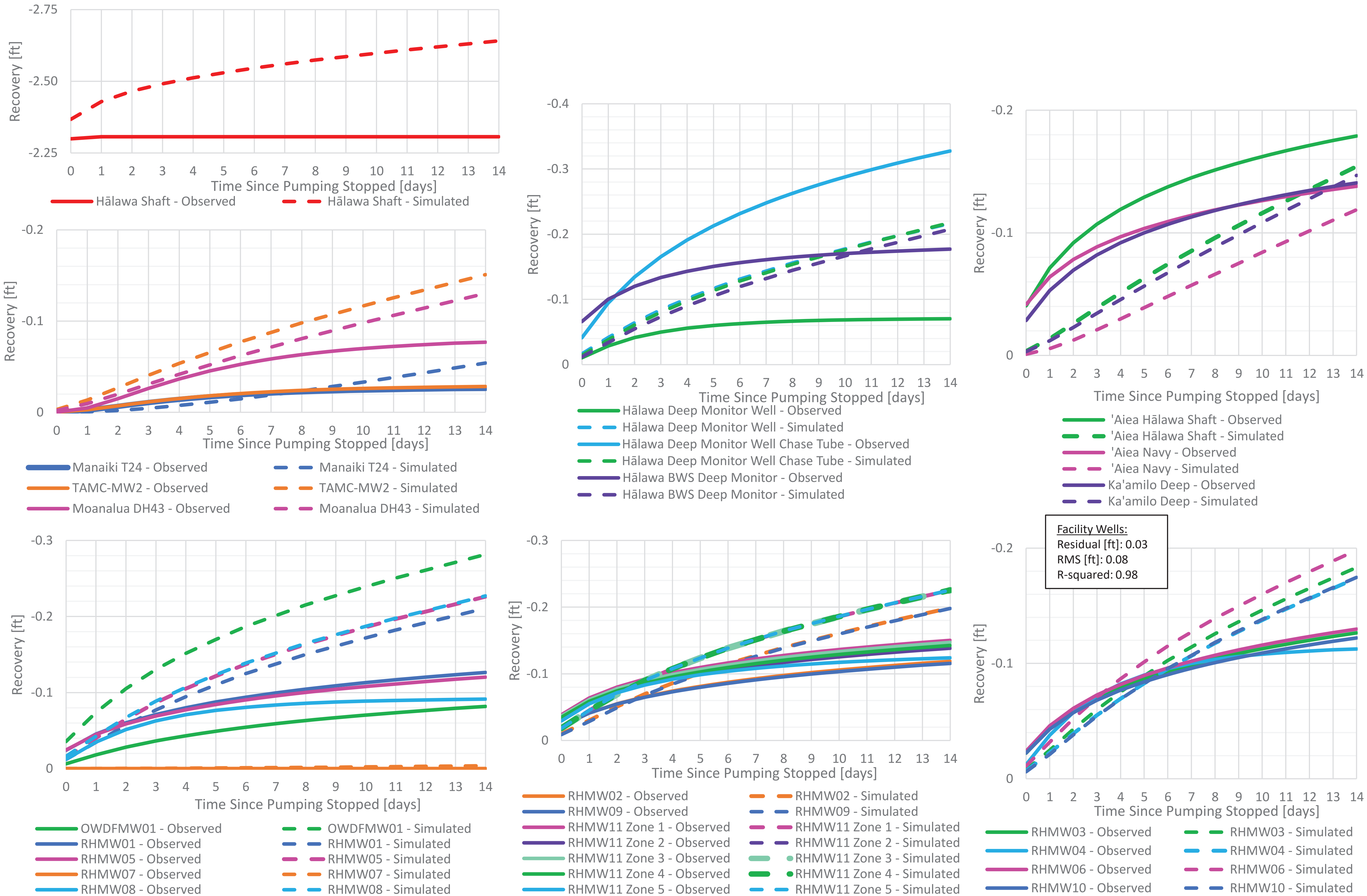
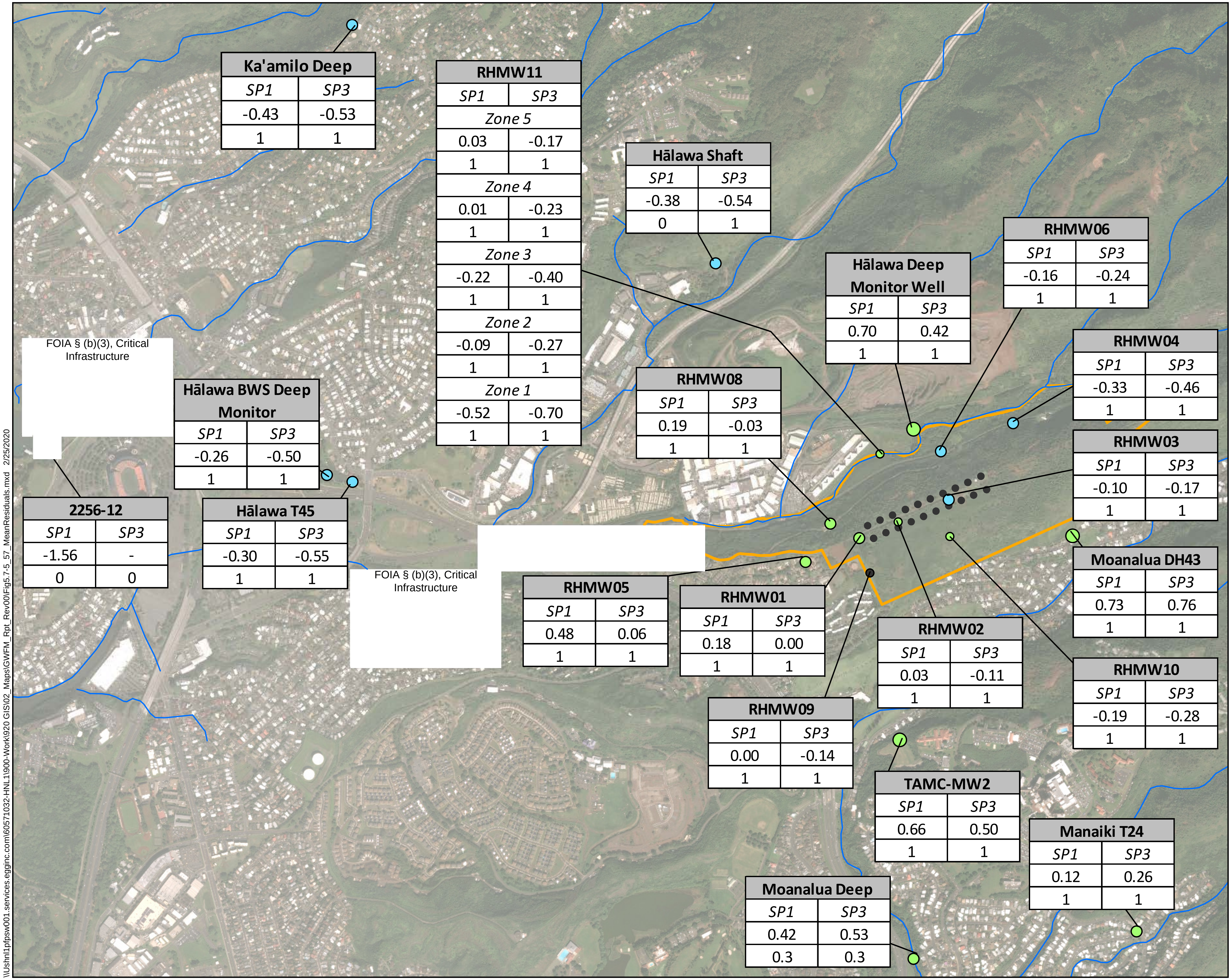
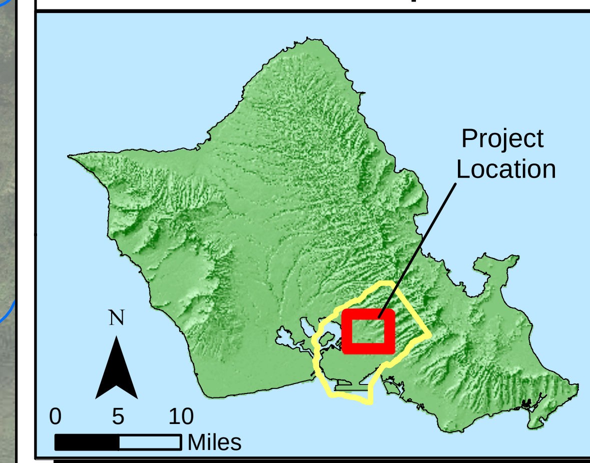


Figure 5.7-4
Model #57: Recharge and Lateral Inflow –
Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, Hawaiʻi



Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Well With Zero Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

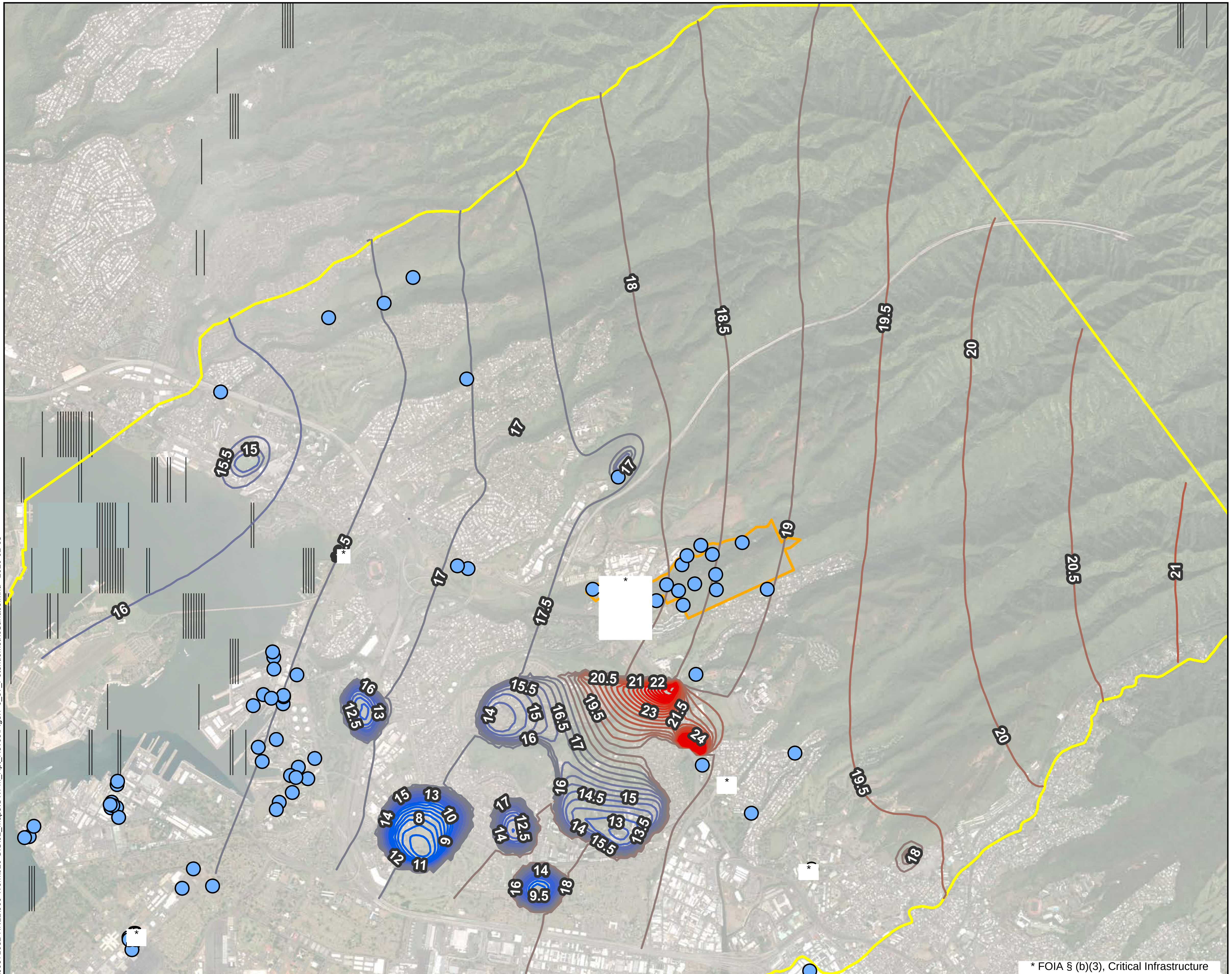
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

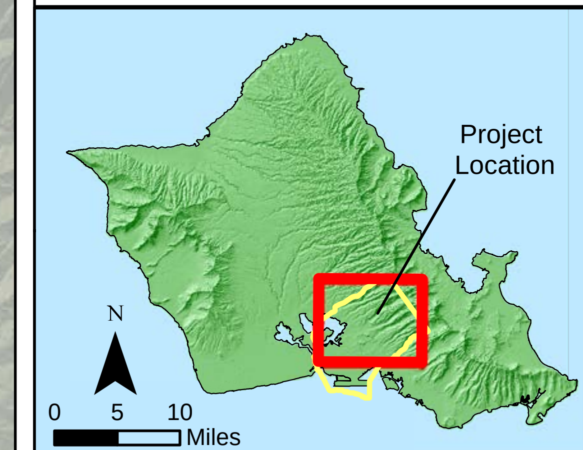
N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.7-5
Model #57: Recharge and Lateral Inflow – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.7-6
Model #57:Recharge and Lateral Inflow – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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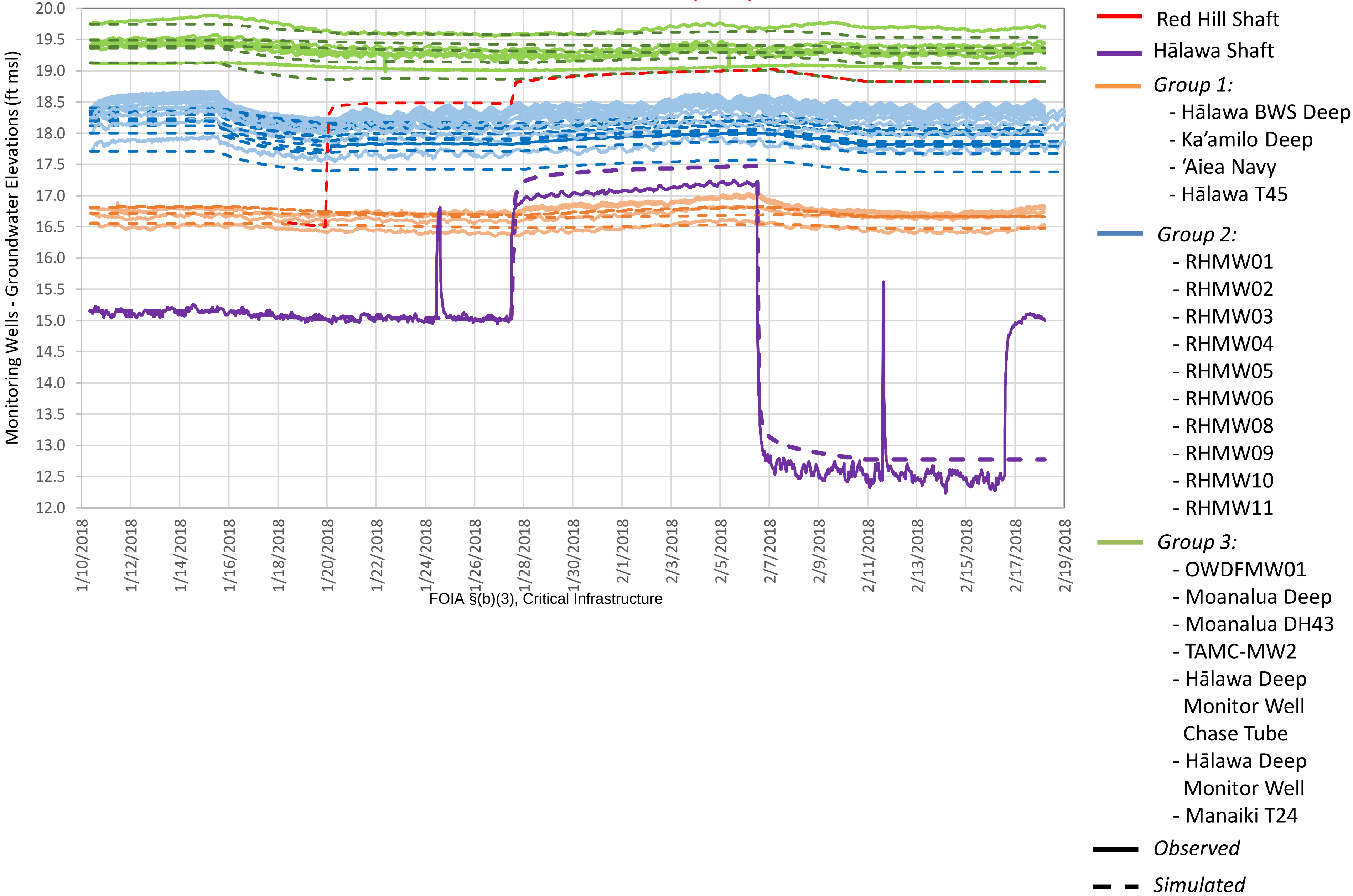


Figure 5.7-7
Model #57: Recharge and Lateral Inflow – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

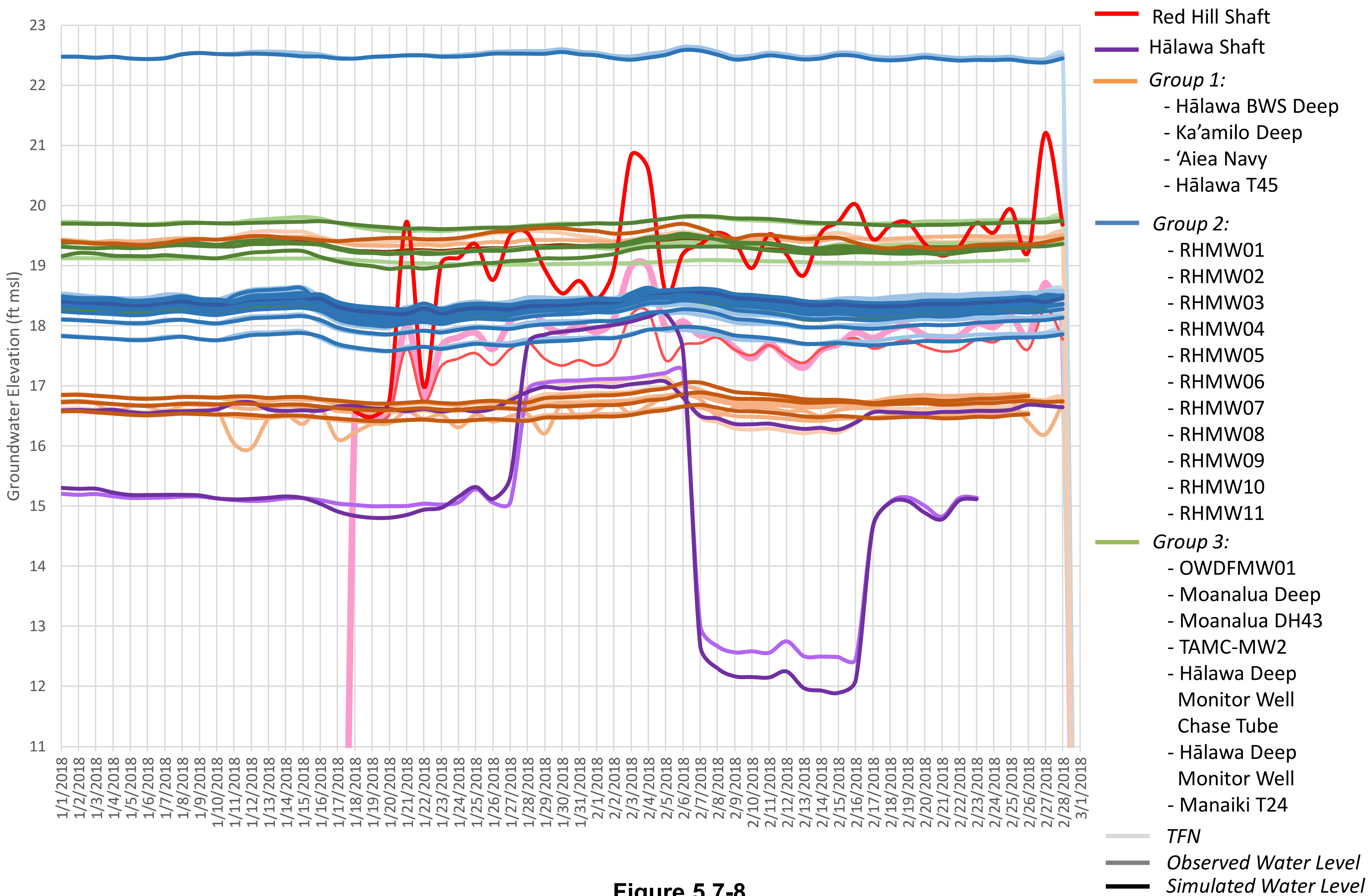
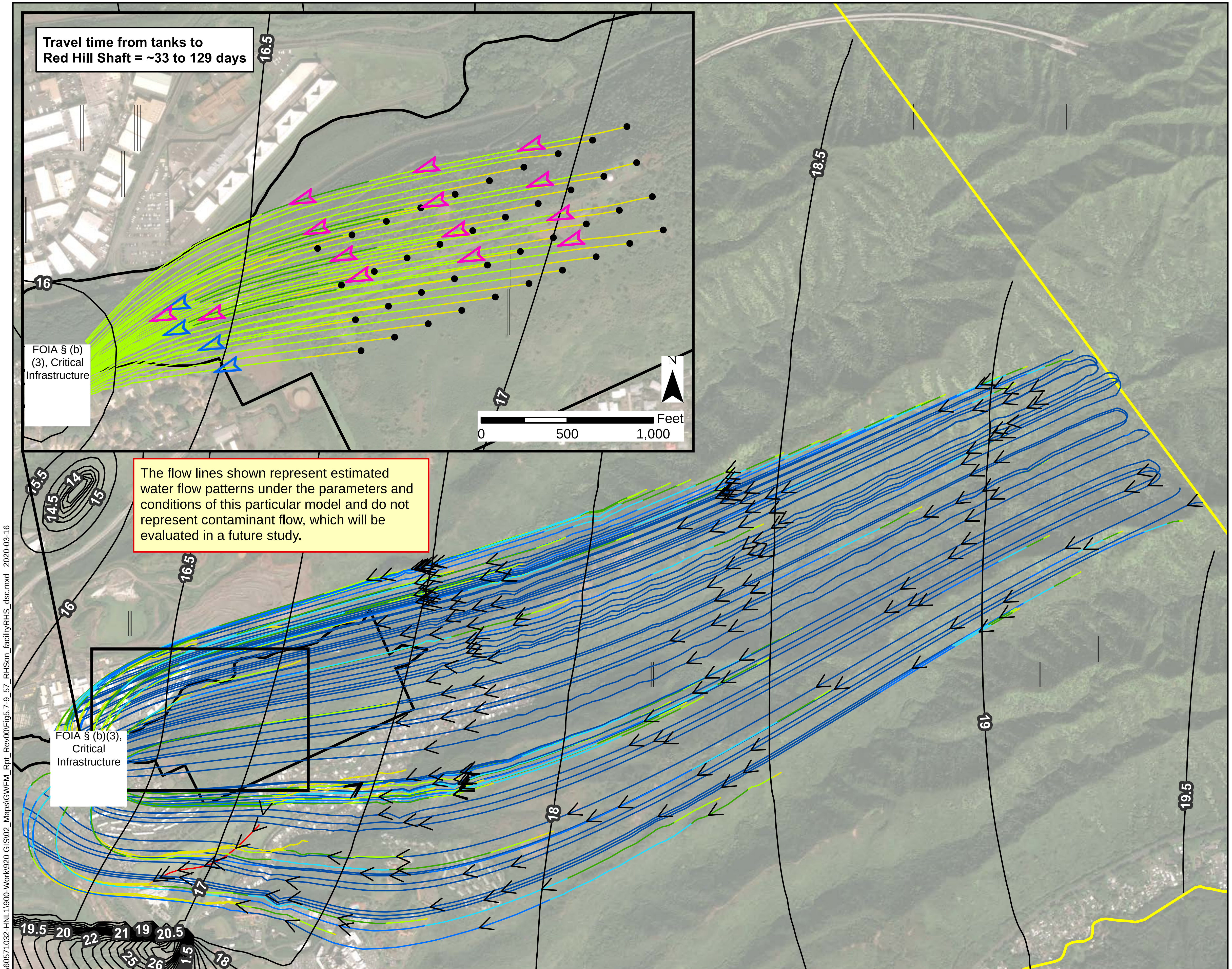
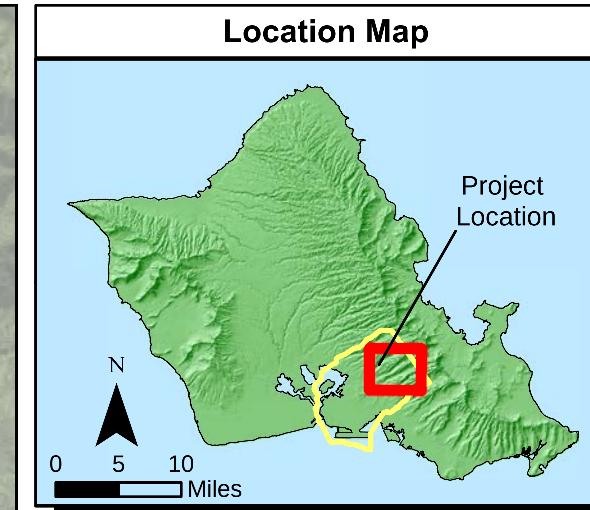


Figure 5.7-8
Model #57: Recharge and Lateral Inflow – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i





Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.7-9
Model #57: Recharge and Lateral Inflow – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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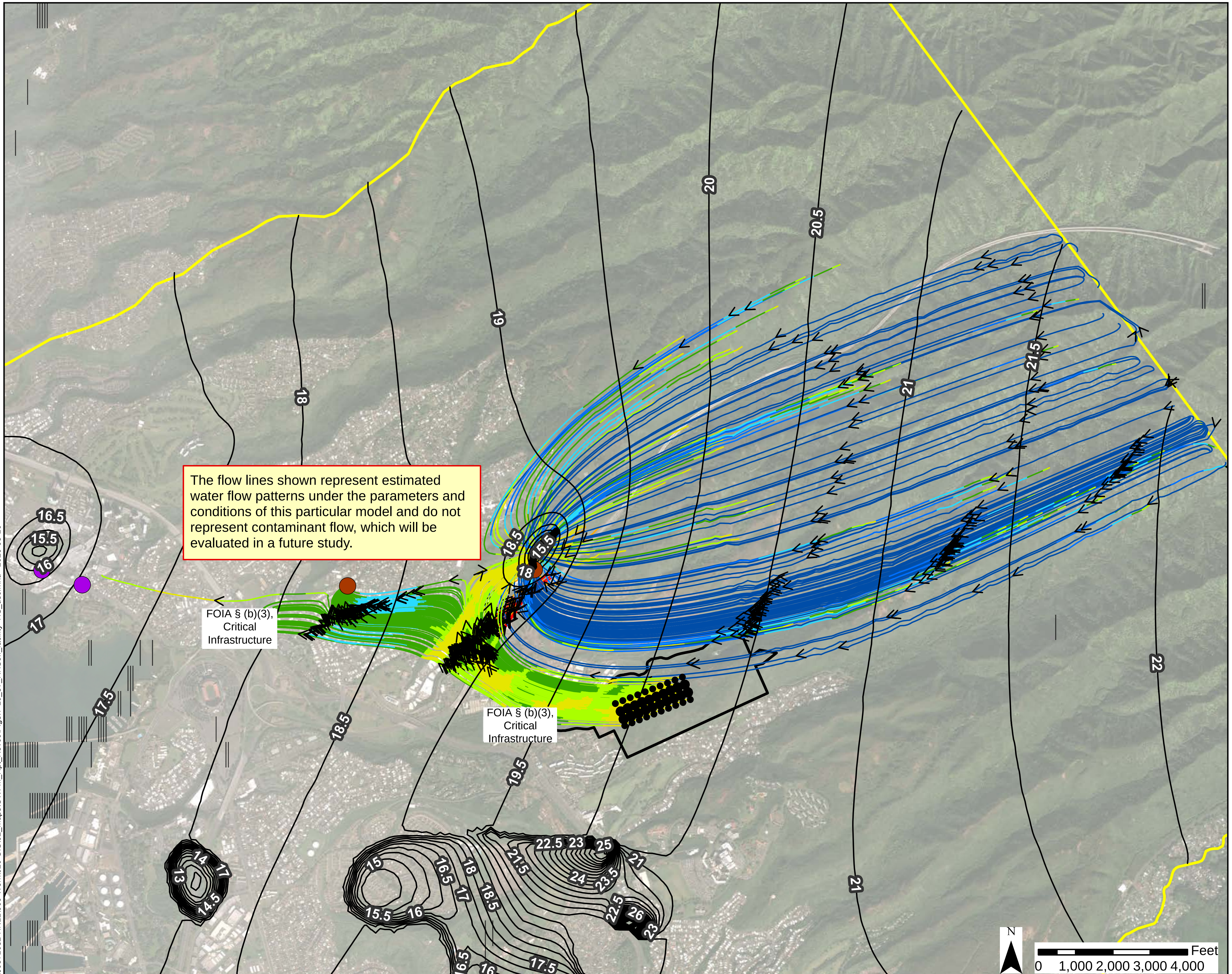

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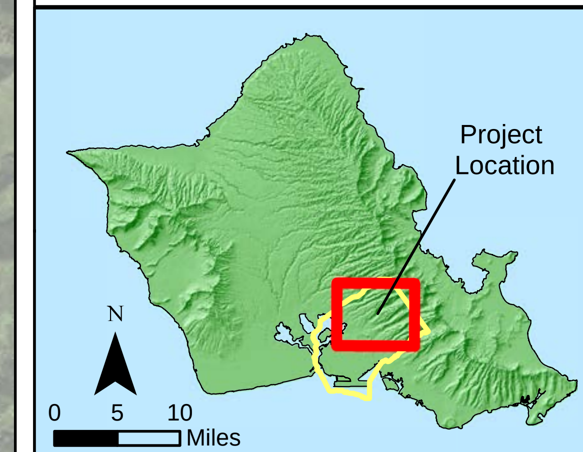
Location Map



Legend

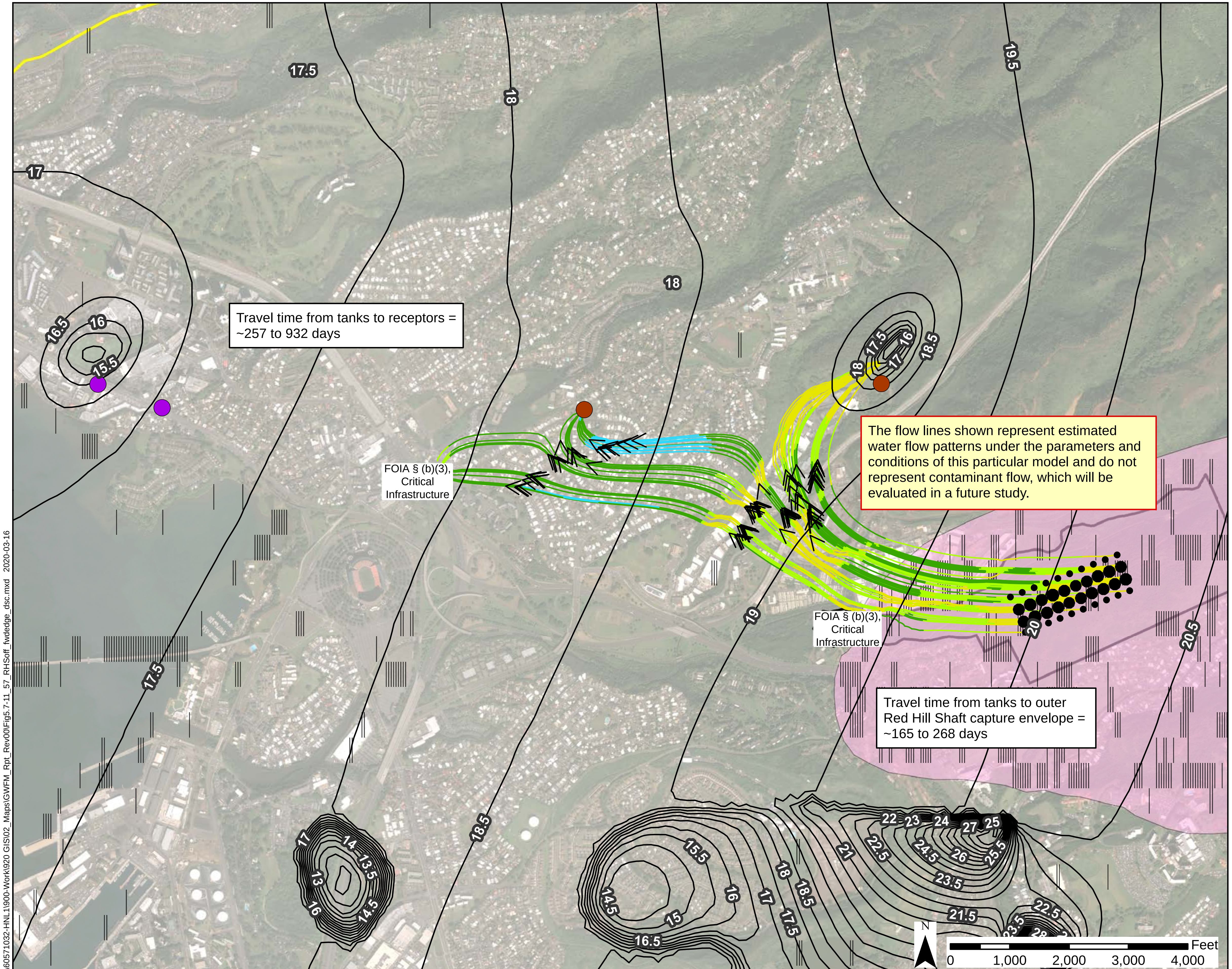
Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

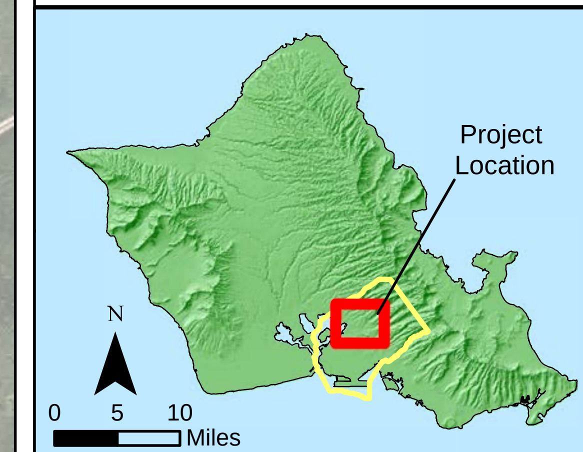
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 1 year.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.7-10
Model #57: Recharge and Lateral Inflow – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 1 year.

Figure 5.7-11
Model #57: Recharge and Lateral Inflow – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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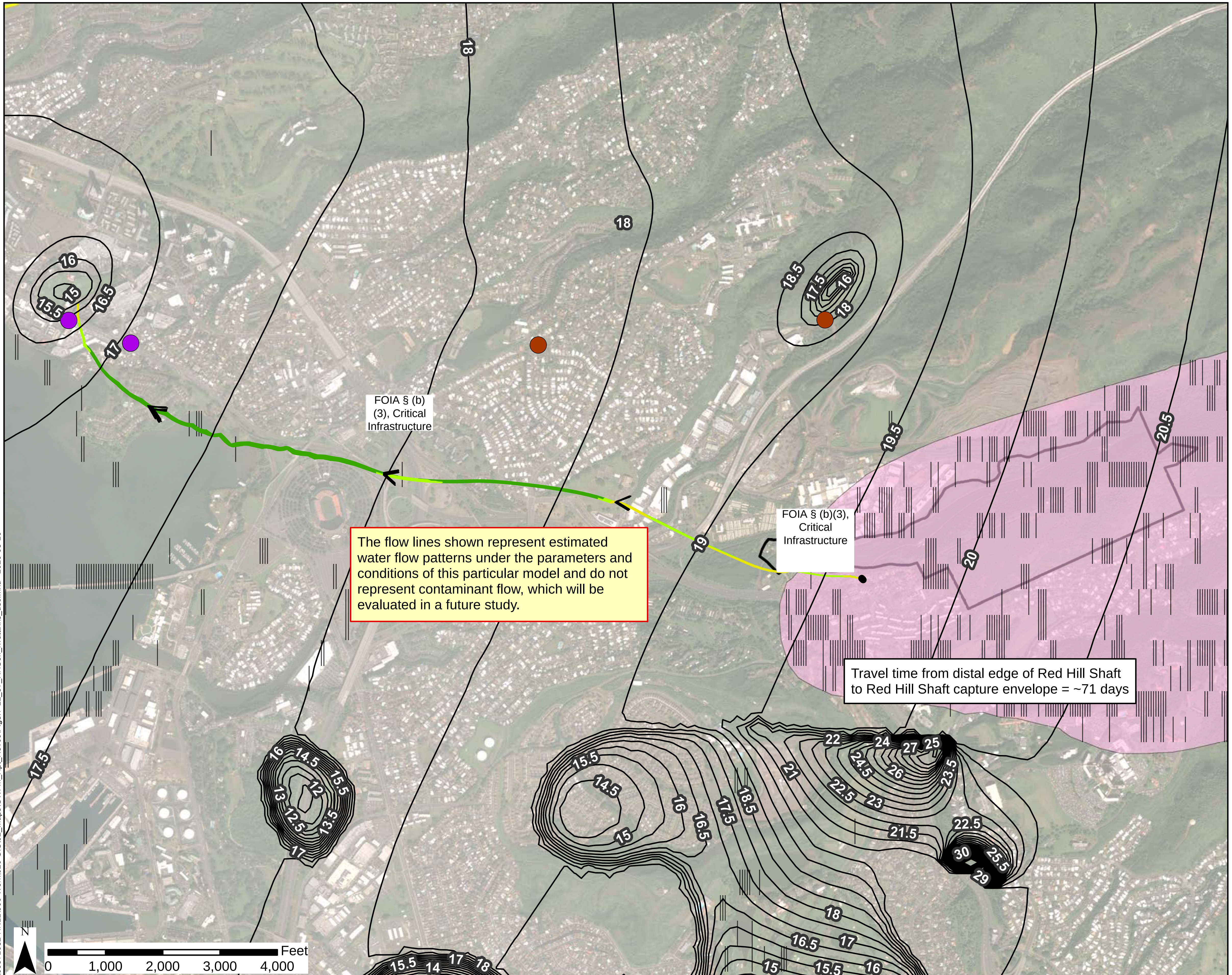
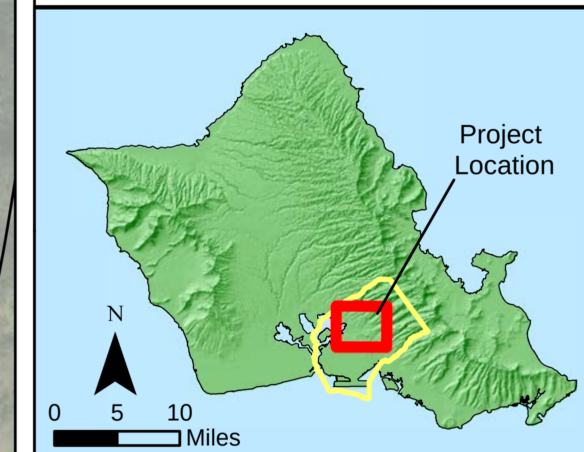


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet
- Red Hill Shaft Capture
- Red Hill Facility Boundary
- Groundwater Model

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 1 year.

Figure 5.7-12
Model #57: Recharge and Lateral Inflow – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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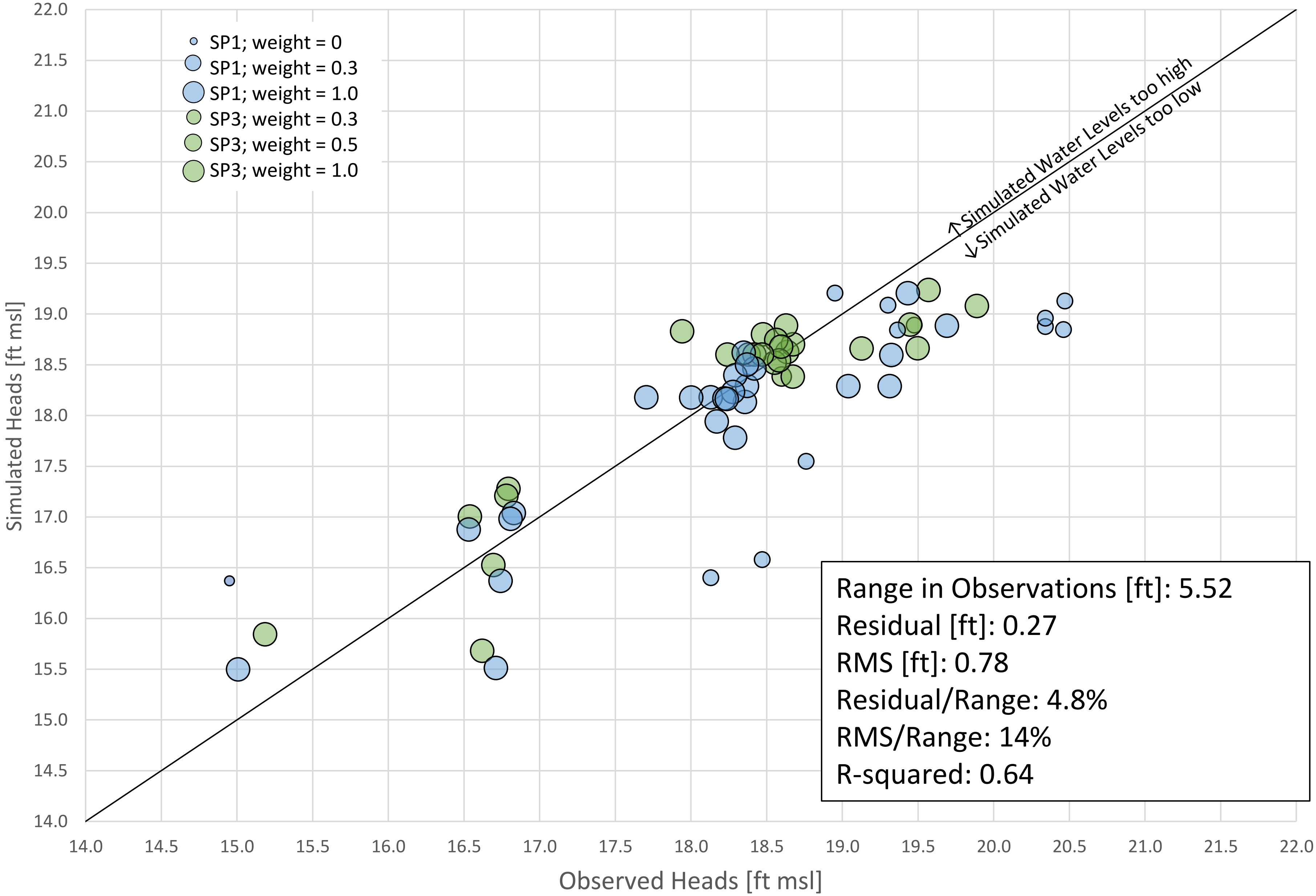
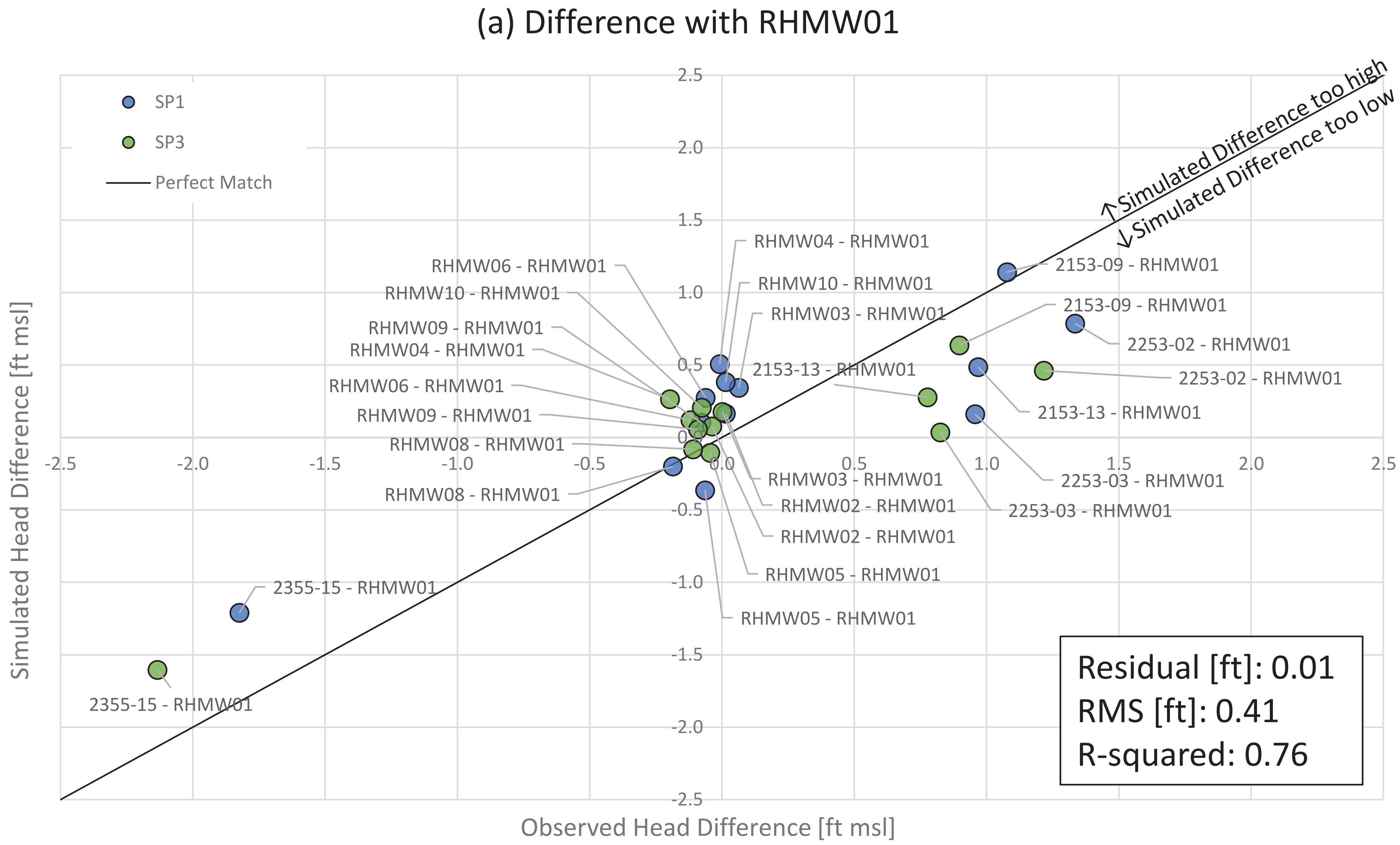


Figure 5.8-1
Model #58: Coastal Marine Discharge Variability – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, Hawaiʻi



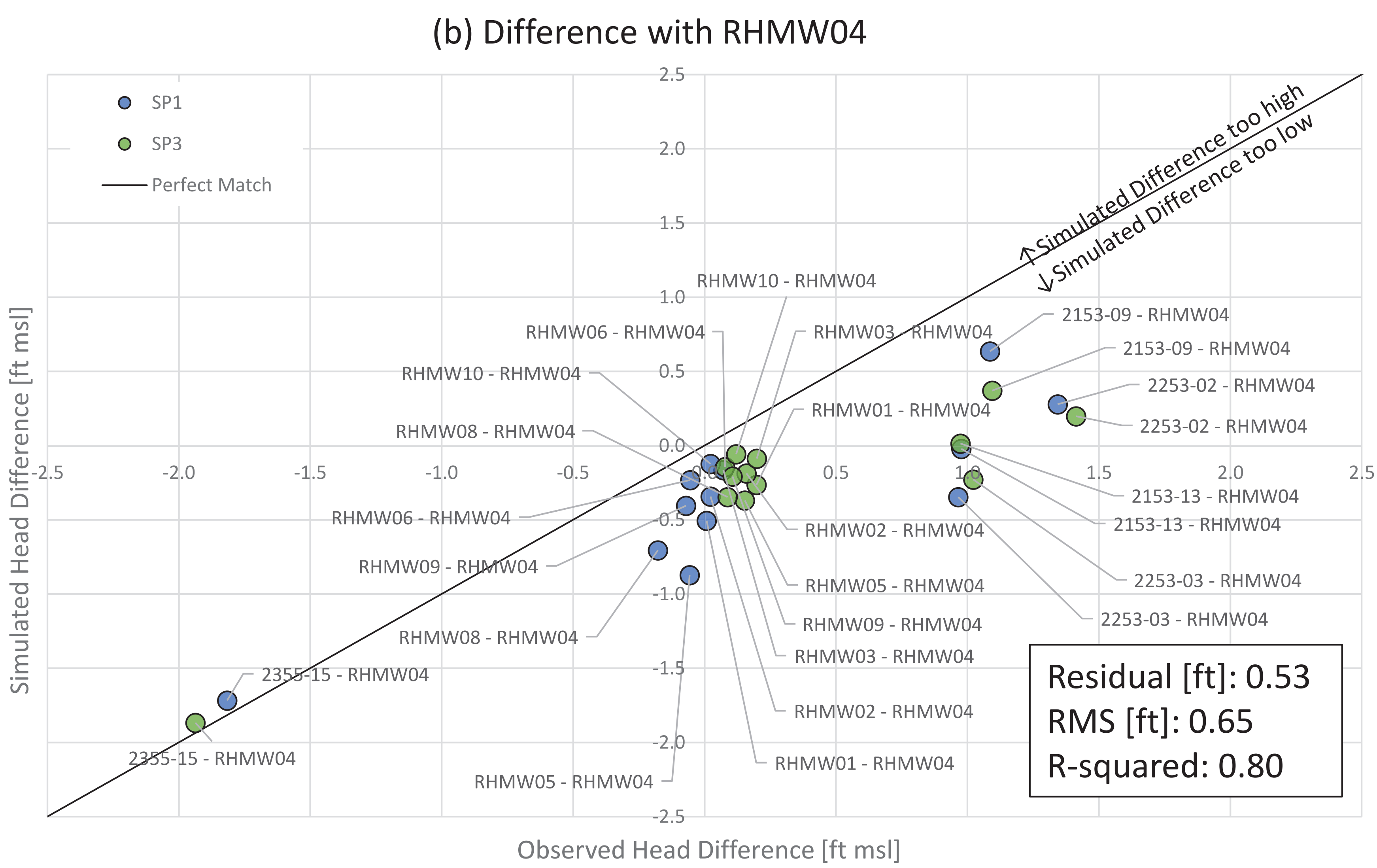


Figure 5.8-2
Model #58: Coastal Marine Discharge Variability–
Scatterplot of Water Level Differences between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, Hawaiʻi

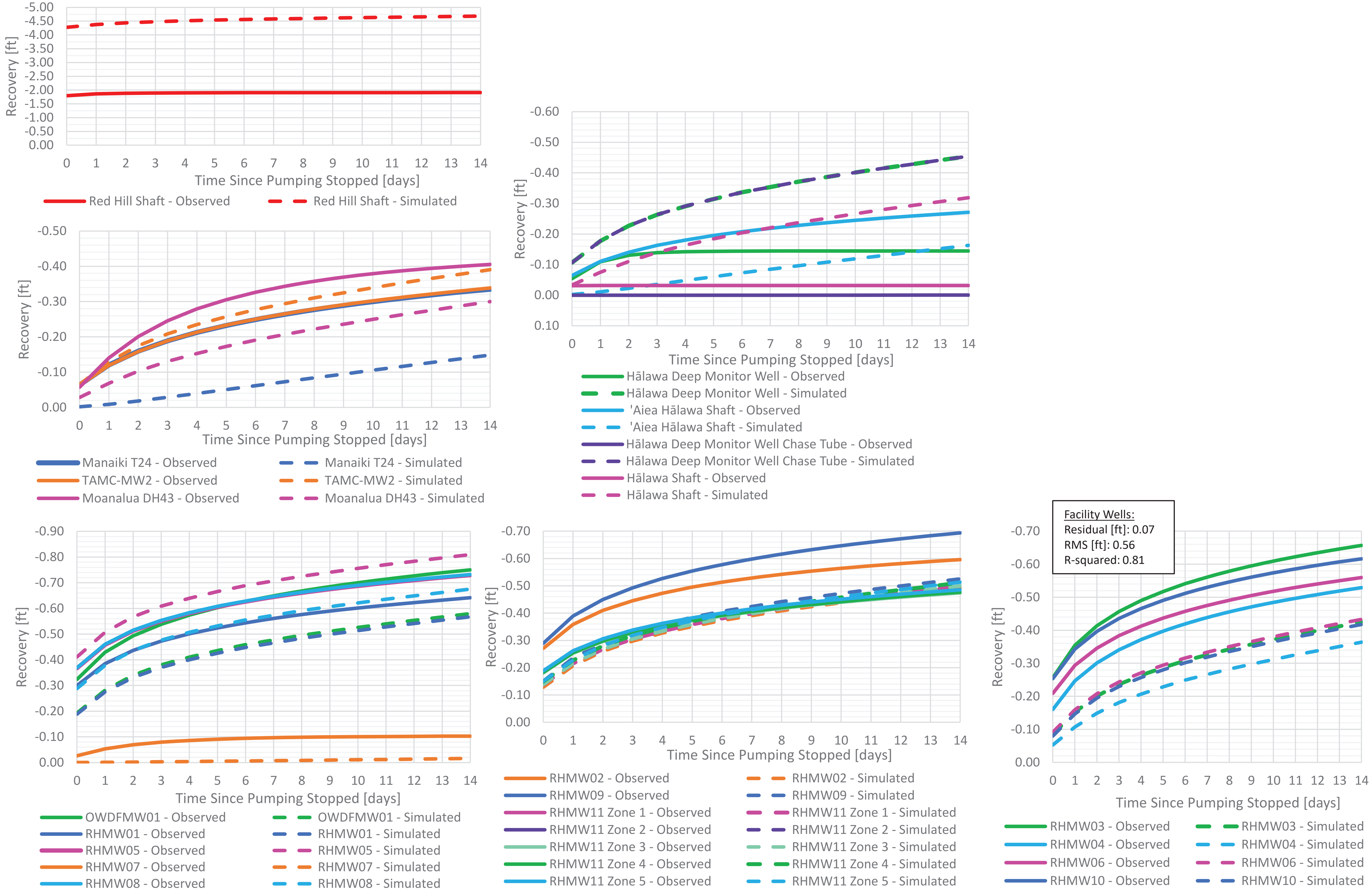


Figure 5.8-3
Model #58: Coastal Marine Discharge Variability –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

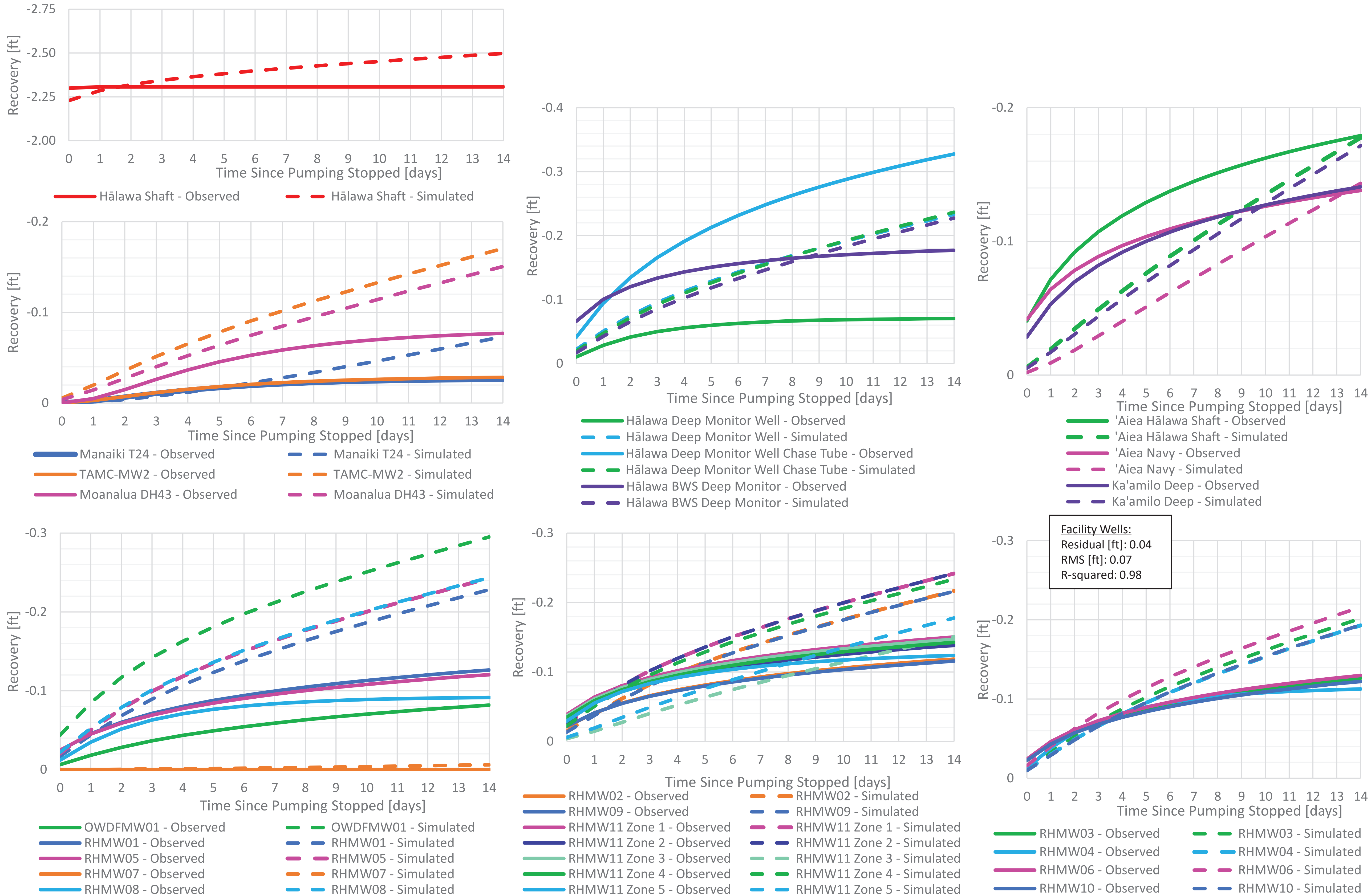
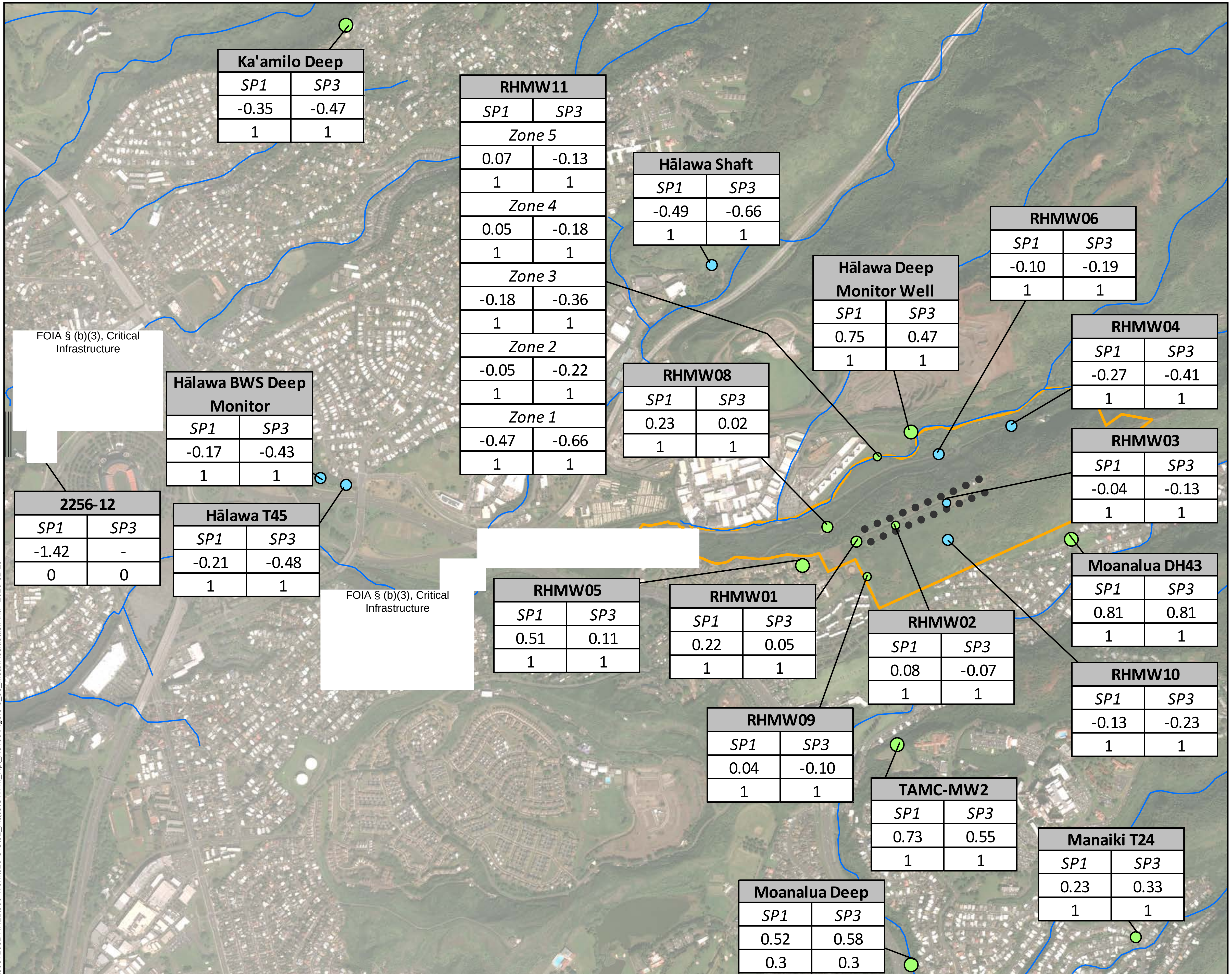


Figure 5.8-4
Model #58: Coastal Marine Discharge Variability –
Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

~~For Red Hill AOC Party Use Only~~



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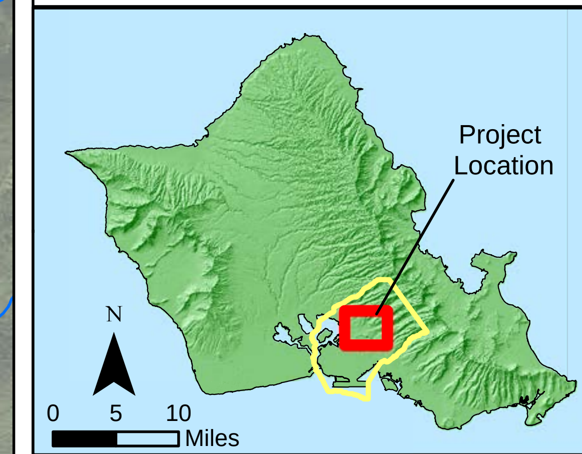
Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

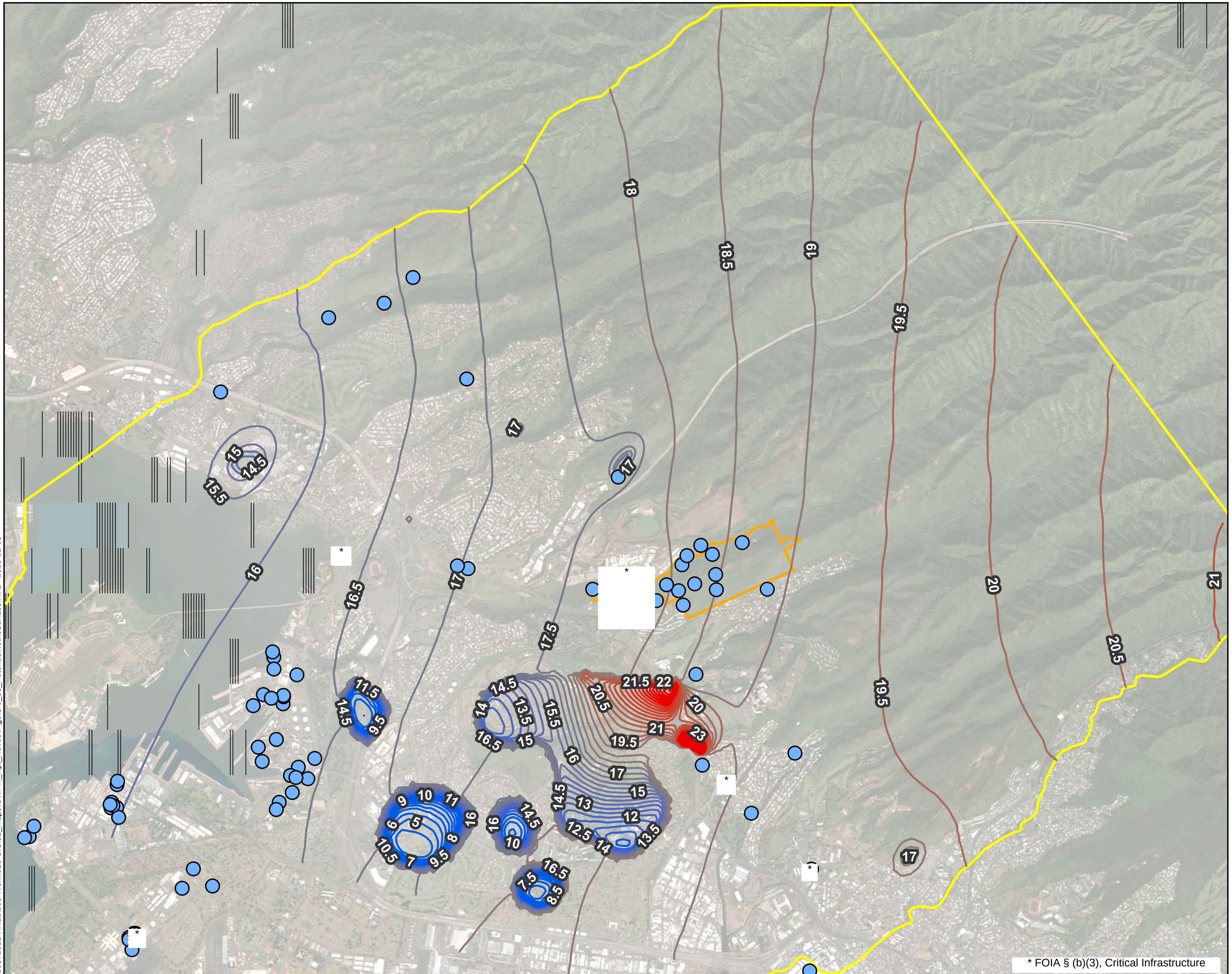
1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

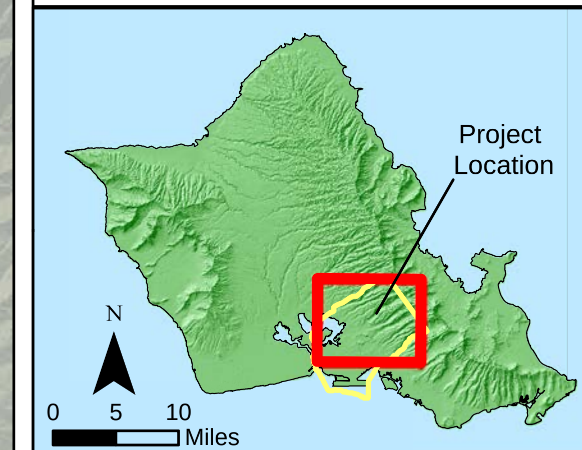
N

0 1,000 2,000 3,000 4,000 Feet

Figure 5.8-5
Model #58: Coastal Marine Discharge Variability – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.8-6
Model #58: Coastal Marine Discharge Variability – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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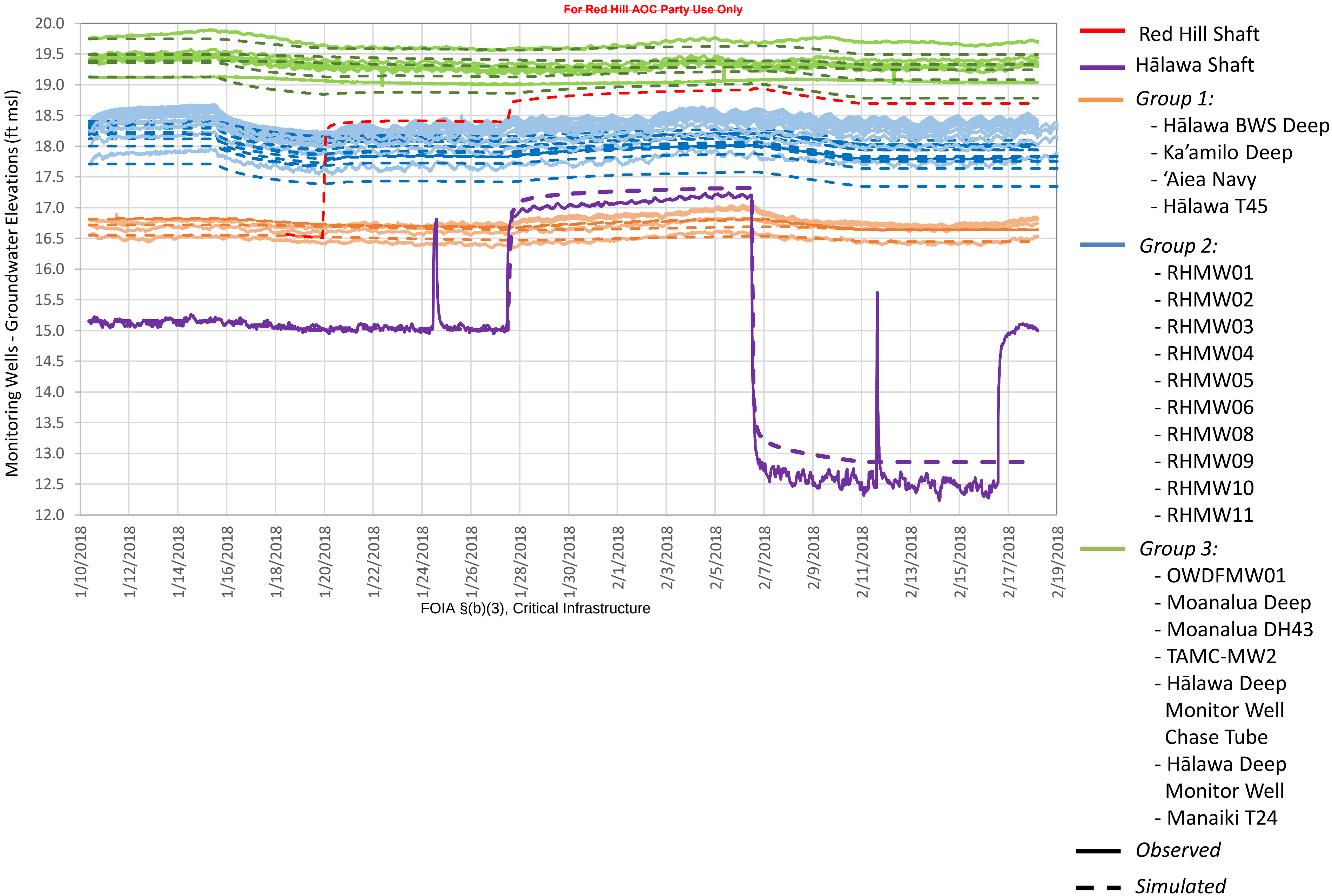


Figure 5.8-7
Model #58: Coastal Marine Discharge Variability – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

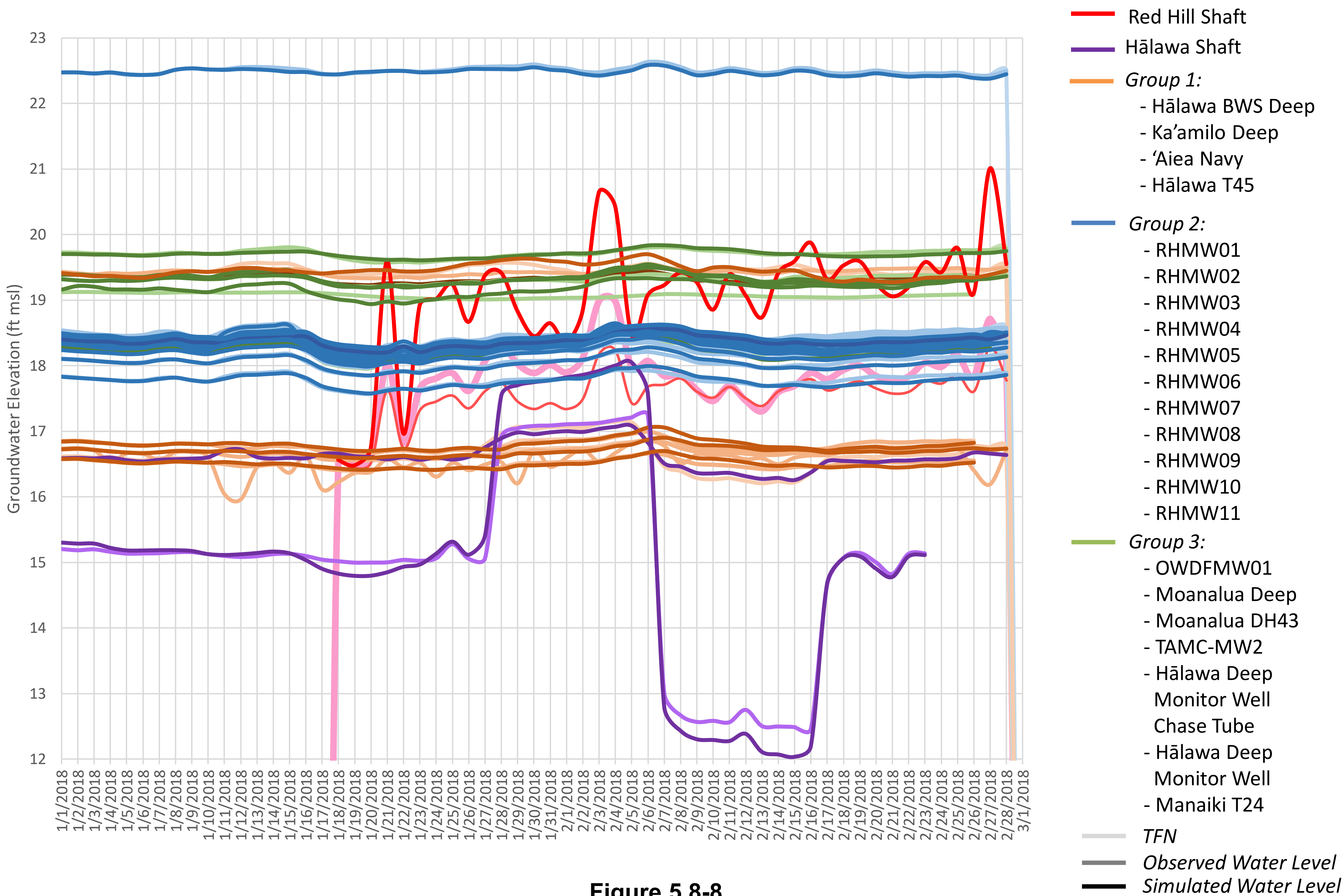
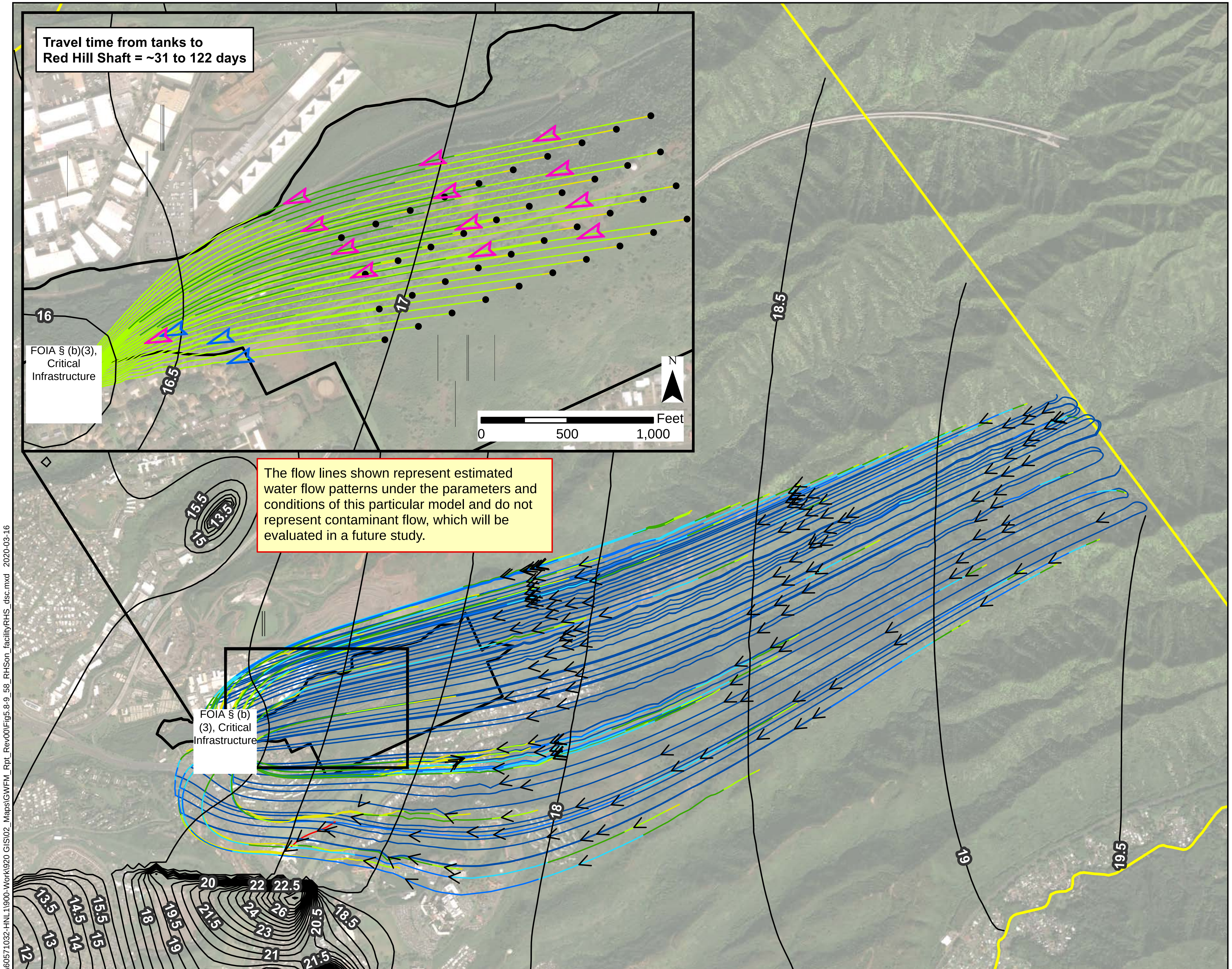


Figure 5.8-8
Model #58: Coastal Marine Discharge Variability – Verification Data Transfer Function-Noise Analysis
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



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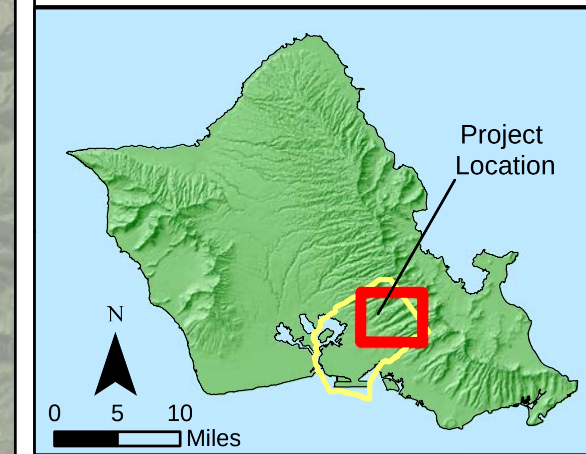
Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

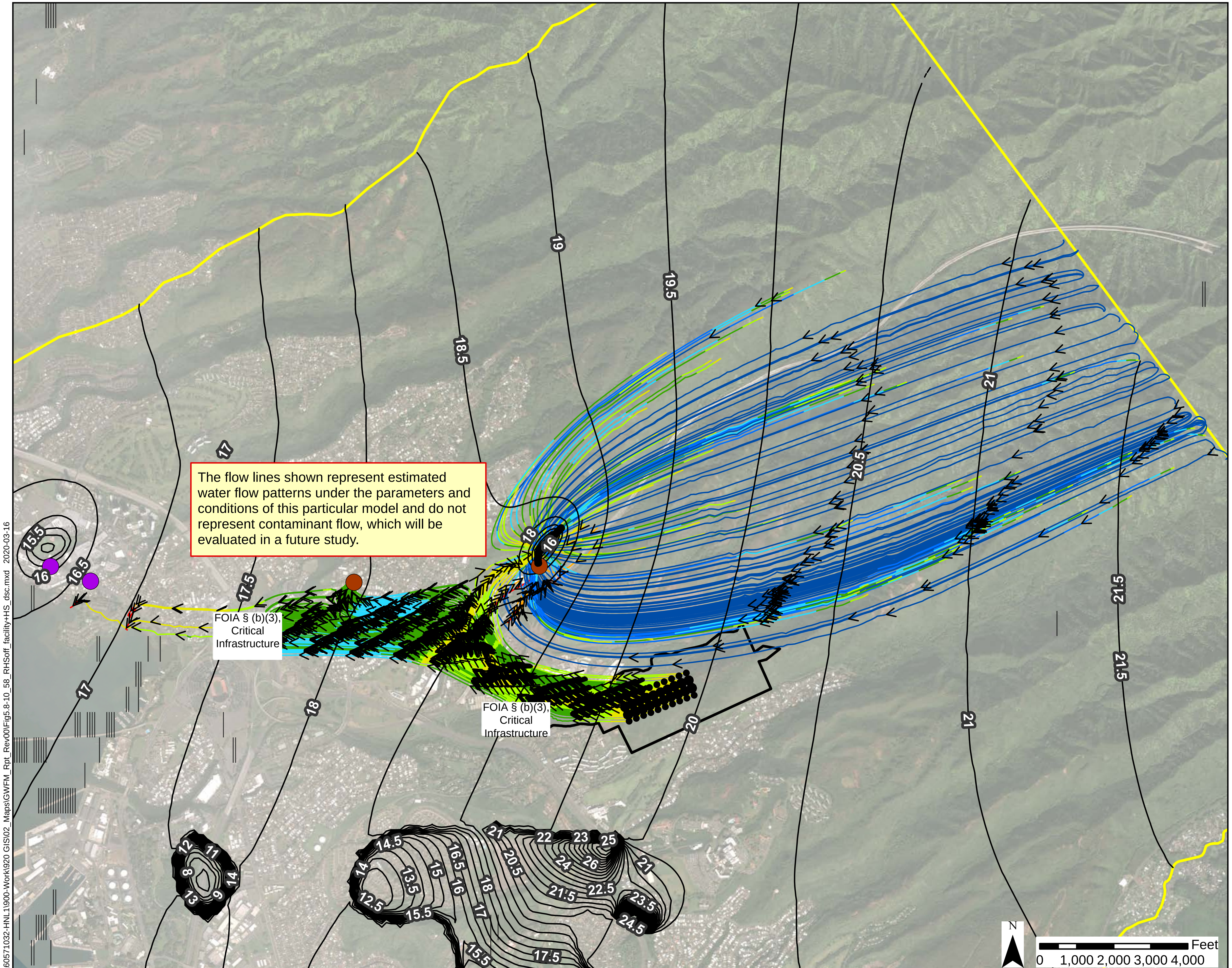
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

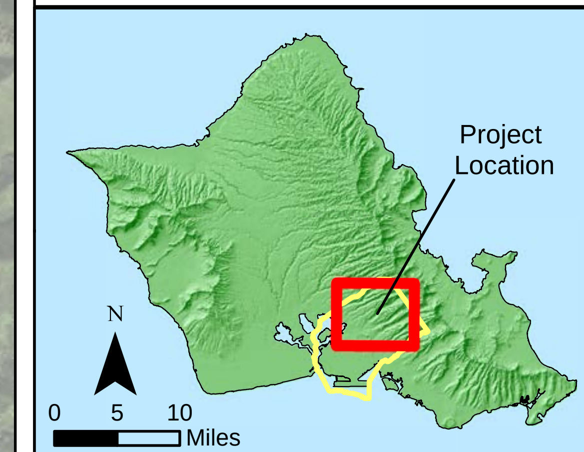
N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.8-9
Model #58: Coastal Marine Discharge Variability – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 30 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.8-10
Model #58: Coastal Marine Variability – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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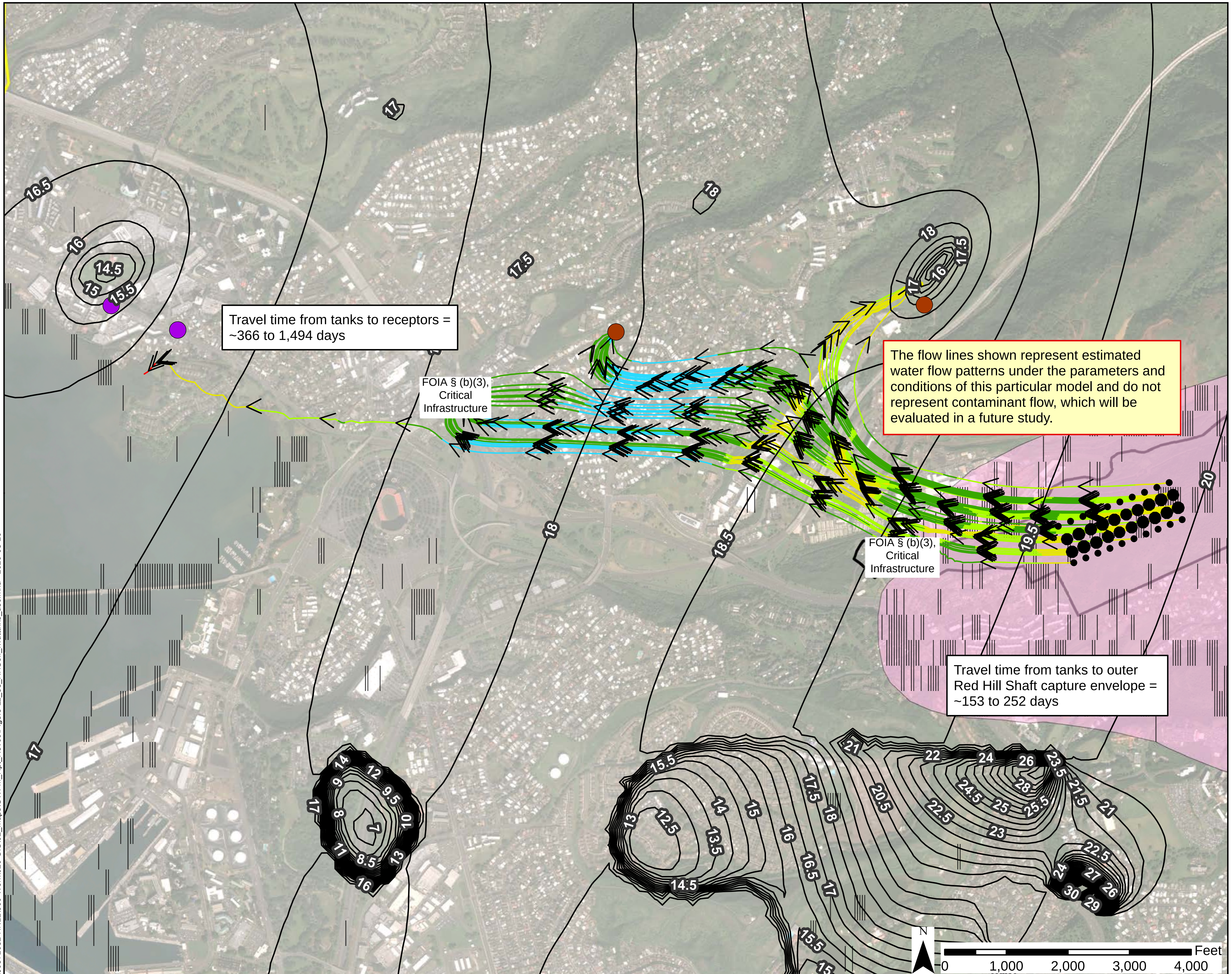
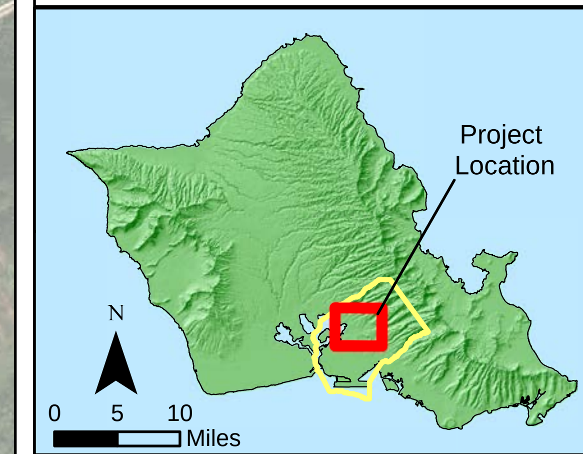


Location Map



Legend

Particle Tracks:

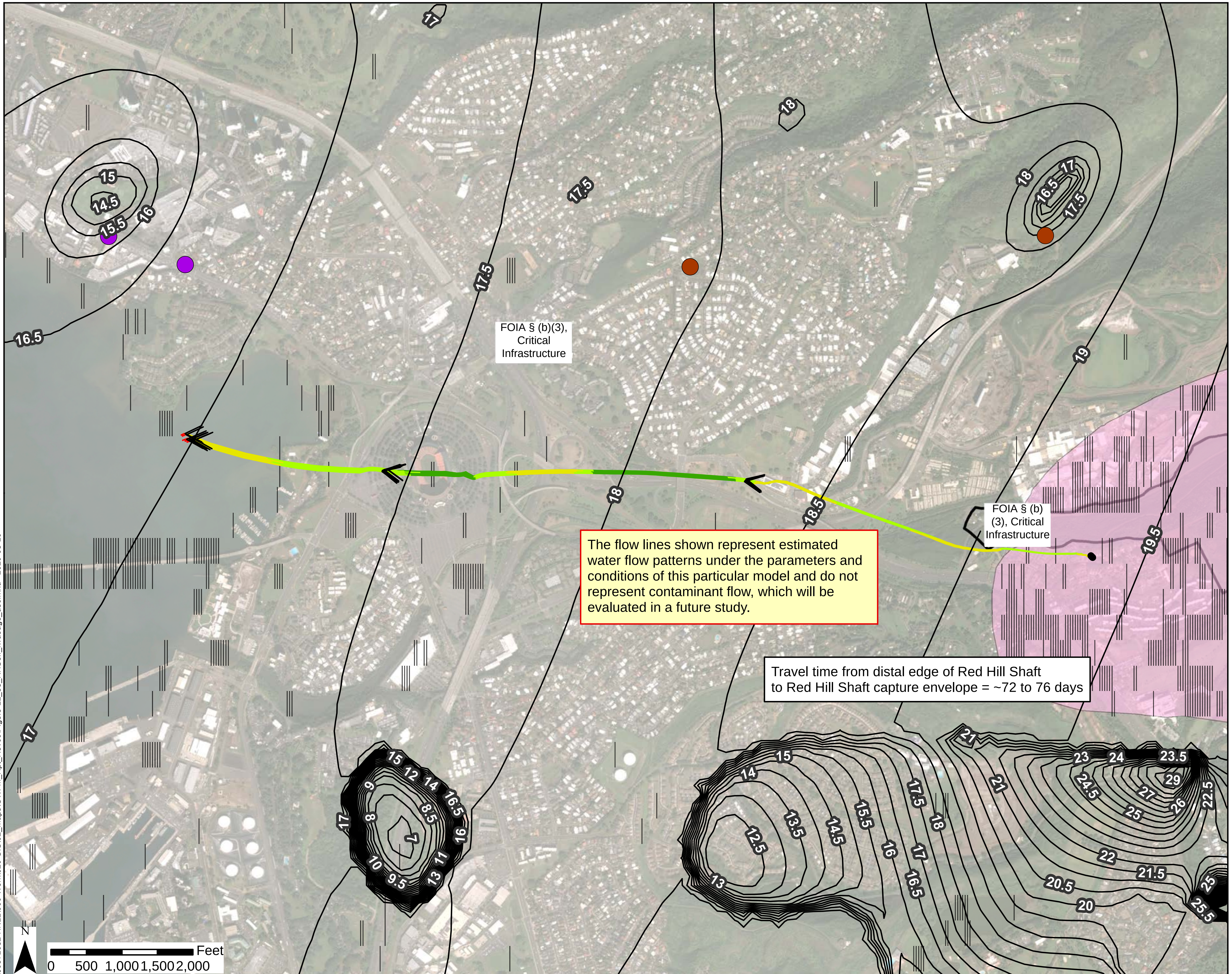
- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

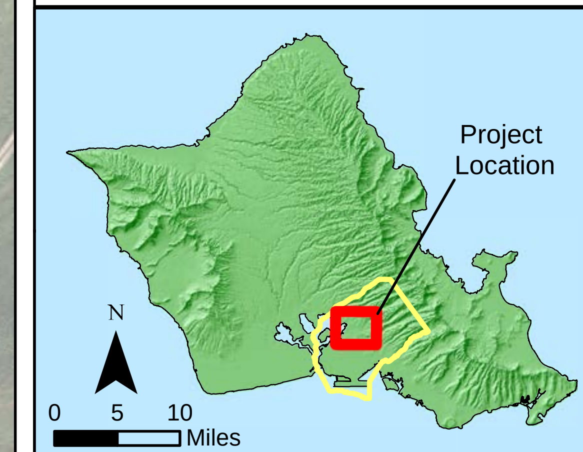
1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.8-11
Model #58: Coastal Marine Discharge Variability – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

B:\60571032-HNL11900-Work\920 GIS\02_Maps\GWFM_Rpt_Rev00\Fig5.8-11_58_RHSoff_fwdtanks_dsc.mxd 2020-03-16



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 1 year.

Figure 5.8-12
Model #58: Coastal Marine Discharge Variability – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

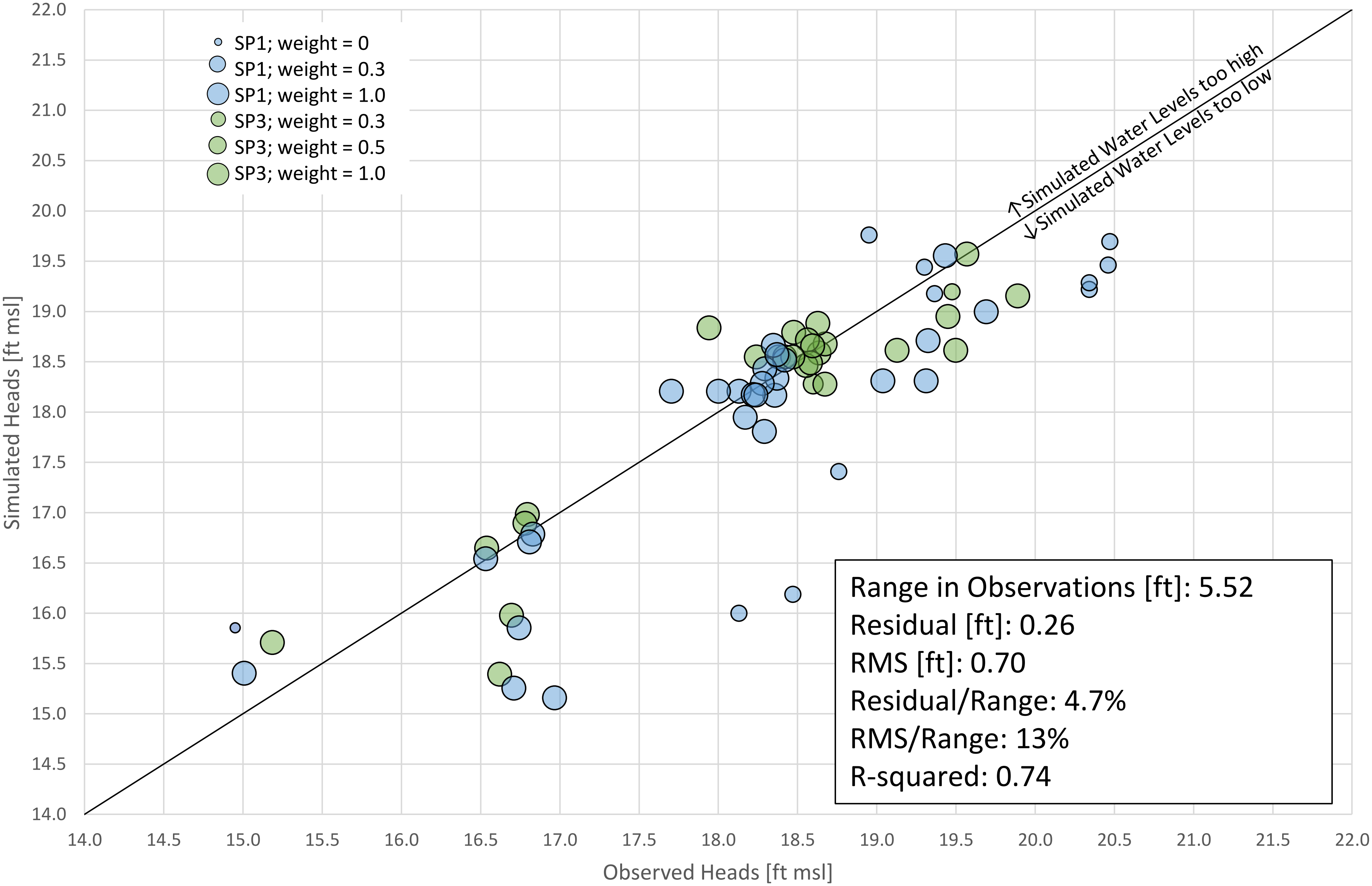
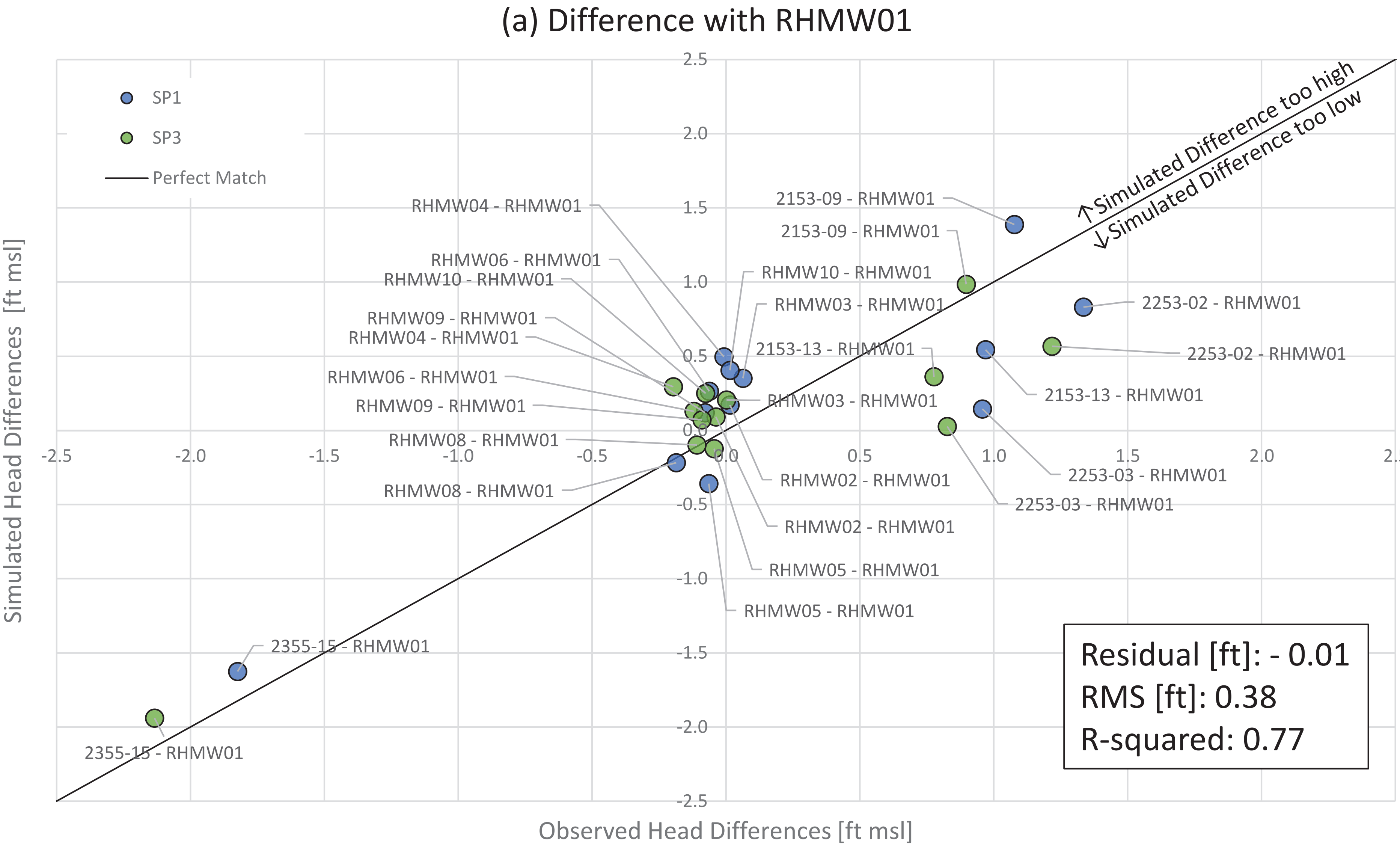


Figure 5.9-1
Model #59: Lateral Inflow from the Southeast – Water Level Scatterplot for Basalt Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i



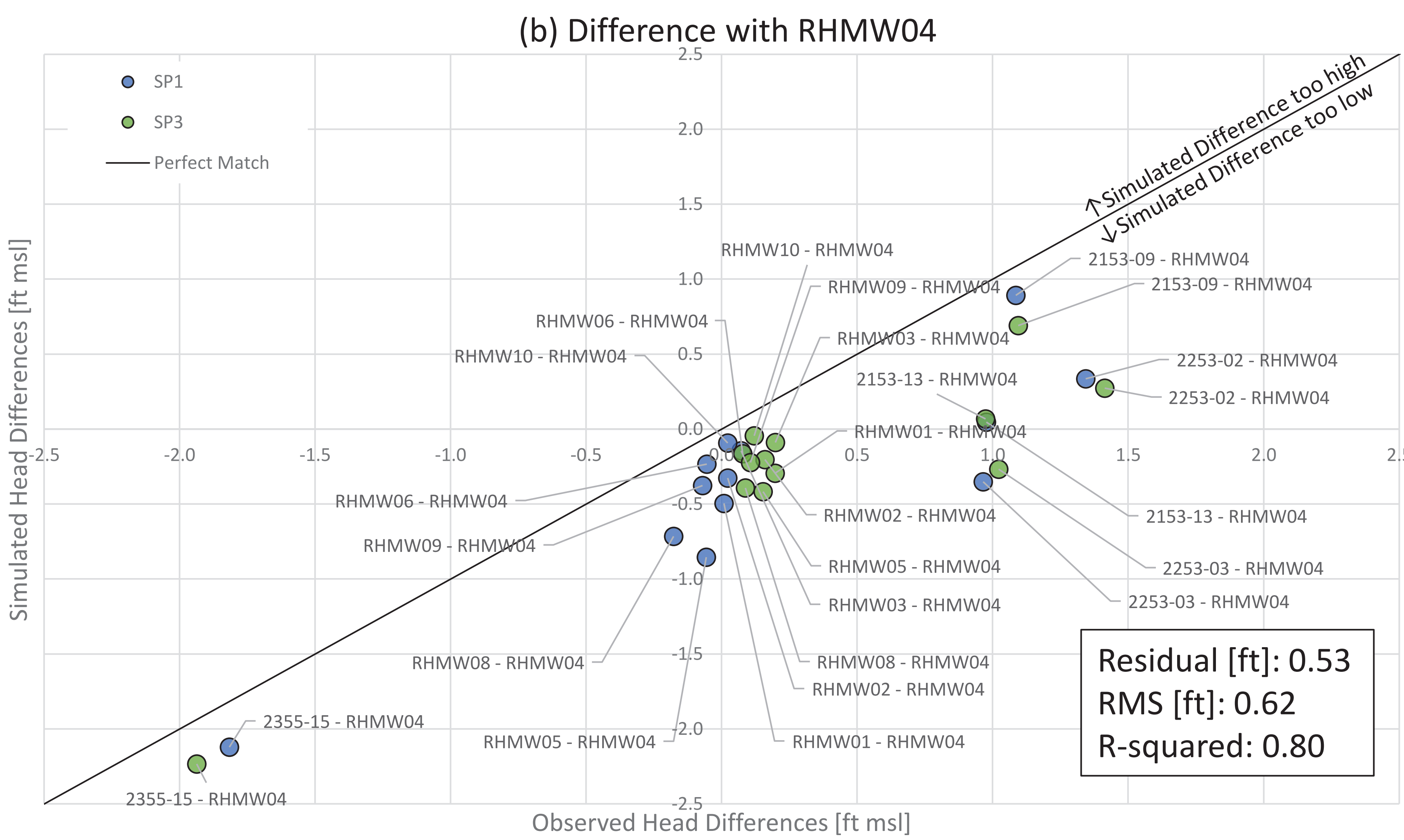


Figure 5.9-2
Model #59: Lateral Inflow from the Southeast –
Scatterplot of Water Level Differences Between Synoptic Study Wells
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

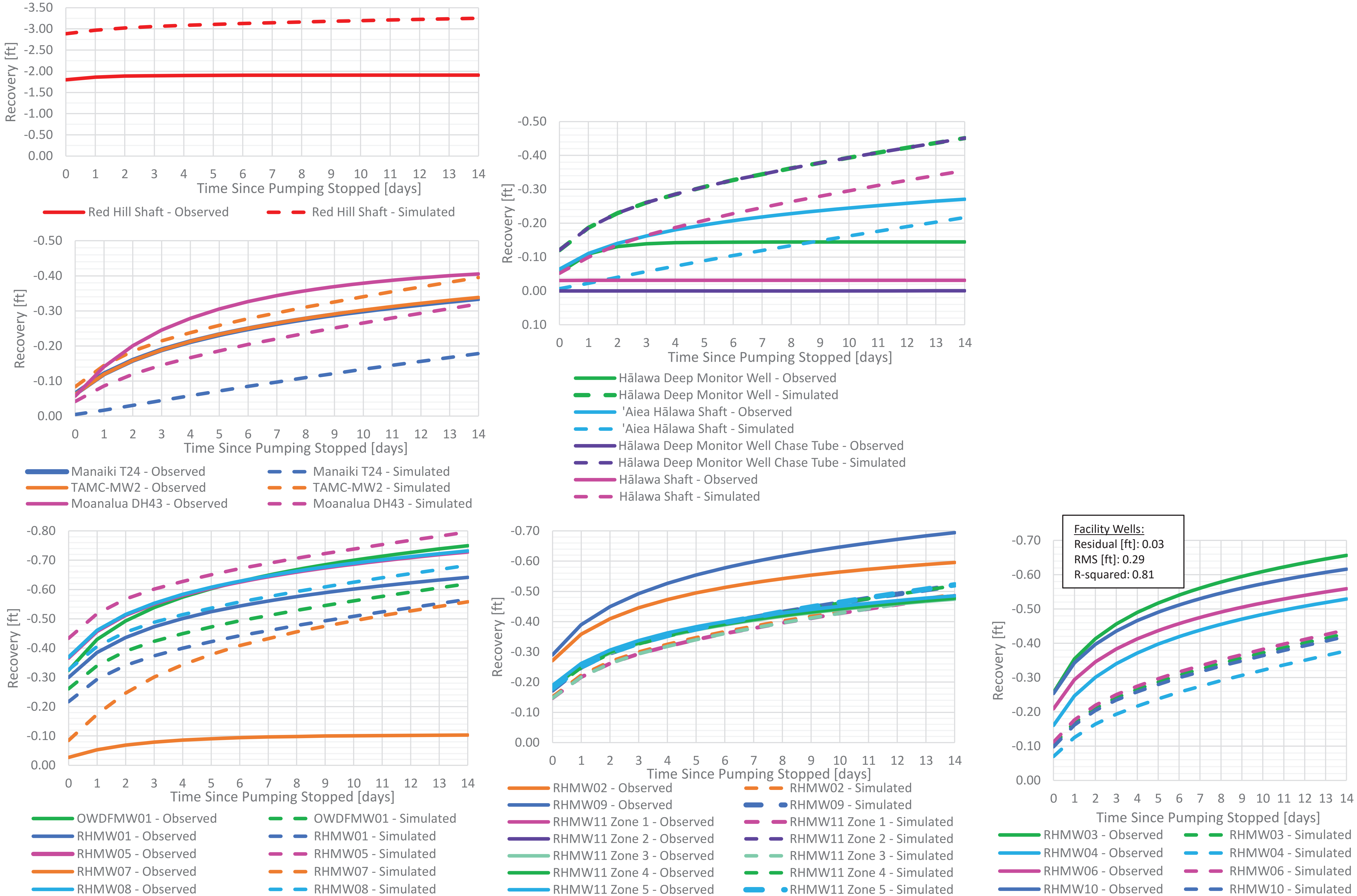


Figure 5.9-3
Model #59: Lateral Inflow from the Southeast –
Drawdown Hydrographs for SP2
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, Hawai‘i

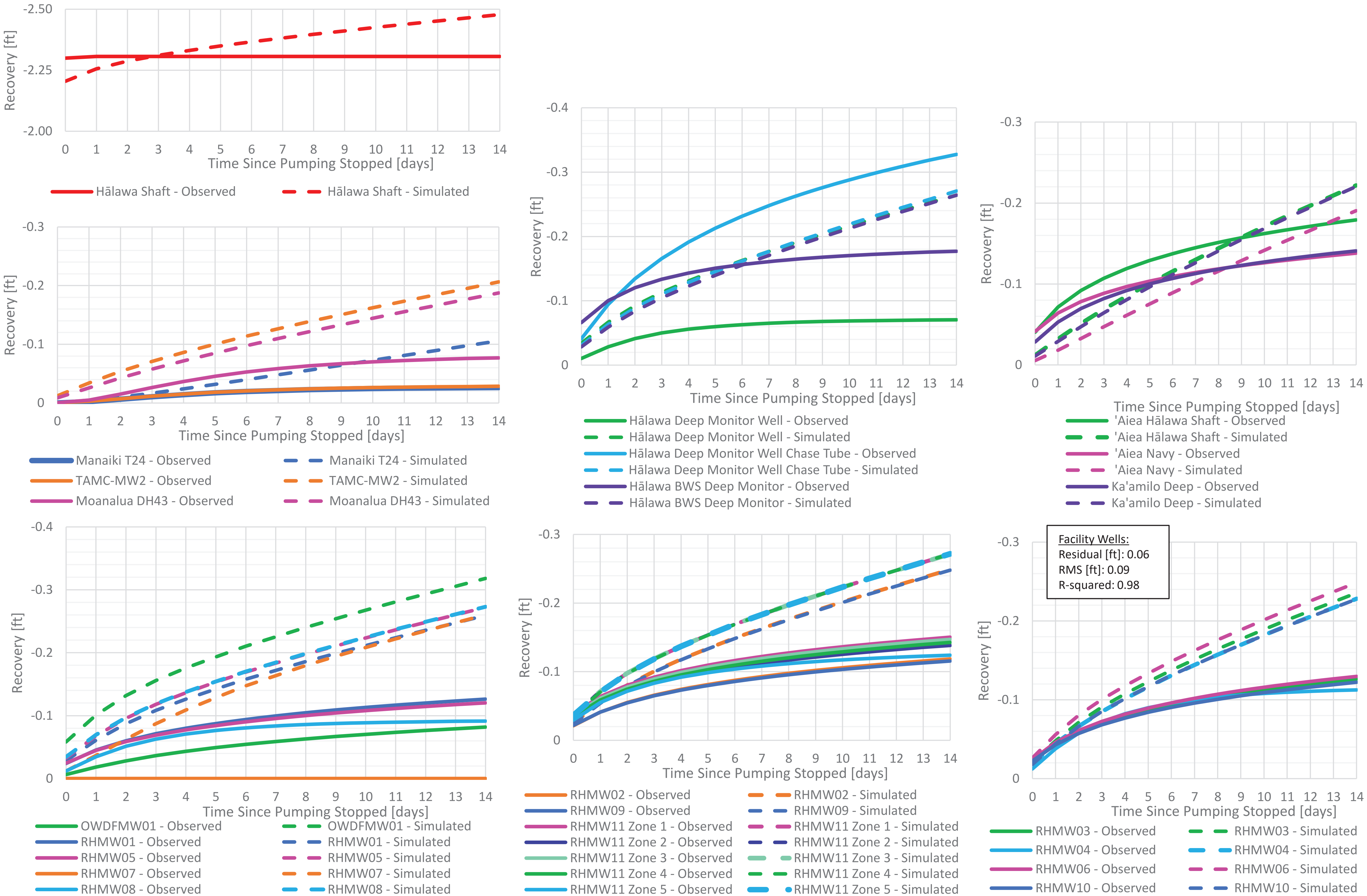
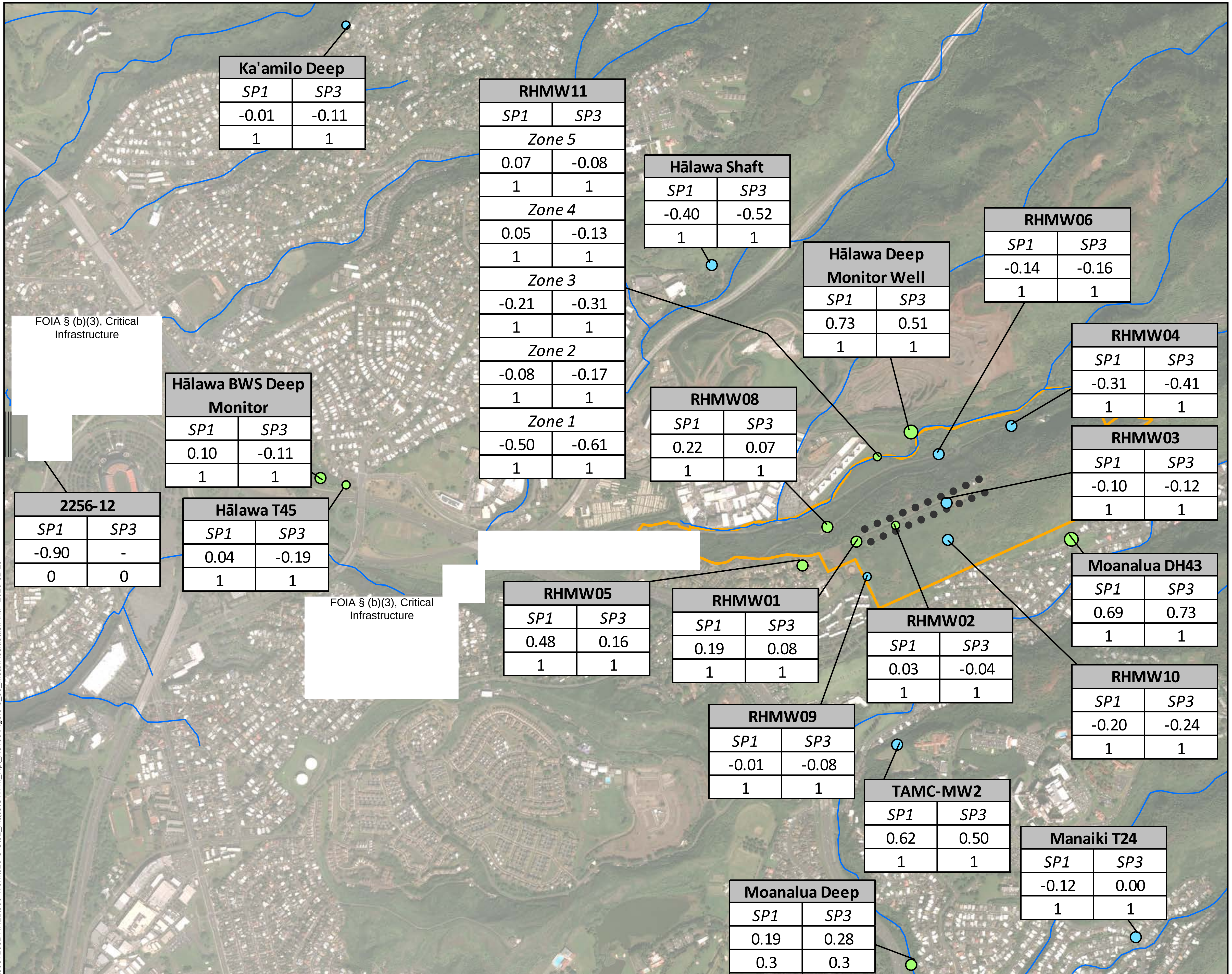
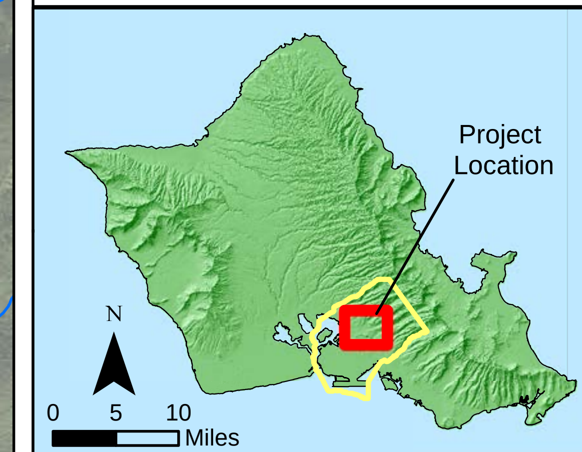


Figure 5.9-4
Model #59: Lateral Inflow from the Southeast –
Drawdown Hydrographs for SP4
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i



Location Map



Legend

- Well With Positive Residual
- Well With Negative Residual
- Stream
- Red Hill Facility Boundary and Fuel Storage Tanks
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 Hawaii State Plane Zone 3 feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. SP1 = Stress Period 1, SP3 = Stress Period 3
4. Size of well marker indicates error magnitude of SP1.

Well Name
Stress Period
Mean Residual in feet
Weight

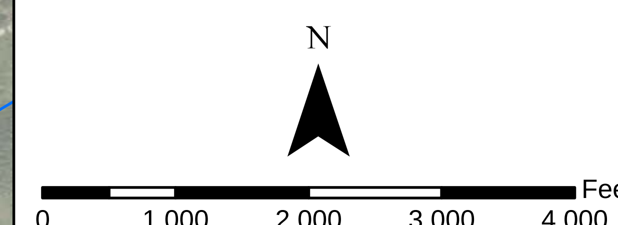


Figure 5.9-5
Model #59: Lateral Inflow from the Southeast – Mean Residual Map
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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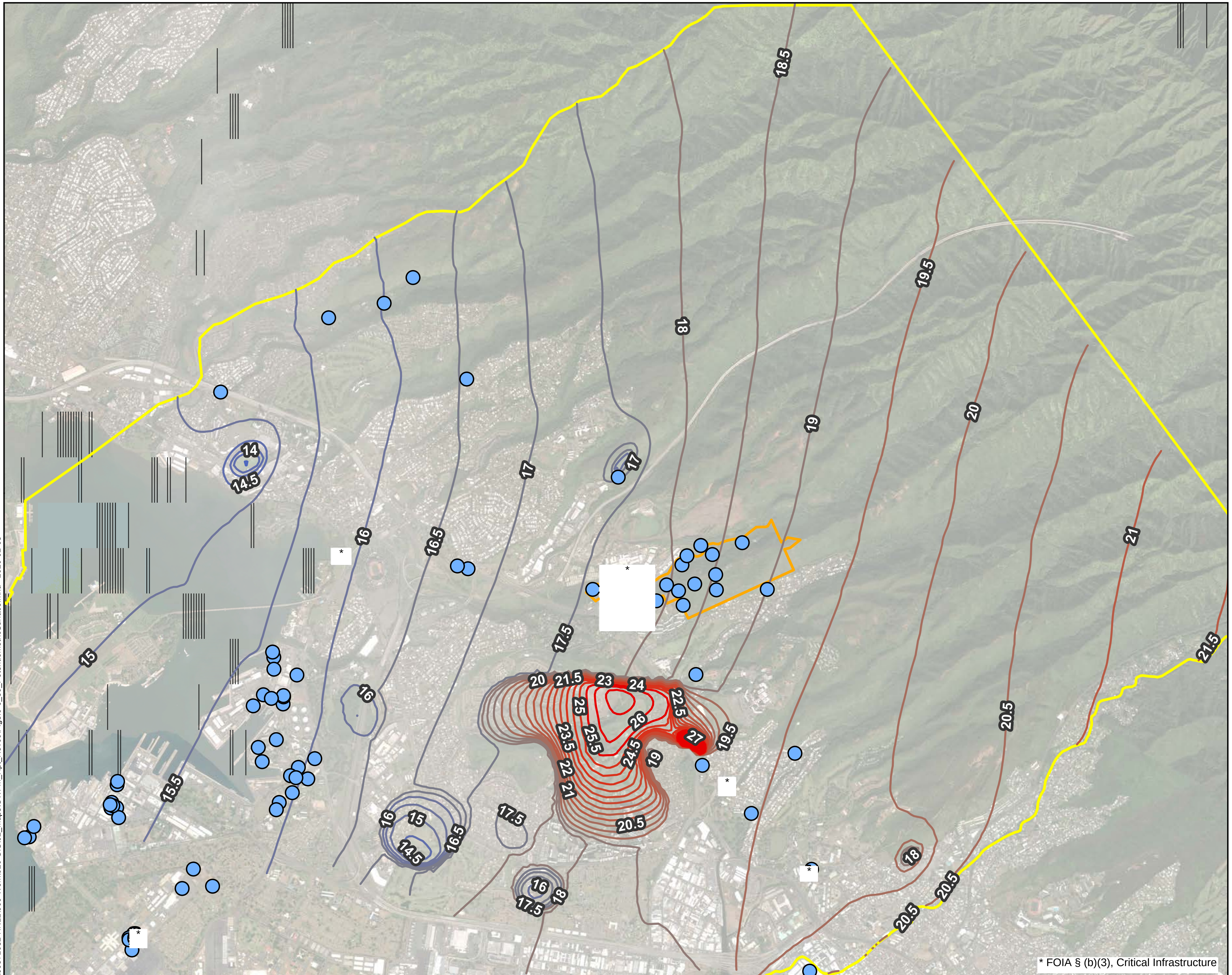
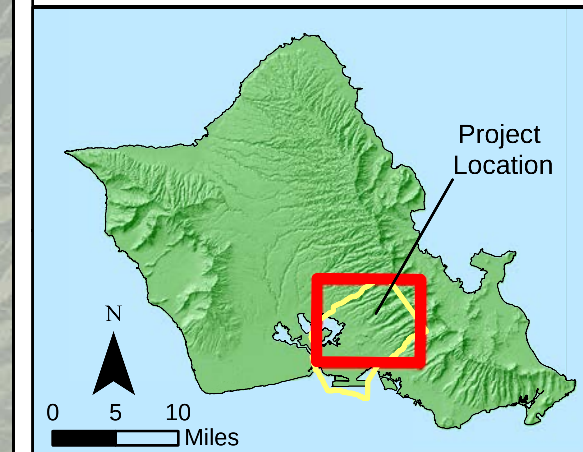


Location Map



Legend

Potentiometric Surface (feet above mean sea level)

- < 10.0
- 10.0 - 11.5
- 11.5 - 13.0
- 13.0 - 14.5
- 14.5 - 16.0
- 16.0 - 17.5
- 17.5 - 19.0
- 19.0 - 20.5
- 20.5 - 22.0
- 22.0 - 23.5
- 23.5 - 25.0
- > 25.0

Stress Period 1 Calibration Target Well

Groundwater Model Domain

Red Hill Facility Boundary

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Contours are plotted for Model Layer 4.

N

0 2,000 4,000 6,000 Feet

Figure 5.9-6
Model #59: Lateral Inflow from the Southeast – Potentiometric Surface for SP1
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, Oʻahu, HI

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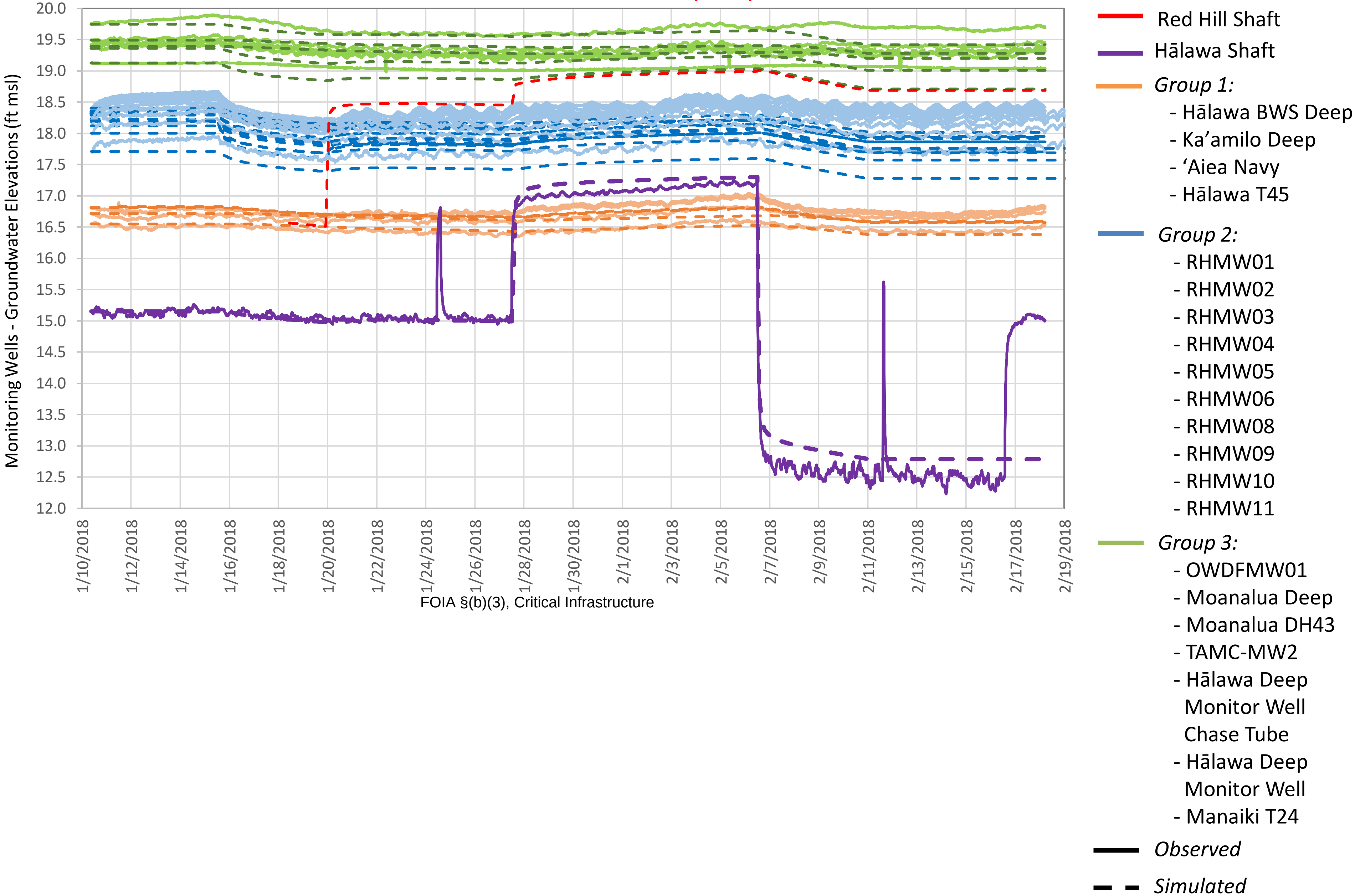


FOIA §(b)(3), Critical Infrastructure

Figure 5.9-7
Model #59: Lateral Inflow from the Southeast – Numerical Verification Results
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, Hawai'i

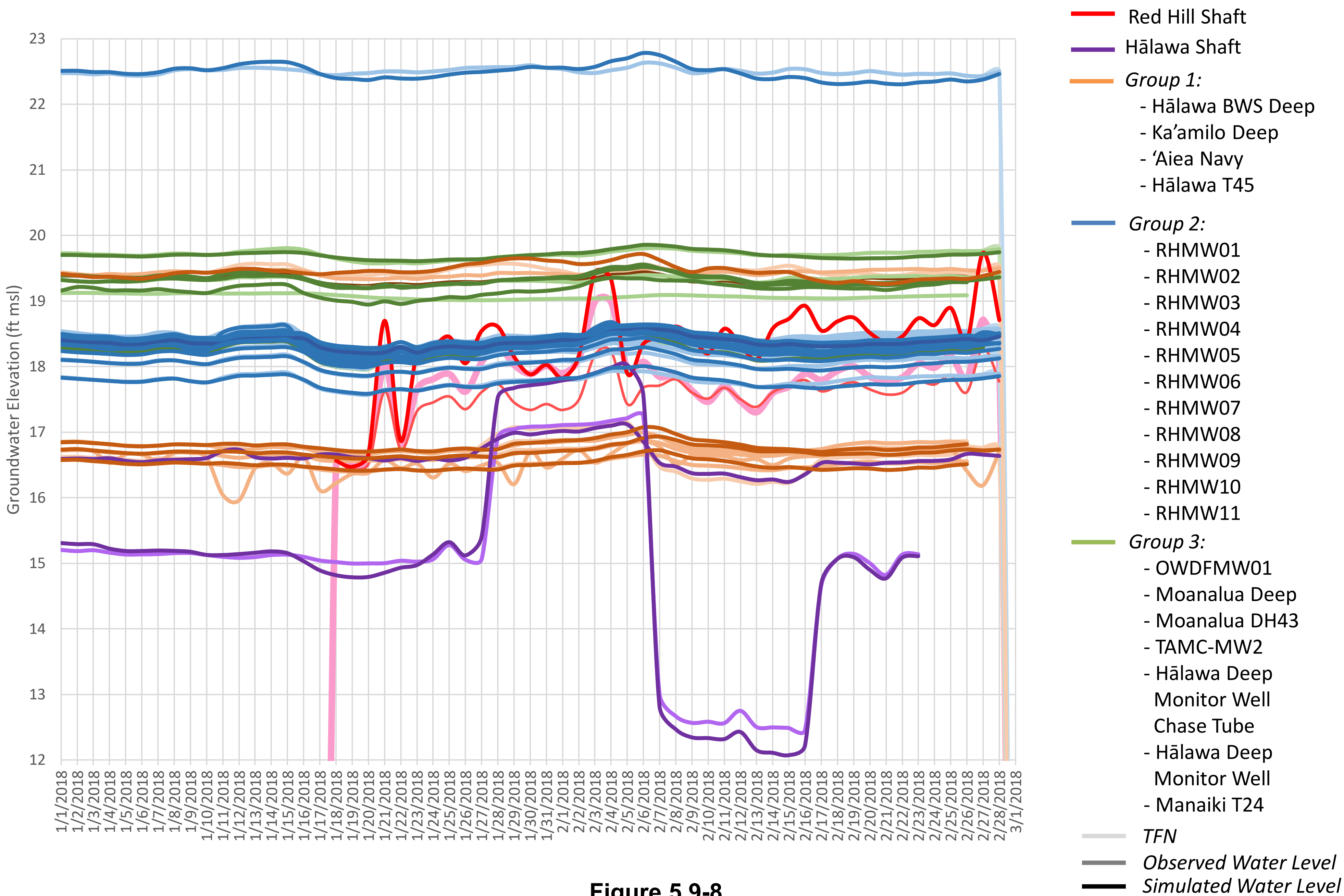


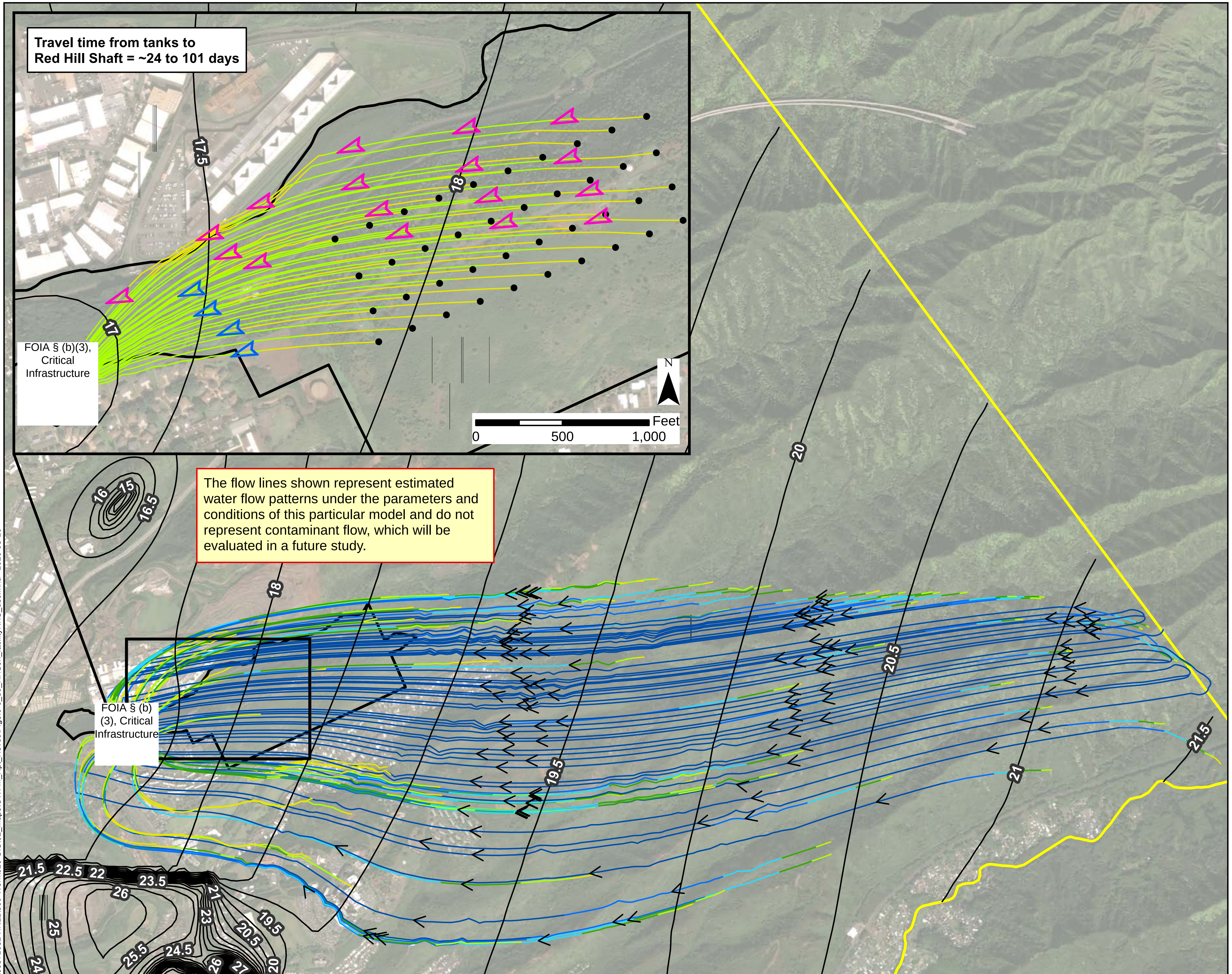
Figure 5.9-8

Model #59: Lateral Inflow from the Southeast – Verification Data Transfer Function-Noise Analysis

Groundwater Flow Model Report

Red Hill Bulk Fuel Storage Facility

JBPHH, O'ahu, Hawai'i



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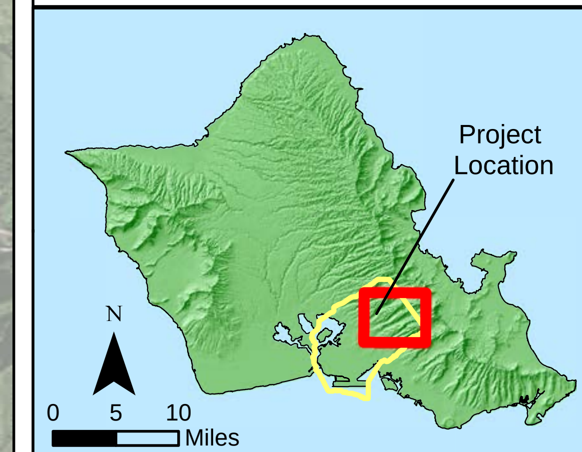
Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

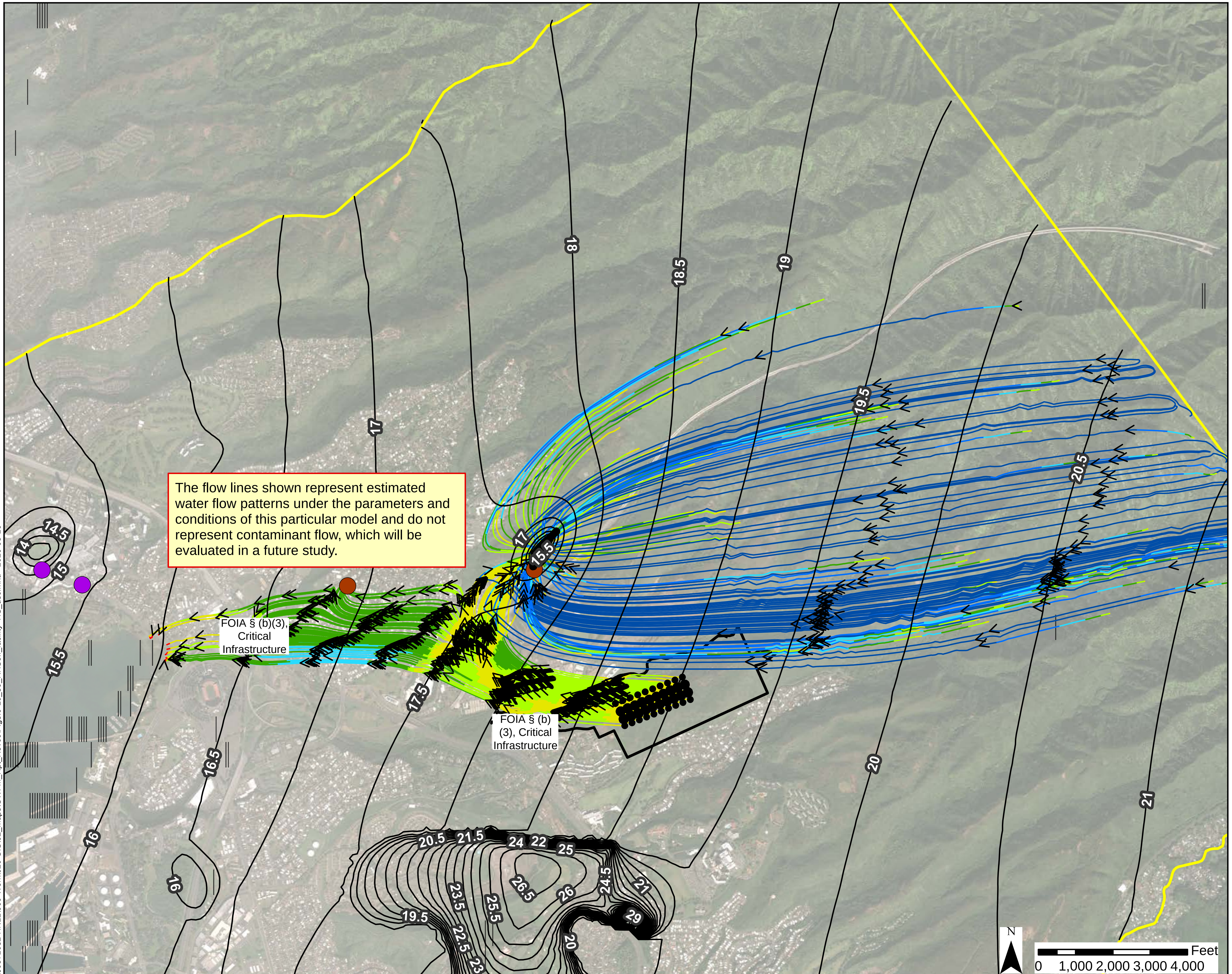
Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 20 days. Pink colored arrows originate from the first row of particles, and blue colored arrows from the last row of particles.
4. Red Hill Shaft reverse pathline arrows = 1 year.

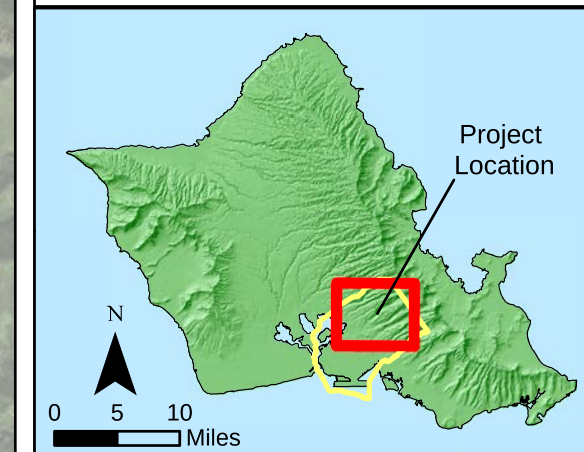
N

Feet
0 1,000 2,000 3,000 4,000

Figure 5.9-9
Model #59: Lateral Inflow from the Southeast – Flow Trajectory from the Facility and Source Water Zone of Red Hill Shaft for Red Hill Shaft On at [redacted] MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI



Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.
4. Hālawa Shaft reverse pathline arrows = 1 year.

Figure 5.9-10
Model #59: Lateral Inflow from the Southeast – Migration from the Facility and Source Water Zone of Hālawa Shaft for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O‘ahu, HI

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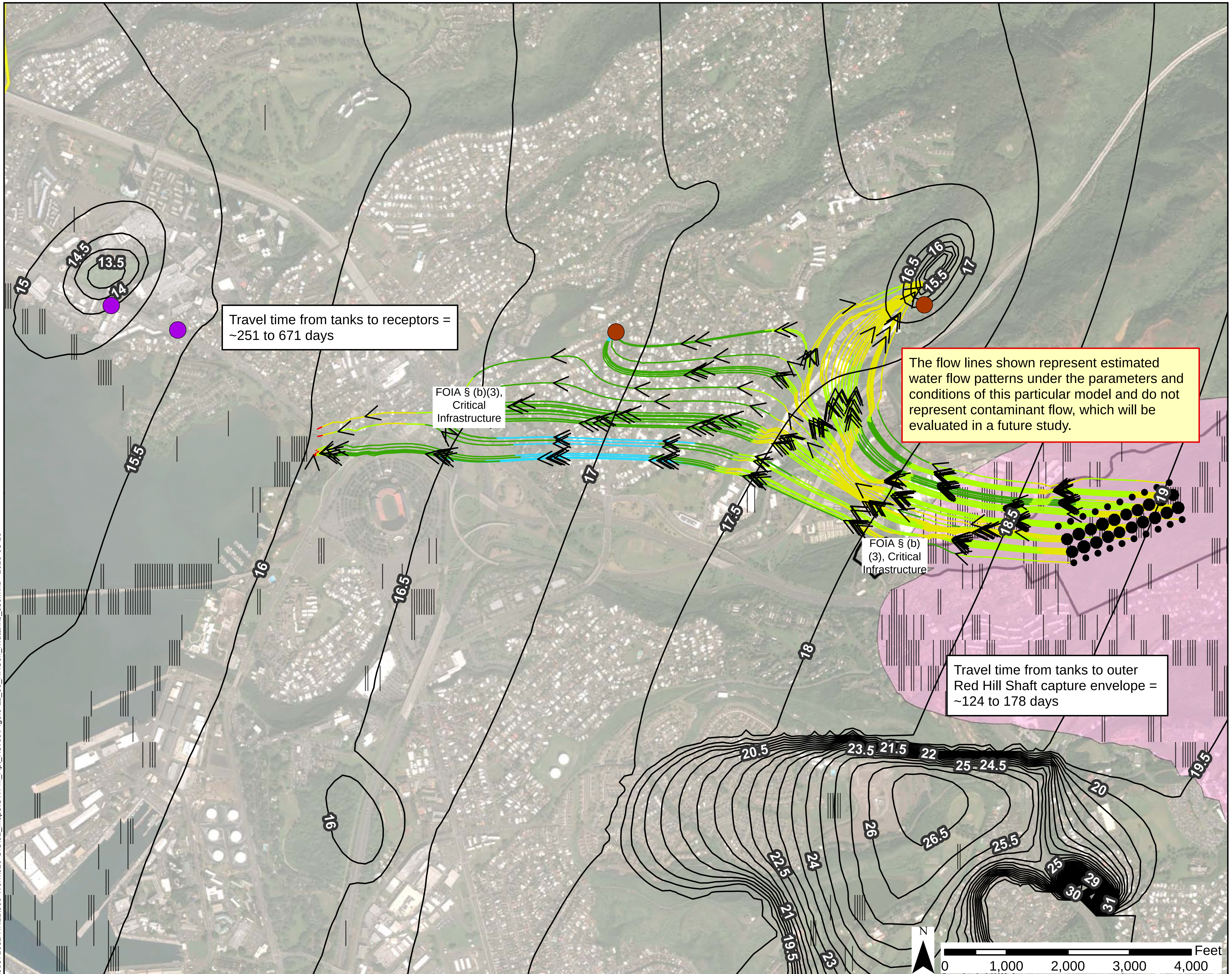
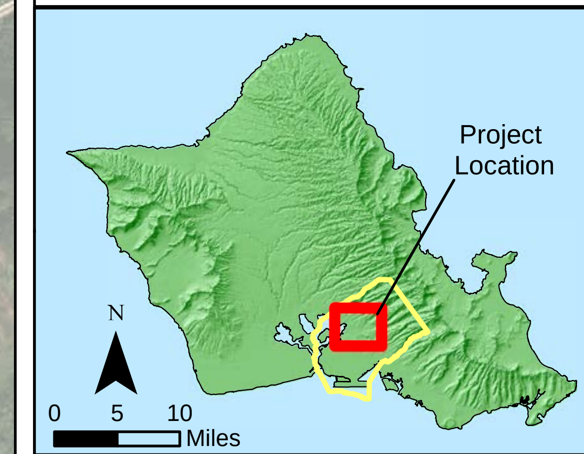


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.9-11
Model #59: Lateral Inflow from the Southeast – Migration from Tanks and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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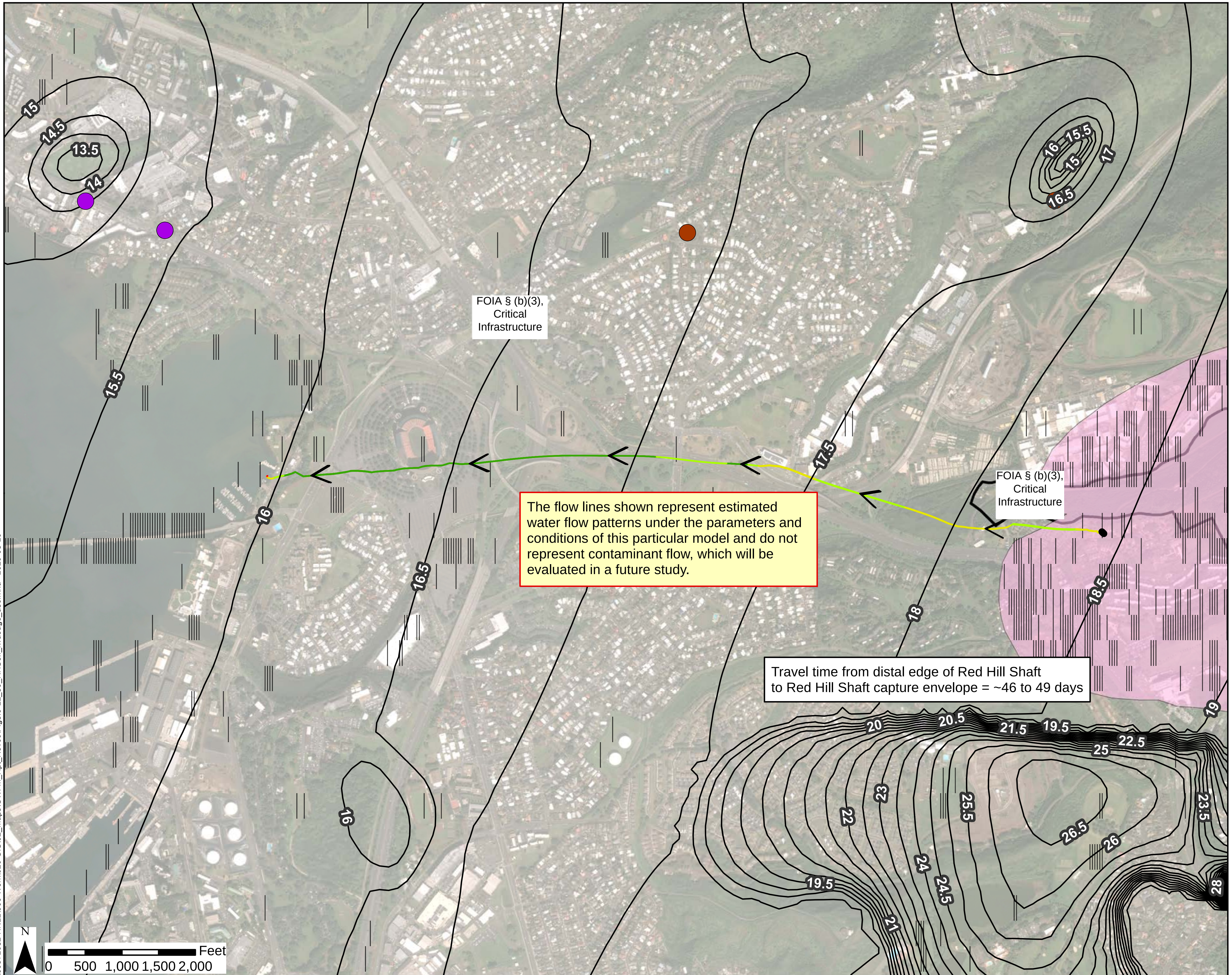
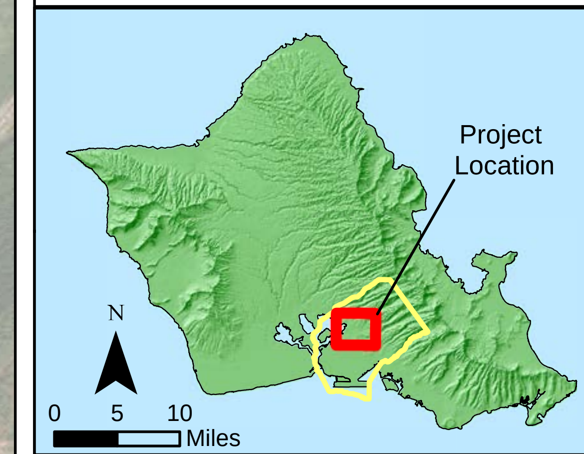


Location Map



Legend

Particle Tracks:

- Layer 2
- Layer 3
- Layer 4
- Layer 5
- Layer 6
- Layer 7
- Layer 8
- Layer 9
- Particle Location
- Spring
- Pumping Well
- Groundwater Contour (feet msl)
- Red Hill Shaft Capture Zone
- Red Hill Facility Boundary
- Groundwater Model Domain

Notes

1. Map projection: NAD 1983 UTM Z4N feet.
2. Base Map: DigitalGlobe, Inc. (DG) and NRCS. Publication_Date: 2015
3. Facility forward pathline arrows = 90 days.

Figure 5.9-12
Model #59: Lateral Inflow from the Southeast – Forward Tracking from the Edge of Red Hill Shaft and Red Hill Shaft Capture Zone for Red Hill Shaft Not Pumping and Hālawa Shaft Pumping at 12 MGD
Groundwater Flow Model Report
Red Hill Bulk Fuel Storage Facility
JBPHH, O'ahu, HI

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Appendix A:
Refined Transfer Function-Noise Analysis

Transfer function-noise (TFN) modeling was applied to analyze selected 2017–2018 synoptic monitoring data to support the calibration of the Red Hill numerical groundwater flow model. Specifically, the resulting transfer functions that represent the unit step response functions associated with Red Hill Shaft and Hālawa Shaft individually were directly used as calibration targets. In addition, individual contributions from groundwater extraction at these shafts, barometric pressure, and ocean/earth tides to the observed water level changes were simultaneously quantified and separated. Equivalent regional-scale aquifer hydraulic properties were estimated.

The initial TFN analysis, including concept, implementation, and initial results of the TFN analysis, was presented in Appendix H of the Red Hill *Conceptual Site Model* (CSM) report (DON 2019). Since publication of the CSM report, the TFN analysis was refined to improve the matching of the TFN model results with the synoptic monitoring data. For reasons presented in the CSM report, the transfer functions were represented by unit step response function based on Hantush (1956). At each groundwater extraction shaft, a zero-lag (i.e., instantaneous-response) term was added to approximate the water-entry head loss. The results of the refined TFN analysis have been presented at the Administrative Order on Consent (AOC) Statement of Work Sections 6 and 7 August 2019 Technical Working Group (TWG) meeting.

Subsequent to the TWG meeting, the TFN analysis was expanded to analyze the synoptic data observed in the following wells:

- ‘Aiea Hālawa Shaft
- Hālawa Deep Monitor Well Chase Tube
- Hālawa Deep Monitor Well (2253-03)
- Ka‘amilo Deep
- Moanalua DH43
- TAMC-MW2
- Moanalua Deep
- Hālawa T-45 (#2255-33)
- Manaiki T-24

‘Aiea Hālawa Shaft was added as a source of hydraulic stress for wells Hālawa BWS Deep Monitoring, ‘Aiea Navy, and Ka‘amilo Deep. It was observed that the water levels at these monitoring wells responded mainly to extraction operations at Hālawa Shaft and ‘Aiea Hālawa Shaft, but not to the extraction operations at Red Hill Shaft.

The transfer functions from TFN model calibrations were applied to compute the individual water level responses to Red Hill Shaft and Hālawa Shaft pumping using the time series of groundwater extraction rates, barometric pressure, and earth tide available from July 1, 2017 through December 31, 2018. The residual time series (difference between the observed water level data and TFN model simulated water levels) were computed and examined.

UPDATED TRANSFER FUNCTIONS

Figure A-1 shows the results from the refined TFN analysis of water level data at monitoring well RHMW08 for the Red Hill Shaft shutdown/restart period (no pumping between January 10, 2018 and January 15, 2018) and the Hālawa Shaft shutdown/restart period (no pumping between January 27, 2018 and February 6, 2018), respectively. This well is used as an example, and key analyses for all wells are provided in Attachment A.1. Figure A-2 shows the observed and TFN model-simulated differences between the water levels at monitoring wells RHMW05 and RHMW10 as an example. All pairs are included in Attachment A.2 and are in good agreement. Figure A-3 shows the transfer functions associated with Red Hill Shaft pumping. Figure A-4 shows the transfer functions associated with Hālawa Shaft pumping. The ratios of the instantaneous response (zero-lag) terms to the total long-term drawdowns are approximately 0.02, 0.05, and 0.17 for Red Hill Shaft, Hālawa Shaft, and ʻAiea Hālawa Shaft, respectively. The updated equivalent regional-scale, homogeneous, and isotropic parameters (Hantush 1956) associated with the unit step response functions at different monitoring wells are summarized in Table A-1 (with Red Hill Shaft and Hālawa Shaft pumping) and Table A-2 (with Hālawa Shaft and ʻAiea Hālawa Shaft pumping).

LONG-TERM WATER LEVELS

The observed and TFN-simulated water level time series from July 1, 2017 through December 31, 2018 are shown on Figure A-5. The corresponding residual water level time series are presented on Figure A-6. The residual water level time series are similar for all the wells, suggesting that they are associated with regional water level changes. They indicate that these variations did not follow a well-defined annual periodic pattern.

Table A-1: Equivalent Regional-Scale Aquifer Hydraulic Properties for Unit Step Response Functions at Monitoring Wells with Red Hill Shaft and Hālawa Shaft Pumping

	Red Hill Shaft Pumping			Hālawa Shaft Pumping		
Monitoring Well	Effective Transmissivity (ft^2/day)	Apparent Storativity	rho	Effective Transmissivity (ft^2/day)	Apparent Storativity	rho
Red Hill Shaft	77,196	0.180	0.542	209,625	0.000	0.326
'Aiea Hālawa Shaft	932,049	0.083	0.000	1,099,786	0.029	0.107
Hālawa Deep Monitor Well Chase Tube	1,751	0.102	0.122	292,203	0.197	2.000
Hālawa Deep Monitor Well (2253-03)	147,641	0.025	1.875	748,205	0.192	1.041
Hālawa Shaft	6,362,610	0.006	0.342	58,408	0.040	0.486
OWDFMW01	496,011	0.053	0.001	1,656,845	0.133	0.001
RHMW01	624,007	0.050	0.001	1,500,200	0.089	0.002
RHMW02	578,376	0.042	0.089	1,551,994	0.076	0.001
RHMW03	521,141	0.022	0.004	1,447,002	0.091	0.001
RHMW04	544,455	0.026	0.003	502,322	0.018	0.980
RHMW05	591,633	0.173	0.003	1,623,801	0.046	0.002
RHMW06	591,839	0.022	0.003	1,442,055	0.085	0.001
RHMW08	591,122	0.045	0.000	569,733	0.021	1.046
RHMW09	520,471	0.055	0.001	1,623,523	0.059	0.001
RHMW10	578,908	0.026	0.001	1,522,745	0.081	0.001
RHMW11 Z1	710,085	0.040	0.002	1,460,152	0.025	0.010
RHMW11 Z2	681,985	0.062	0.001	1,561,566	0.131	0.001
RHMW11 Z3	710,338	0.050	0.002	1,465,228	0.115	0.001
RHMW11 Z4	708,870	0.055	0.001	1,495,633	0.120	0.001
RHMW11 Z5	698,672	0.019	0.025	1,077,067	0.200	0.419
Moanalua DH43	288,531	0.048	0.588	186,995	0.199	2.000
TAMC-MW2	657,712	0.012	0.001	660,046	0.075	1.796
Moanalua Deep	339,260	0.005	0.549	812,352	0.156	0.001
Hālawa T-45 (#2255-33)	—	—	—	483,502	0.029	0.070
Manaiki T-24	675,316	0.009	0.002	558,280	0.051	2.000

Table A-2: Equivalent Regional-Scale Aquifer Hydraulic Properties for Unit Step Response Functions with Hālawa Shaft and 'Aiea Hālawa Shaft Pumping

	Hālawa Shaft Pumping			'Aiea Hālawa Shaft Pumping		
Monitoring Well	Effective Transmissivity (ft^2/day)	Apparent Storativity	rho	Effective Transmissivity (ft^2/day)	Apparent Storativity	rho
'Aiea Hālawa Shaft	See Table A-1	See Table A-1	See Table A-1	385,139	0.019	0.001
Hālawa BWS Deep Monitor	1,000,753	0.008	0.295	927,186	0.053	0.131
'Aiea Navy	1,736,886	0.017	0.008	1,291,471	0.013	0.077
Ka'amilo Deep	1,303,725	0.037	0.137	971,159	0.007	0.528

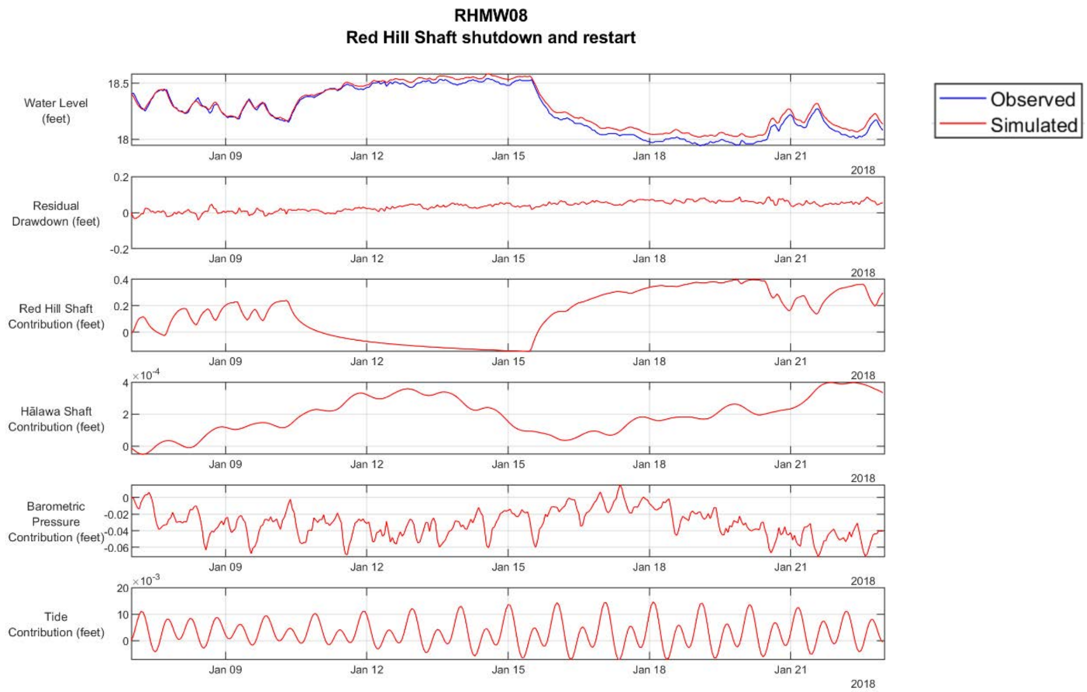
REFERENCES

Department of the Navy (DON). 2019. *Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, O'ahu, Hawai'i; June 30, 2019, Revision 01*. Prepared by AECOM Technical Services, Inc., Honolulu, HI. Prepared for Defense Logistics Agency Energy, Fort Belvoir, VA, under Naval Facilities Engineering Command, Hawaii, JBPHH HI.

Hantush, M. S. 1956. "Analysis of Data from Pumping Tests in Leaky Aquifers." *Eos, Transactions American Geophysical Union* 37 (6): 702–714. https://doi.org/10.1029/TR037i006p00702.

Figures

Figure A-1: TFN Analysis Results for RHMW08 Red Hill Shaft Shutdown/Restart Period (top) and Hālawa Shaft Shutdown/Restart Period (bottom)



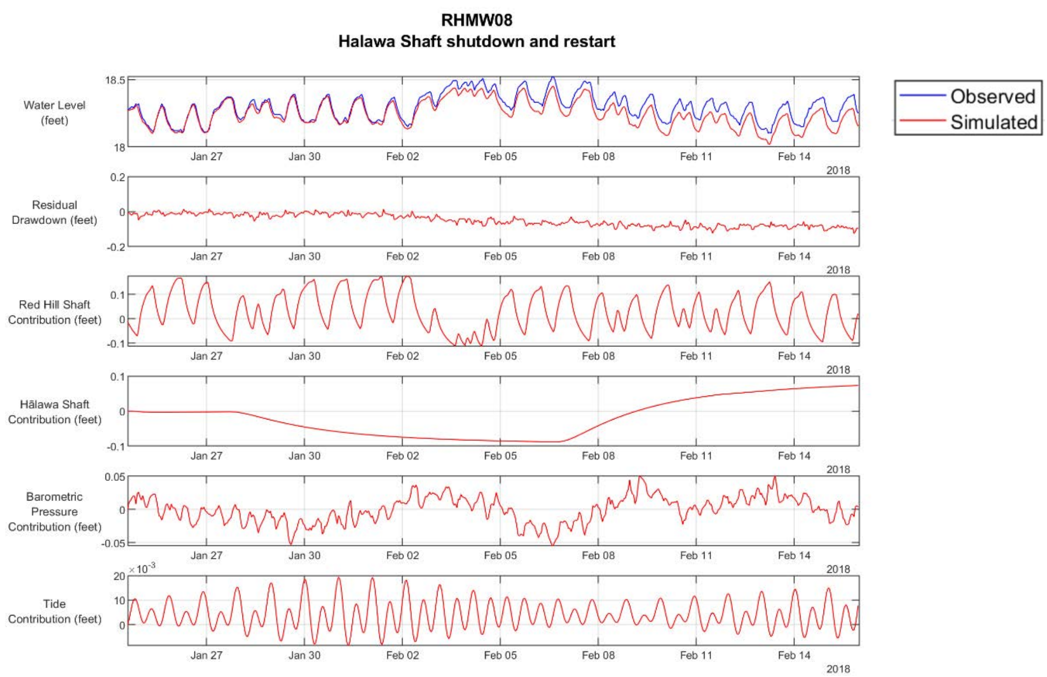


Figure A-2: Comparison of Observed and Computed Differences Between Water Levels at RHMW05 and RHMW10

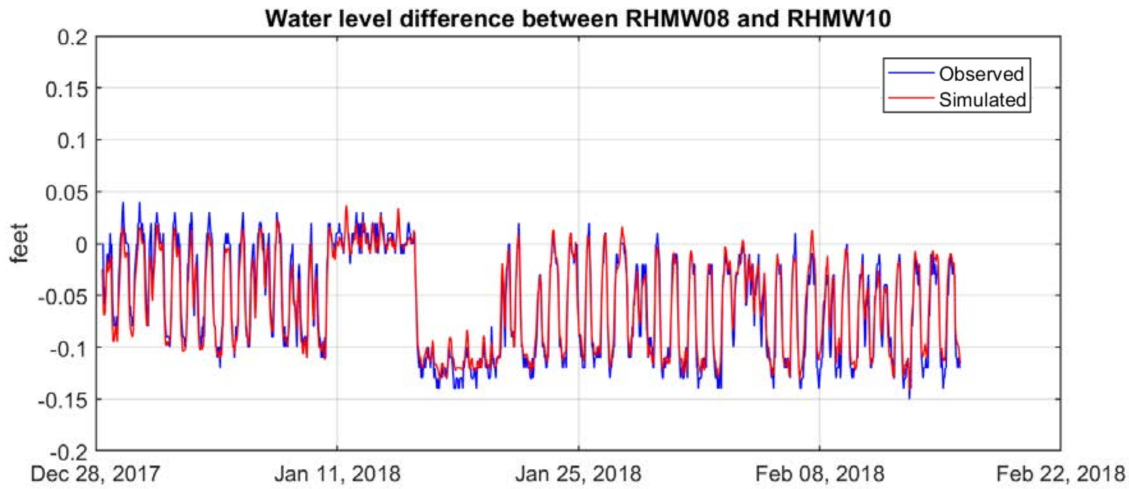


Figure A-3: Transfer Functions Associated with Red Hill Shaft Pumping

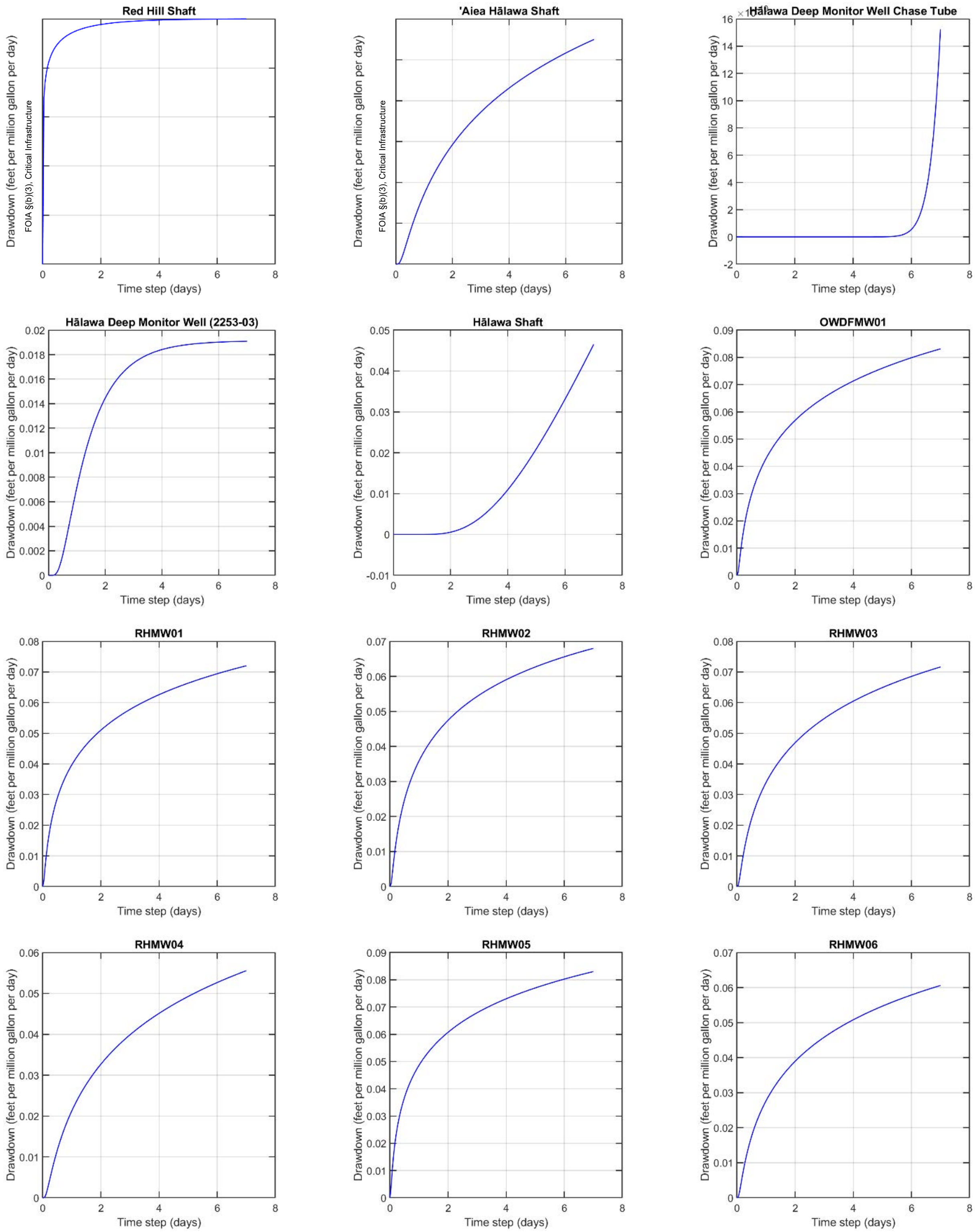


Figure A-3: Transfer Functions Associated with Red Hill Shaft Pumping (continued)

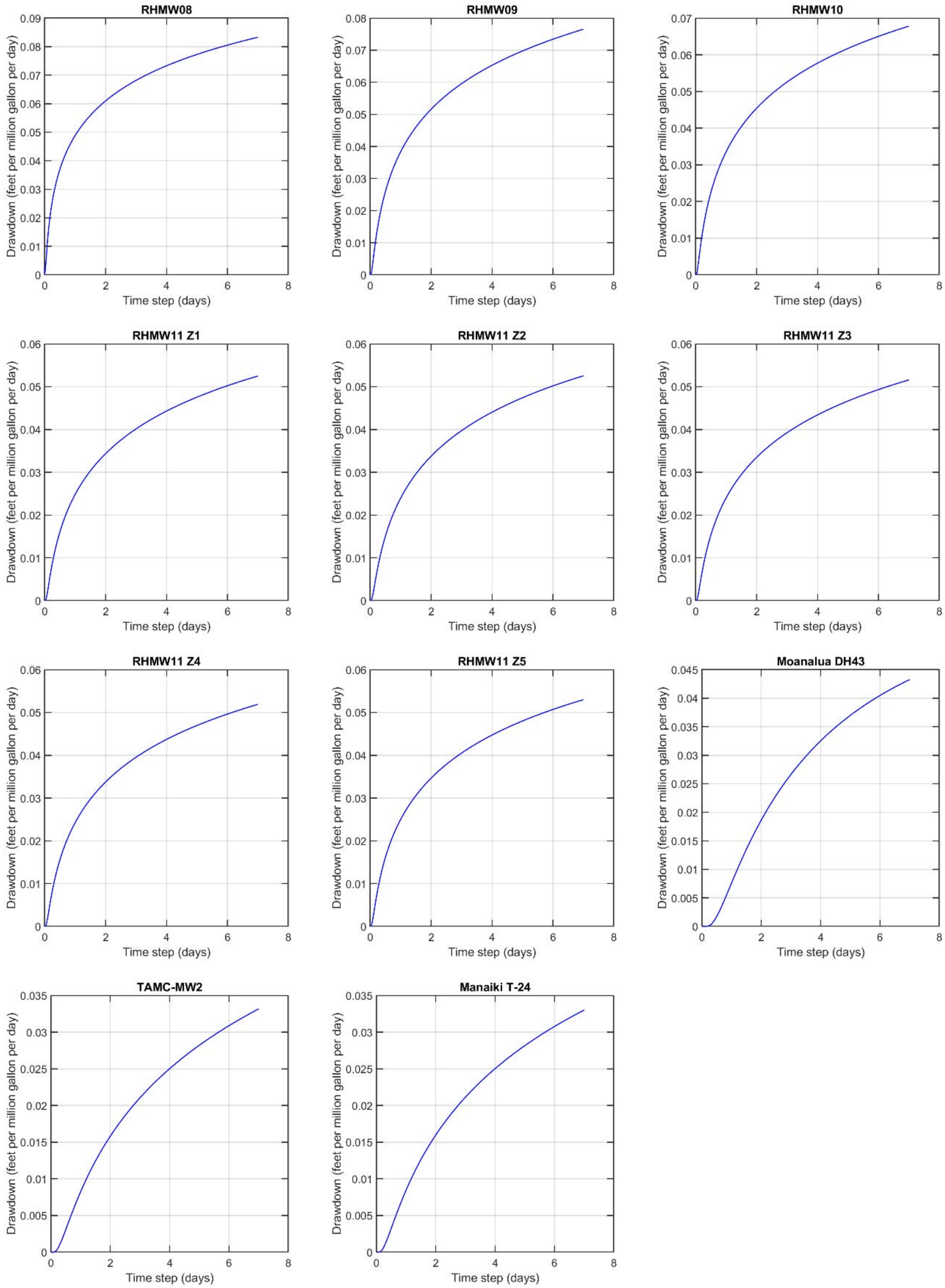


Figure A-4: Transfer Functions Associated with Hālawa Shaft Pumping

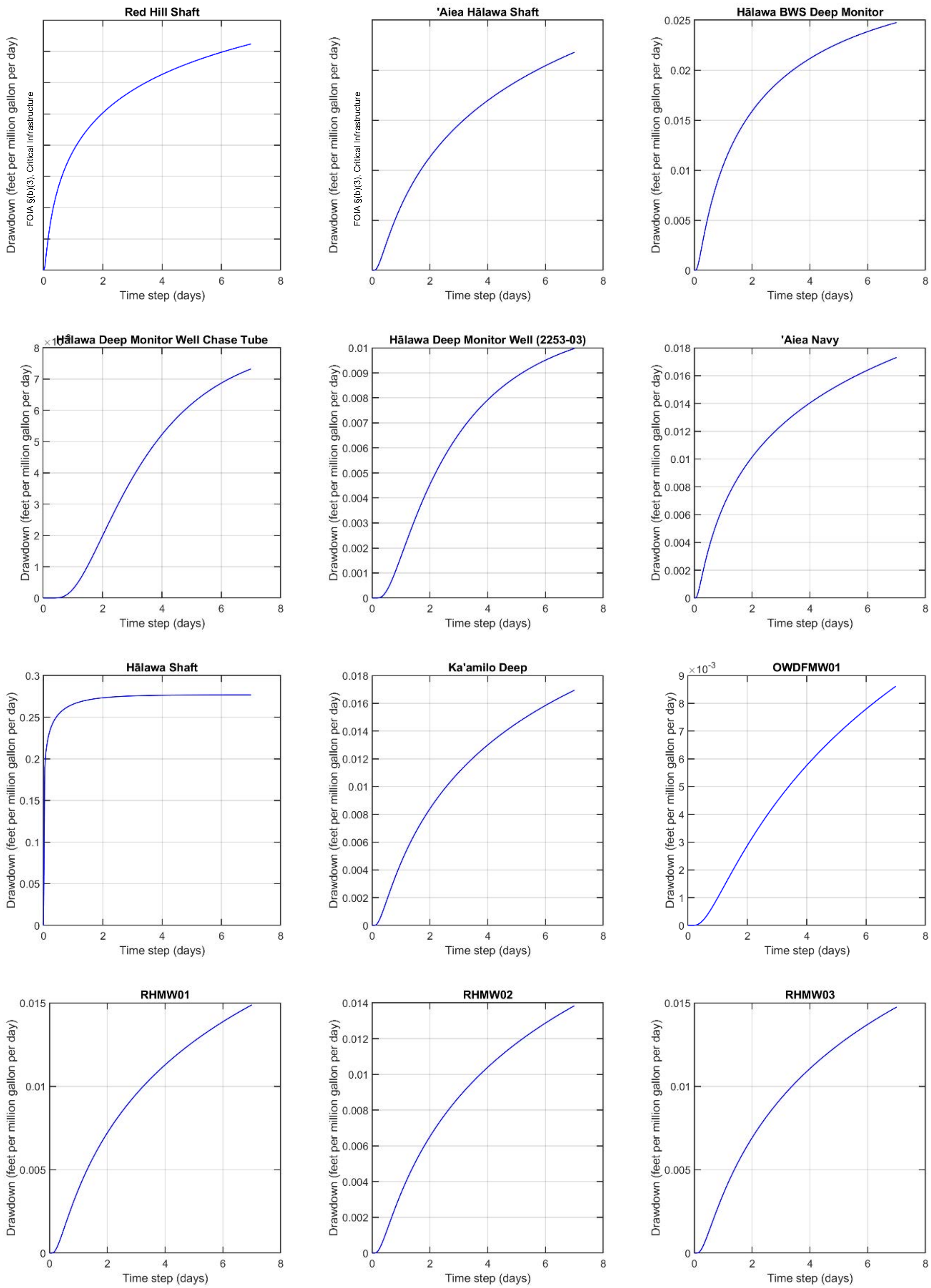


Figure A-4: Transfer Functions Associated with Hālawa Shaft Pumping (continued)

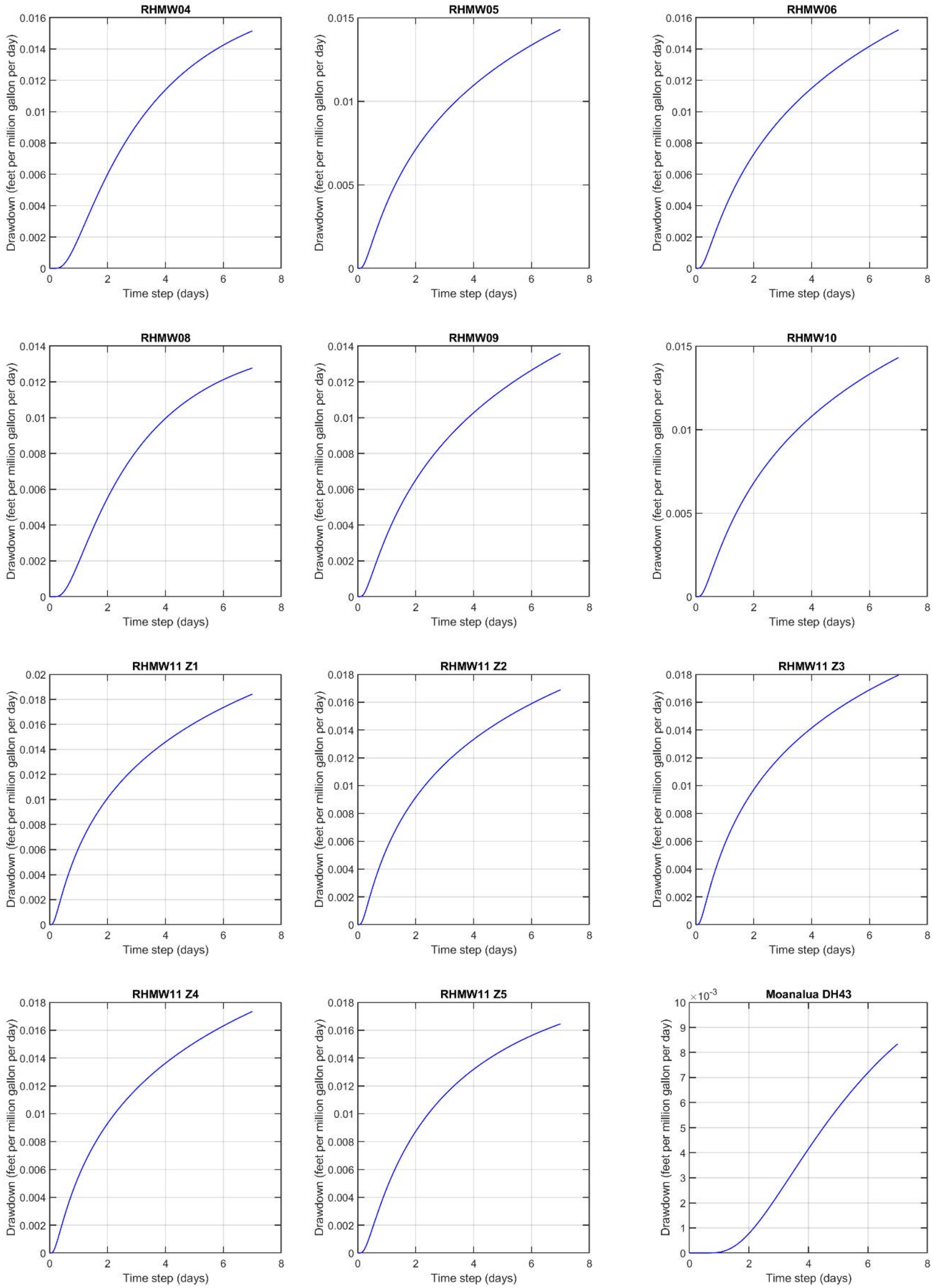


Figure A-4: Transfer Functions Associated with Hālawa Shaft Pumping (continued)

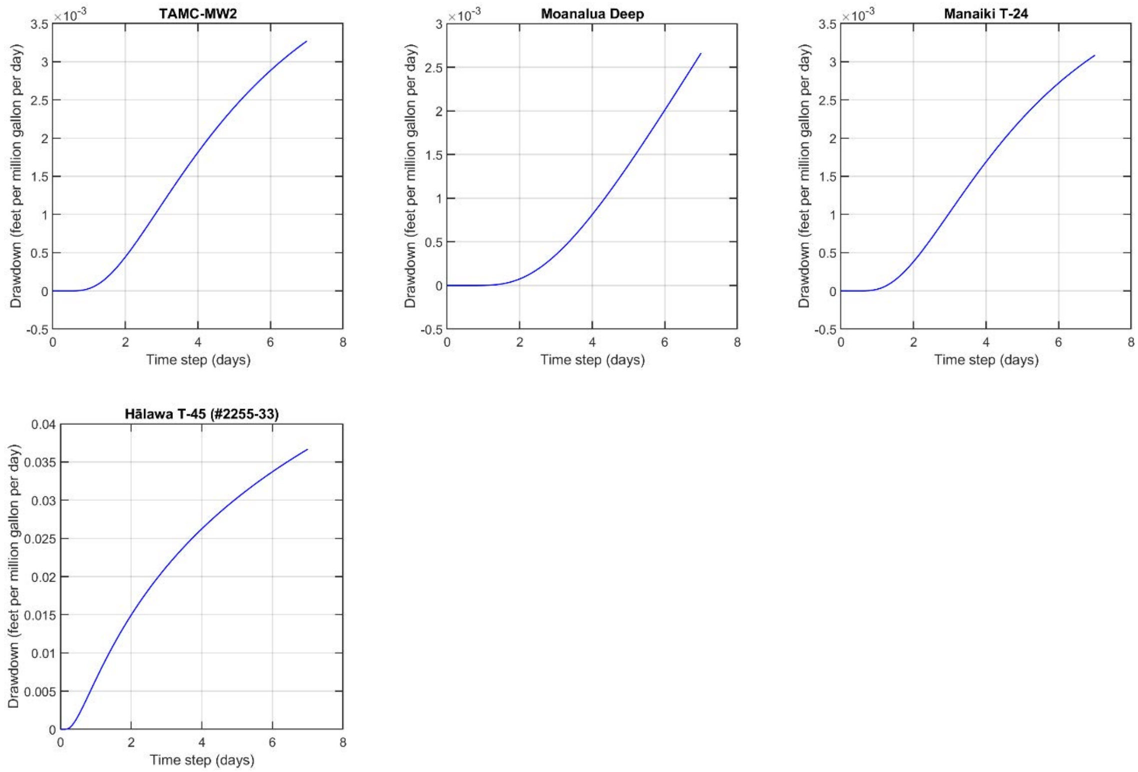


Figure A-5: TFN Simulated and Observed Water Levels from July 1, 2017 through December 31, 2018

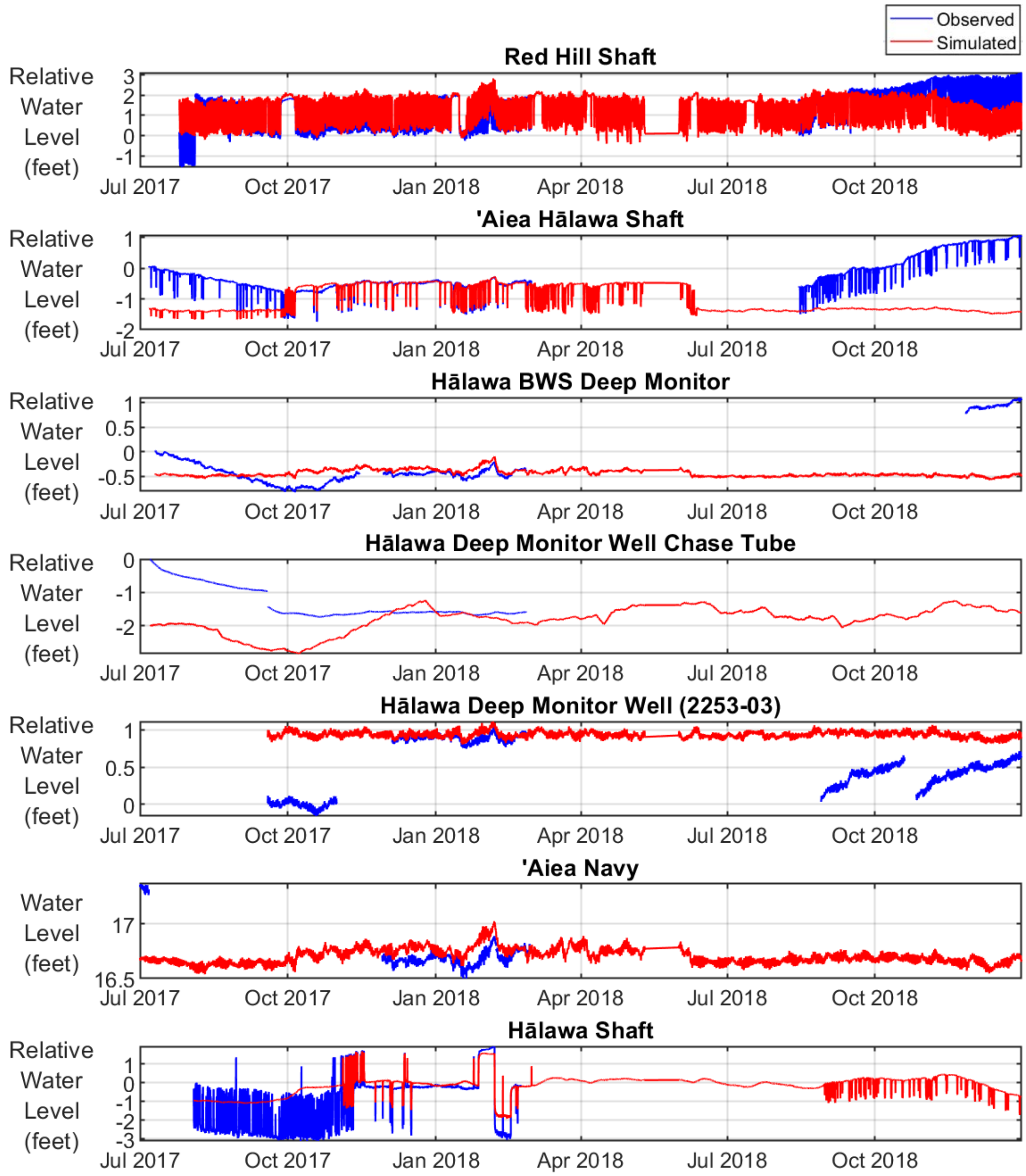


Figure A-5: TFN Simulated and Observed Water Levels from July 1, 2017 through December 31, 2018 (continued)

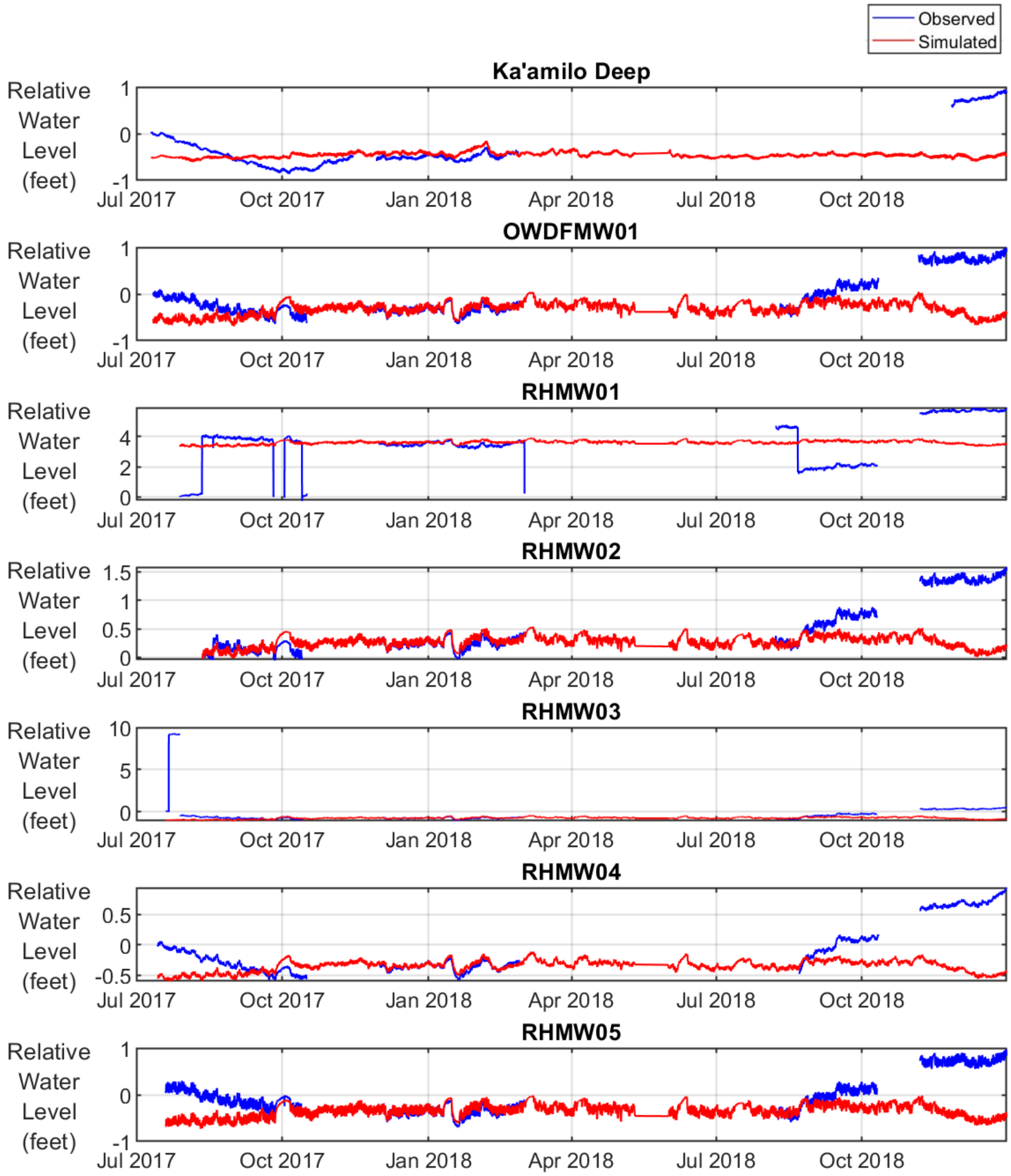


Figure A-5: TFN Simulated and Observed Water Levels from July 1, 2017 through December 31, 2018 (continued)

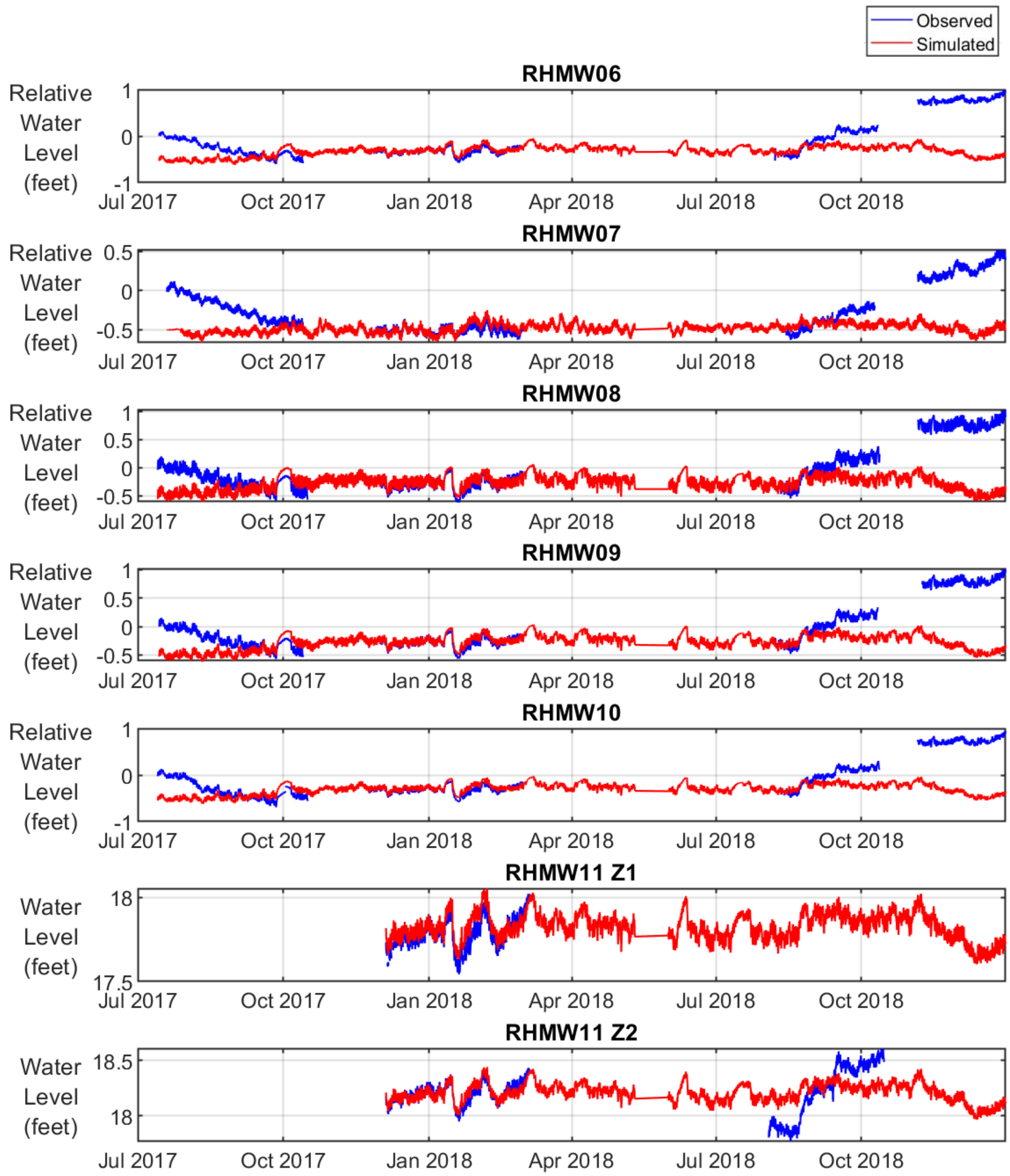
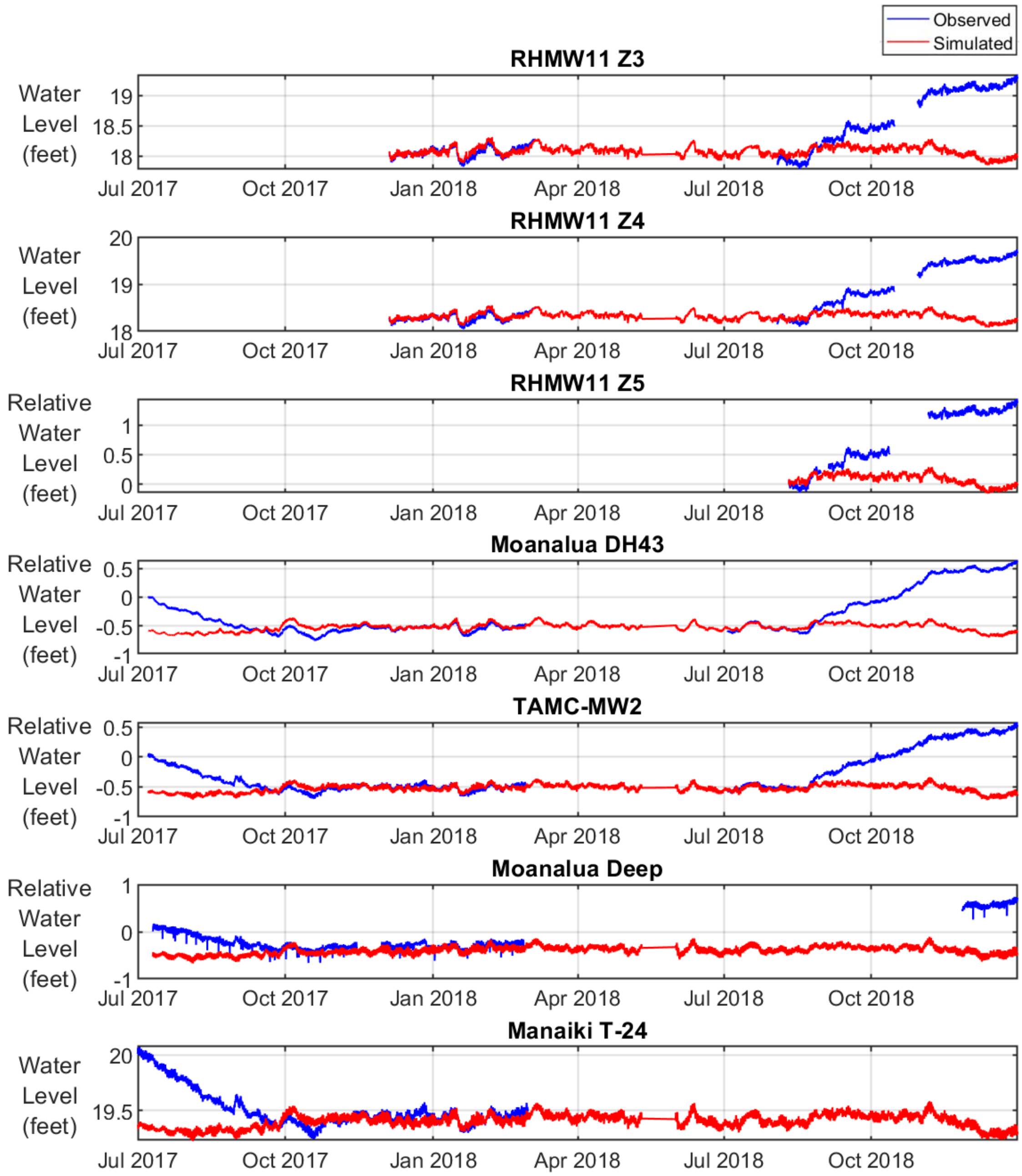


Figure A-5: TFN Simulated and Observed Water Levels from July 1, 2017 through December 31, 2018 (continued)



1 **Figure A-6: Residual Water Levels of TFN Simulations from July 1, 2017 through December 31, 2018**

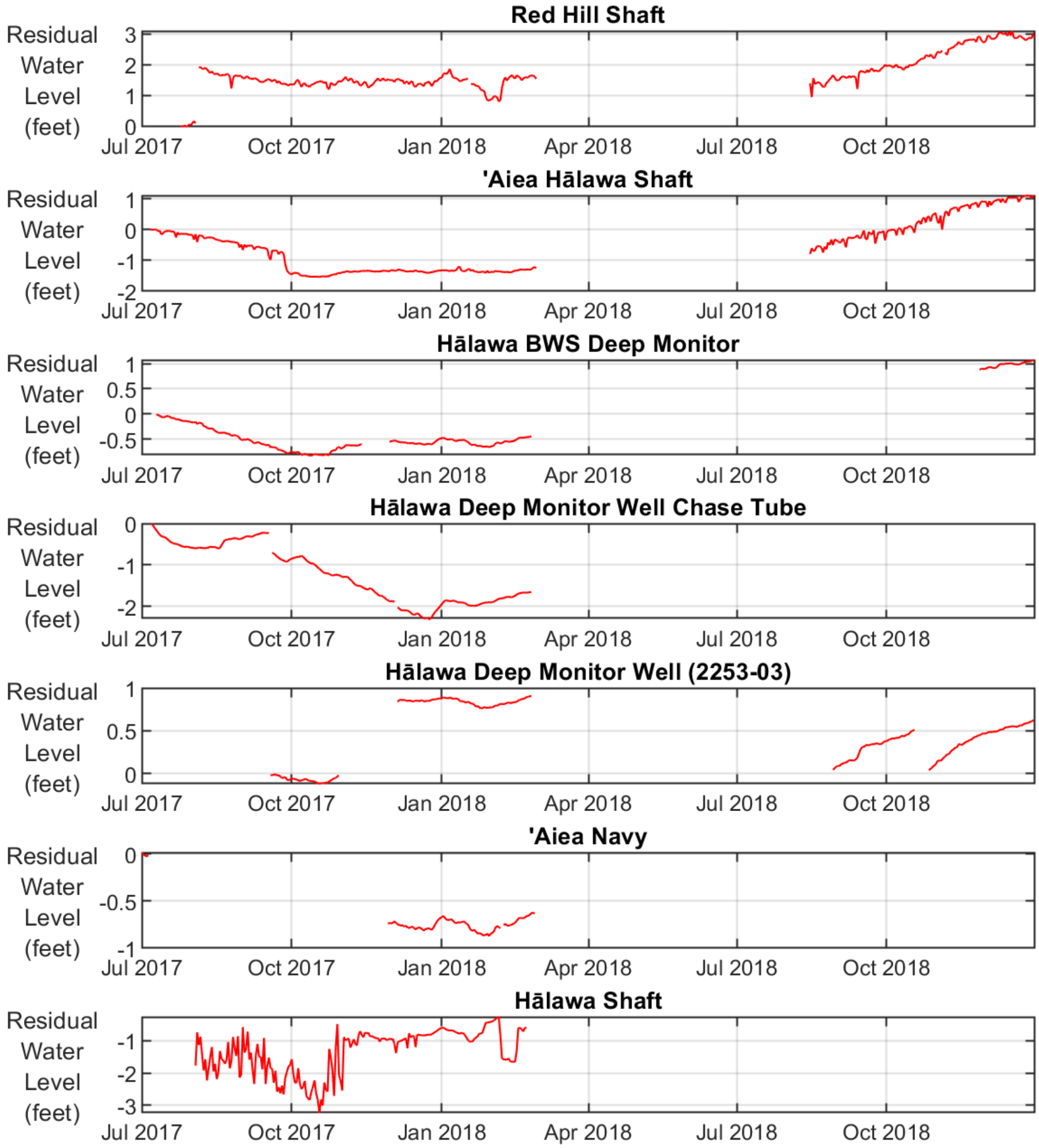


Figure A-6: Residual Water Levels of TFN Simulations from July 1, 2017 through December 31, 2018 (continued)

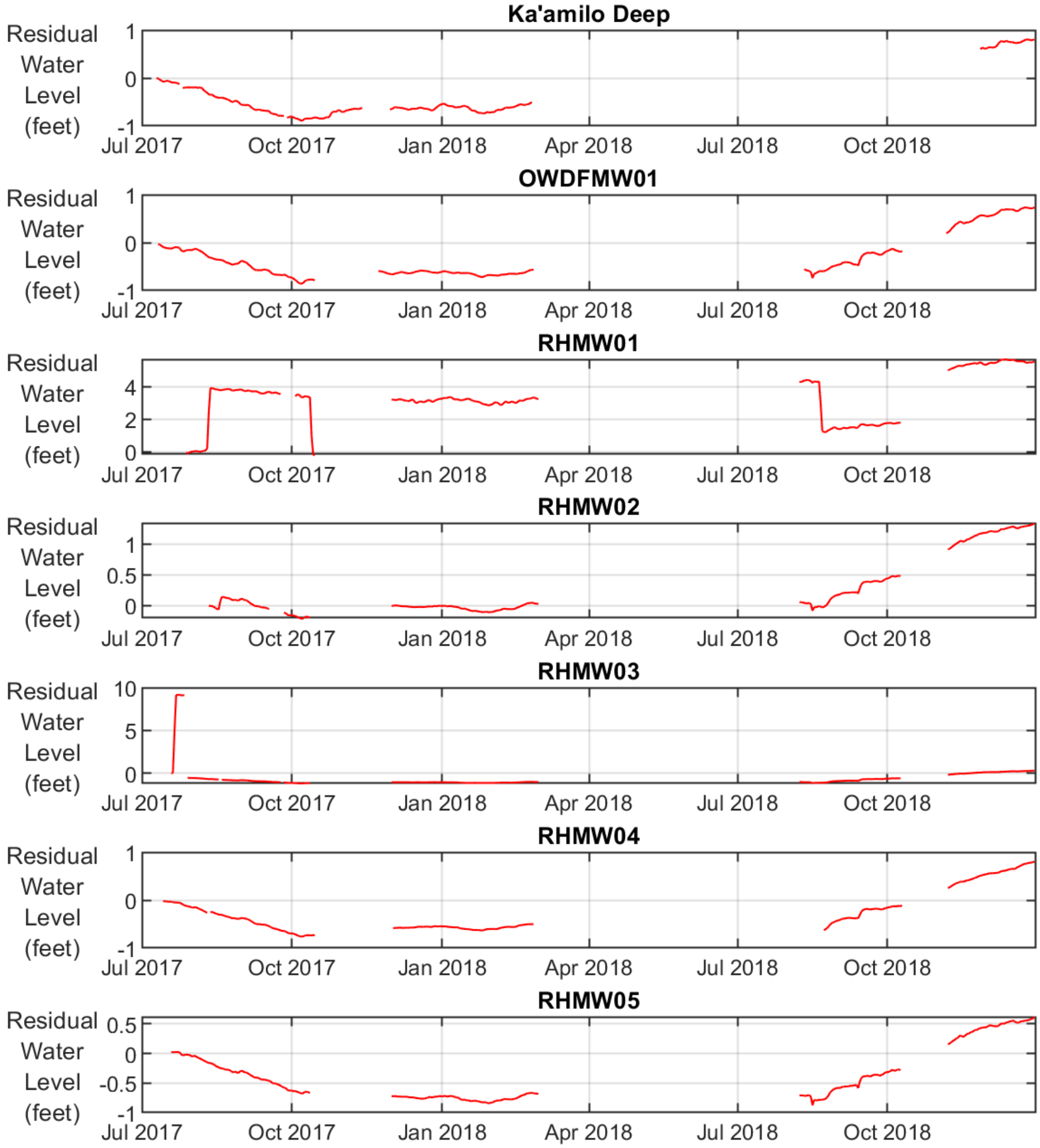


Figure A-6: Residual Water Levels of TFN Simulations from July 1, 2017 through December 31, 2018 (continued)

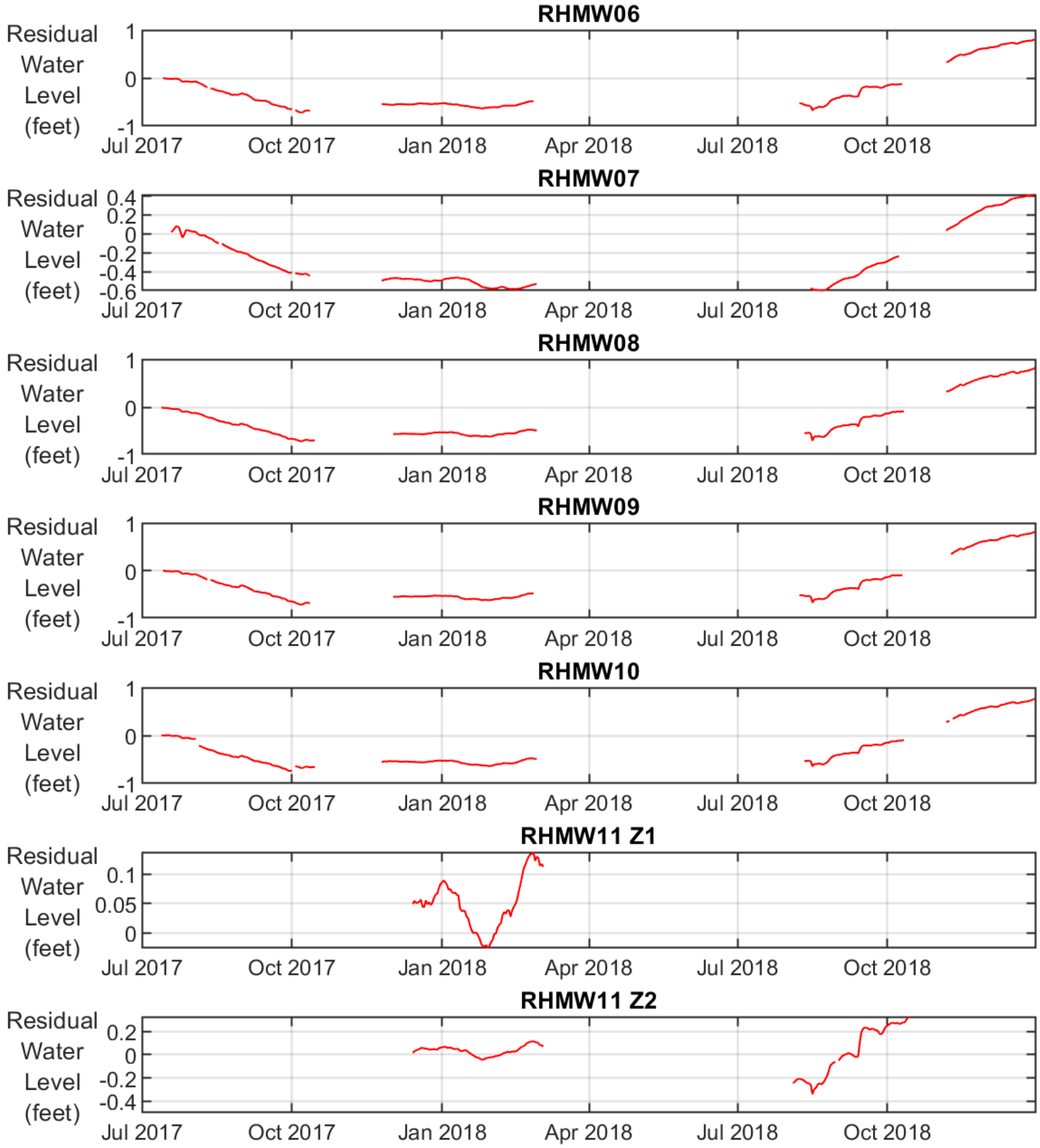
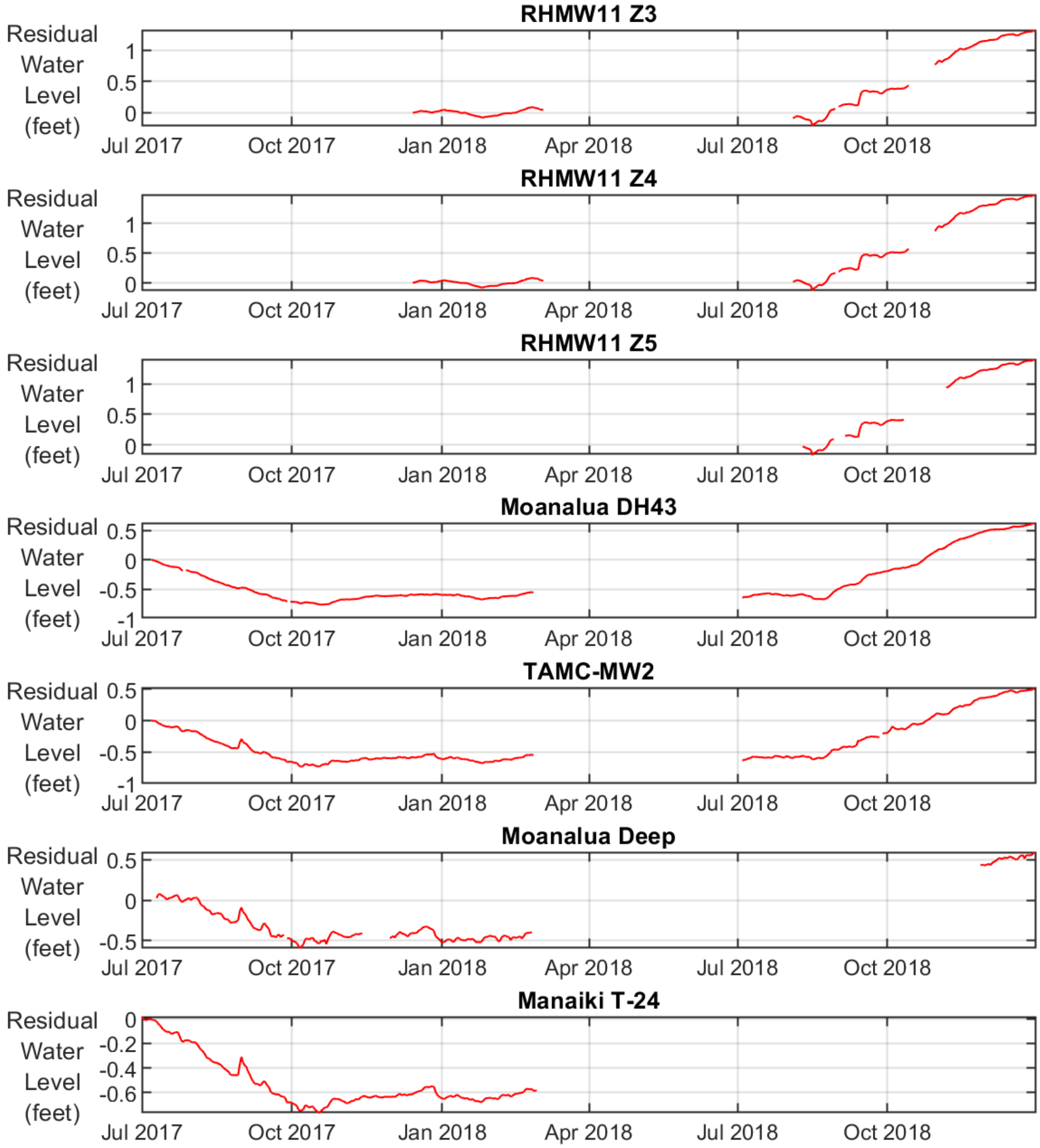


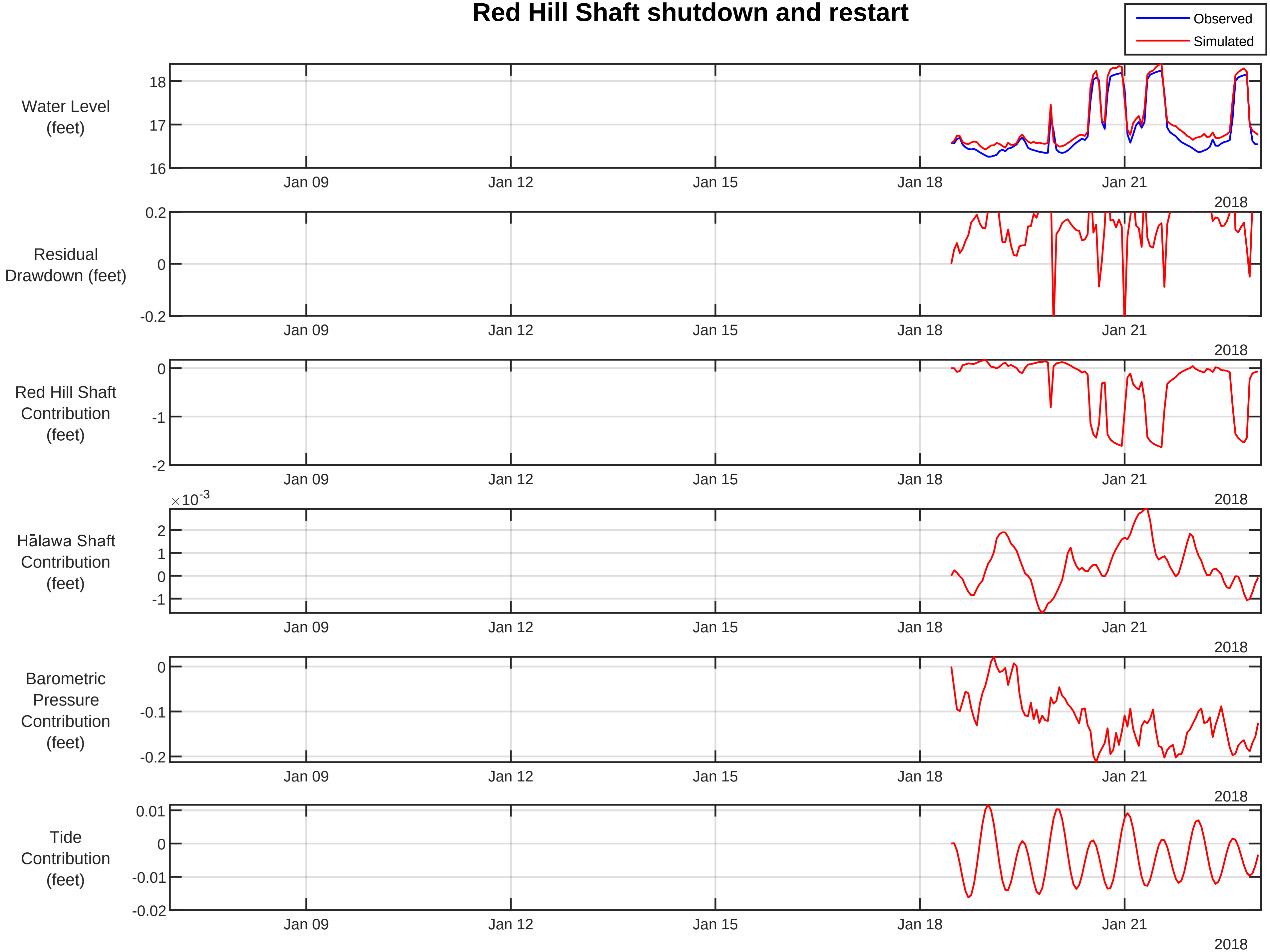
Figure A-6: Residual Water Levels of TFN Simulations from July 1, 2017 through December 31, 2018 (continued)



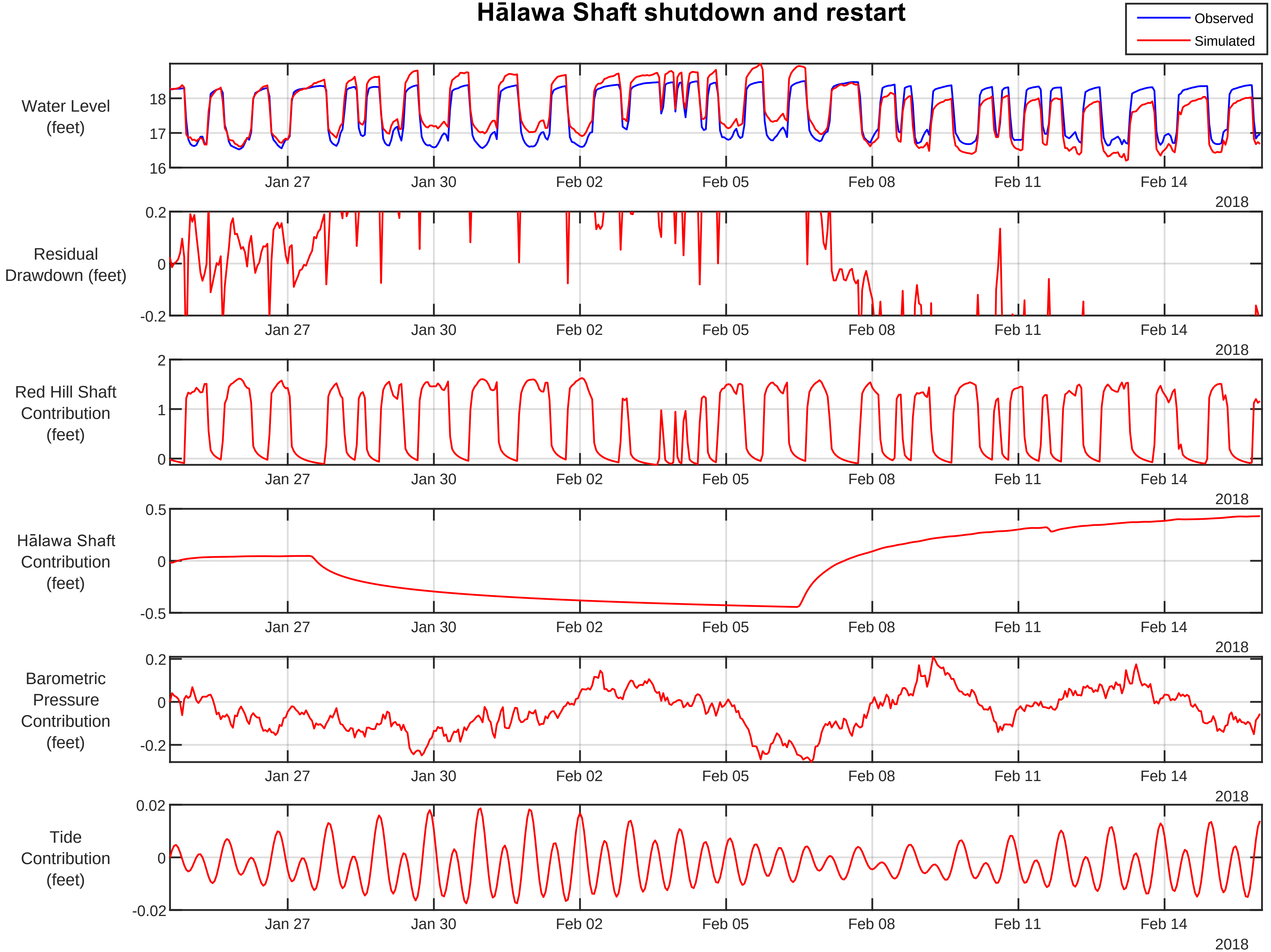
Attachment A.1
Contributions to Water Level Changes
Simulated by Transfer Function-Noise Analysis

For Red Hill AOC Party Use Only

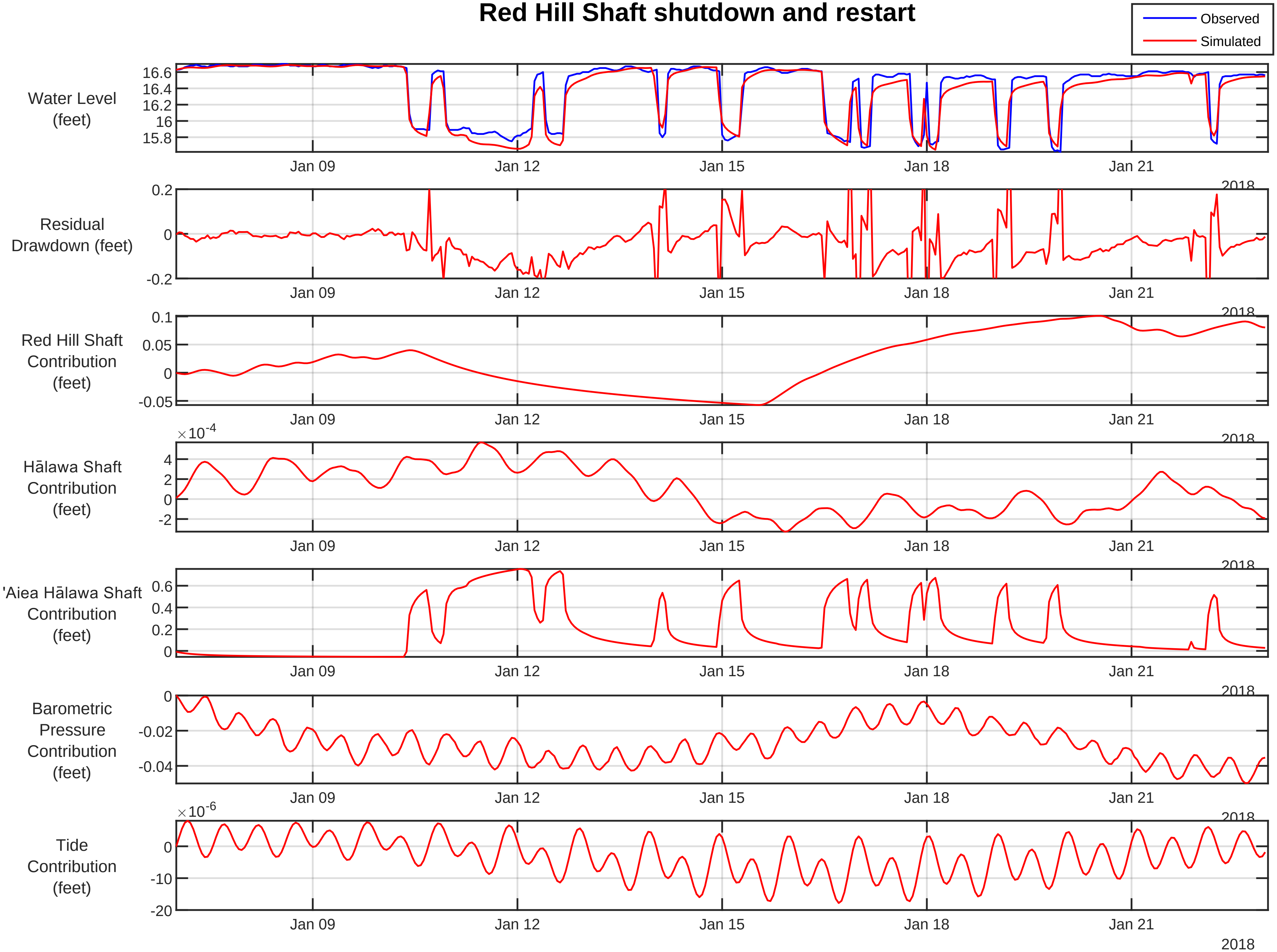
Red Hill Shaft
Red Hill Shaft shutdown and restart



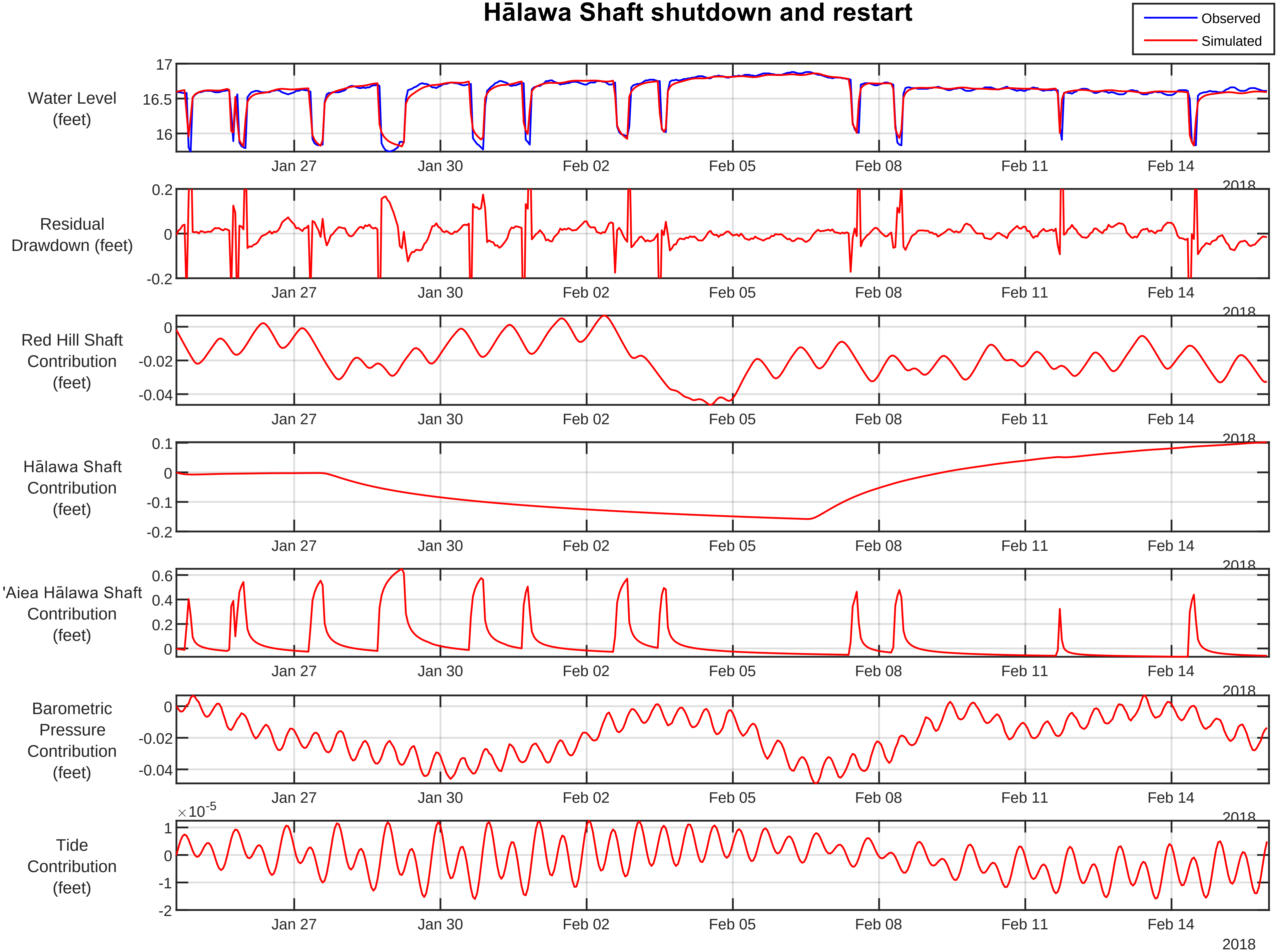
Red Hill Shaft
Hālawa Shaft shutdown and restart

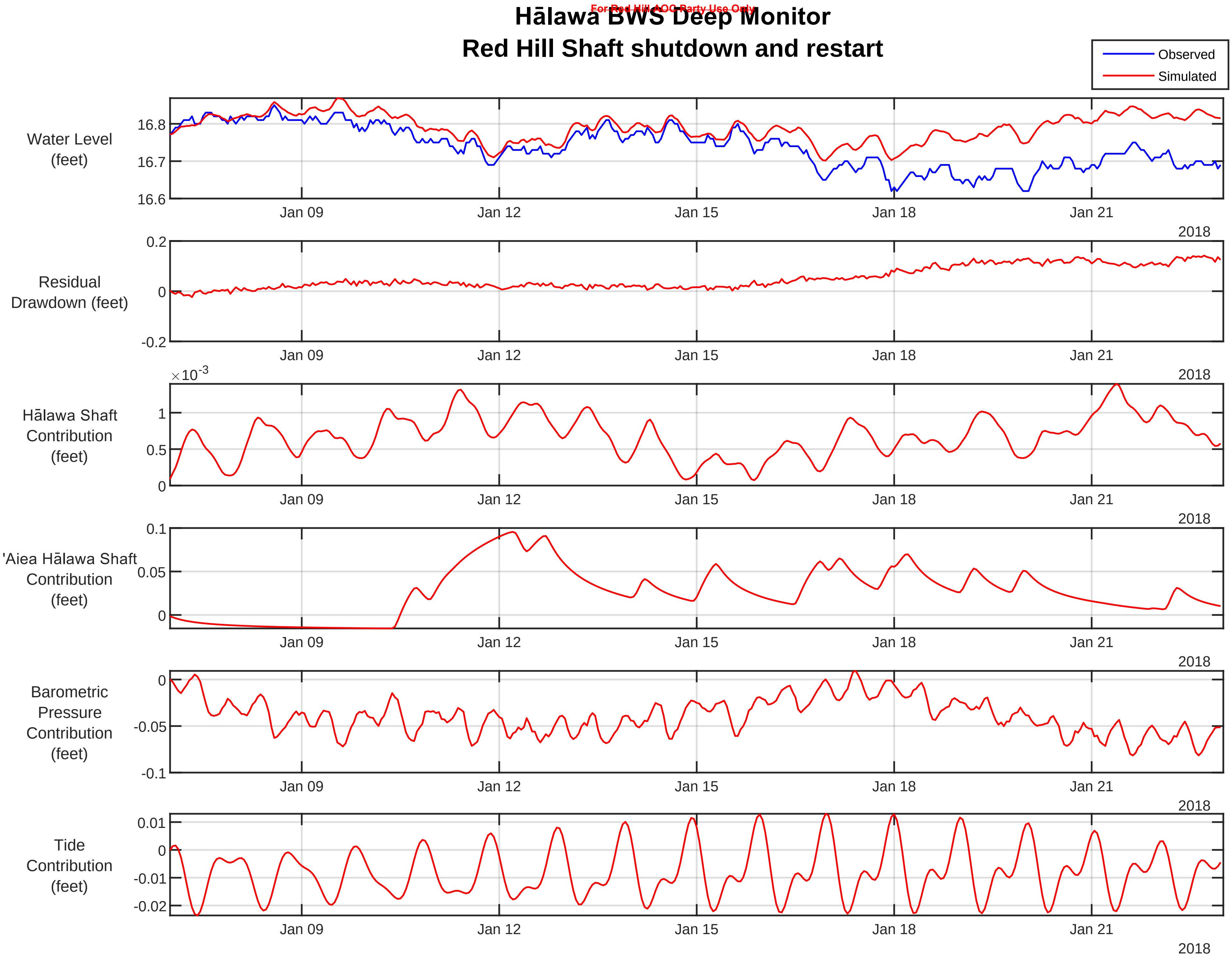


'Aiea Hālawa Shaft
Red Hill Shaft shutdown and restart



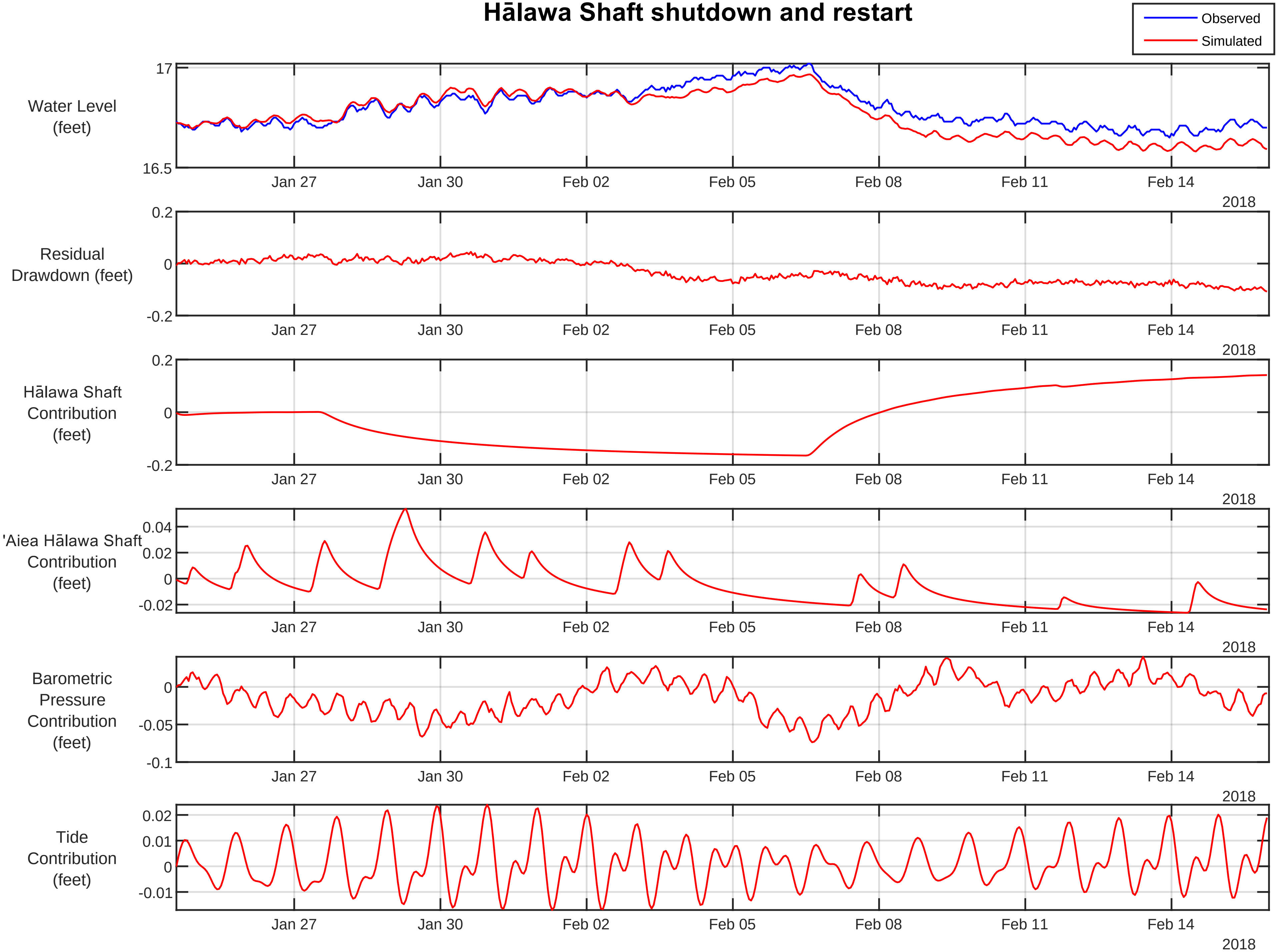
'Aiea Hālawa Shaft
Hālawa Shaft shutdown and restart





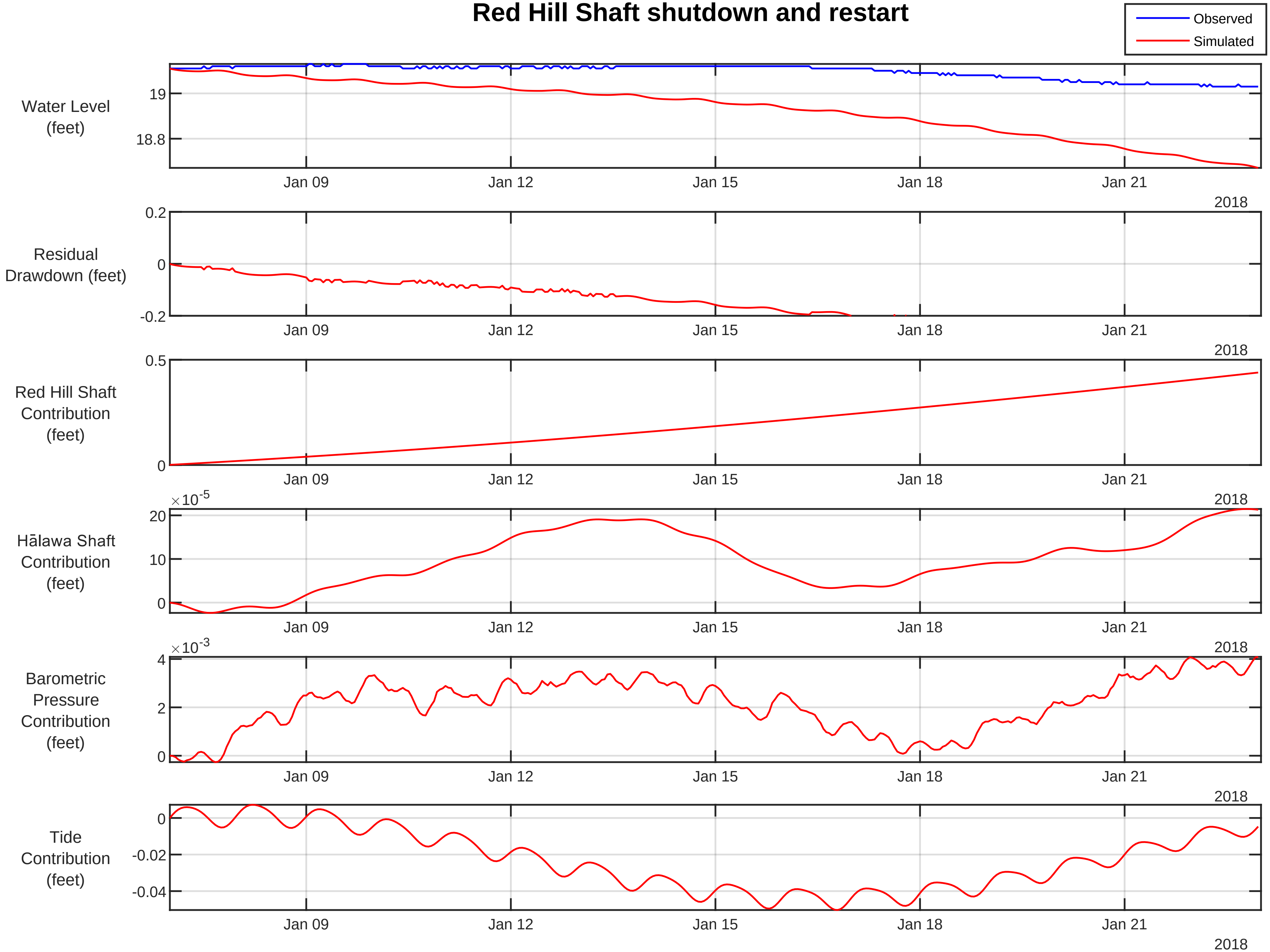
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
16.8
16.7
16.6
Residual Drawdown (feet)
0.2
0
-0.2
Hālawa Shaft Contribution (feet)
×10-3
1
0.5
0
'Aiea Hālawa Shaft Contribution (feet)
0.1
0.05
0
Barometric Pressure Contribution (feet)
0
-0.05
-0.1
Tide Contribution (feet)
0.01
0
-0.01
-0.02
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

Hālawa BWS Deep Monitor
Hālawa Shaft shutdown and restart

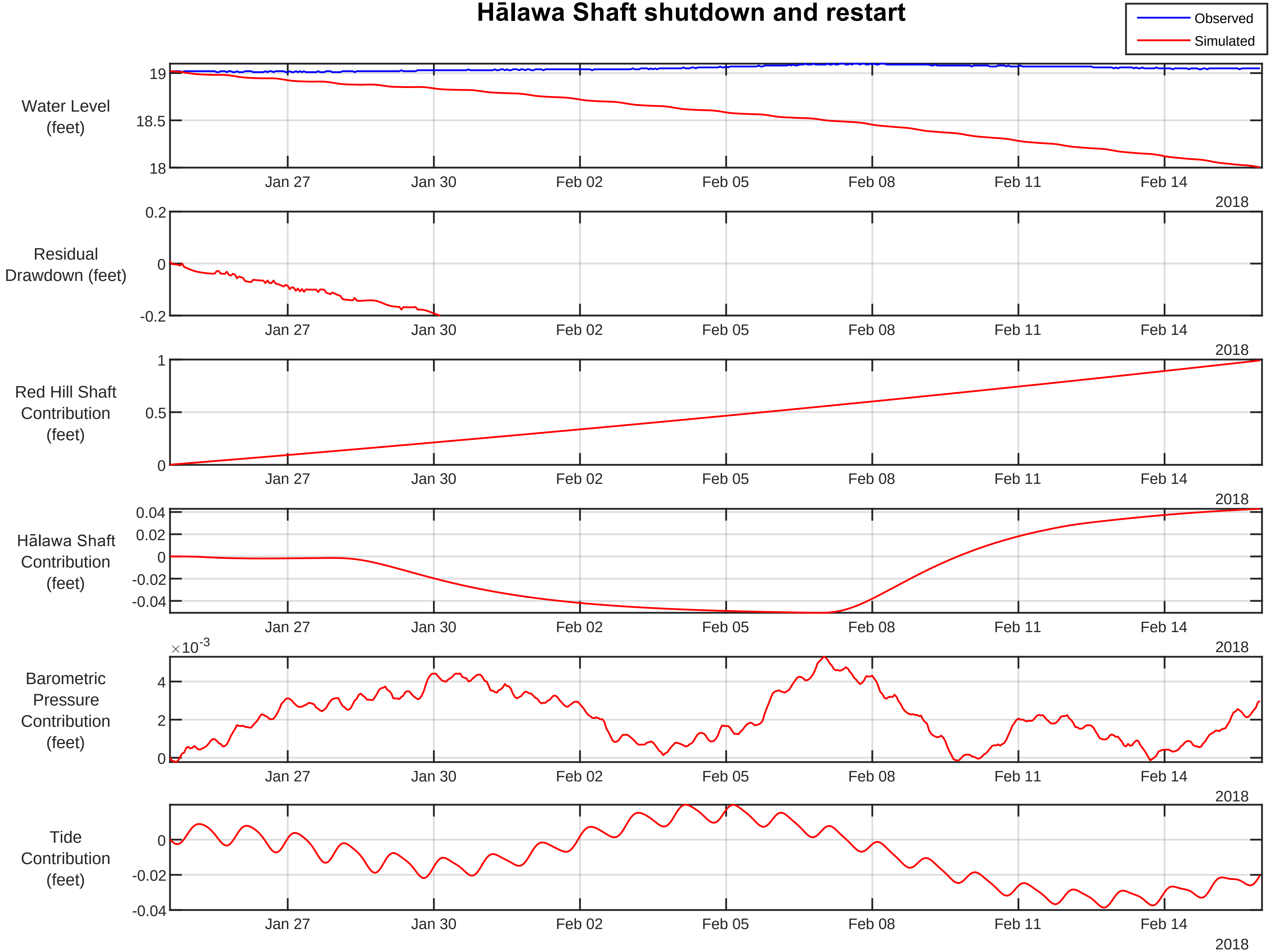


For Red Hill AOC Party Use Only

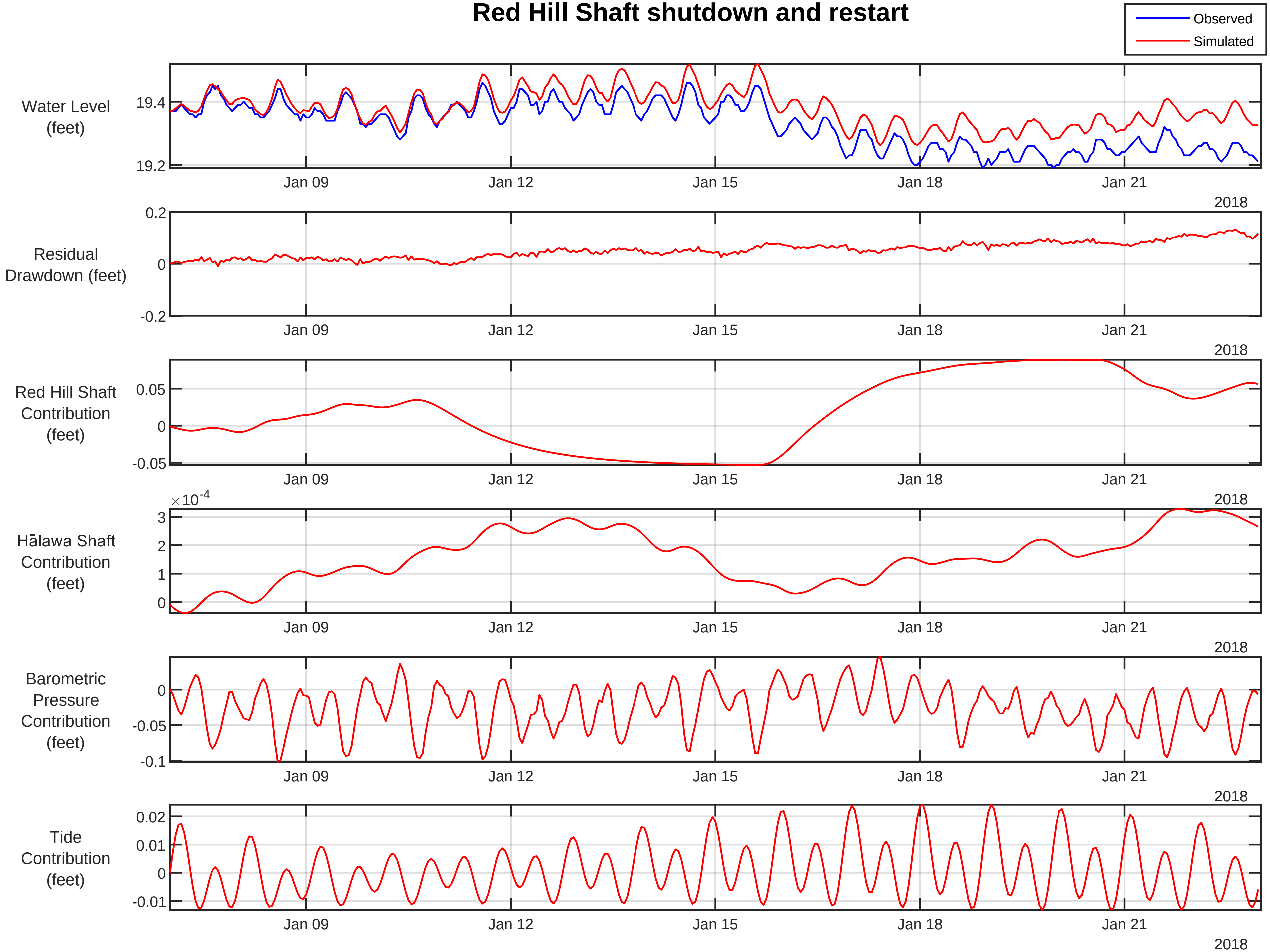
Hālawa Deep Monitor Well Chase Tube
Red Hill Shaft shutdown and restart



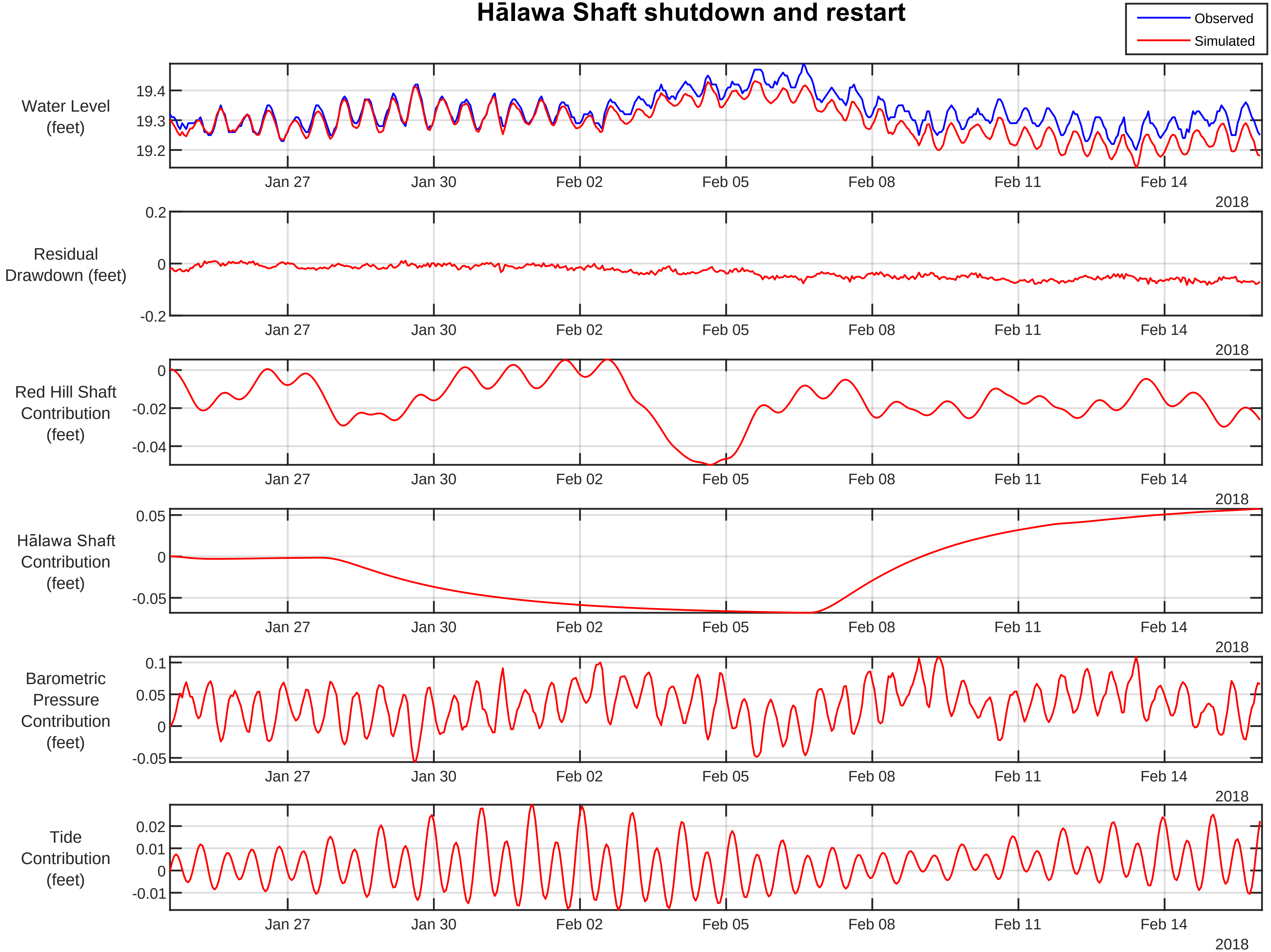
Hālawa Deep Monitor Well Chase Tube
Hālawa Shaft shutdown and restart



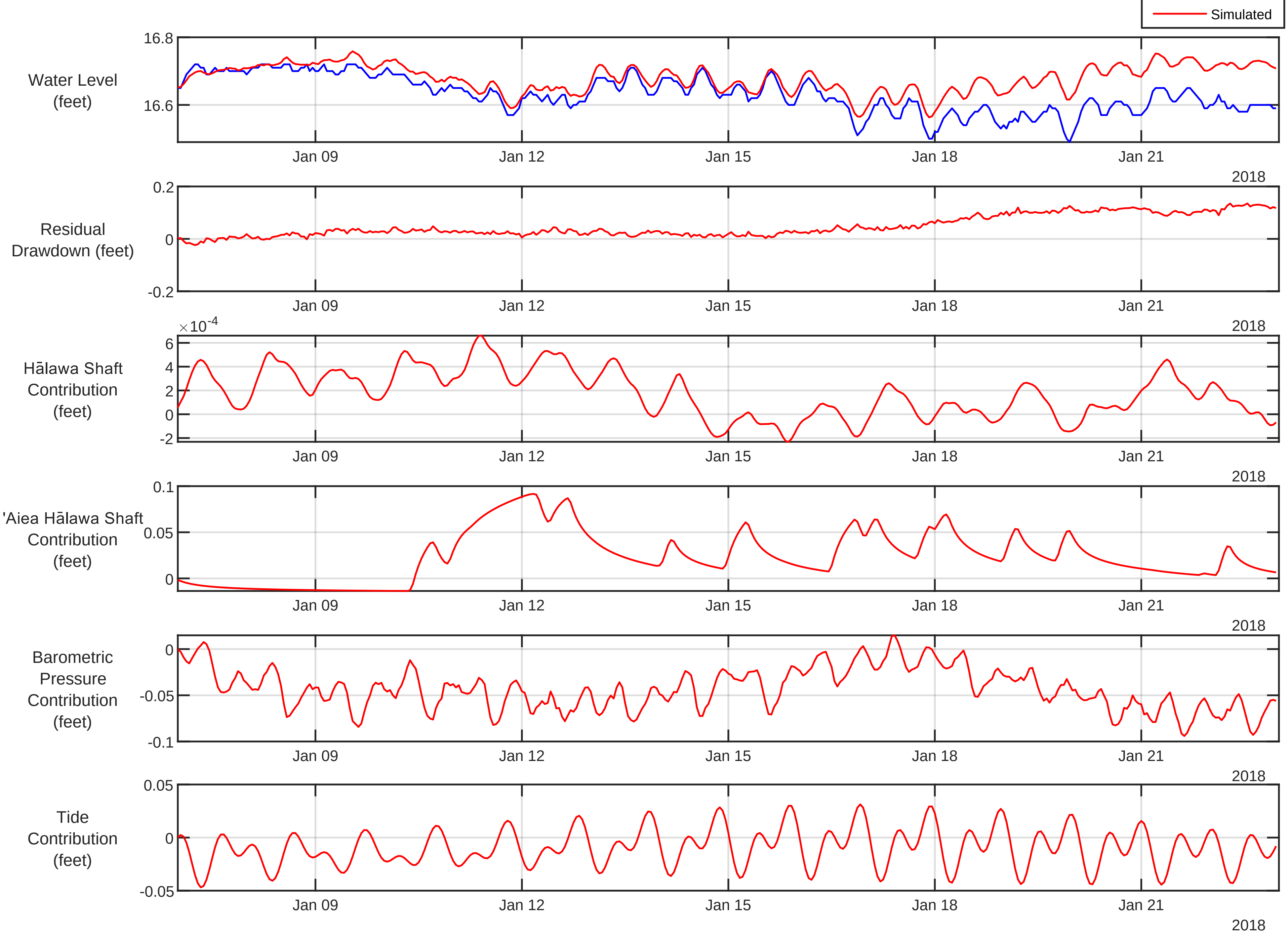
Hālawa Deep Monitor Well (2253-03)
Red Hill Shaft shutdown and restart



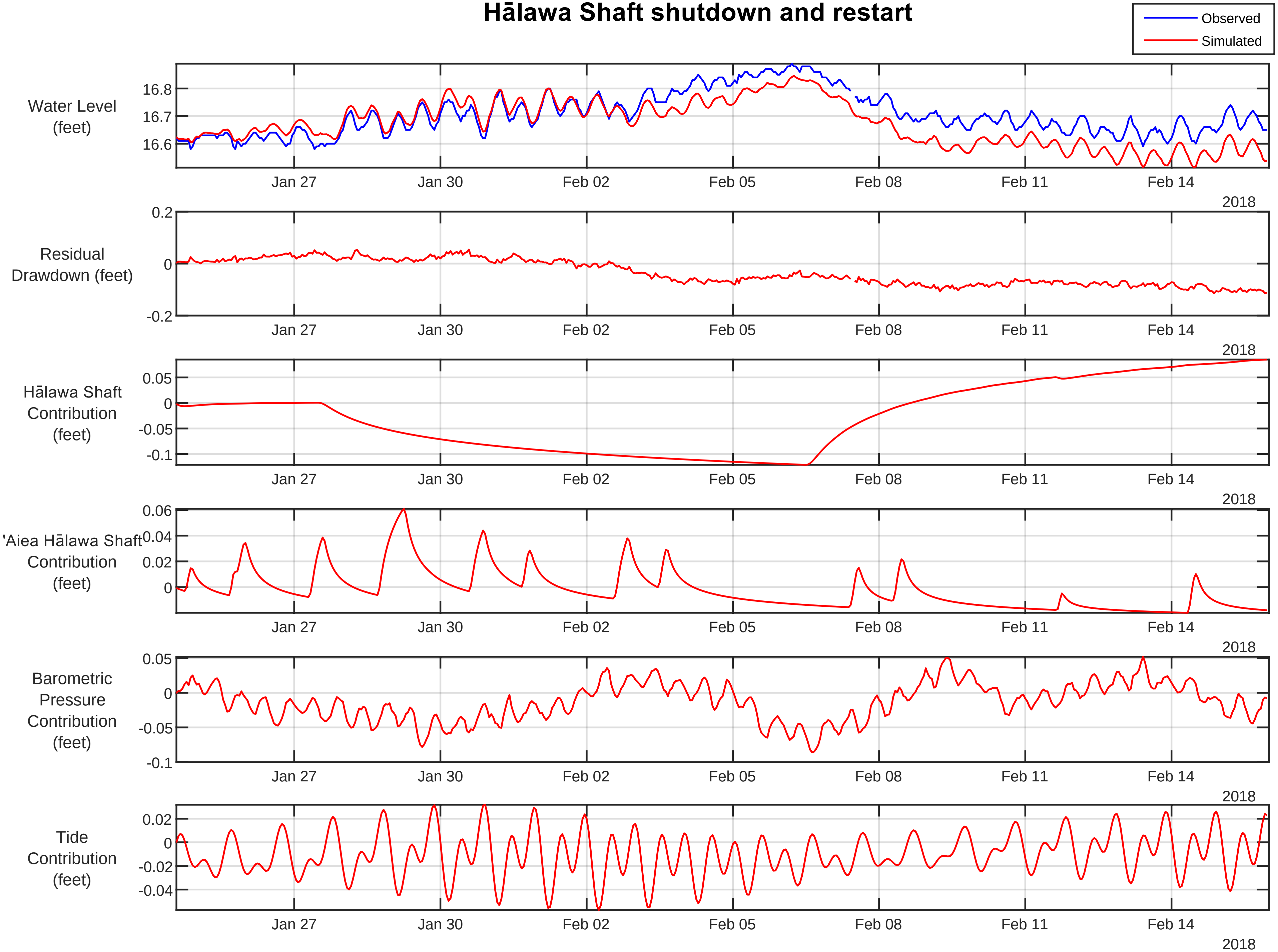
Hālawa Deep Monitor Well (2253-03)
Hālawa Shaft shutdown and restart

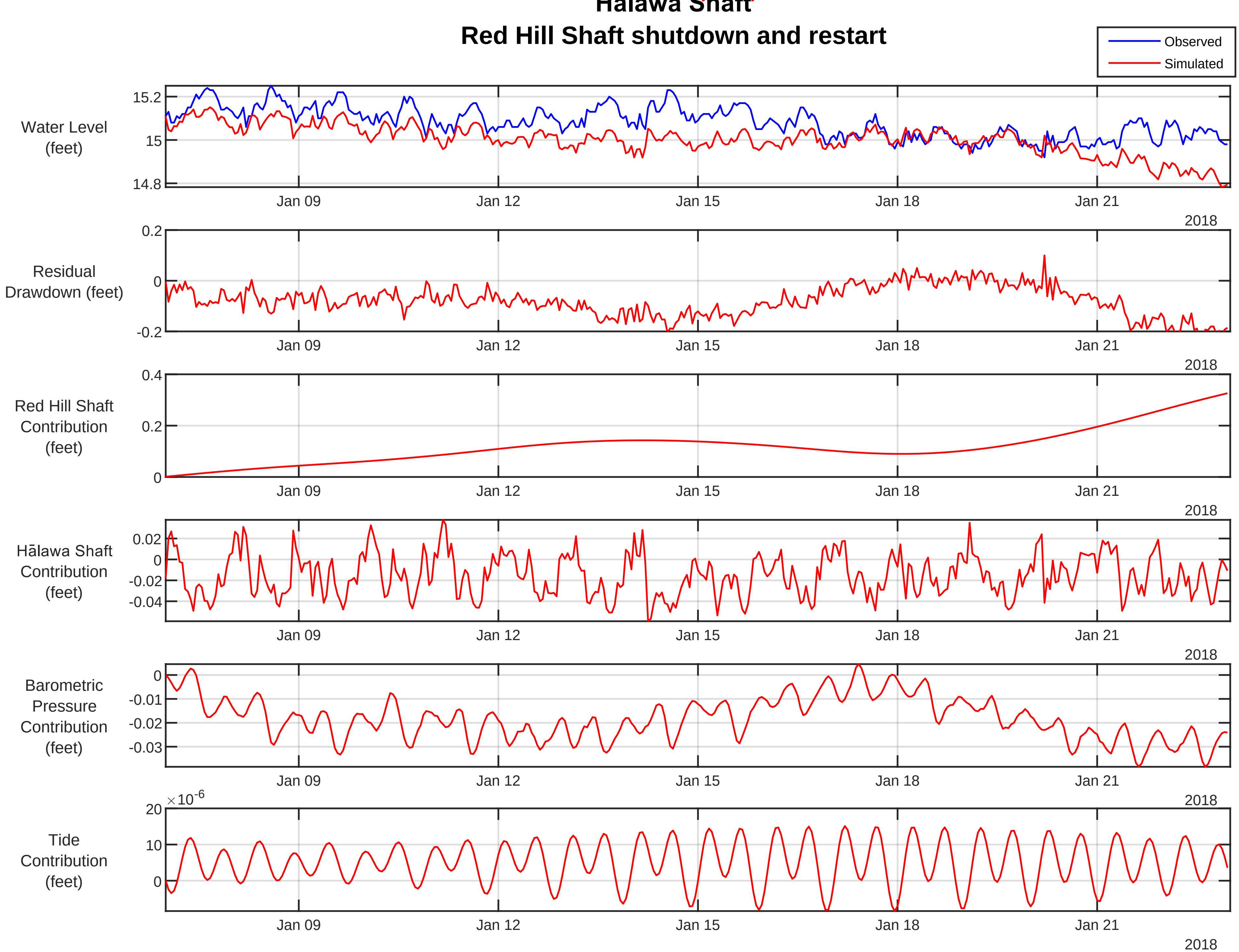


'Aiea Navy
Red Hill Shaft shutdown and restart



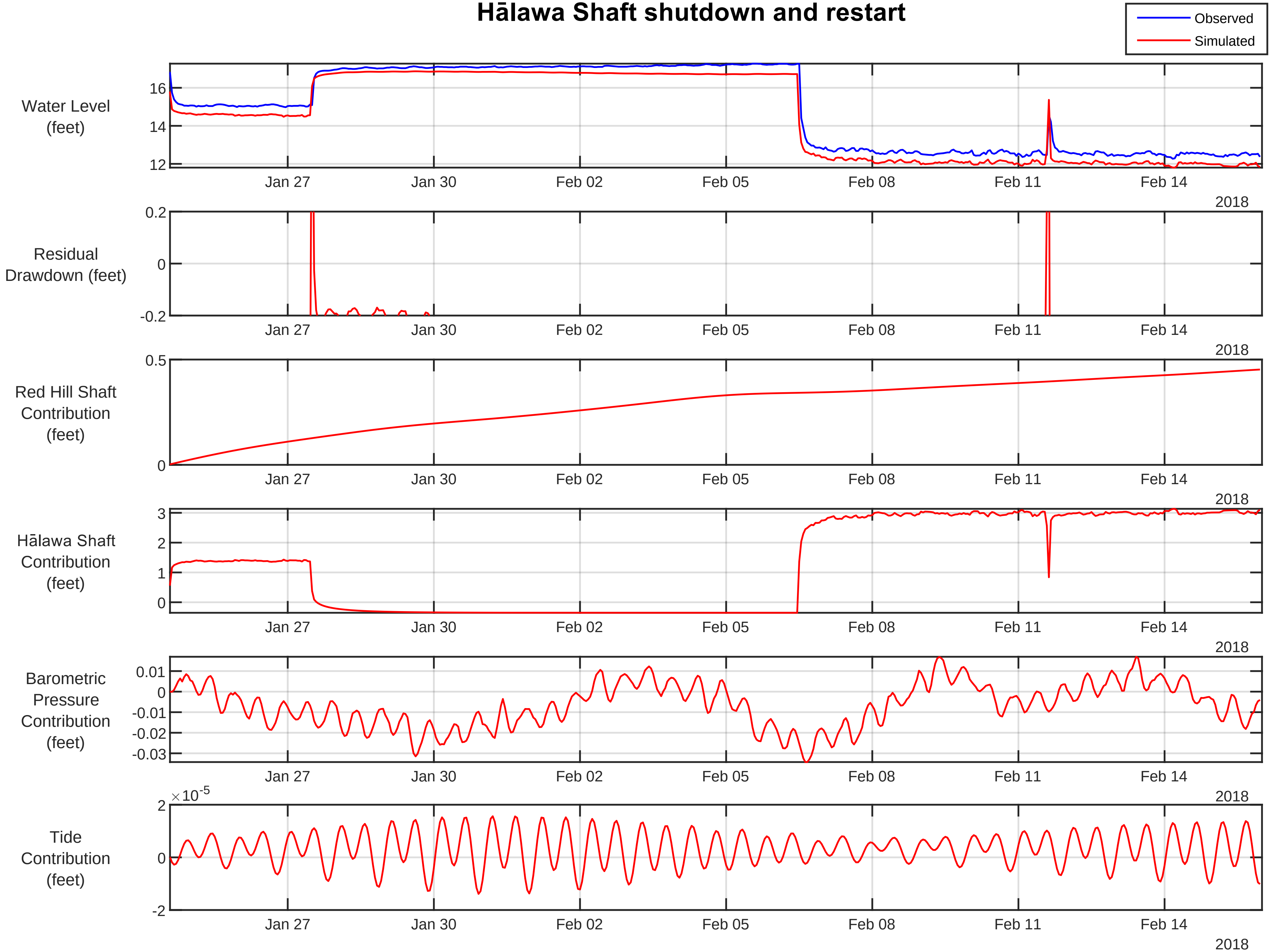
'Aiea Navy
Hālawa Shaft shutdown and restart

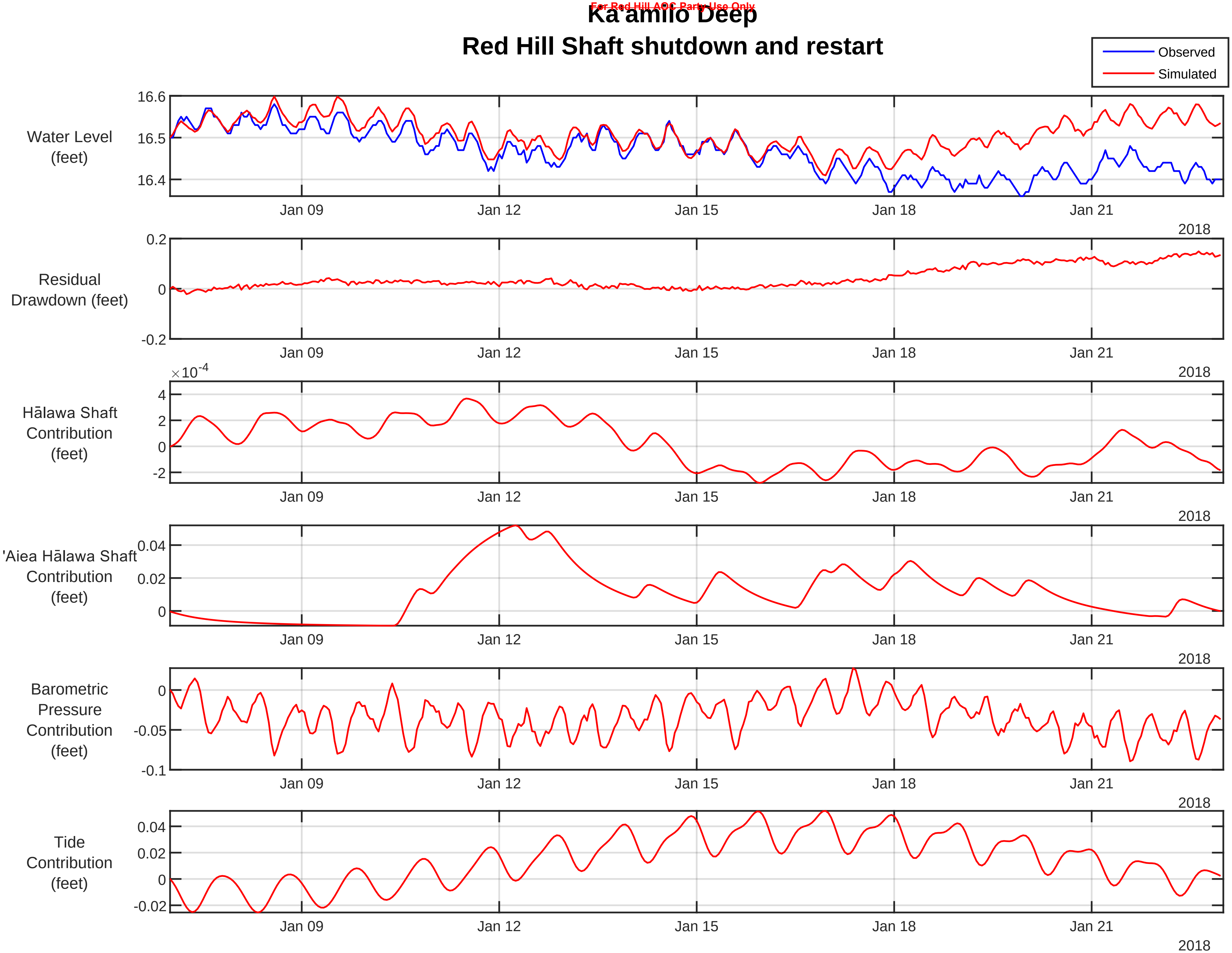



Hālawa Shaft
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
15.2
15
14.8
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.4
0.2
0
Hālawa Shaft Contribution (feet)
0.02
0
-0.02
-0.04
Barometric Pressure Contribution (feet)
0
-0.01
-0.02
-0.03
Tide Contribution (feet)
×10^-6
20
10
0
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

Hālawa Shaft

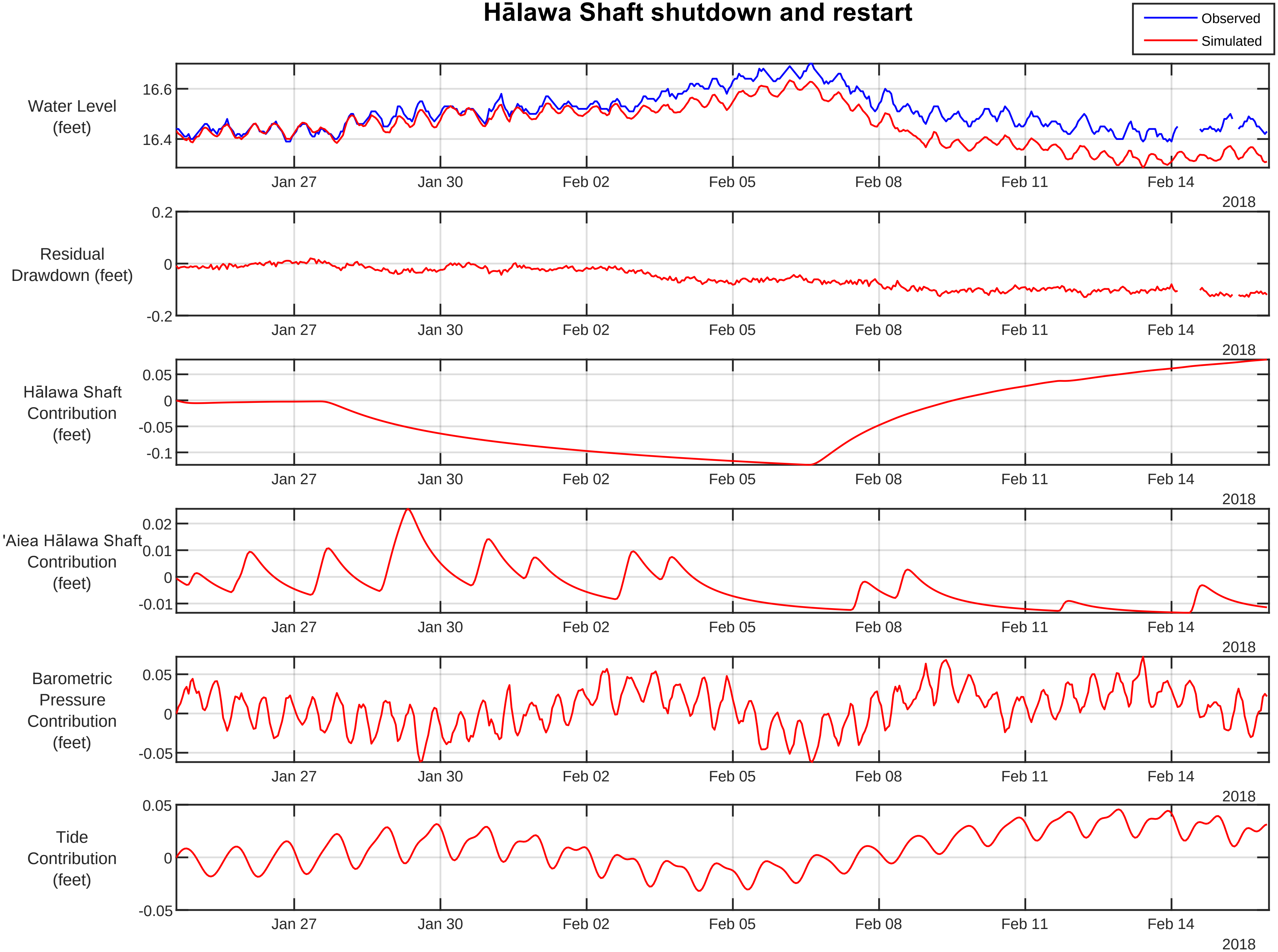
Hālawa Shaft shutdown and restart

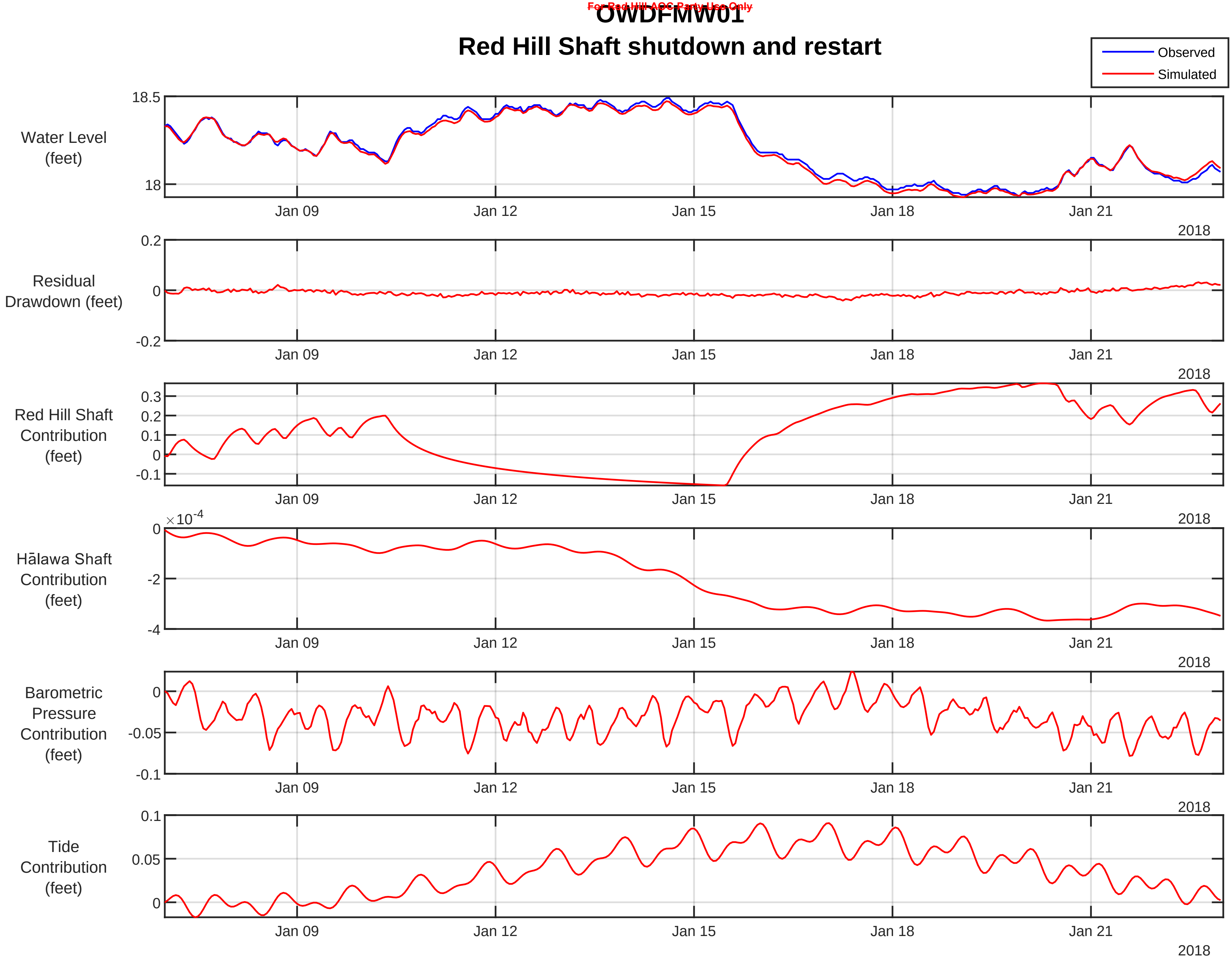


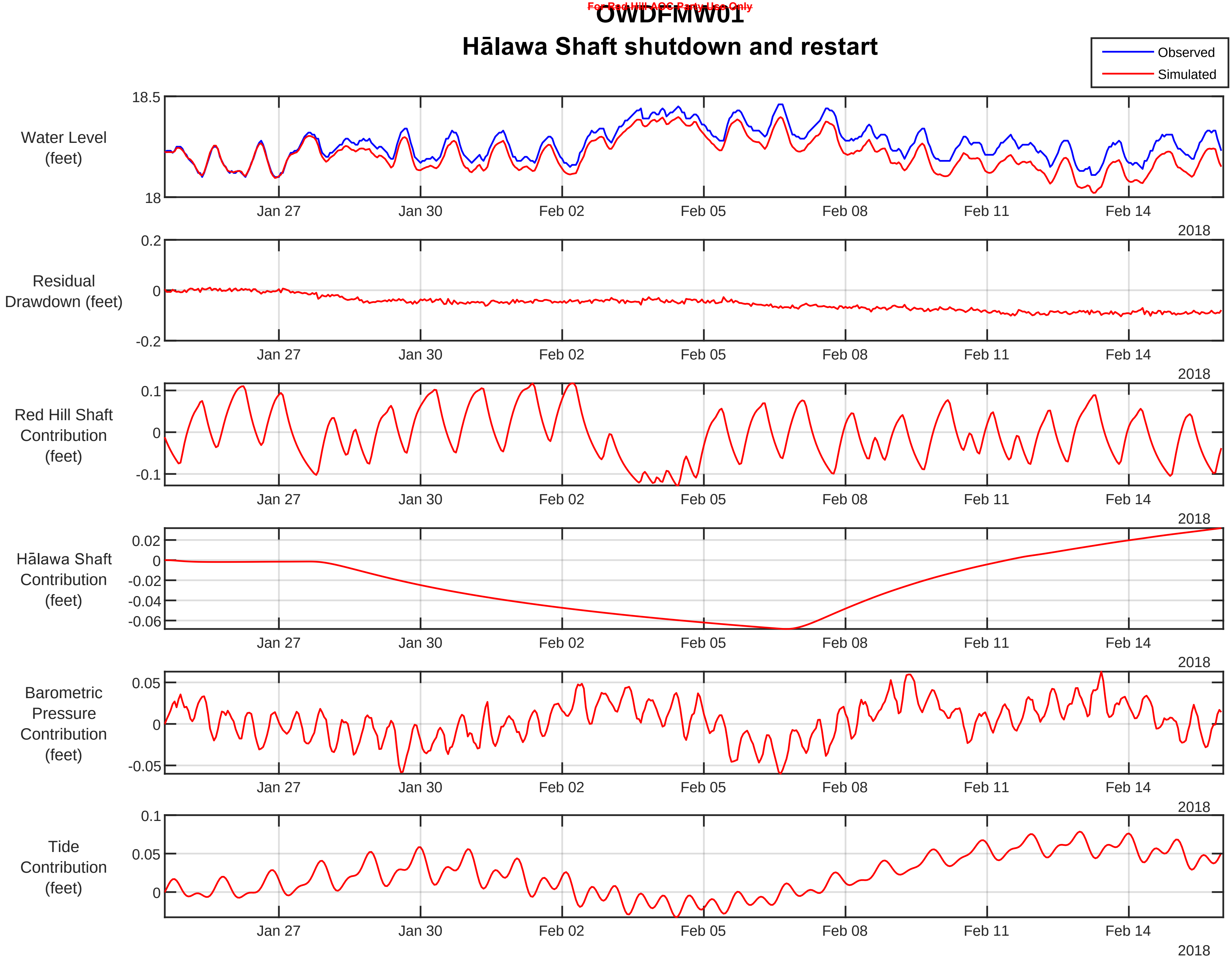


Ka'amilo Deep
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
16.6
16.5
16.4
Residual Drawdown (feet)
0.2
0
-0.2
Hālawa Shaft Contribution (feet)
×10-4
4
2
0
-2
'Aiea Hālawa Shaft Contribution (feet)
0.04
0.02
0
Barometric Pressure Contribution (feet)
0
-0.05
-0.1
Tide Contribution (feet)
0.04
0.02
0
-0.02
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

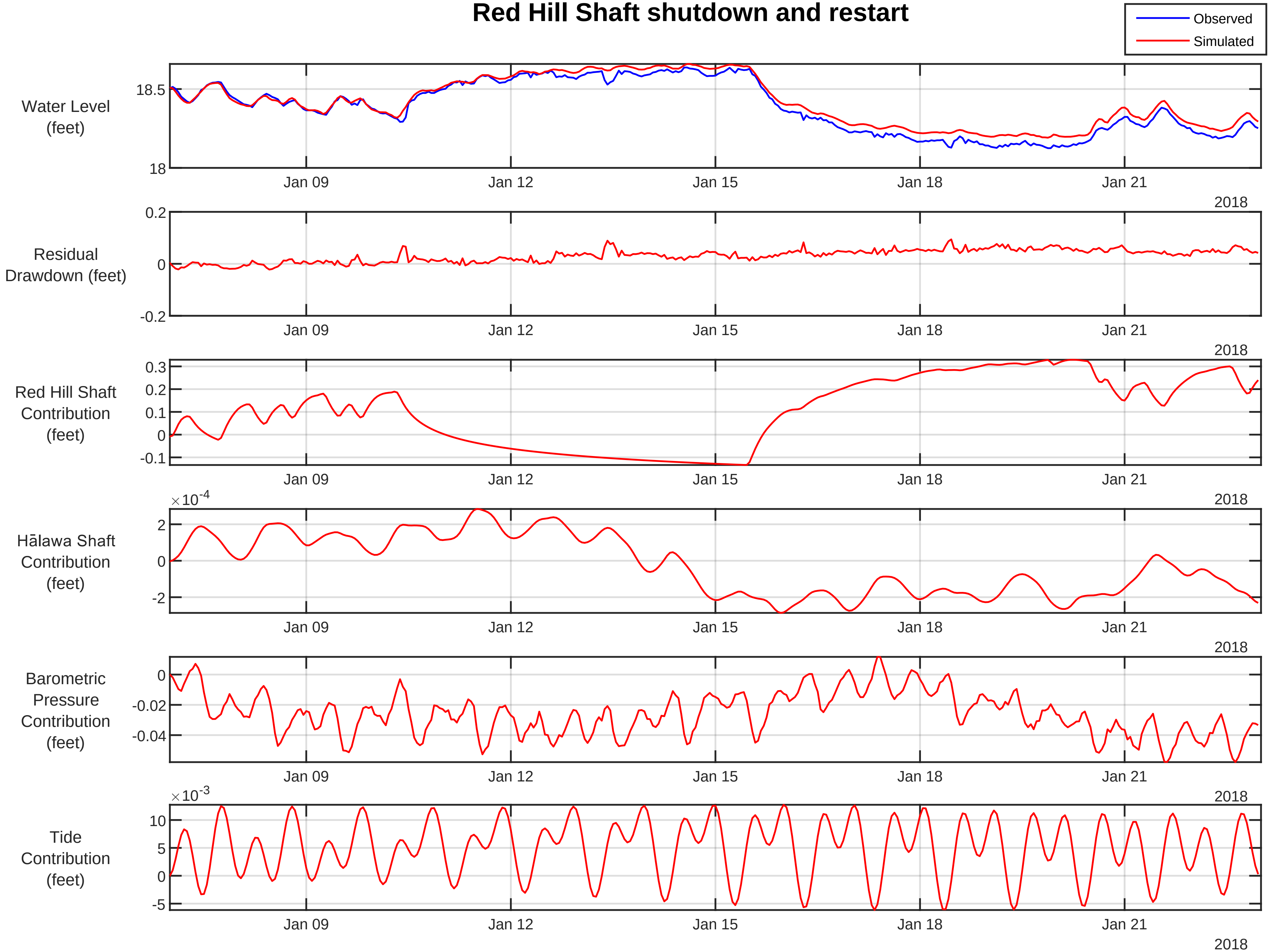
Ka'amilo Deep
Hālawa Shaft shutdown and restart

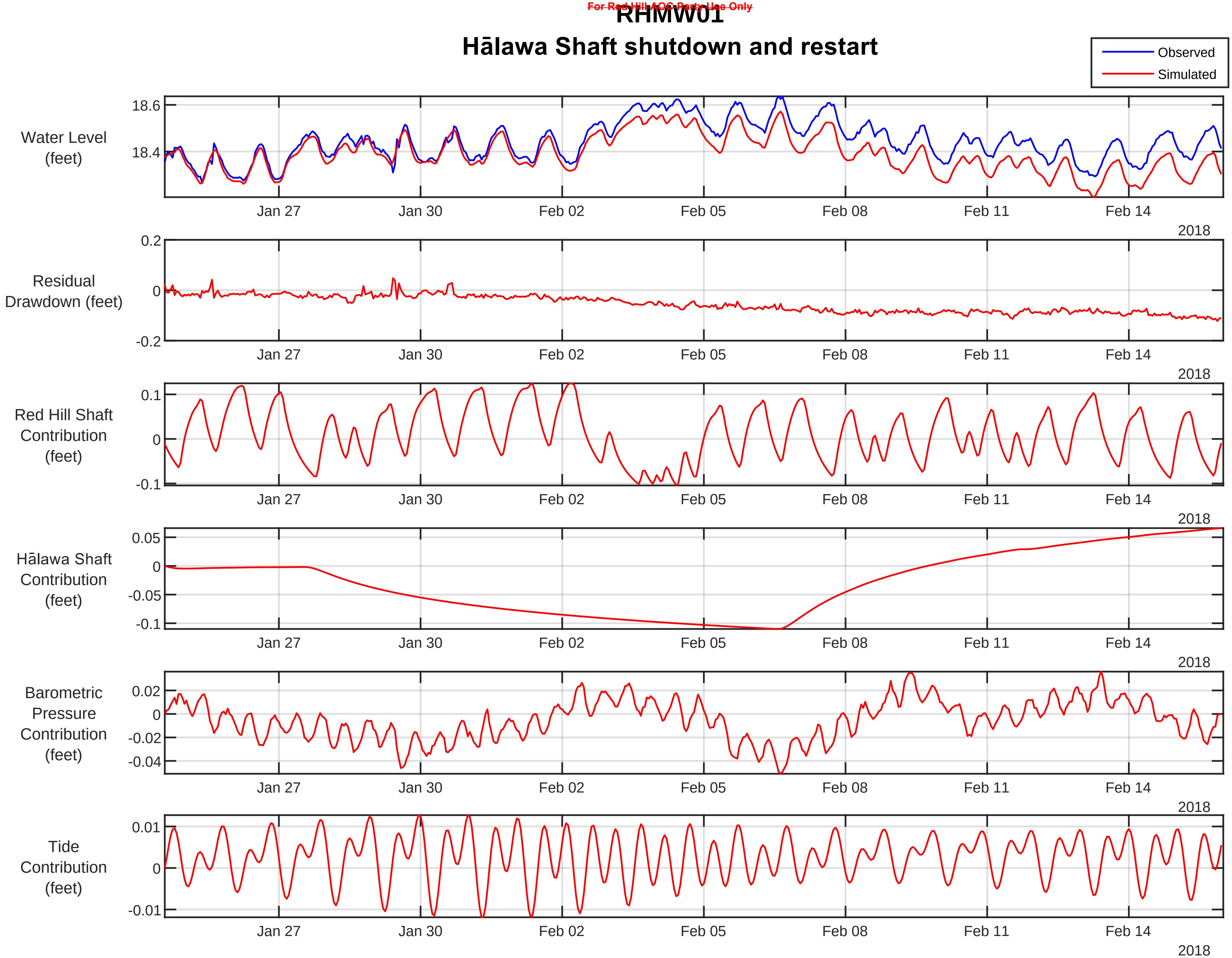


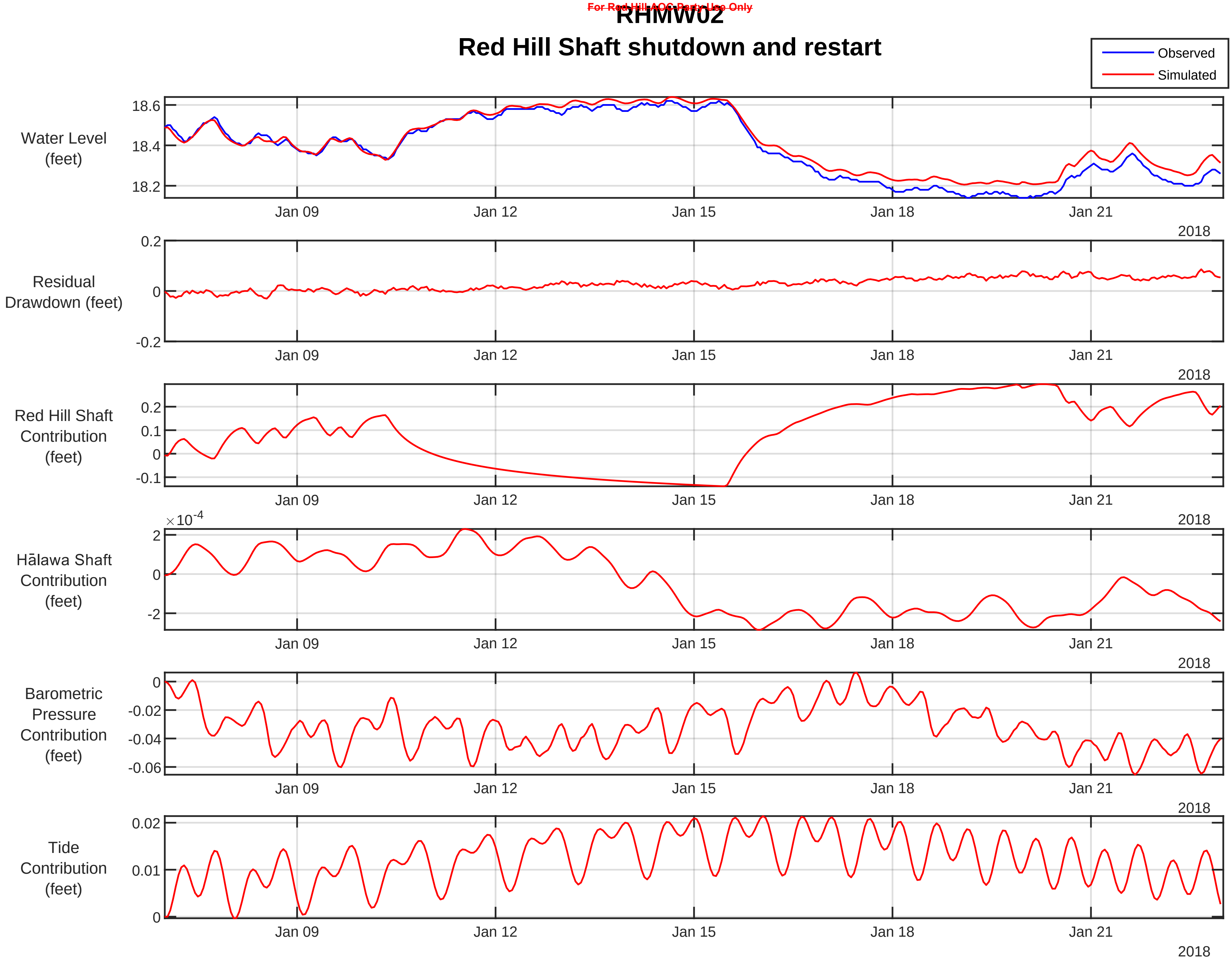

OWDFMW01
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.5
18
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.3
0.2
0.1
0
-0.1
Hālawa Shaft Contribution (feet)
×10^-4
0
-2
-4
Barometric Pressure Contribution (feet)
0
-0.05
-0.1
Tide Contribution (feet)
0.1
0.05
0
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

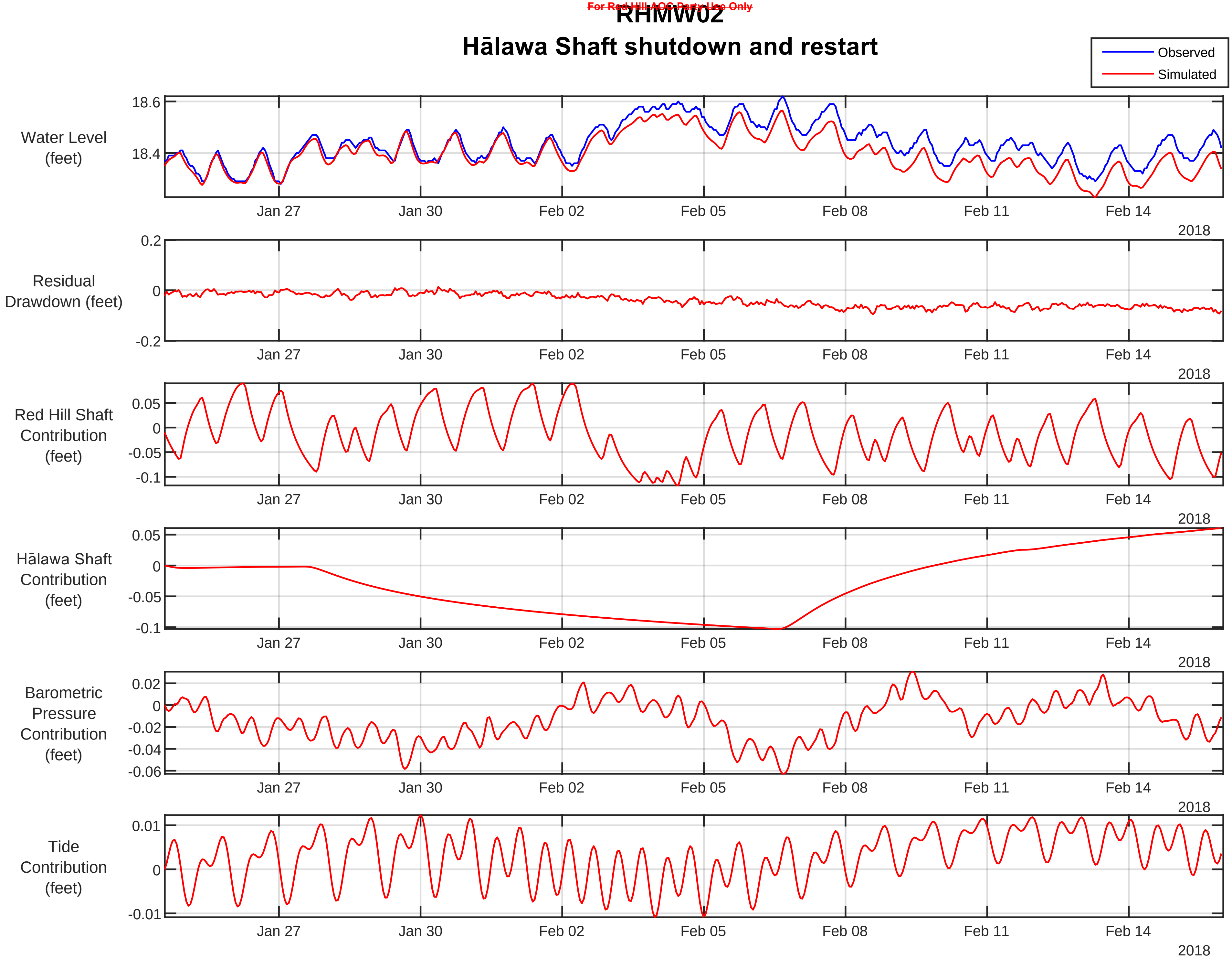

OWDFMW01
Hālawa Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.5
18
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.1
0
-0.1
Hālawa Shaft Contribution (feet)
0.02
0
-0.02
-0.04
-0.06
Barometric Pressure Contribution (feet)
0.05
0
-0.05
Tide Contribution (feet)
0.1
0.05
0
Jan 27
Jan 30
Feb 02
Feb 05
Feb 08
Feb 11
Feb 14
2018

RHMW01
Red Hill Shaft shutdown and restart



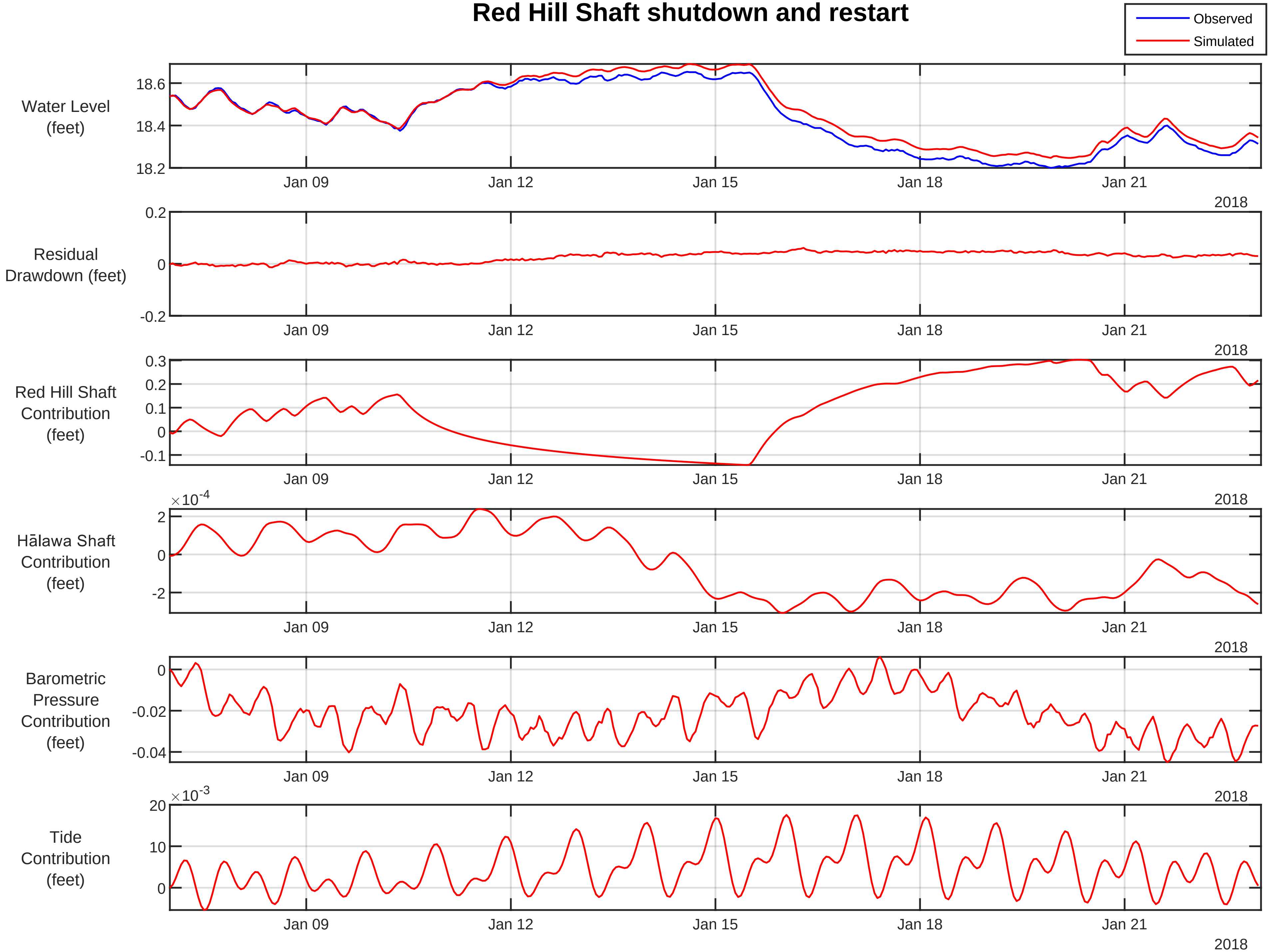

RHMW01
Hālawa Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.6
18.4
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.1
0
-0.1
Hālawa Shaft Contribution (feet)
0.05
0
-0.05
-0.1
Barometric Pressure Contribution (feet)
0.02
0
-0.02
-0.04
Tide Contribution (feet)
0.01
0
-0.01
Jan 27
Jan 30
Feb 02
Feb 05
Feb 08
Feb 11
Feb 14
2018


RHMW02
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.6
18.4
18.2
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.2
0.1
0
-0.1
×10^-4
Hālawa Shaft Contribution (feet)
2
0
-2
Barometric Pressure Contribution (feet)
0
-0.02
-0.04
-0.06
Tide Contribution (feet)
0.02
0.01
0
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018


RHMW02
Hālawa Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.6
18.4
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.05
0
-0.05
-0.1
Hālawa Shaft Contribution (feet)
0.05
0
-0.05
-0.1
Barometric Pressure Contribution (feet)
0.02
0
-0.02
-0.04
-0.06
Tide Contribution (feet)
0.01
0
-0.01
Jan 27
Jan 30
Feb 02
Feb 05
Feb 08
Feb 11
Feb 14
2018

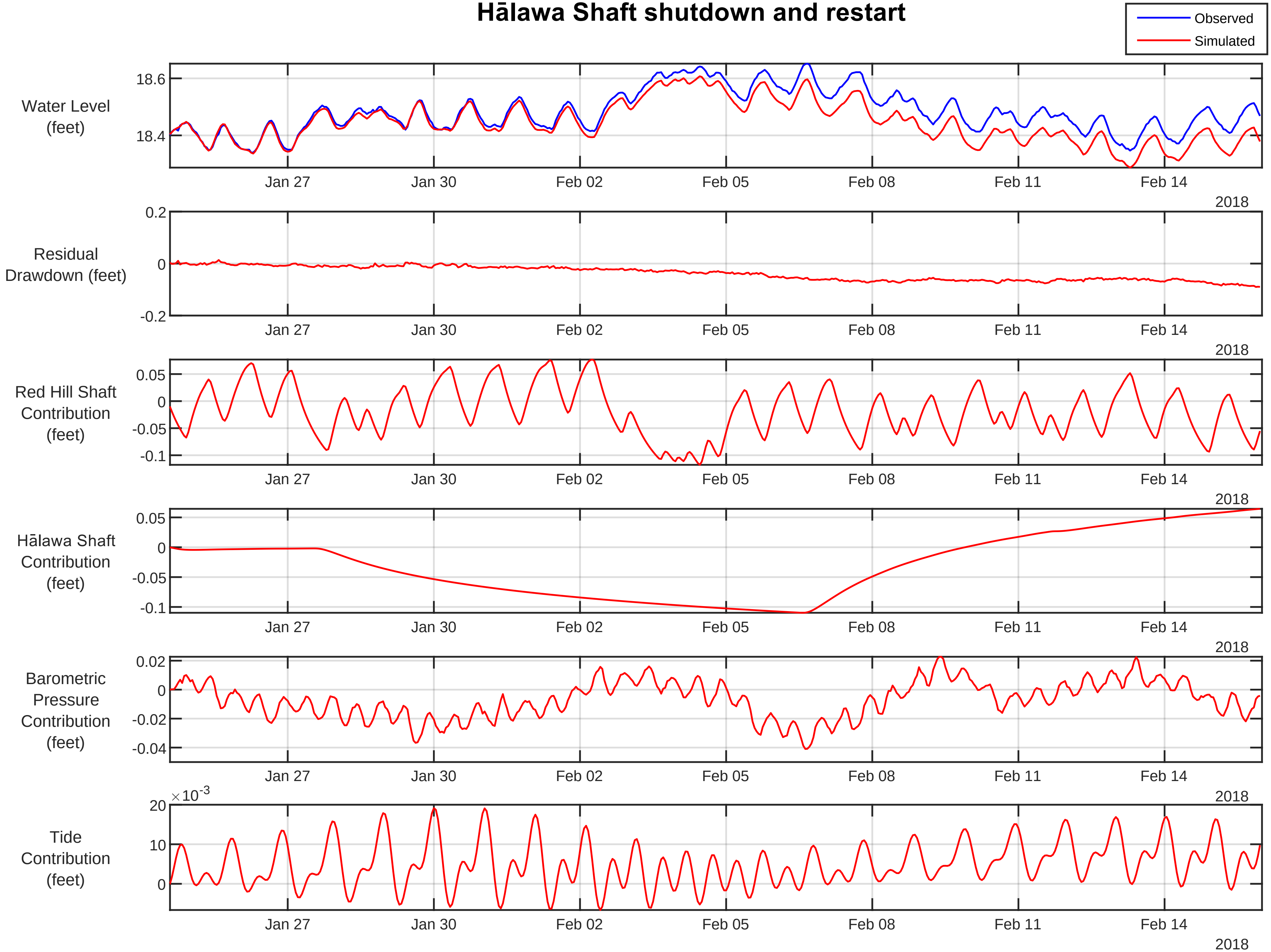
RHMW03

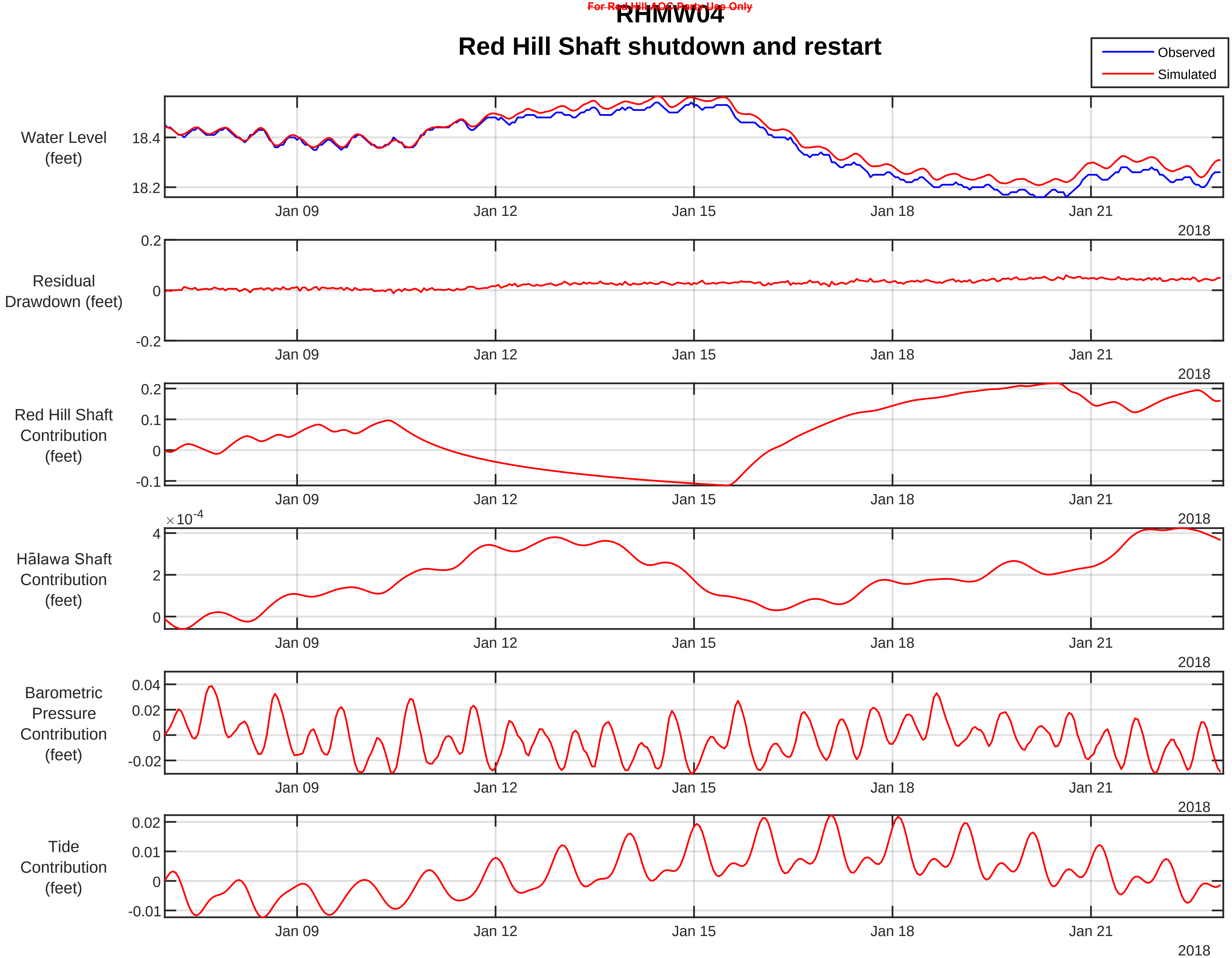
Red Hill Shaft shutdown and restart



RHMW03

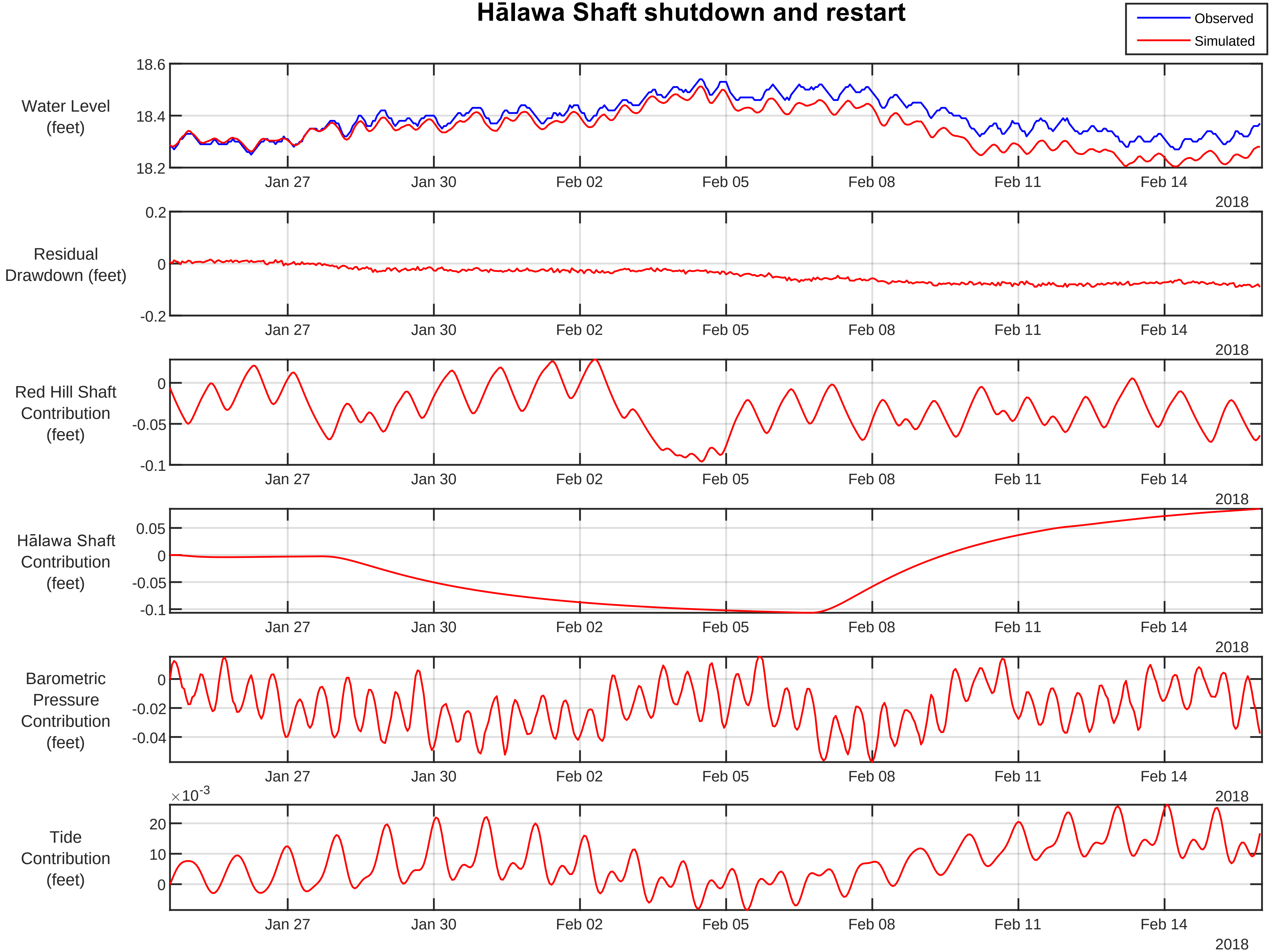
Hālawa Shaft shutdown and restart



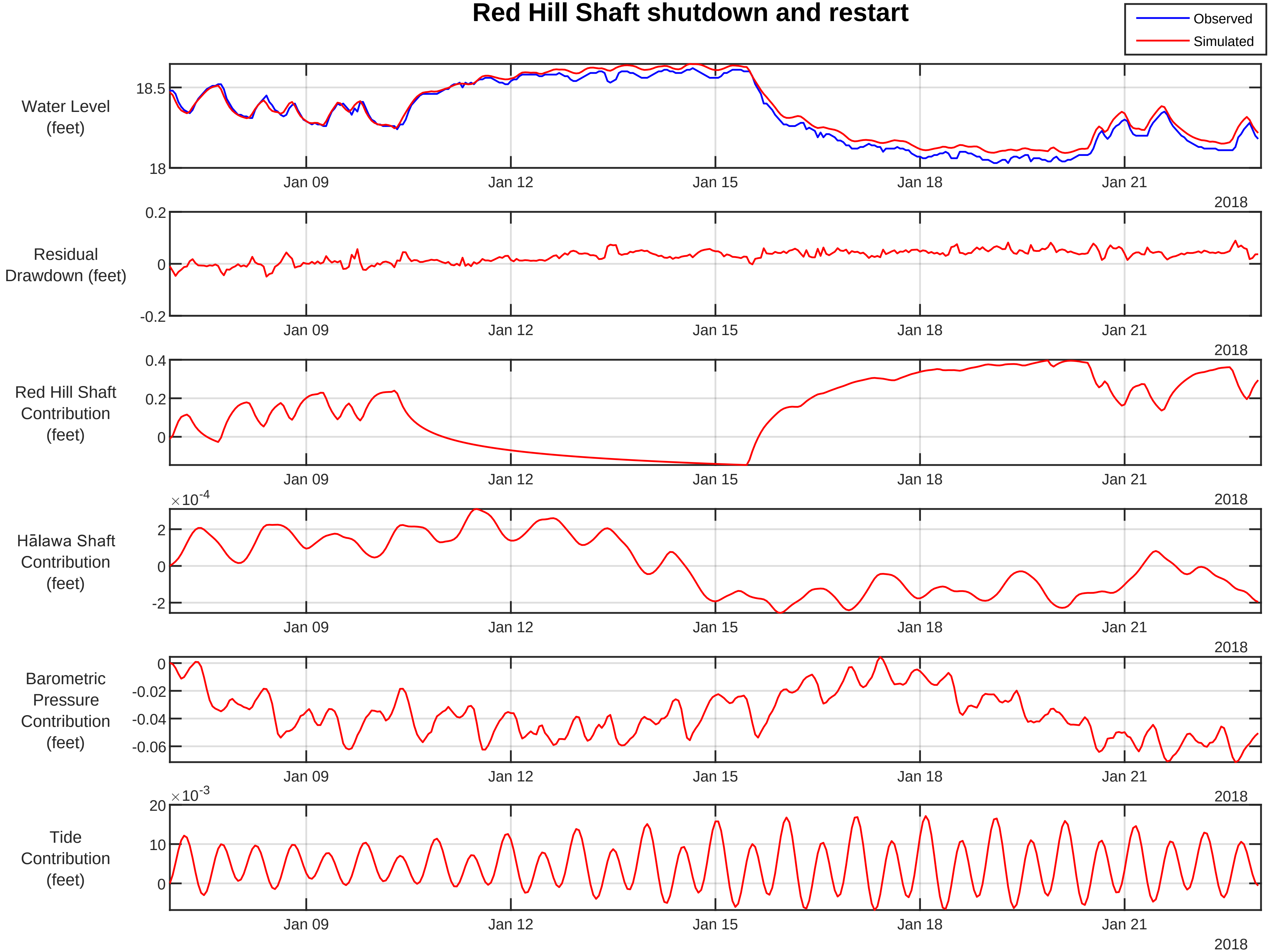

RHMW04
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.4
18.2
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.2
0.1
0
-0.1
Hālawa Shaft Contribution (feet)
×10^-4
4
2
0
Barometric Pressure Contribution (feet)
0.04
0.02
0
-0.02
Tide Contribution (feet)
0.02
0.01
0
-0.01
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

RHMW04

Hālawa Shaft shutdown and restart

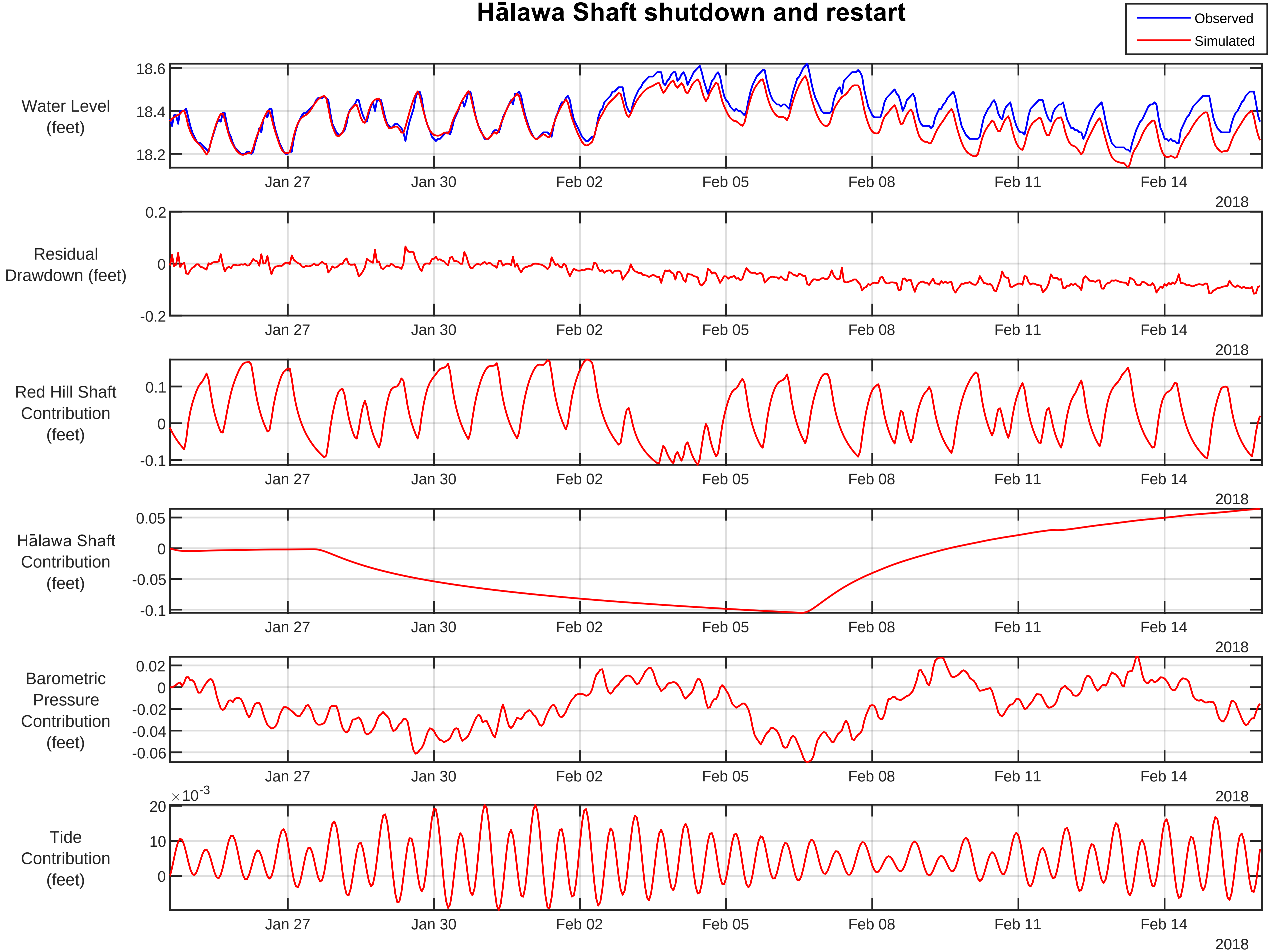


RHMW05
Red Hill Shaft shutdown and restart

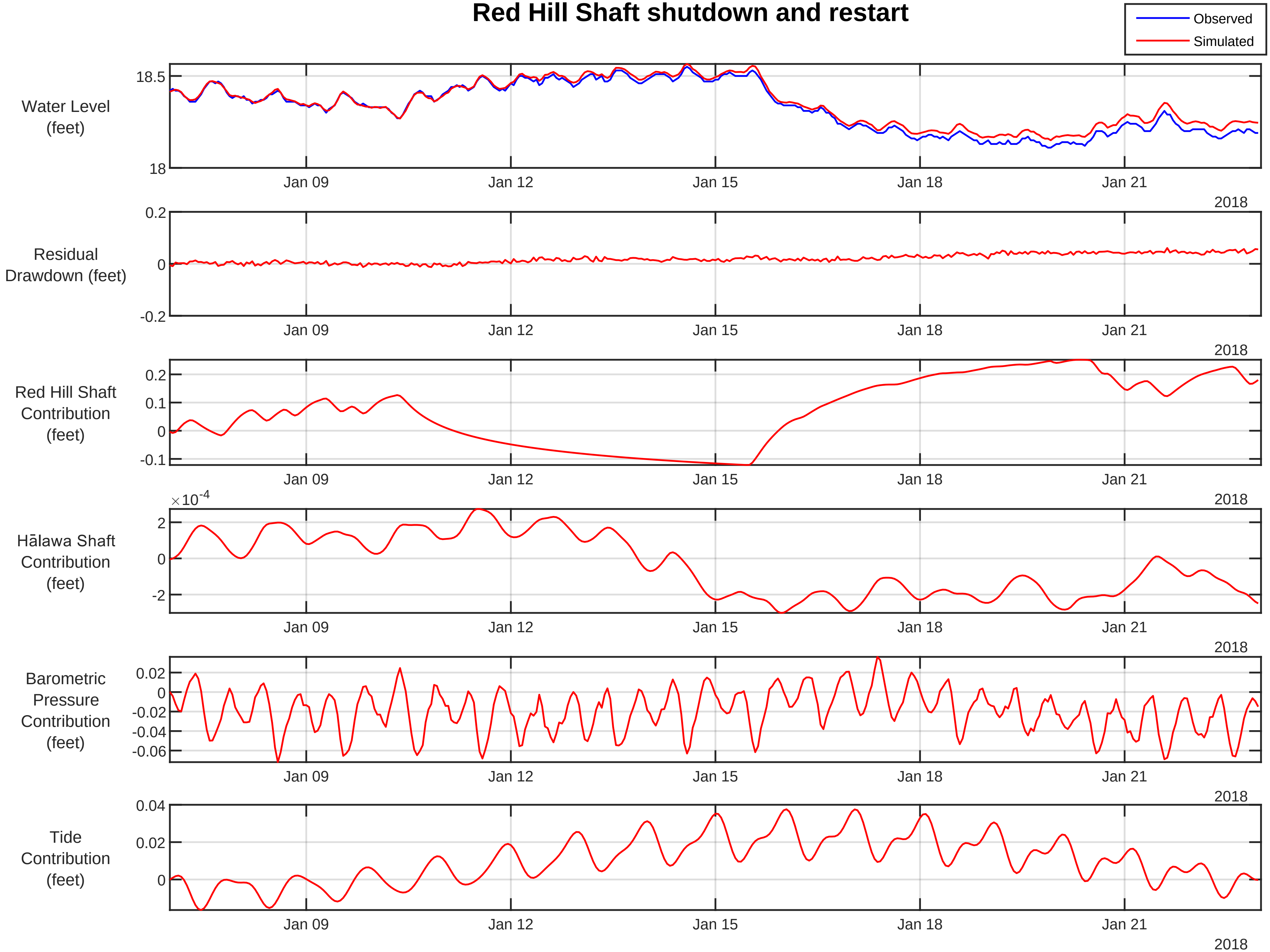


RHMW05

Hālawa Shaft shutdown and restart

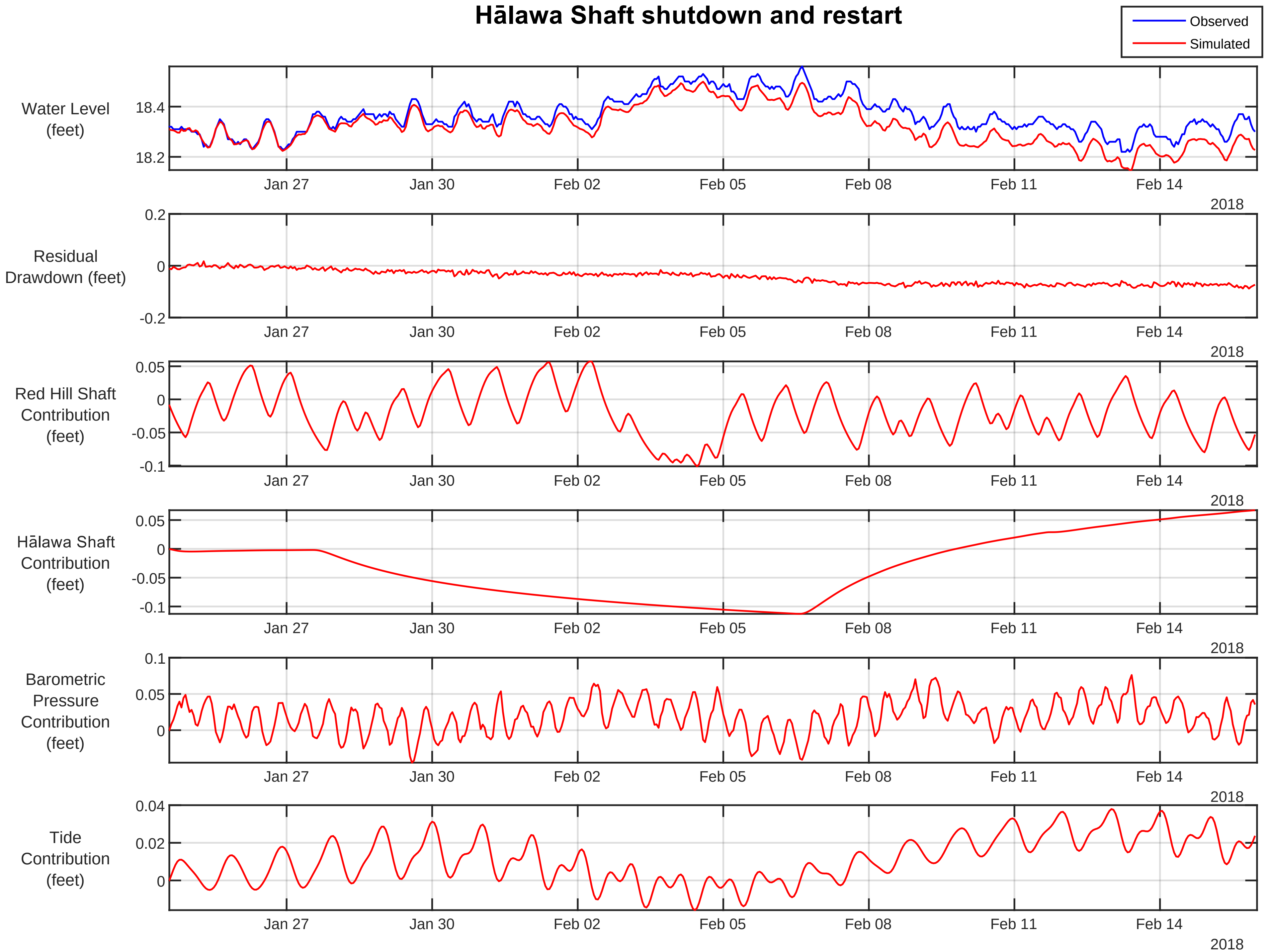


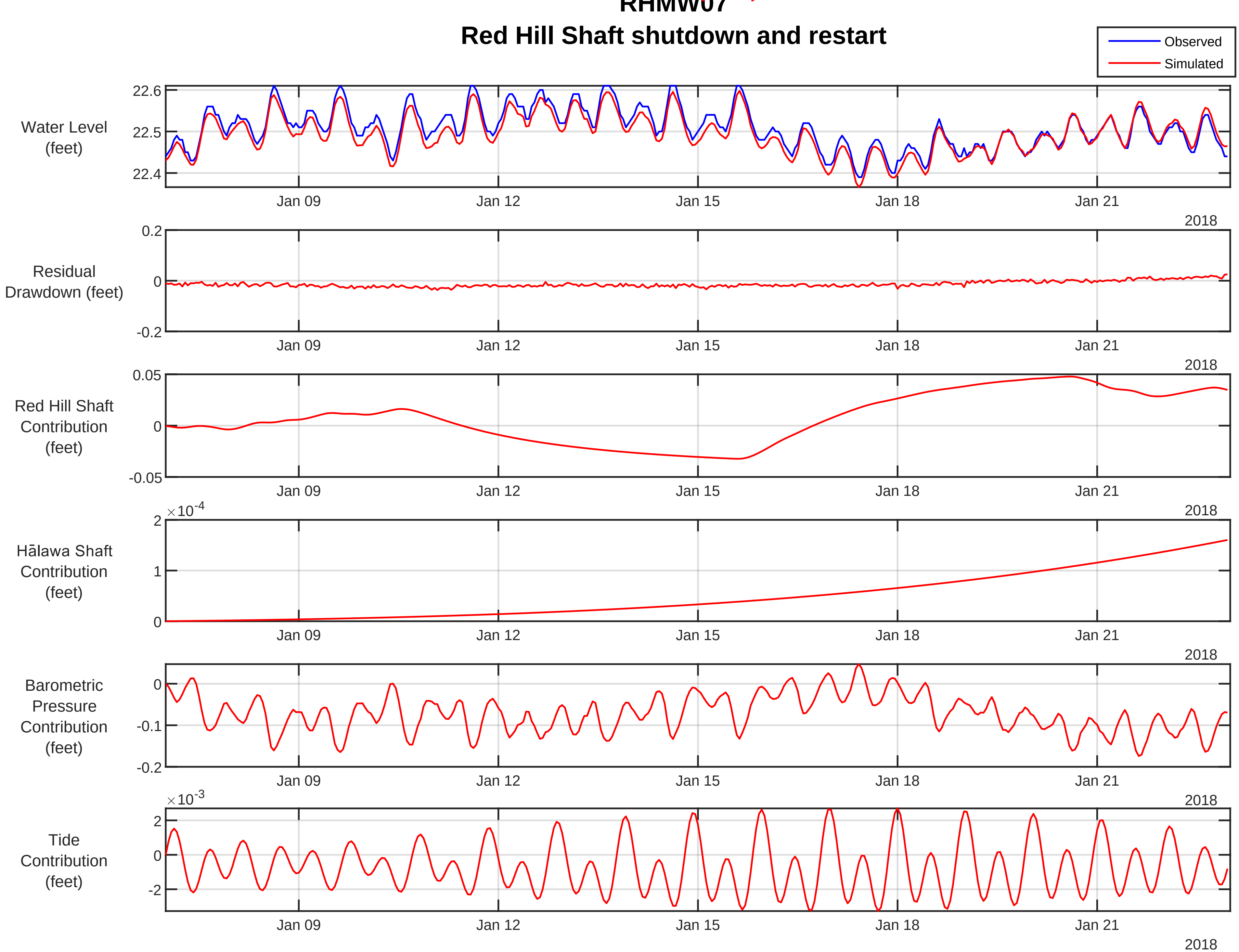
RHMW06
Red Hill Shaft shutdown and restart

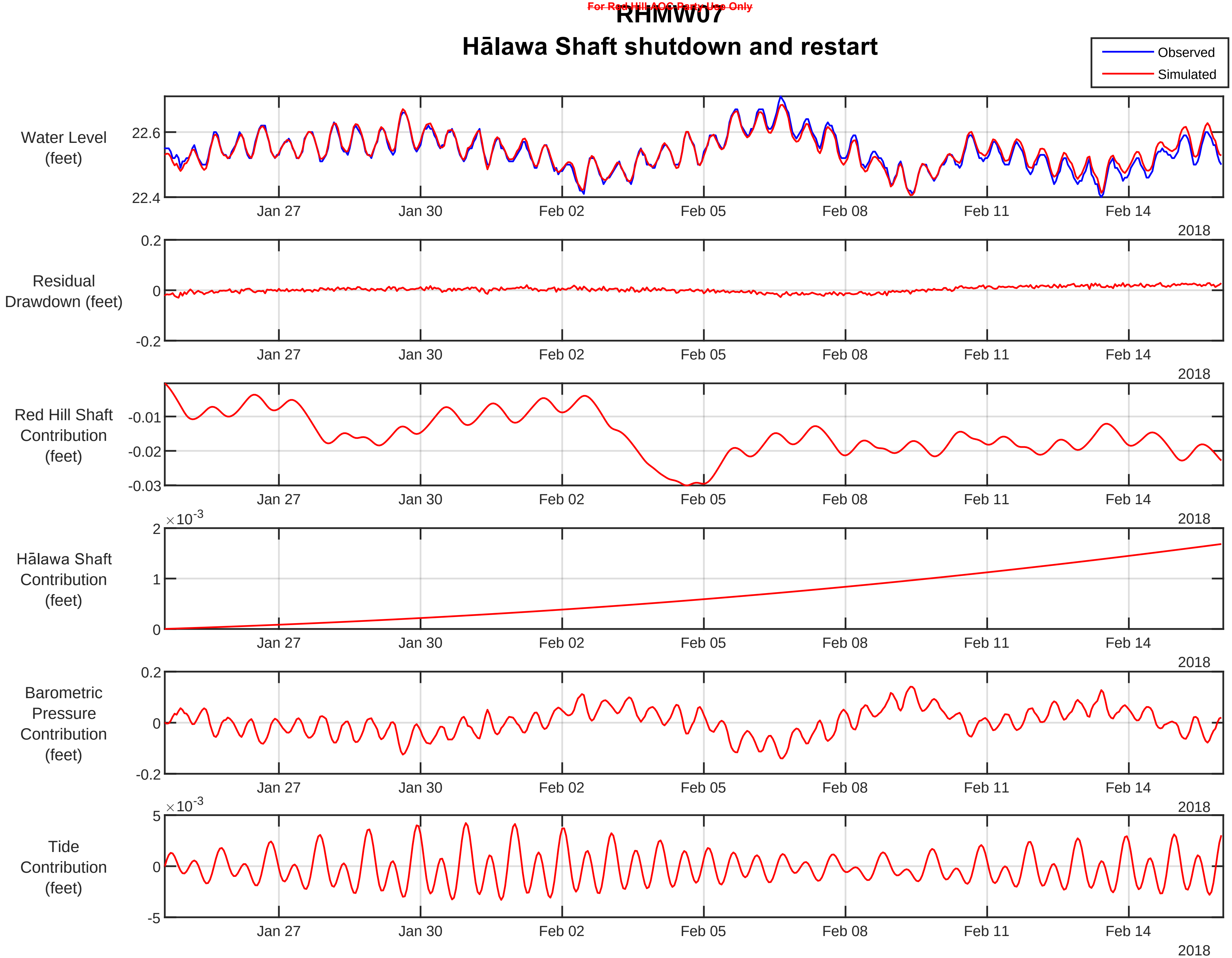


RHMW06

Hālawa Shaft shutdown and restart

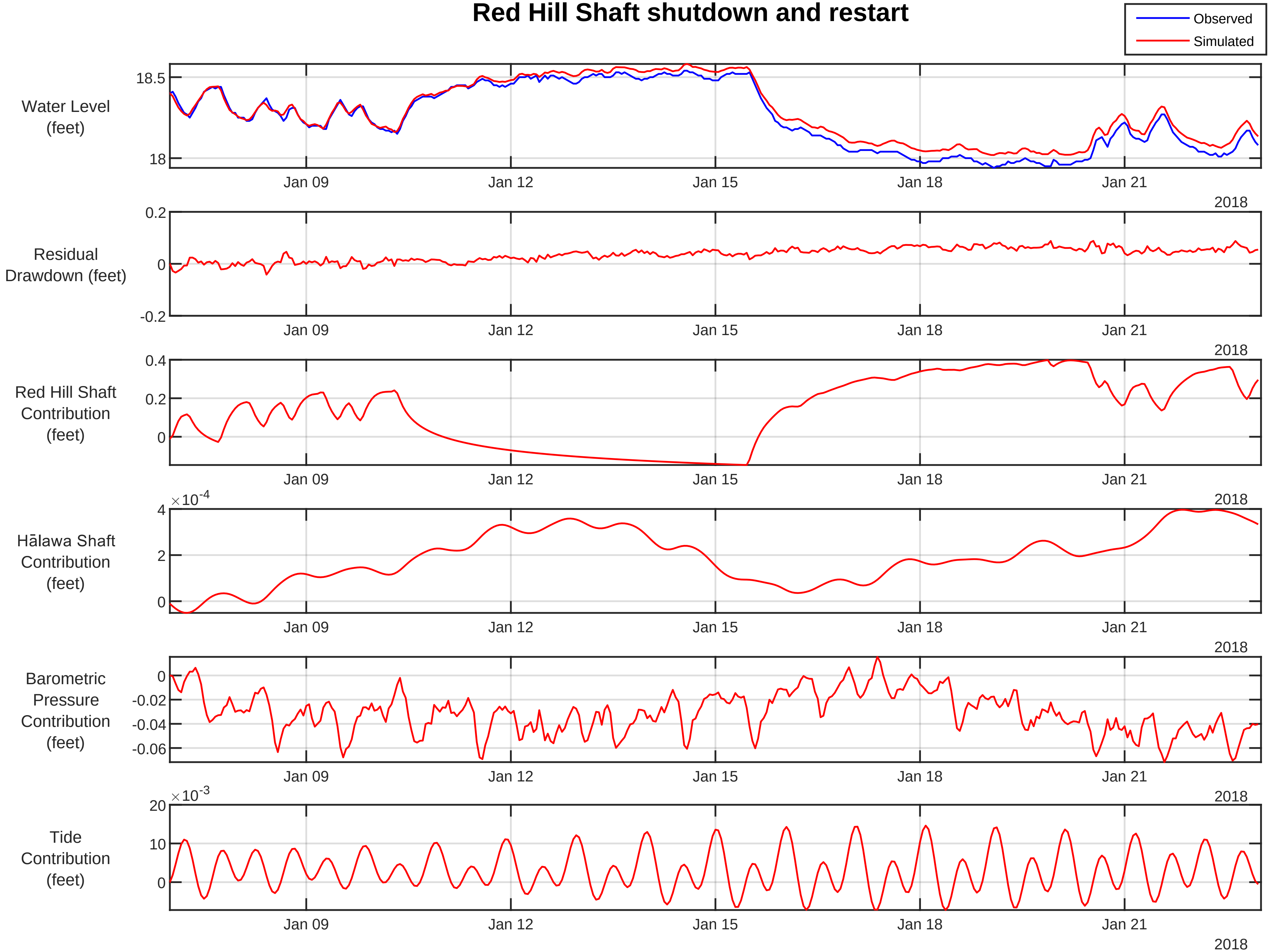



RHMW07
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
22.6
22.5
22.4
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.05
0
-0.05
Hālawa Shaft Contribution (feet)
×10-4
2
1
0
Barometric Pressure Contribution (feet)
0
-0.1
-0.2
Tide Contribution (feet)
×10-3
2
0
-2
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

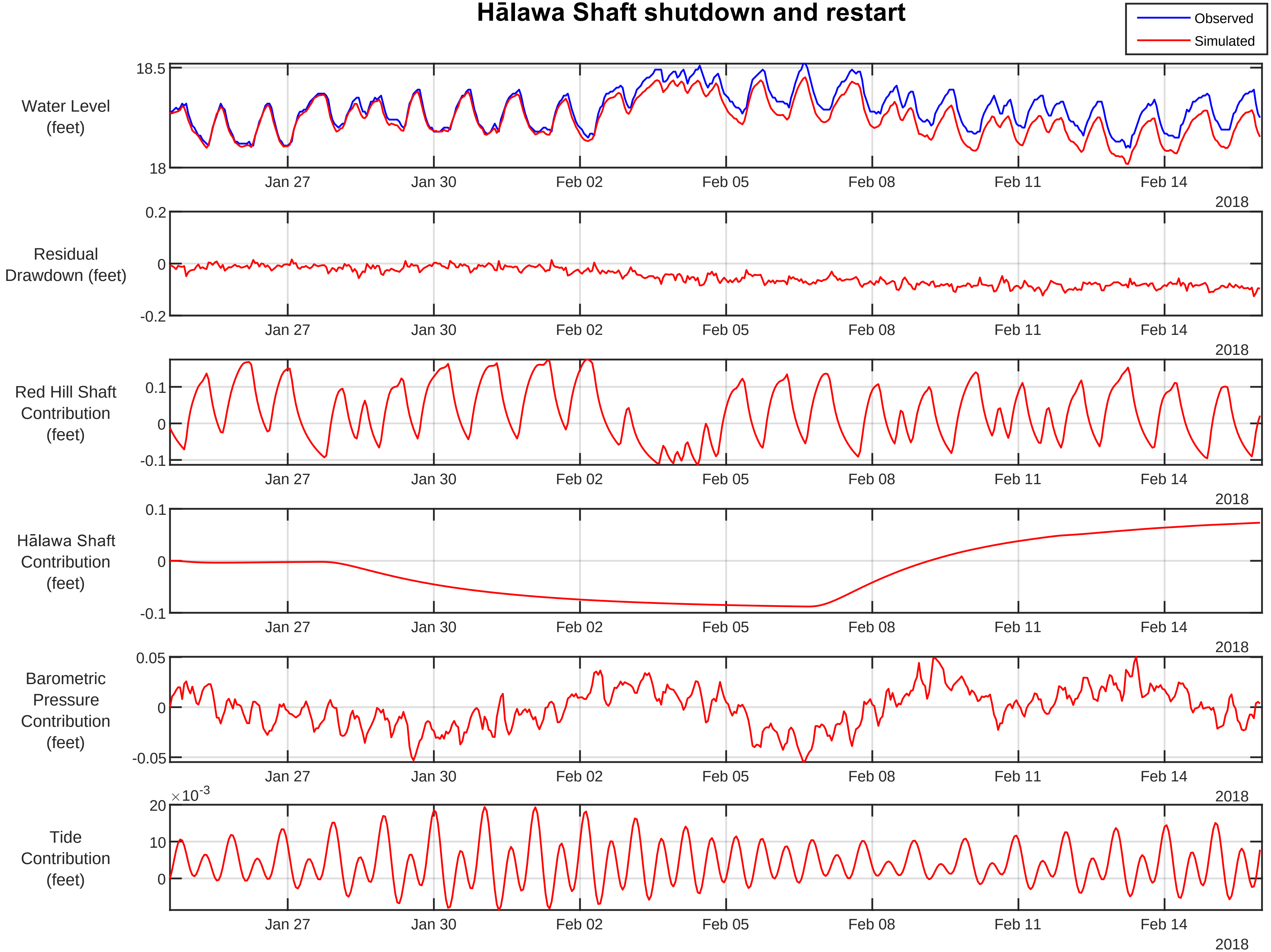


RHMW07
Hālawa Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
22.6
22.4
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
-0.01
-0.02
-0.03
Hālawa Shaft Contribution (feet)
×10^-3
2
1
0
Barometric Pressure Contribution (feet)
0.2
0
-0.2
Tide Contribution (feet)
×10^-3
5
0
-5
Jan 27
Jan 30
Feb 02
Feb 05
Feb 08
Feb 11
Feb 14
2018

RHMW08
Red Hill Shaft shutdown and restart

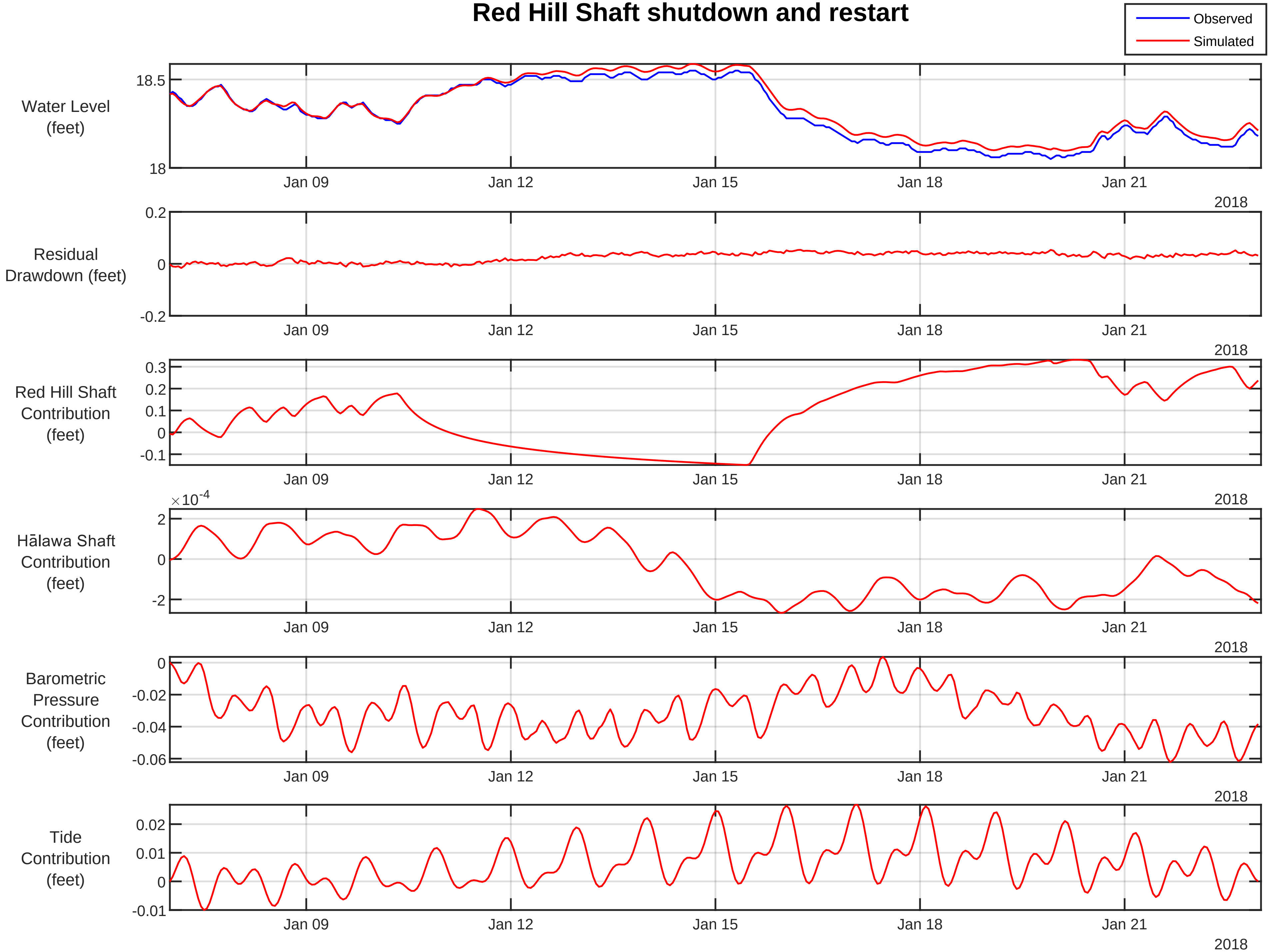


RHMW08
Hālawa Shaft shutdown and restart

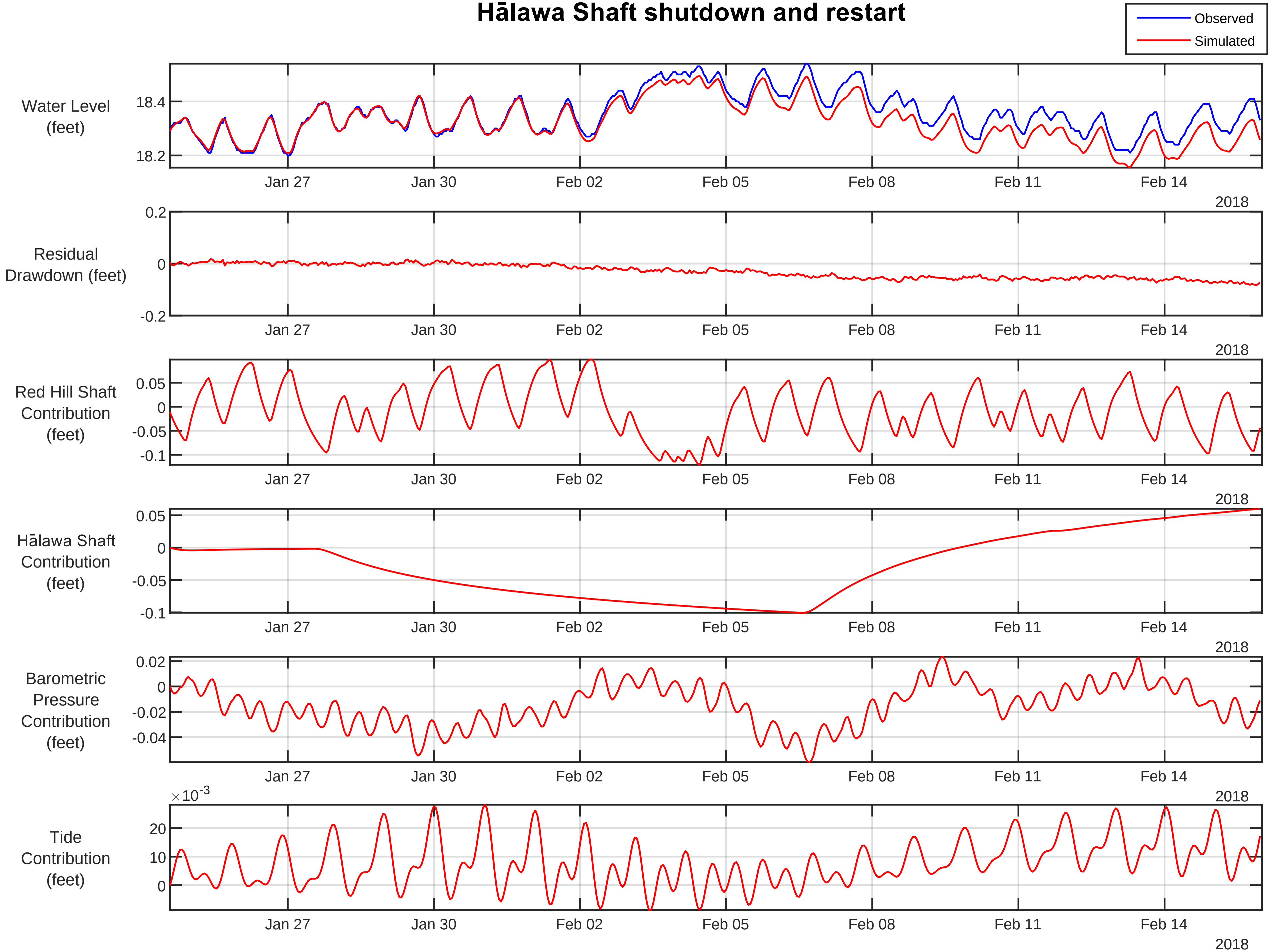


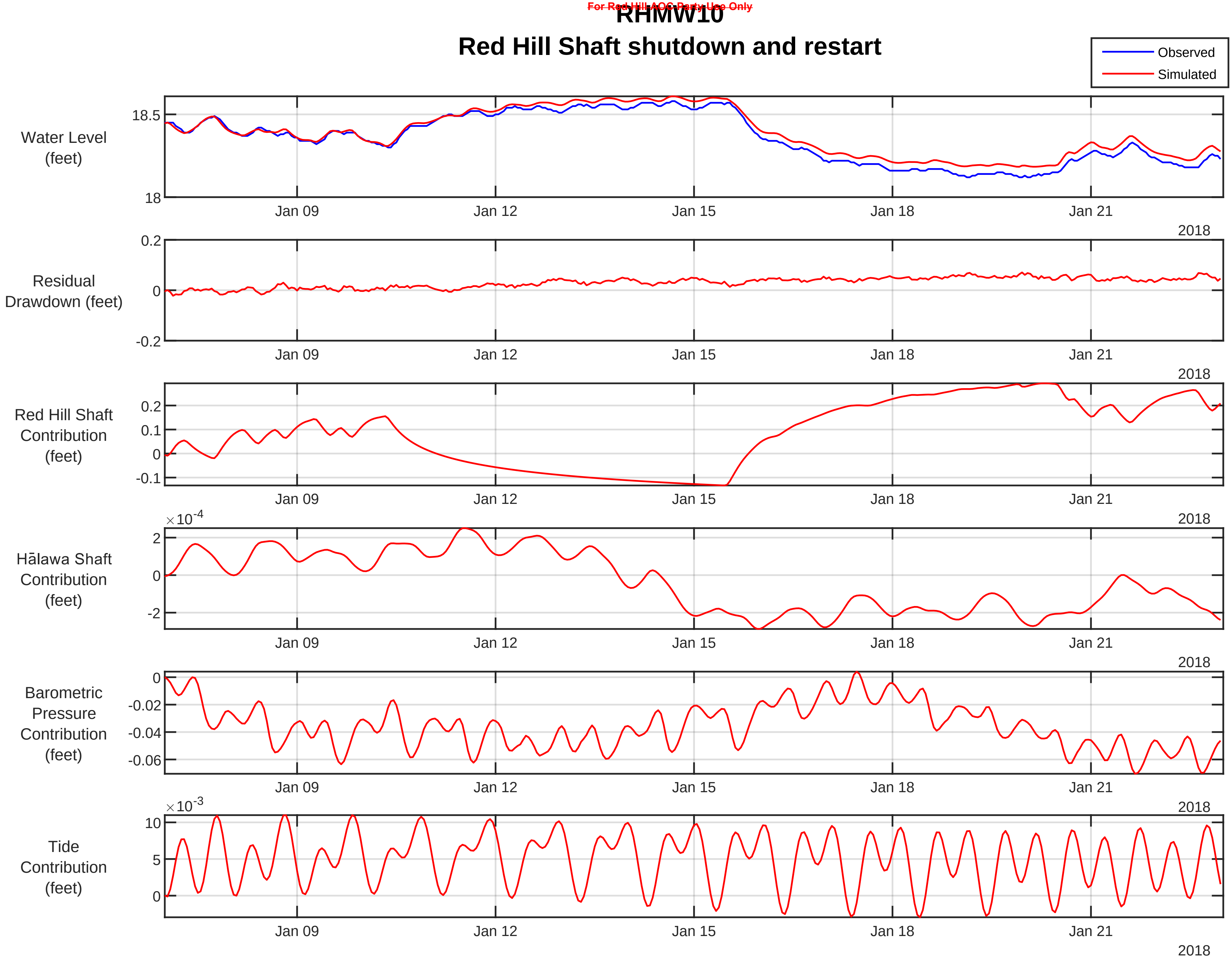
RHMW09

Red Hill Shaft shutdown and restart



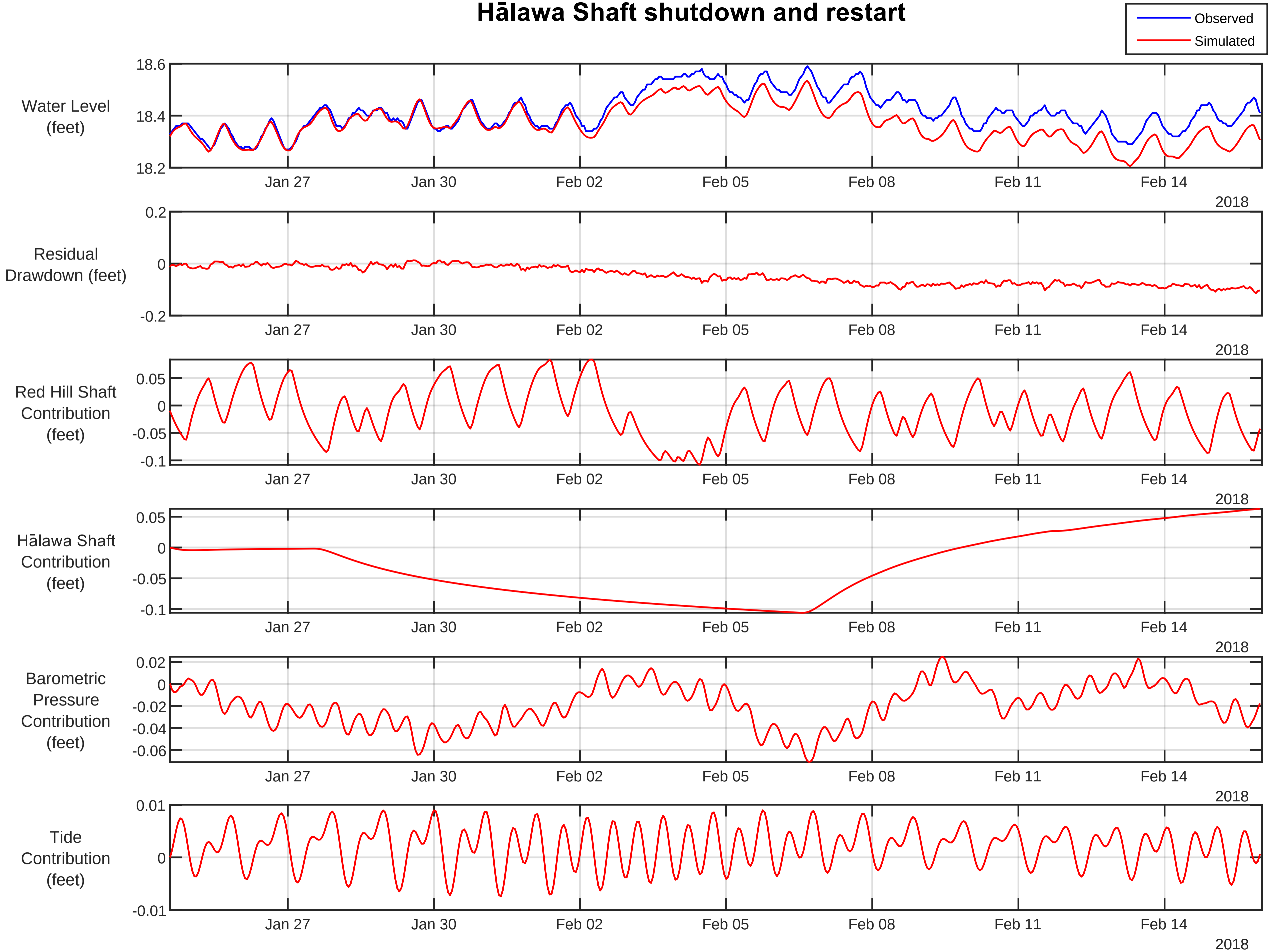
RHMW09
Hālawa Shaft shutdown and restart





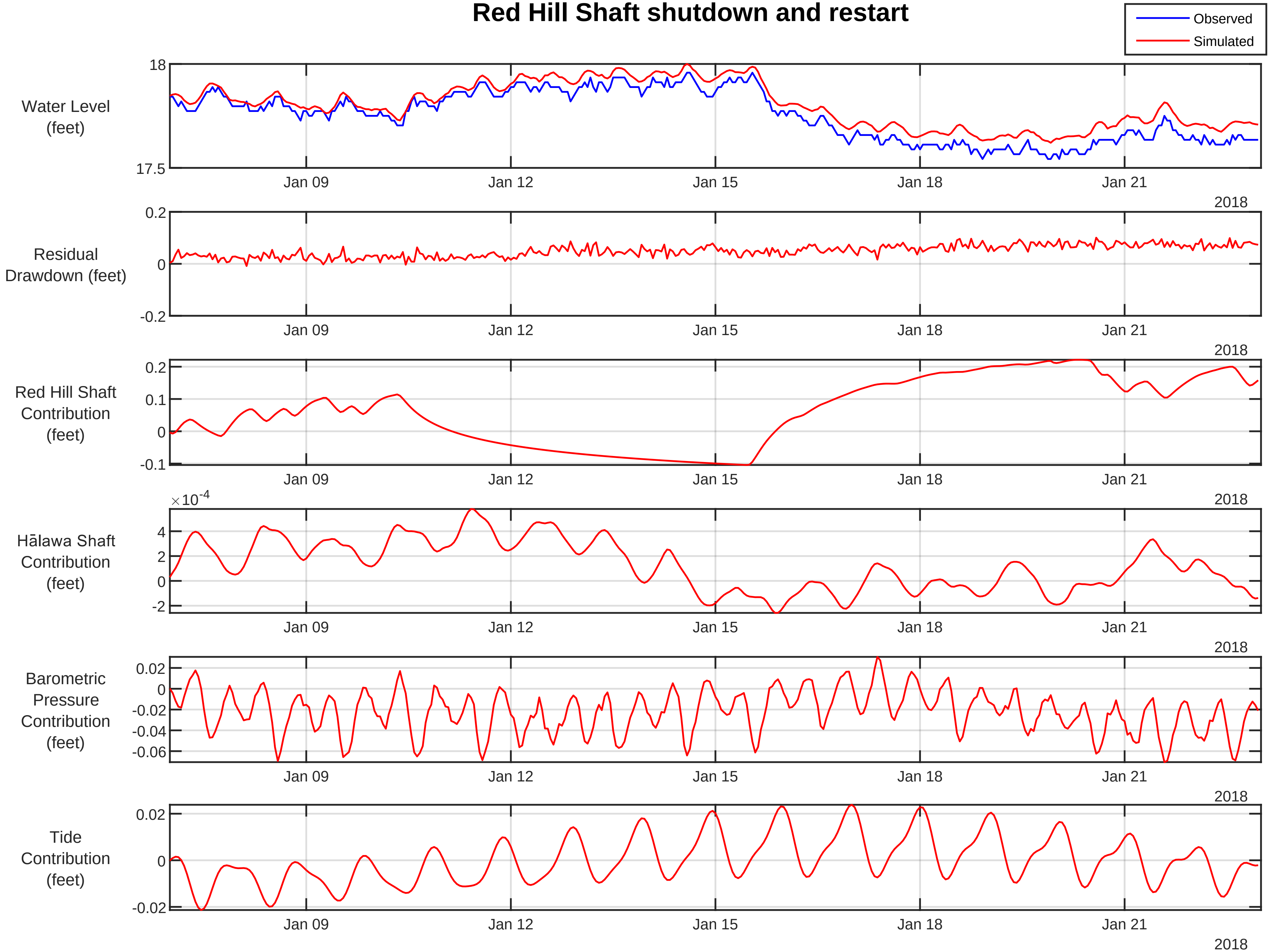
RHMW10
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.5
18
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.2
0.1
0
-0.1
Hālawa Shaft Contribution (feet)
×10-4
2
0
-2
Barometric Pressure Contribution (feet)
0
-0.02
-0.04
-0.06
Tide Contribution (feet)
×10-3
10
5
0
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

RHMW10
Hālawa Shaft shutdown and restart

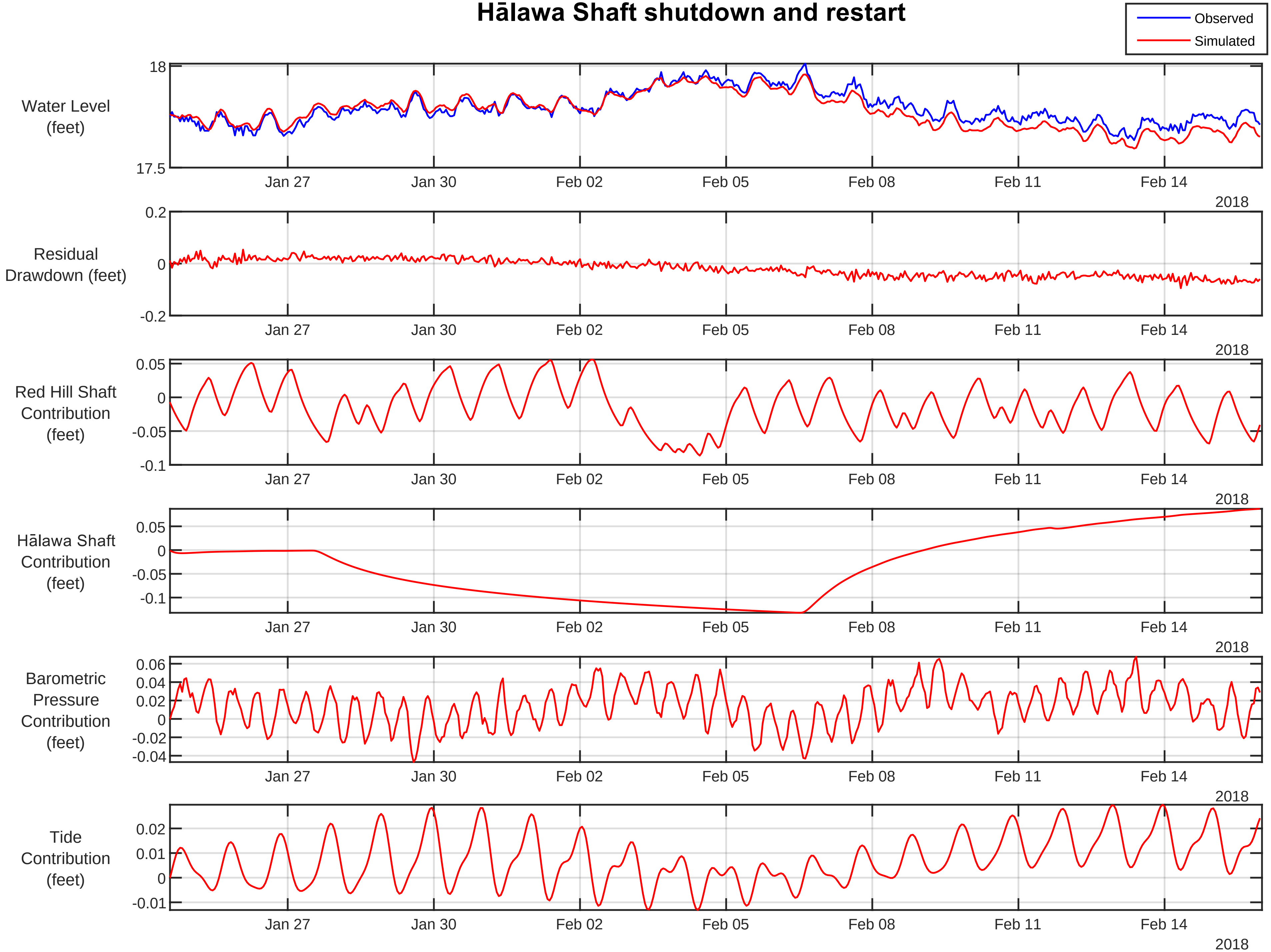


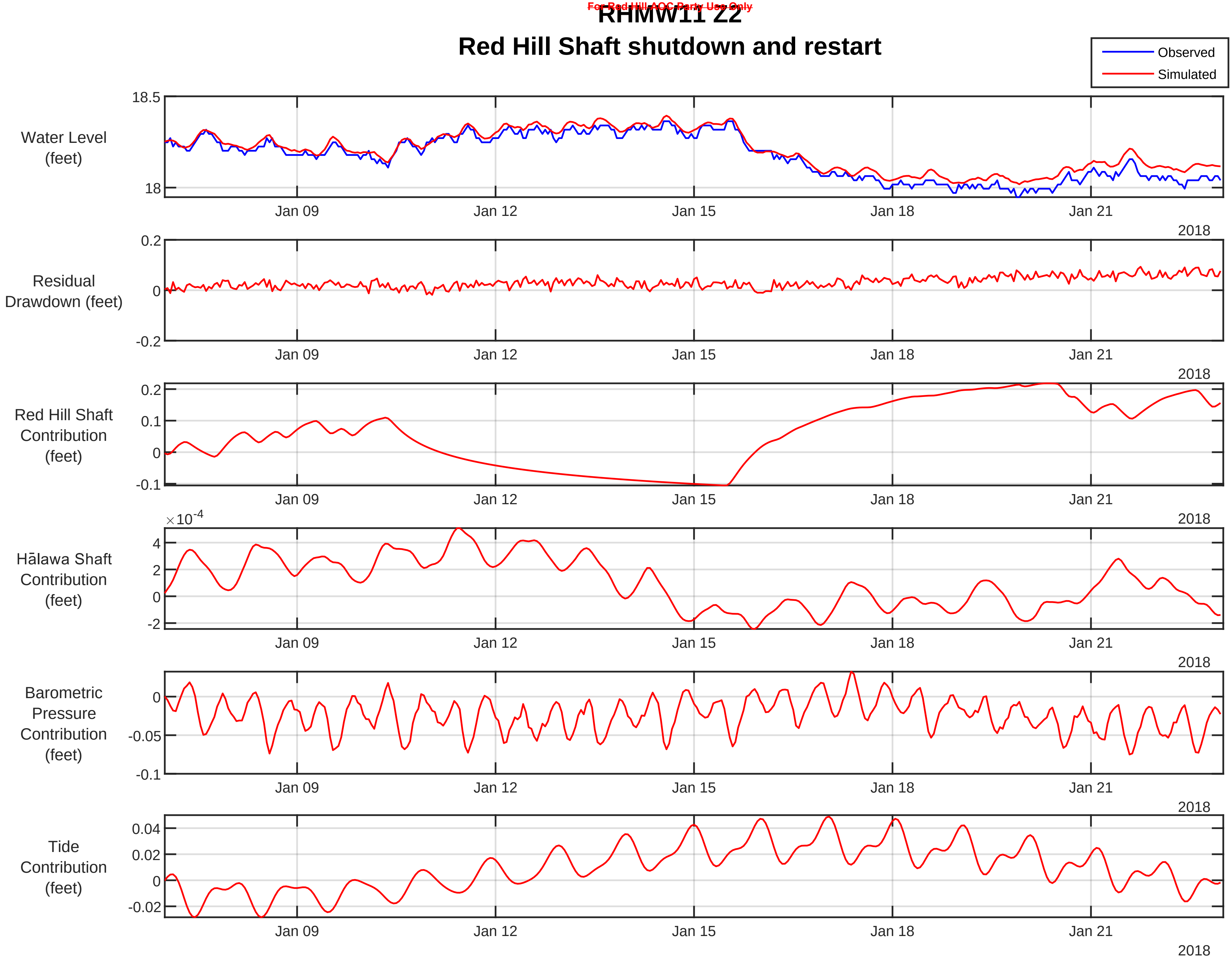
RHMW11 Z1

Red Hill Shaft shutdown and restart

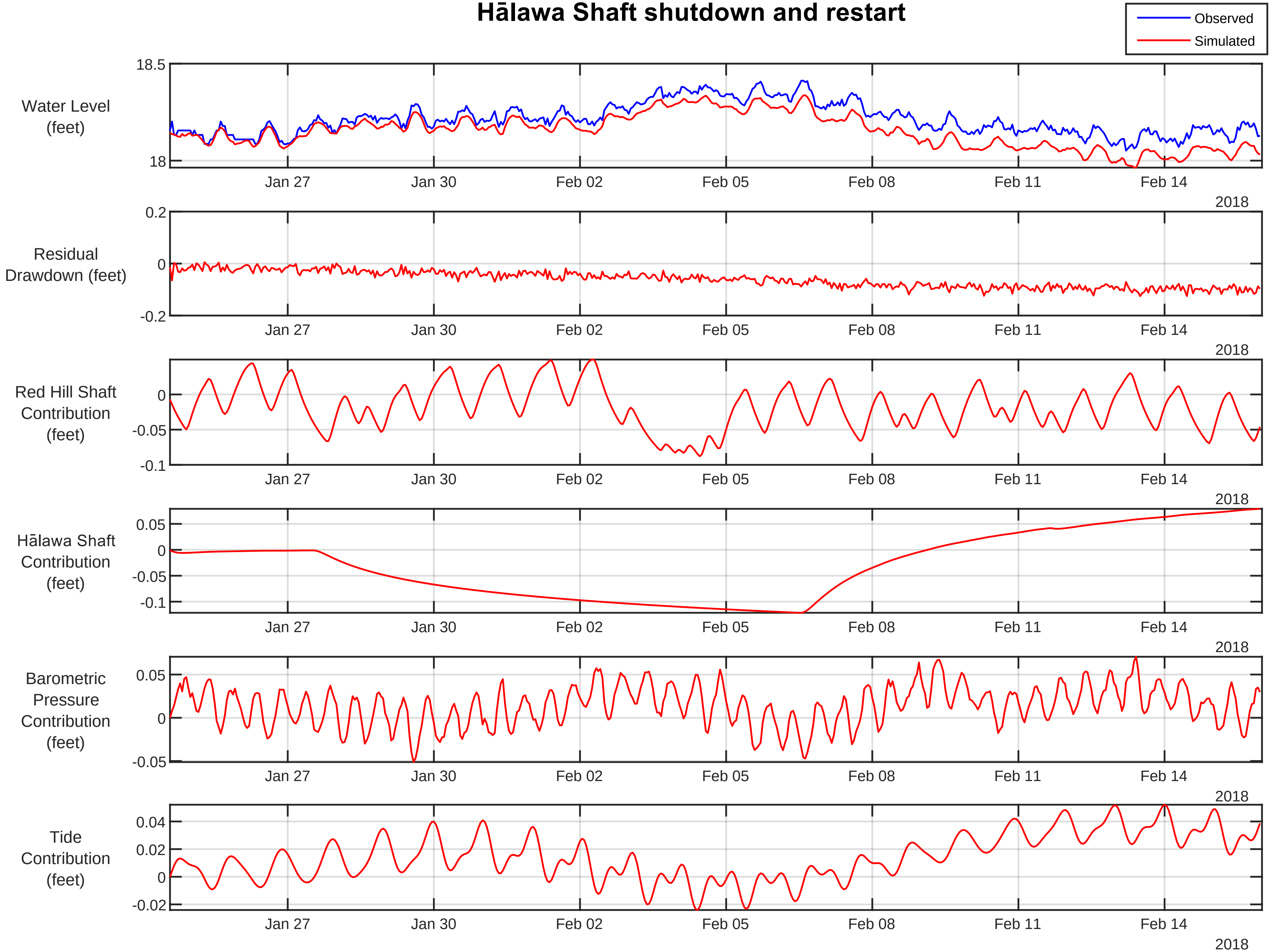


RHMW11 Z1
Hālawa Shaft shutdown and restart

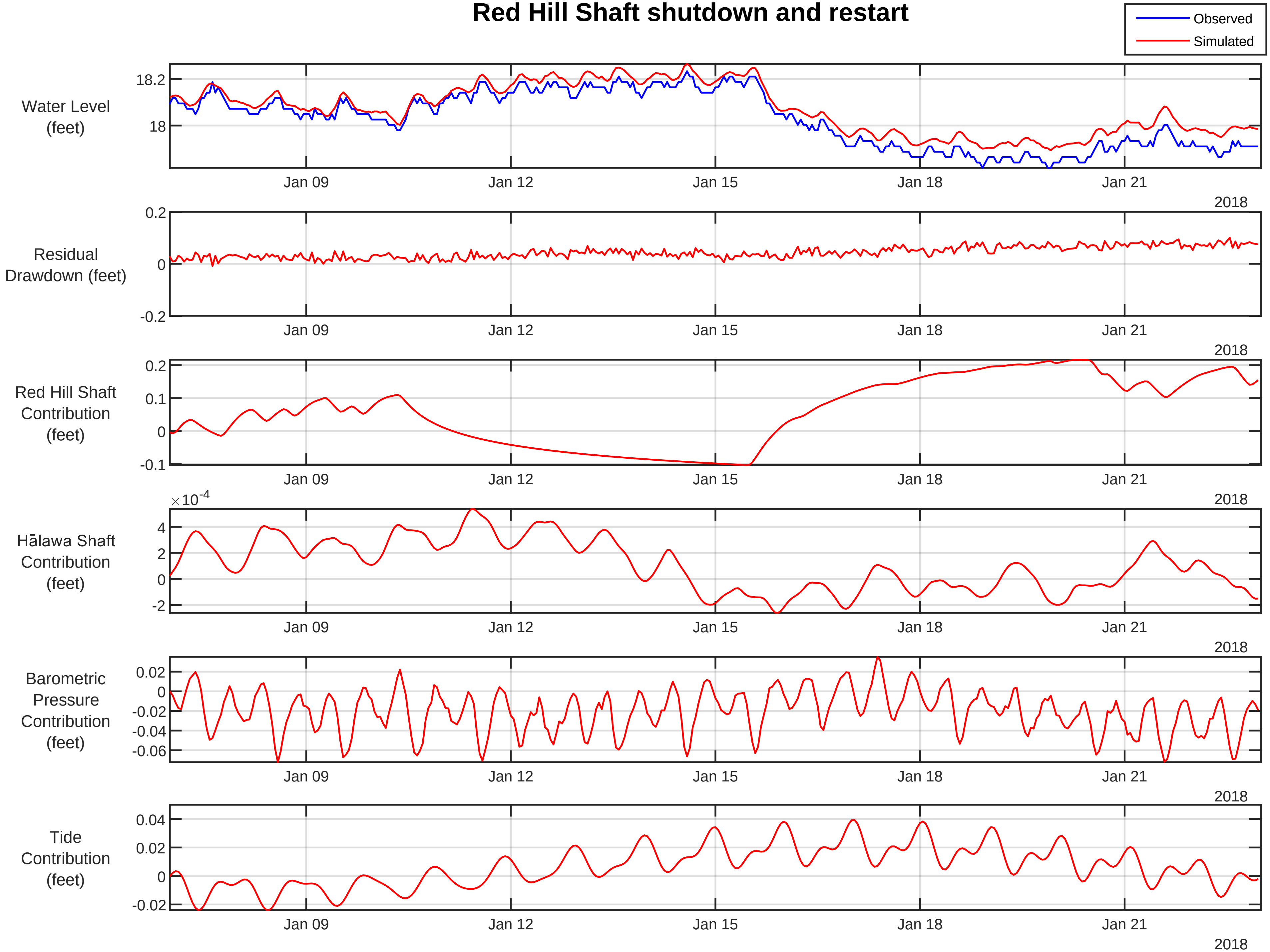



RHMW11 Z2
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.5
18
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.2
0.1
0
-0.1
Hālawa Shaft Contribution (feet)
×10^-4
4
2
0
-2
Barometric Pressure Contribution (feet)
0
-0.05
-0.1
Tide Contribution (feet)
0.04
0.02
0
-0.02
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

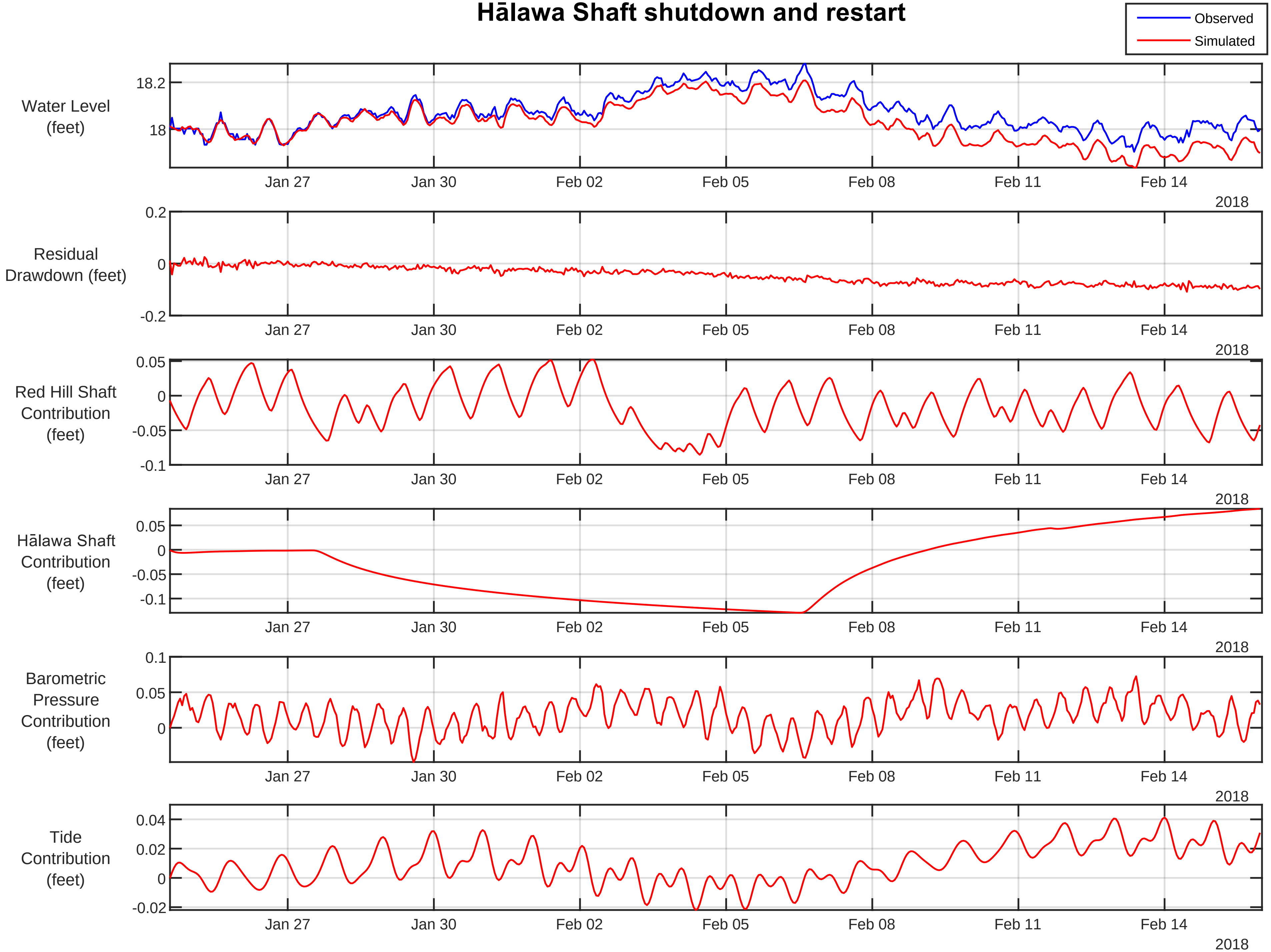
RHMW11 Z2
Hālawa Shaft shutdown and restart



RHMW11 Z3
Red Hill Shaft shutdown and restart

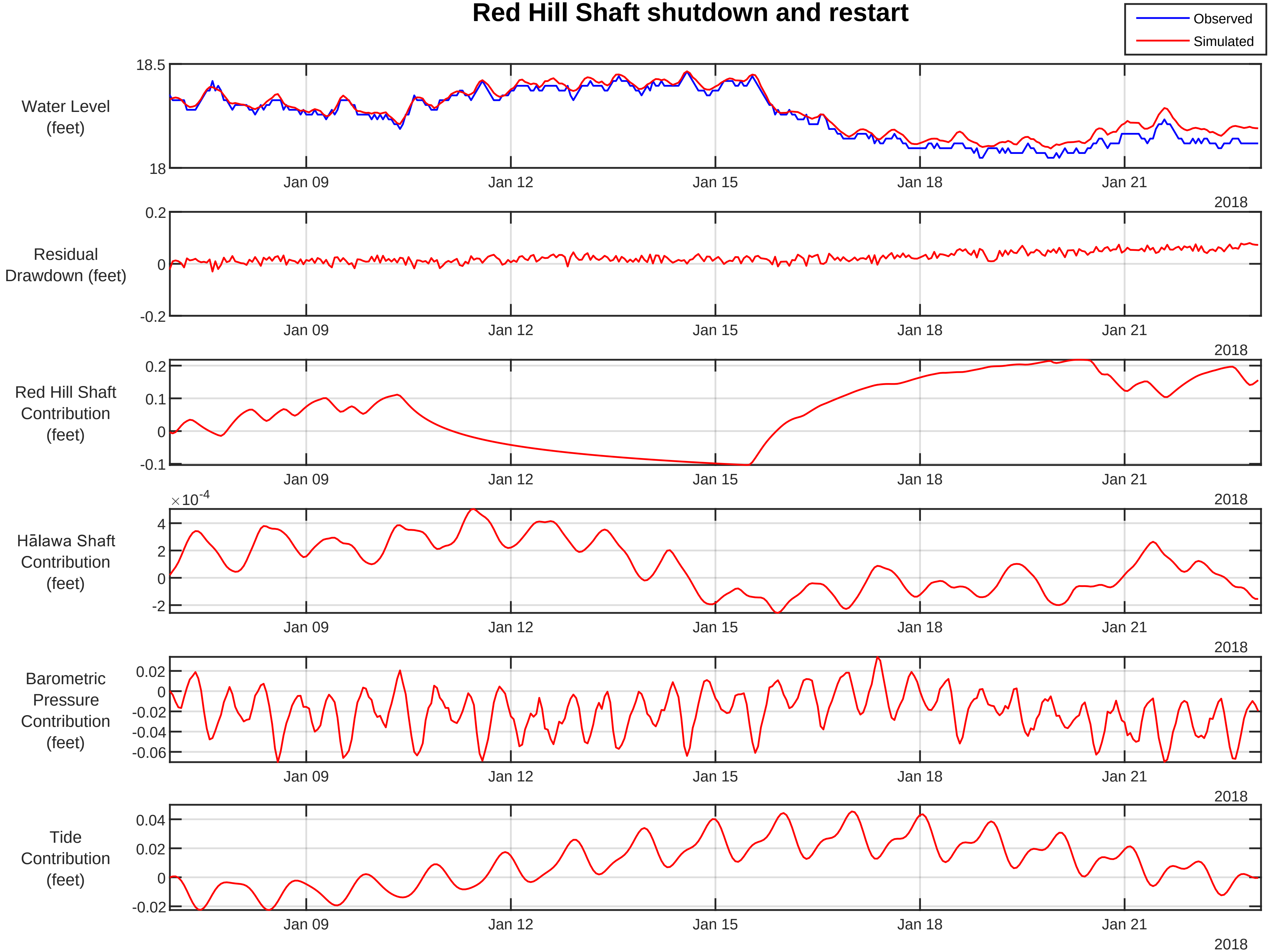


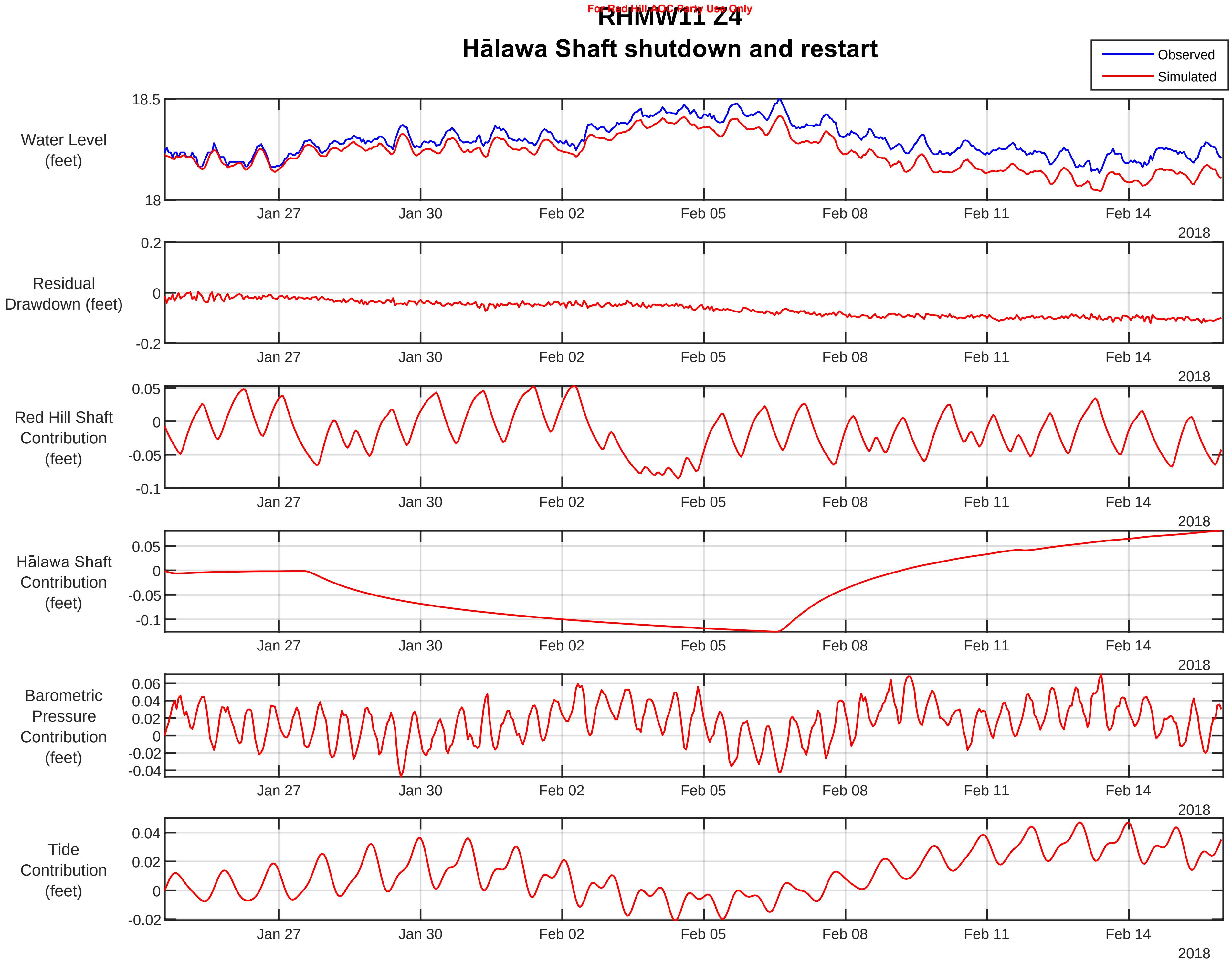
RHMW11 Z3
Hālawa Shaft shutdown and restart



RHMW11 24

Red Hill Shaft shutdown and restart

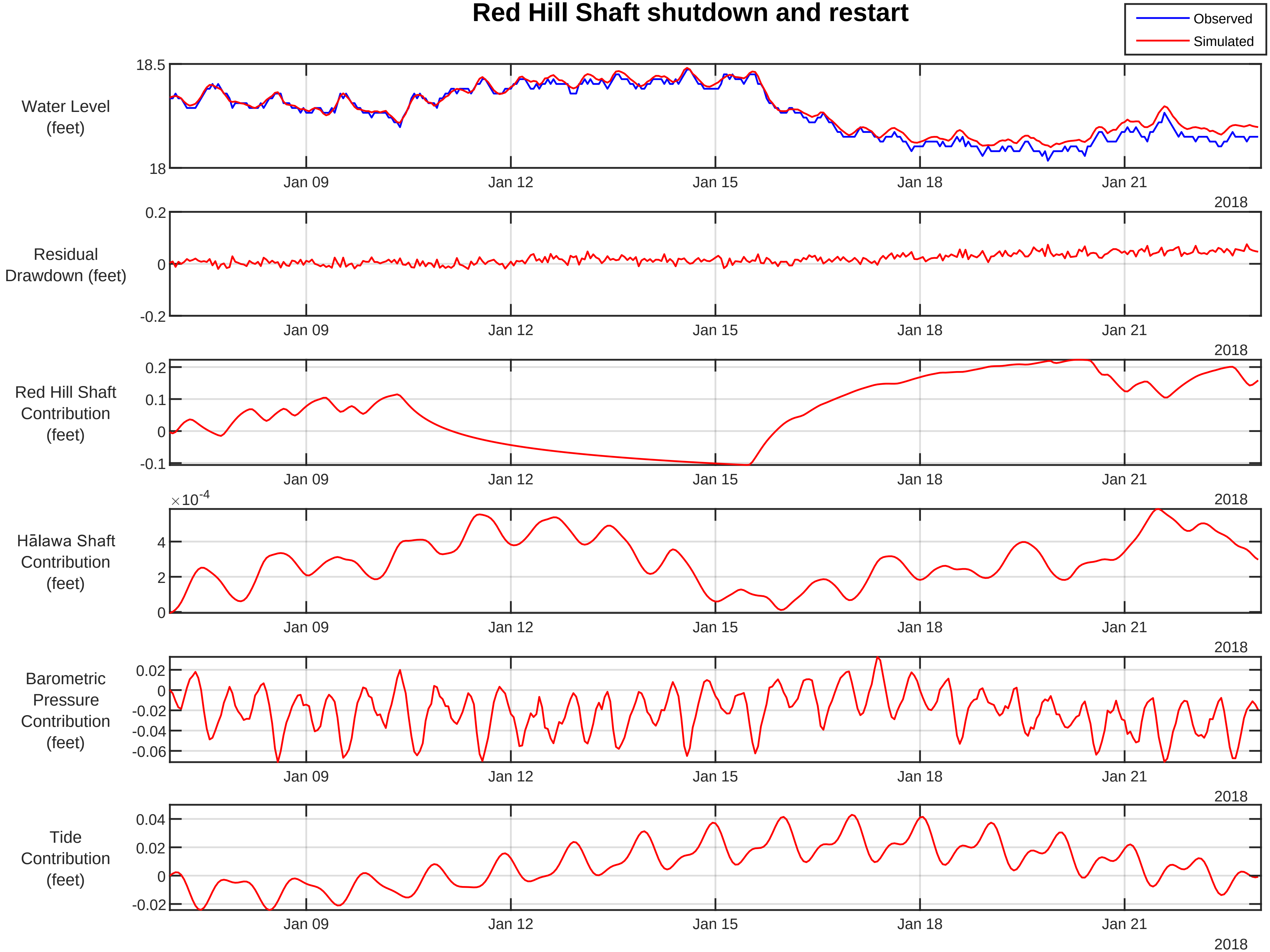




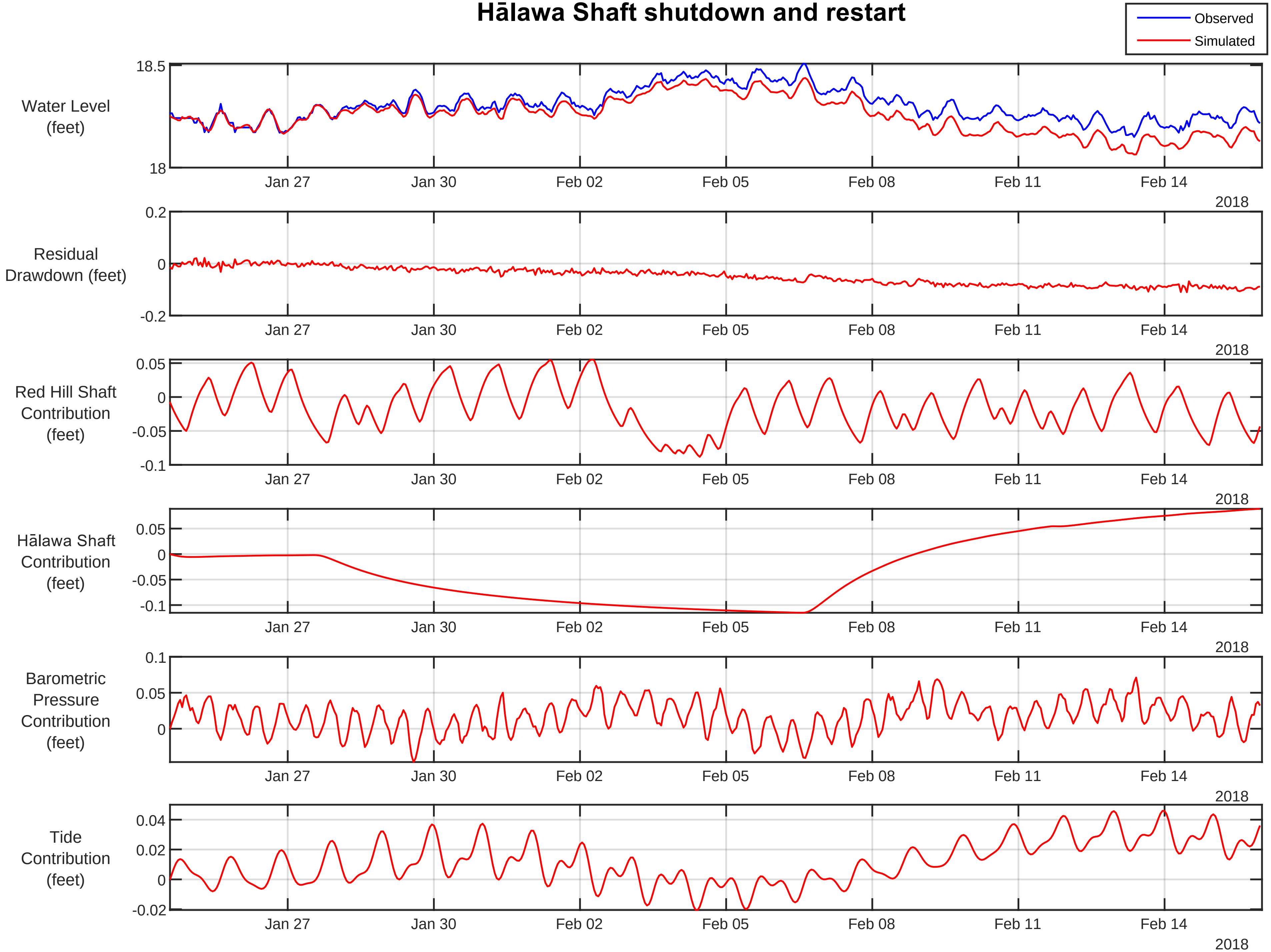
For Red Hill AOC Party Use Only
RHMW11 Z4
Hālawa Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
18.5
18
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.05
0
-0.05
-0.1
Hālawa Shaft Contribution (feet)
0.05
0
-0.05
-0.1
Barometric Pressure Contribution (feet)
0.06
0.04
0.02
0
-0.02
-0.04
Tide Contribution (feet)
0.04
0.02
0
-0.02
Jan 27
Jan 30
Feb 02
Feb 05
Feb 08
Feb 11
Feb 14
2018

RHMW11 Z5

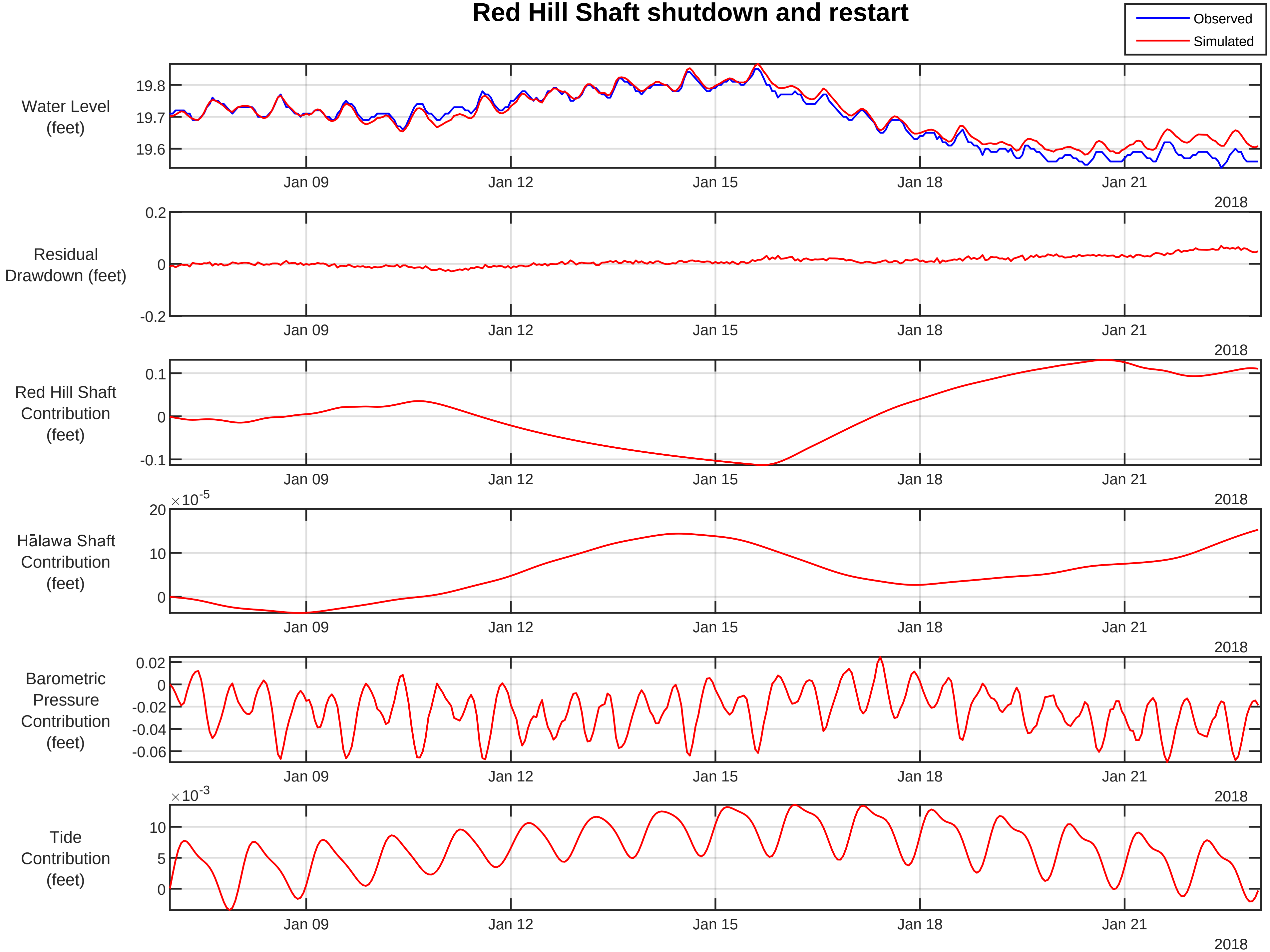
Red Hill Shaft shutdown and restart



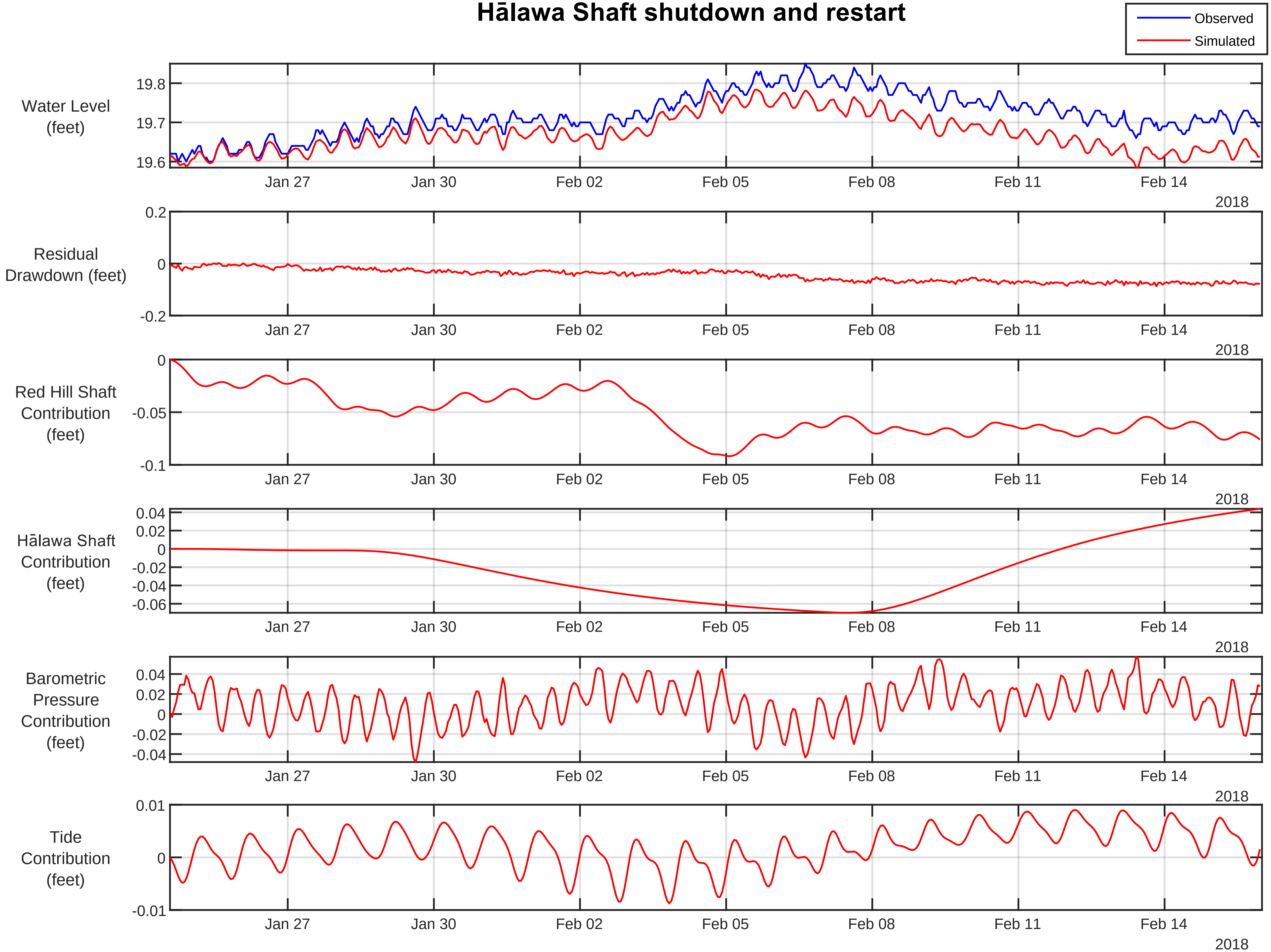
RHMW11 Z5
Hālawa Shaft shutdown and restart

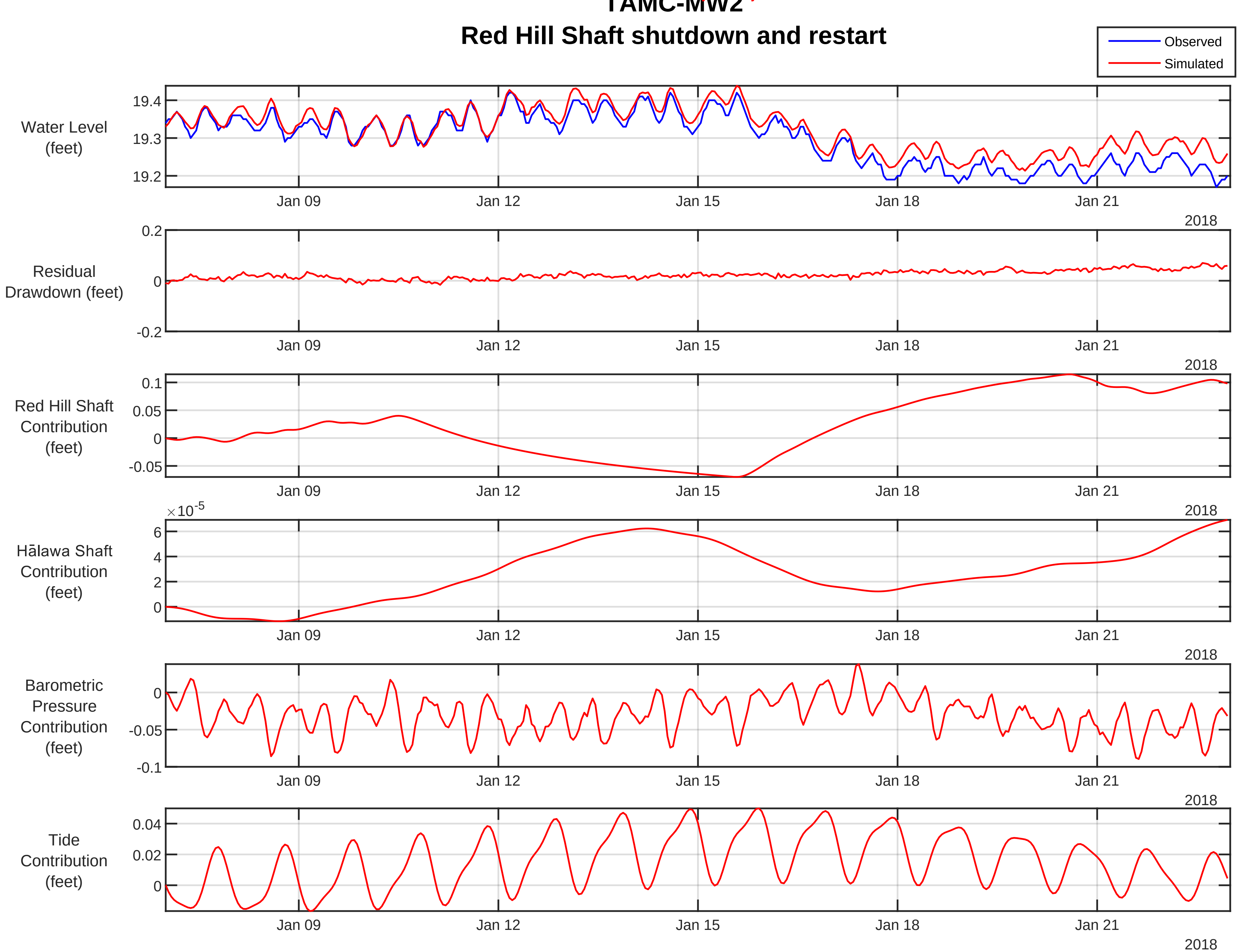


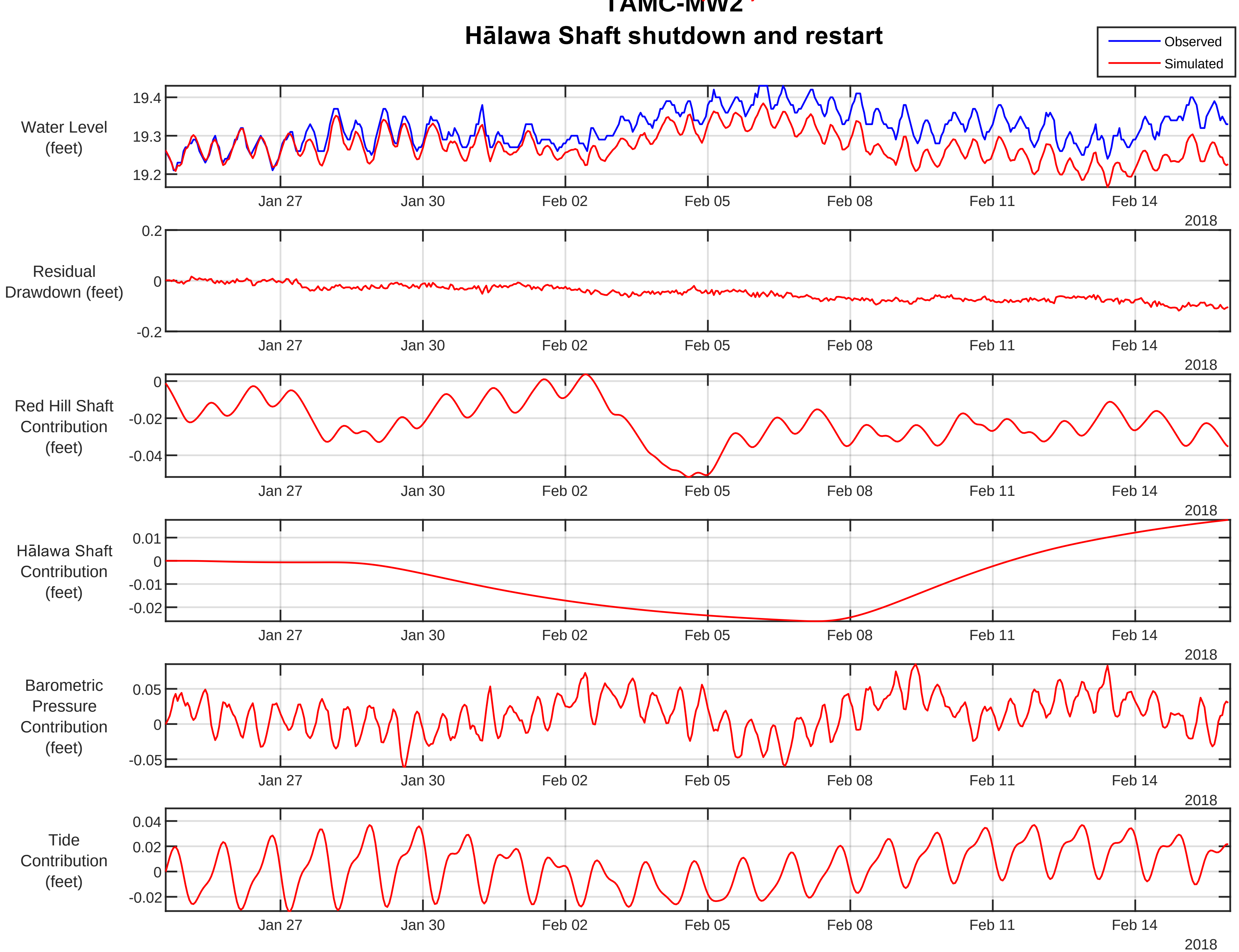
Moanalua DH43
Red Hill Shaft shutdown and restart

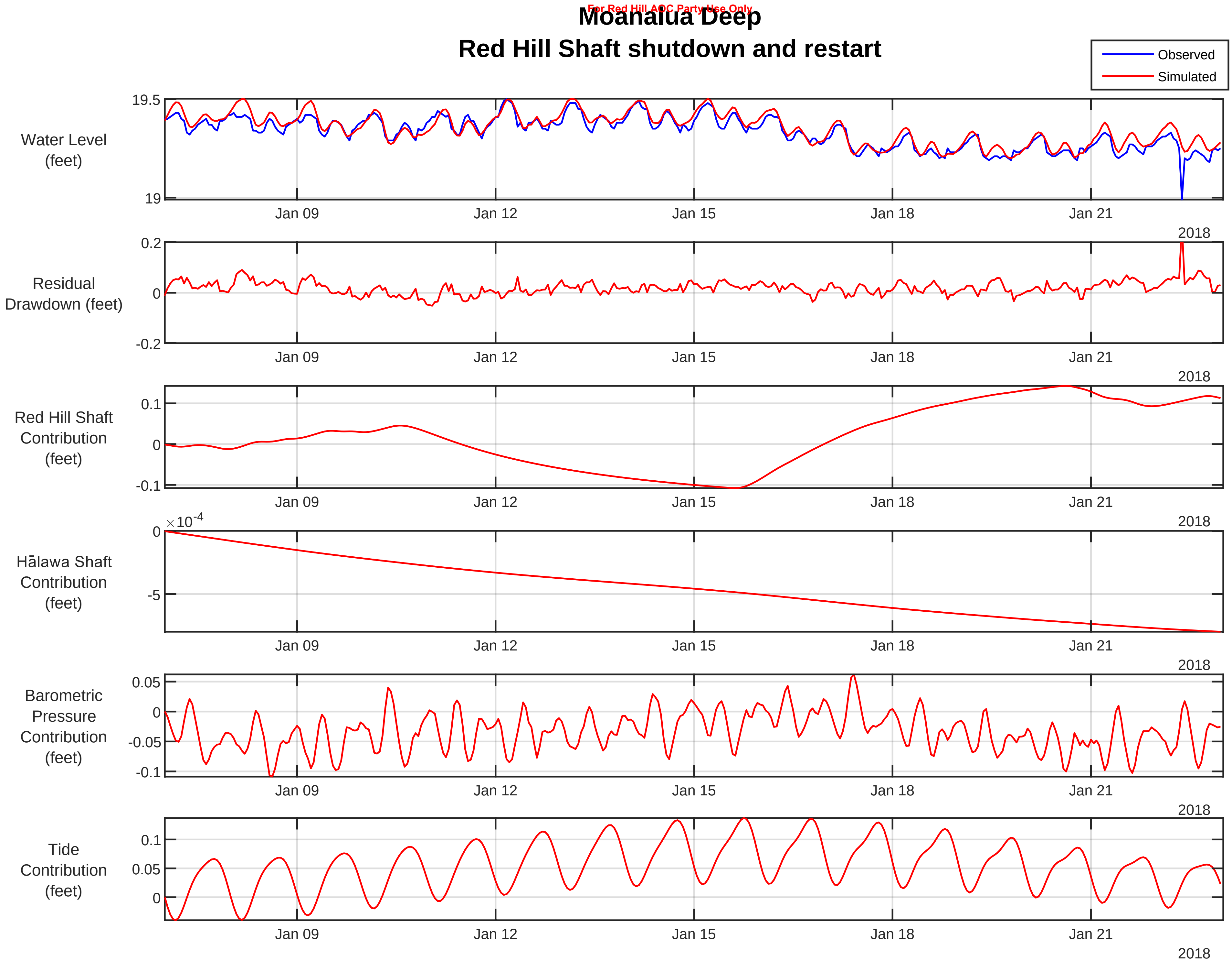


Moanalua DH43
Hālawa Shaft shutdown and restart

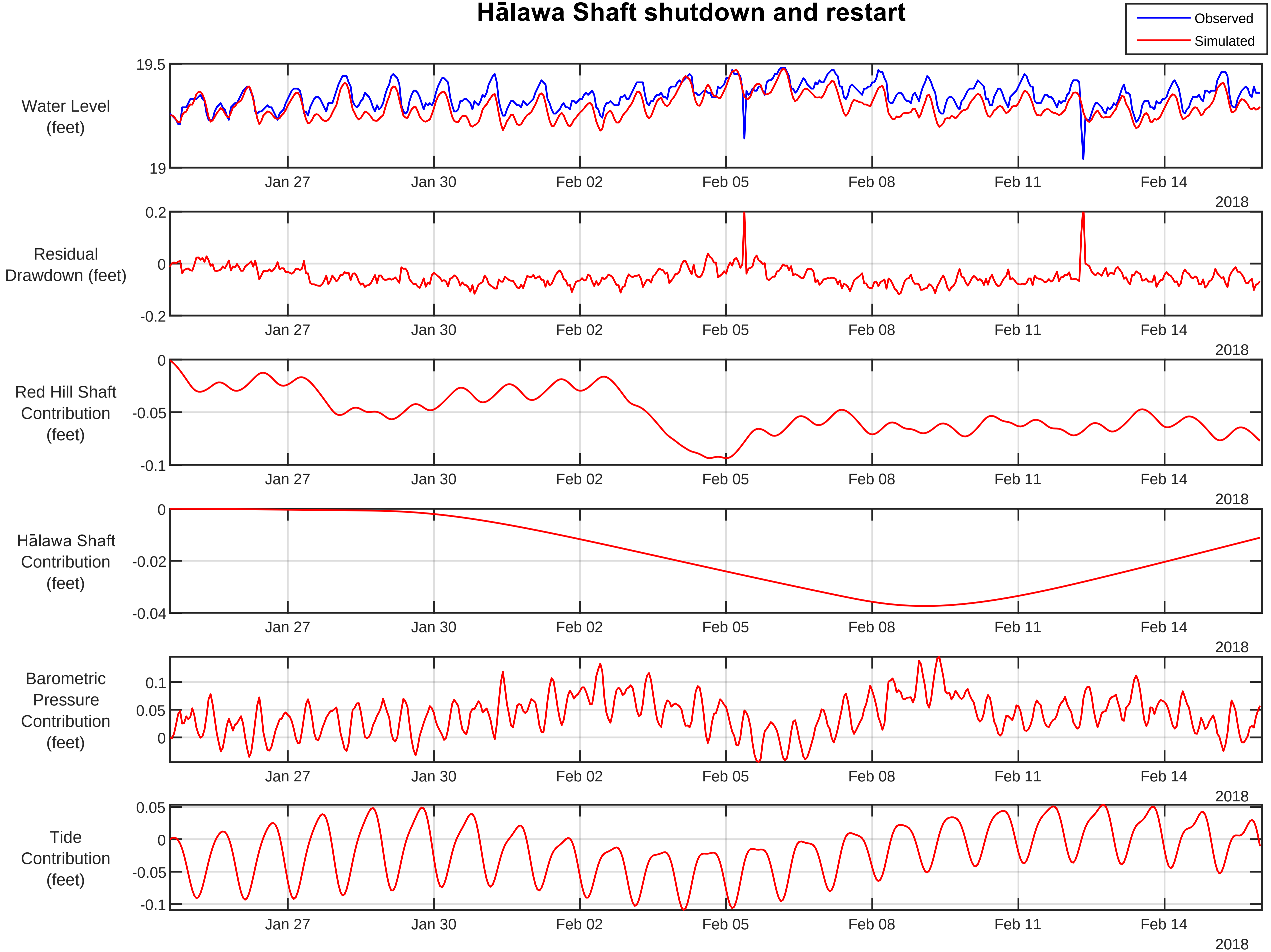


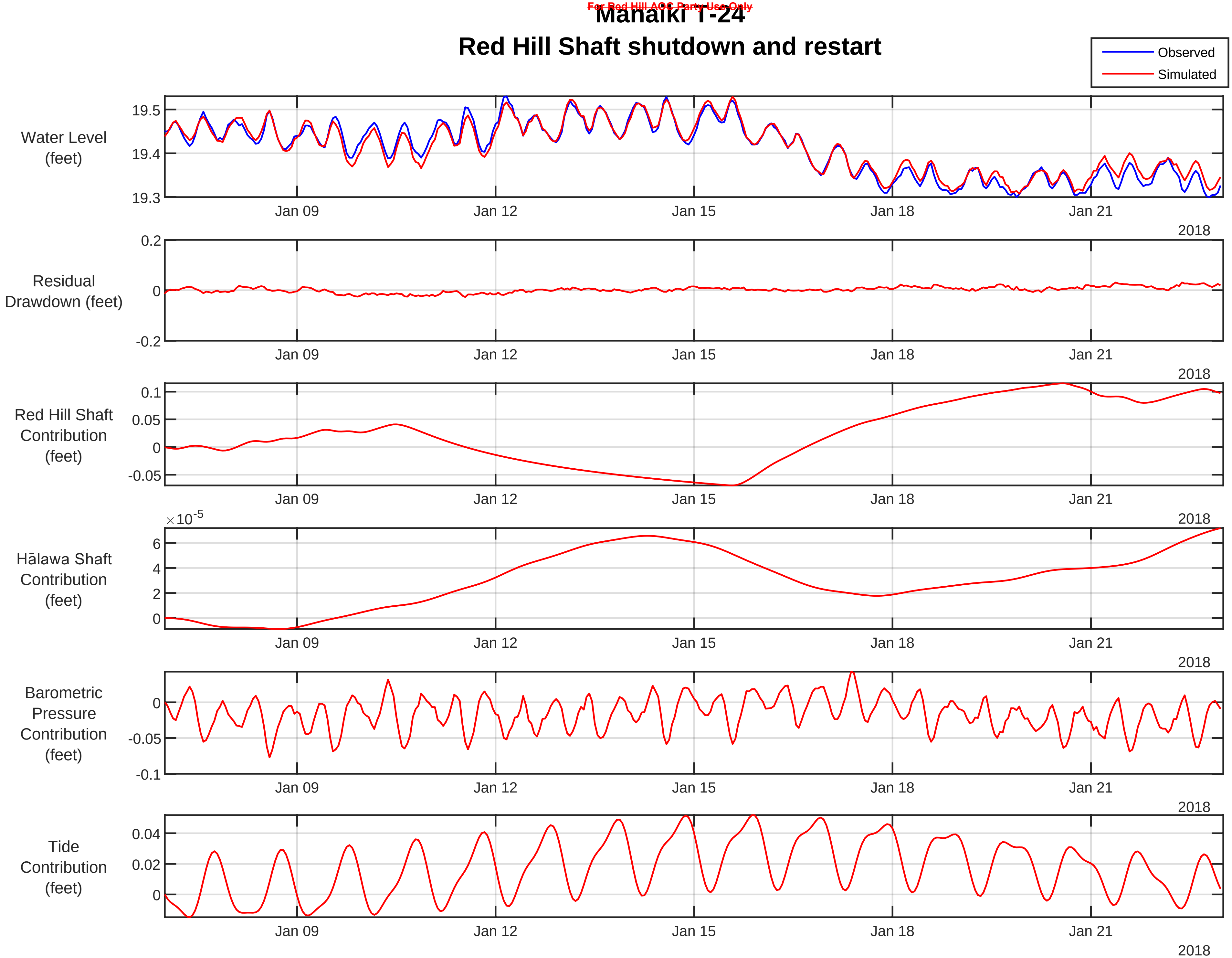

TAMC-MW2
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
19.4
19.3
19.2
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.1
0.05
0
-0.05
Hālawa Shaft Contribution (feet)
×10^-5
6
4
2
0
Barometric Pressure Contribution (feet)
0
-0.05
-0.1
Tide Contribution (feet)
0.04
0.02
0
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018


TAMC-MW2
Hālawa Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
19.4
19.3
19.2
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0
-0.02
-0.04
Hālawa Shaft Contribution (feet)
0.01
0
-0.01
-0.02
Barometric Pressure Contribution (feet)
0.05
0
-0.05
Tide Contribution (feet)
0.04
0.02
0
-0.02
Jan 27
Jan 30
Feb 02
Feb 05
Feb 08
Feb 11
Feb 14
2018


Moanalua Deep
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
19.5
19
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.1
0
-0.1
Hālawa Shaft Contribution (feet)
×10-4
0
-5
Barometric Pressure Contribution (feet)
0.05
0
-0.05
-0.1
Tide Contribution (feet)
0.1
0.05
0
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

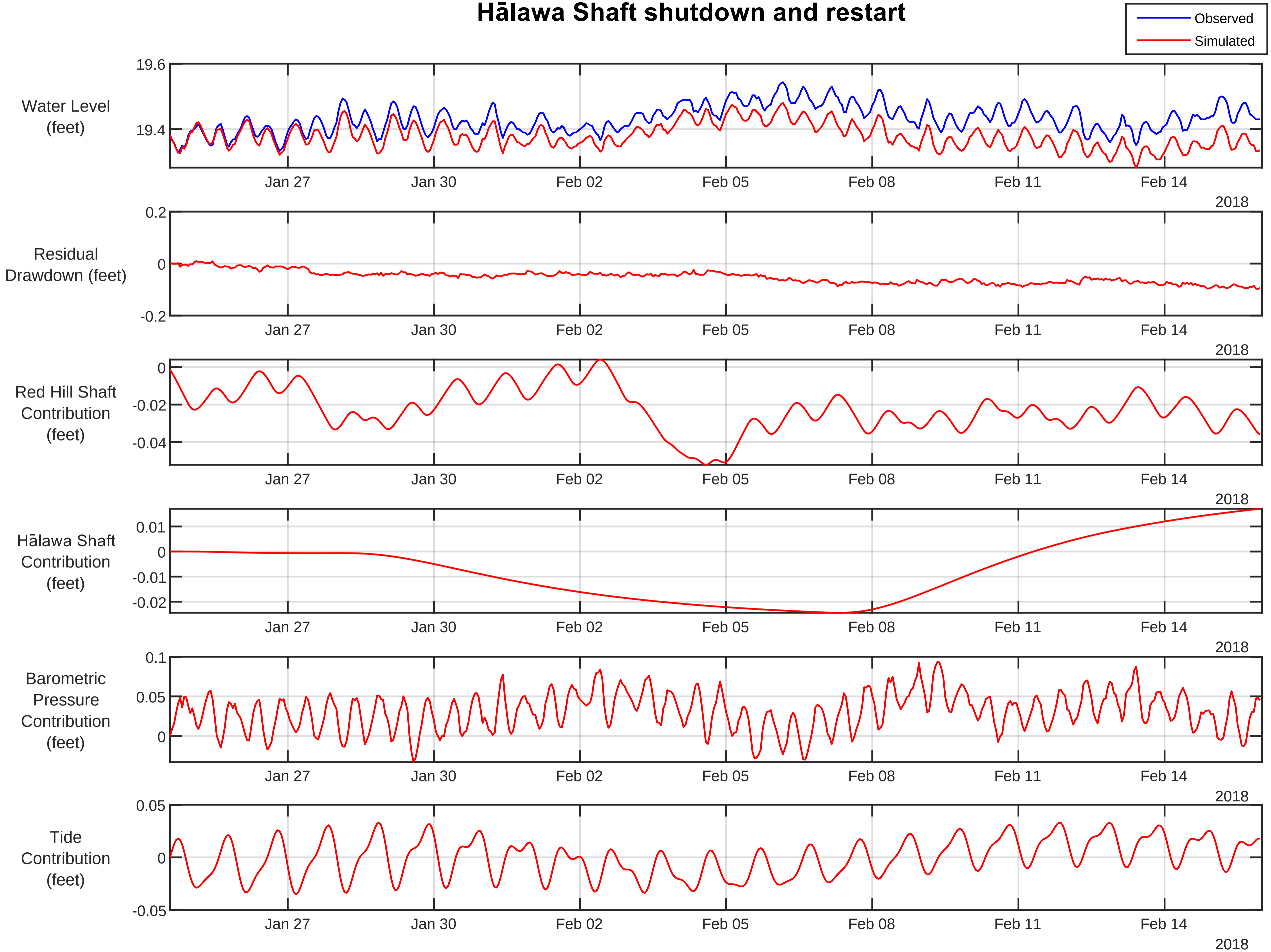
Moanalua Deep
Hālawa Shaft shutdown and restart



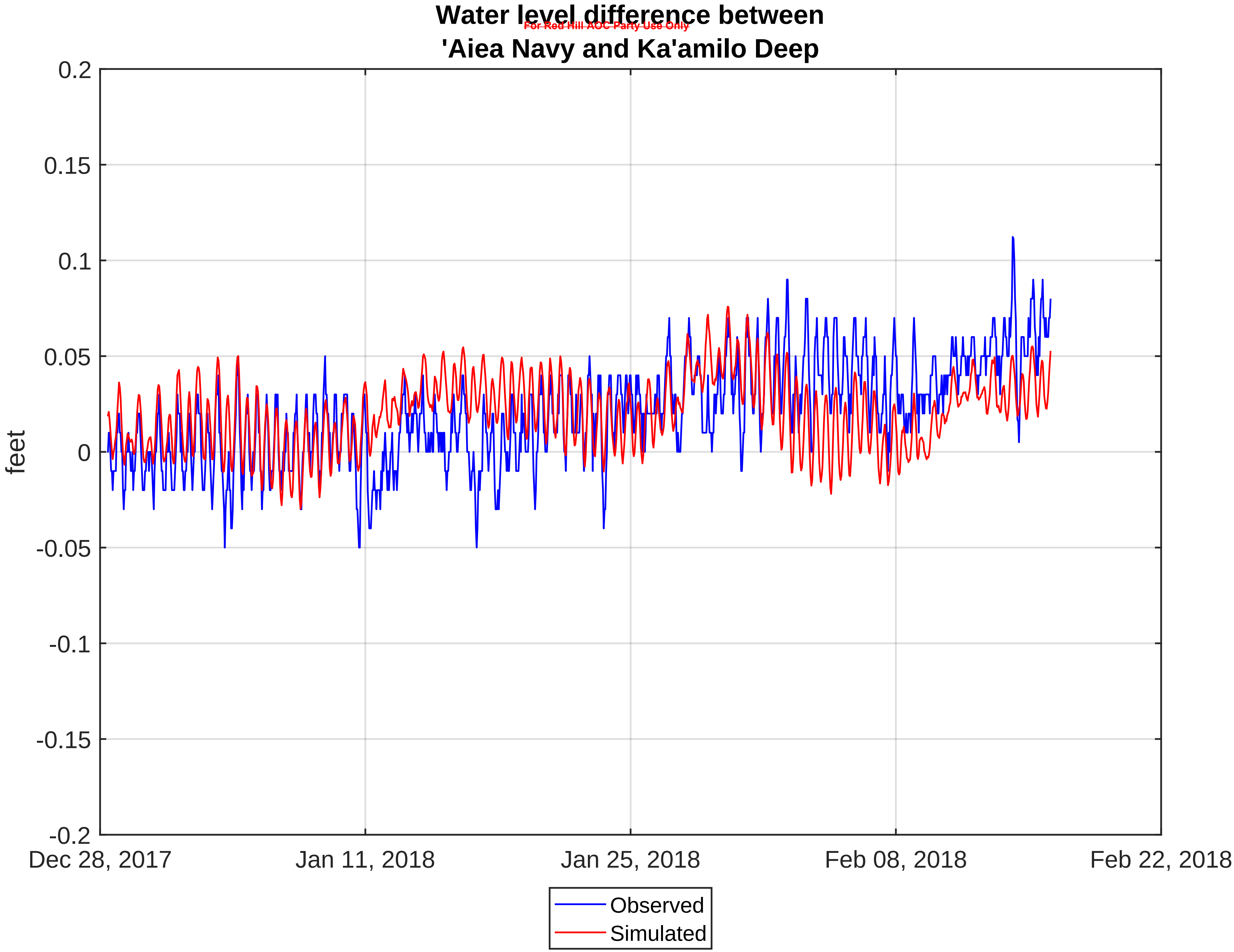


Manaiki T-24
Red Hill Shaft shutdown and restart
Observed
Simulated
Water Level (feet)
19.5
19.4
19.3
Residual Drawdown (feet)
0.2
0
-0.2
Red Hill Shaft Contribution (feet)
0.1
0.05
0
-0.05
×10^-5
Hālawa Shaft Contribution (feet)
6
4
2
0
Barometric Pressure Contribution (feet)
0
-0.05
-0.1
Tide Contribution (feet)
0.04
0.02
0
Jan 09
Jan 12
Jan 15
Jan 18
Jan 21
2018

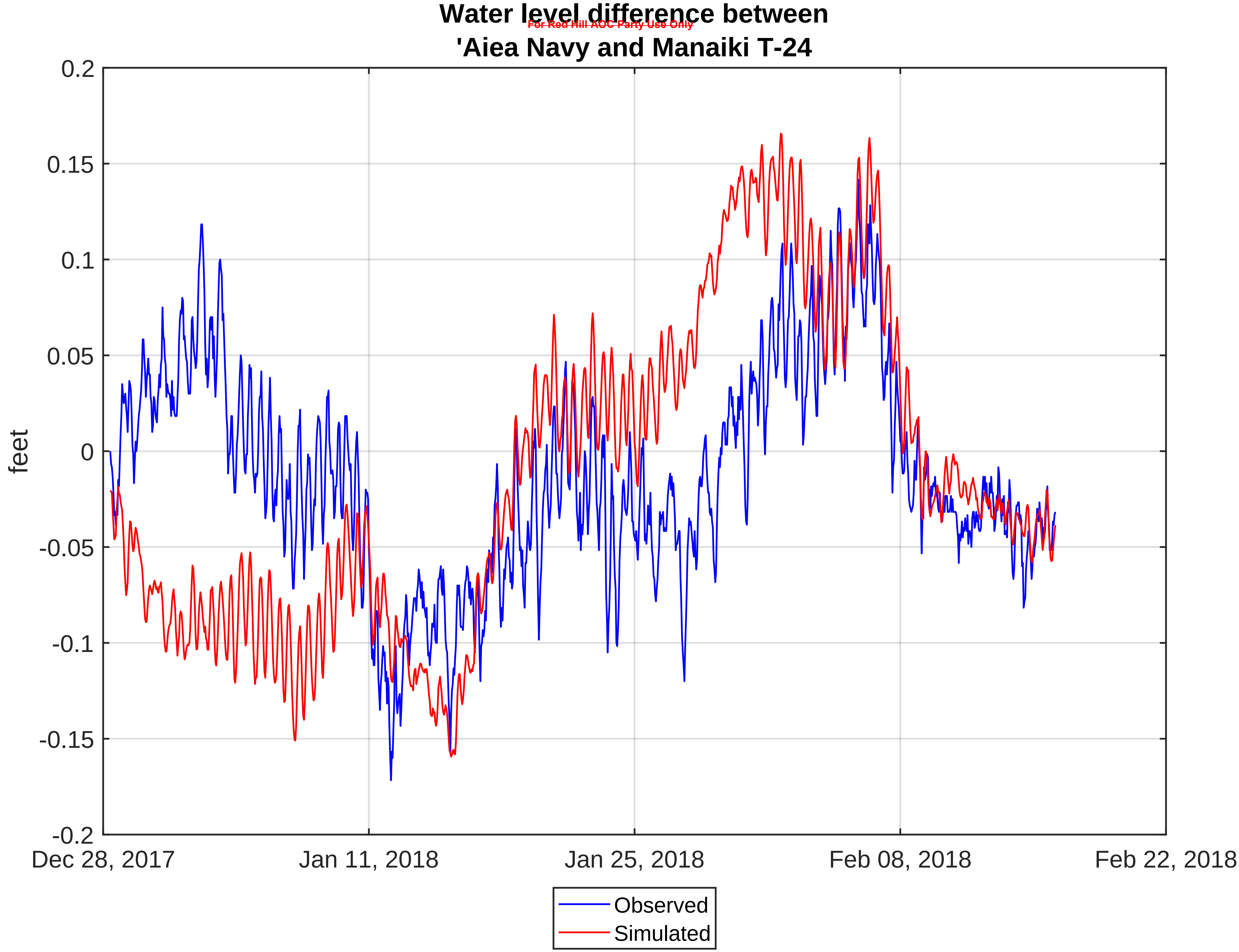
Manaiki T-24
Hālawa Shaft shutdown and restart



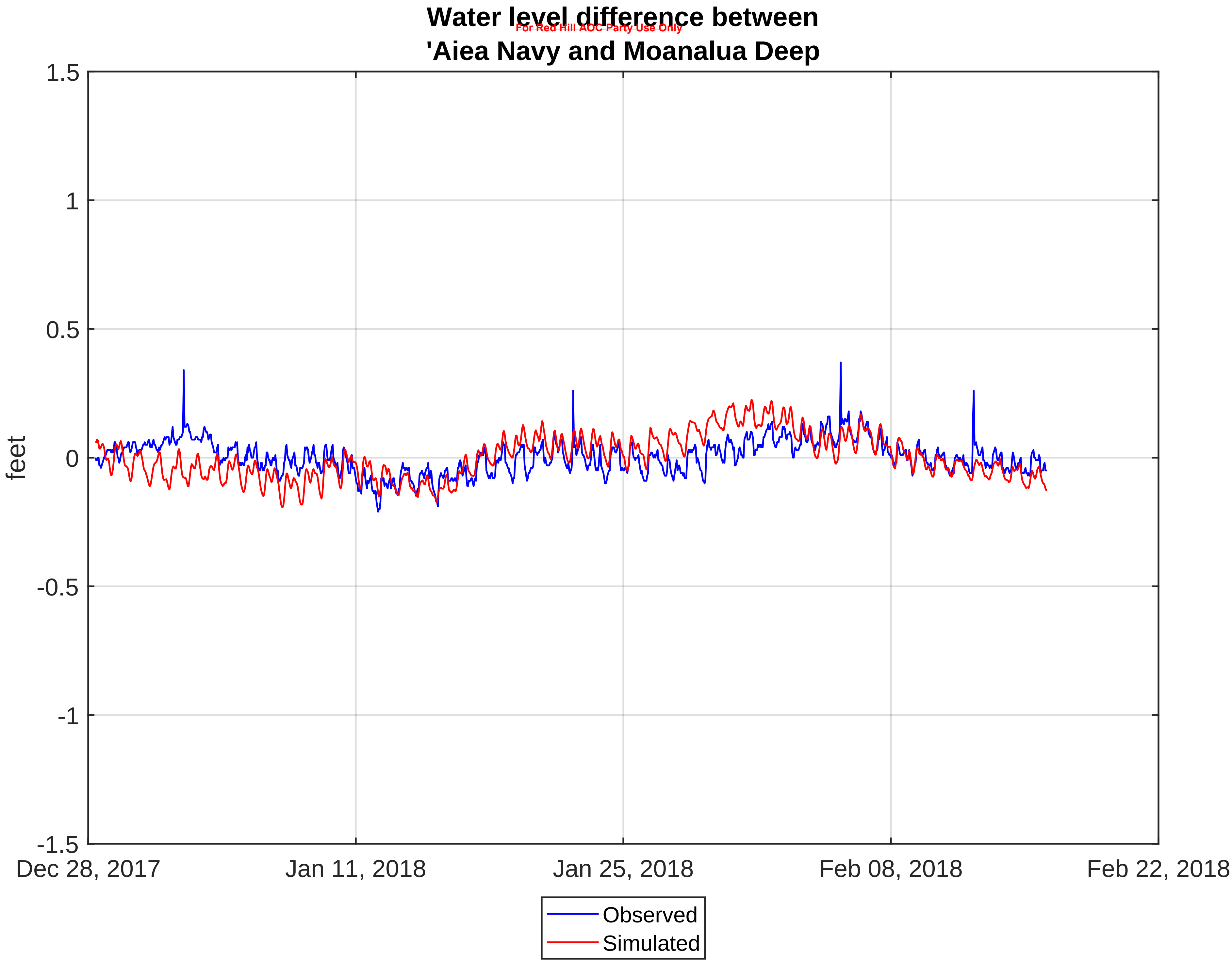
Attachment A.2
Comparison of Transfer Function-Noise Model Simulated and Observed Water Level Differences Between Well Pairs



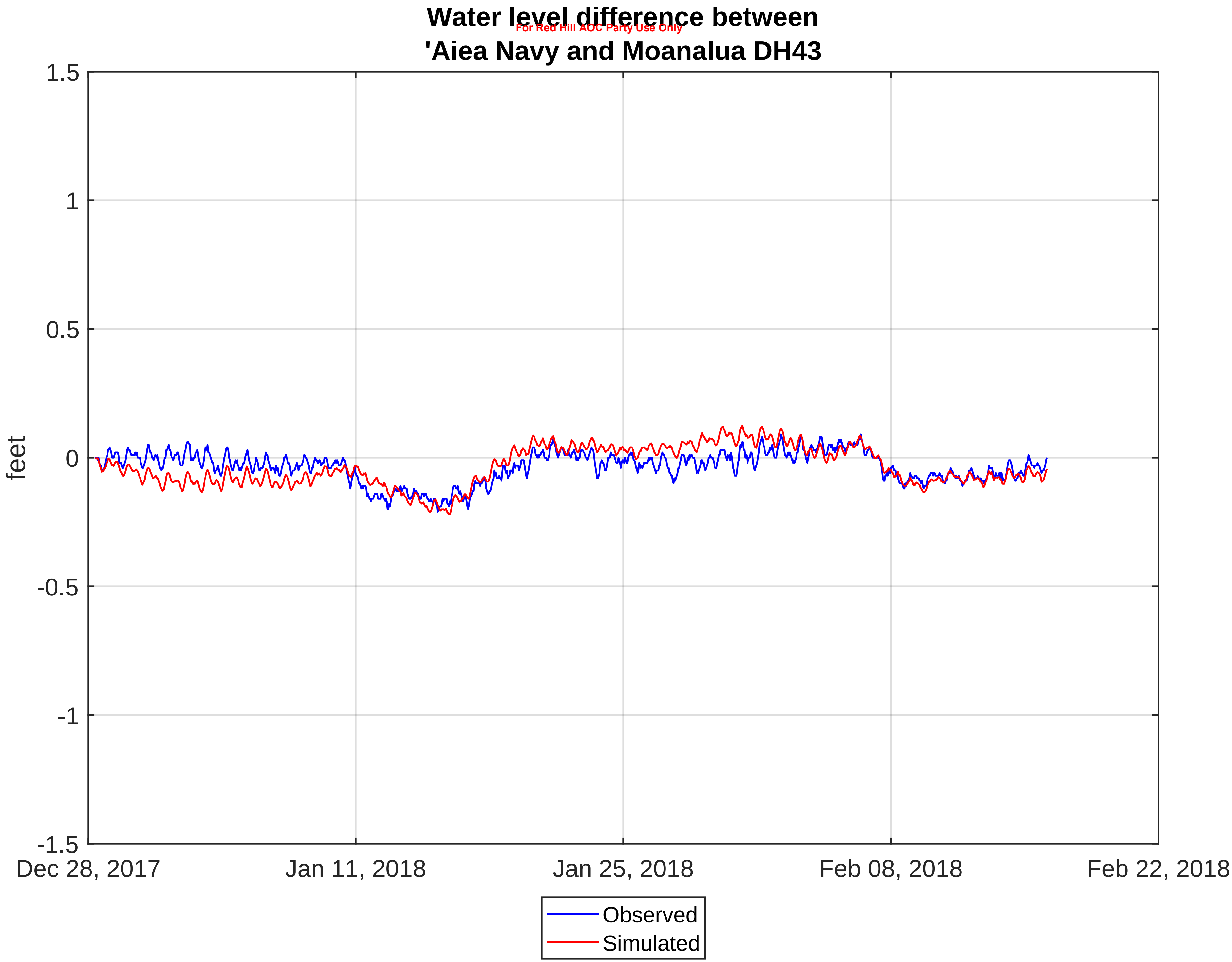
Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and Ka'amilo Deep
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

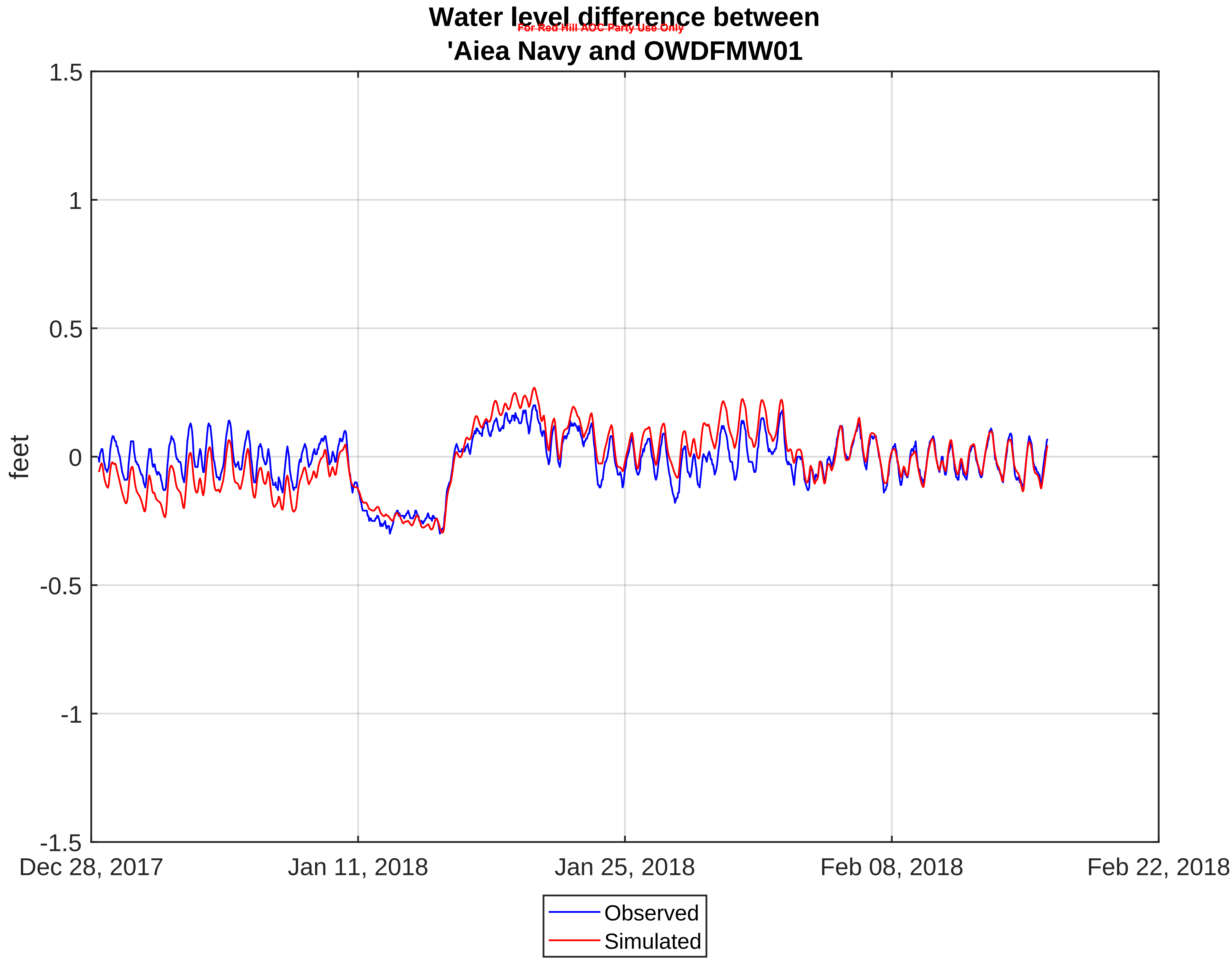


Water level difference between
'Aiea Navy and Manaiki T-24
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

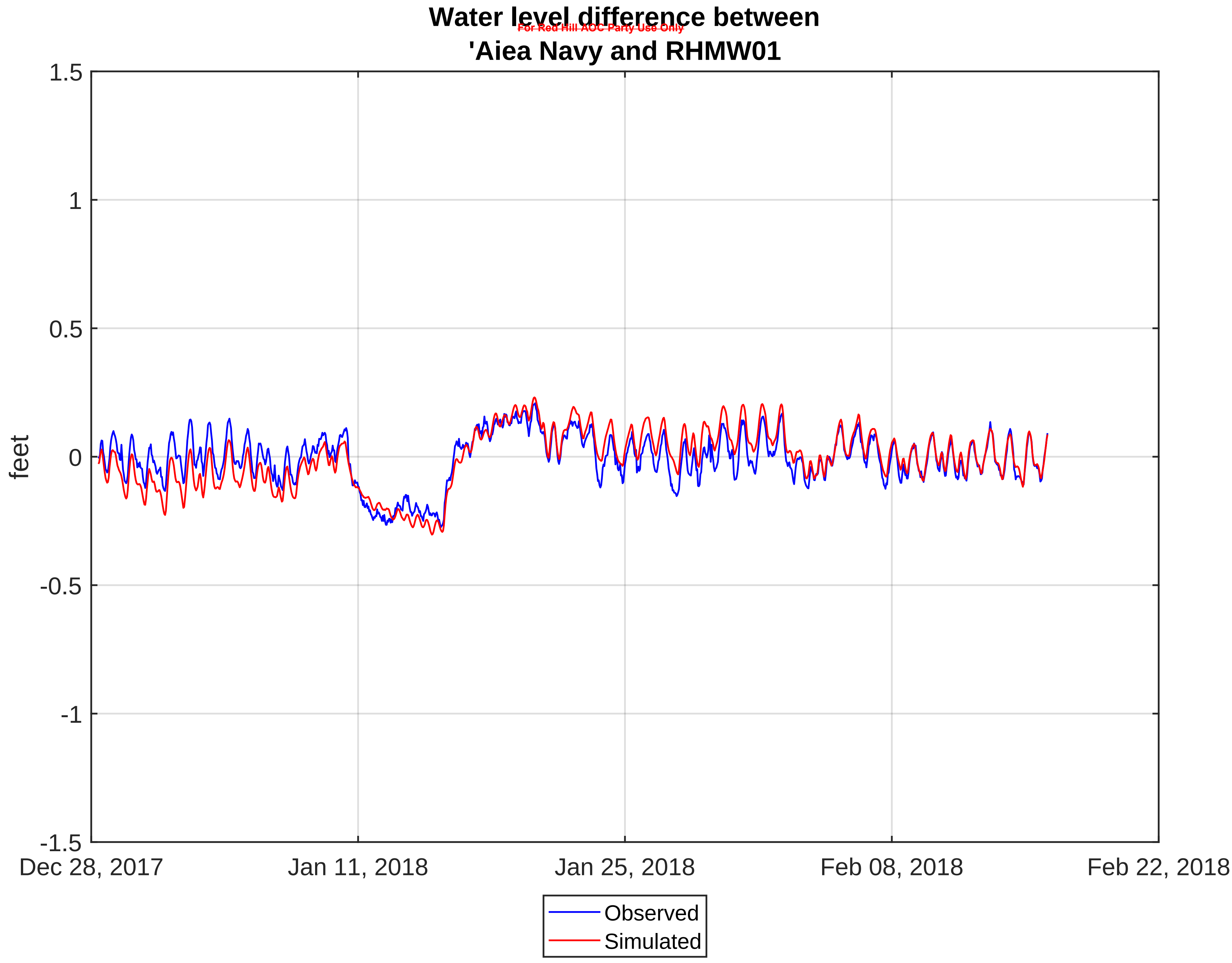


Water level difference between
'Aiea Navy and Moanalua Deep
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

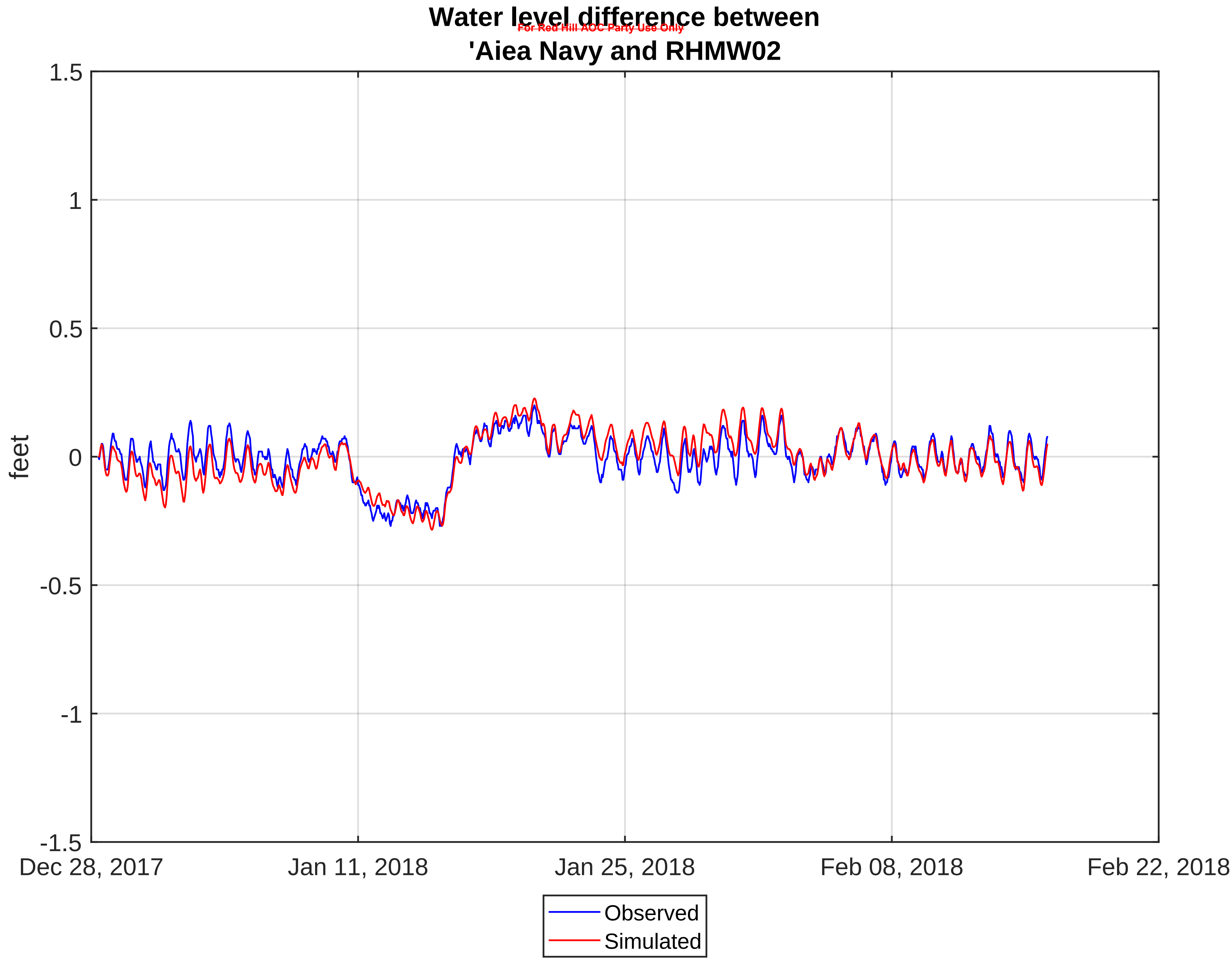

Water level difference between
'Aiea Navy and Moanalua DH43
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
'Aiea Navy and OWDFMW01
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

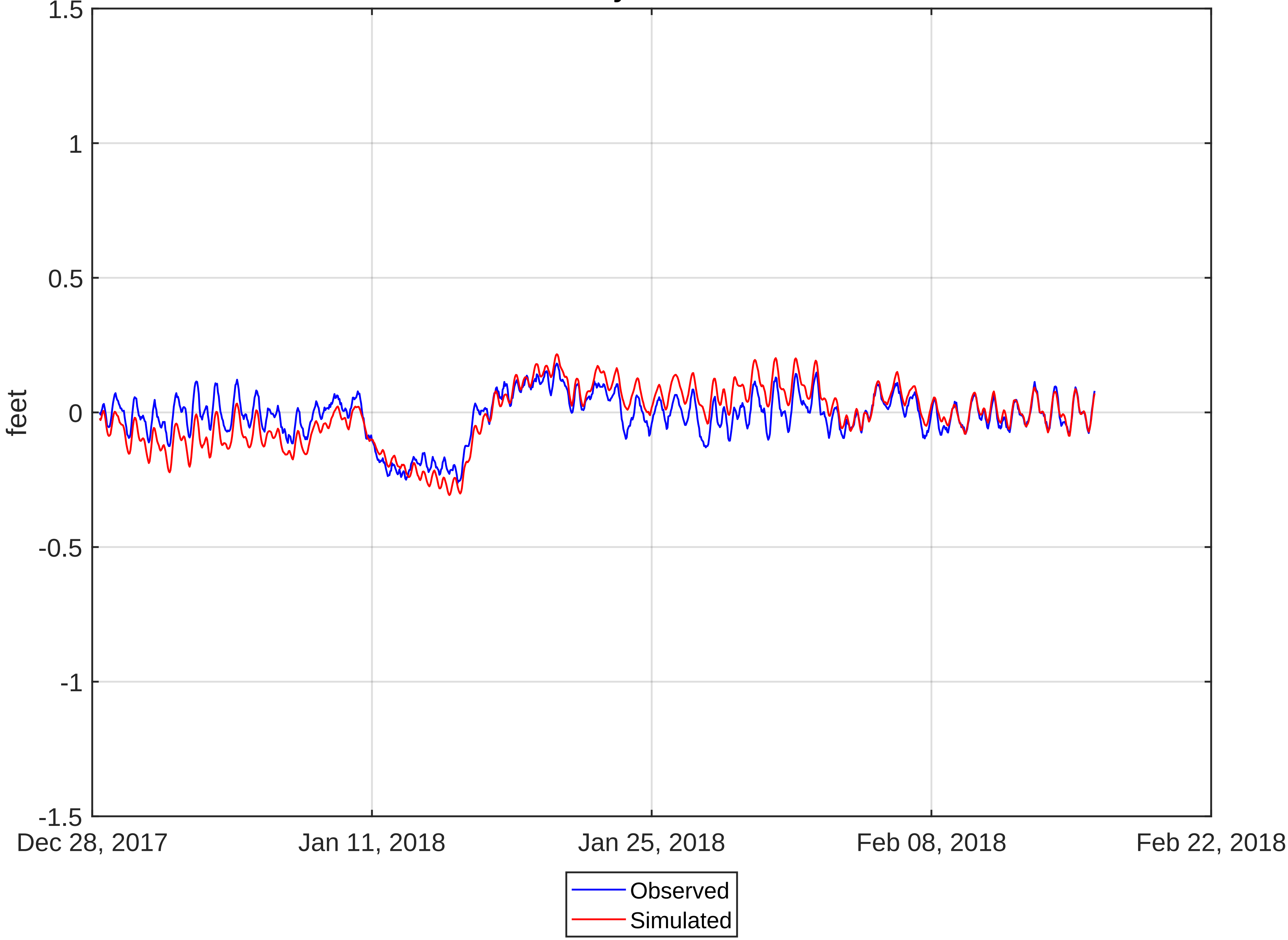


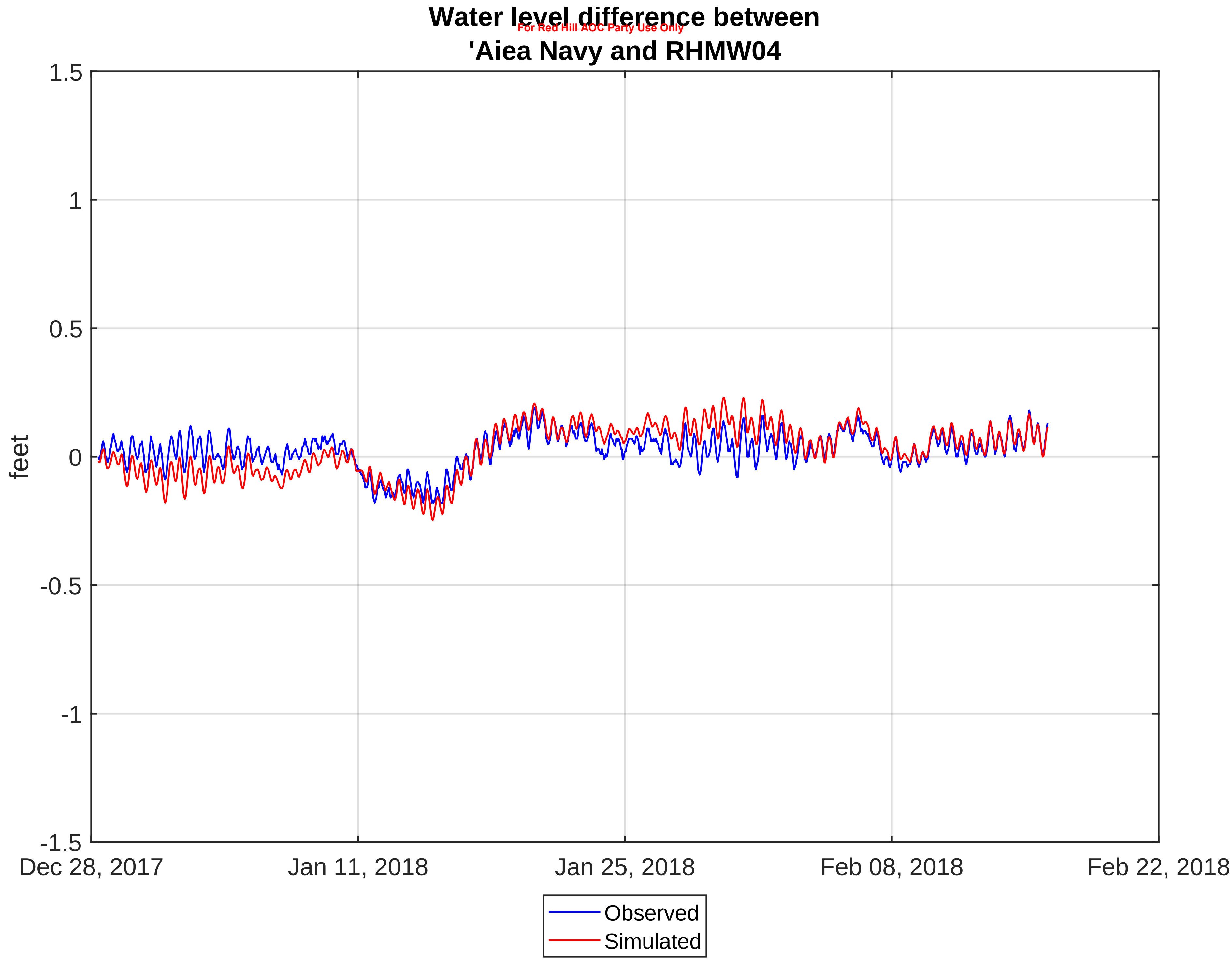
Water level difference between
'Aiea Navy and RHMW01
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and RHMW02
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

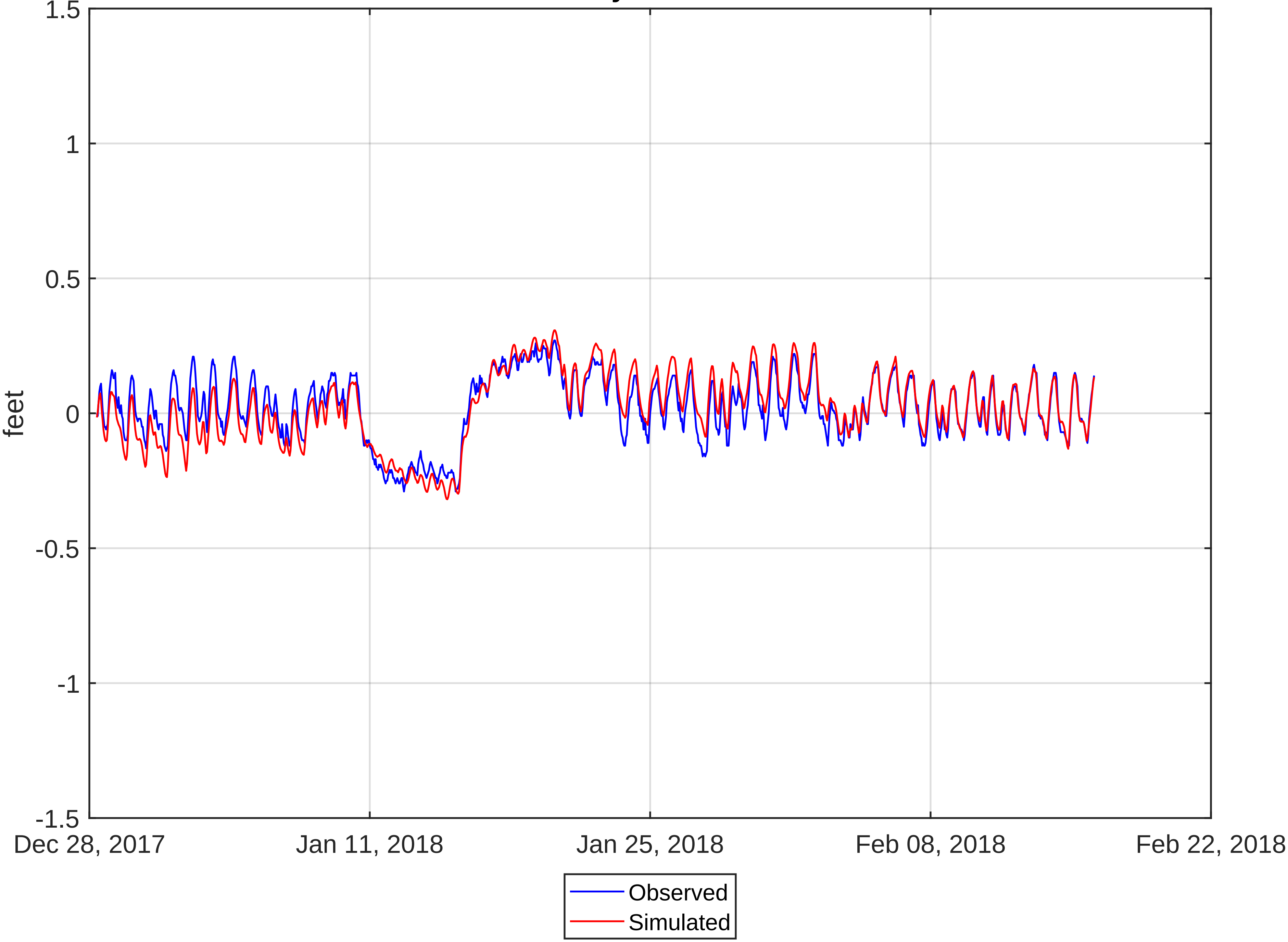
Water level difference between 'Aiea Navy and RHMW03

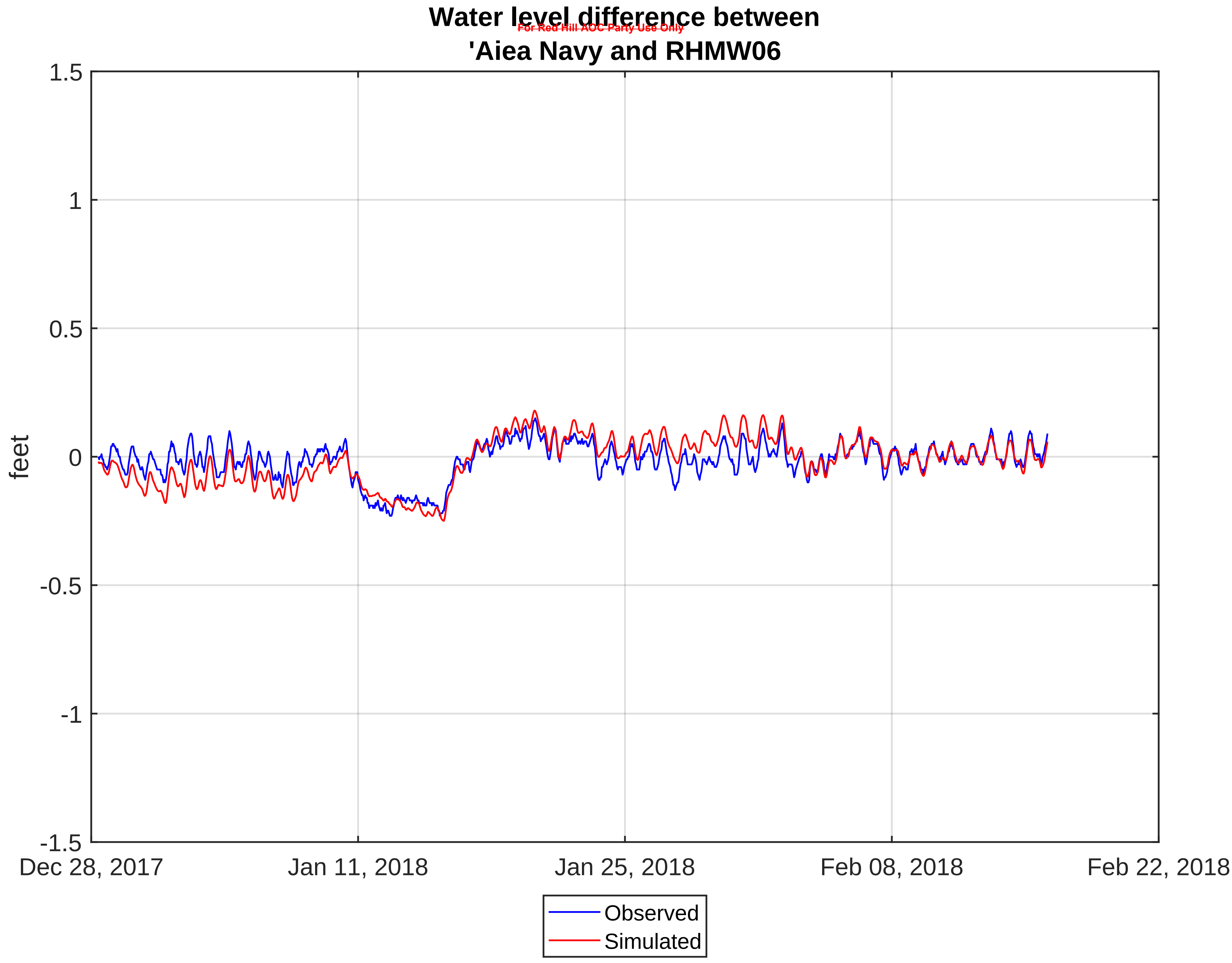




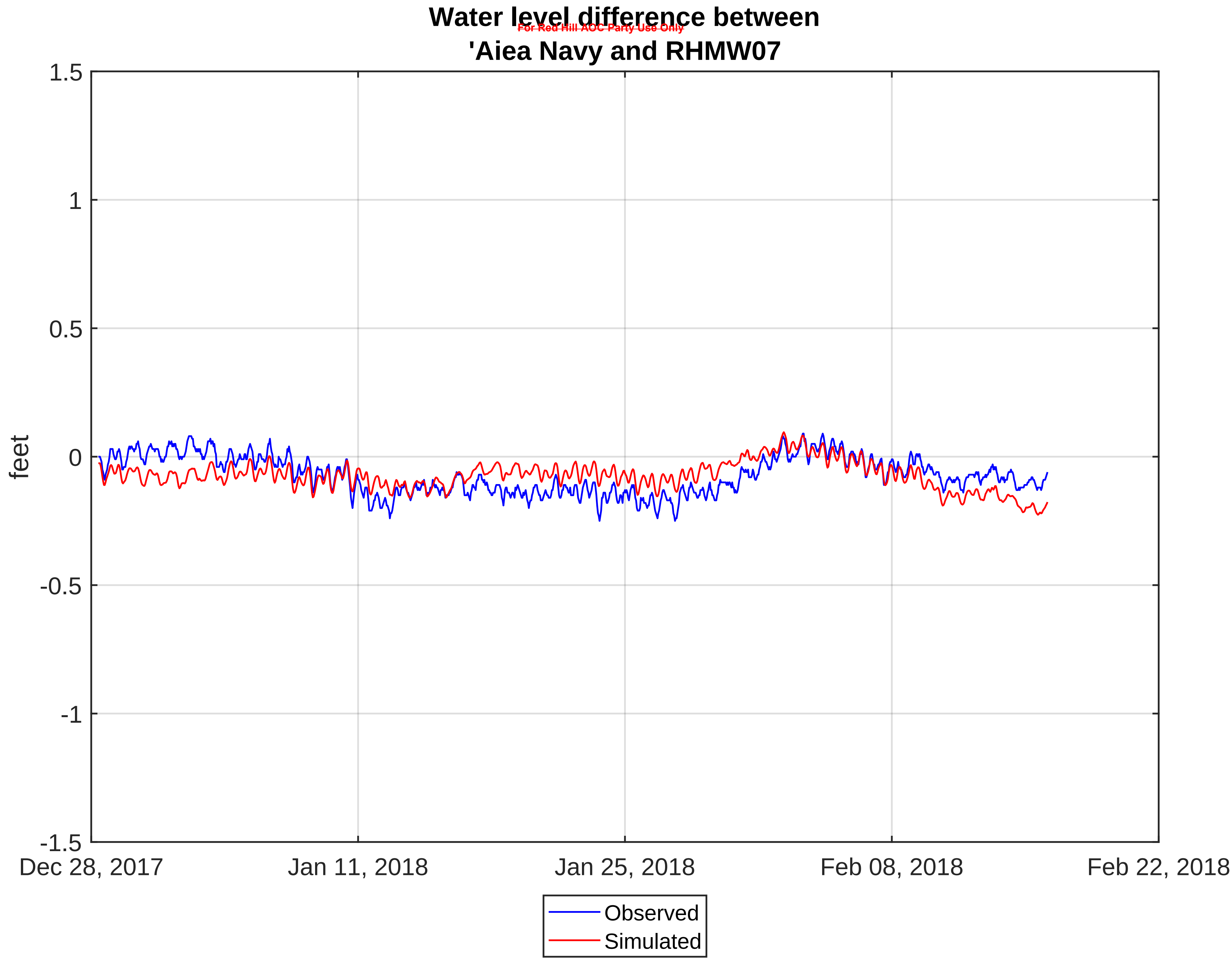
Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and RHMW04
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between 'Aiea Navy and RHMW05

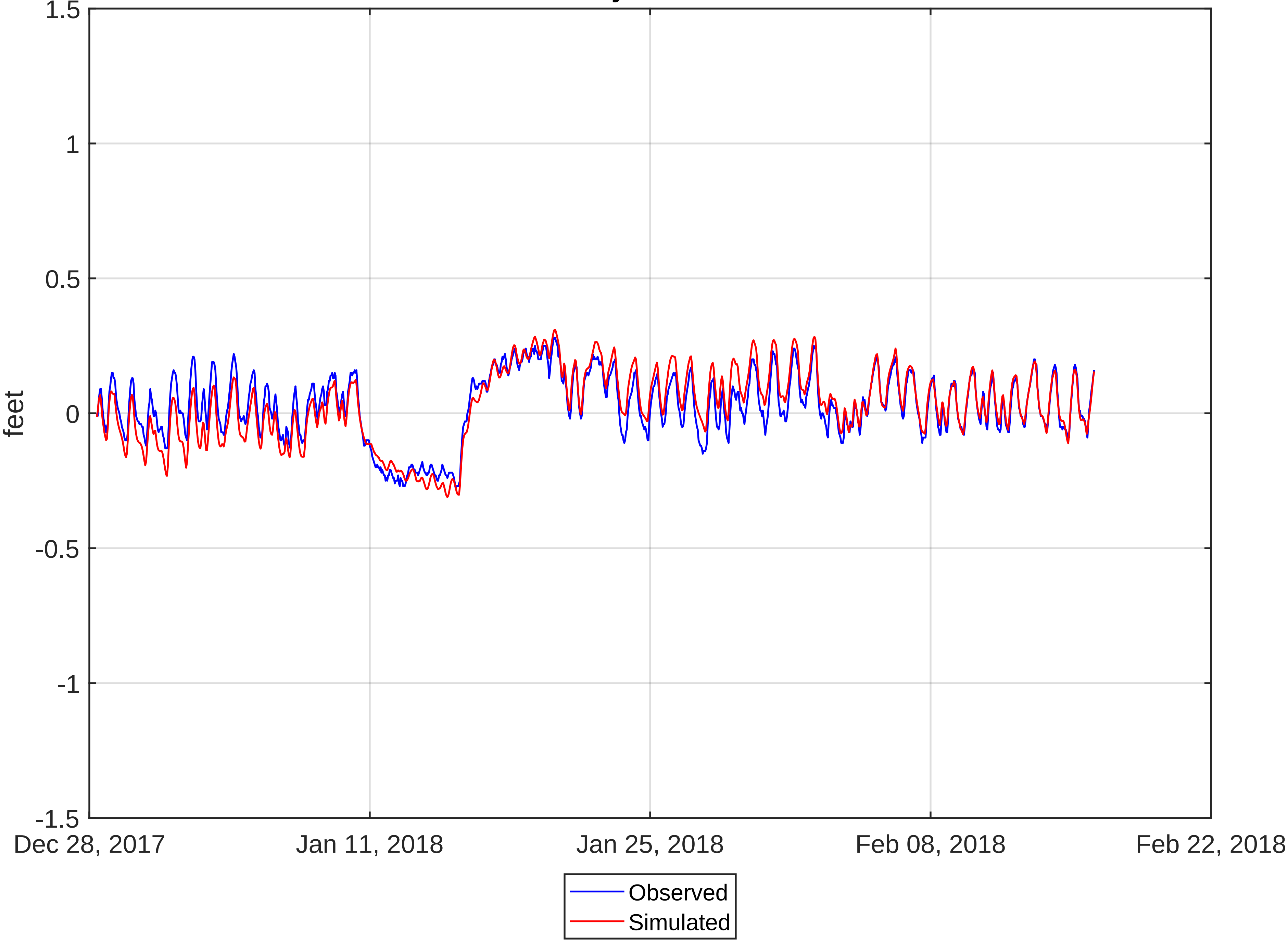


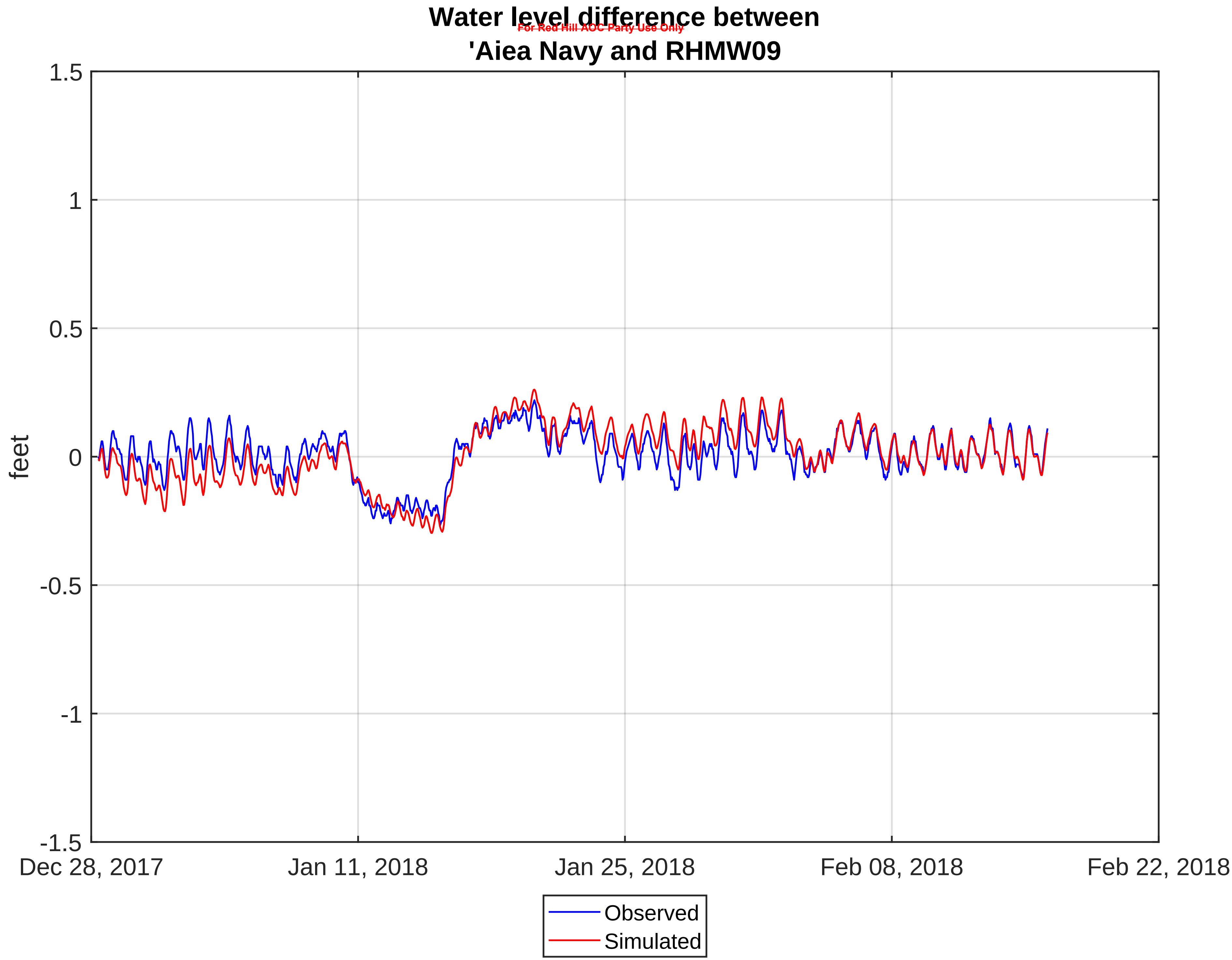


Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and RHMW06
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and RHMW07
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

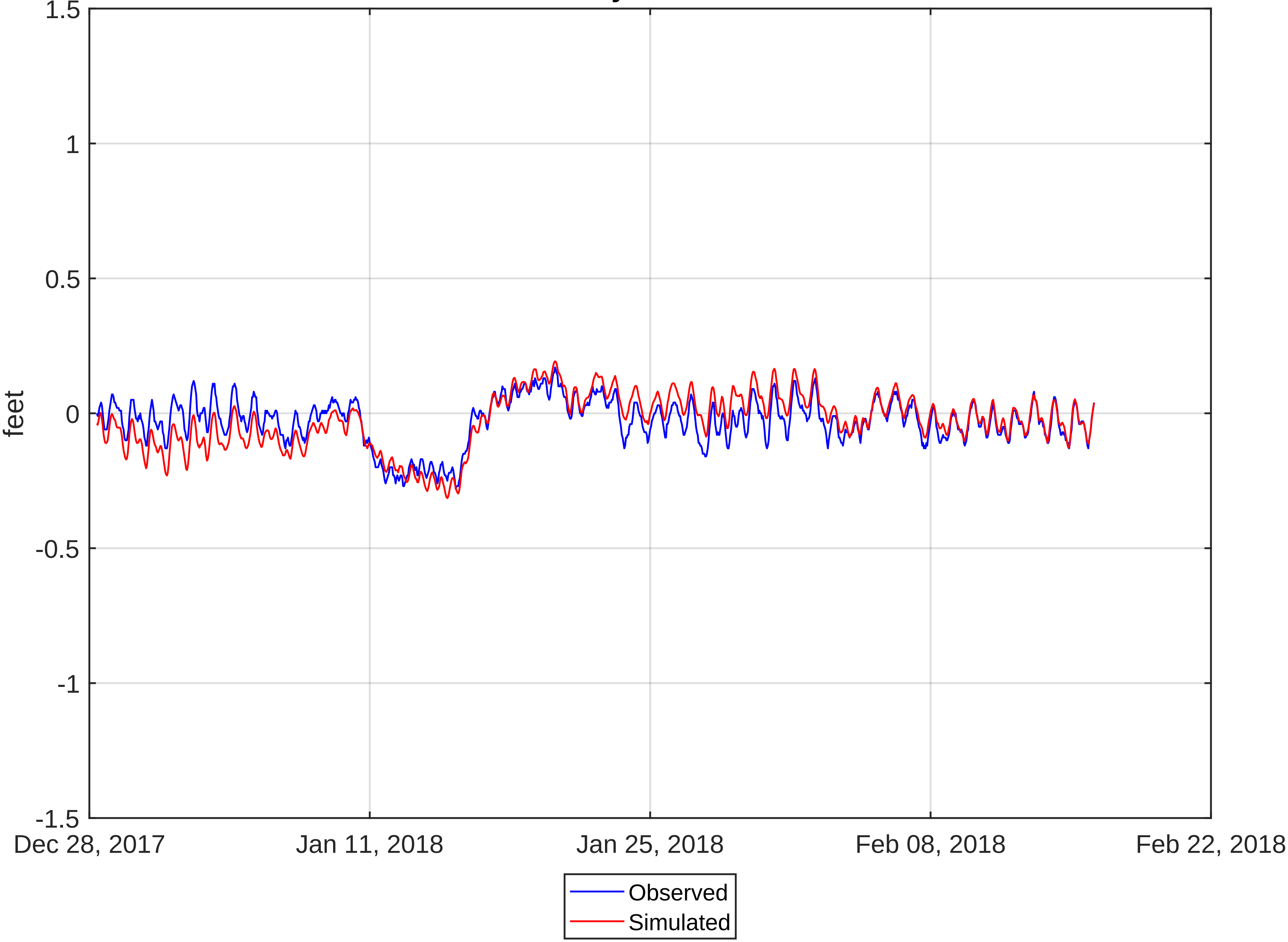
Water level difference between 'Aiea Navy and RHMW08

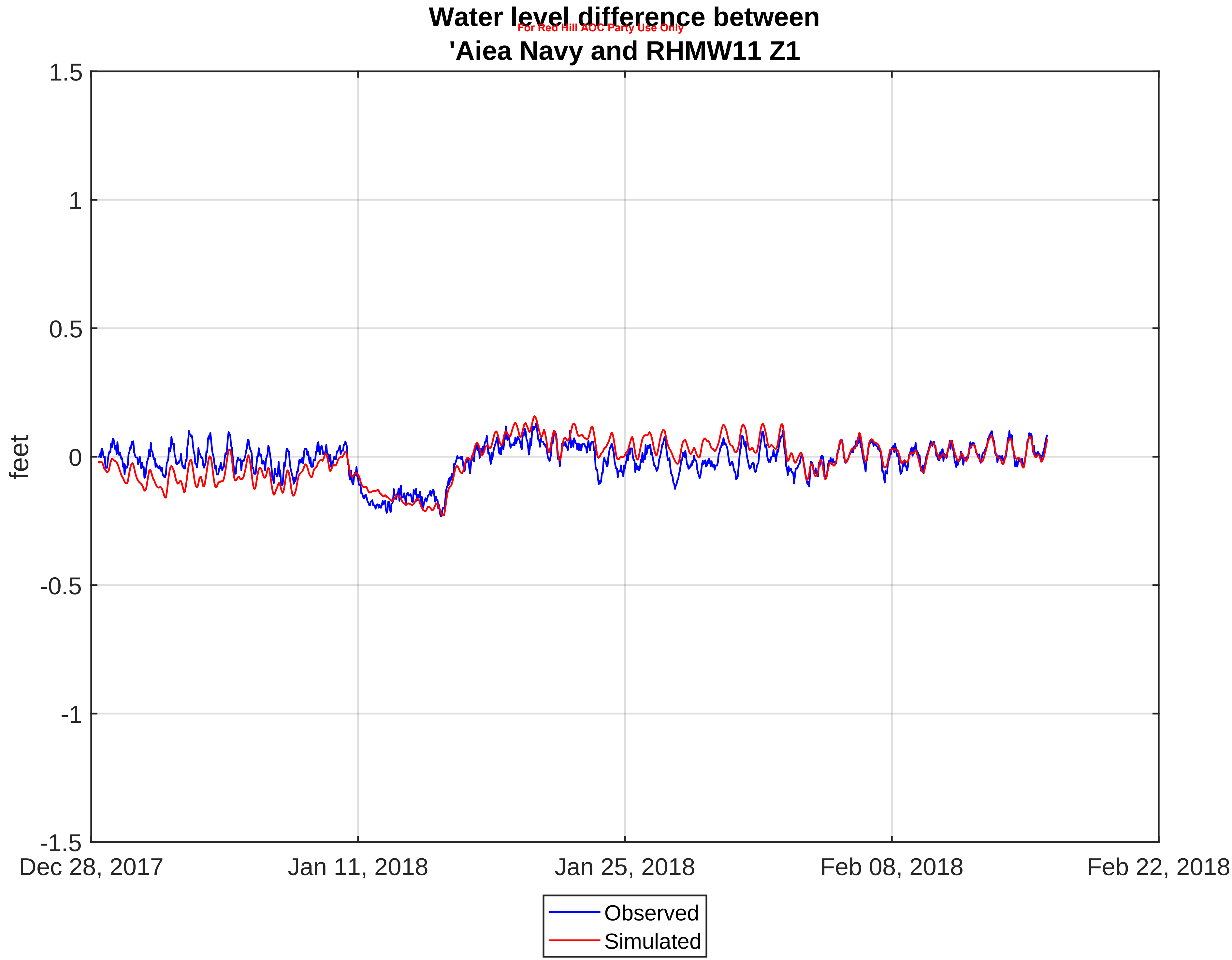




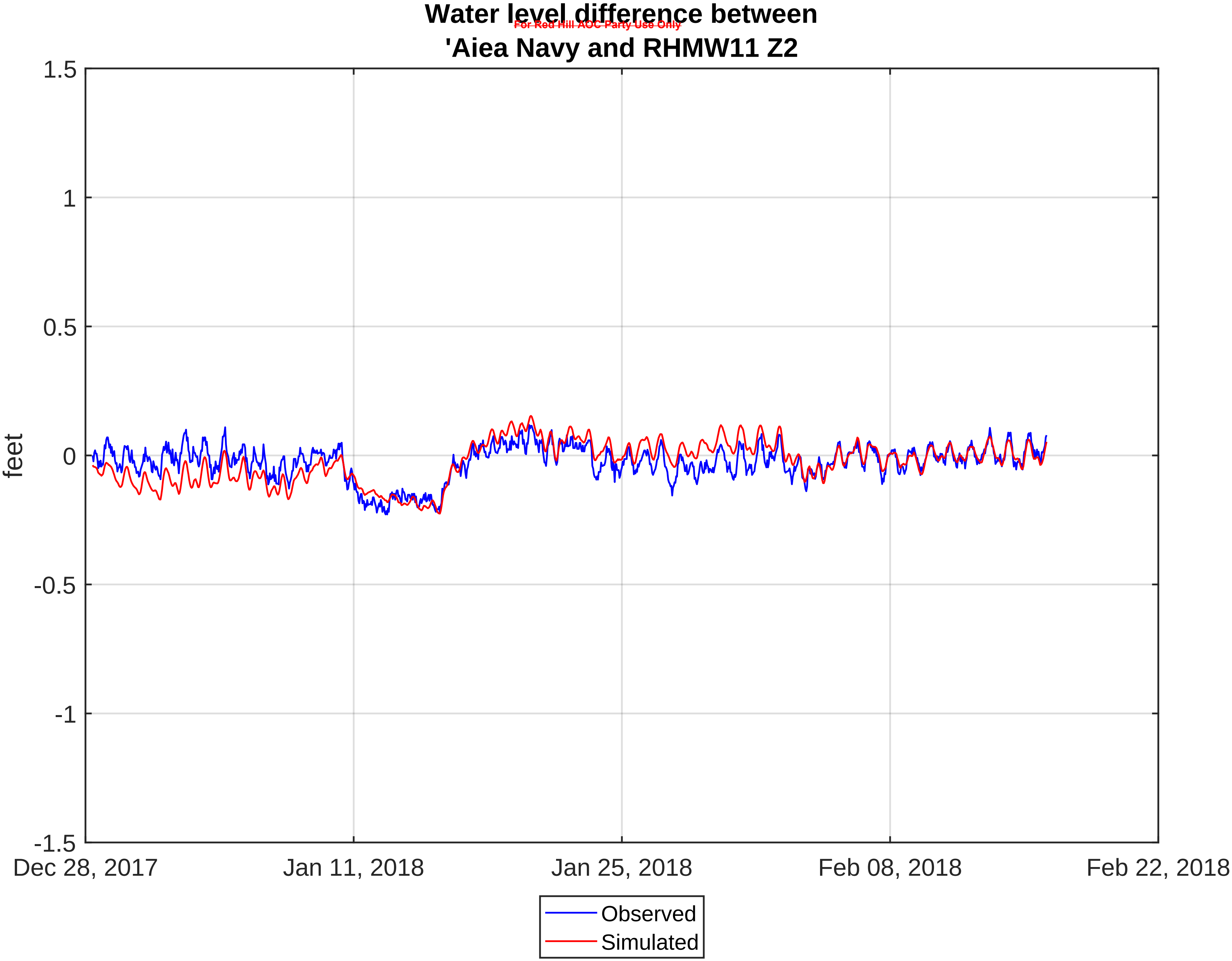
Water level difference between
'Aiea Navy and RHMW09
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between 'Aiea Navy and RHMW10

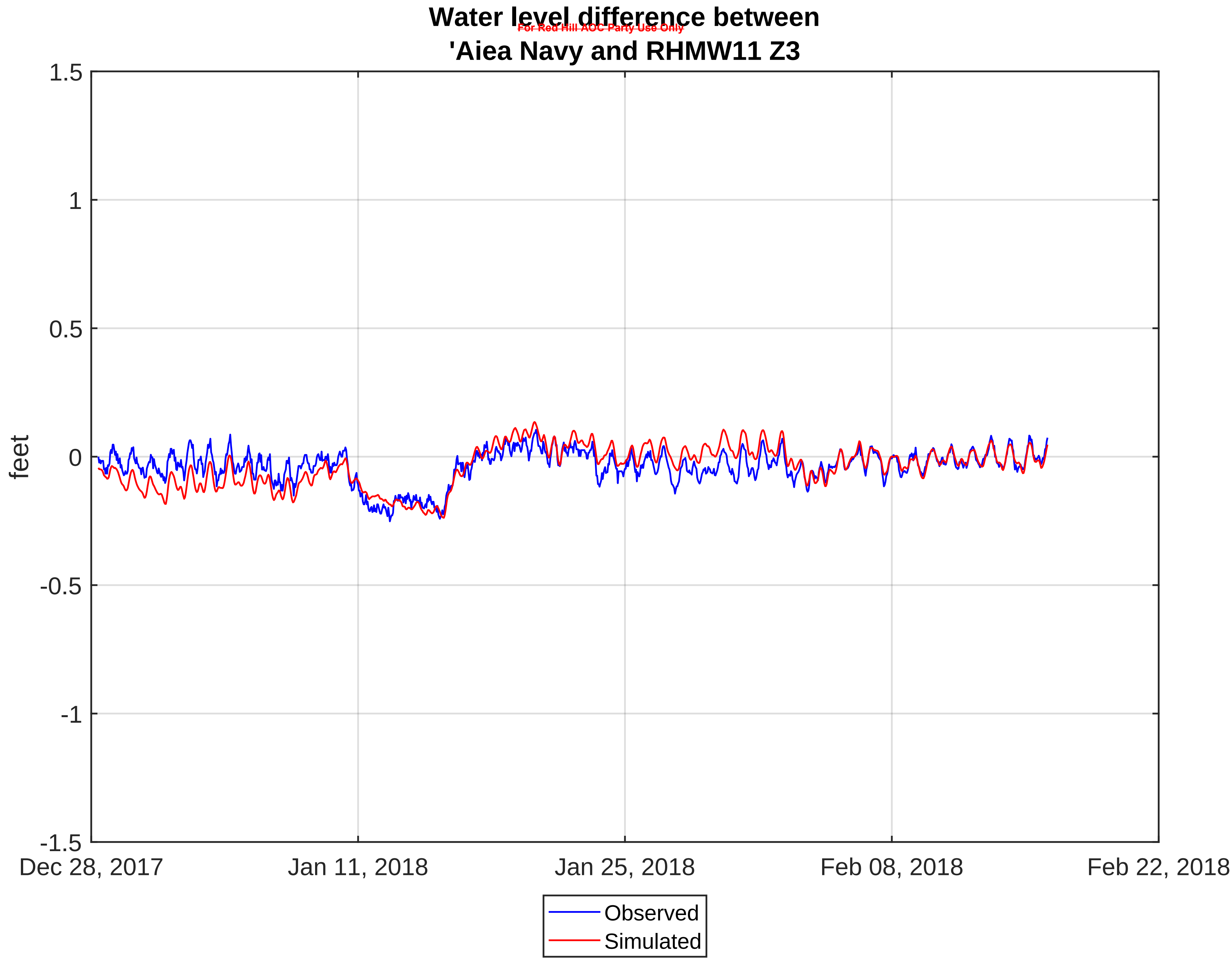




Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and RHMW11 Z1
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

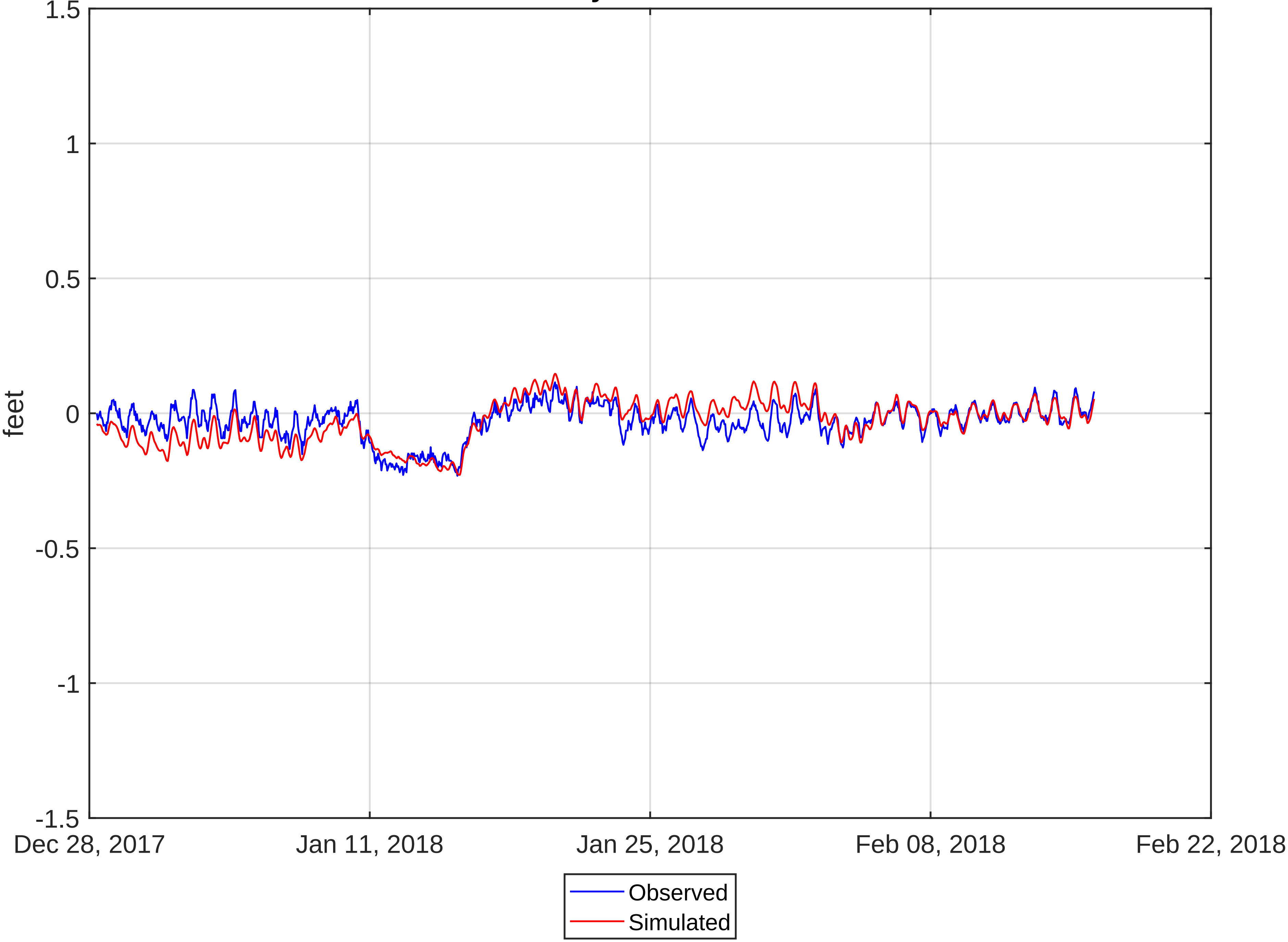


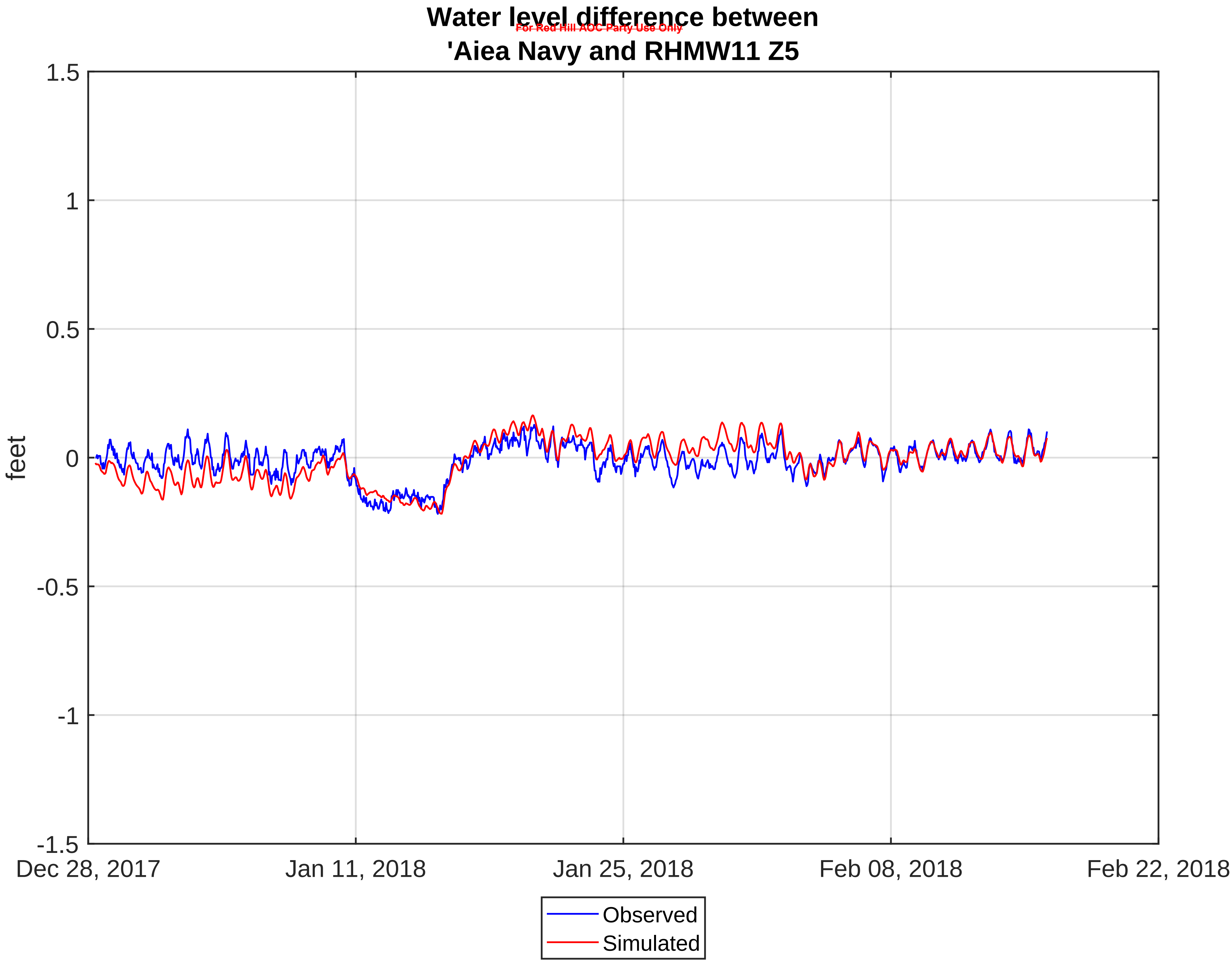
Water level difference between
'Aiea Navy and RHMW11 Z2
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

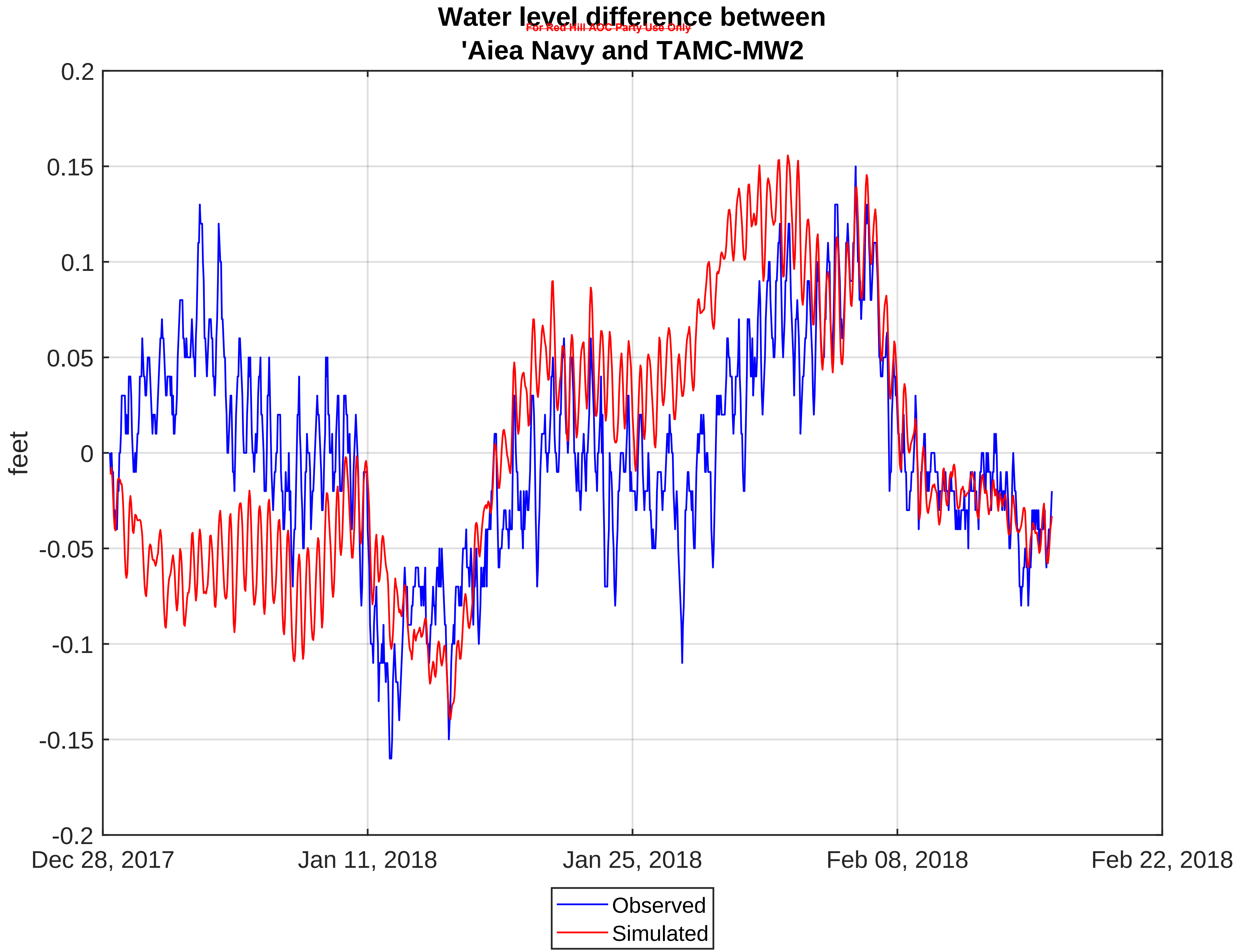


Water level difference between
'Aiea Navy and RHMW11 Z3
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

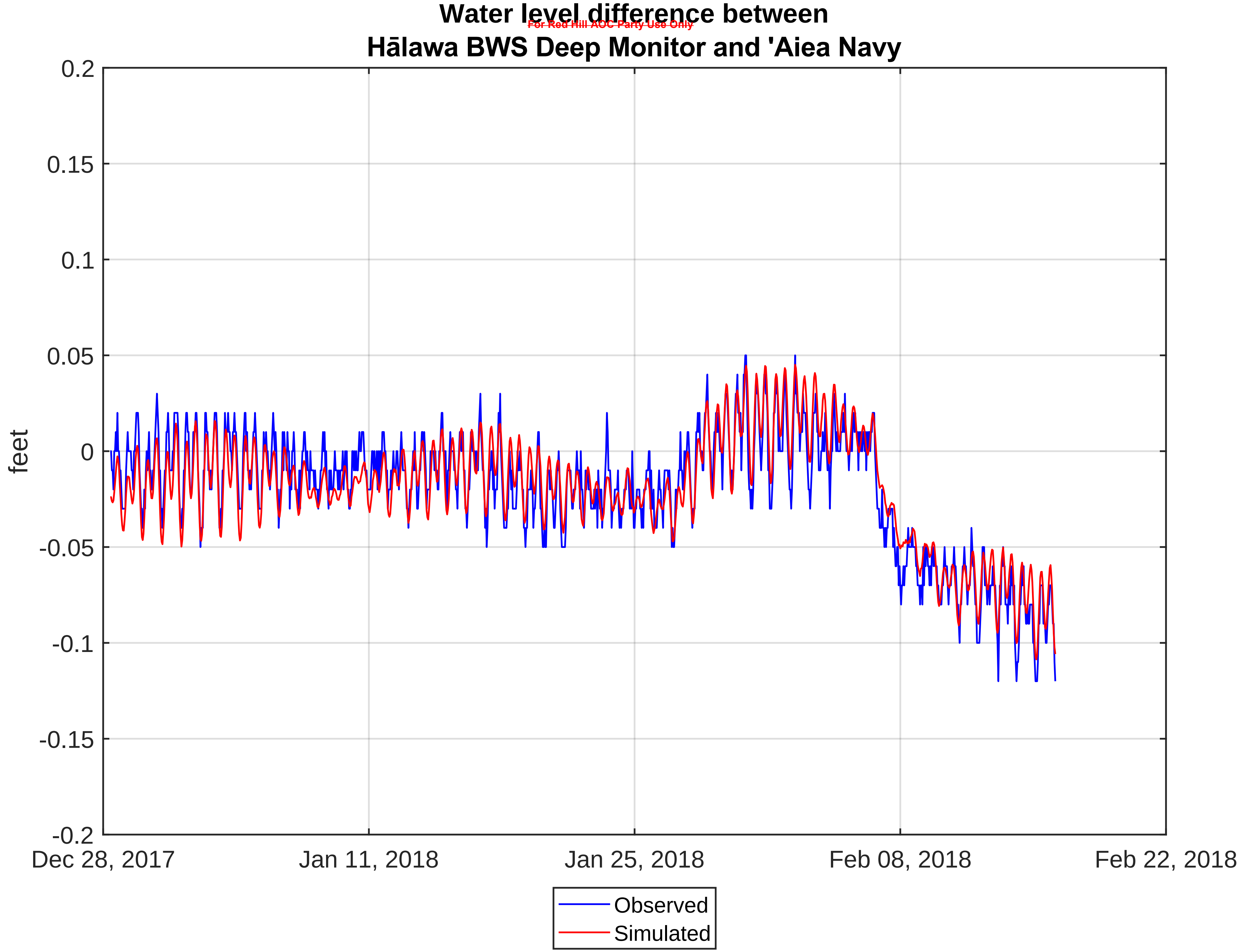
Water level difference between
'Aiea Navy and RHMW11 Z4



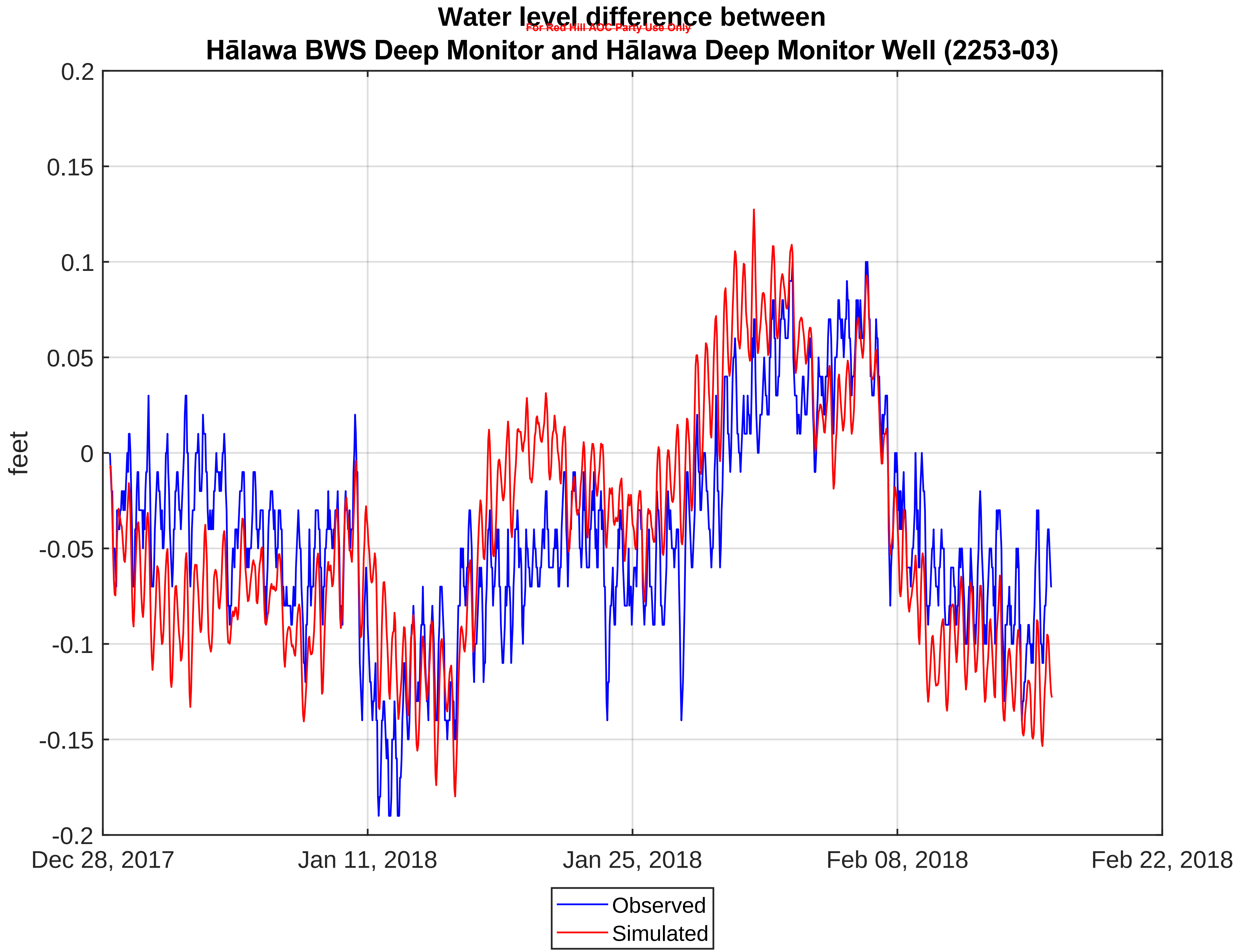

Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and RHMW11 Z5
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



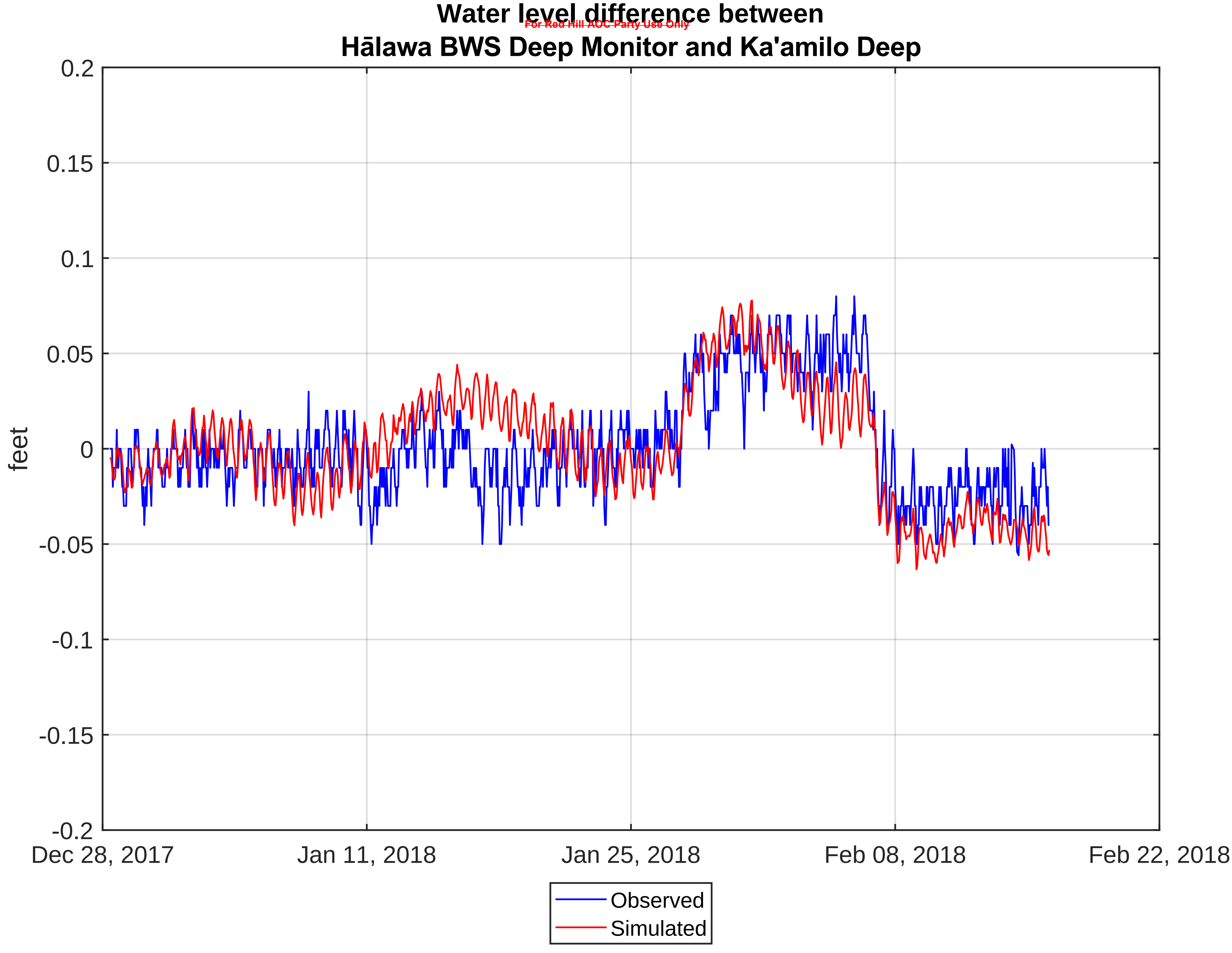
Water level difference between
For Red Hill AOC Party Use Only
'Aiea Navy and TAMC-MW2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



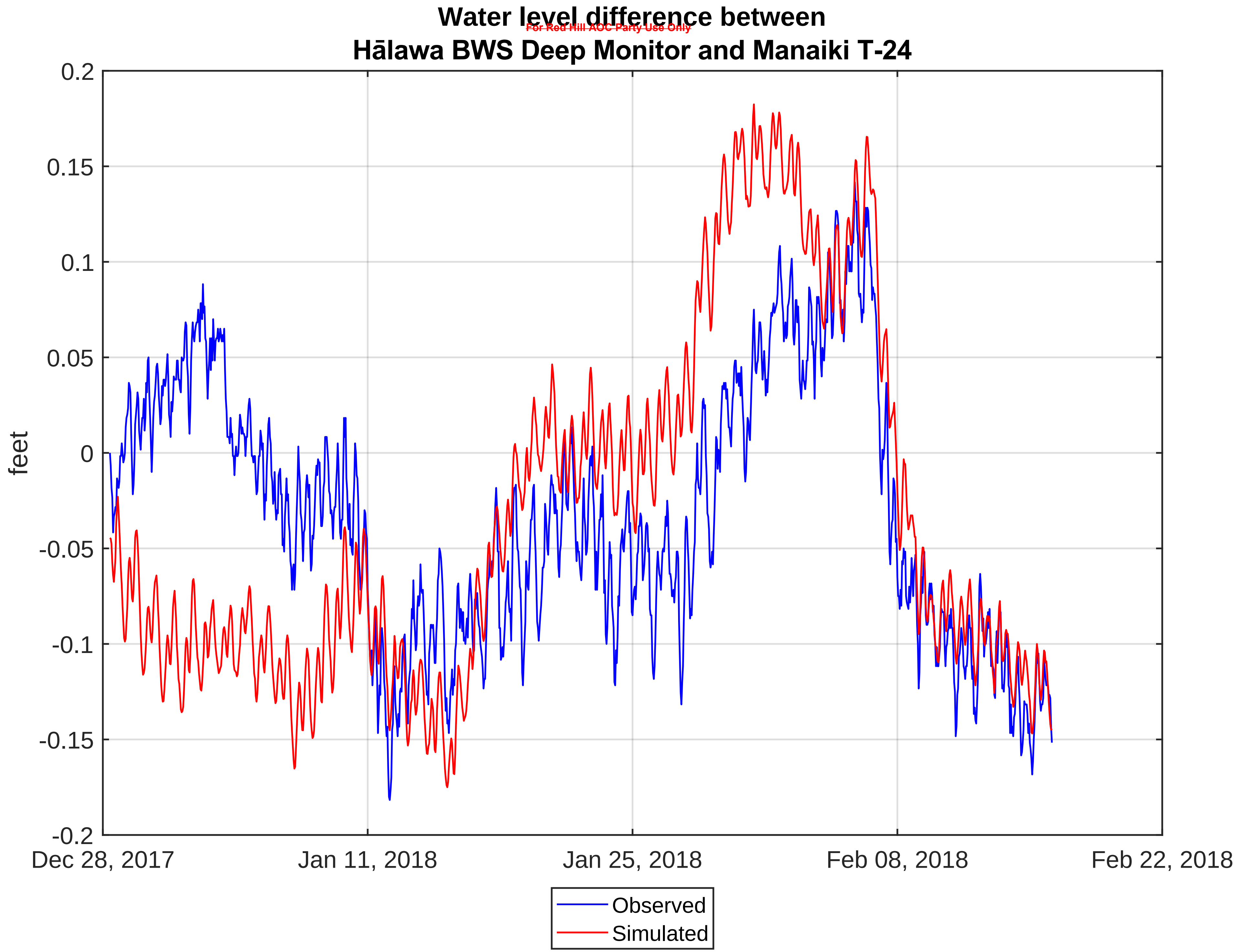
Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and 'Aiea Navy
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

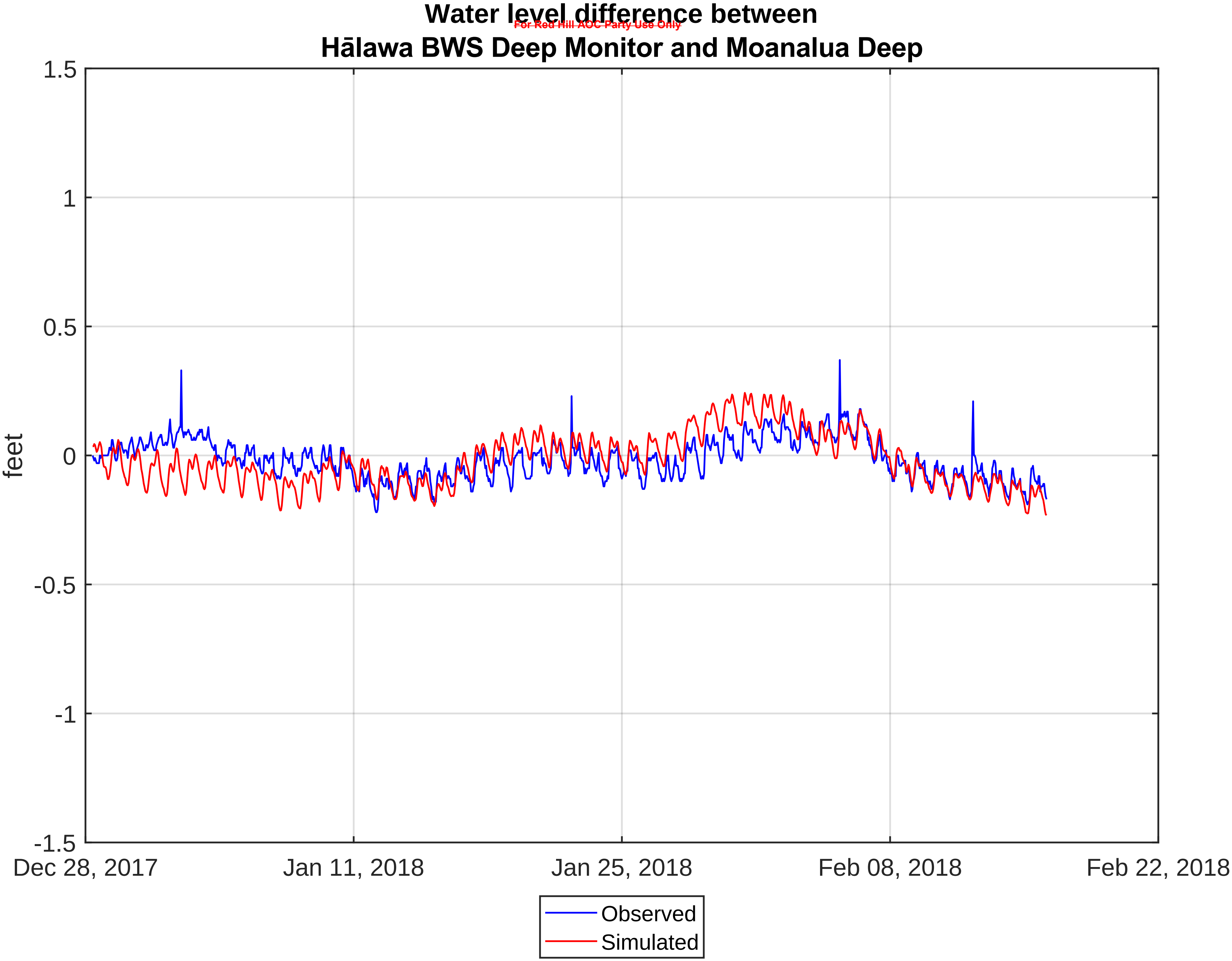


Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and Hālawa Deep Monitor Well (2253-03)
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
Hālawa BWS Deep Monitor and Ka'amilo Deep
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

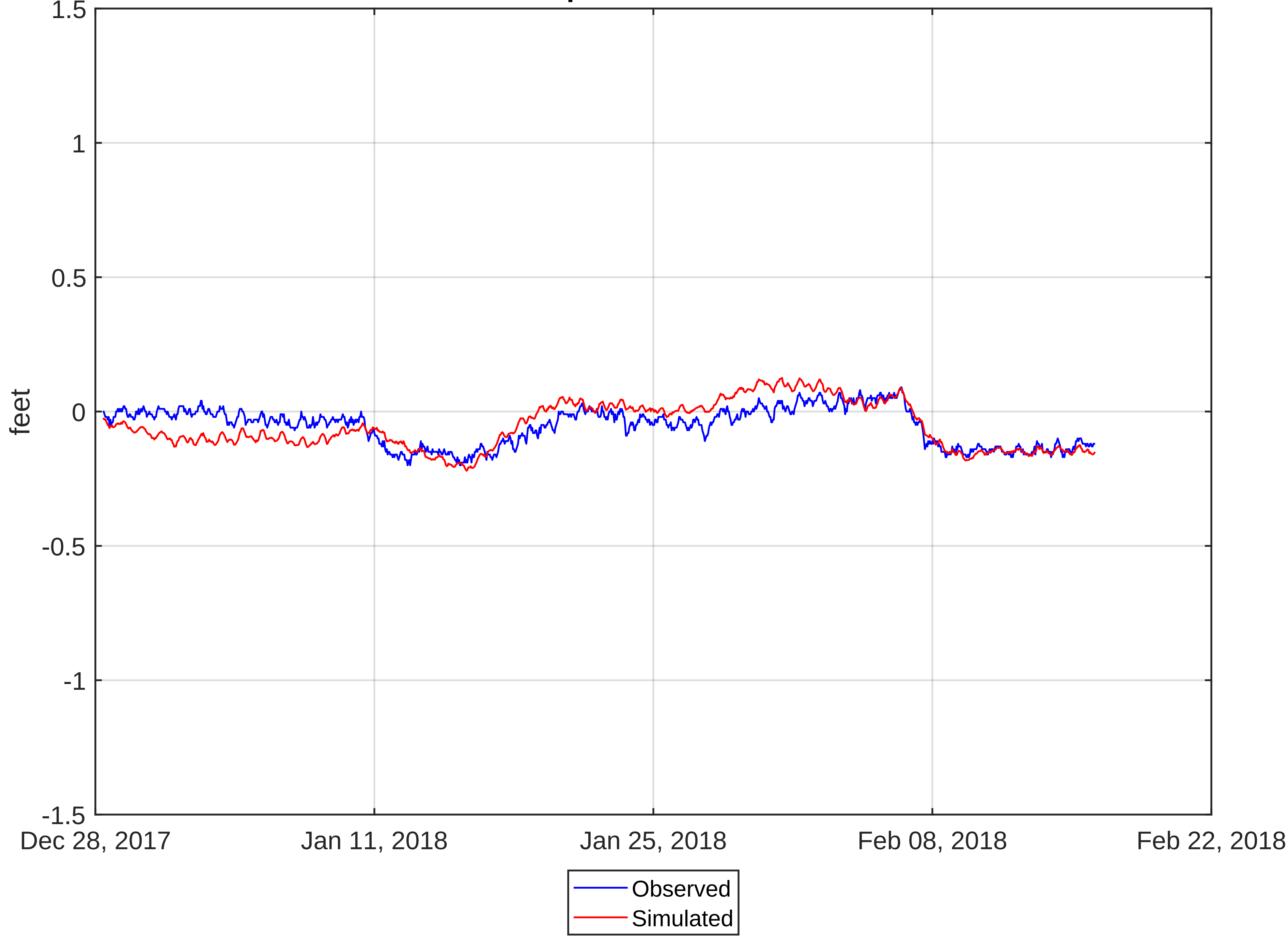

Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and Manaiki T-24
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

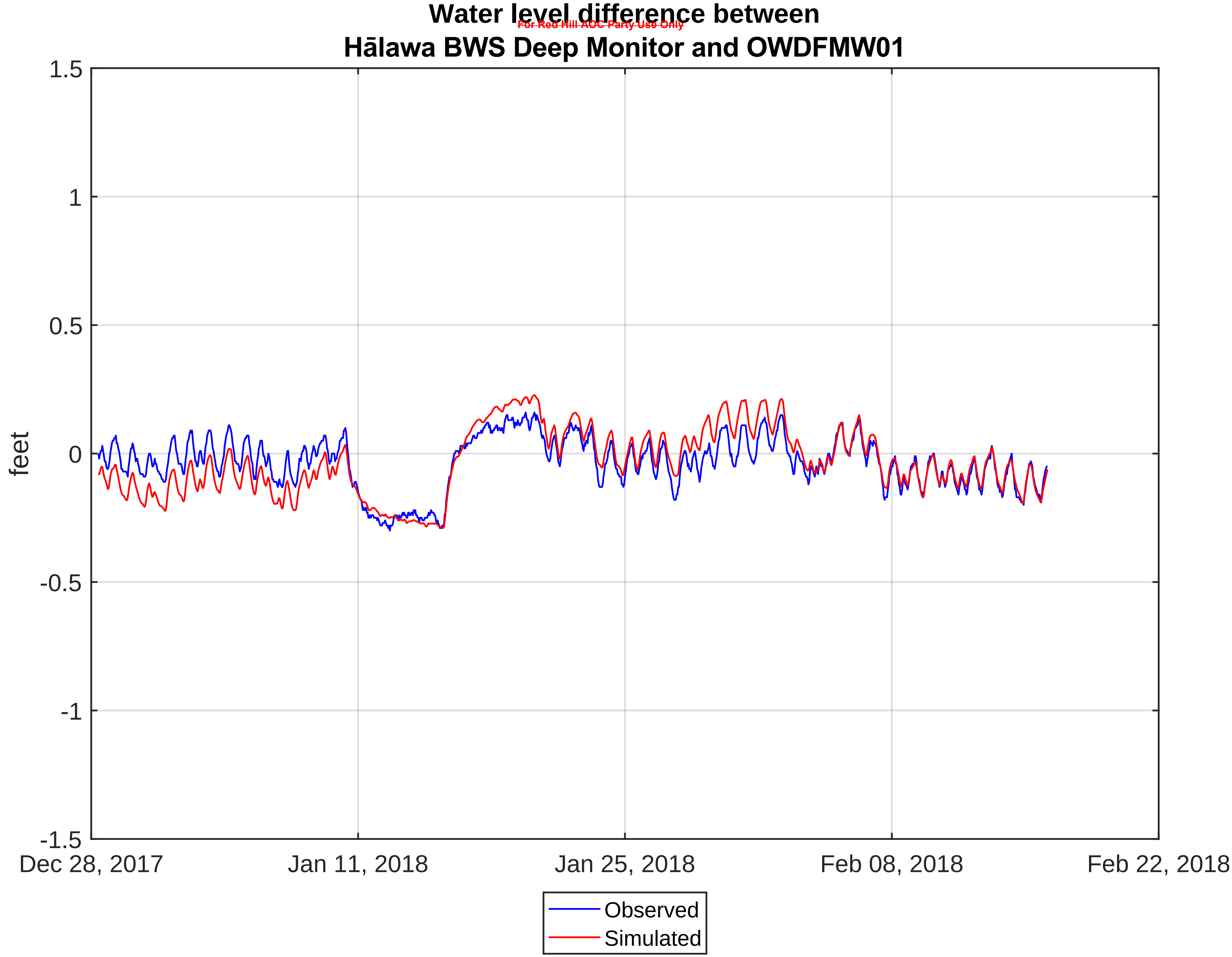


Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and Moanalua Deep
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

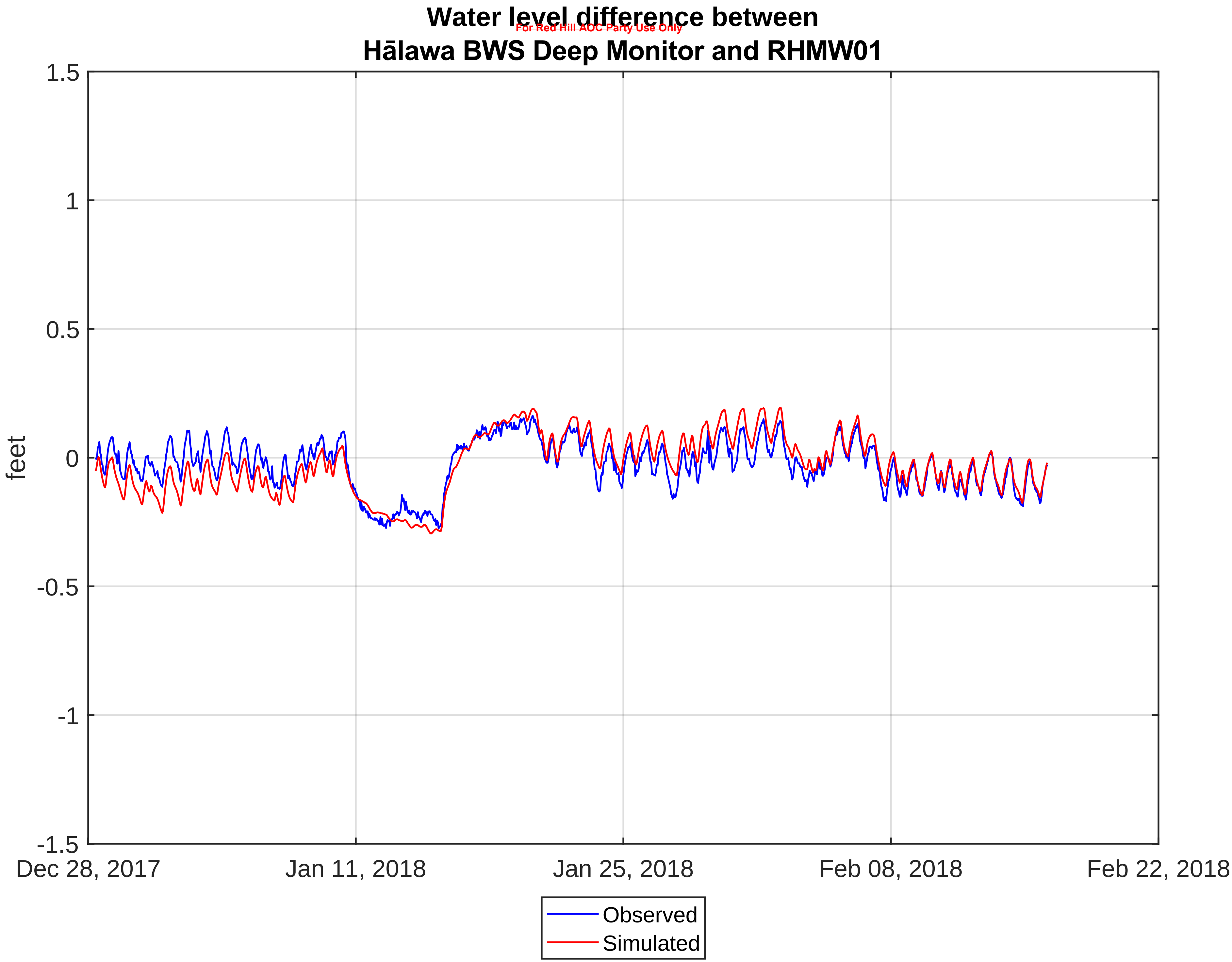
Water level difference between

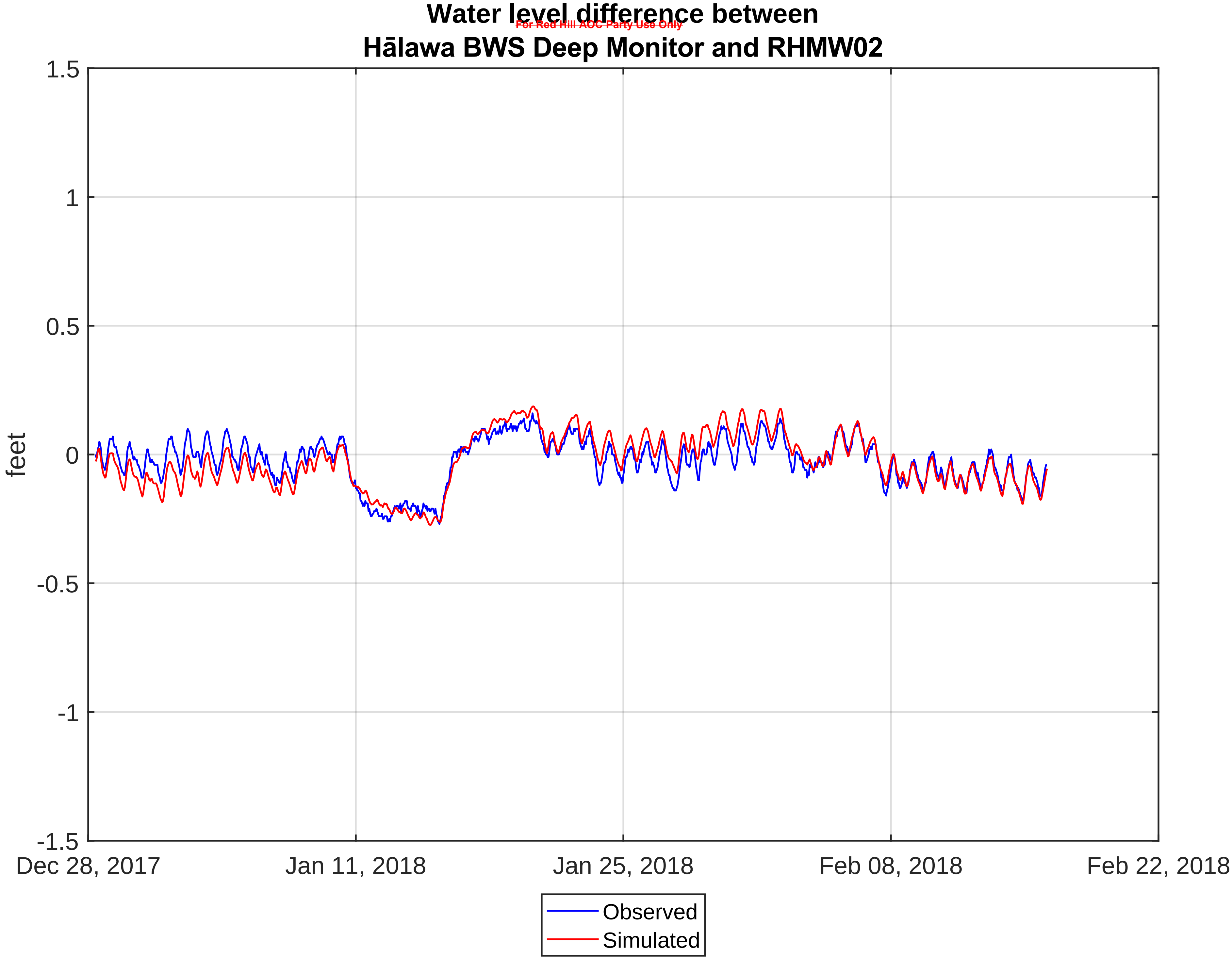
Hālawa BWS Deep Monitor and Moanalua DH43



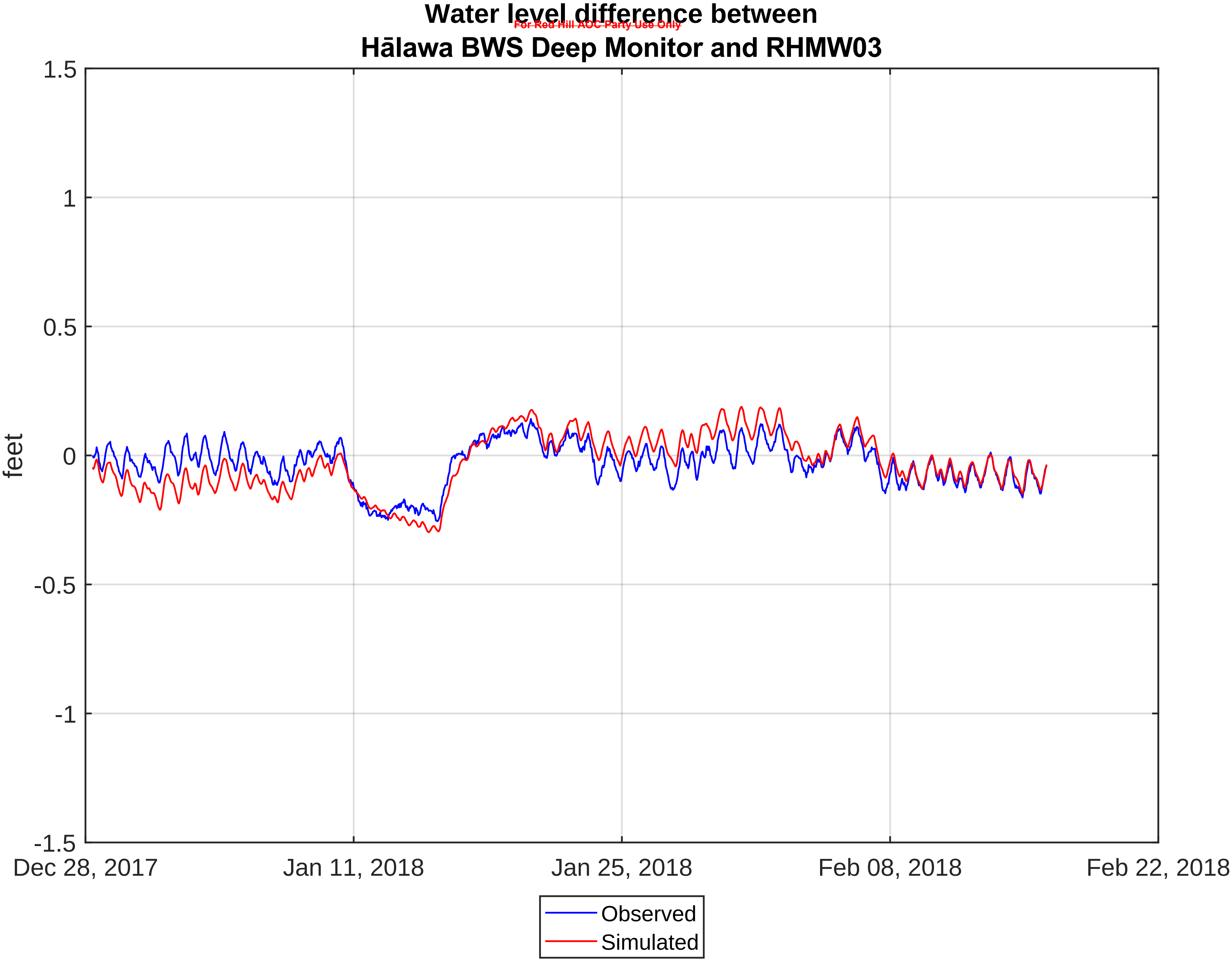


Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and OWDFMW01
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

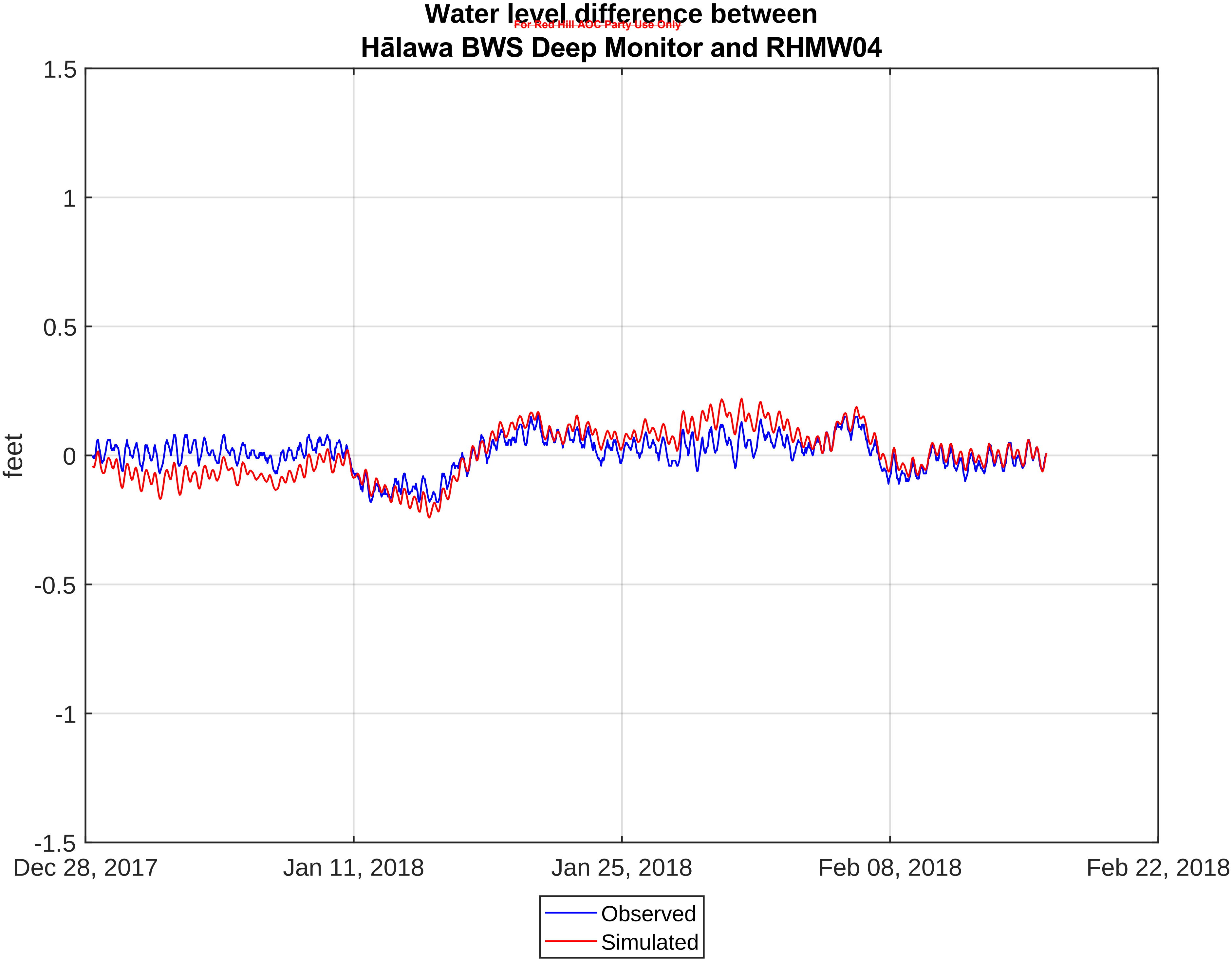

Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW01
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



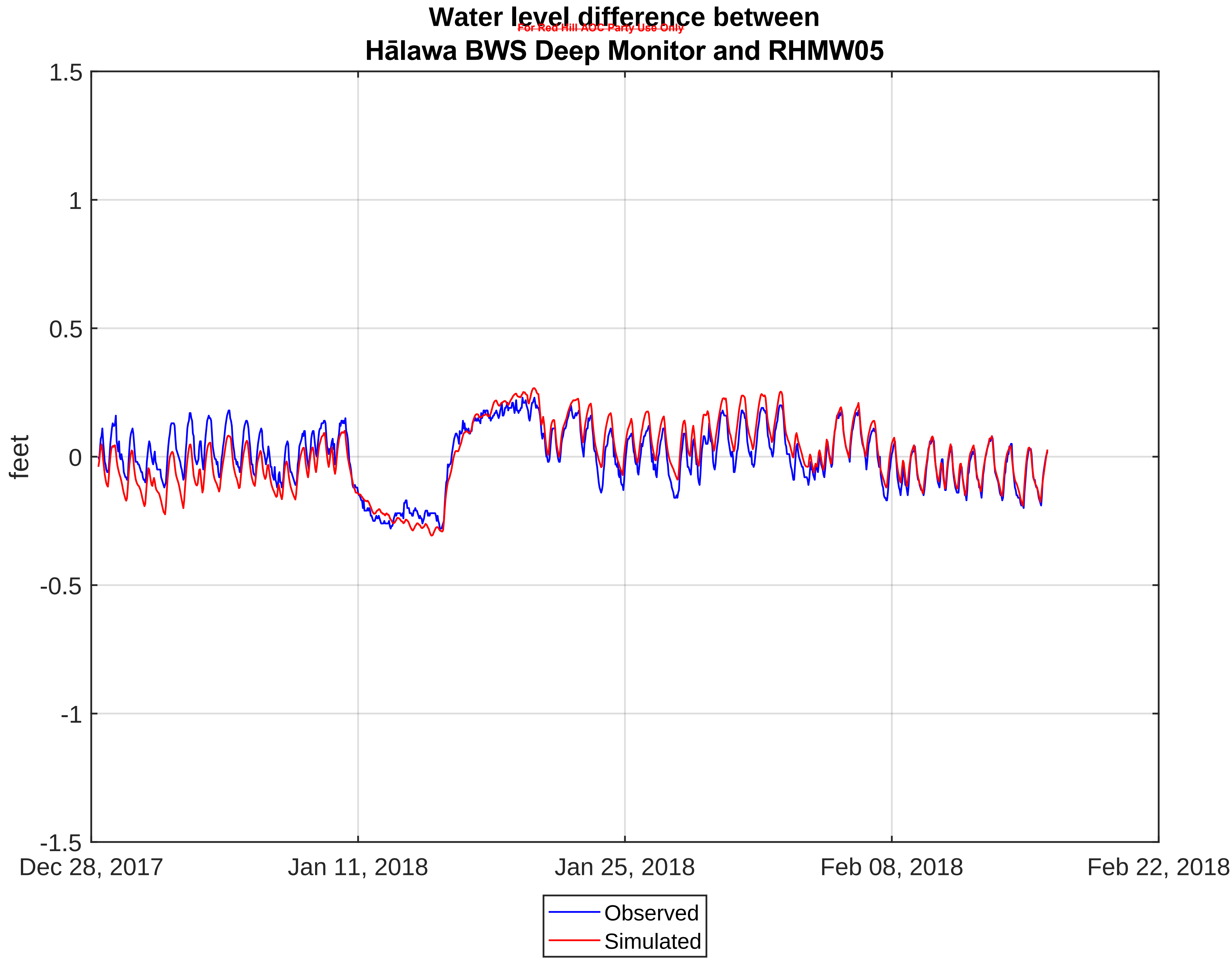
Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW02
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW03
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW04
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

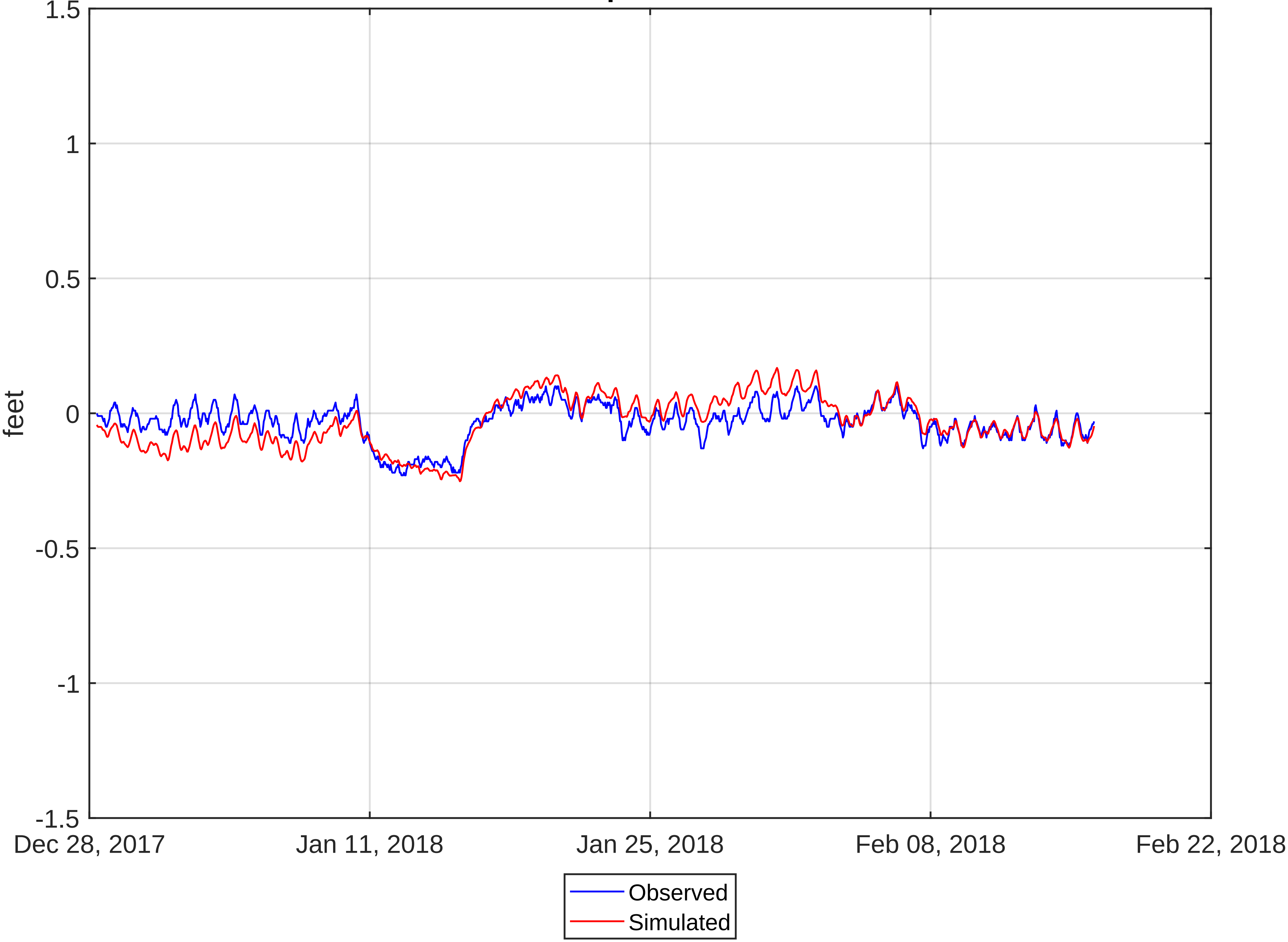


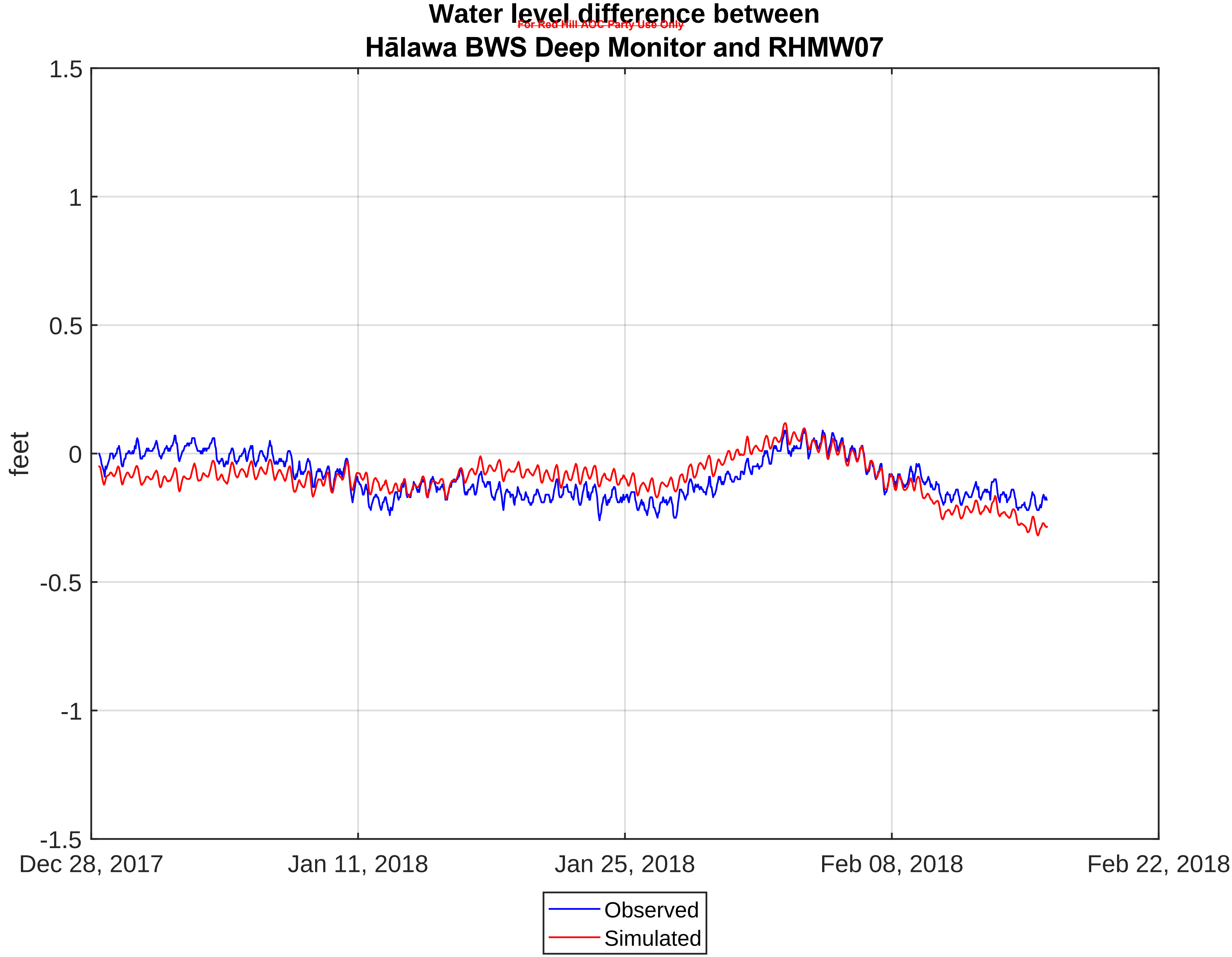
Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW05
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between

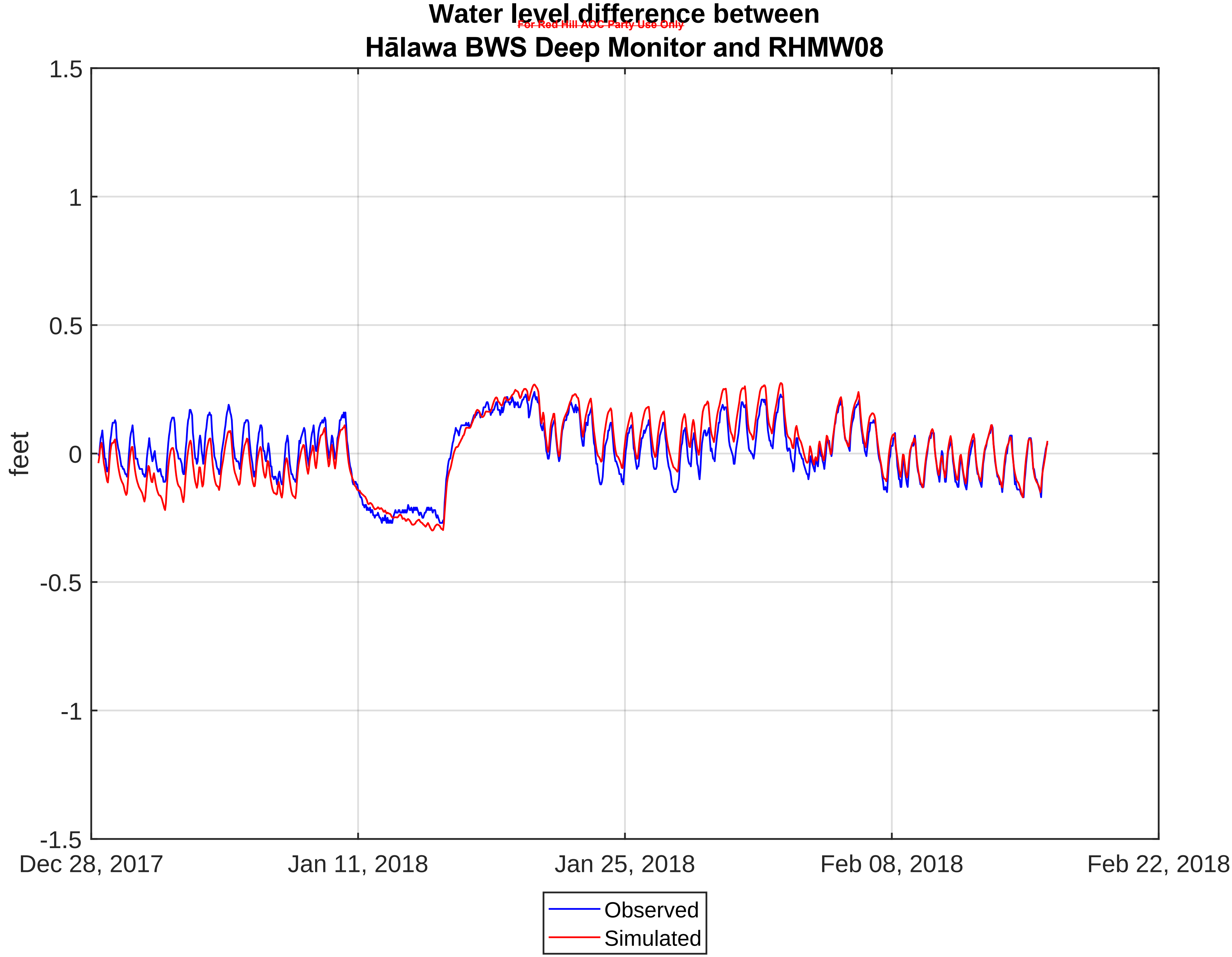
For Red Hill AOC Party Use Only

Hālawa BWS Deep Monitor and RHMW06

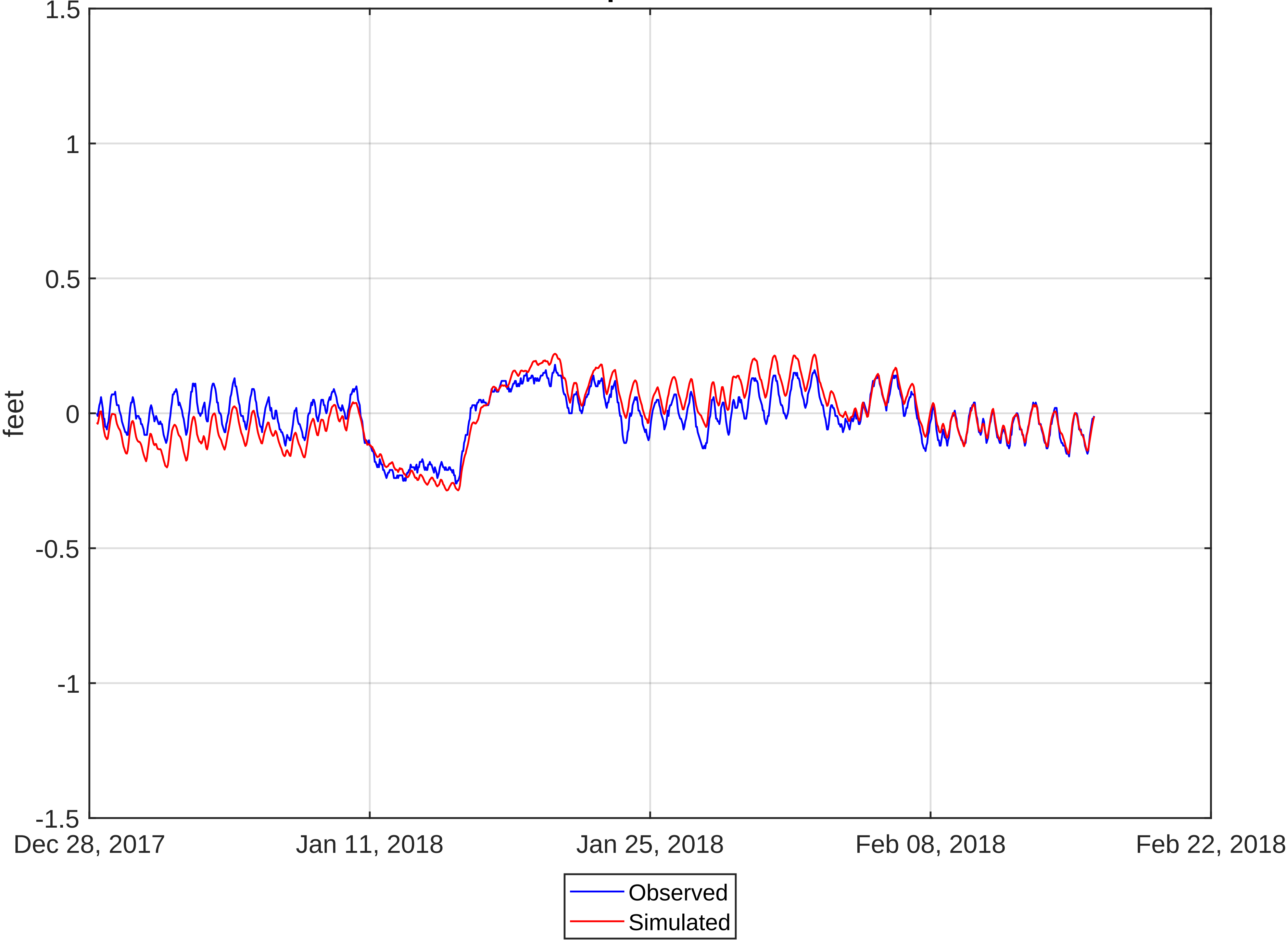


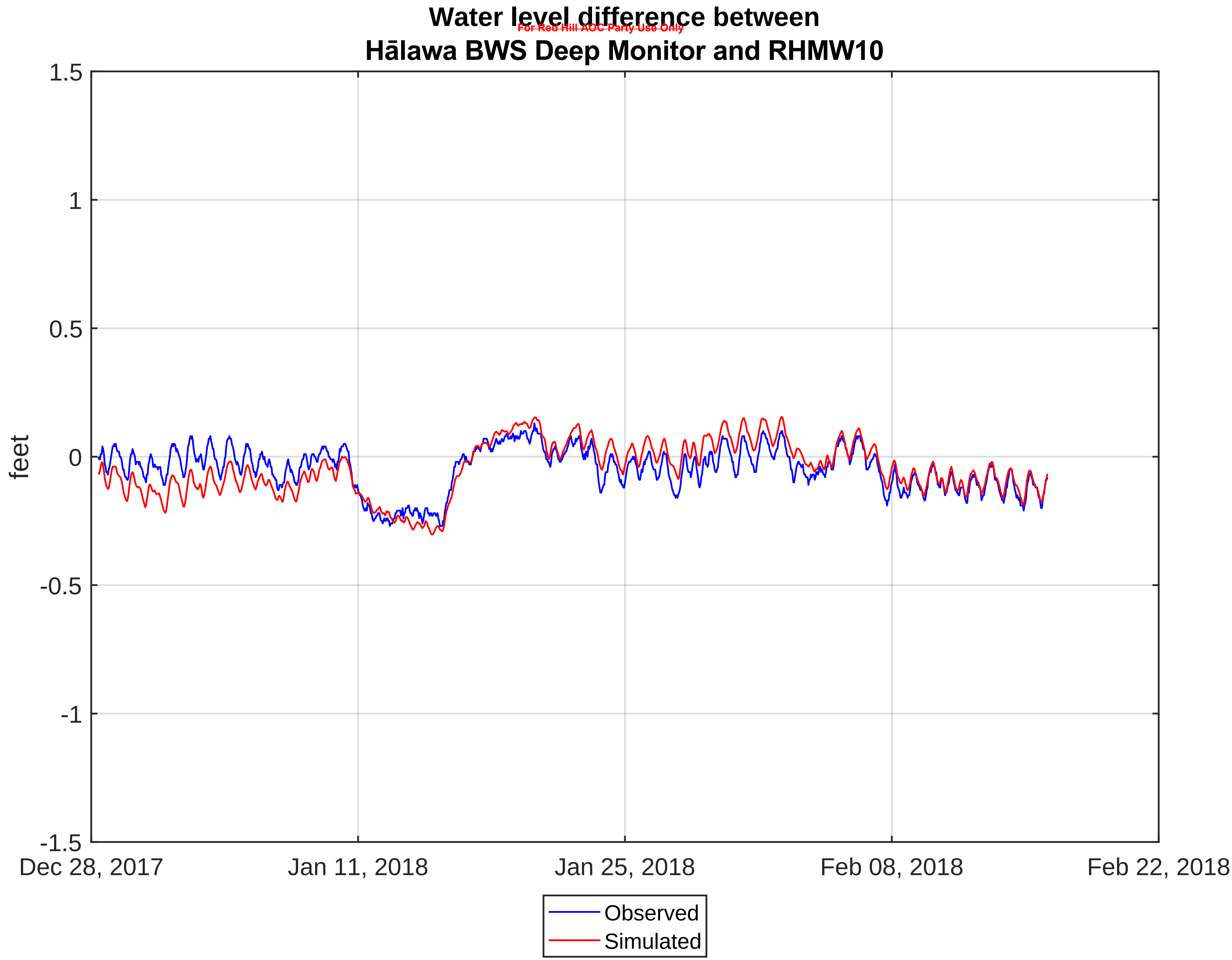


Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW07
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

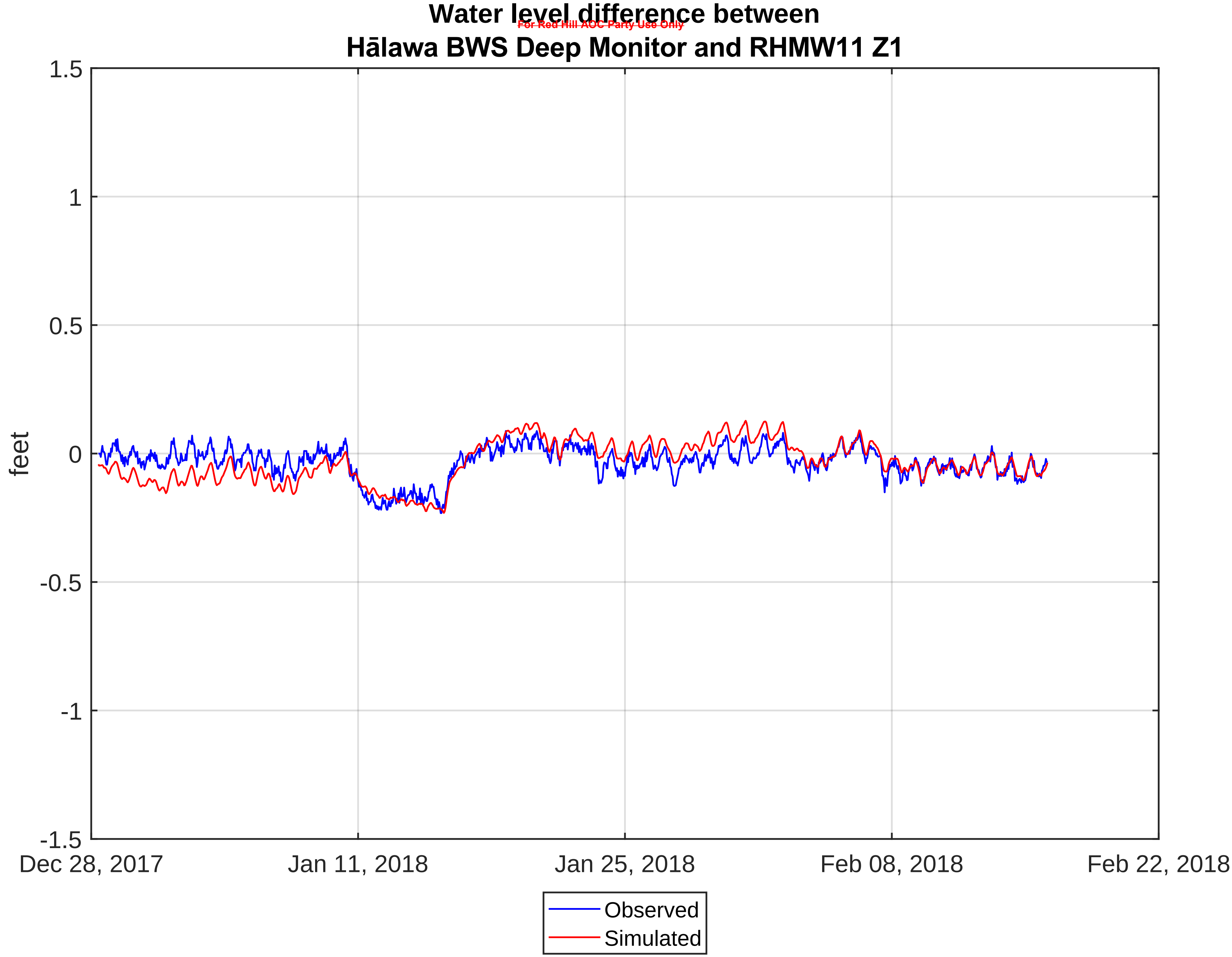

Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW08
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between Hālawa BWS Deep Monitor and RHMW09

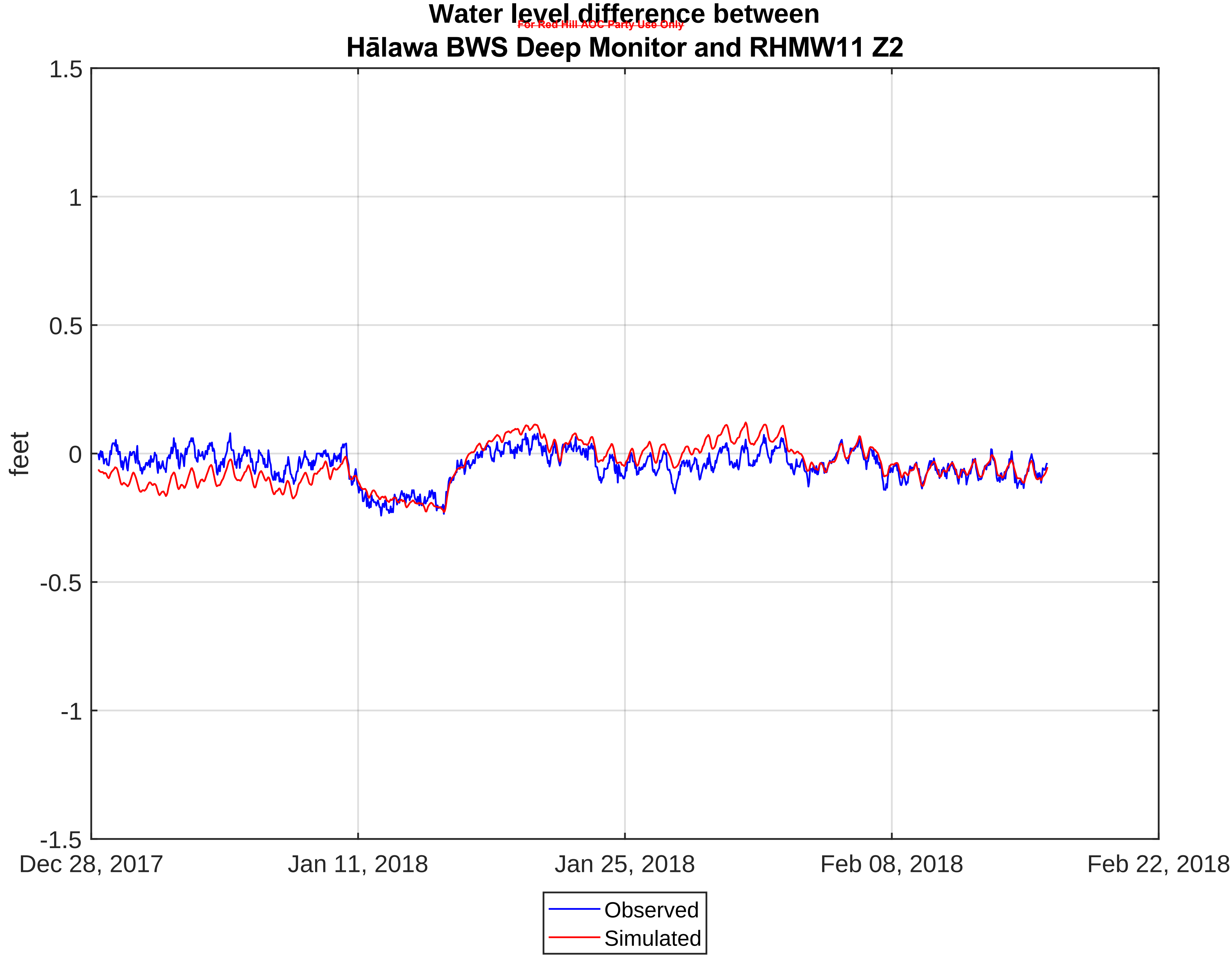




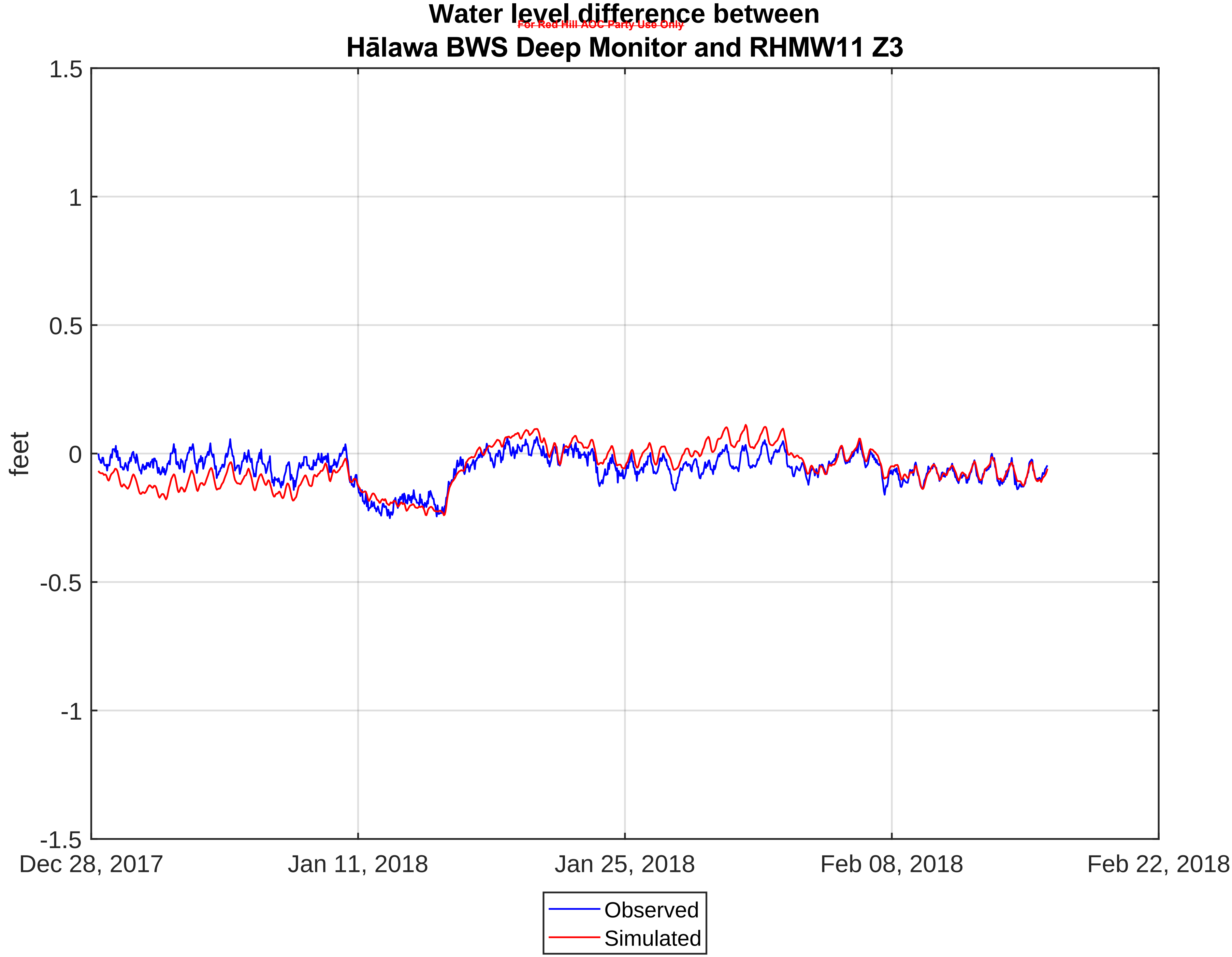
Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW10
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

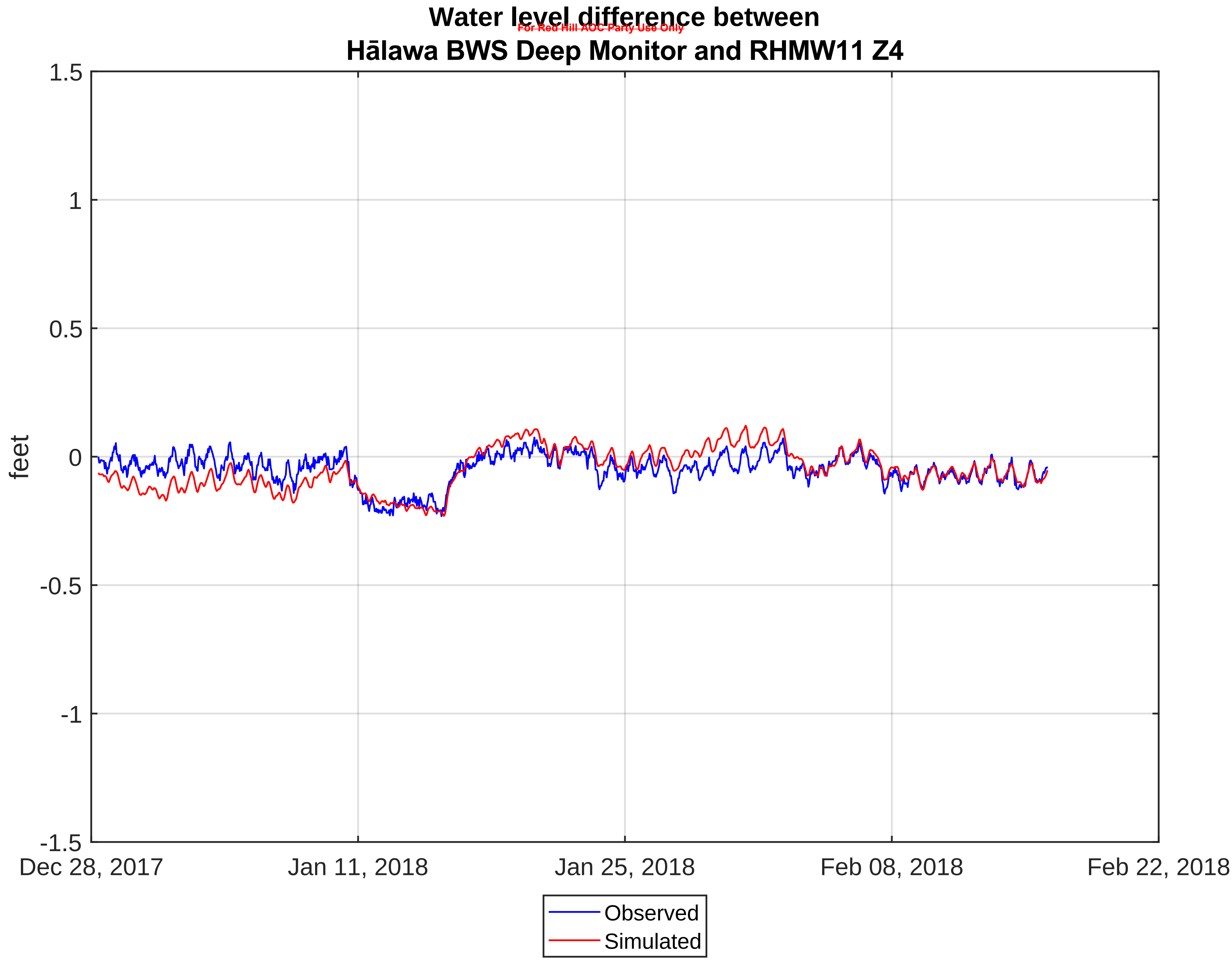


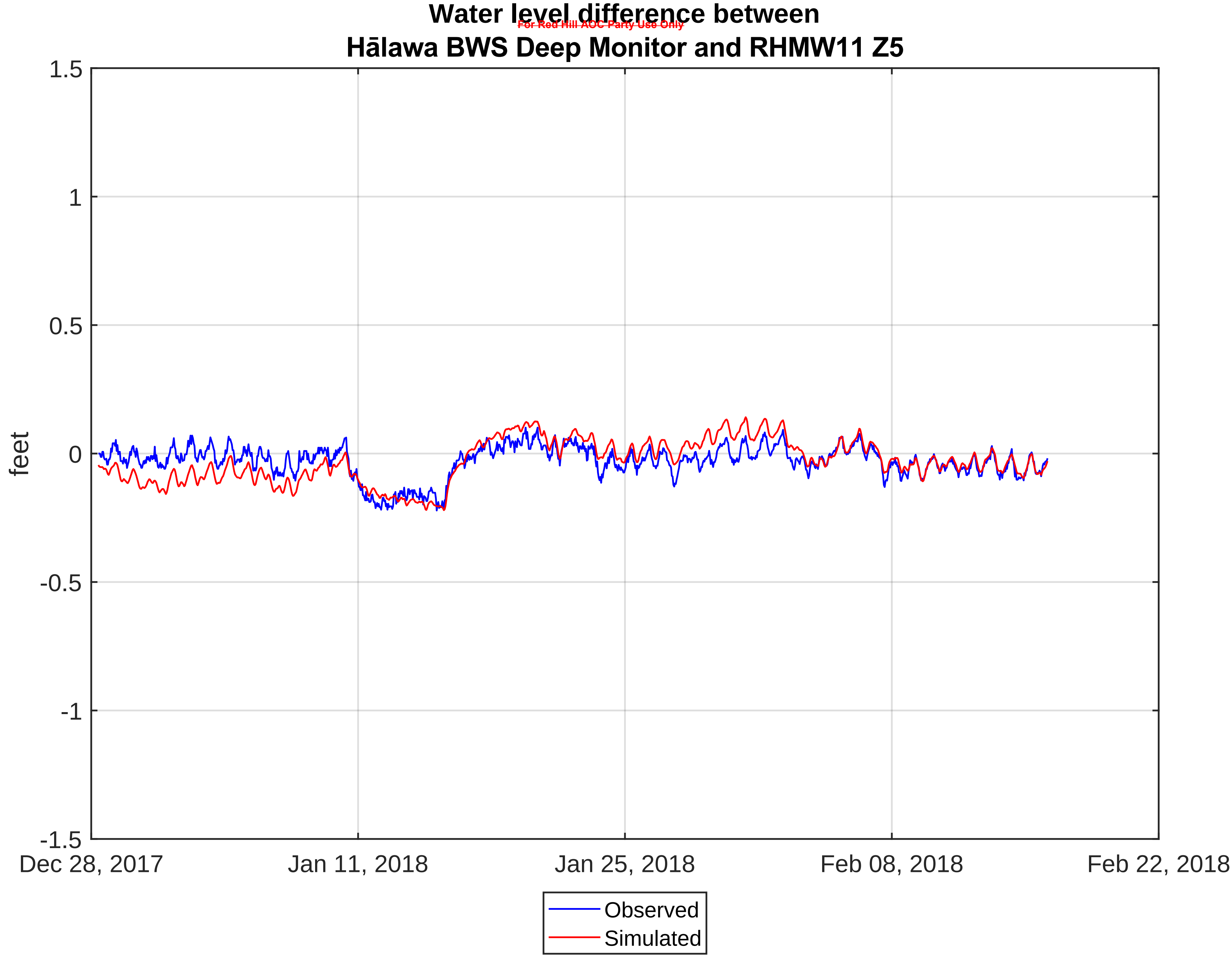
Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW11 Z1
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



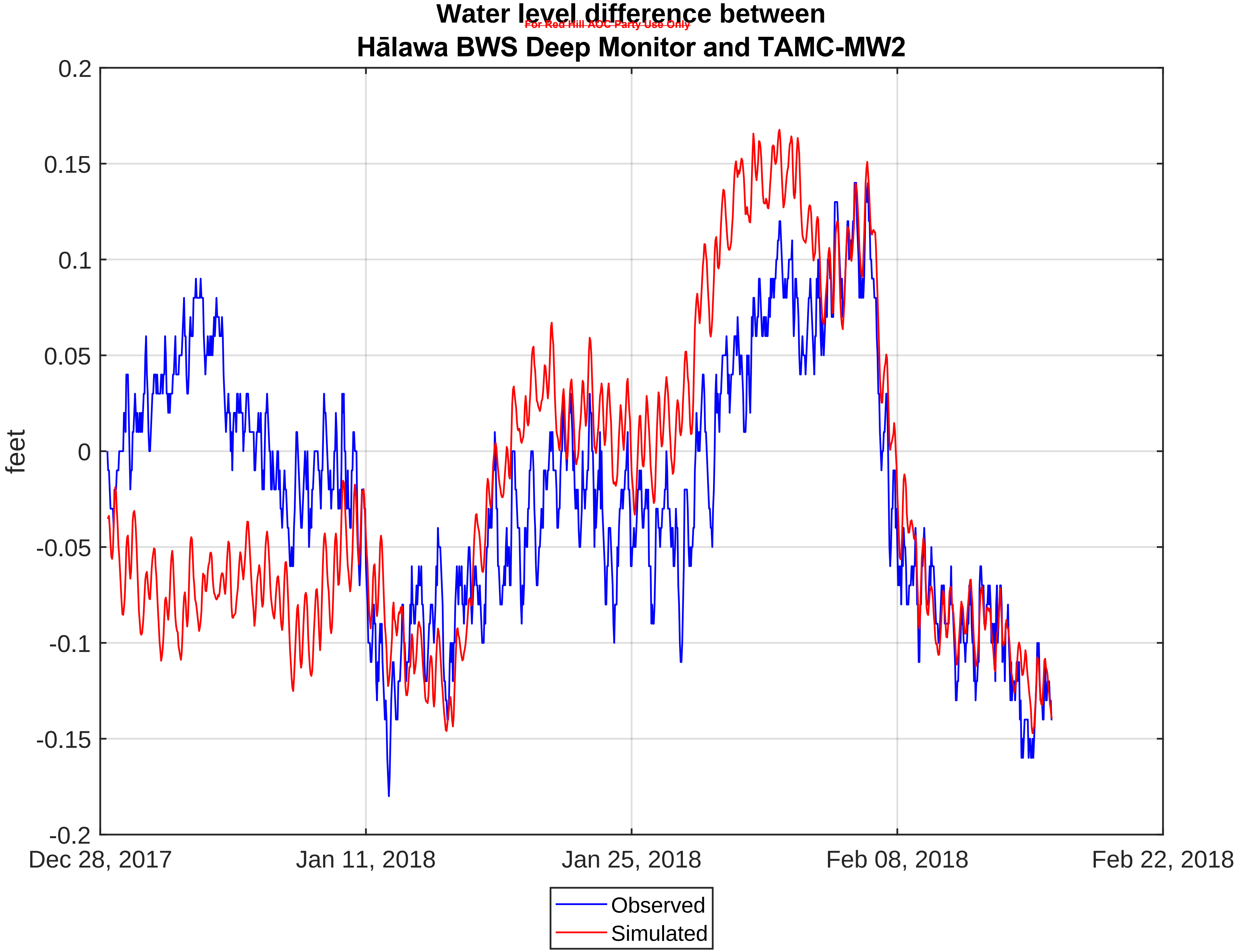
Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW11 Z2
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW11 Z3
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

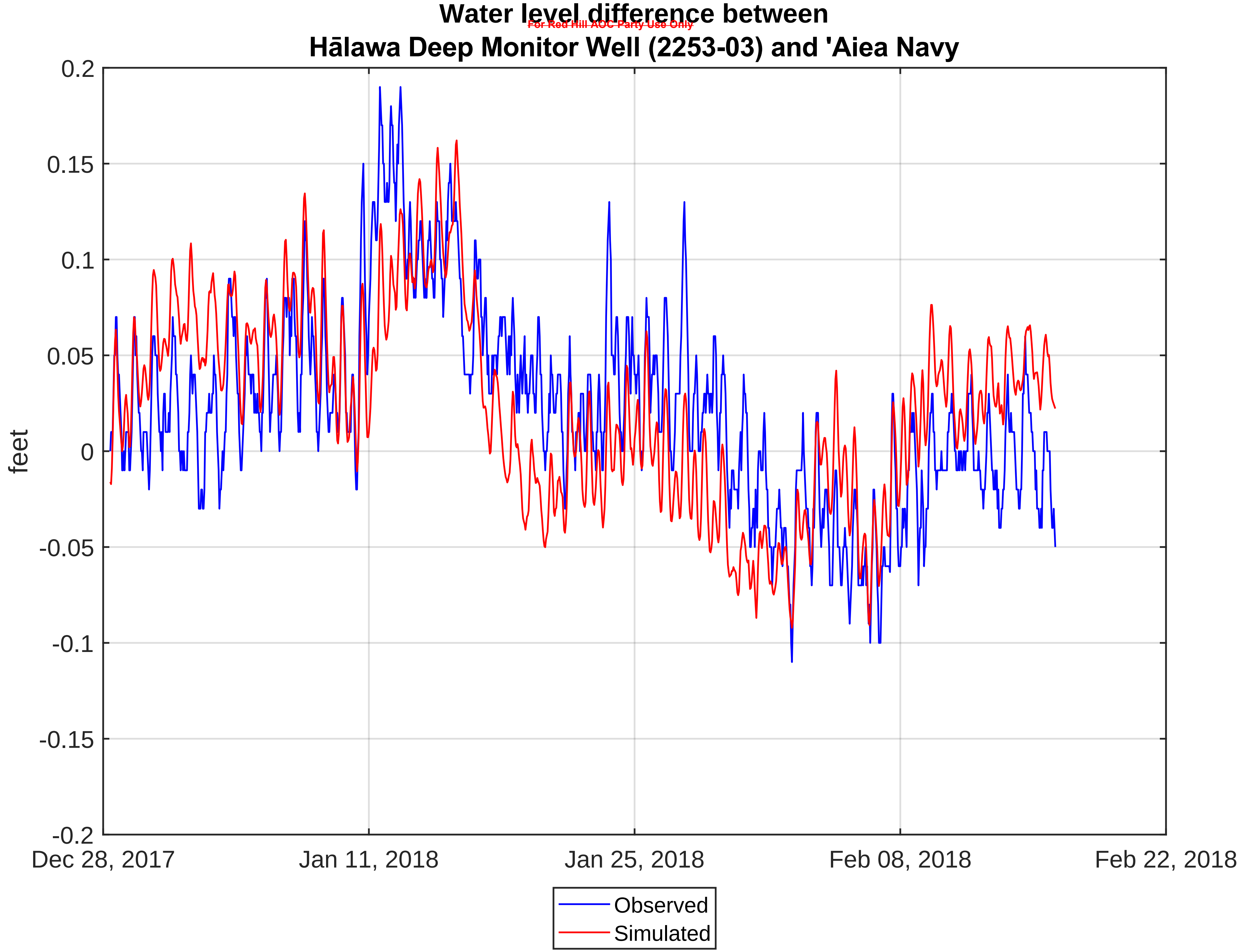

Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW11 Z4
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

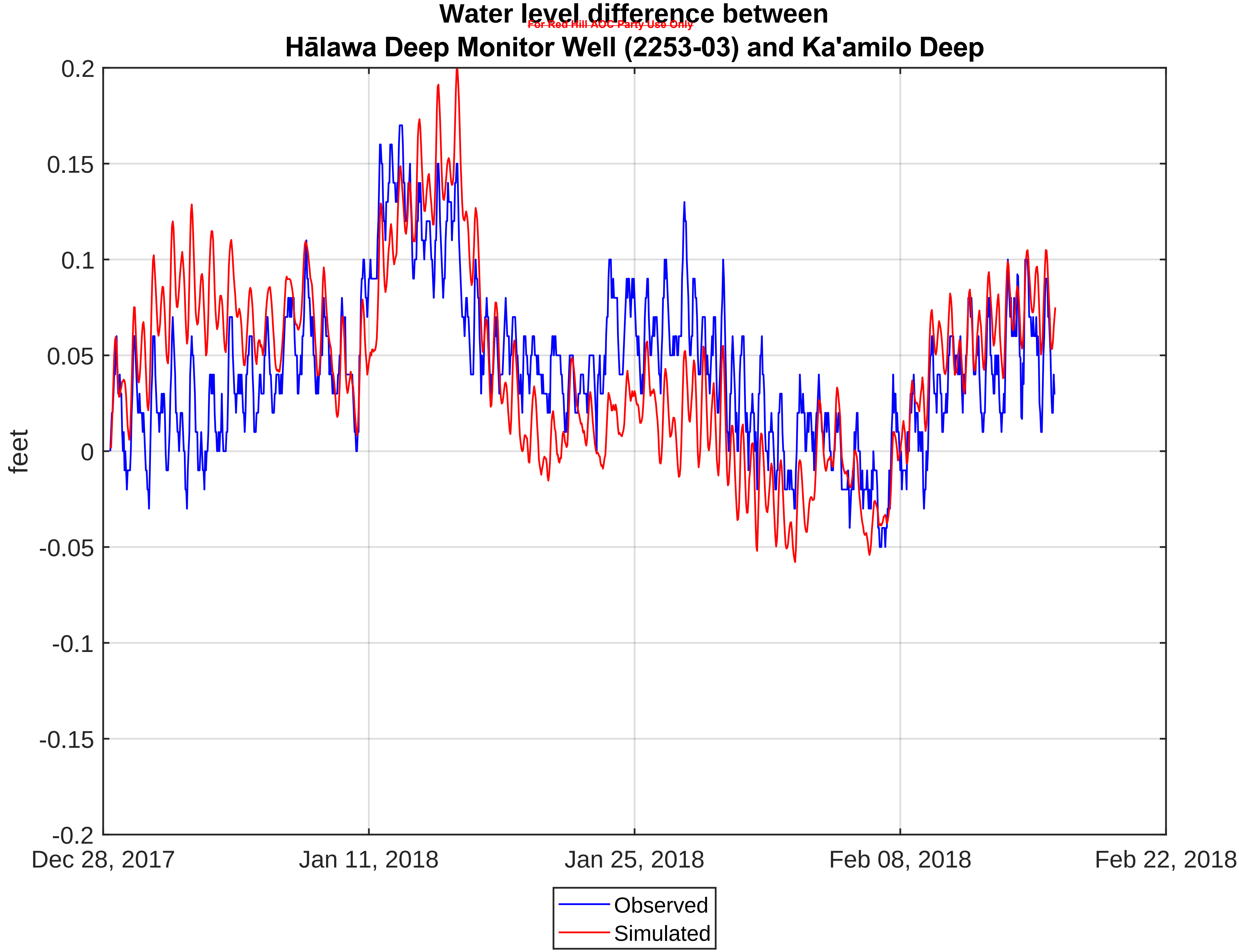


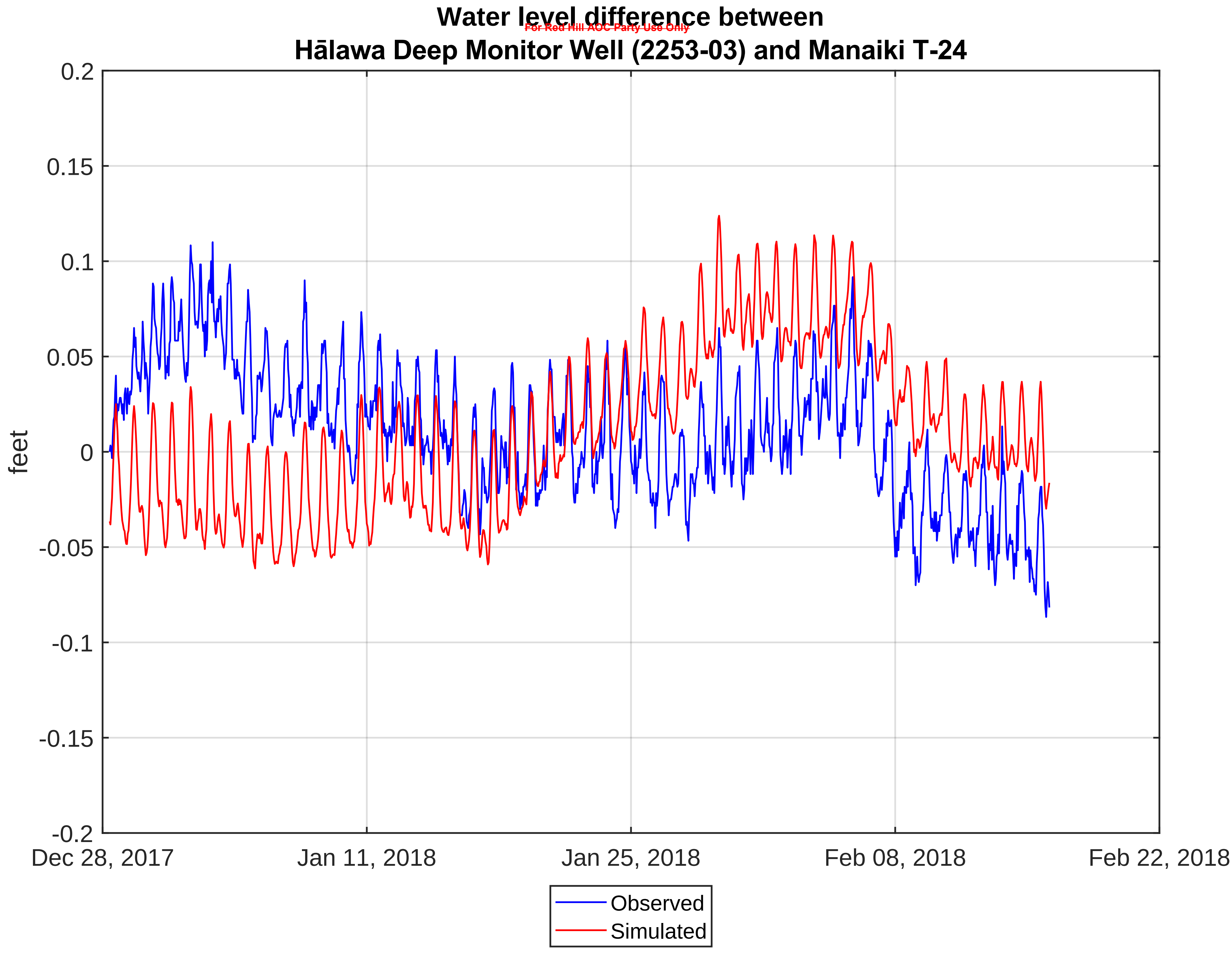
Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and RHMW11 Z5
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Hālawa BWS Deep Monitor and TAMC-MW2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and 'Aiea Navy
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
Hālawa Deep Monitor Well (2253-03) and Ka'amilo Deep
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

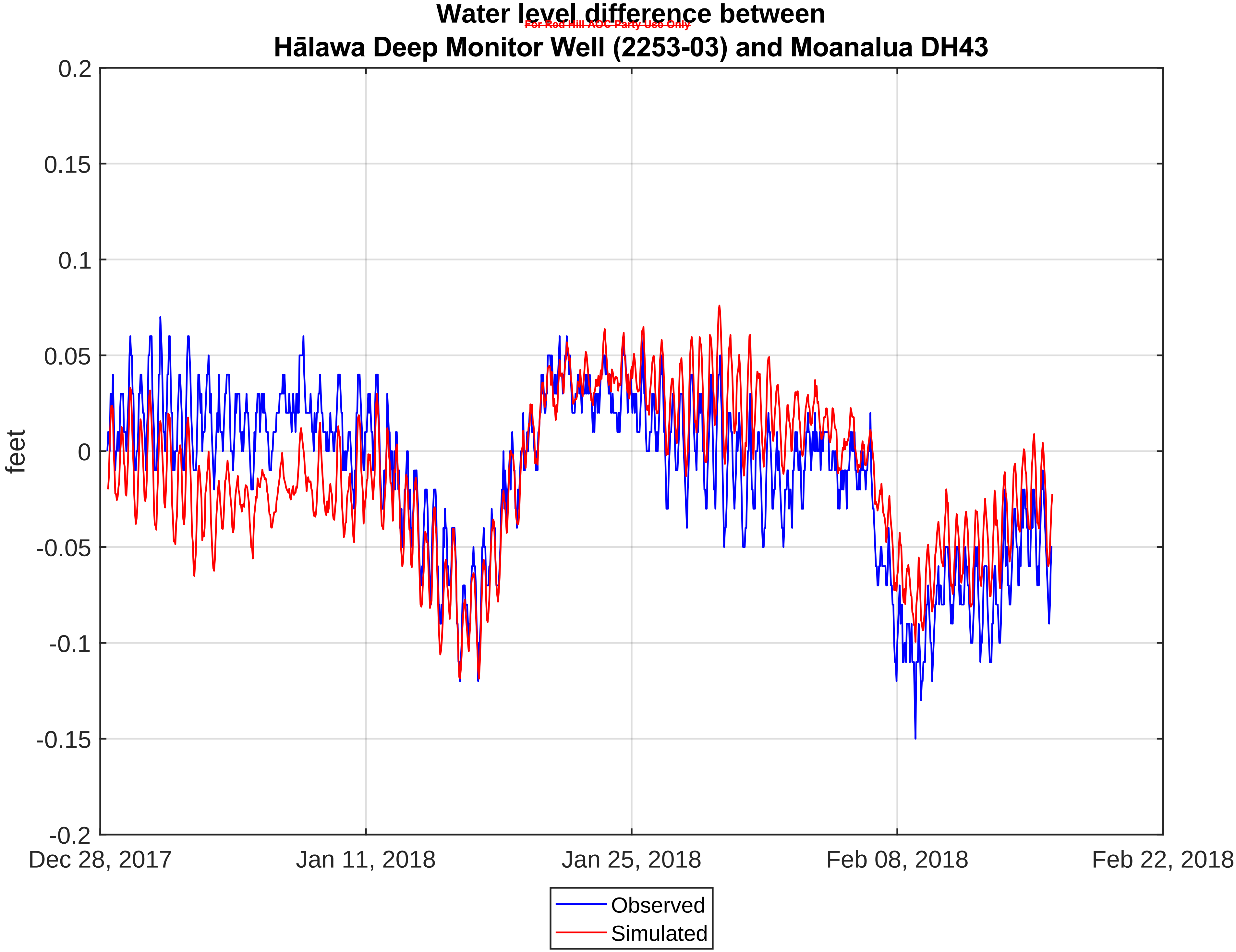


Water level difference between
Hālawa Deep Monitor Well (2253-03) and Manaiki T-24
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

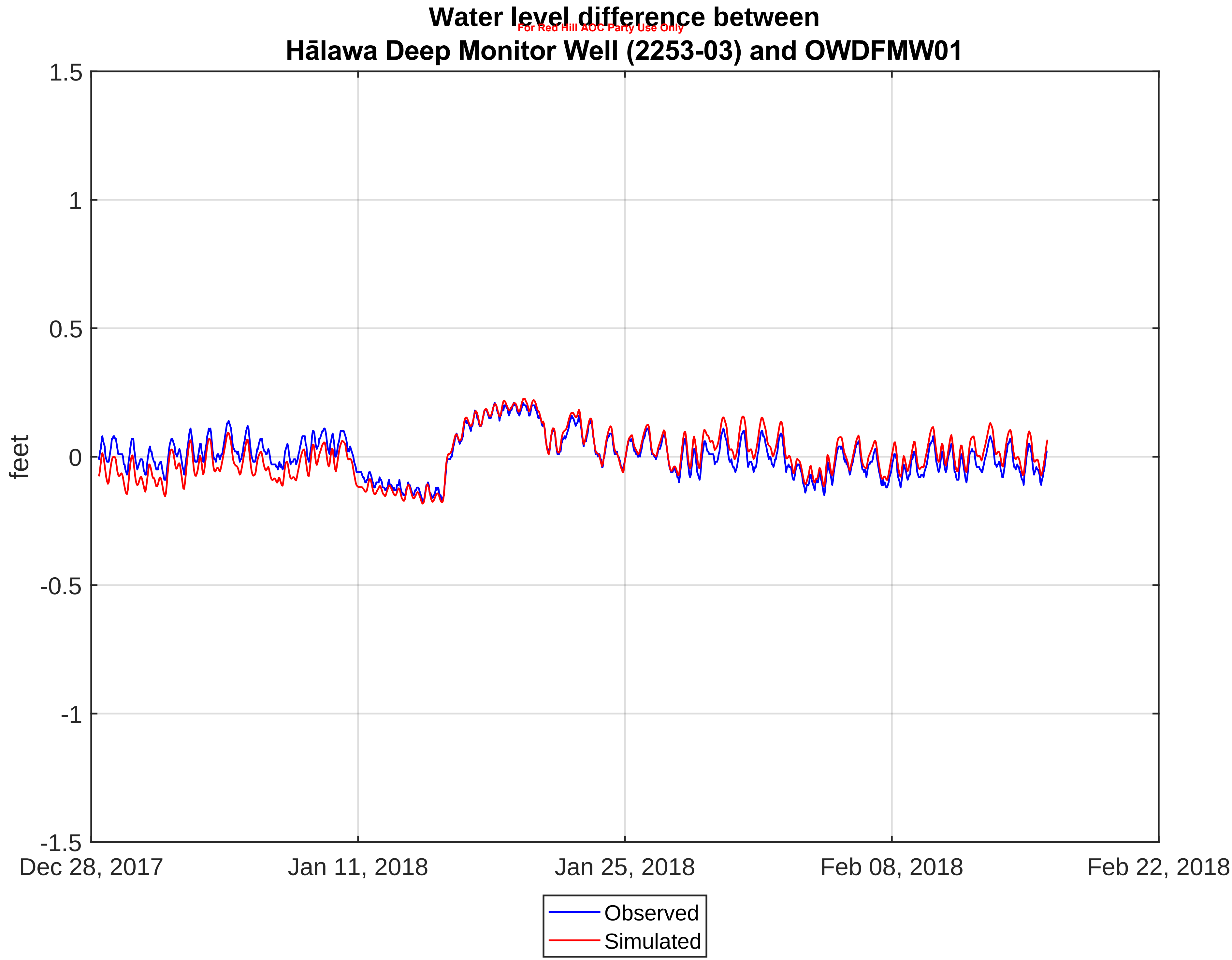
Water level difference between

For Red Hill AOC Party Use Only

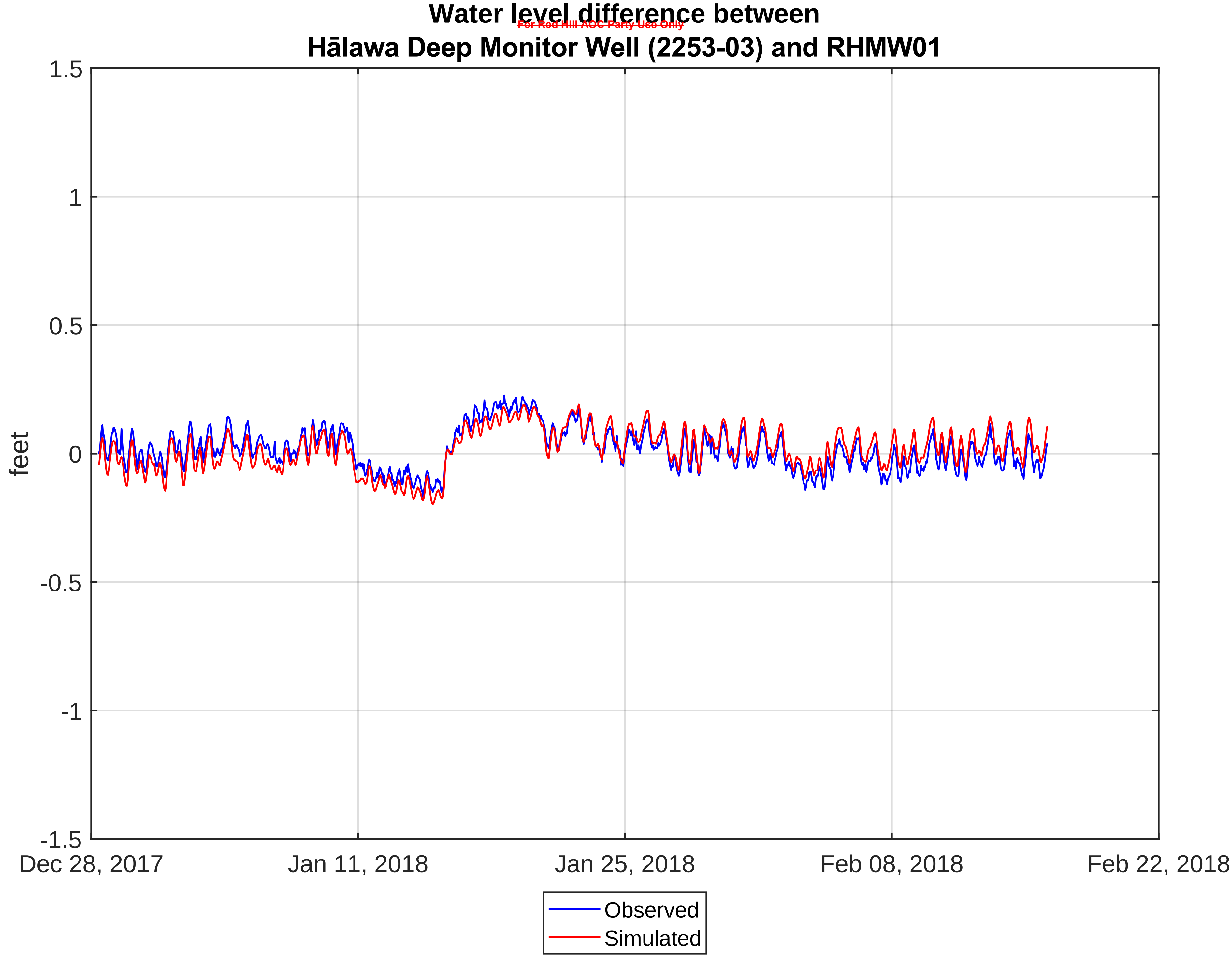
Hālawa Deep Monitor Well (2253-03) and Moanalua Deep



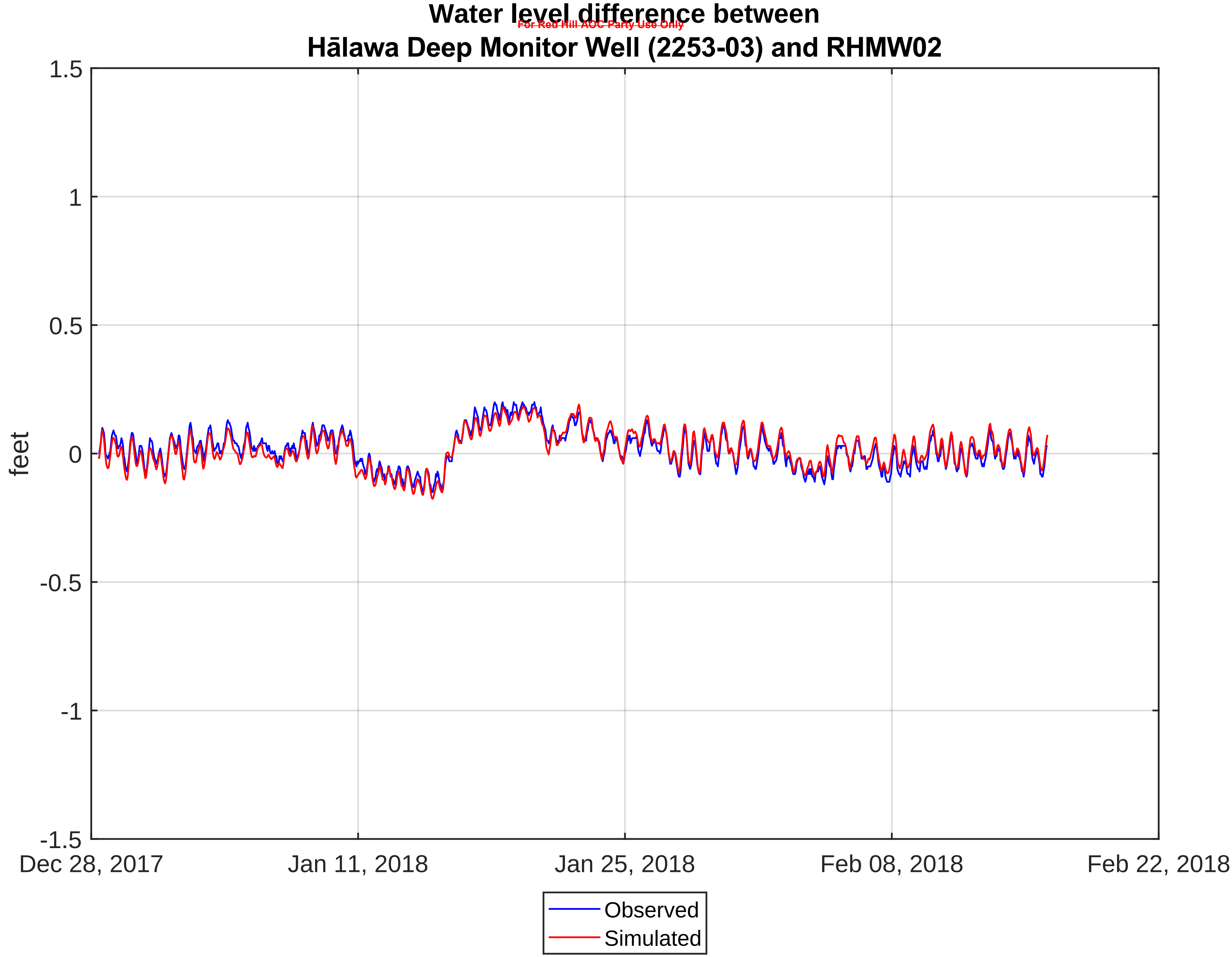
Water level difference between
Hālawa Deep Monitor Well (2253-03) and Moanalua DH43
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



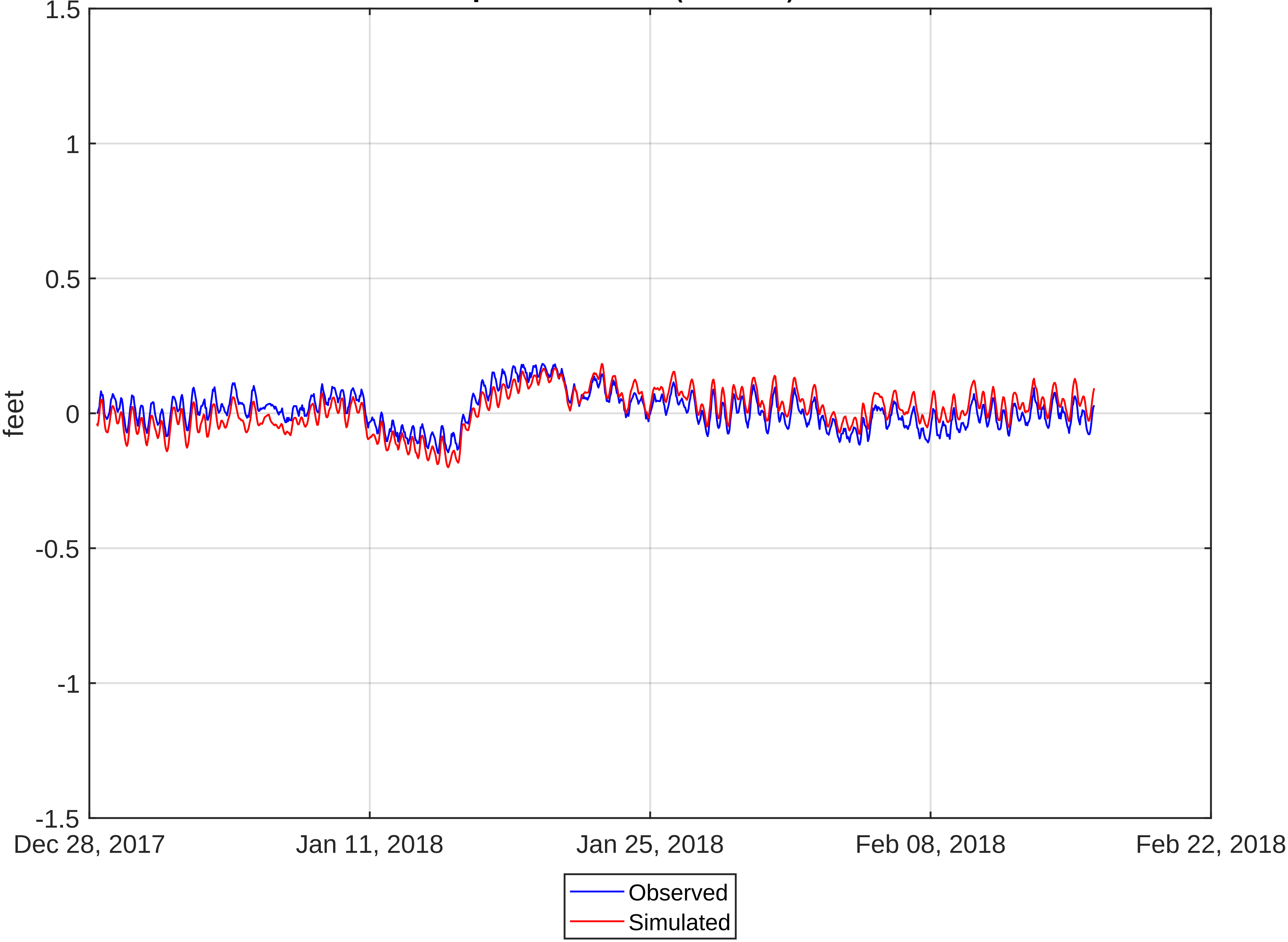
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and OWDFMW01
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

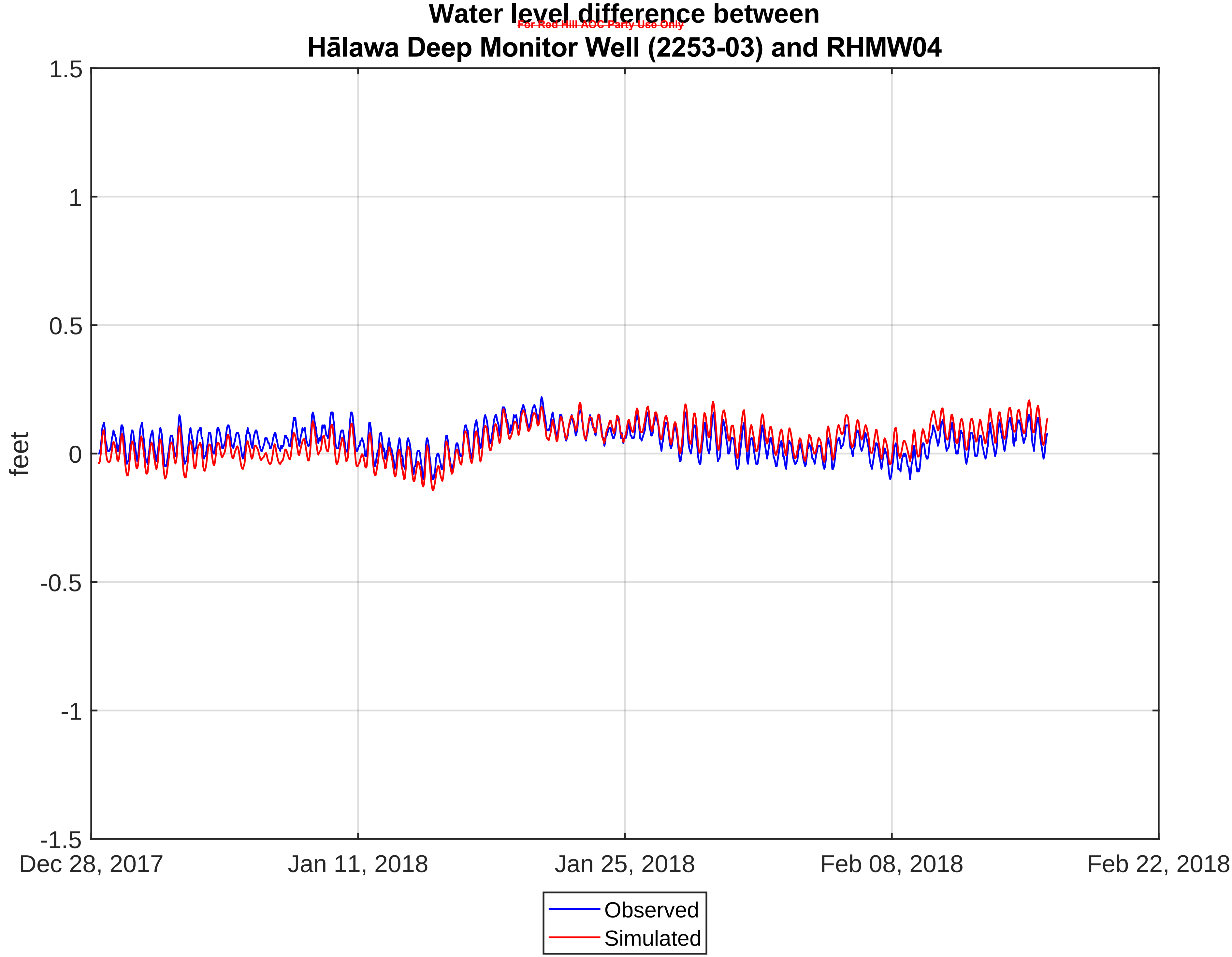


Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW01
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

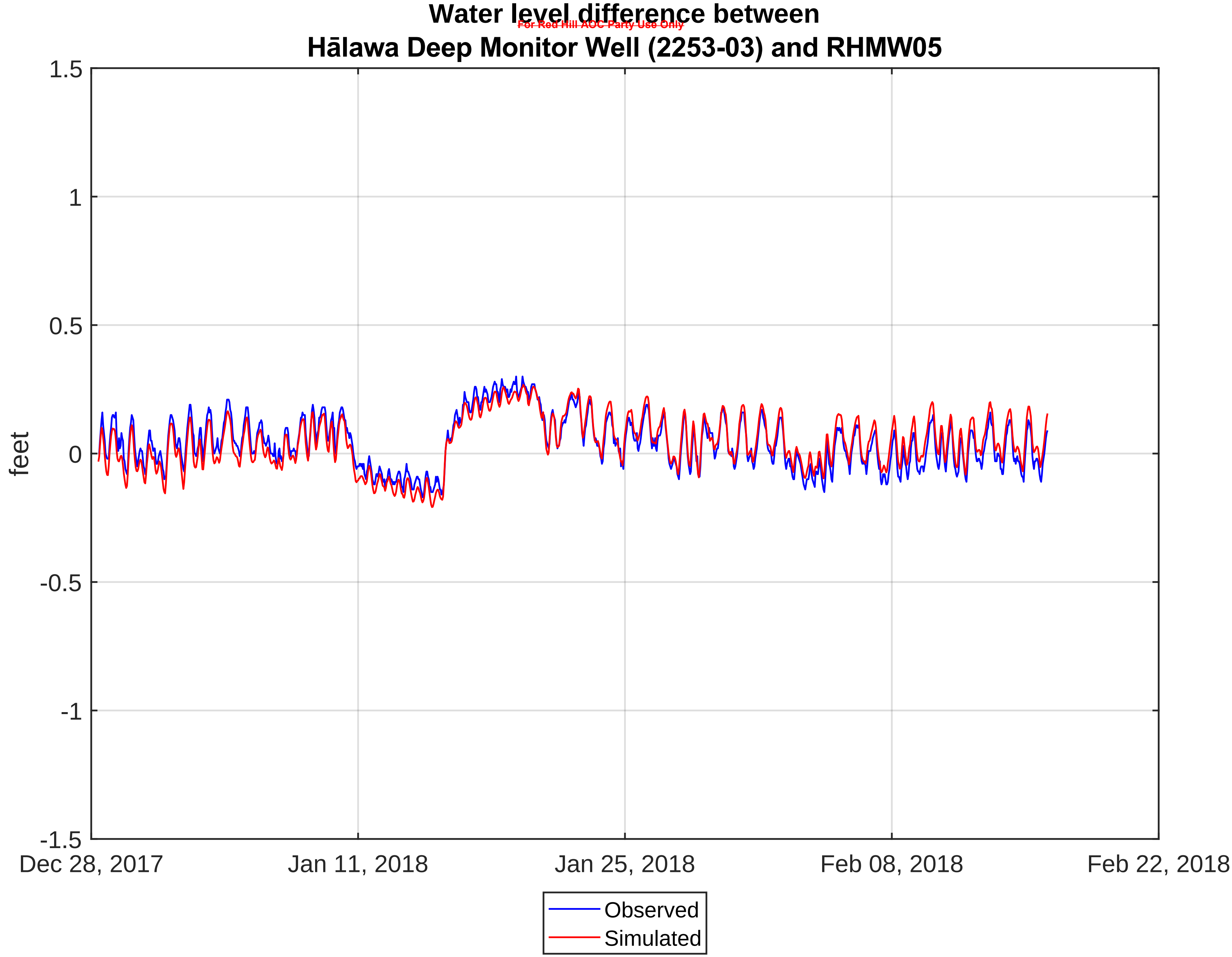

Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW02
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

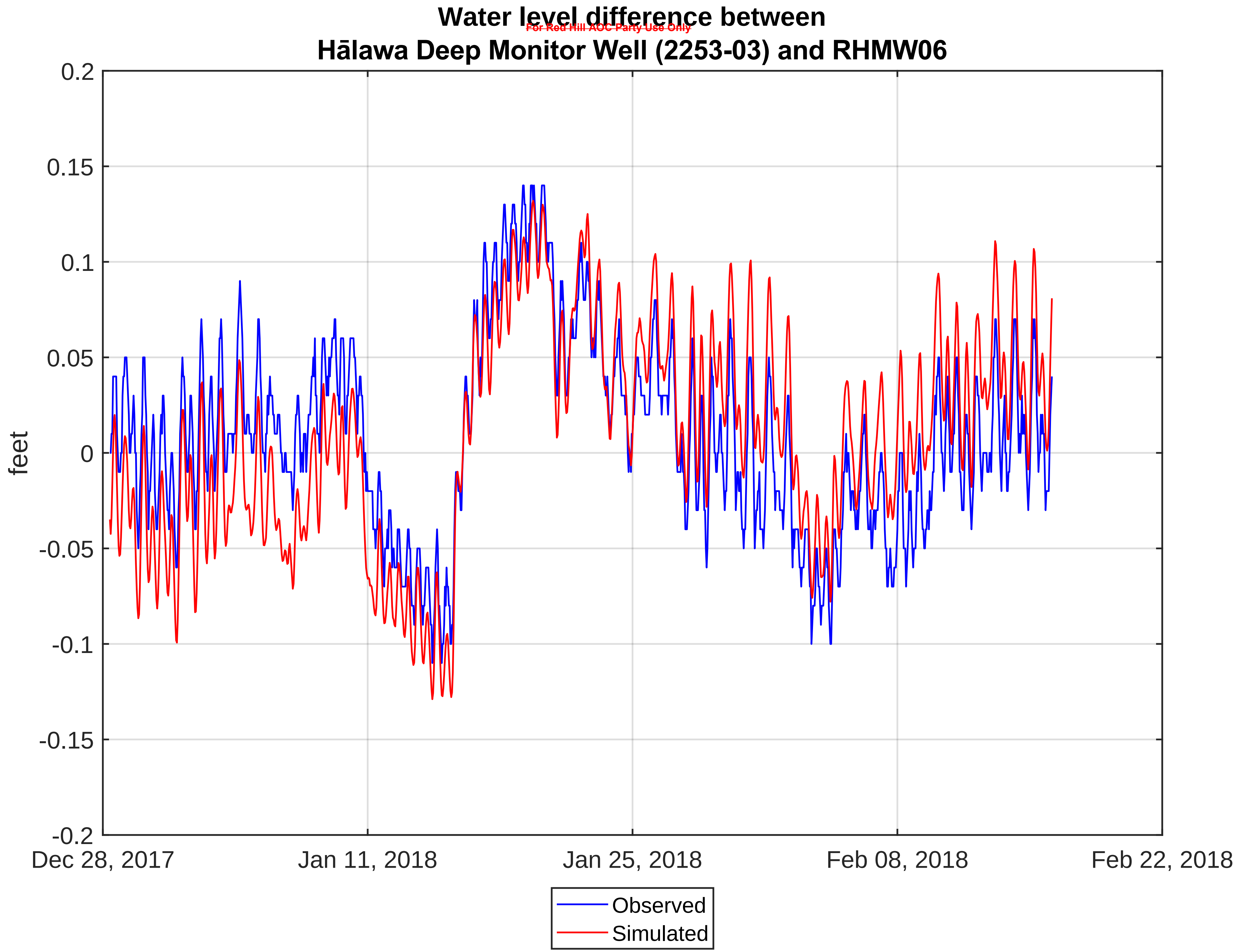
Water level difference between Hālawa Deep Monitor Well (2253-03) and RHMW03



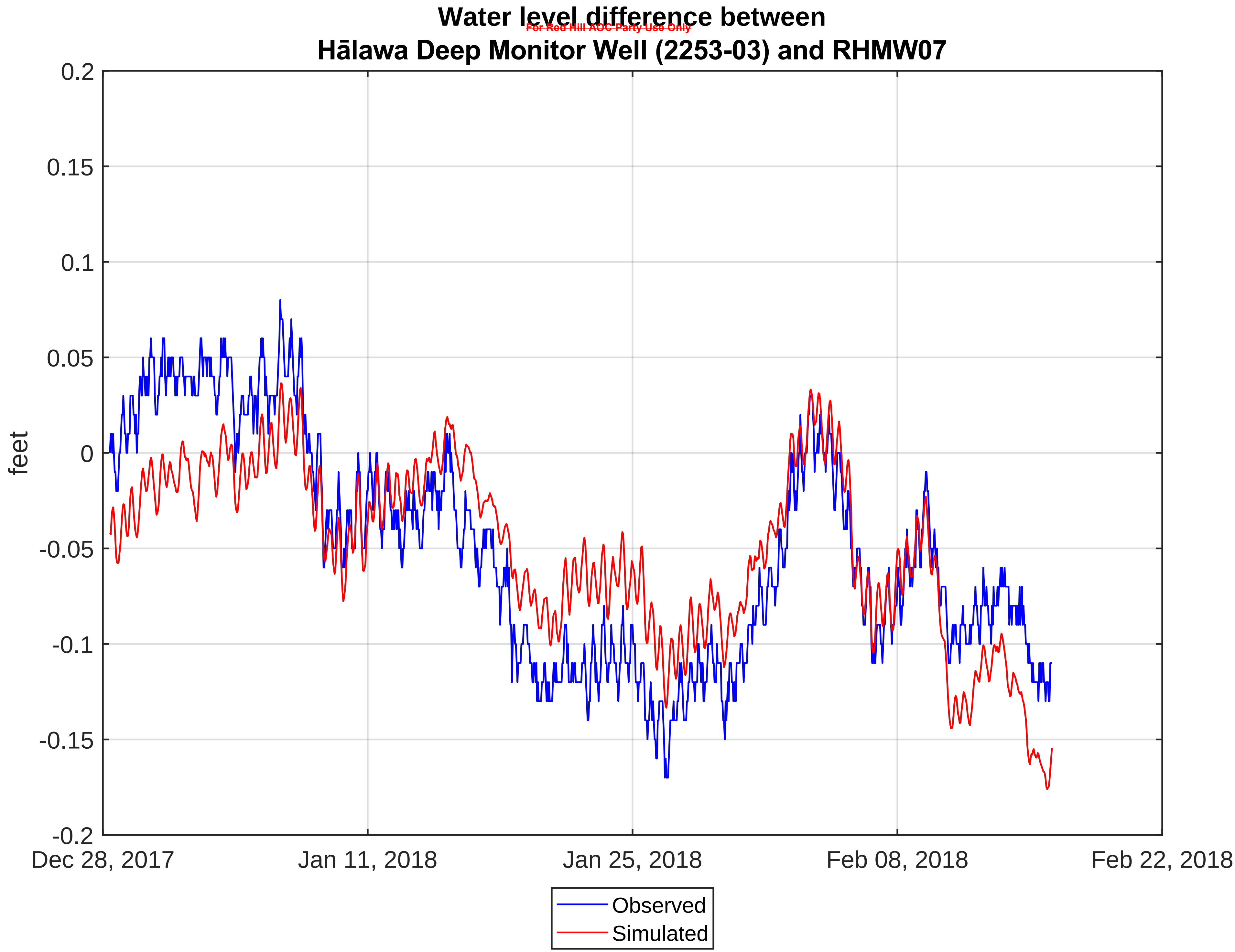


Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW04
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

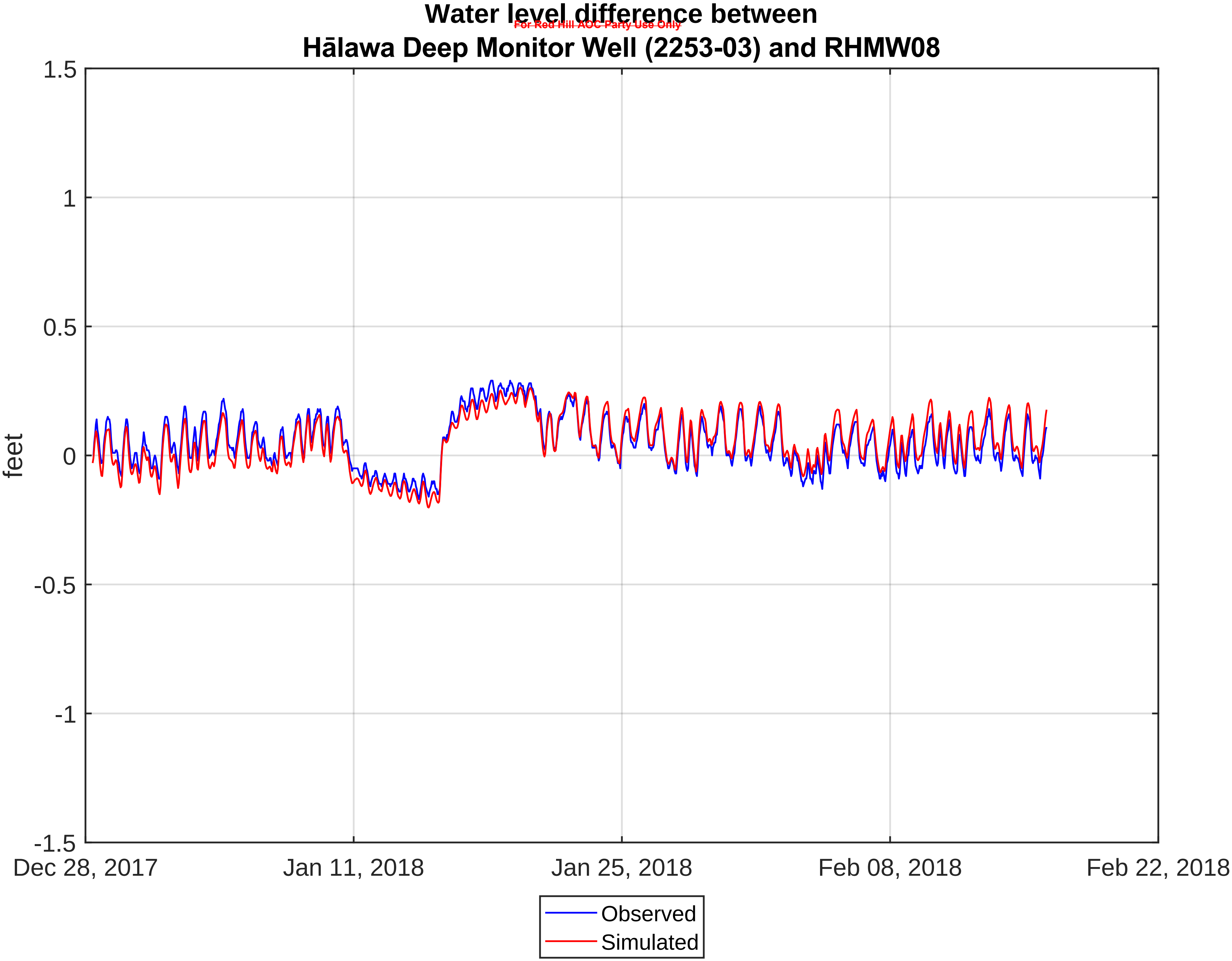

Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW05
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



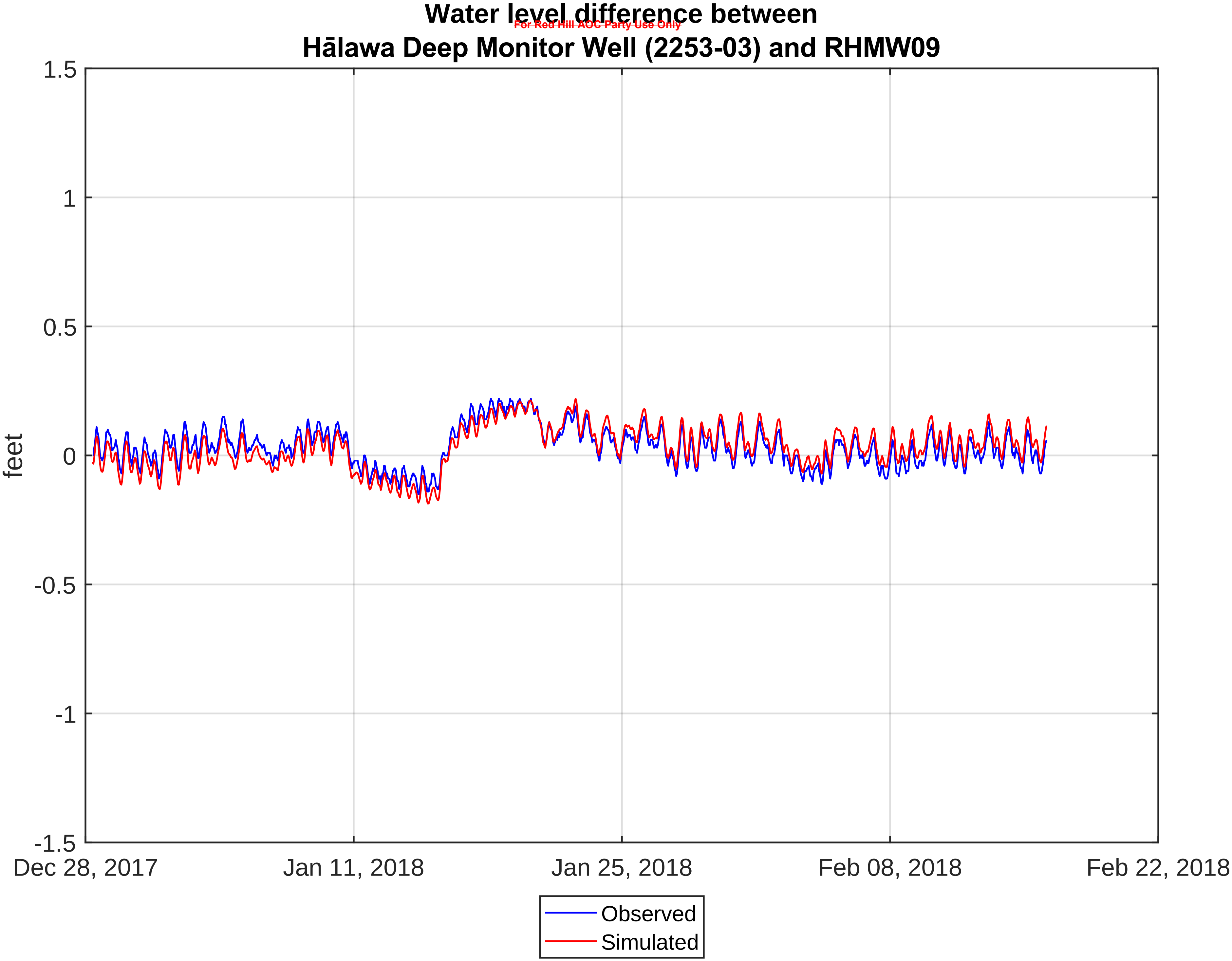
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW06
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW07
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

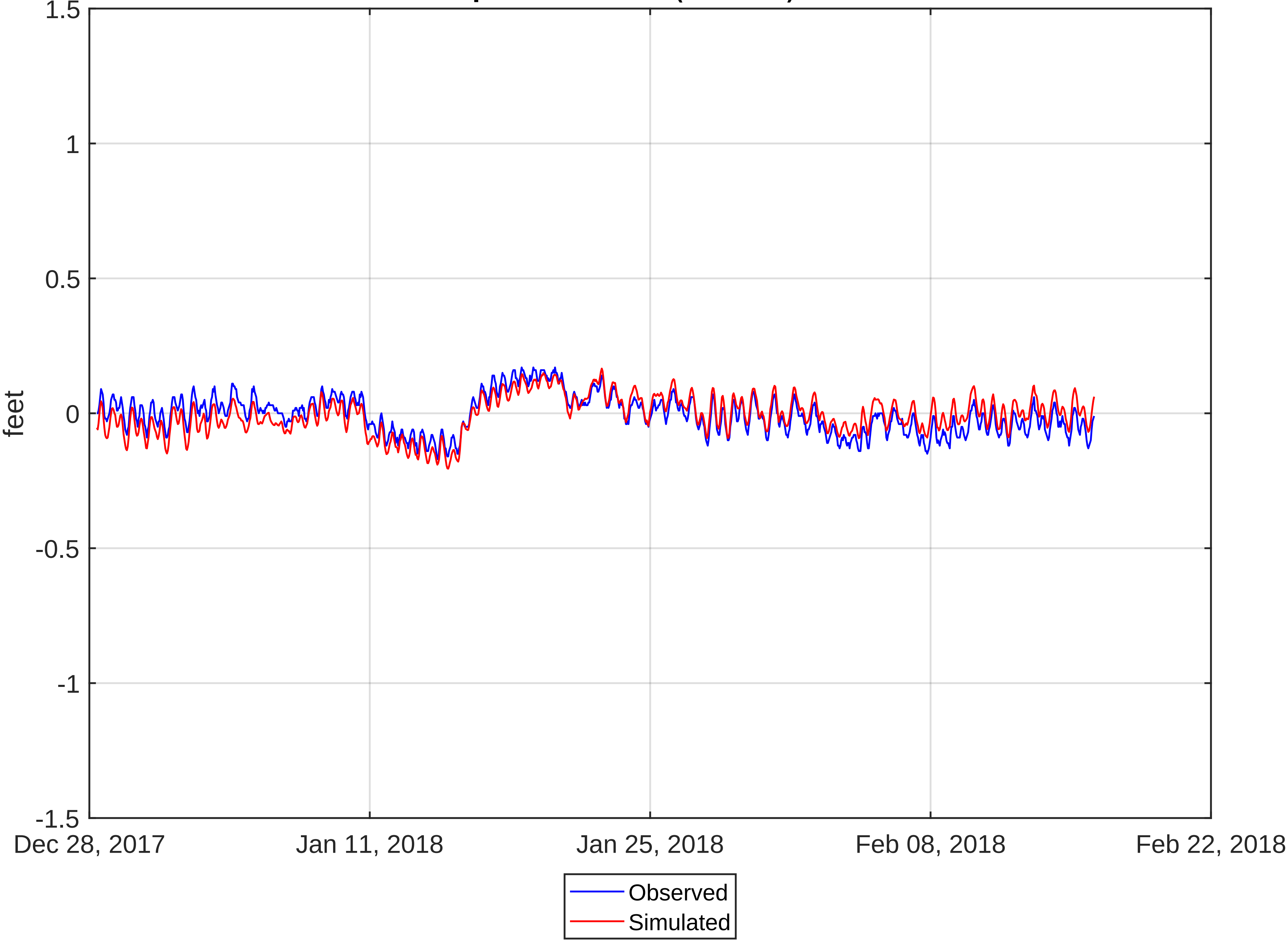


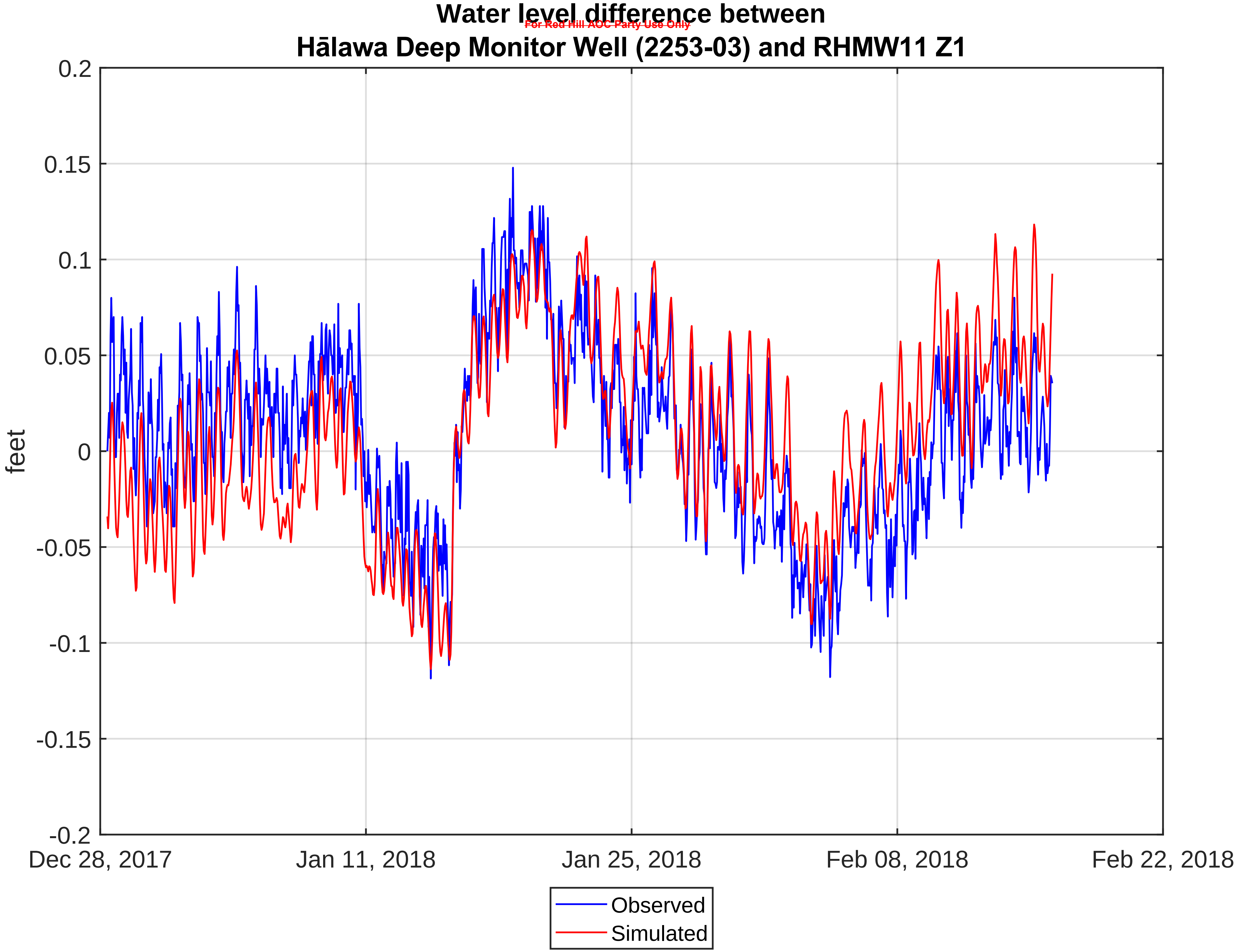
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW08
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



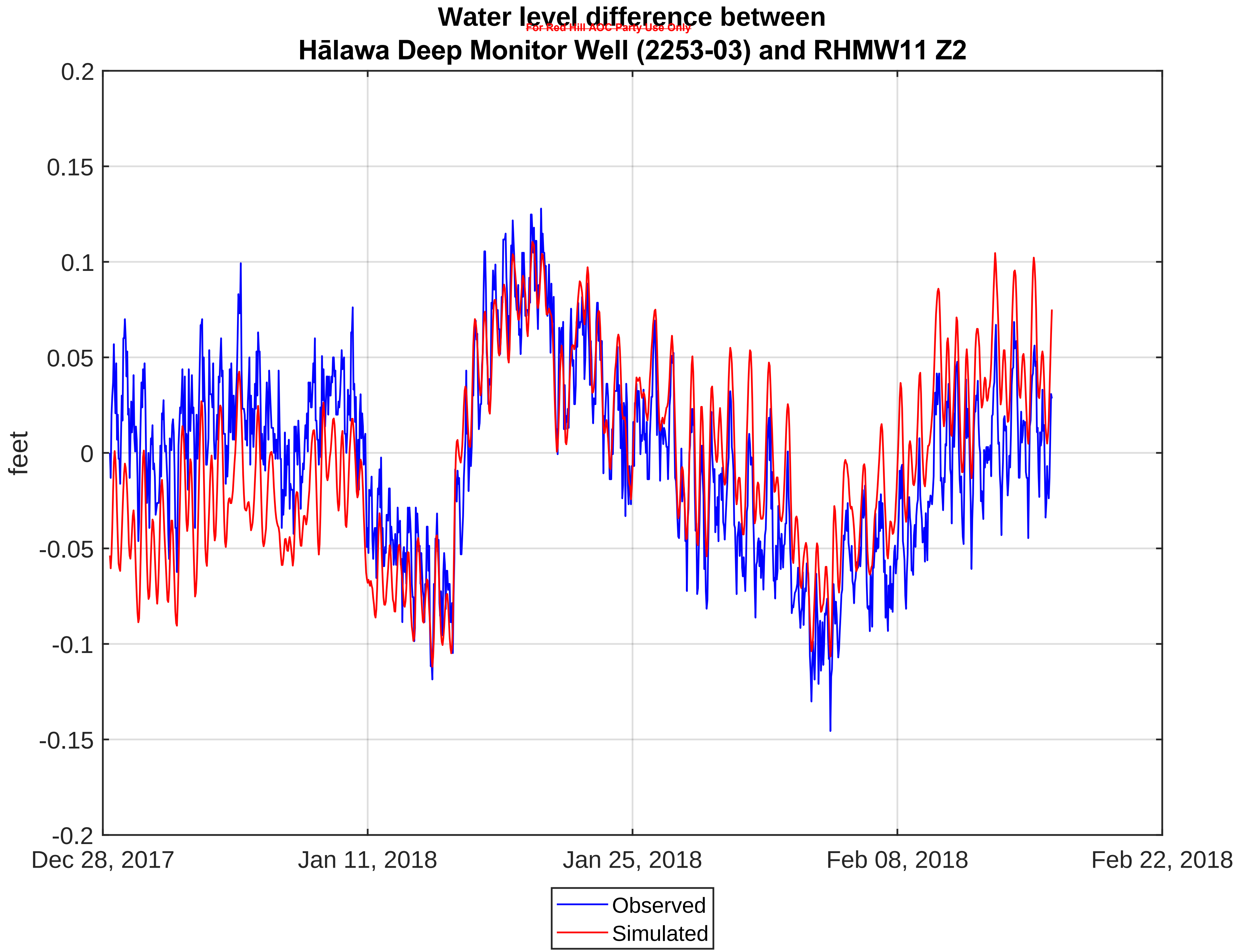
Water level difference between
Hālawa Deep Monitor Well (2253-03) and RHMW09
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW10

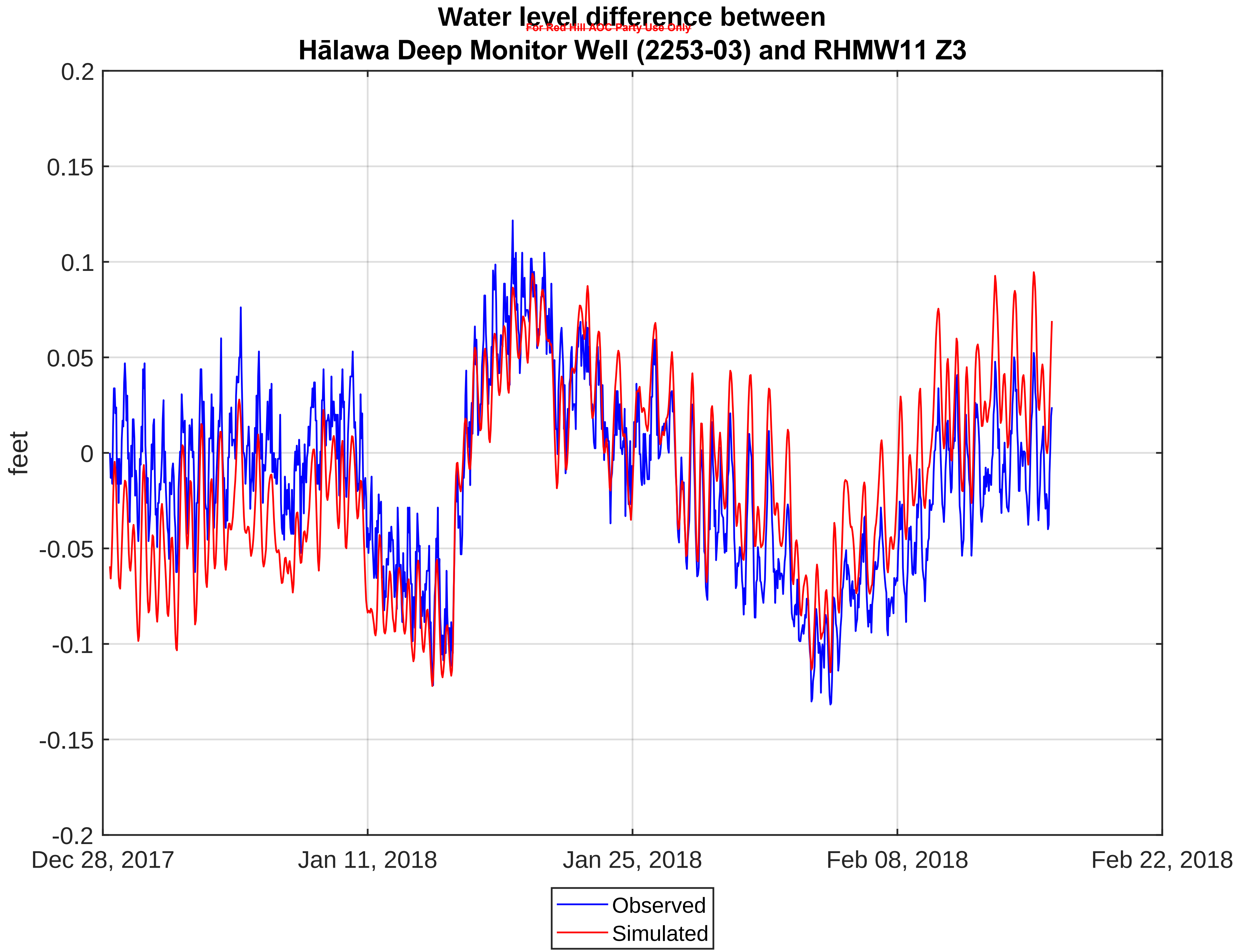




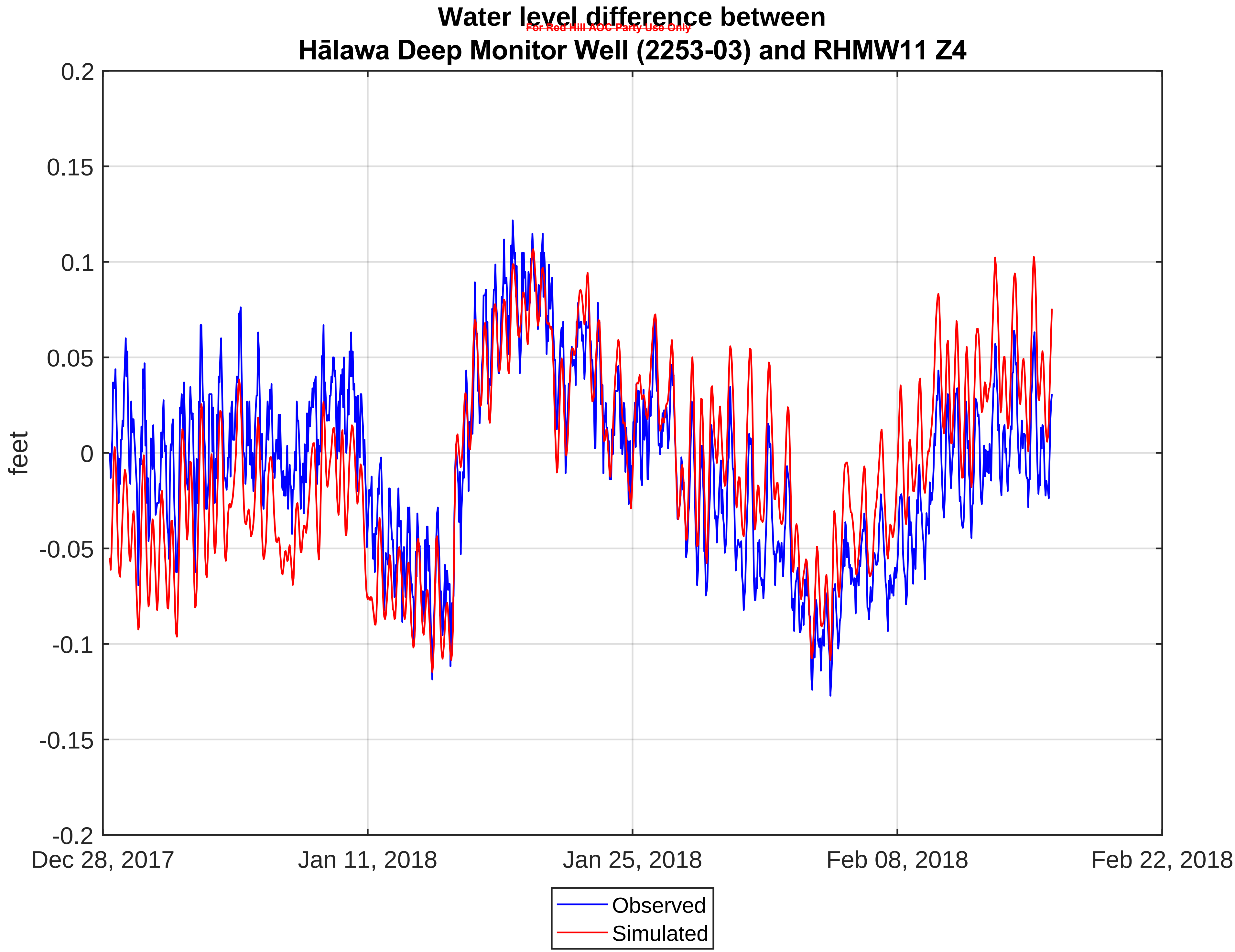
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW11 Z1
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



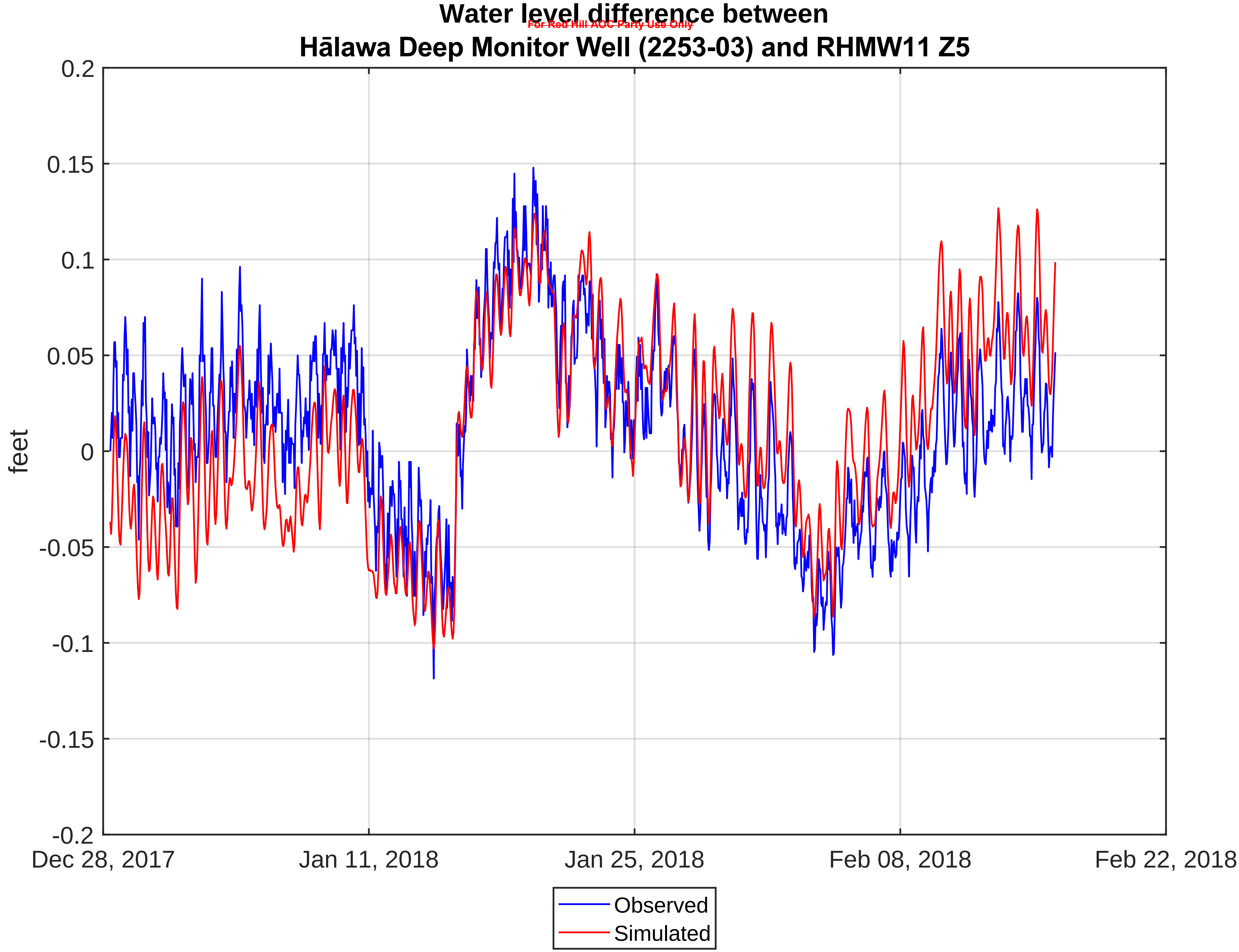
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW11 Z2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW11 Z3
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



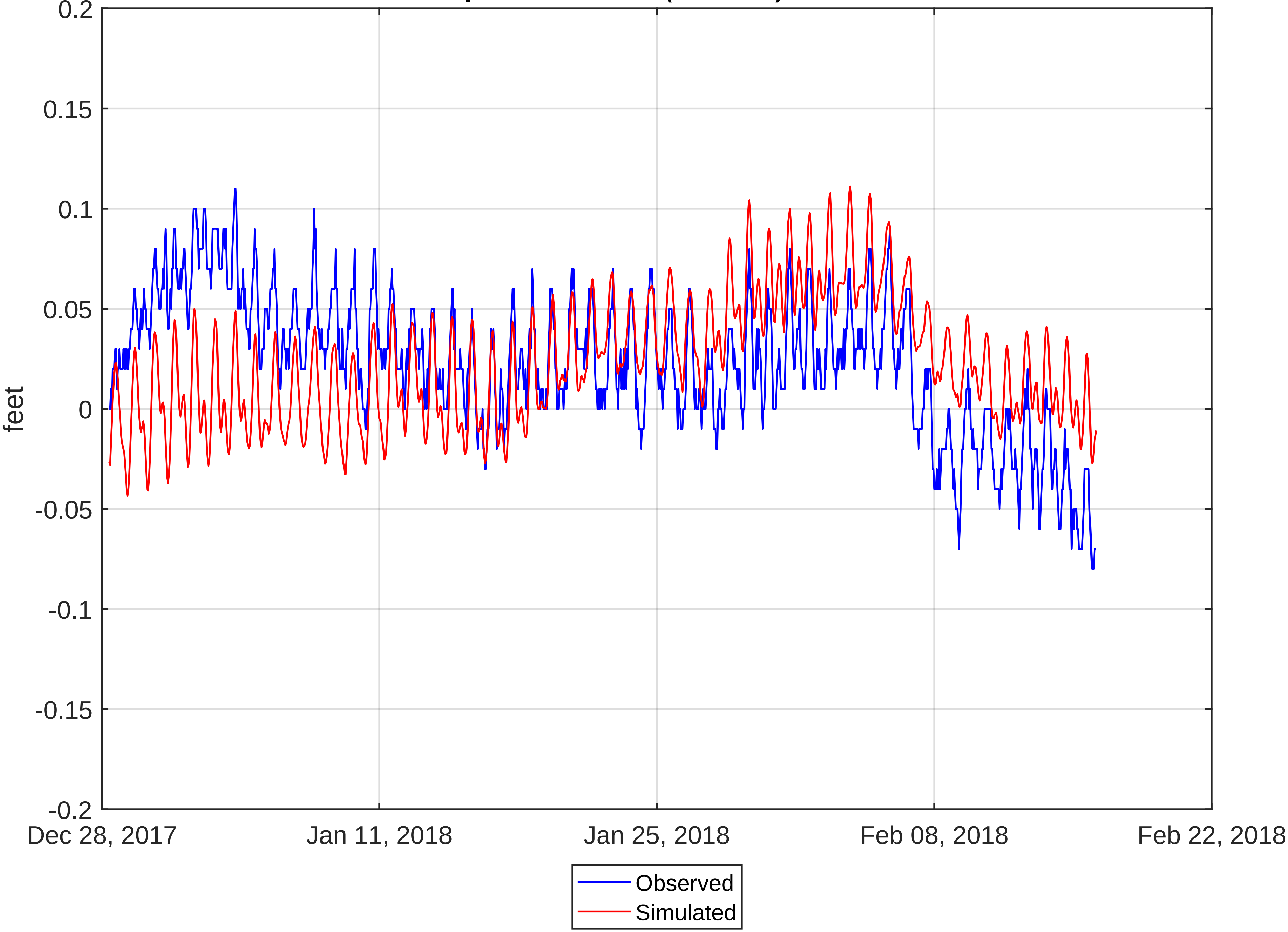
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW11 Z4
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

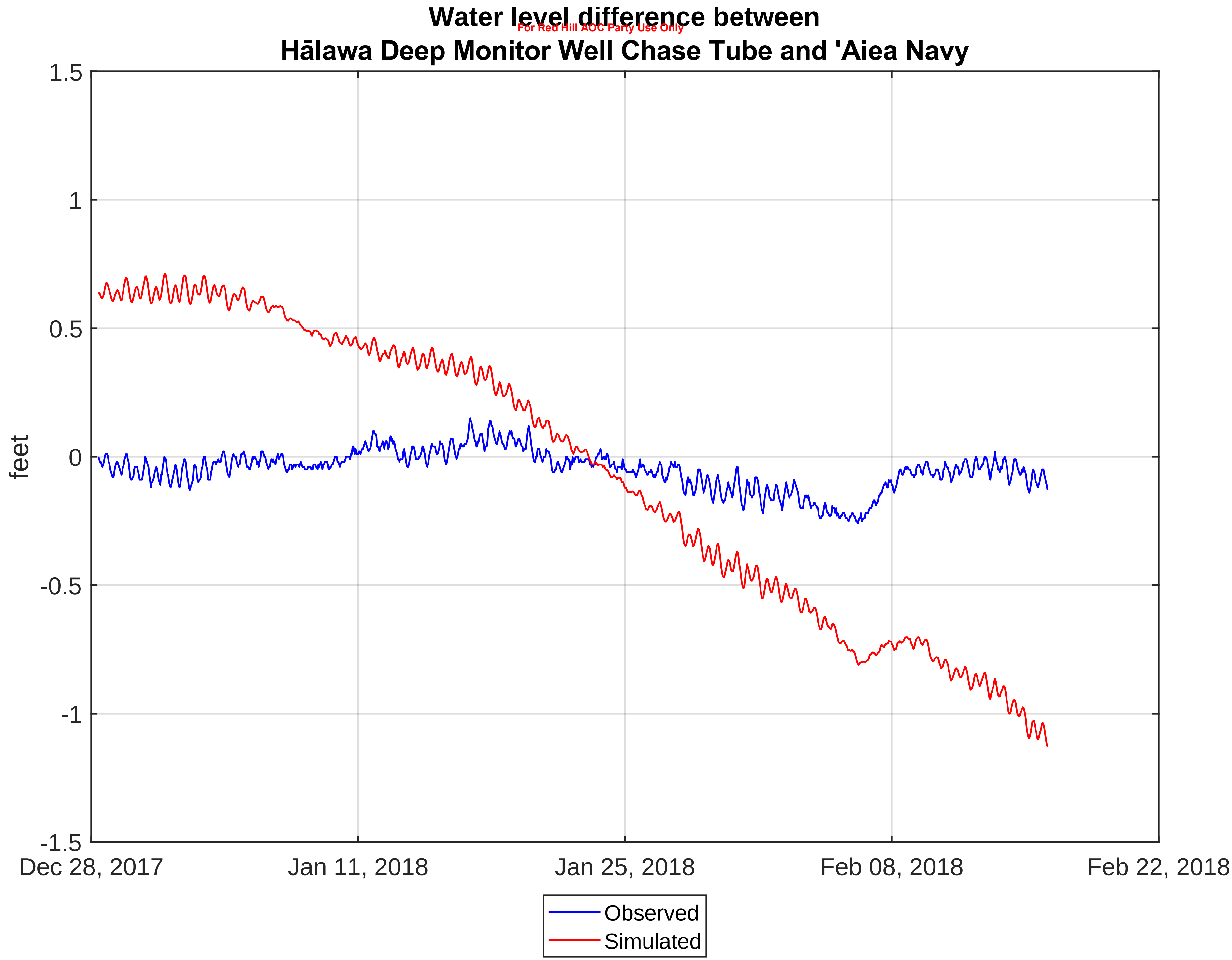


Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well (2253-03) and RHMW11 Z5
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

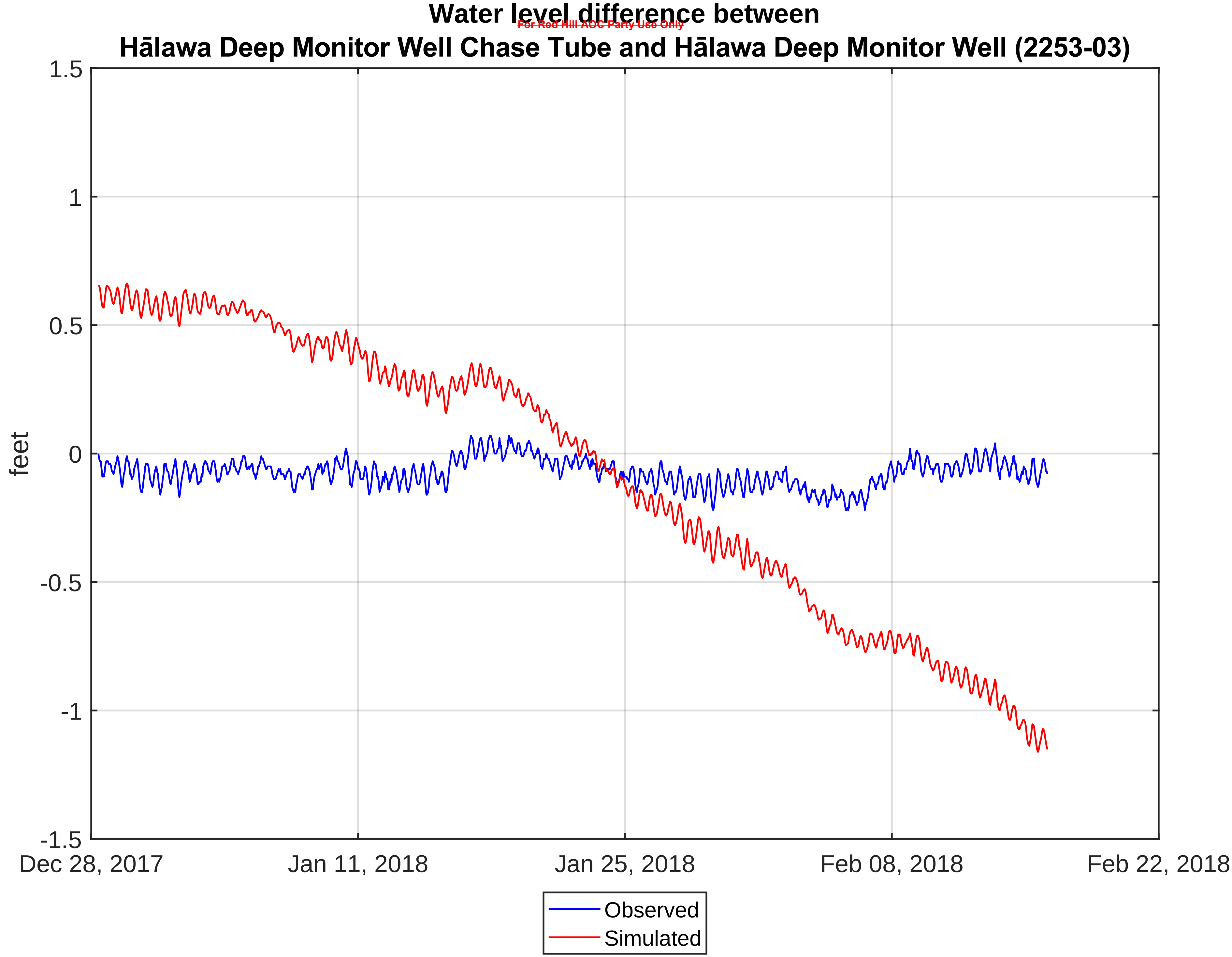
Water level difference between Hālawa Deep Monitor Well (2253-03) and TAMC-MW2

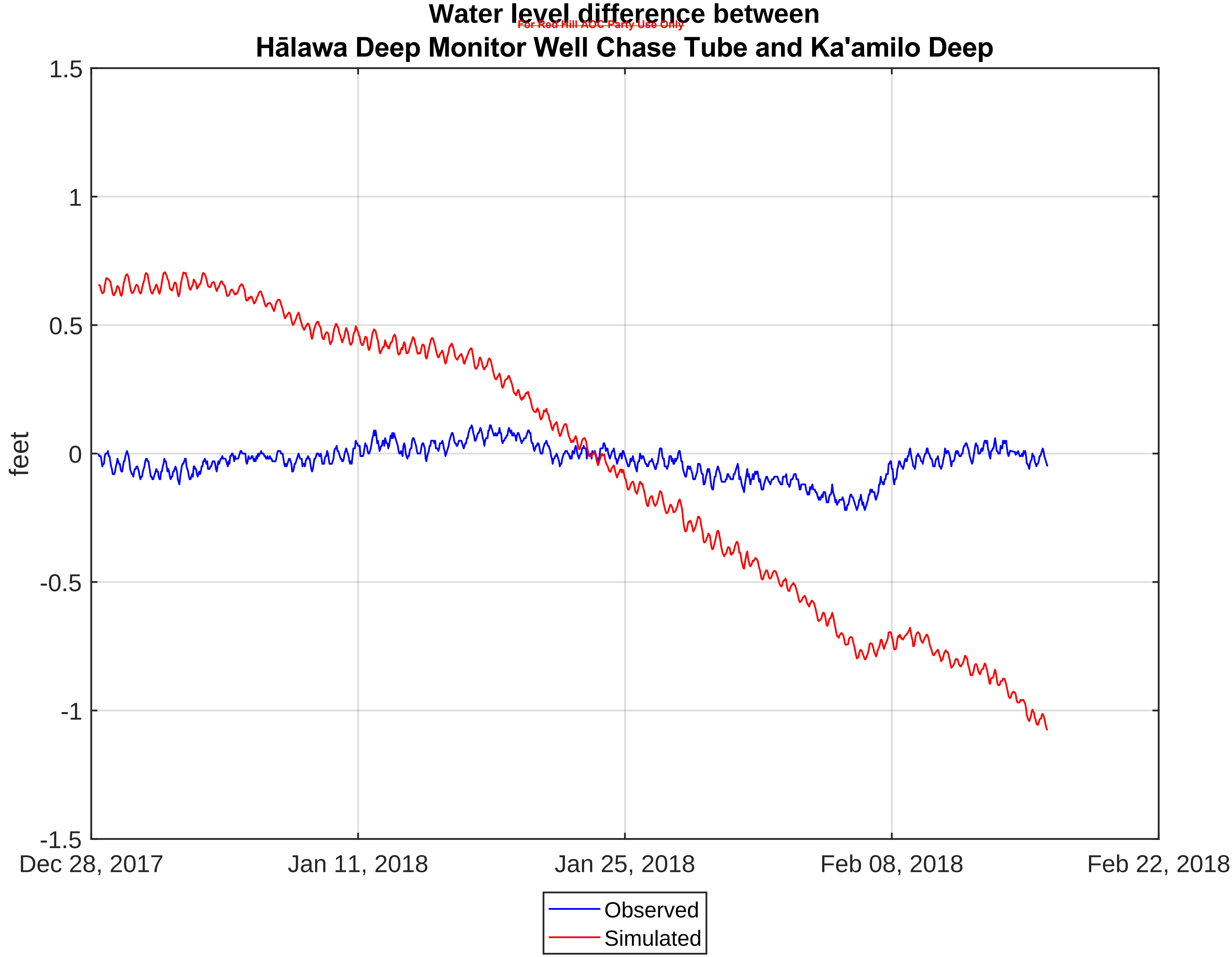
For Red Hill AOC Party Use Only



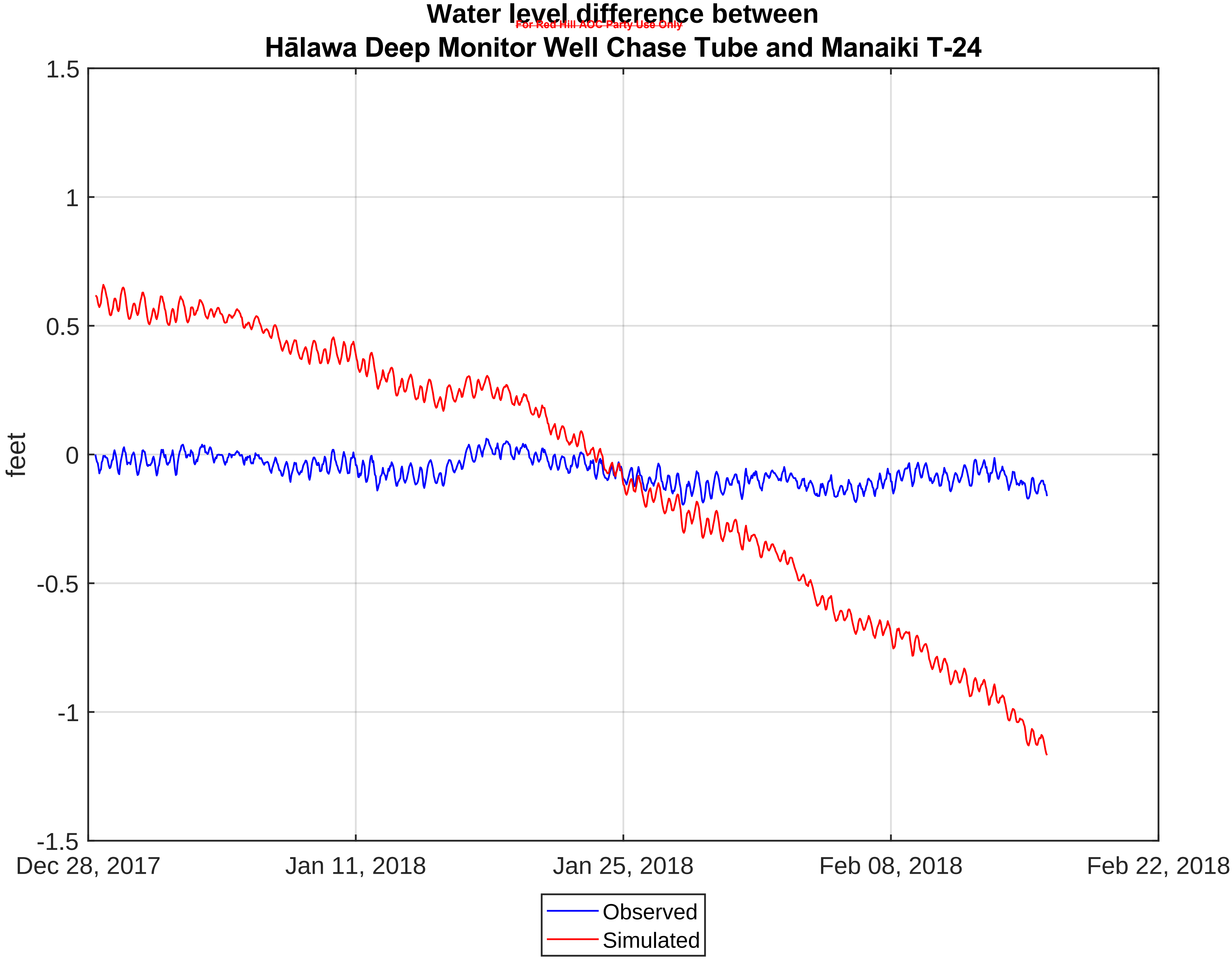


Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and 'Aiea Navy
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

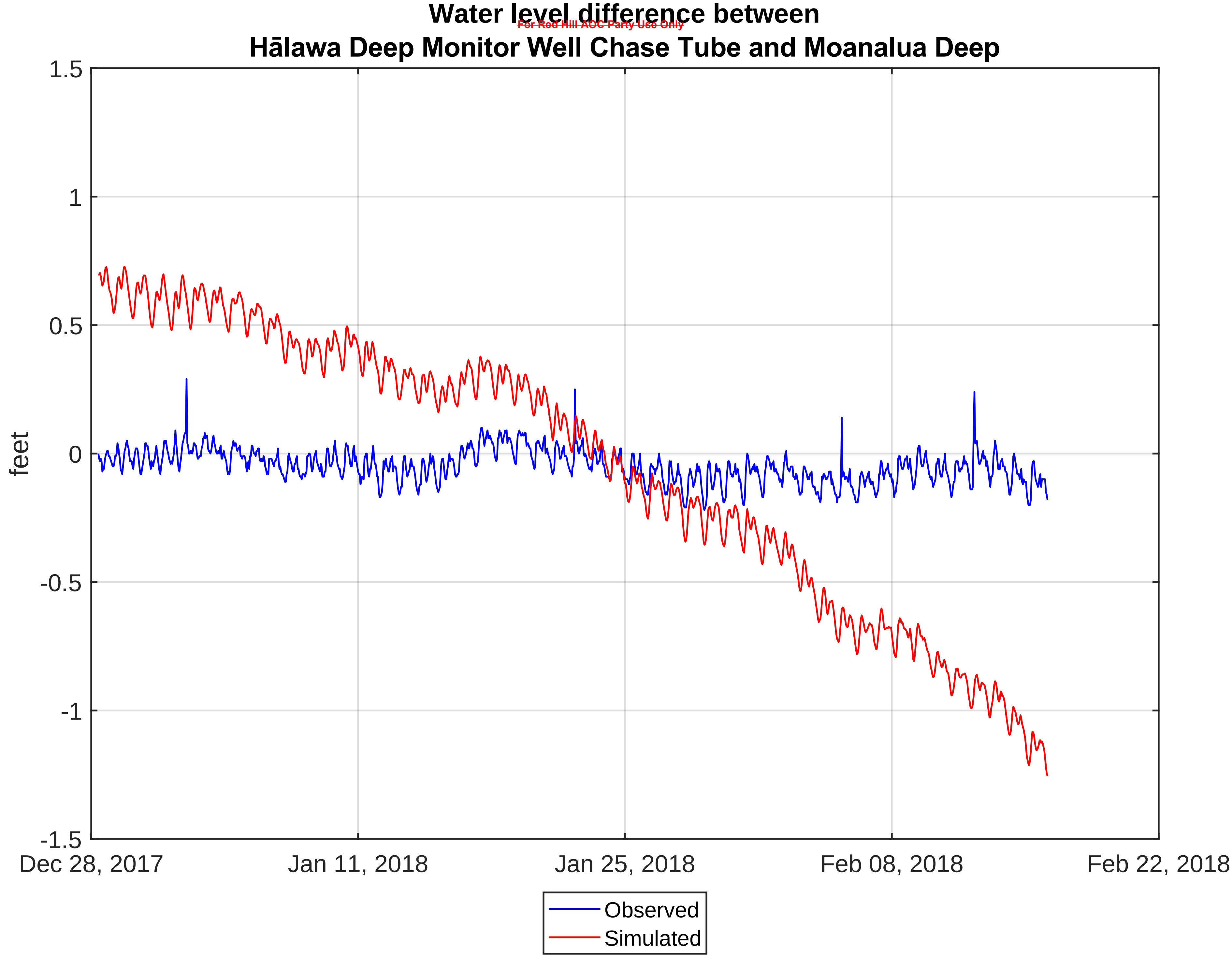

Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and Hālawa Deep Monitor Well (2253-03)
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



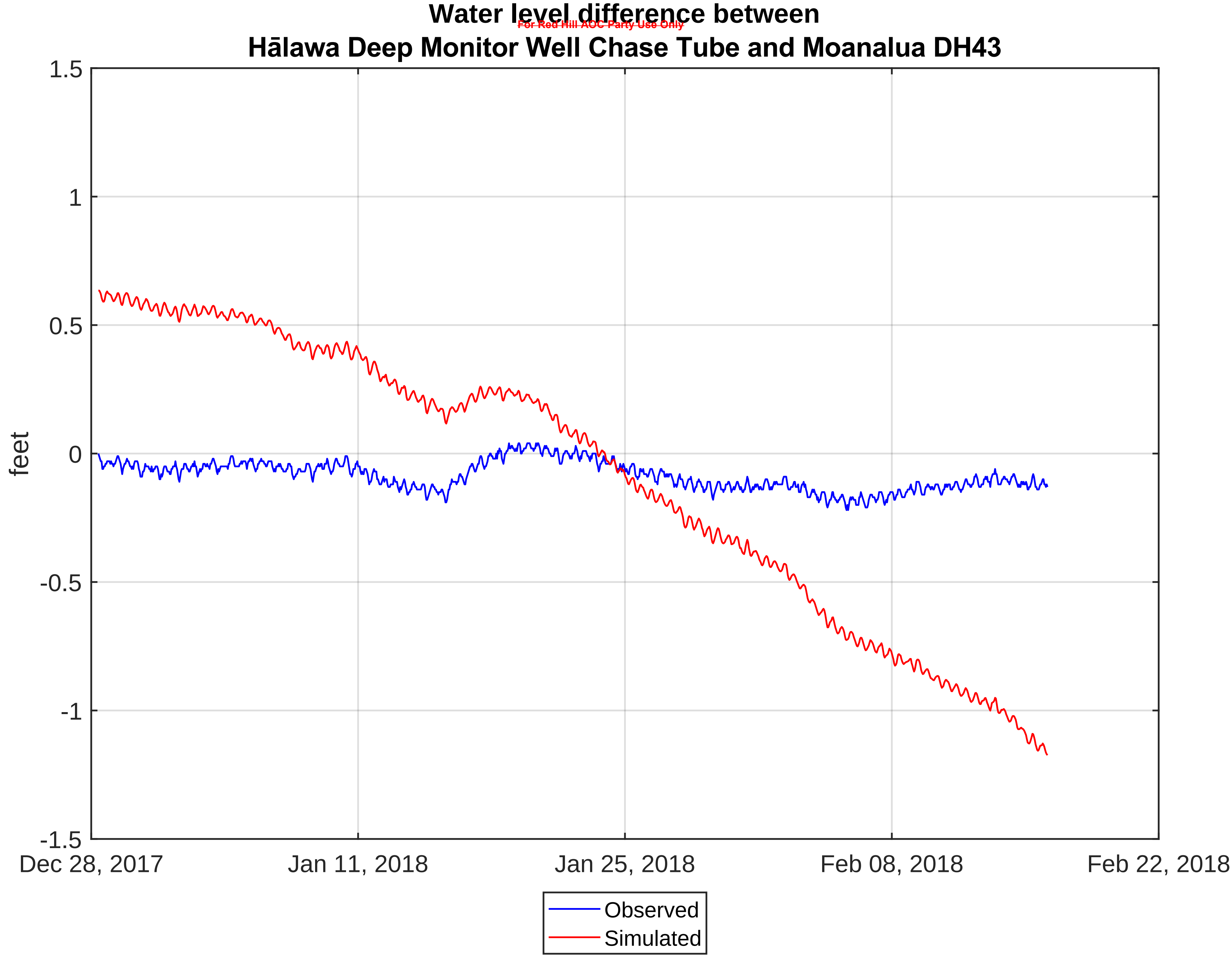
Water level difference between
Hālawa Deep Monitor Well Chase Tube and Ka'amilo Deep
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and Manaiki T-24
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



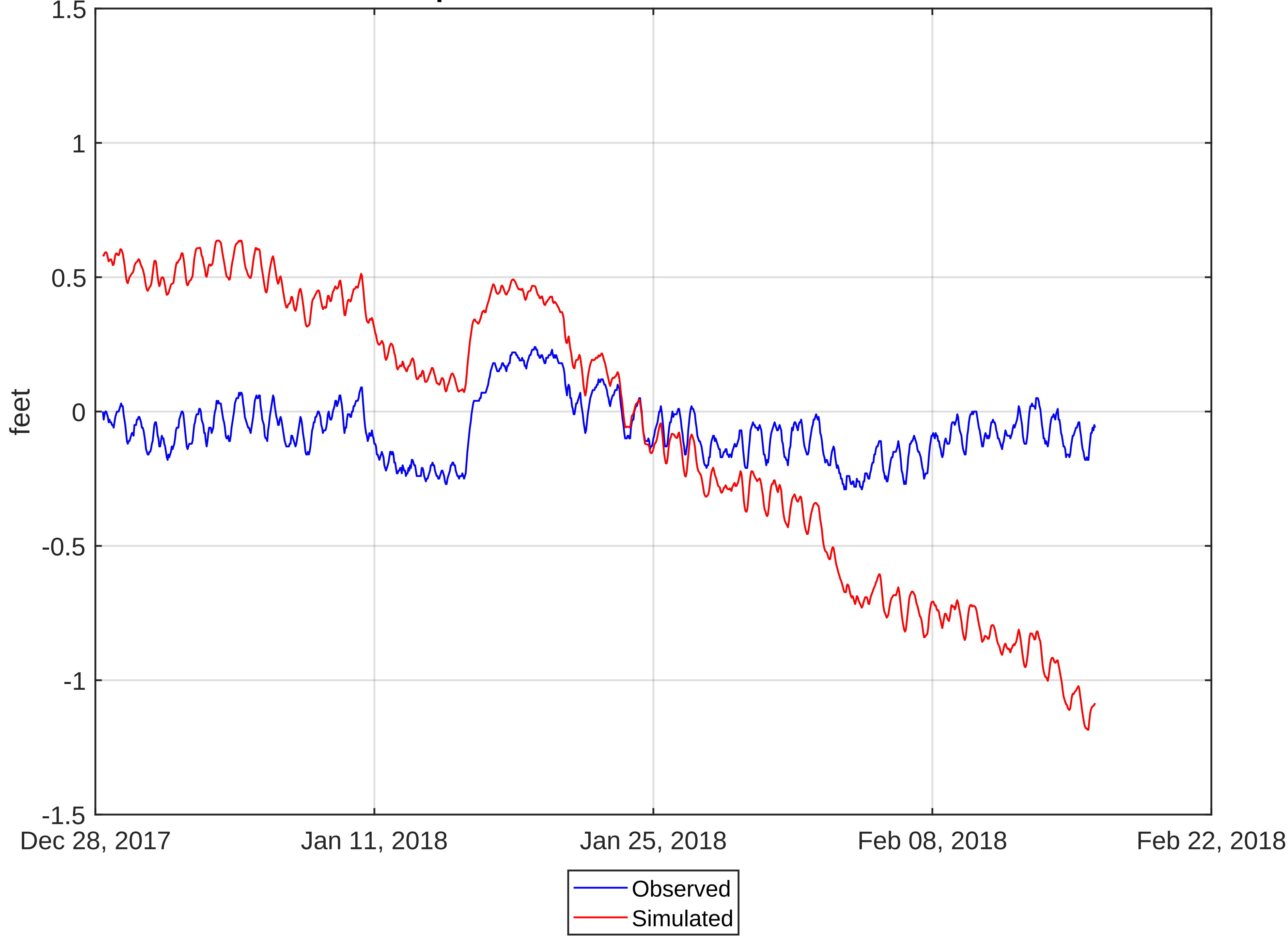
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and Moanalua Deep
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and Moanalua DH43
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

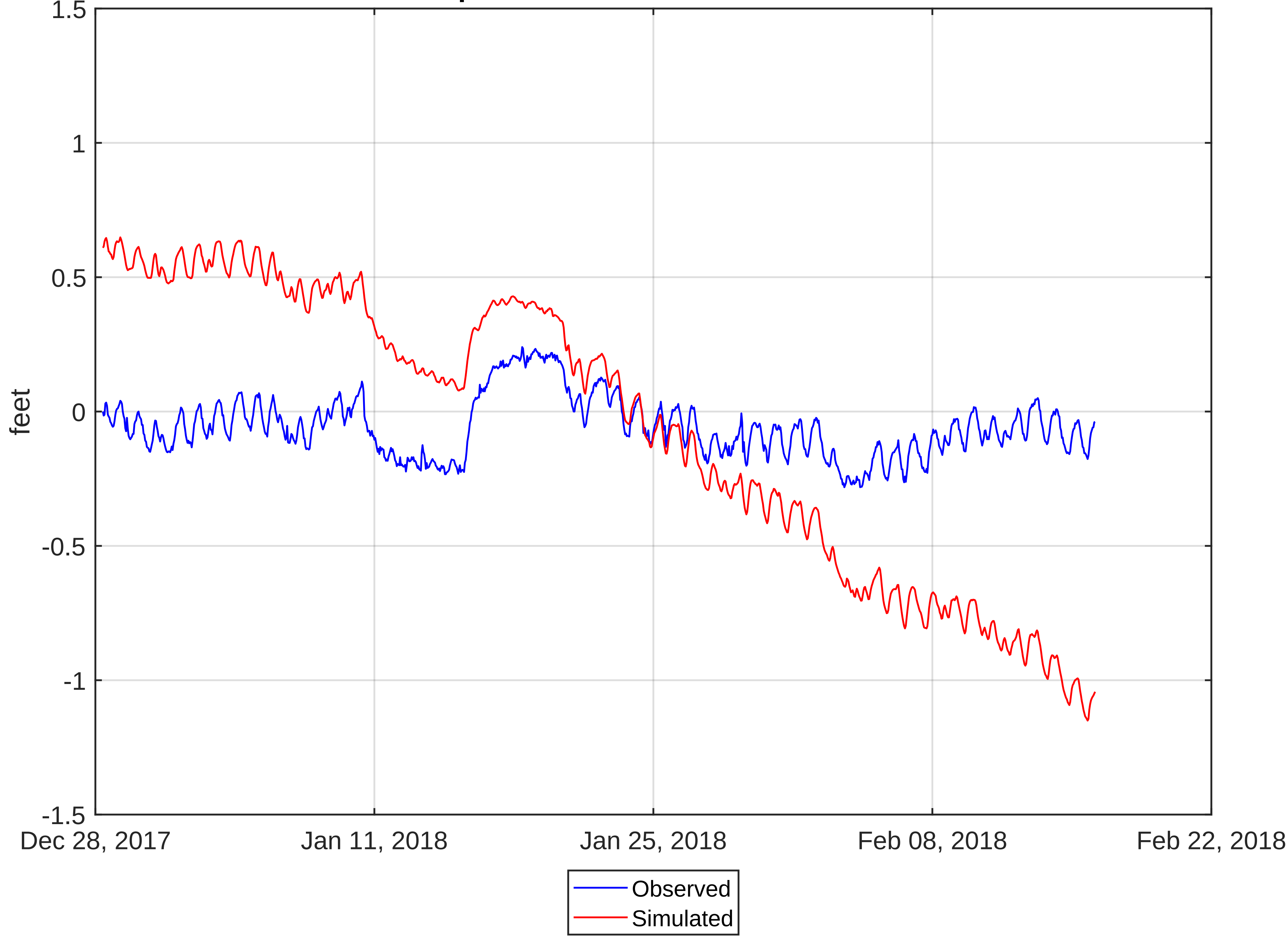
Water level difference between

Hālawa Deep Monitor Well Chase Tube and OWDFMW01



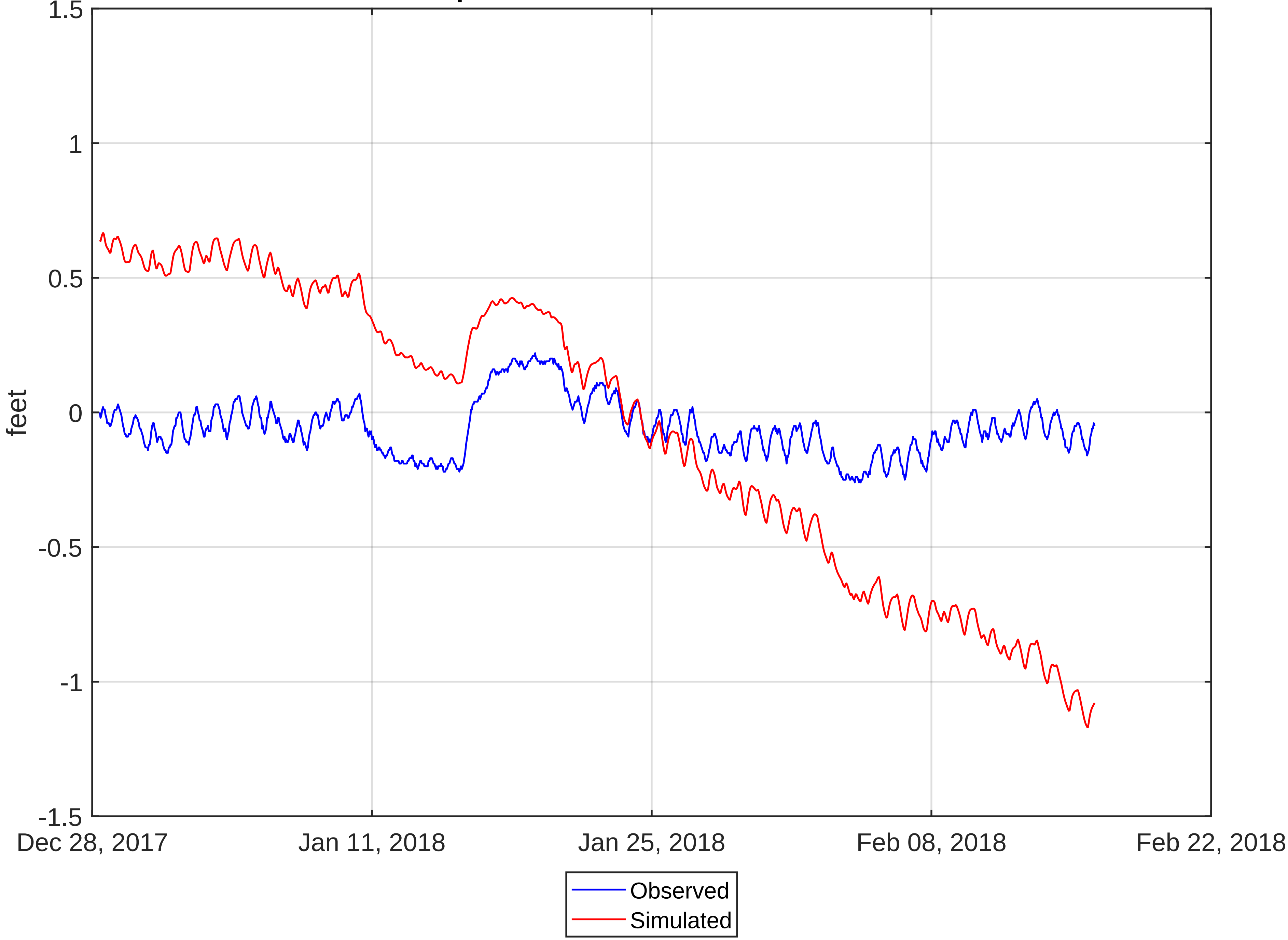
Water level difference between

Hālawa Deep Monitor Well Chase Tube and RHMW01

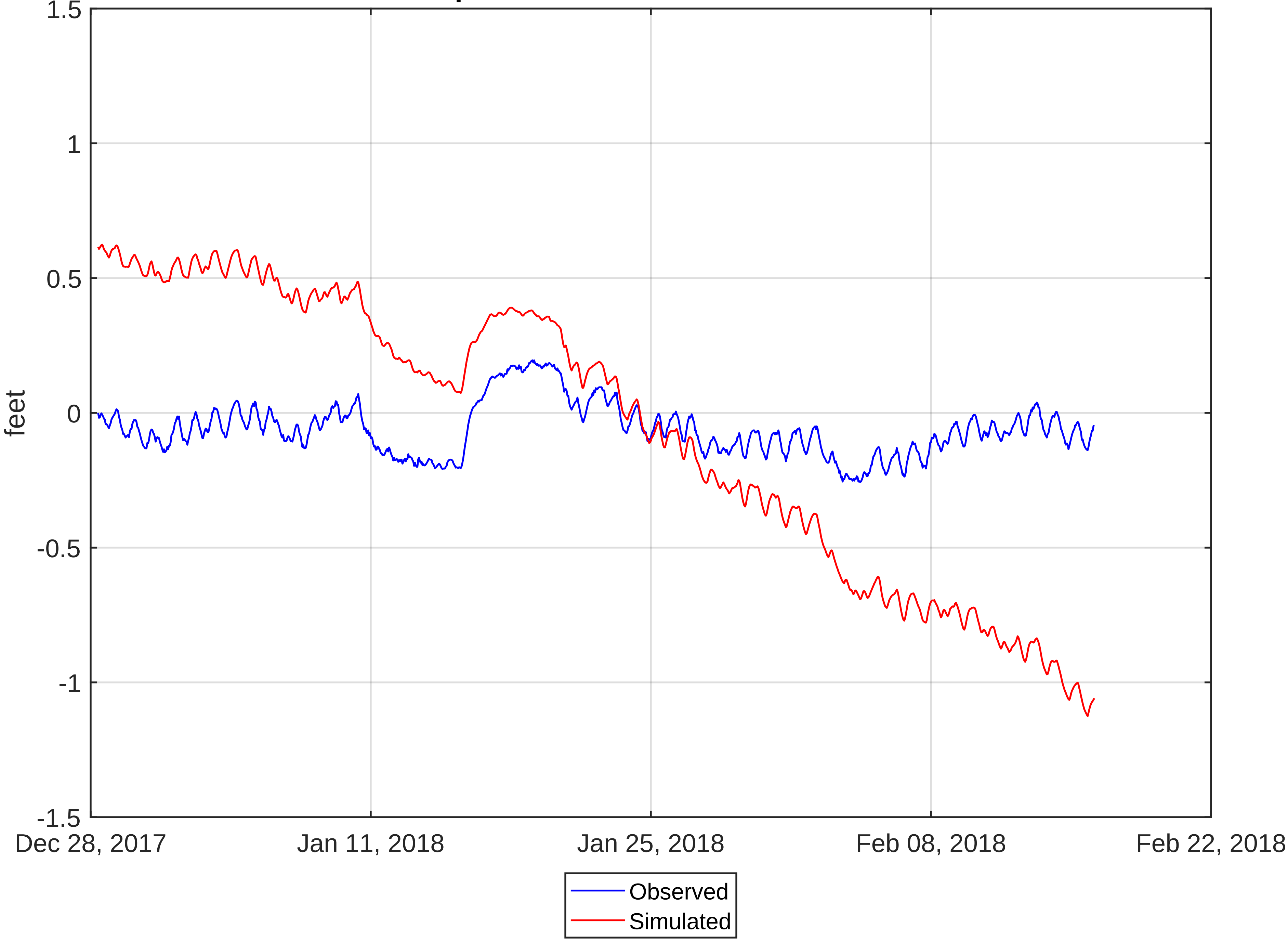


Water level difference between

Hālawa Deep Monitor Well Chase Tube and RHMW02

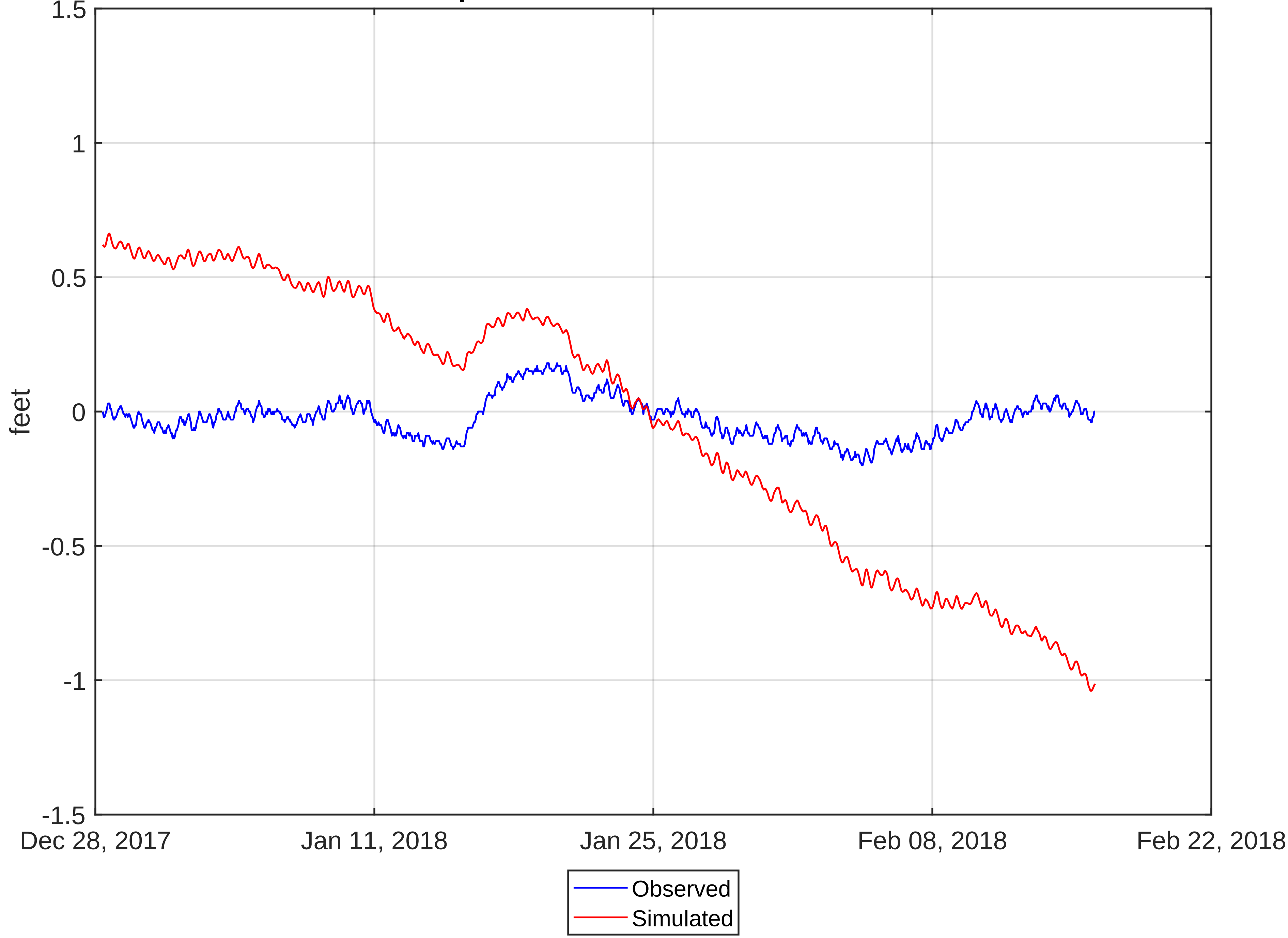


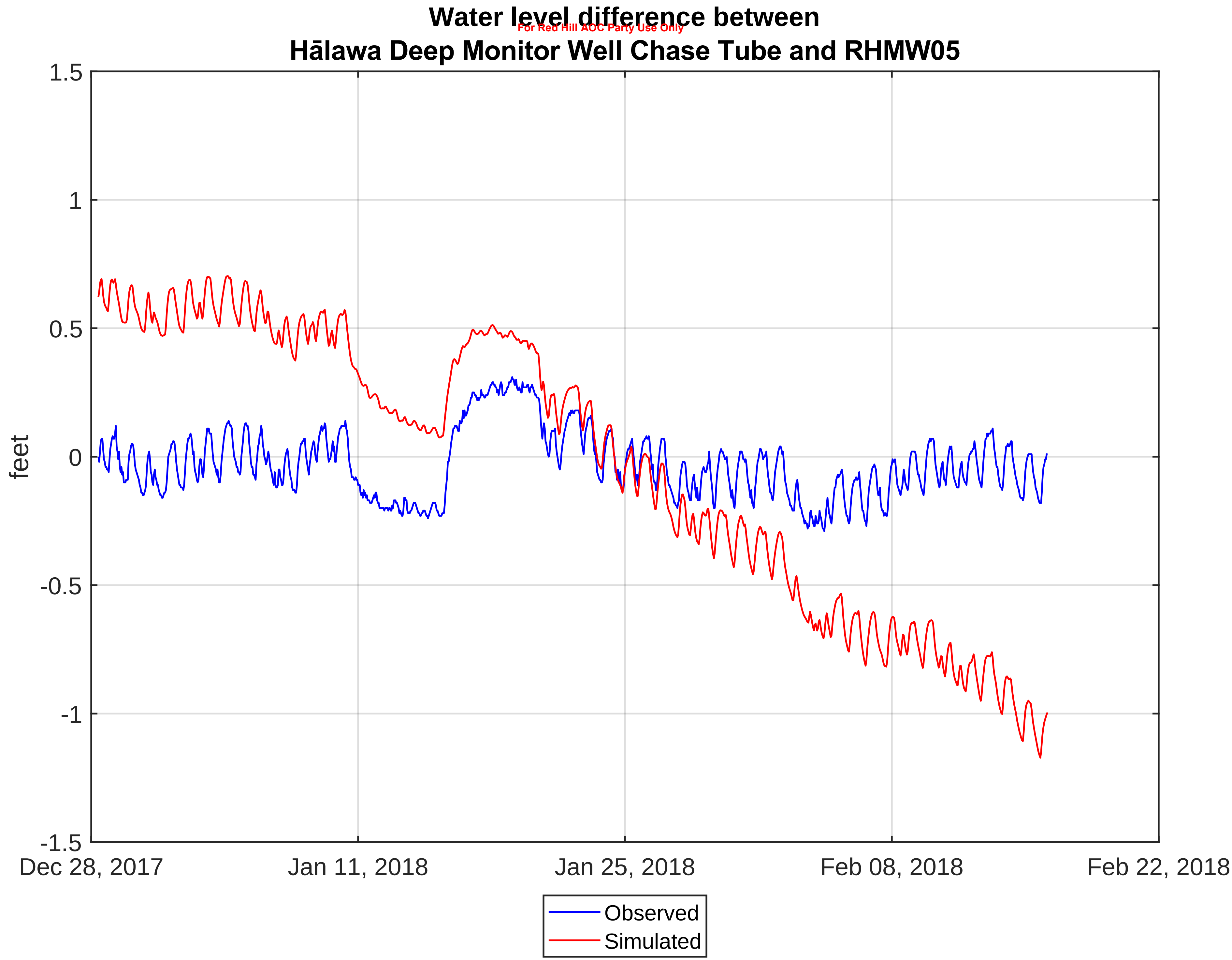
Water level difference between Hālawa Deep Monitor Well Chase Tube and RHMW03



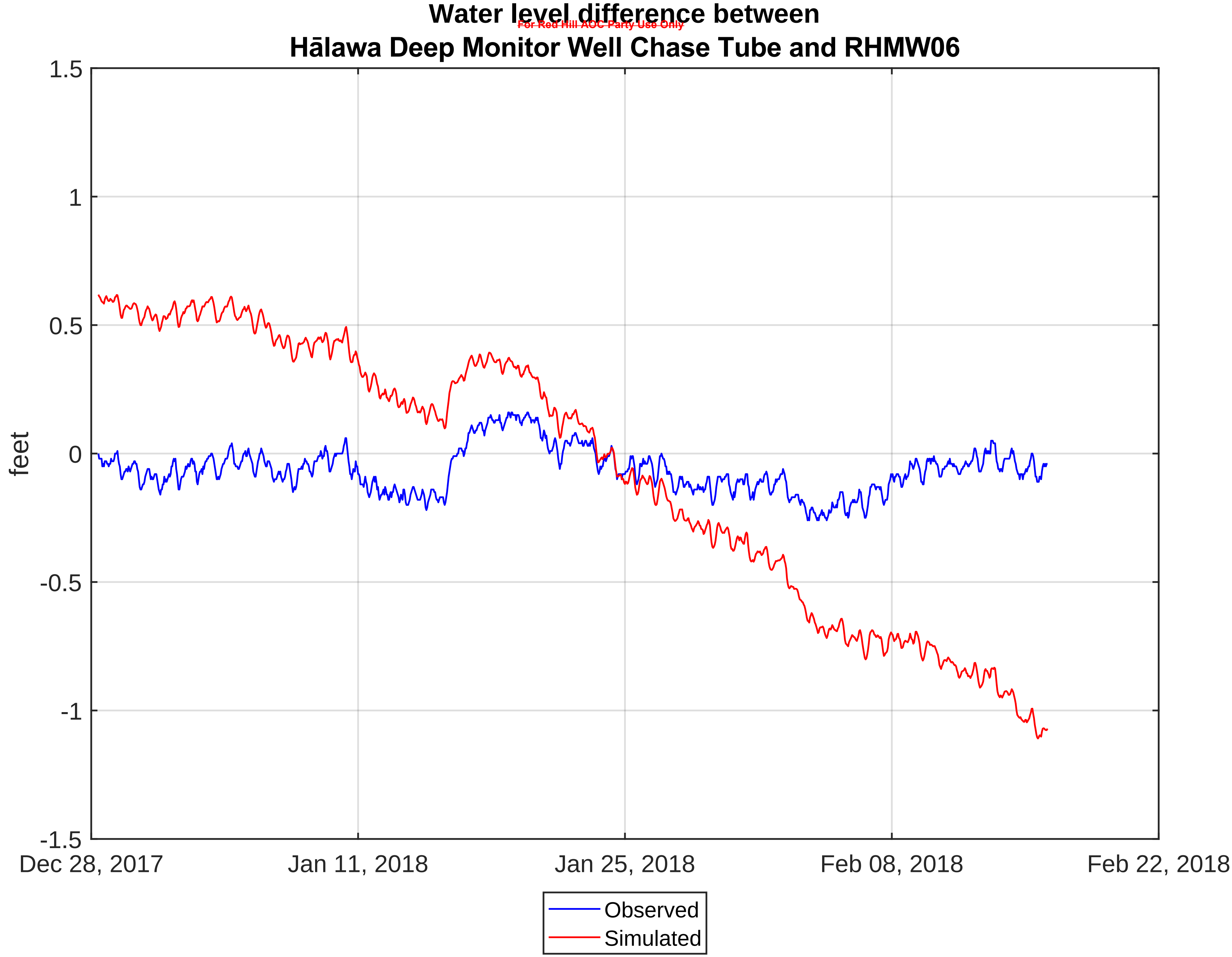
Water level difference between

Hālawa Deep Monitor Well Chase Tube and RHMW04

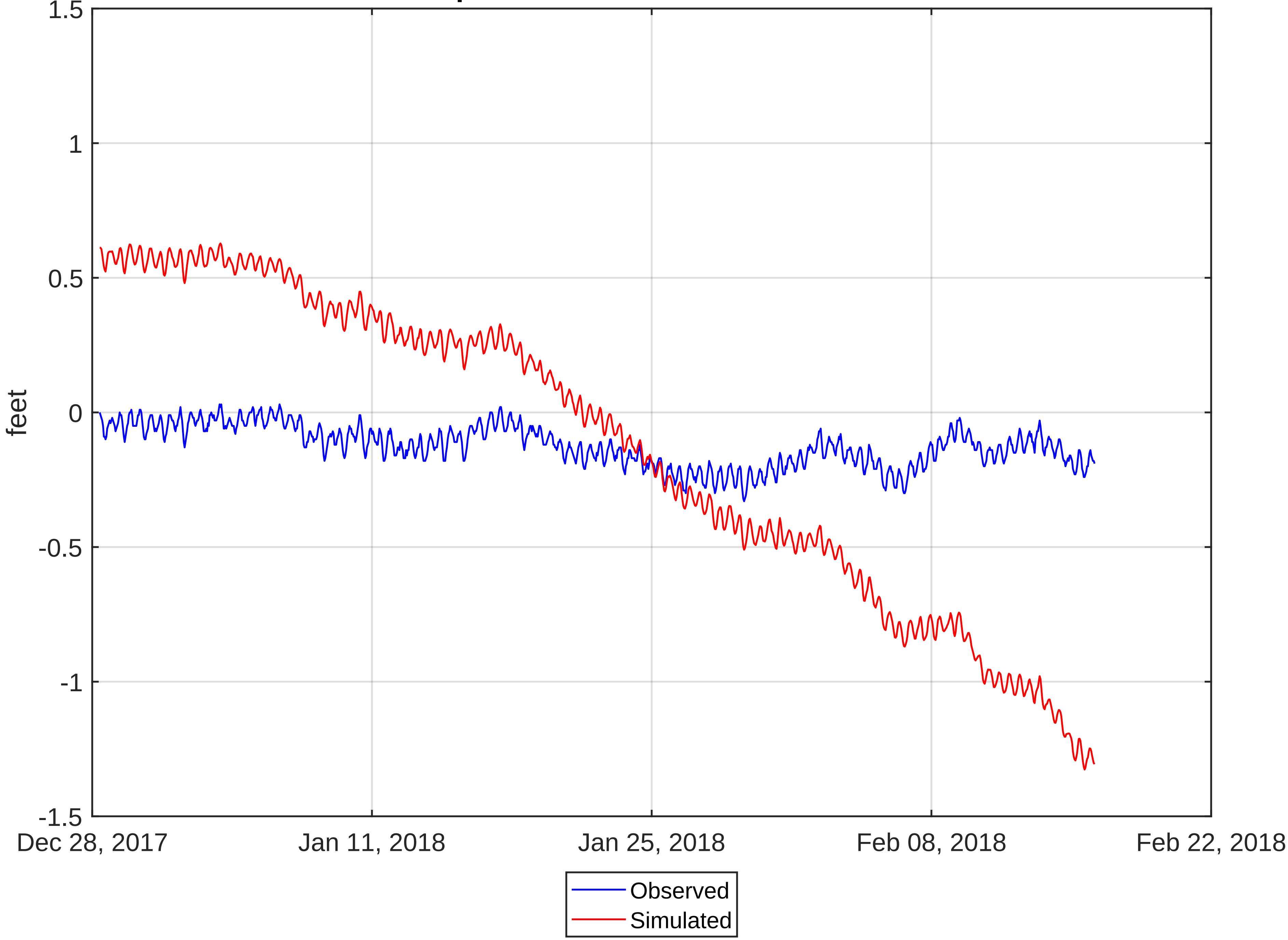


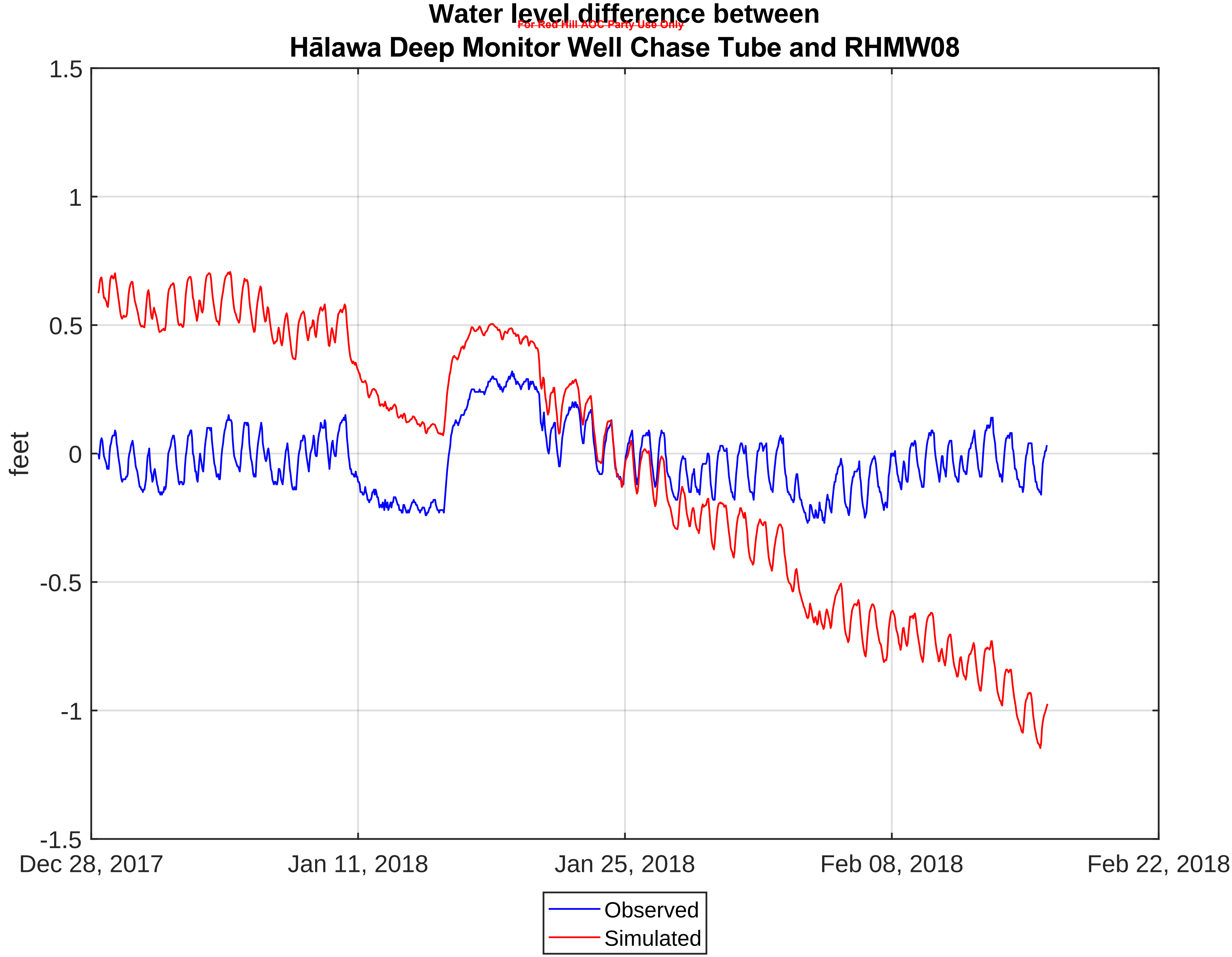


Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and RHMW05
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
Hālawa Deep Monitor Well Chase Tube and RHMW06
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

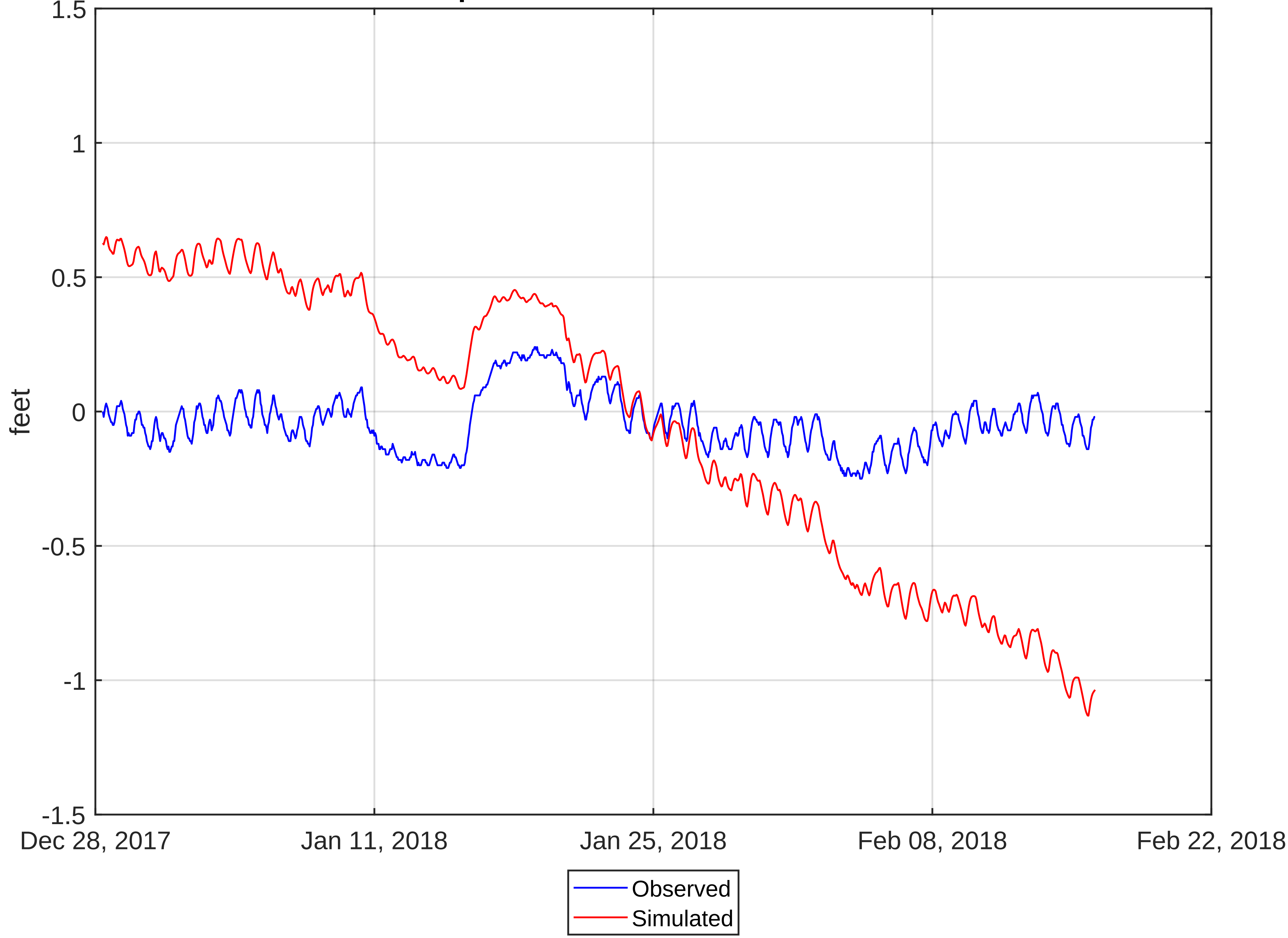
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and RHMW07



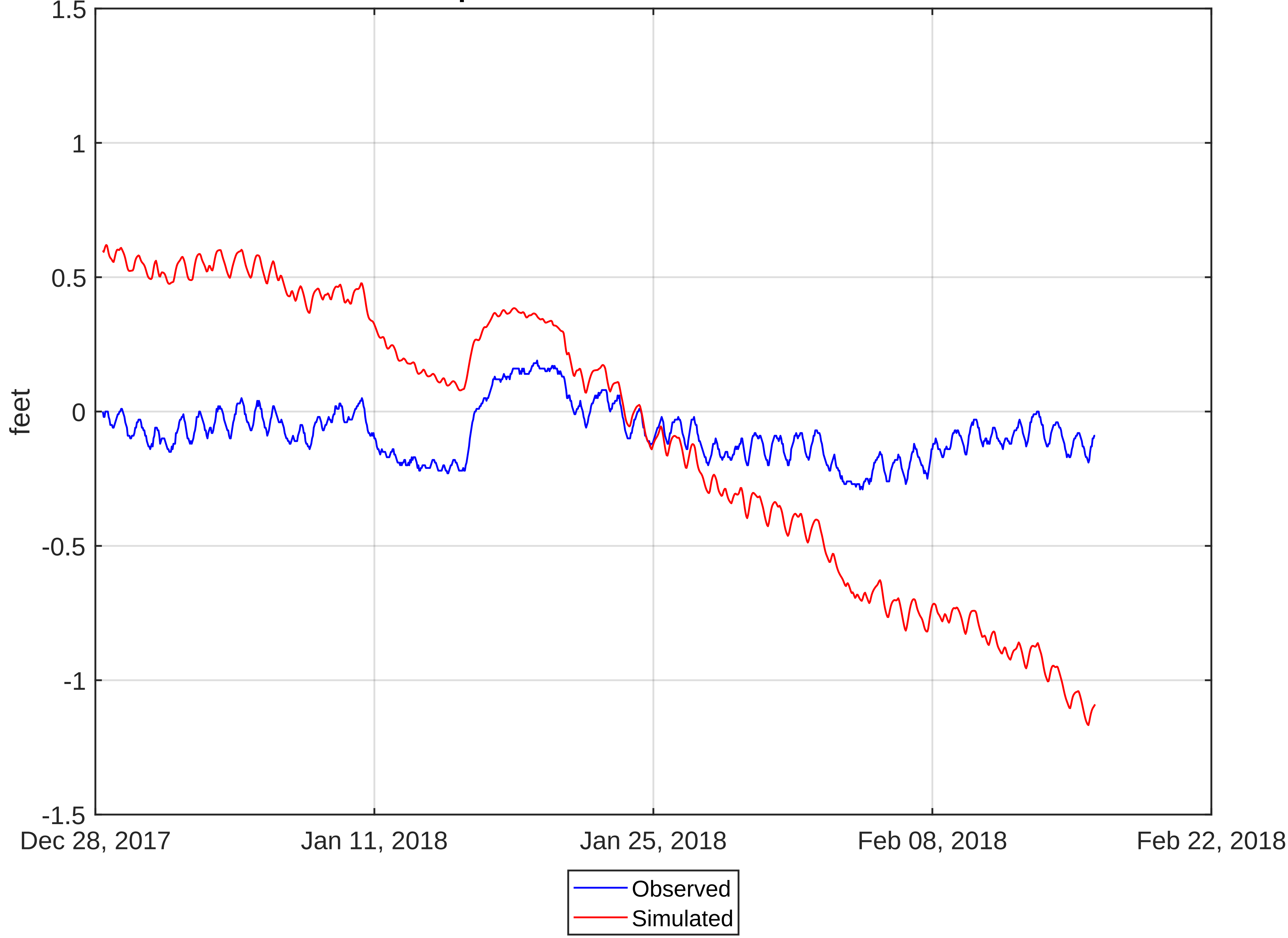


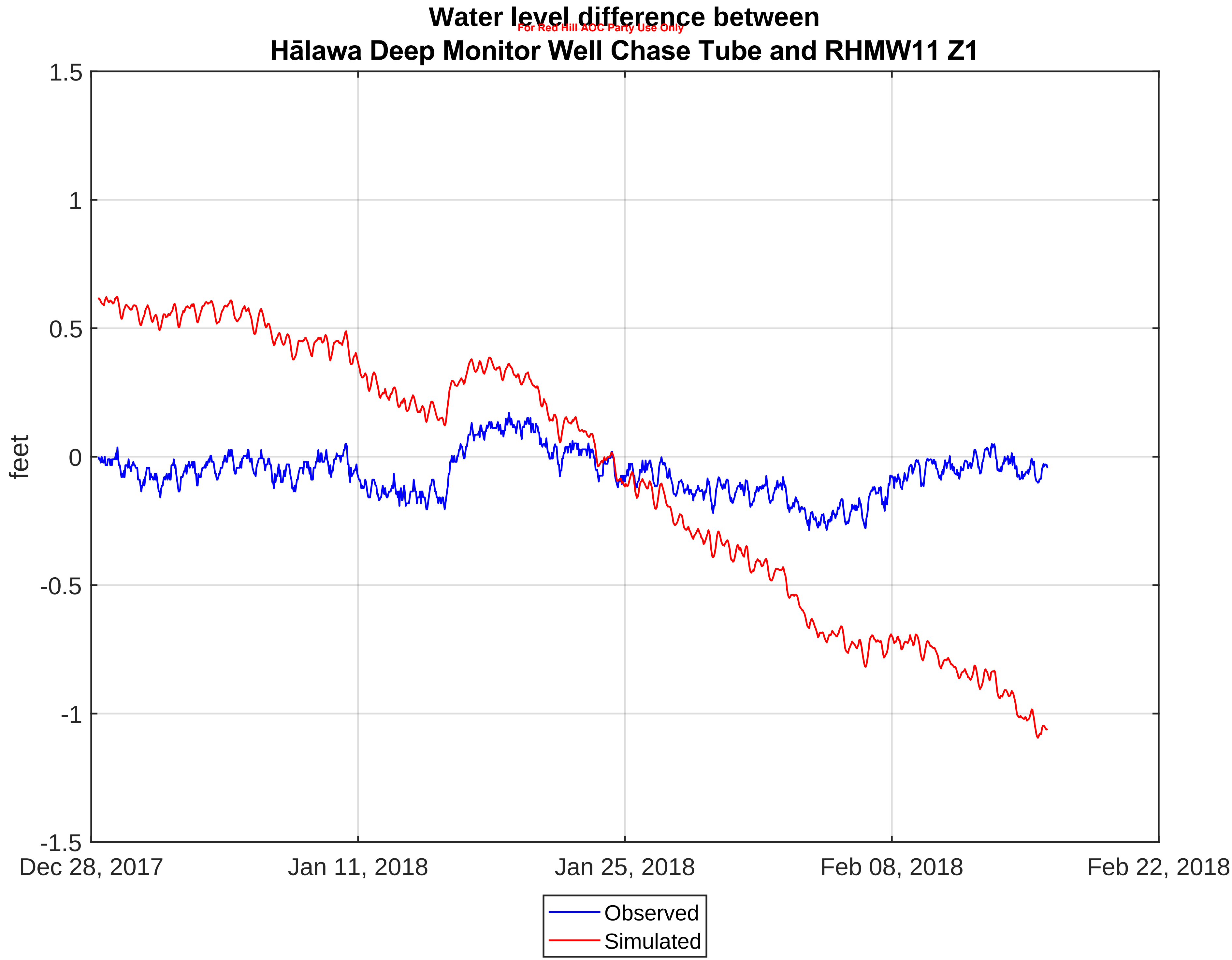
Water level difference between
Hālawa Deep Monitor Well Chase Tube and RHMW08
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
Hālawa Deep Monitor Well Chase Tube and RHMW09

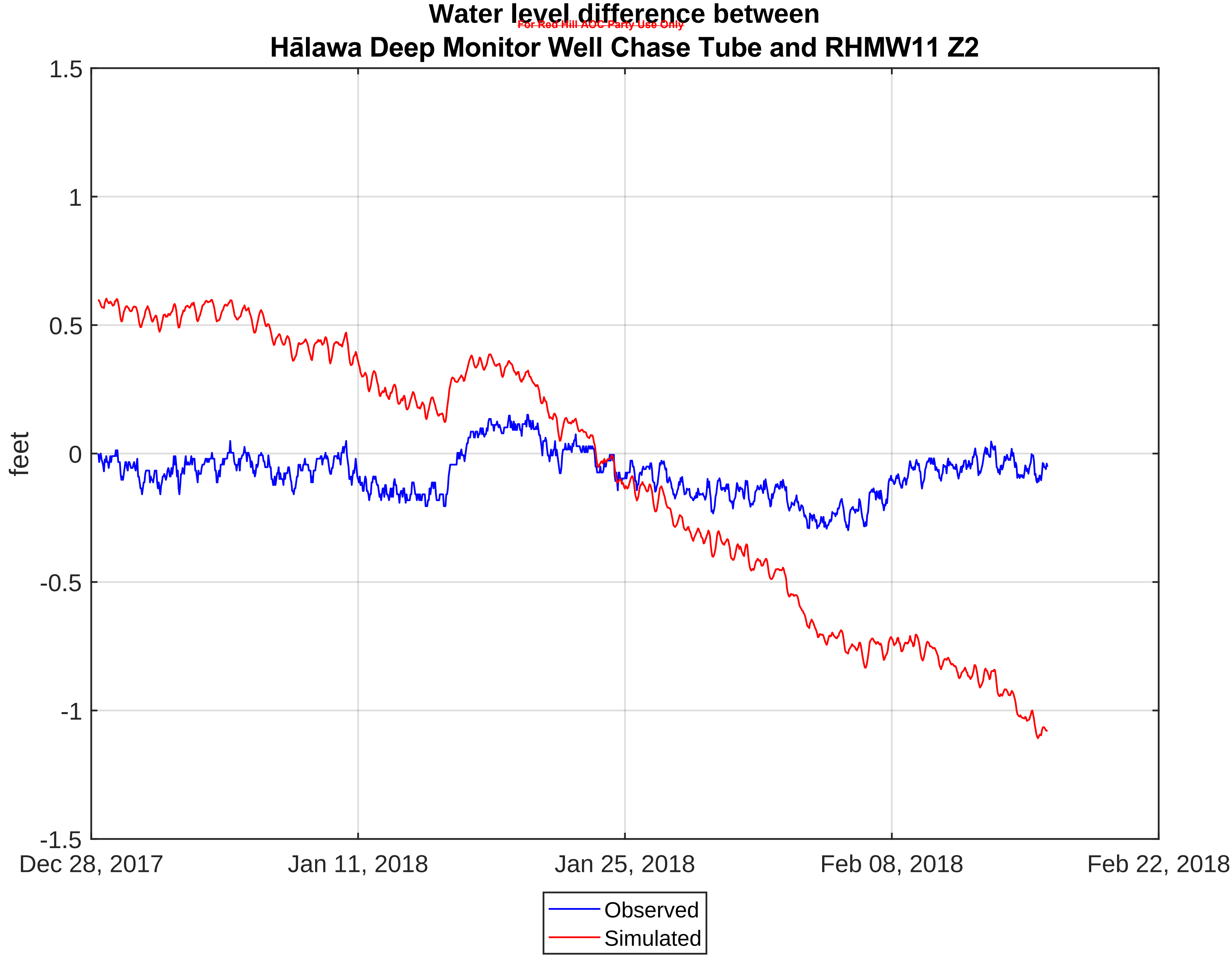


Water level difference between Hālawa Deep Monitor Well Chase Tube and RHMW10

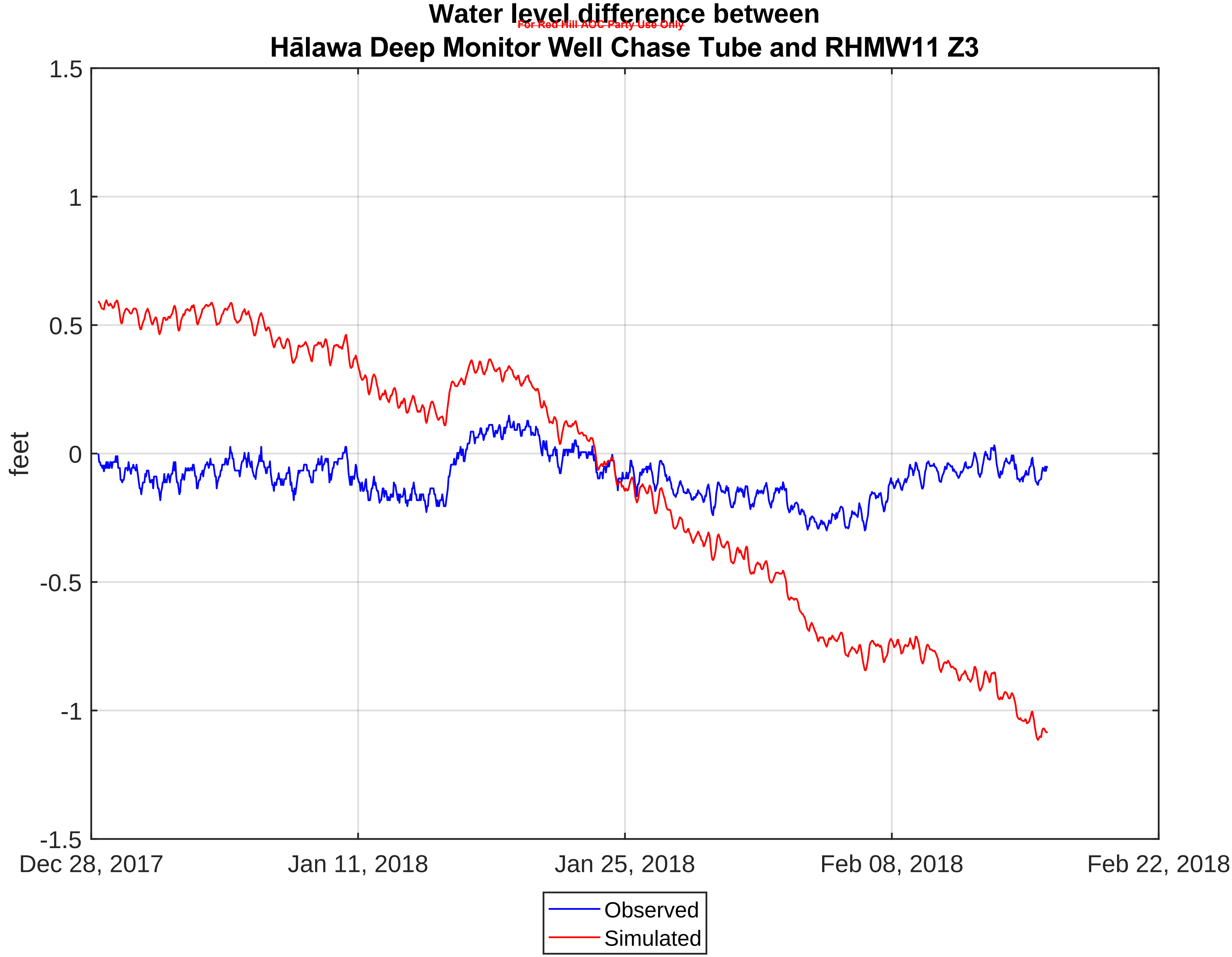




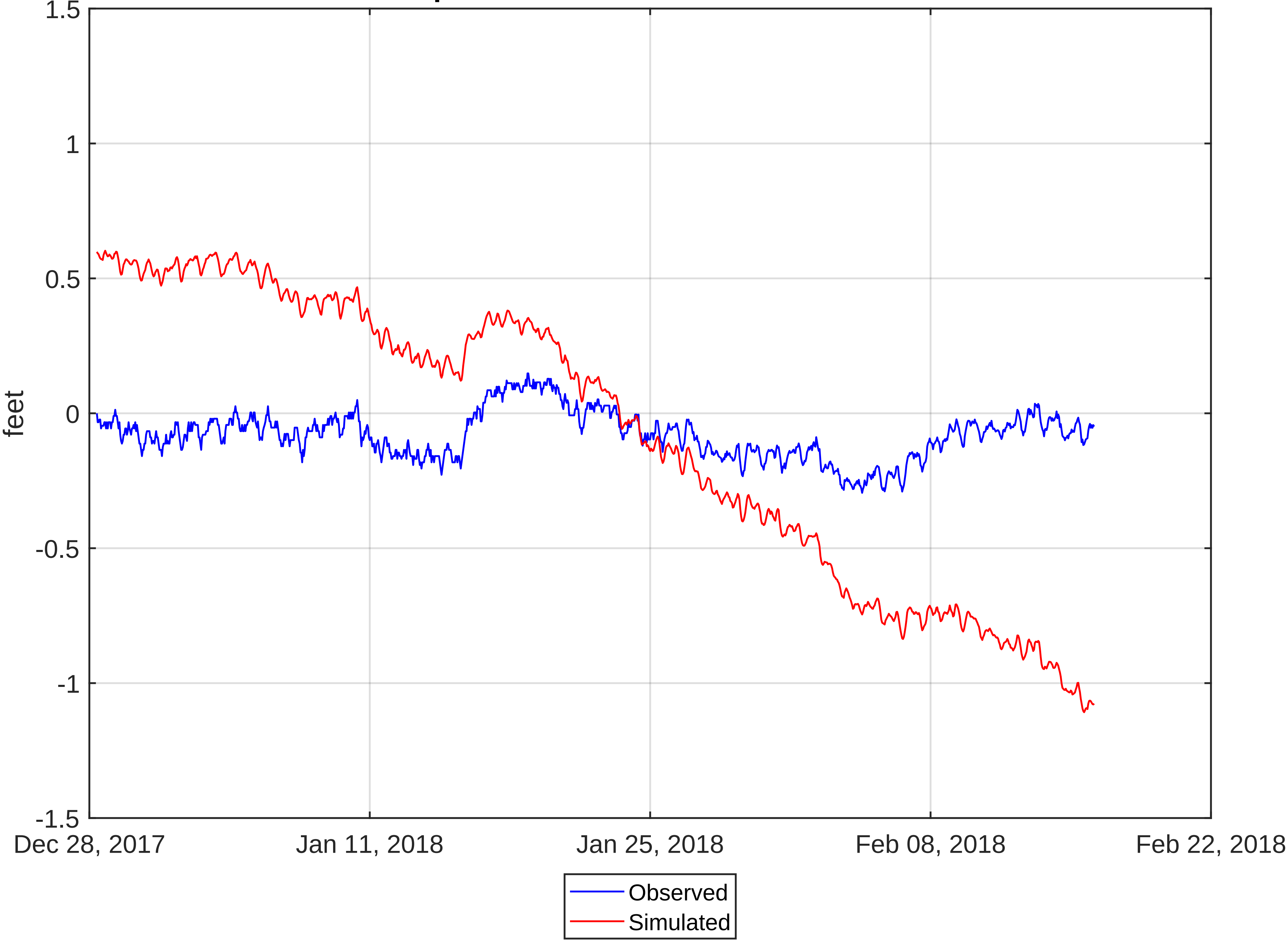
Water level difference between
Hālawa Deep Monitor Well Chase Tube and RHMW11 Z1
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



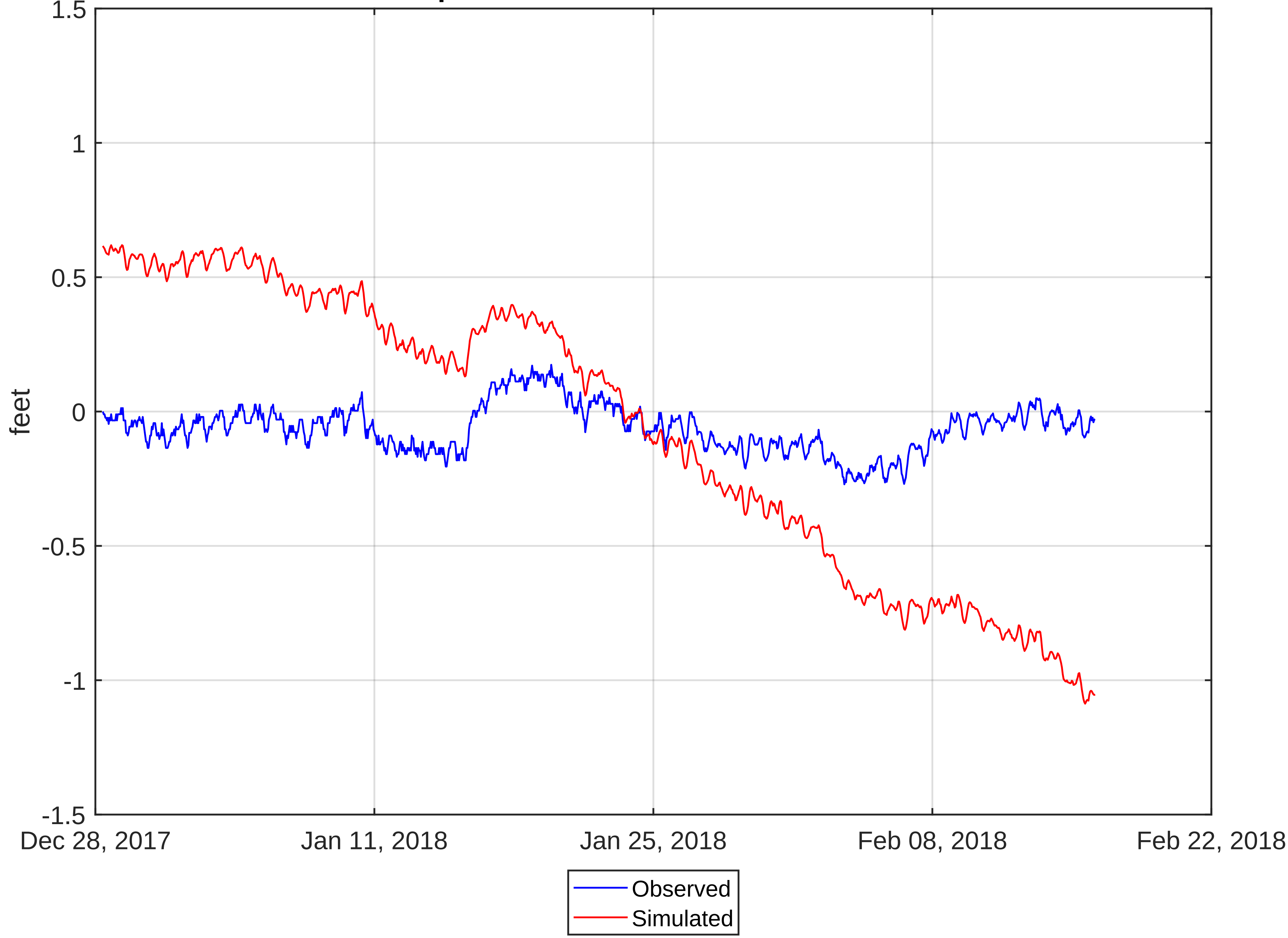
Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and RHMW11 Z2
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

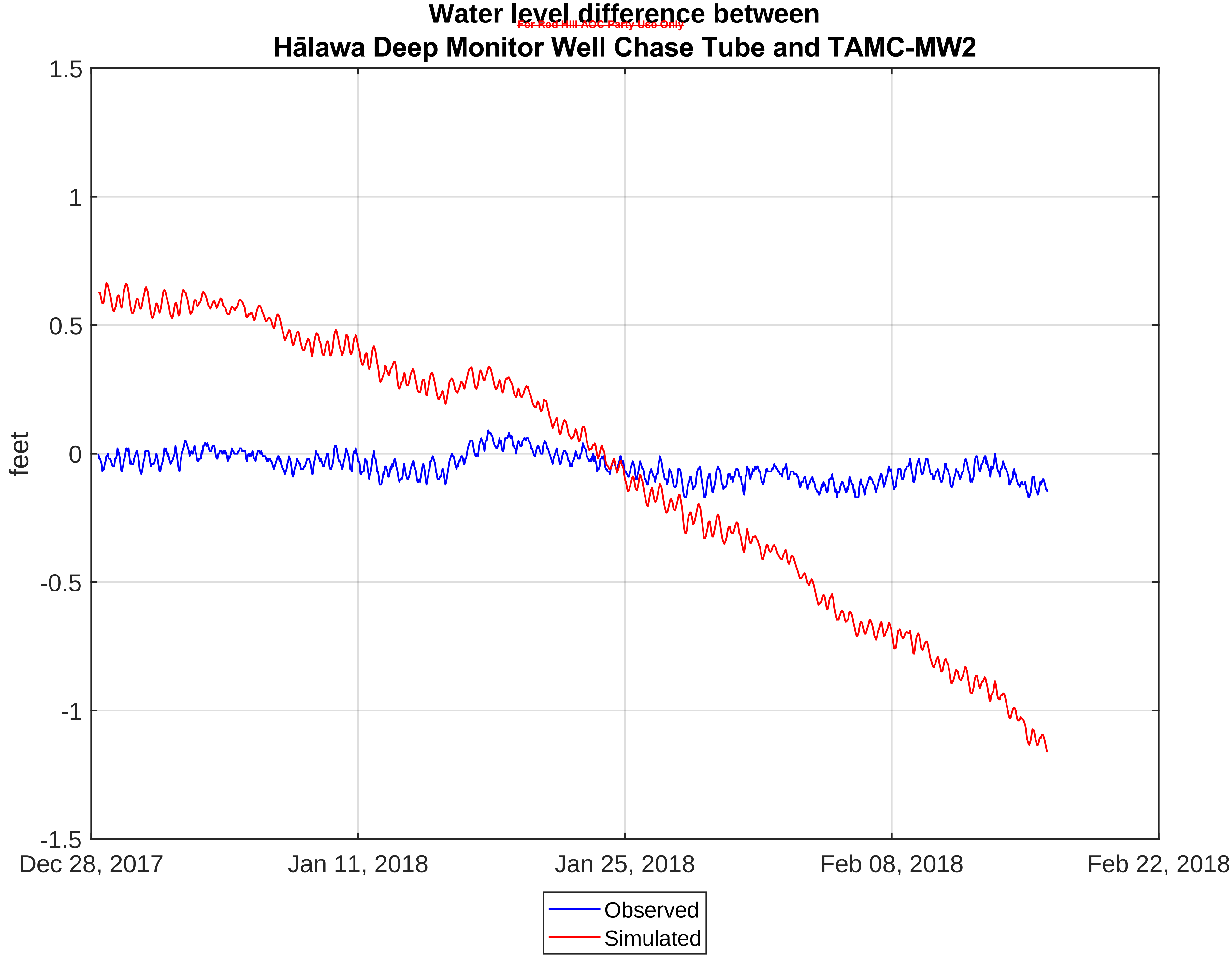

Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and RHMW11 Z3
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
Hālawa Deep Monitor Well Chase Tube and RHMW11 Z4



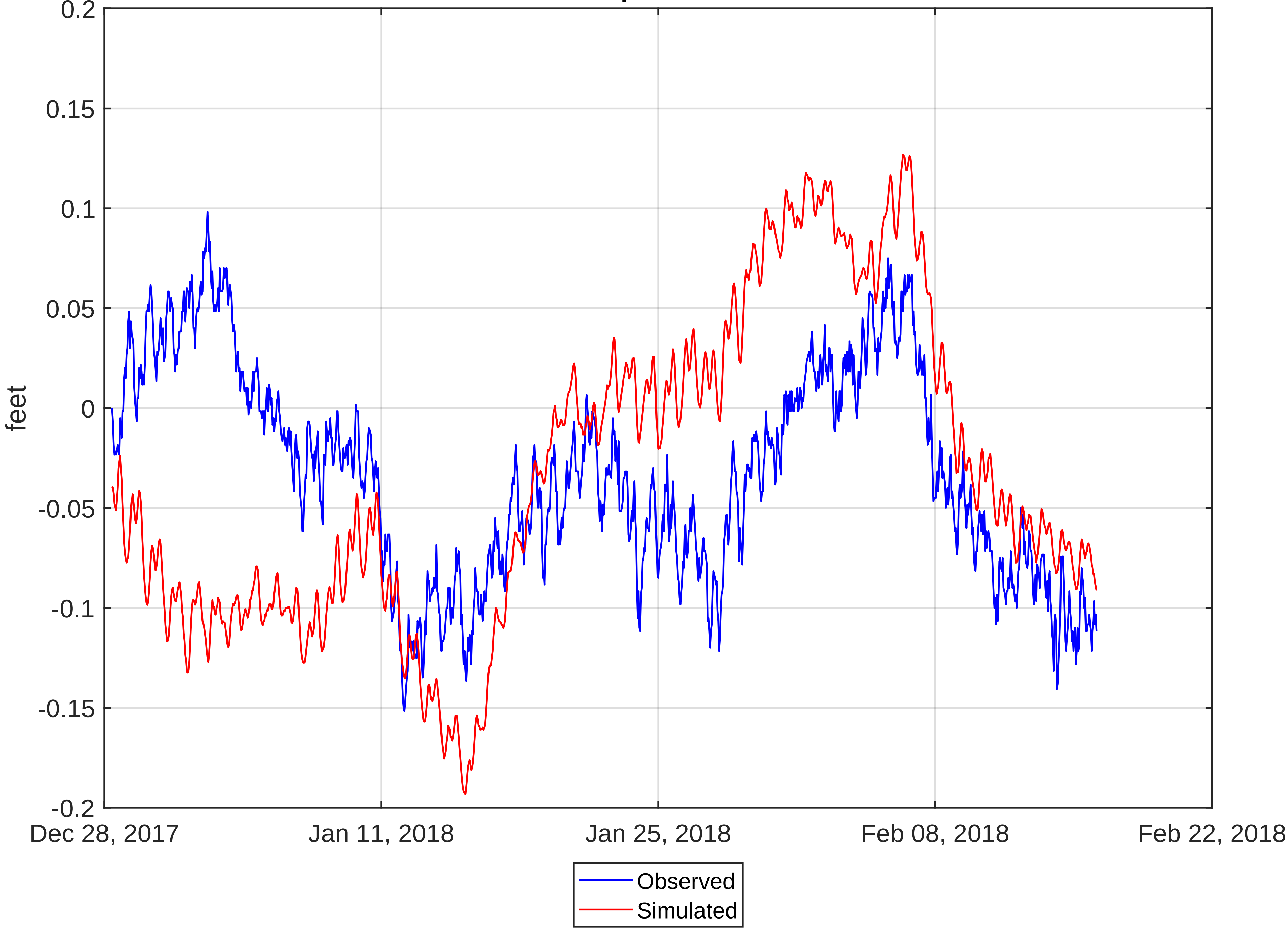
Water level difference between
Hālawa Deep Monitor Well Chase Tube and RHMW11 Z5

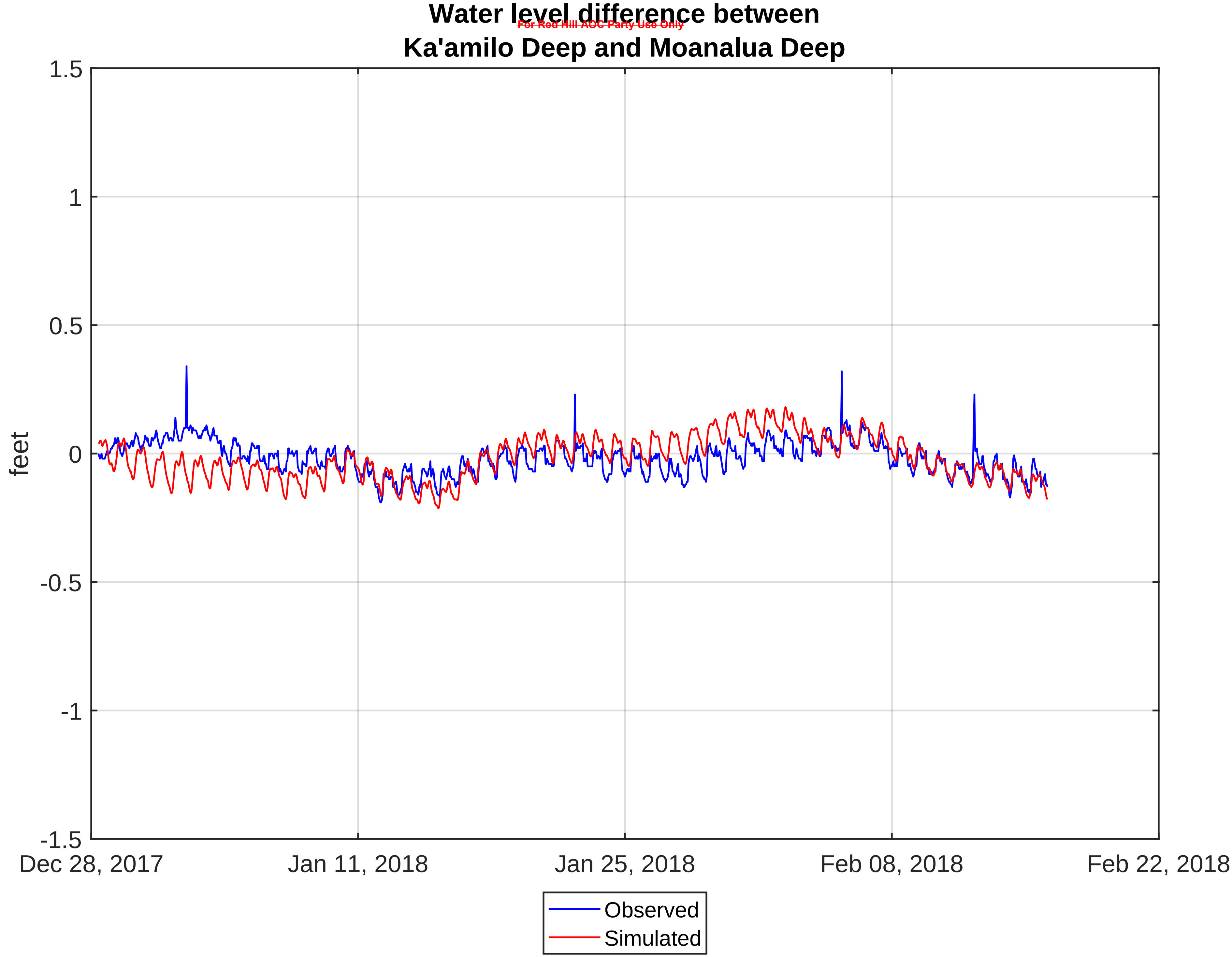


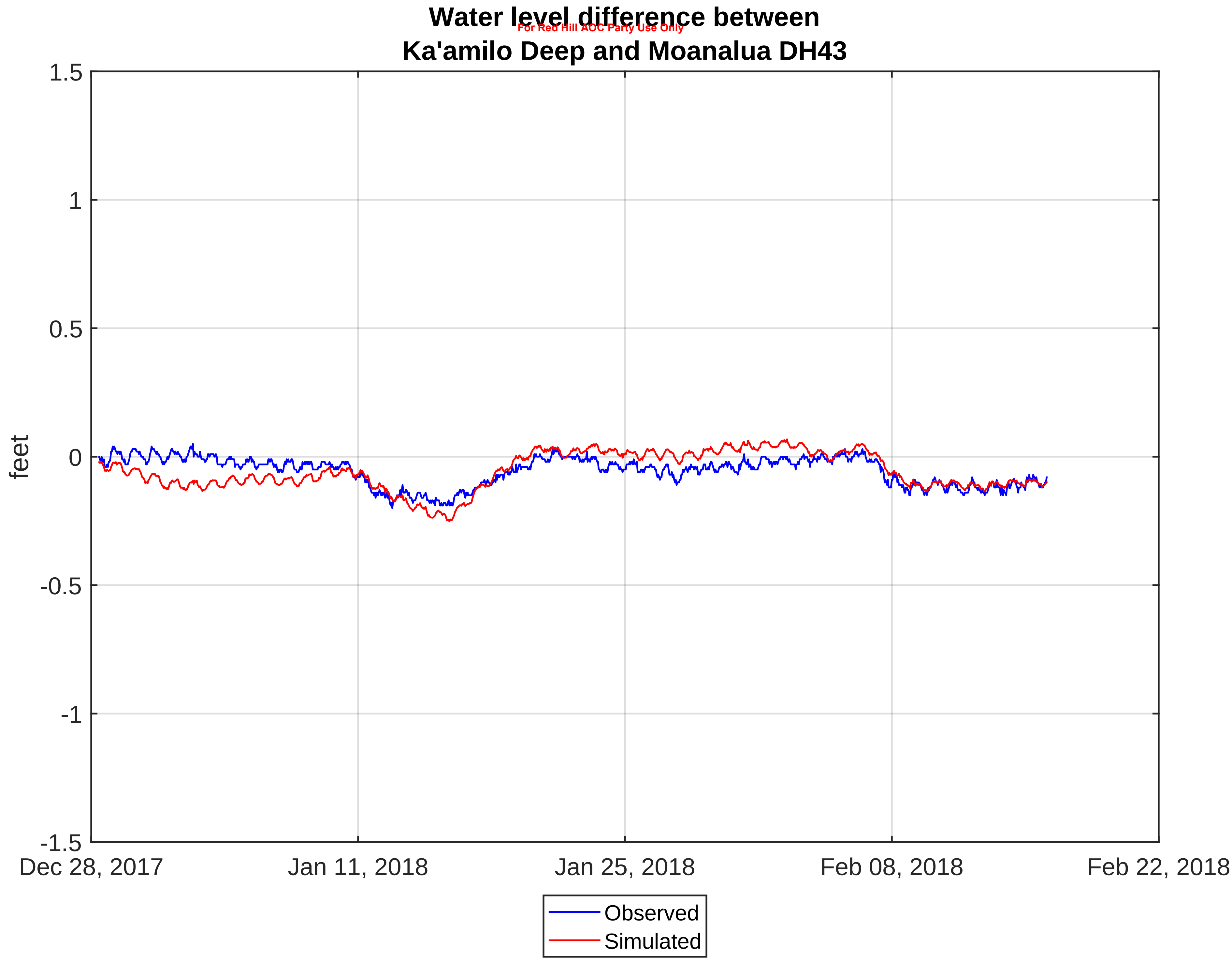


Water level difference between
For Red Hill AOC Party Use Only
Hālawa Deep Monitor Well Chase Tube and TAMC-MW2
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

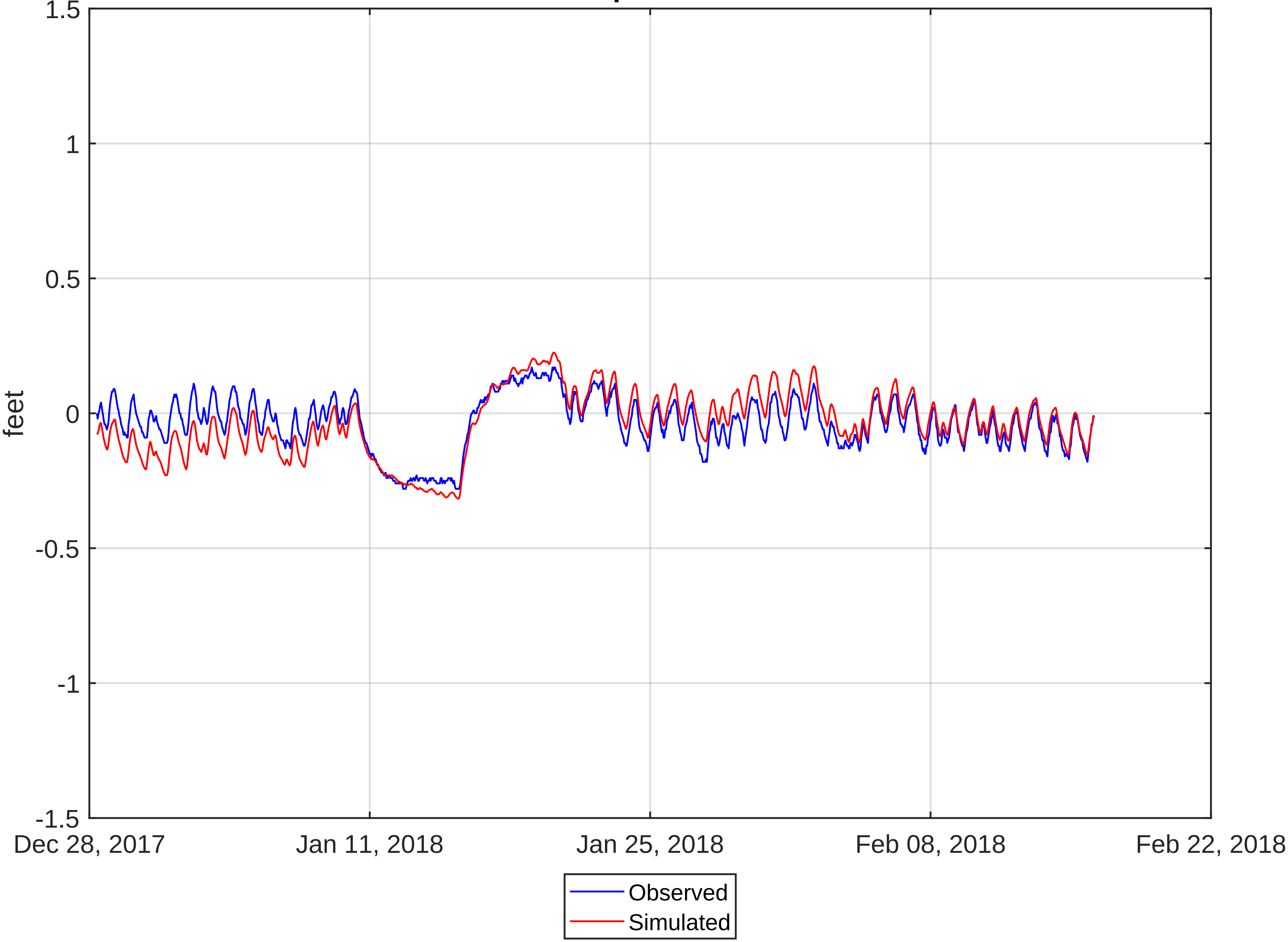
Water level difference between
Ka'amilo Deep and Manaiki T-24

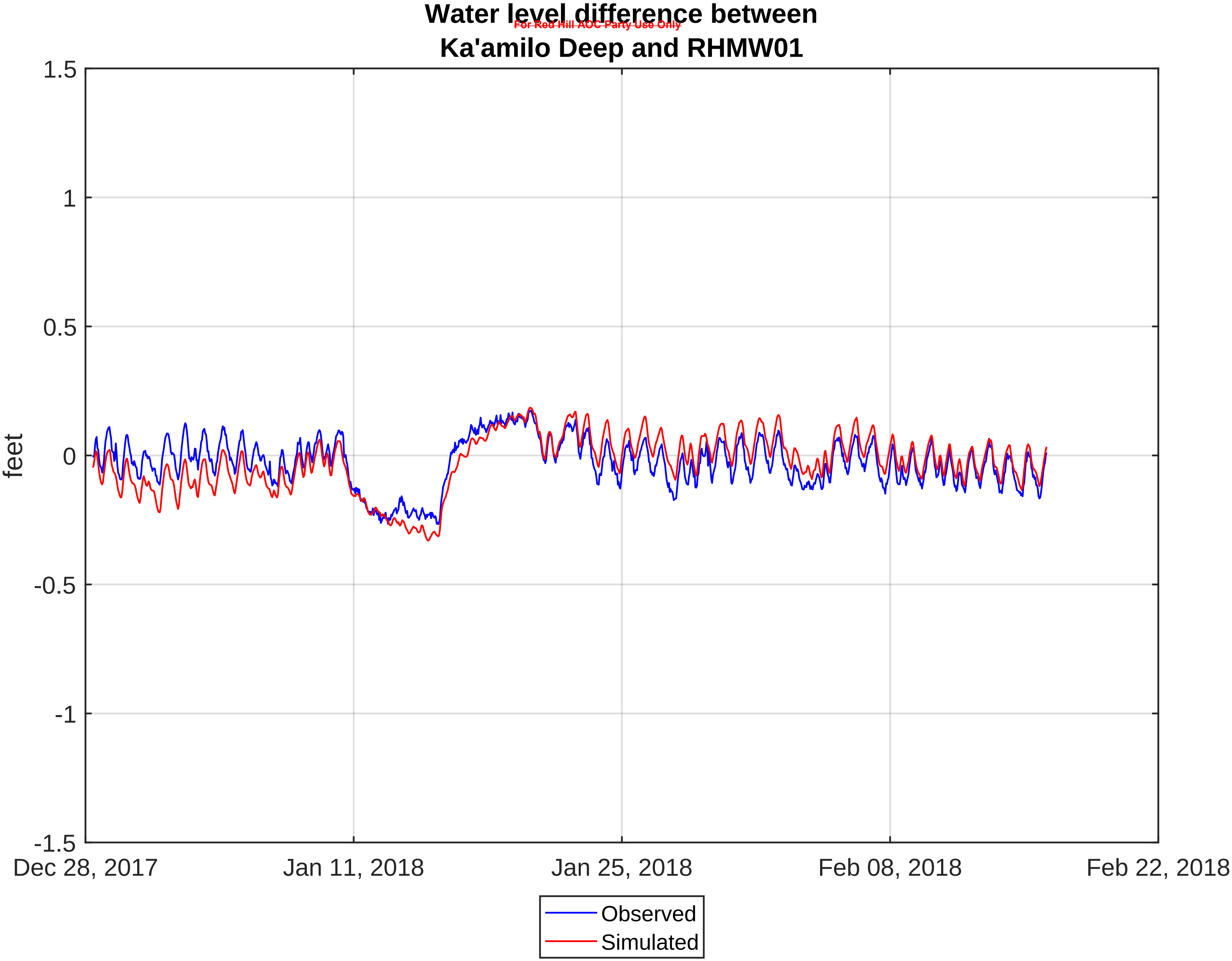



Water level difference between
Ka'amilo Deep and Moanalua Deep
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

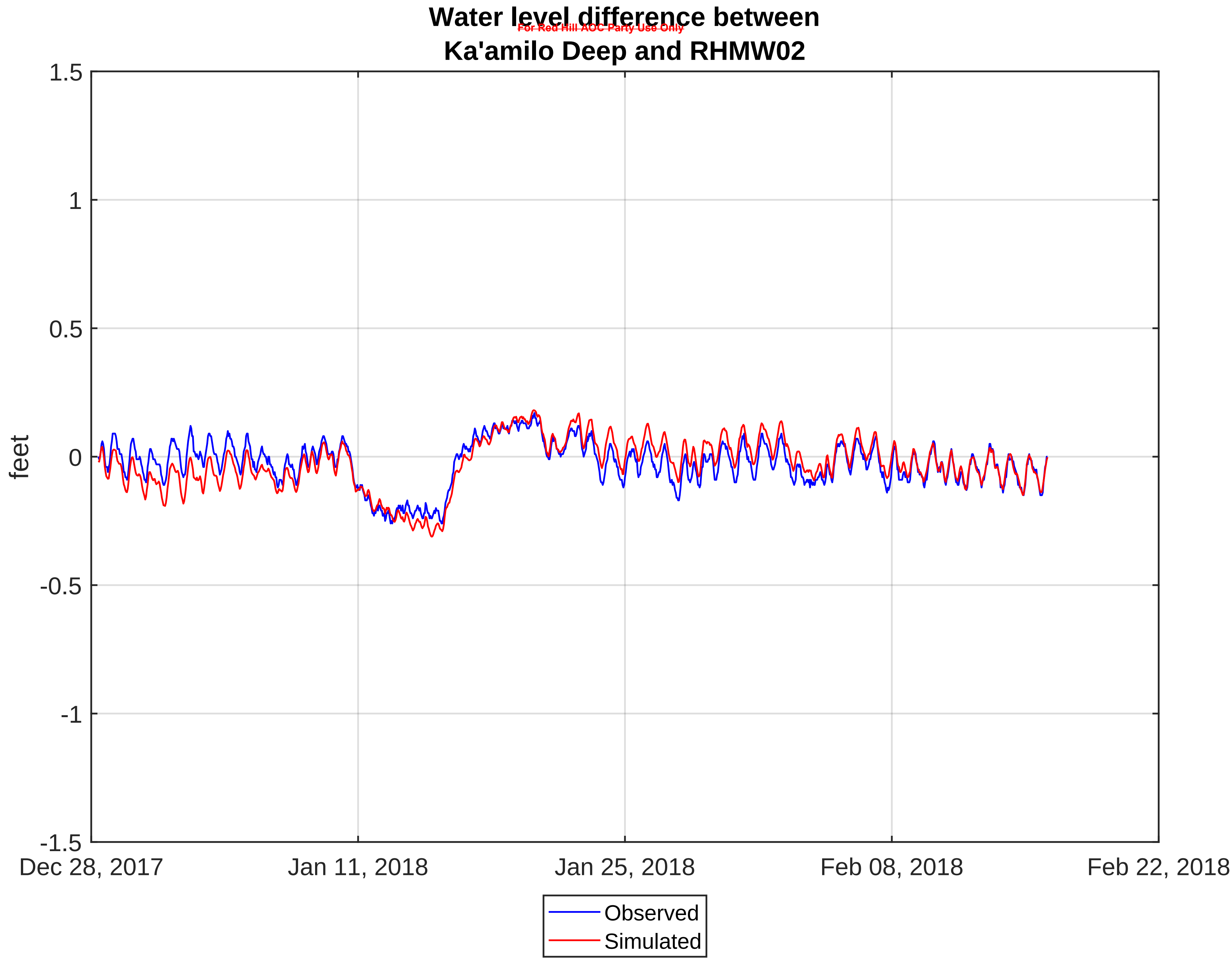

Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and Moanalua DH43
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

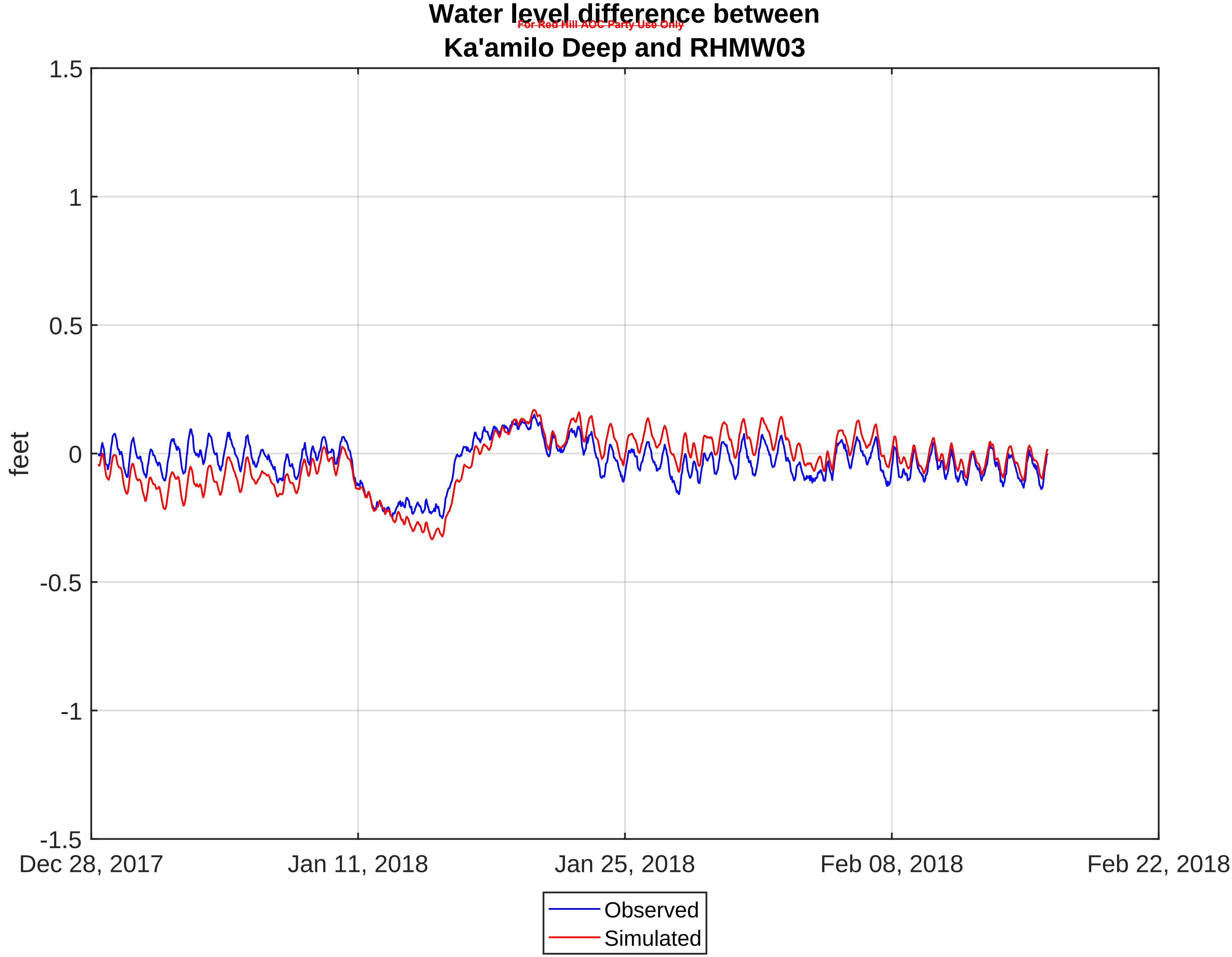
Water level difference between Ka'amilo Deep and OWDFMW01



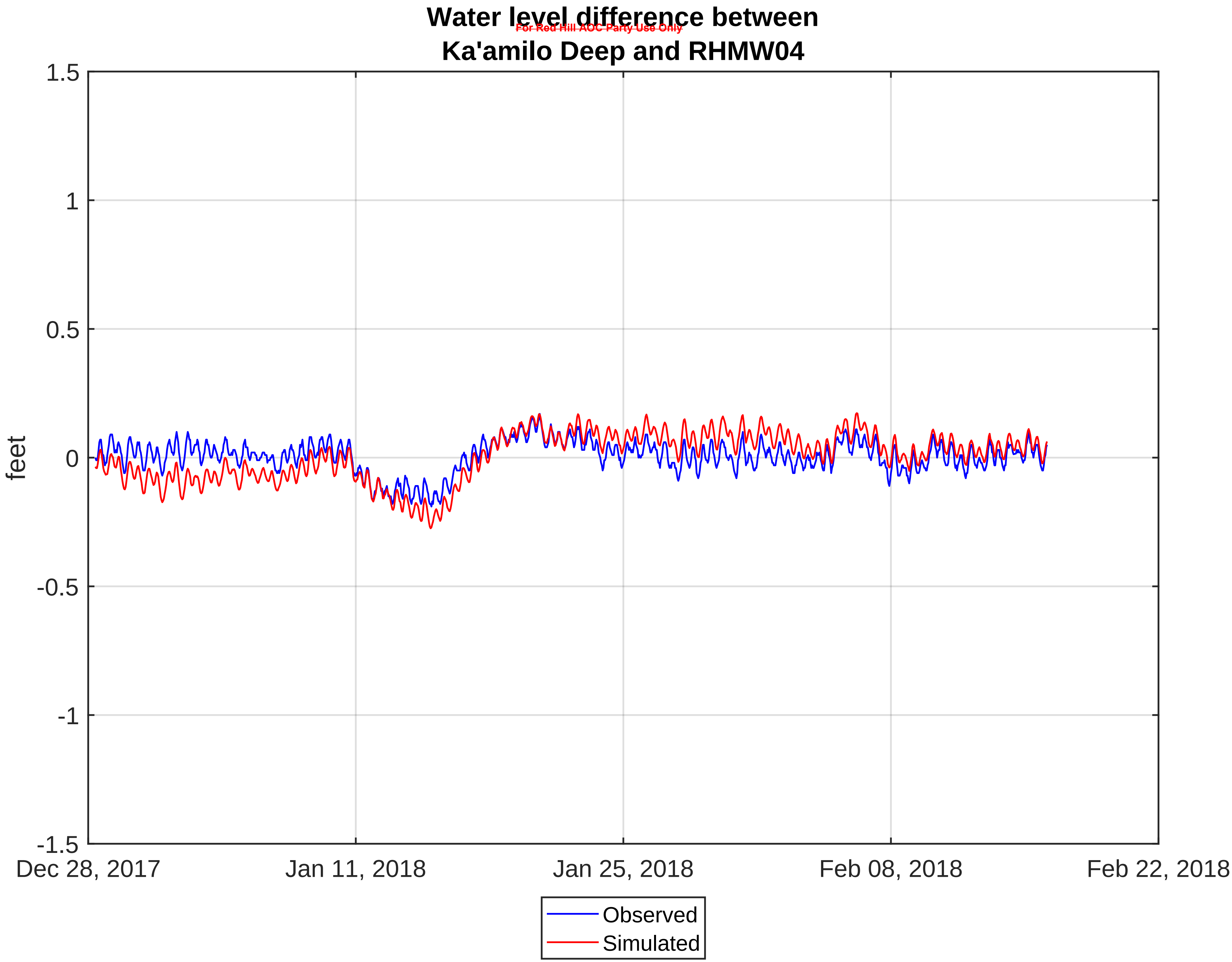


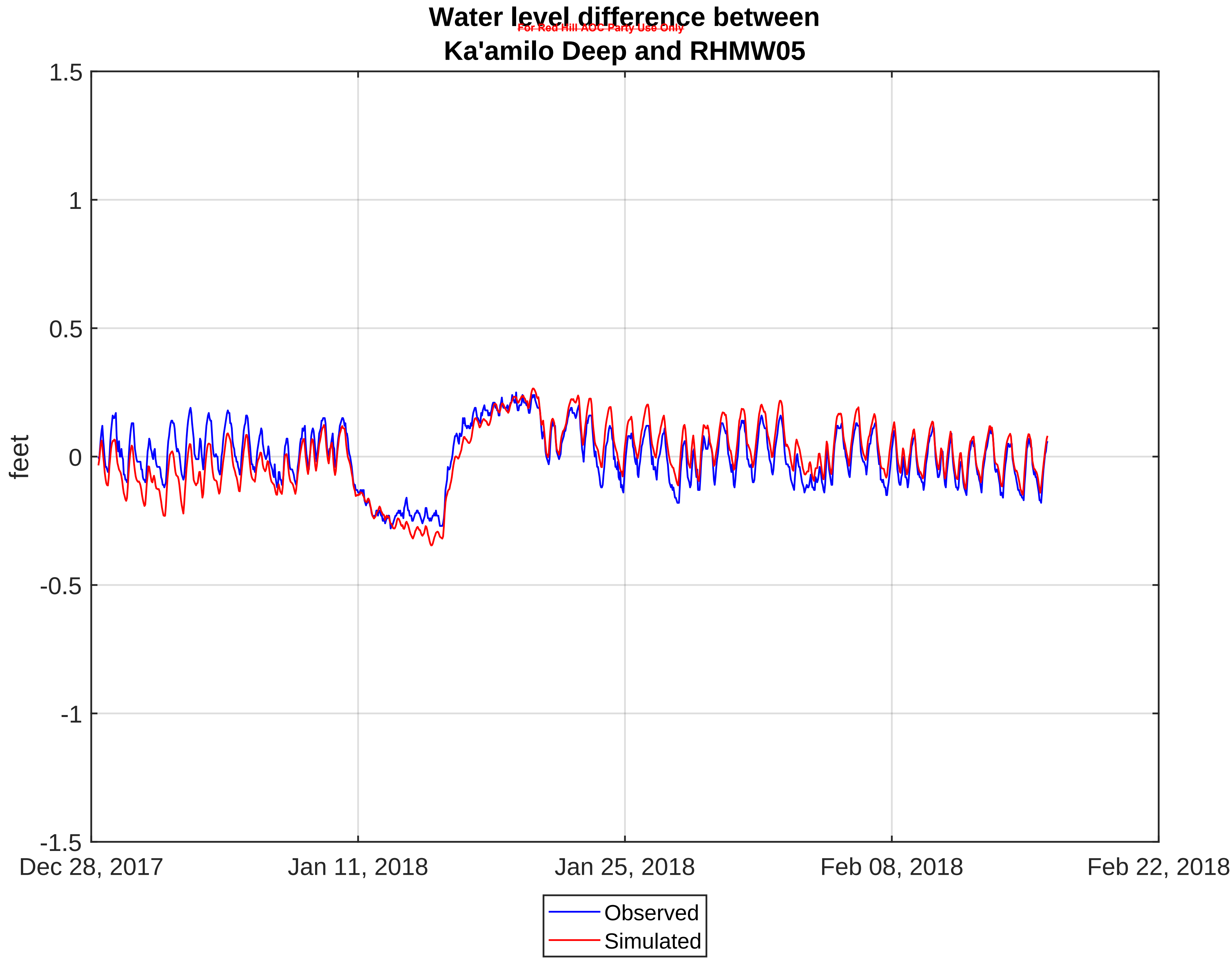
Water level difference between
Ka'amilo Deep and RHMW01
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

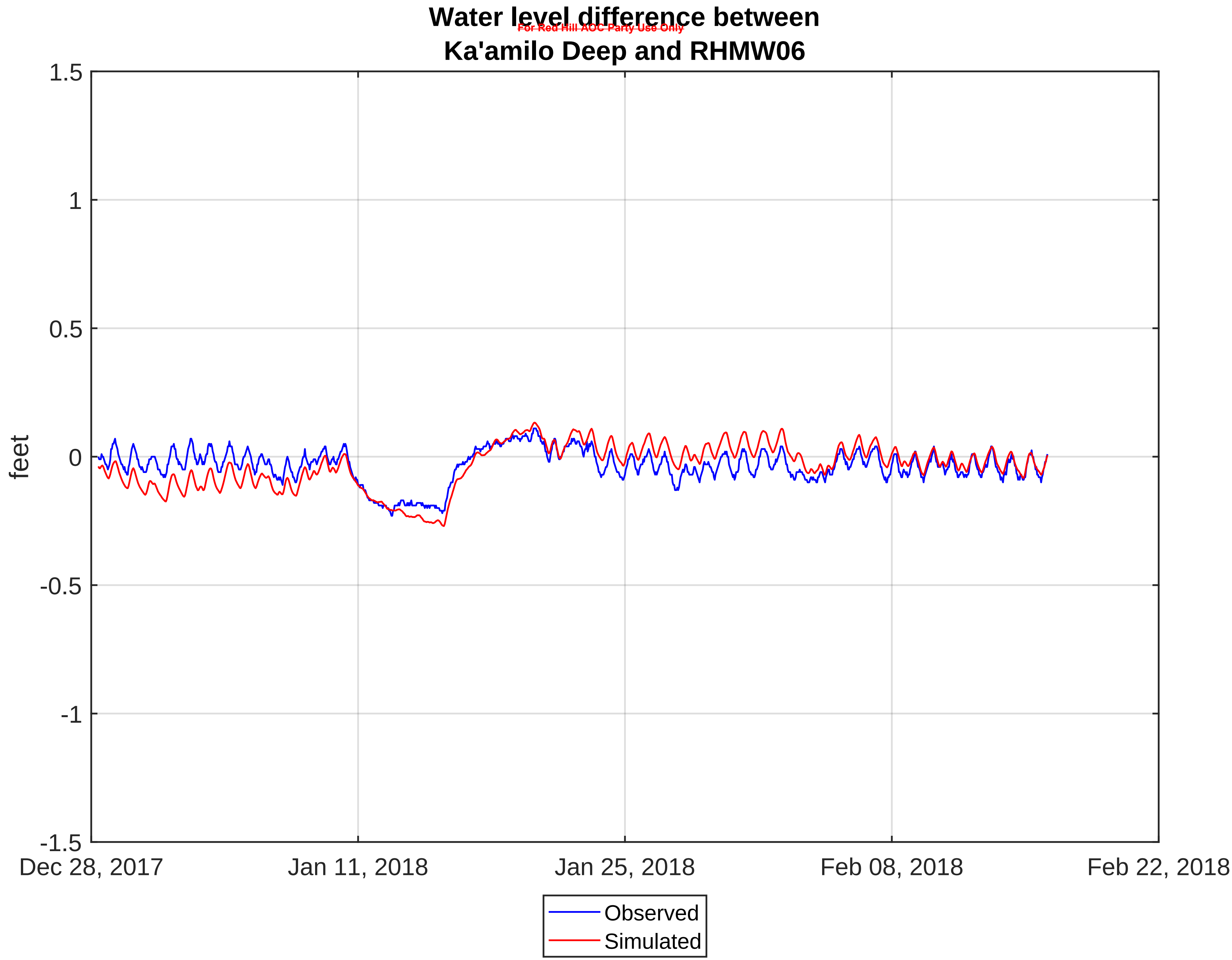

Water level difference between
Ka'amilo Deep and RHMW02
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

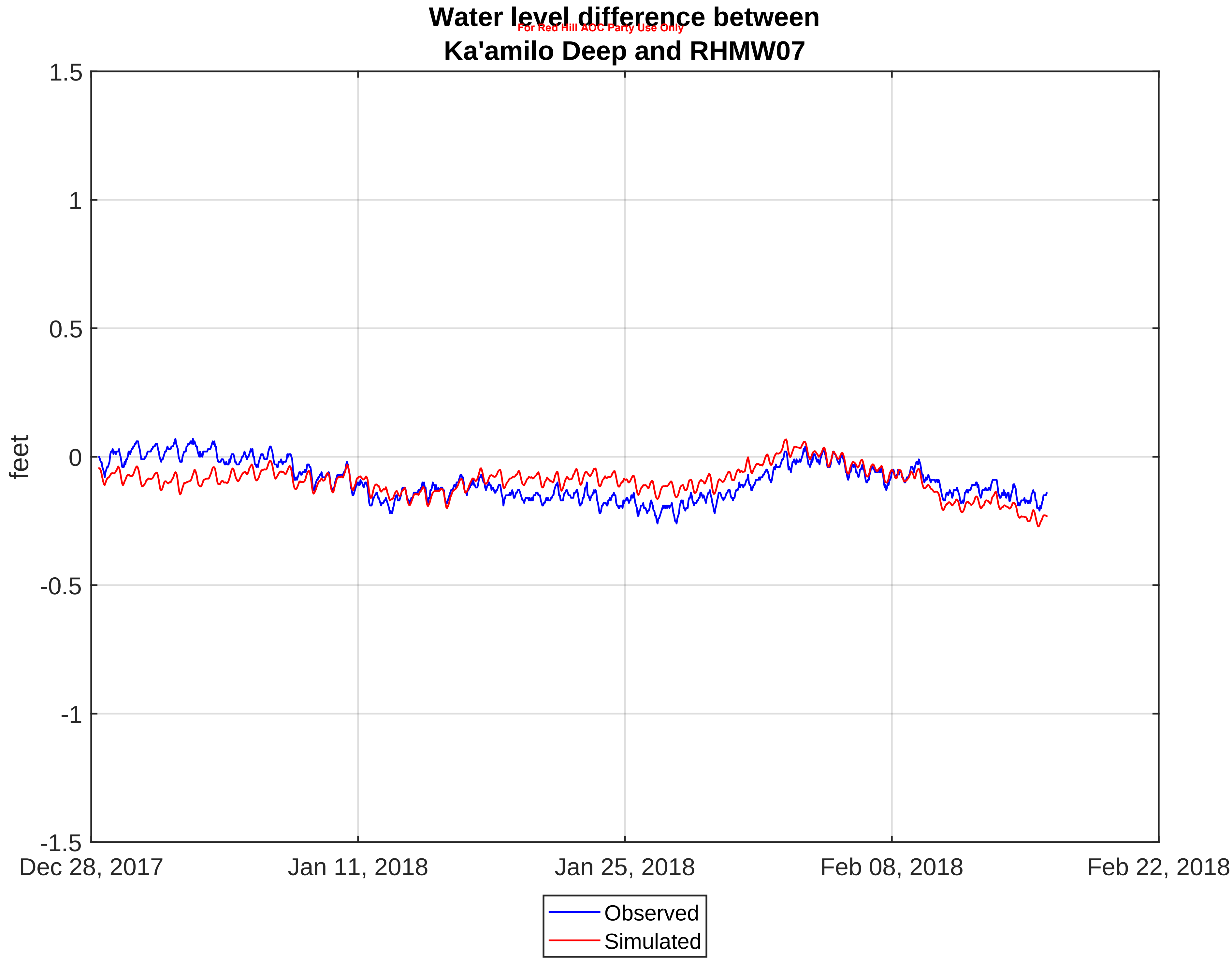


Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW03
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

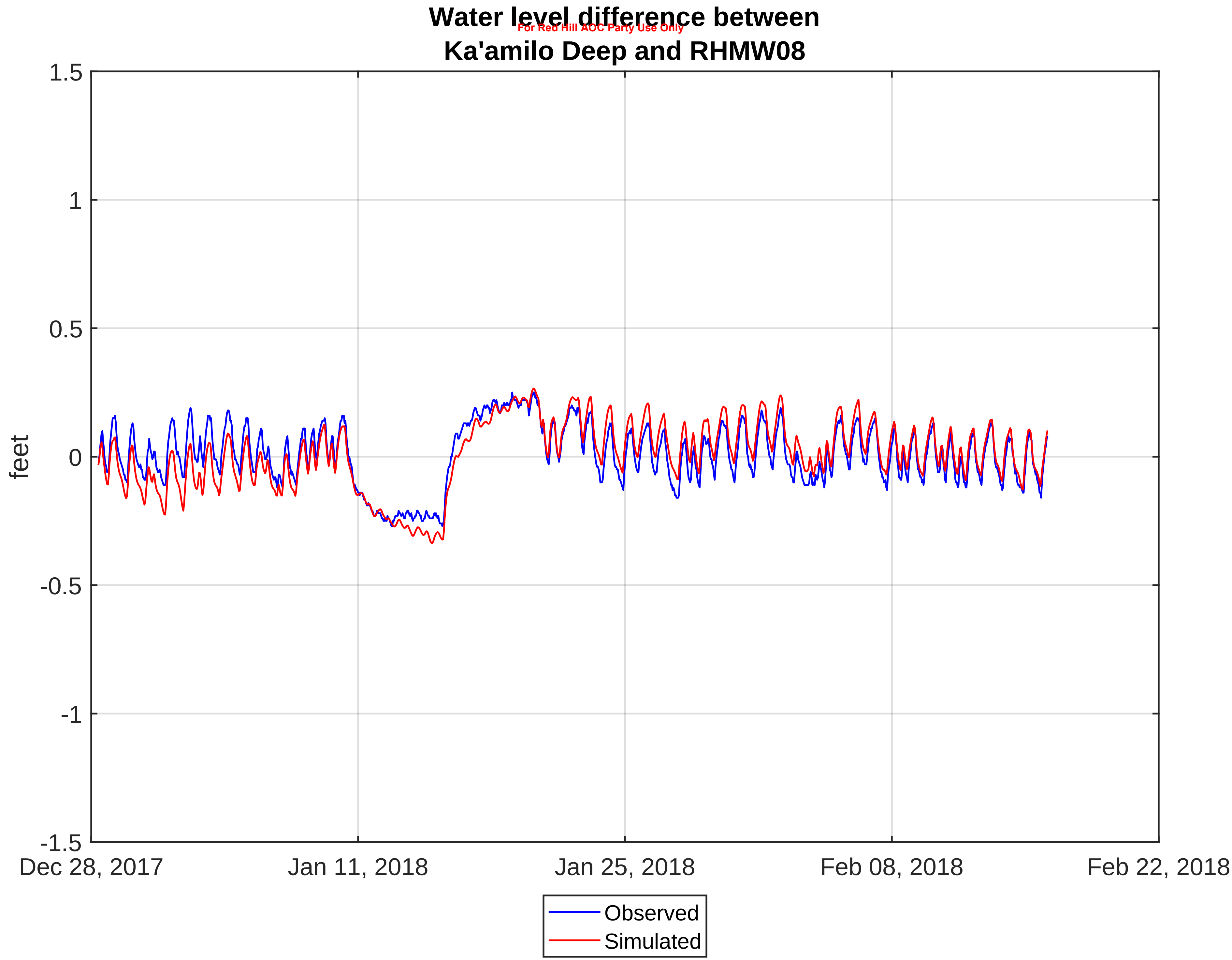

Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW04
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW05
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

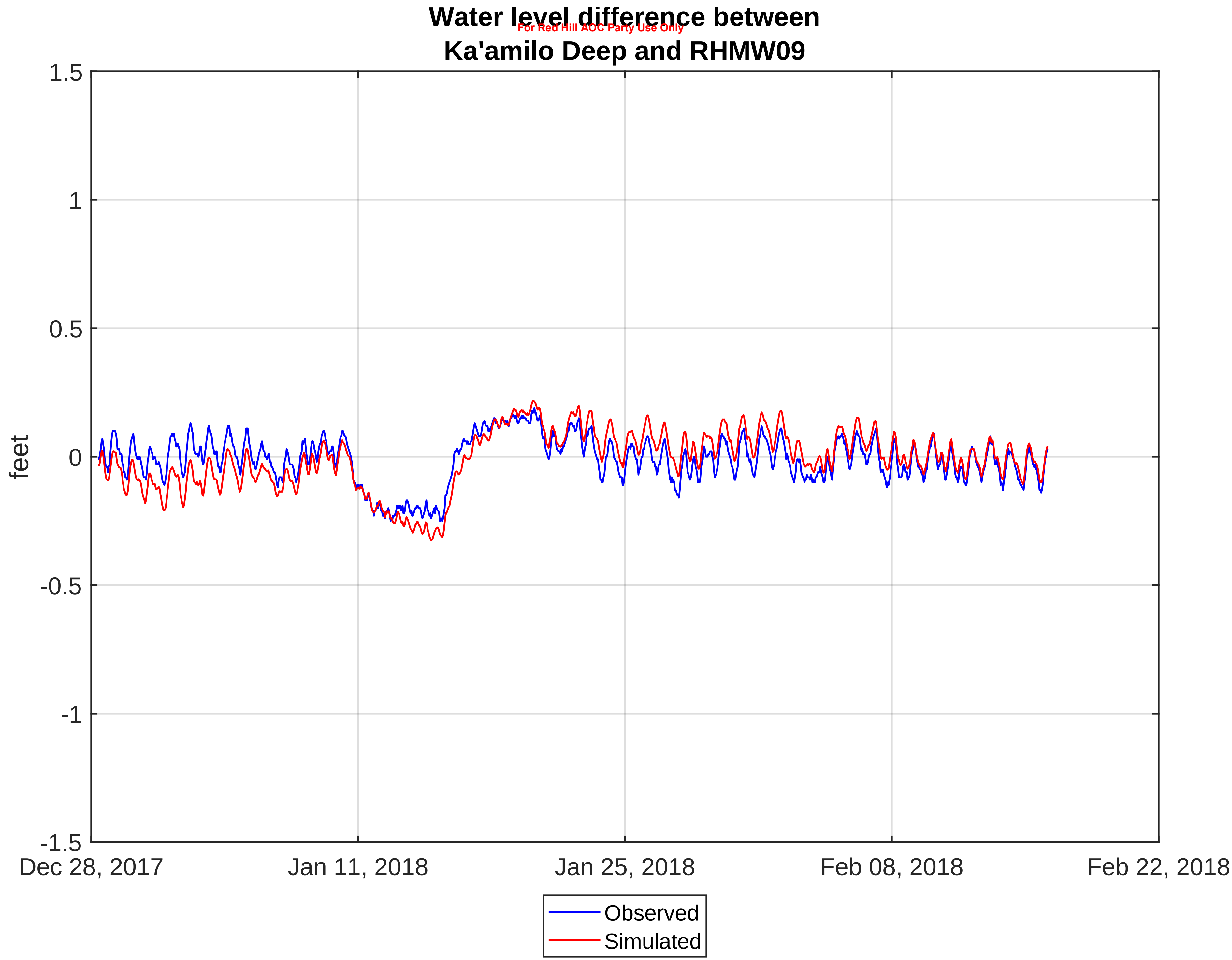

Water level difference between
Ka'amilo Deep and RHMW06
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



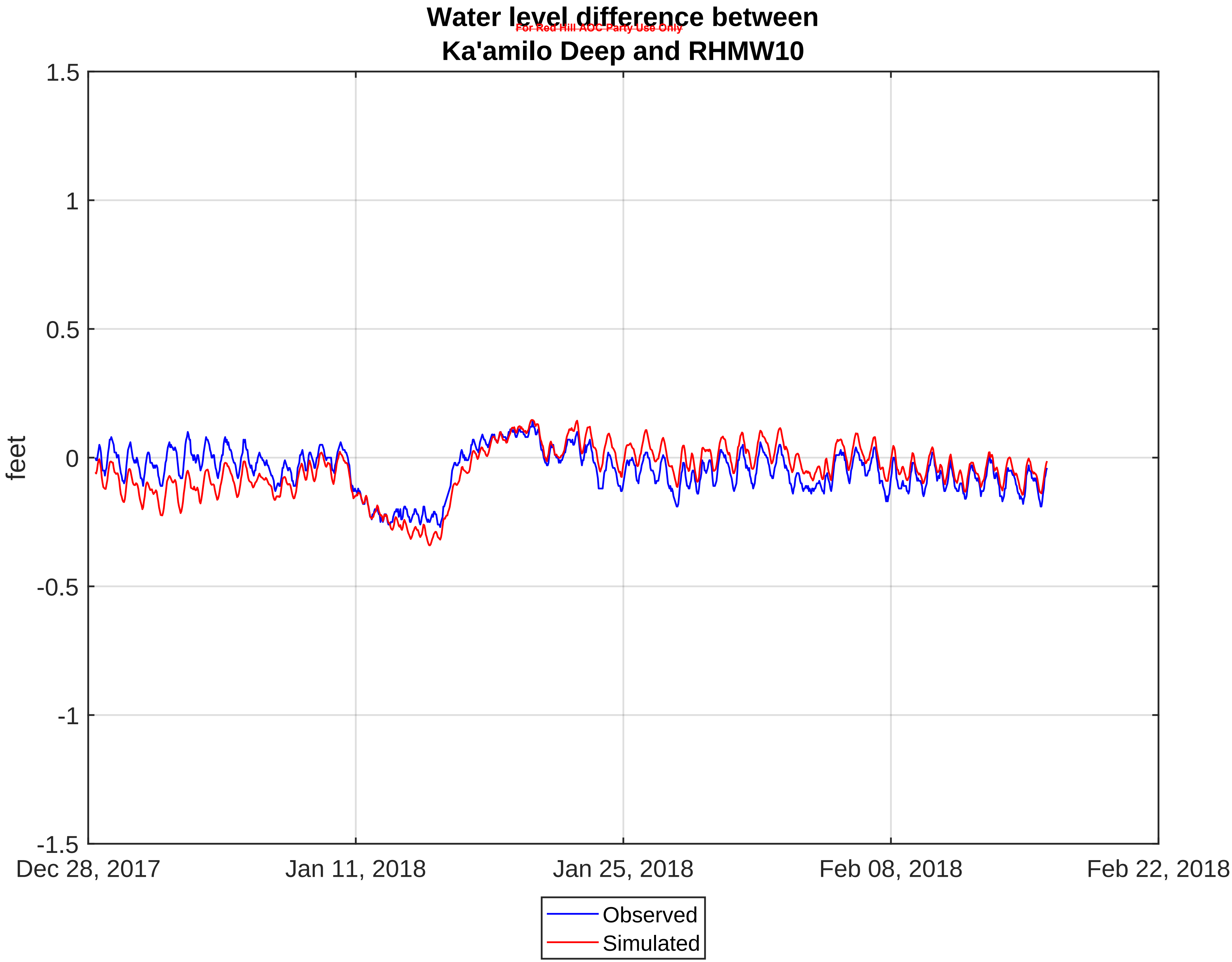
Water level difference between
Ka'amilo Deep and RHMW07
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW08
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

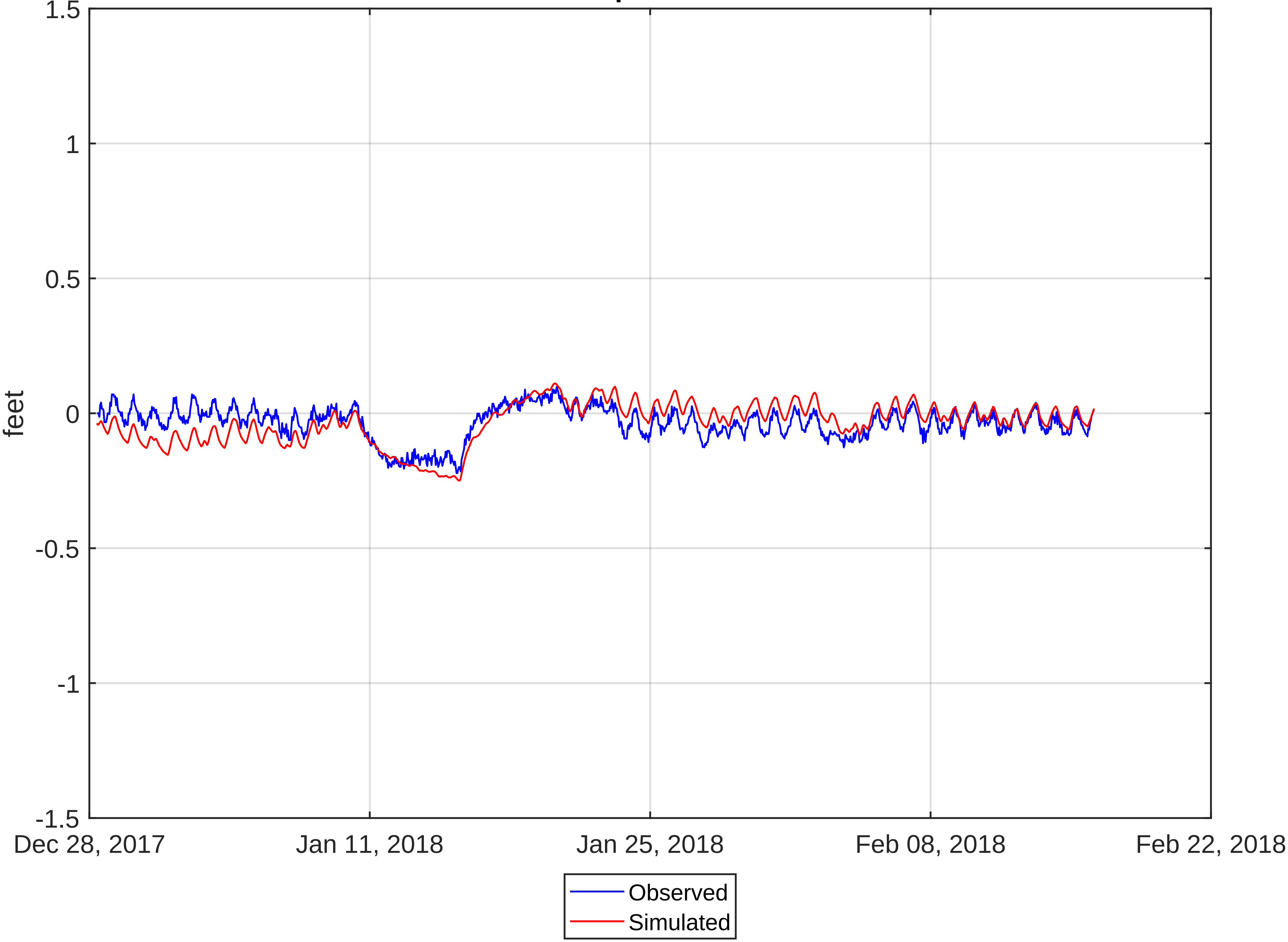


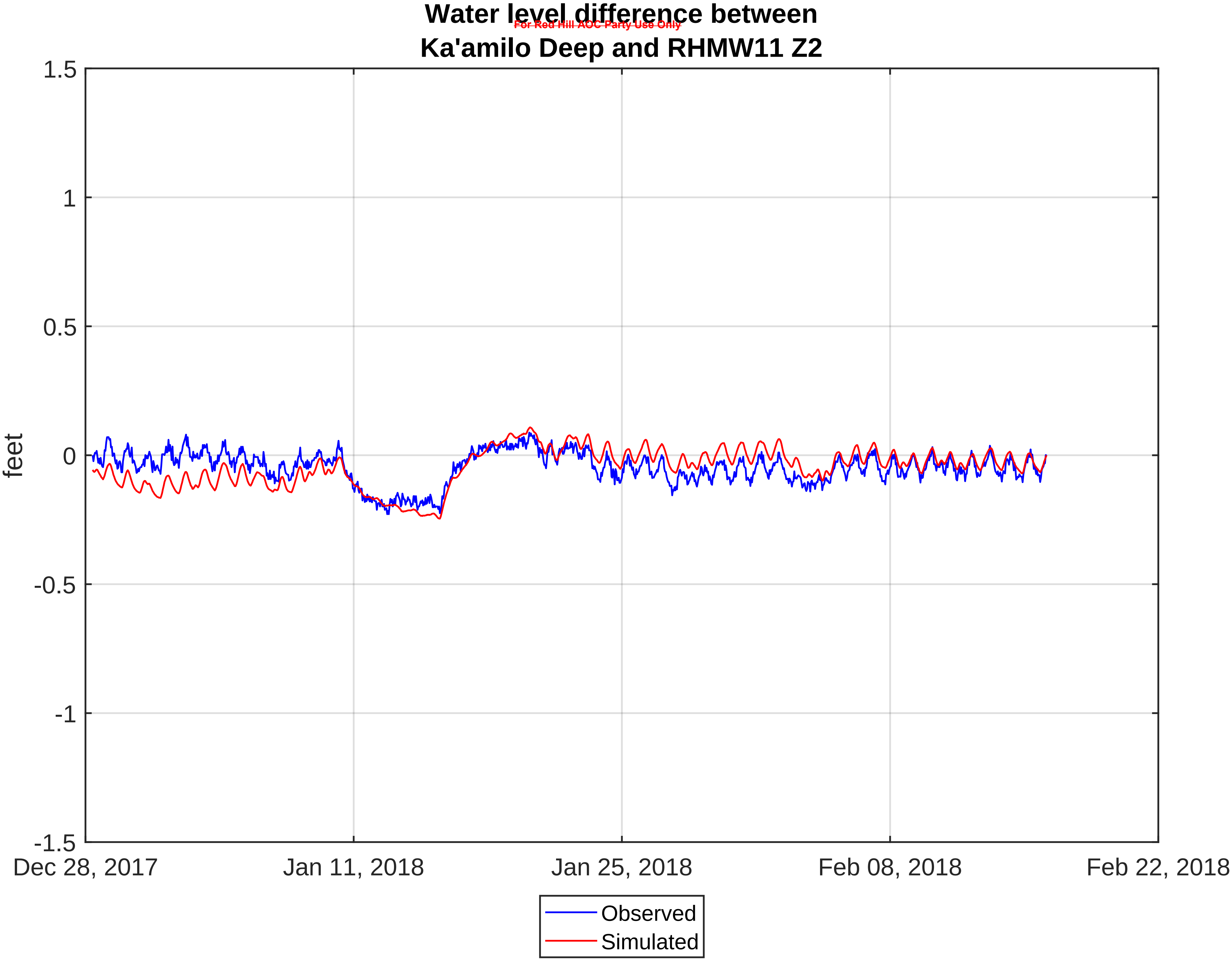
Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW09
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



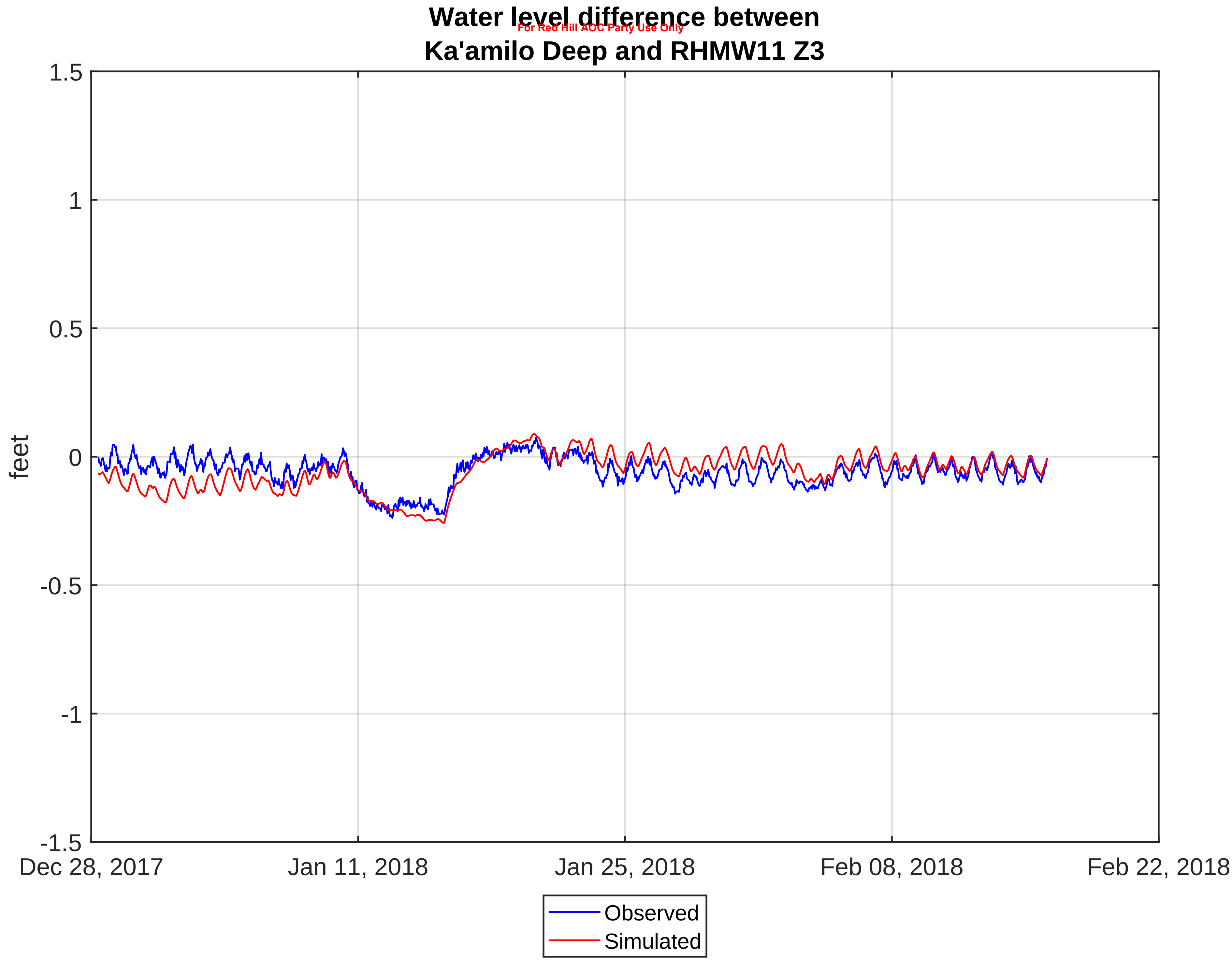
Water level difference between
Ka'amilo Deep and RHMW10
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
Ka'amilo Deep and RHMW11 Z1

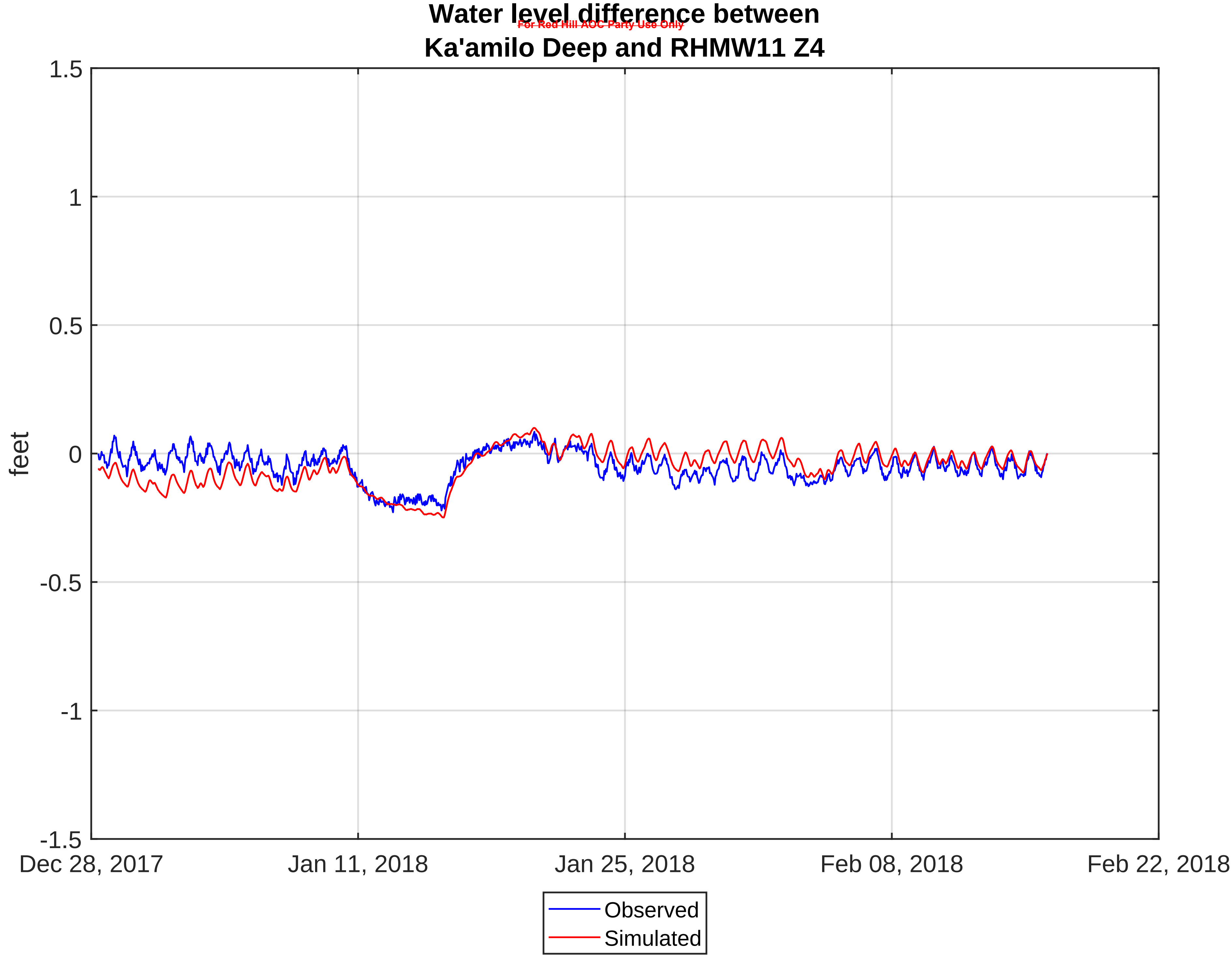




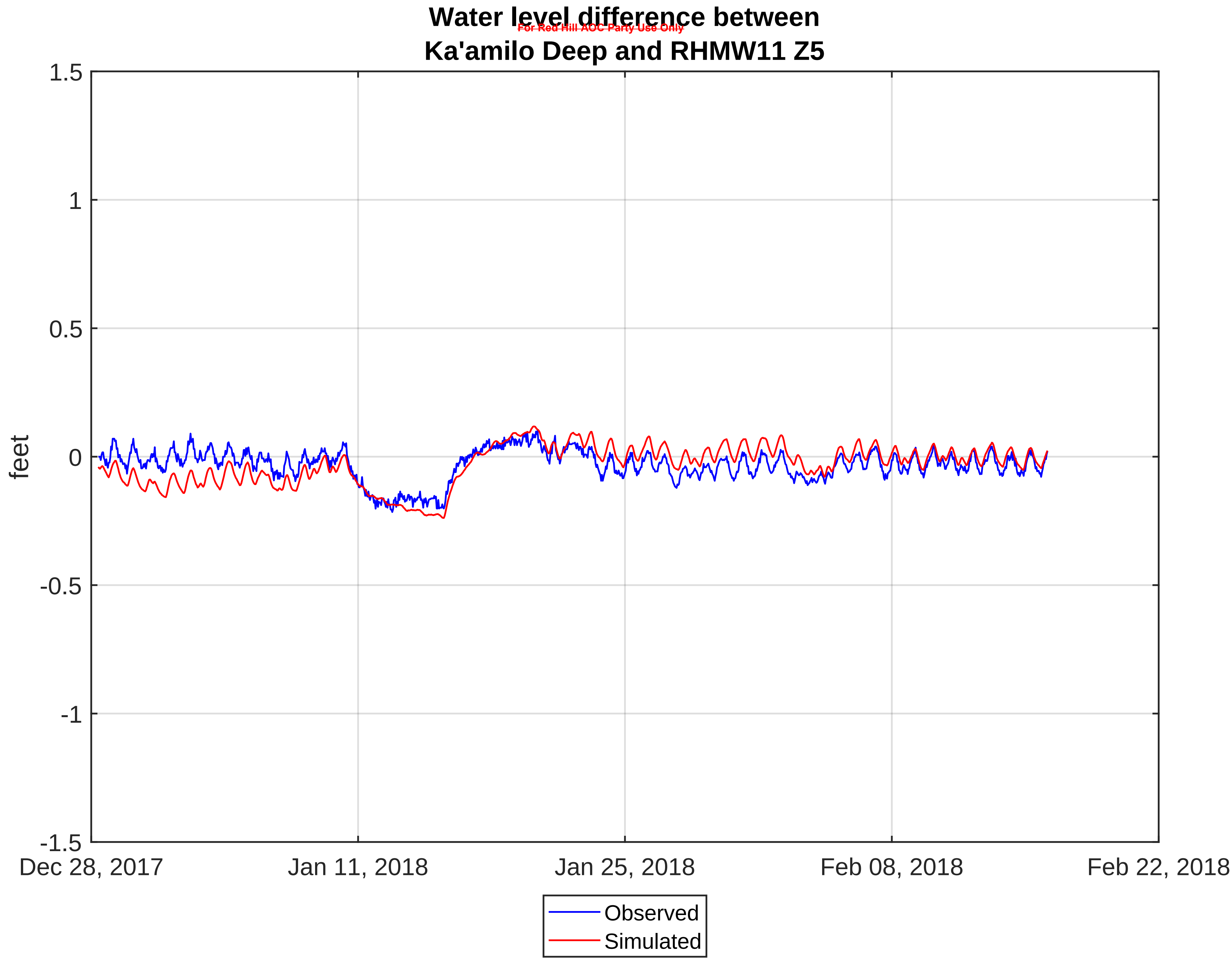
Water level difference between
Ka'amilo Deep and RHMW11 Z2
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

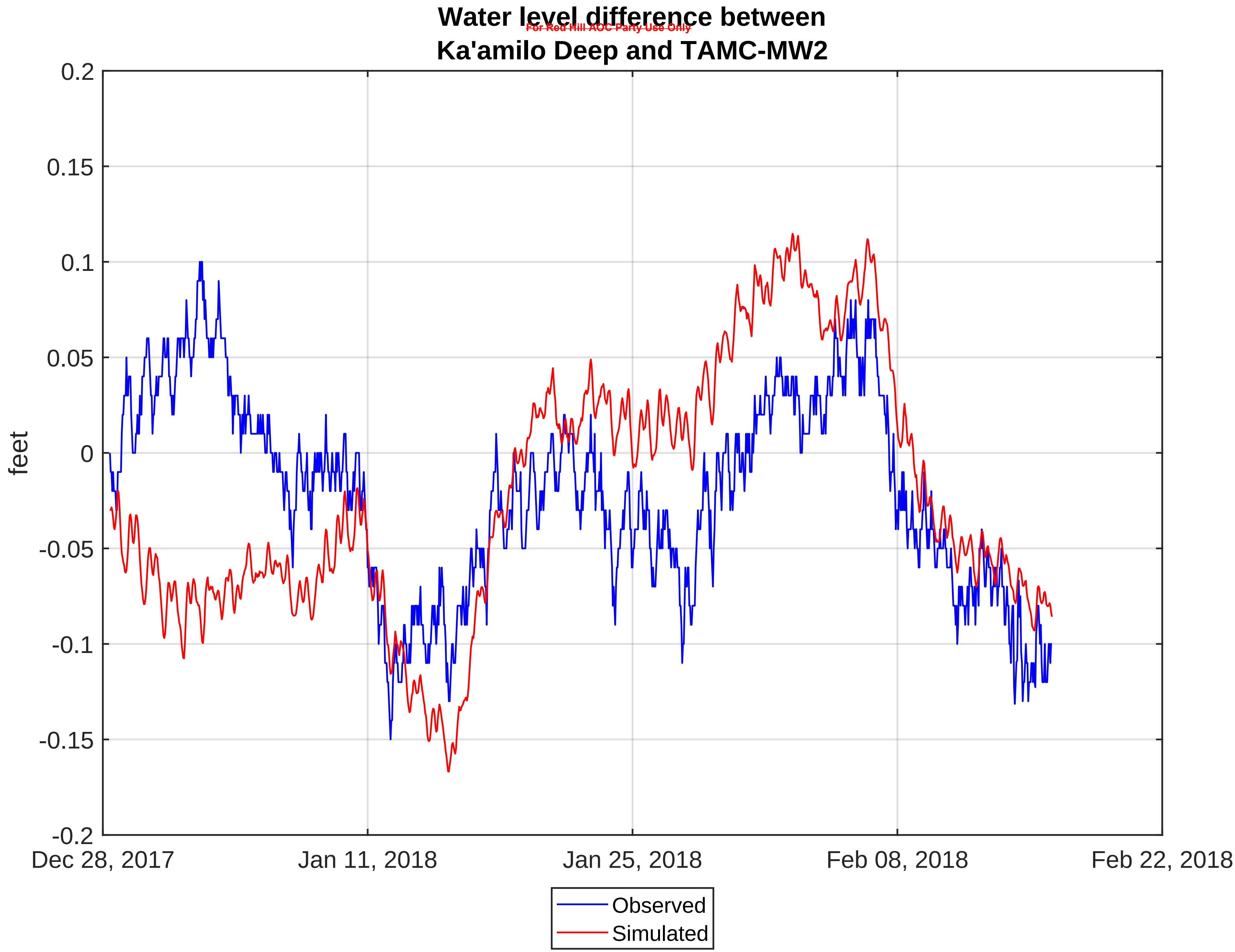


Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW11 Z3
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

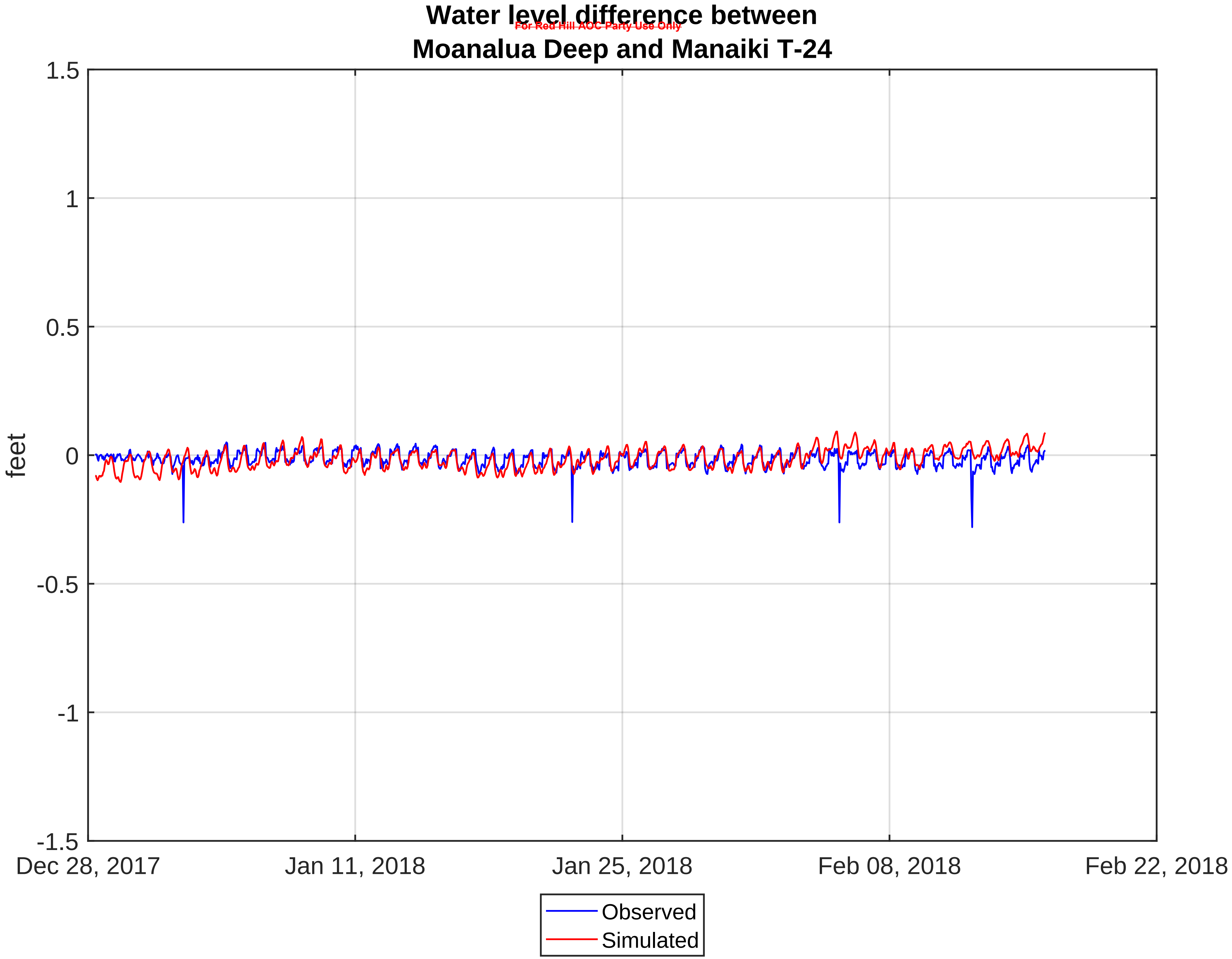


Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW11 Z4
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

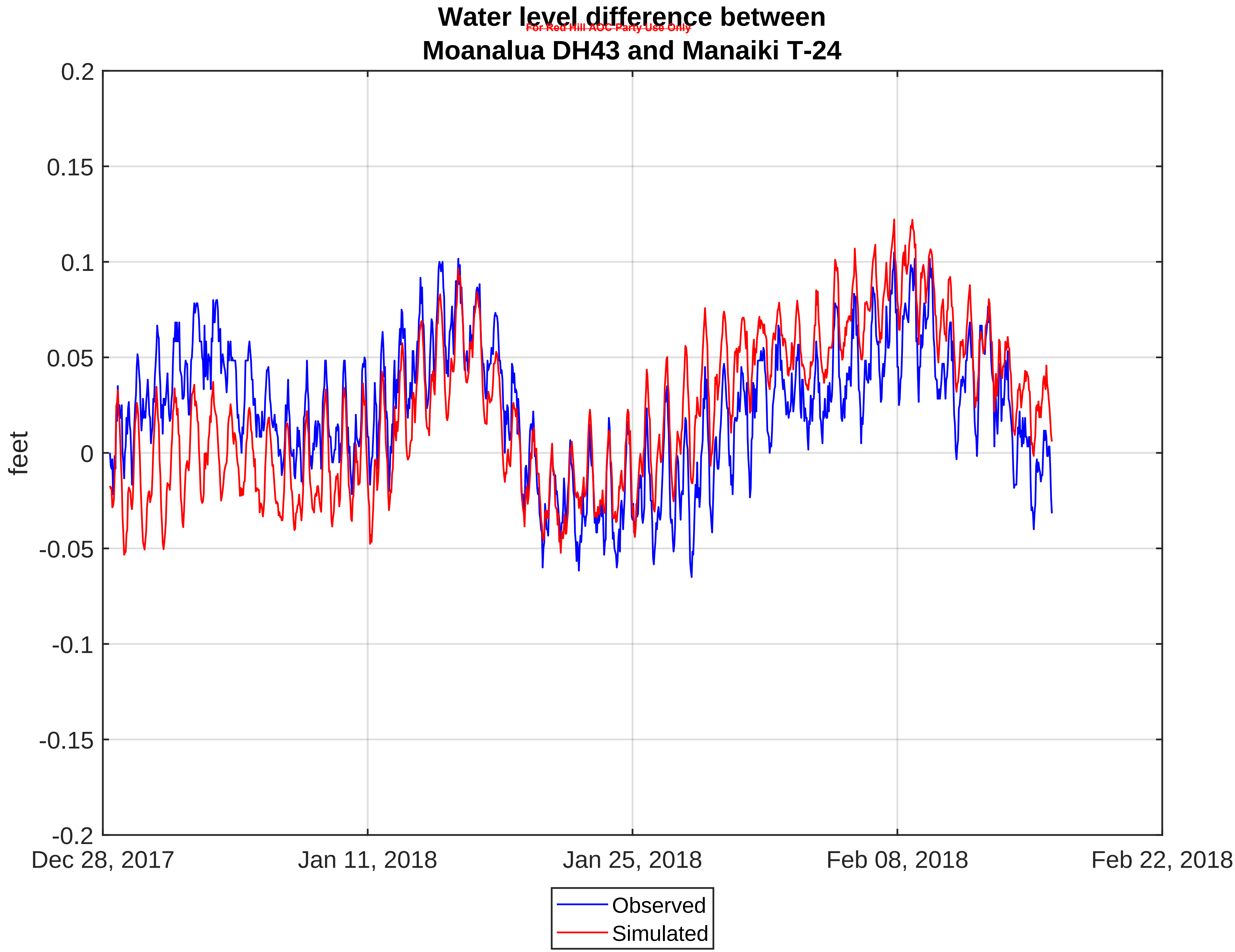

Water level difference between
For Red Hill AOC Party Use Only
Ka'amilo Deep and RHMW11 Z5
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
Ka'amilo Deep and TAMC-MW2
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



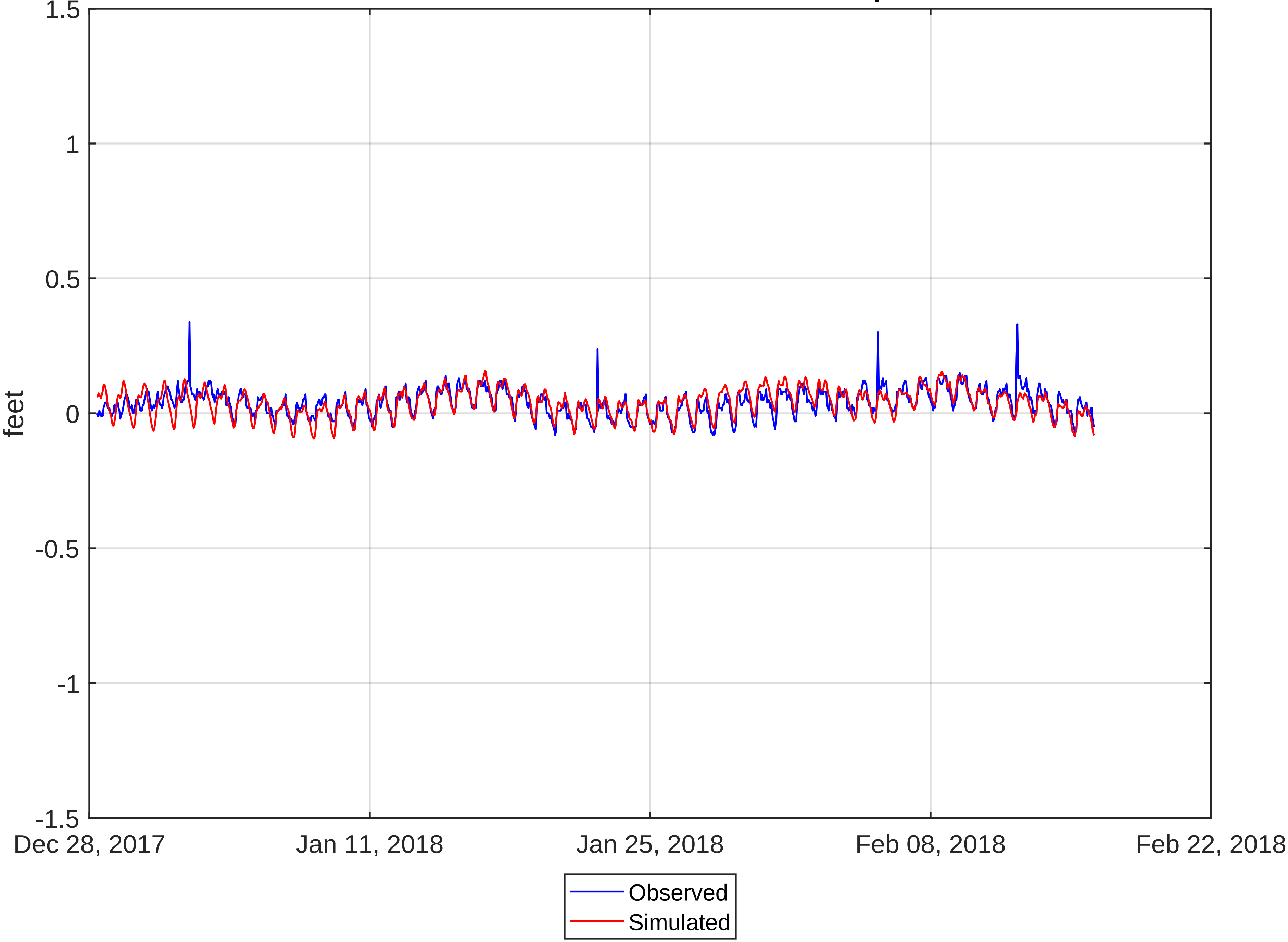
Water level difference between
For Red Hill AOC Party Use Only
Moanalua Deep and Manaiki T-24
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

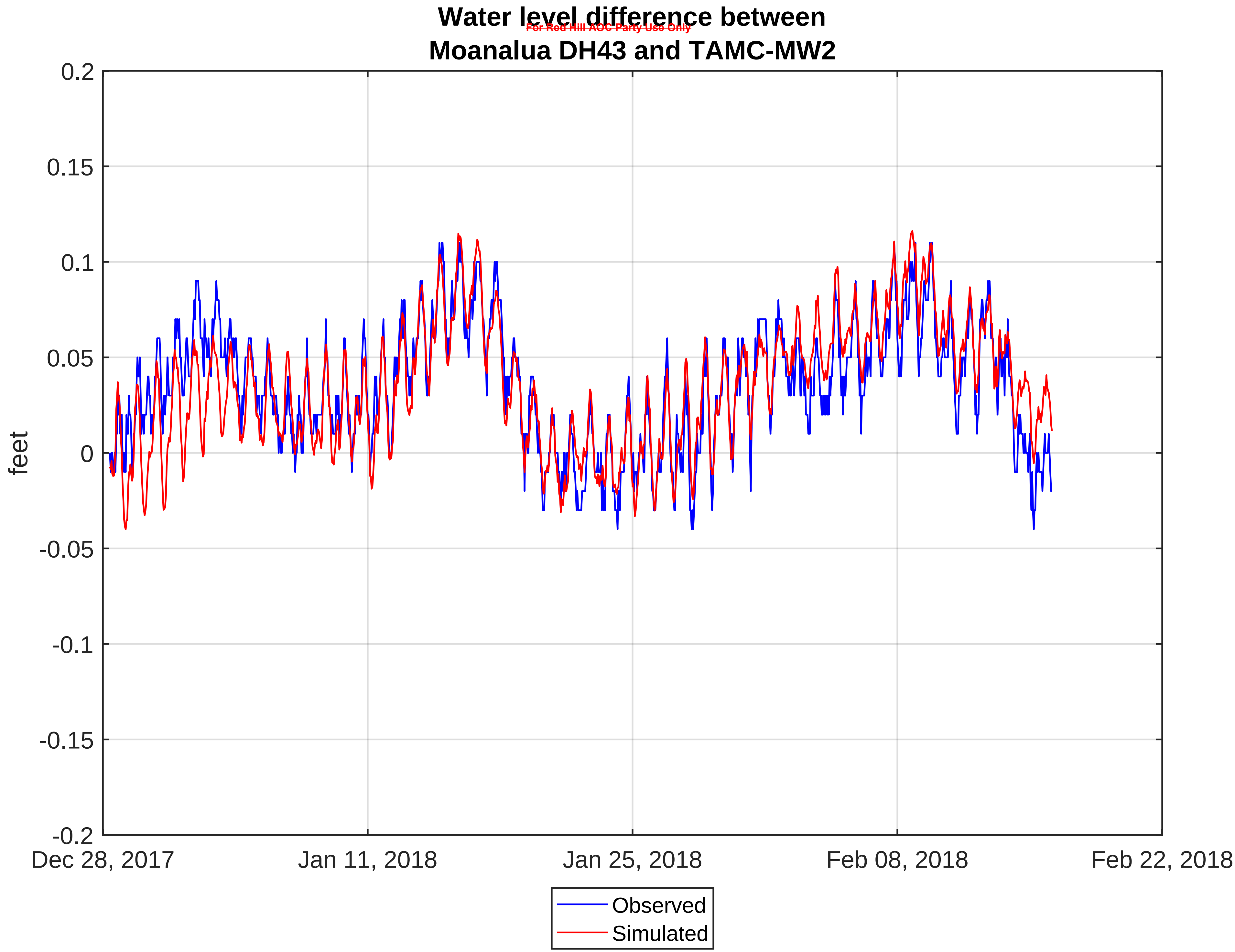


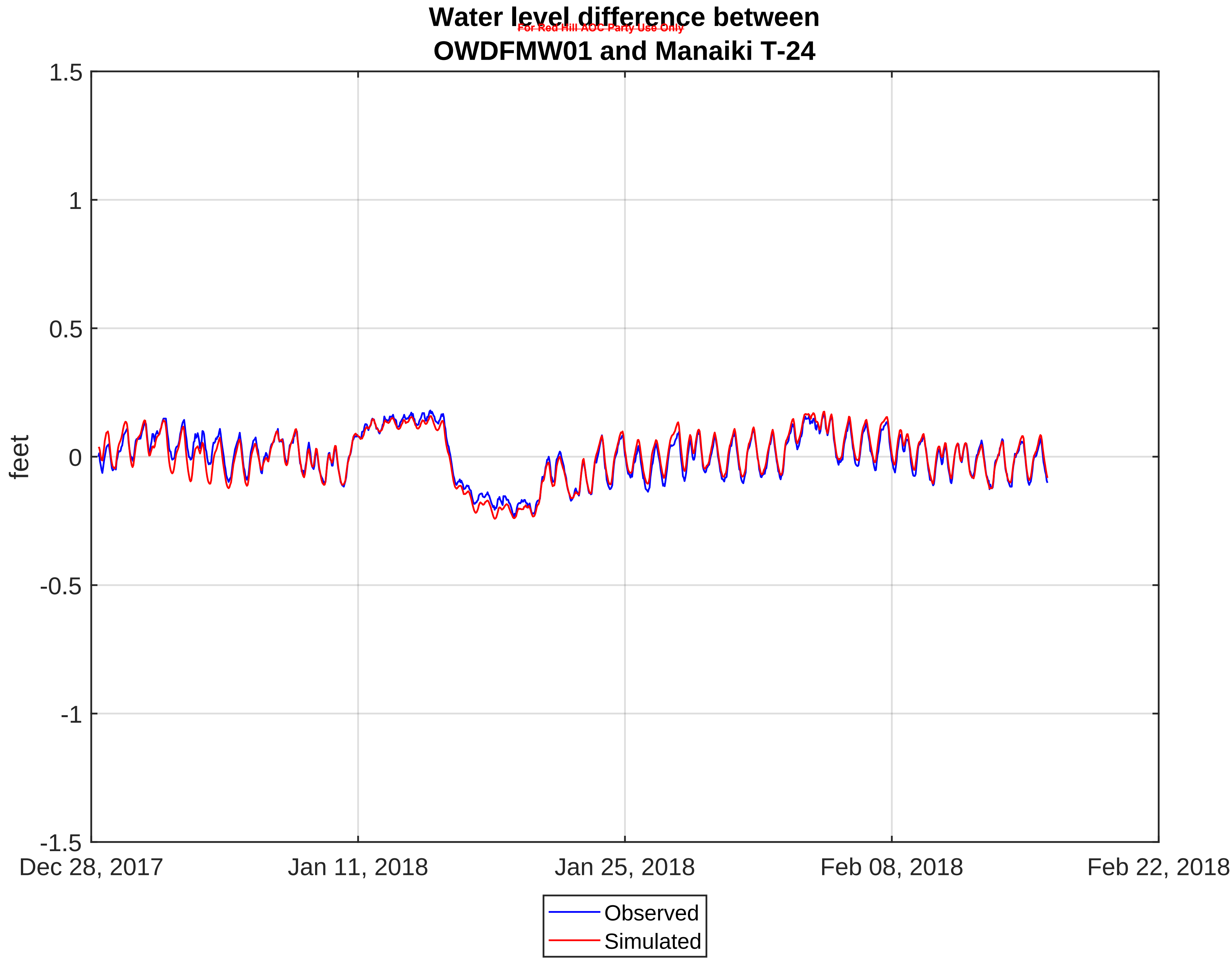
Water level difference between
For Red Hill AOC Party Use Only
Moanalua DH43 and Manaiki T-24
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between

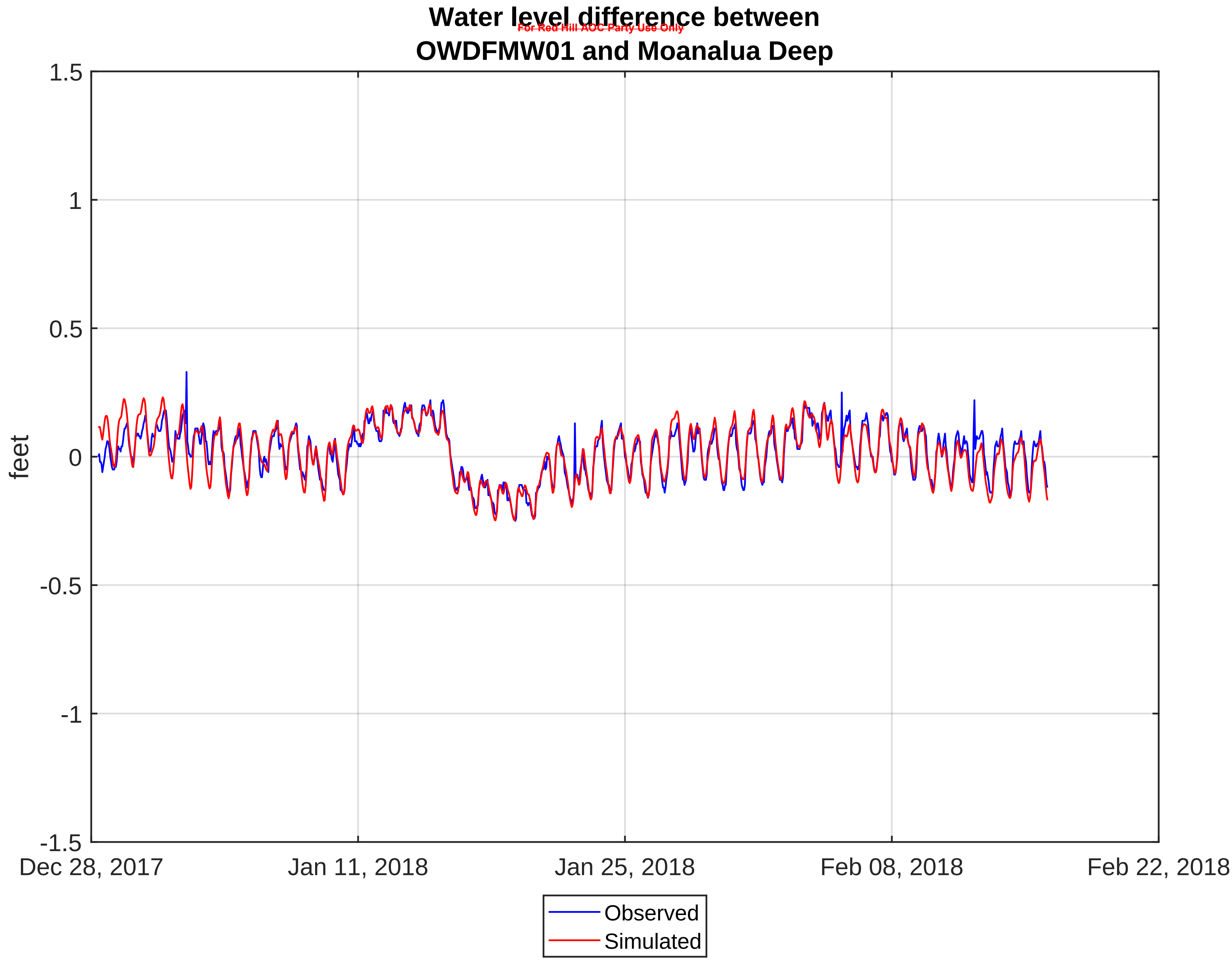
Moanalua DH43 and Moanalua Deep



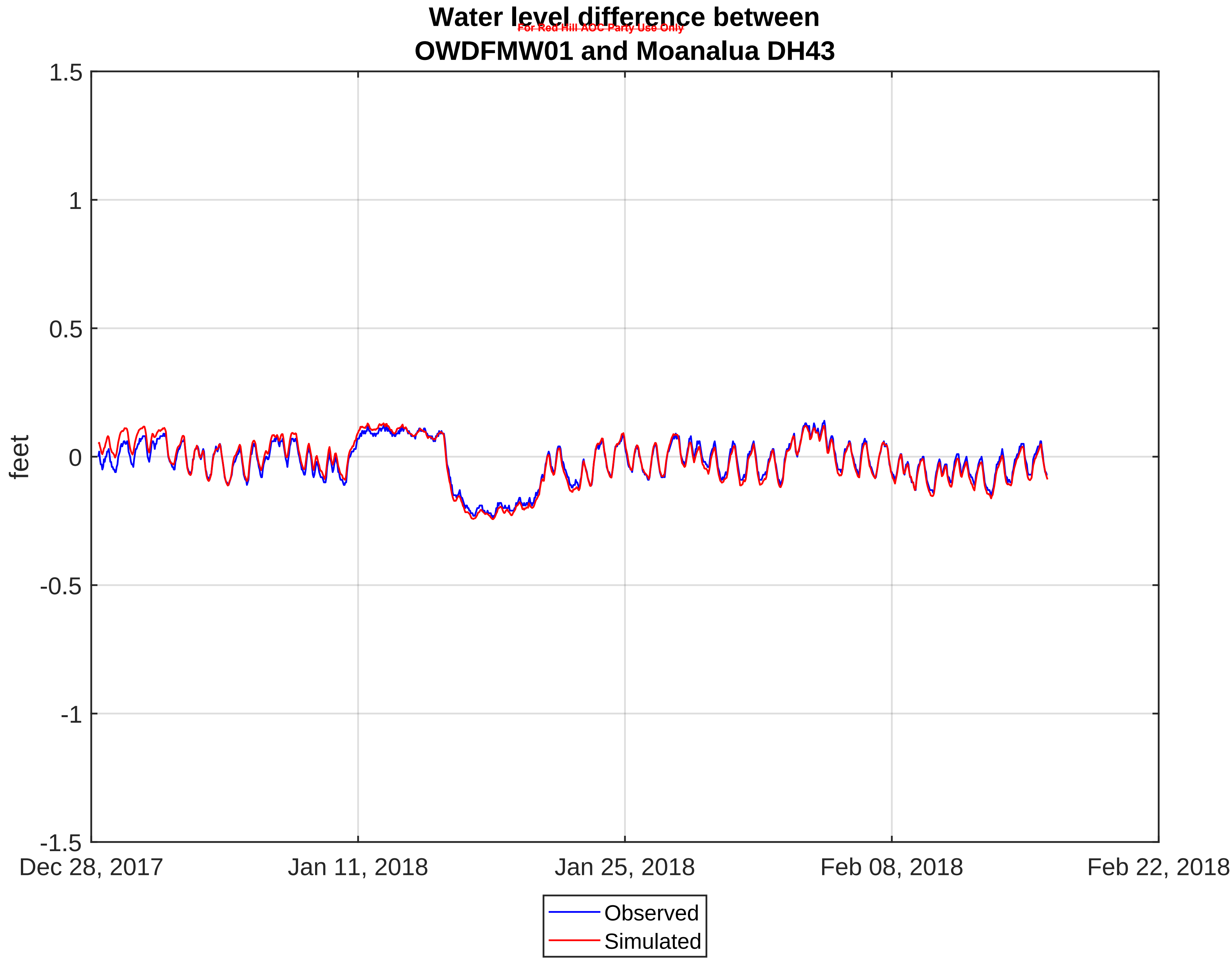

Water level difference between
For Red Hill AOC Party Use Only
Moanalua DH43 and TAMC-MW2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



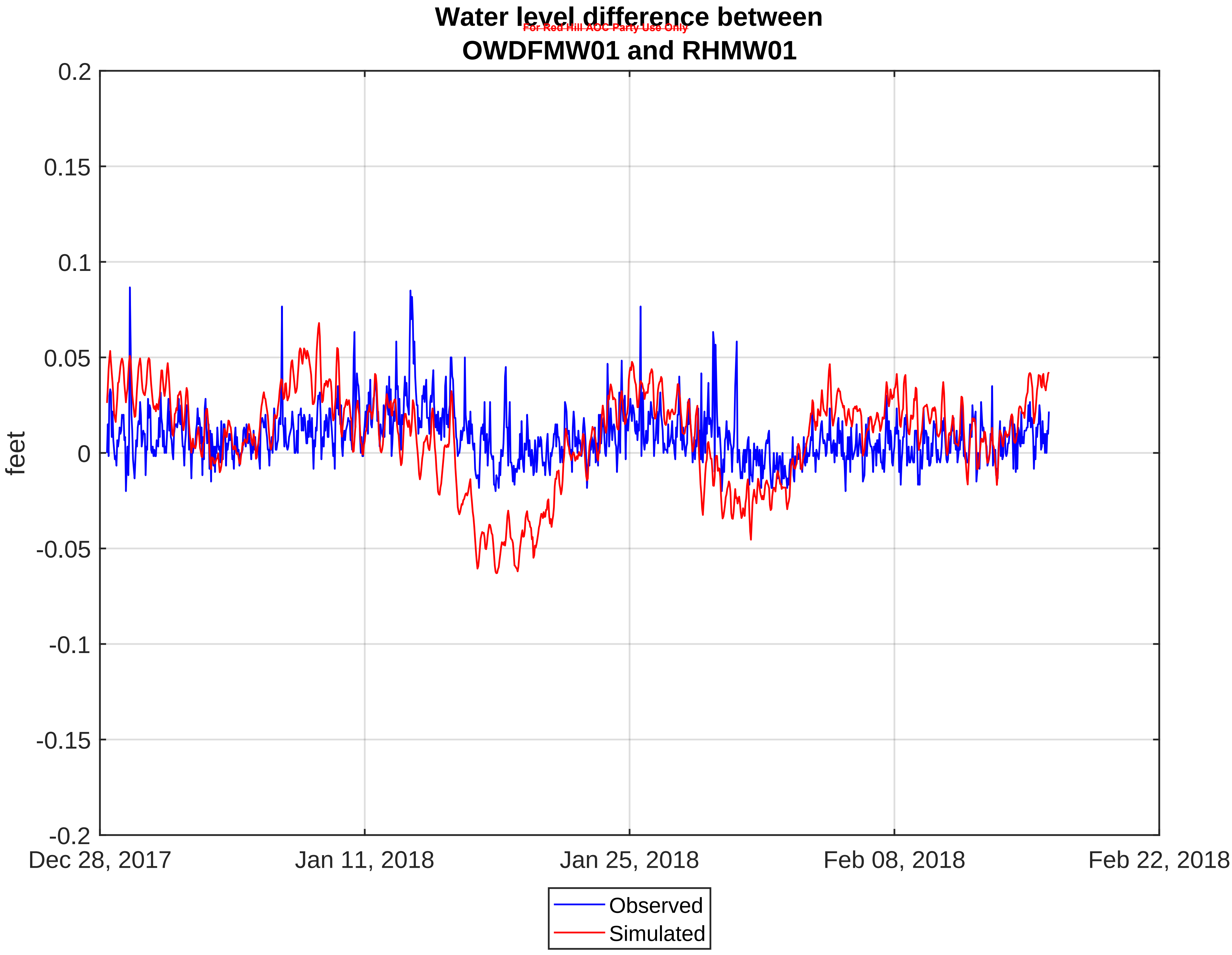
Water level difference between
OWDFMW01 and Manaiki T-24
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
OWDFMW01 and Moanalua Deep
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



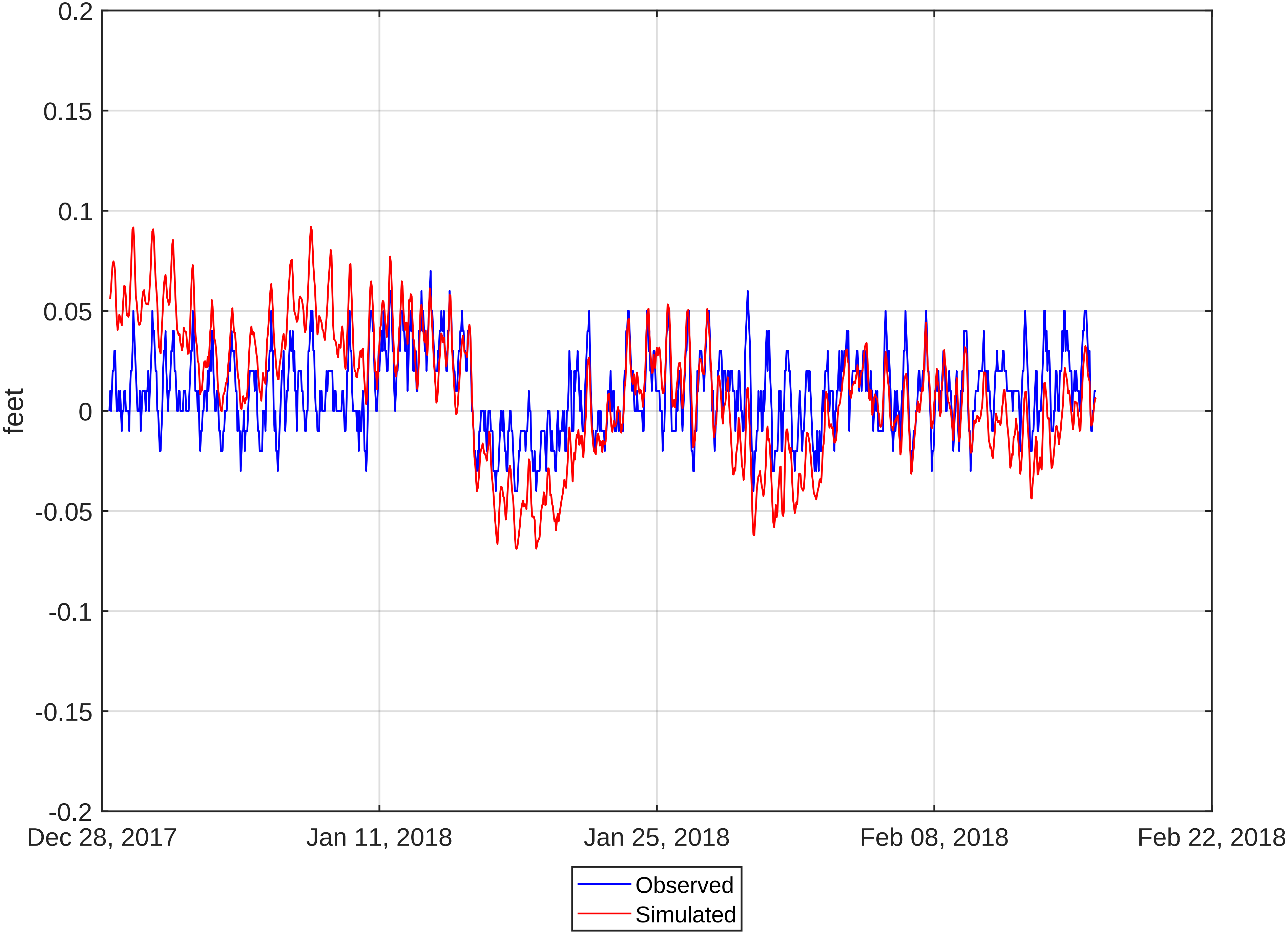
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and Moanalua DH43
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

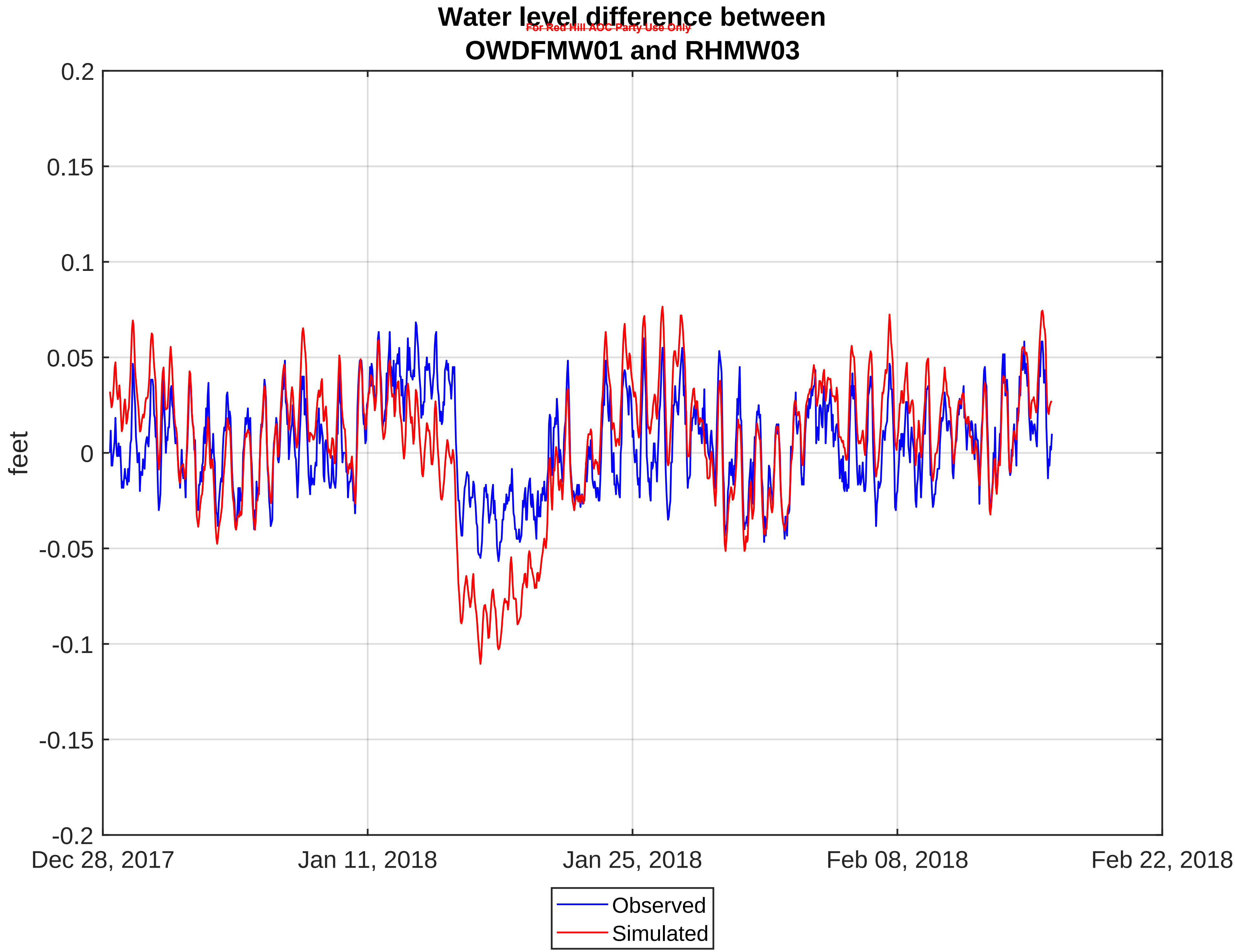


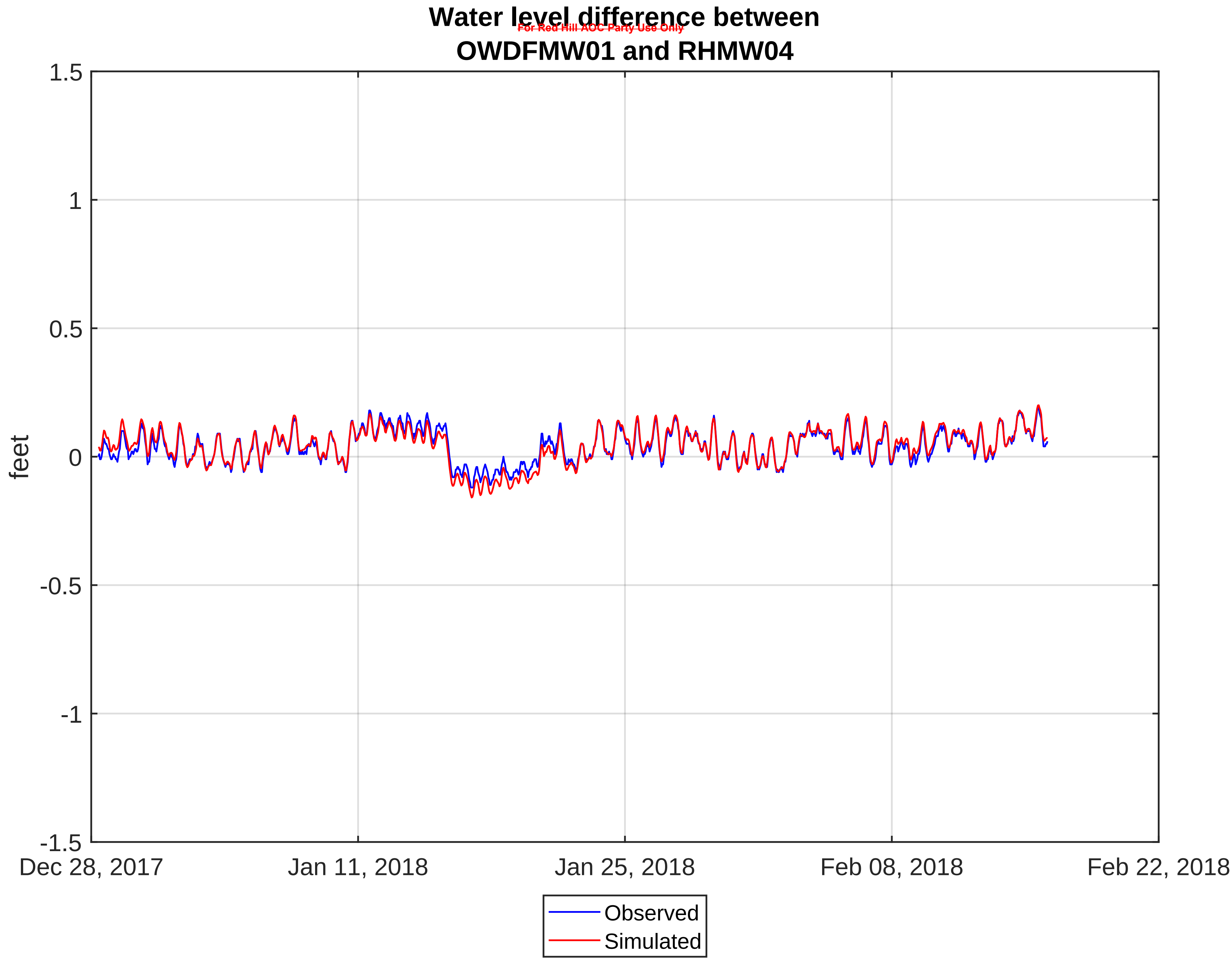
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW01
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between

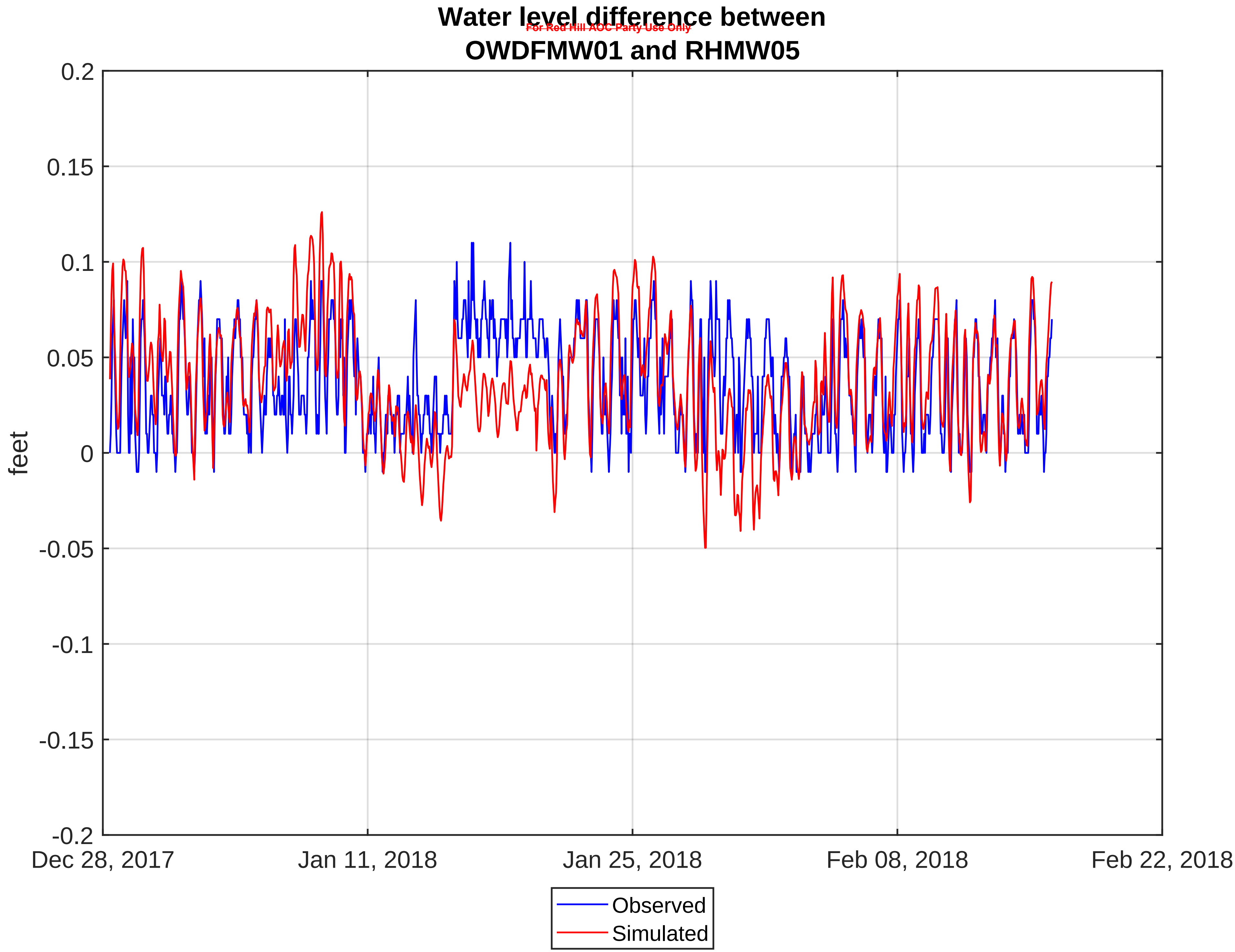
OWDFMW01 and RHMW02



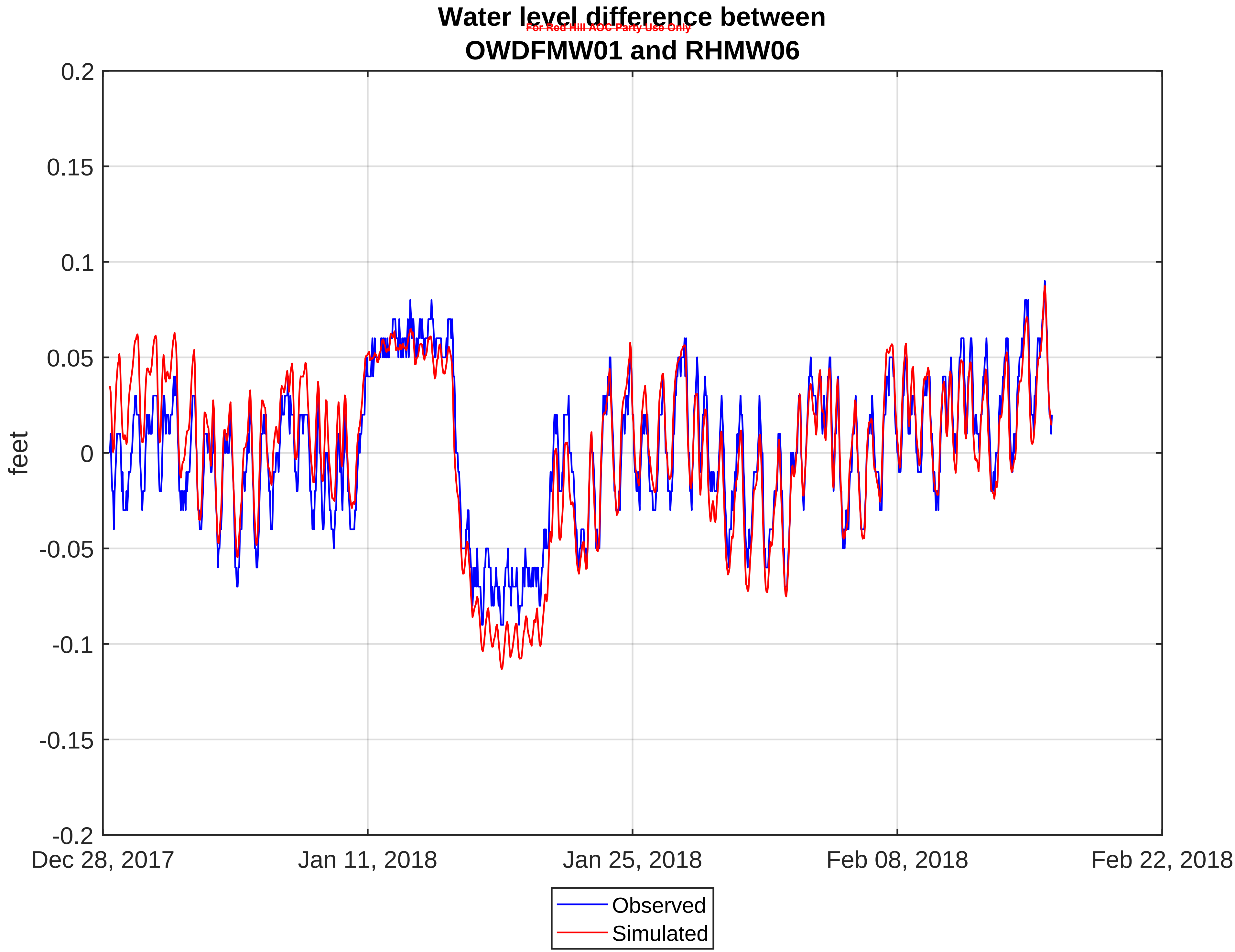

Water level difference between
OWDFMW01 and RHMW03
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



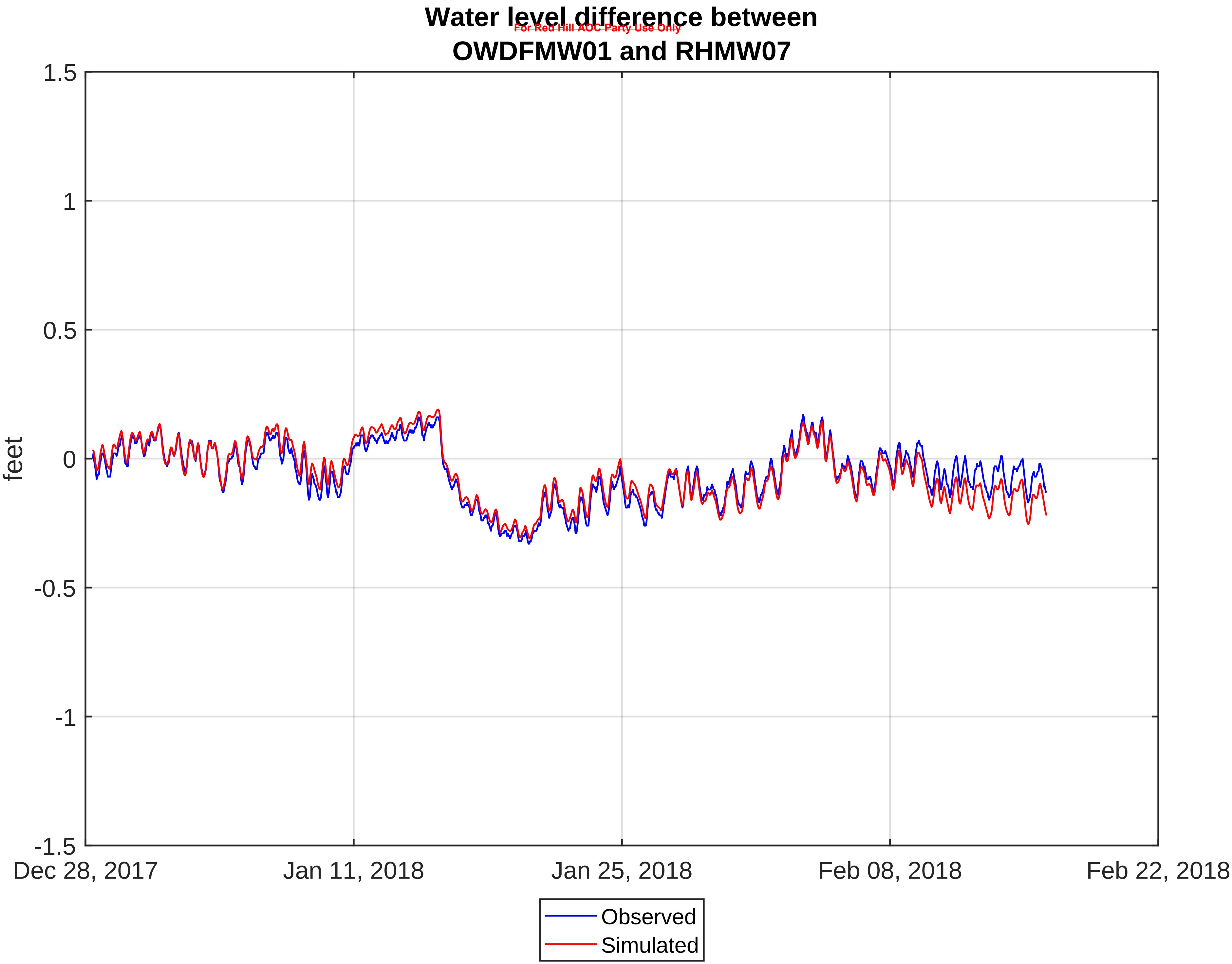
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW04
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW05
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



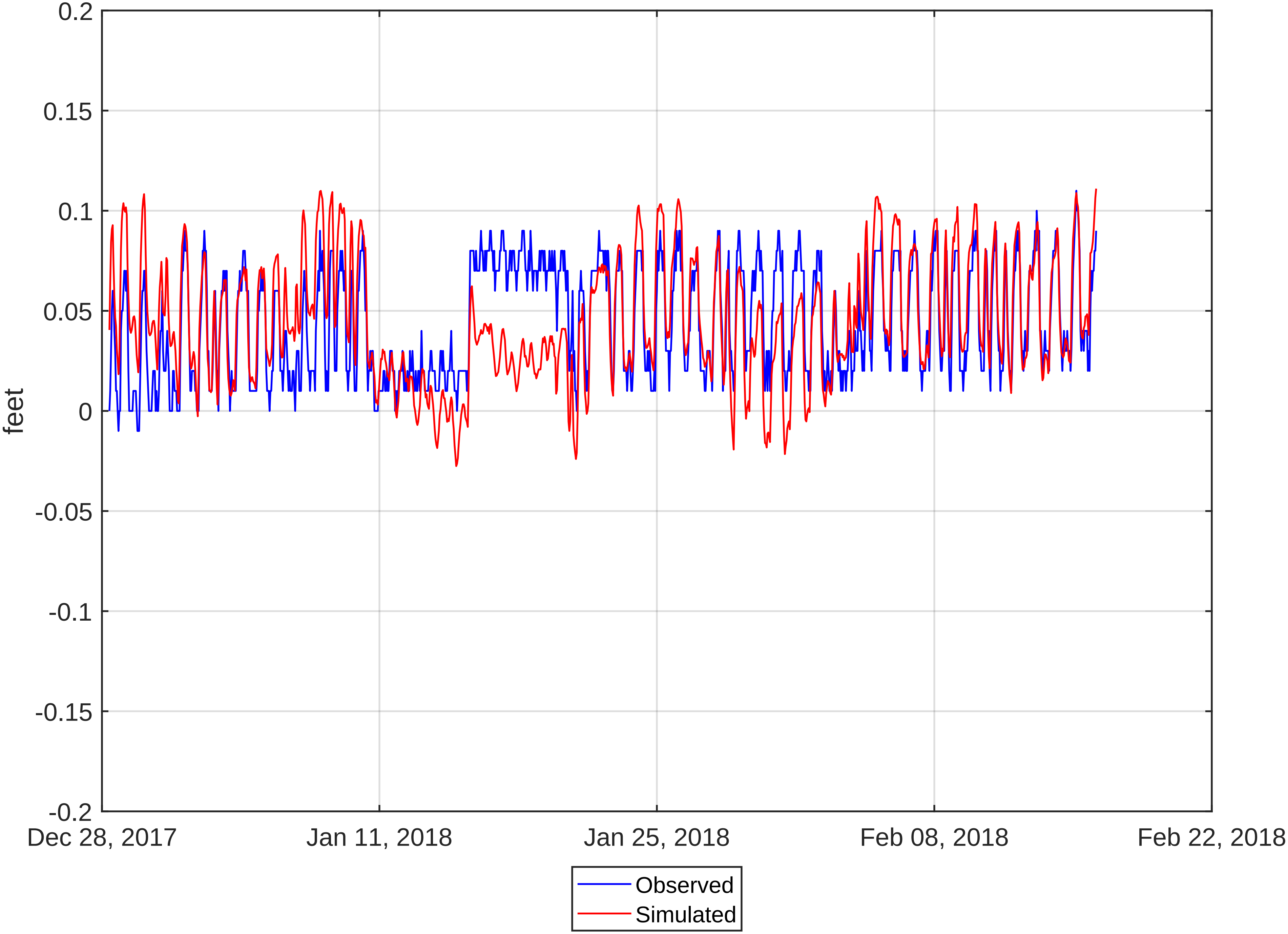
Water level difference between
OWDFMW01 and RHMW06
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

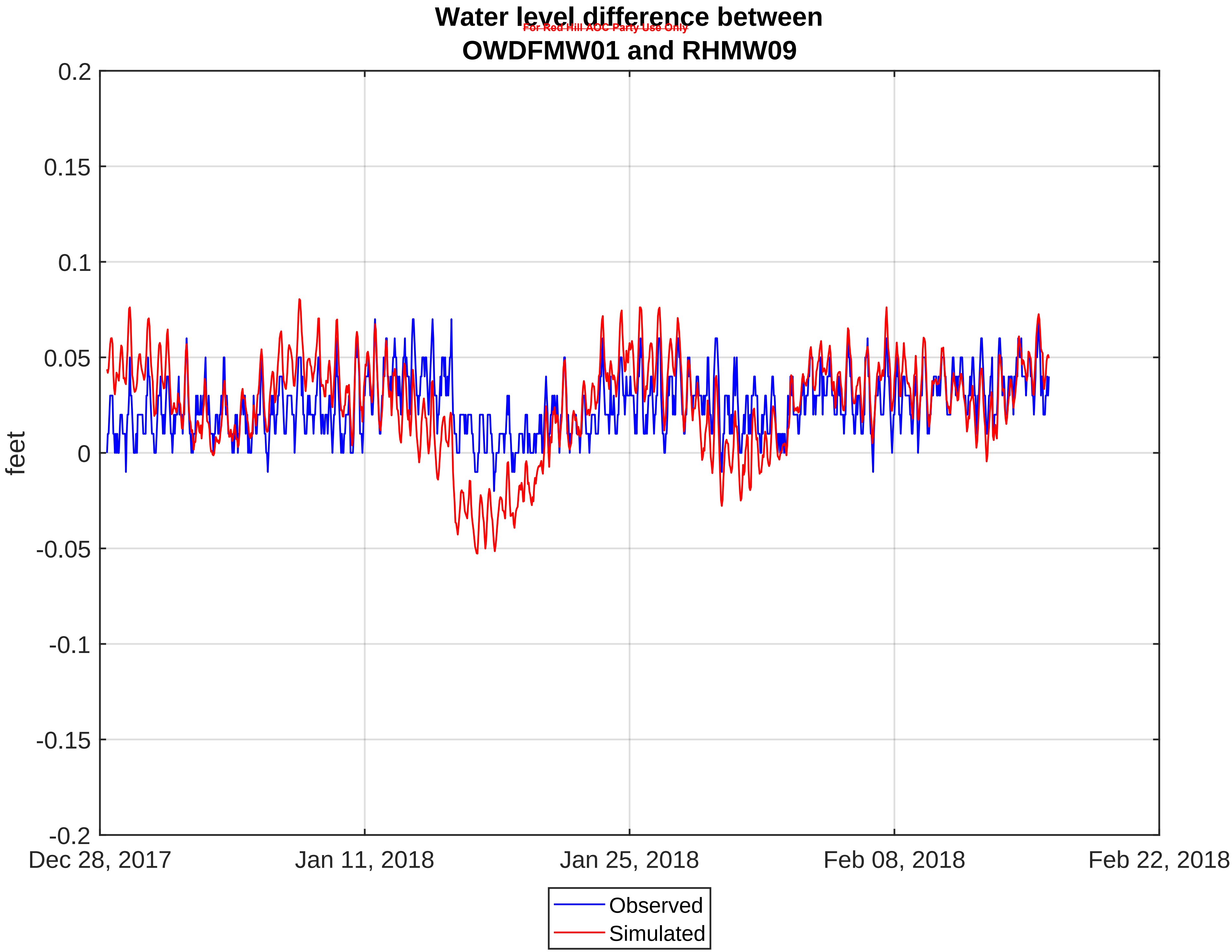


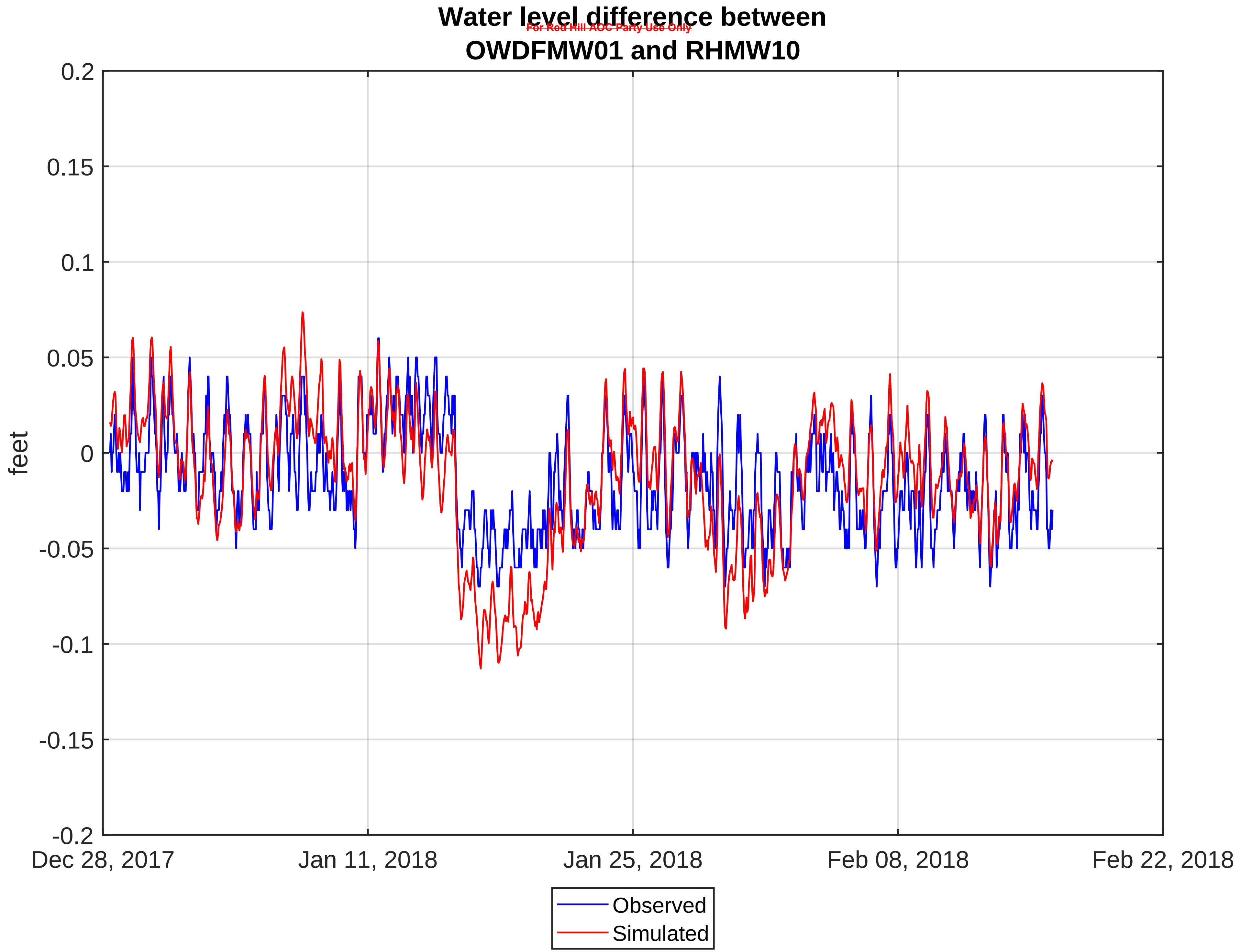
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW07
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between

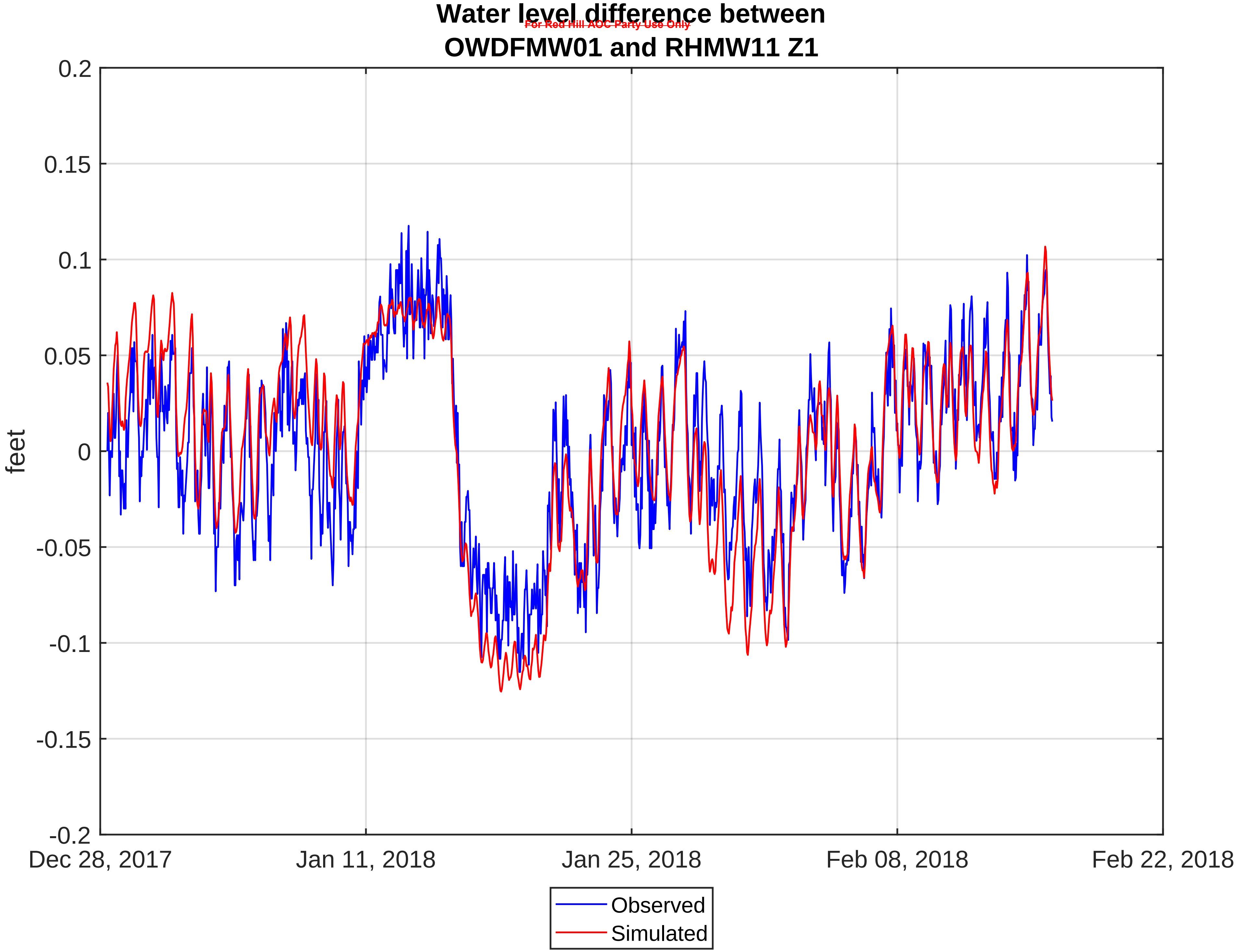
OWDFMW01 and RHMW08



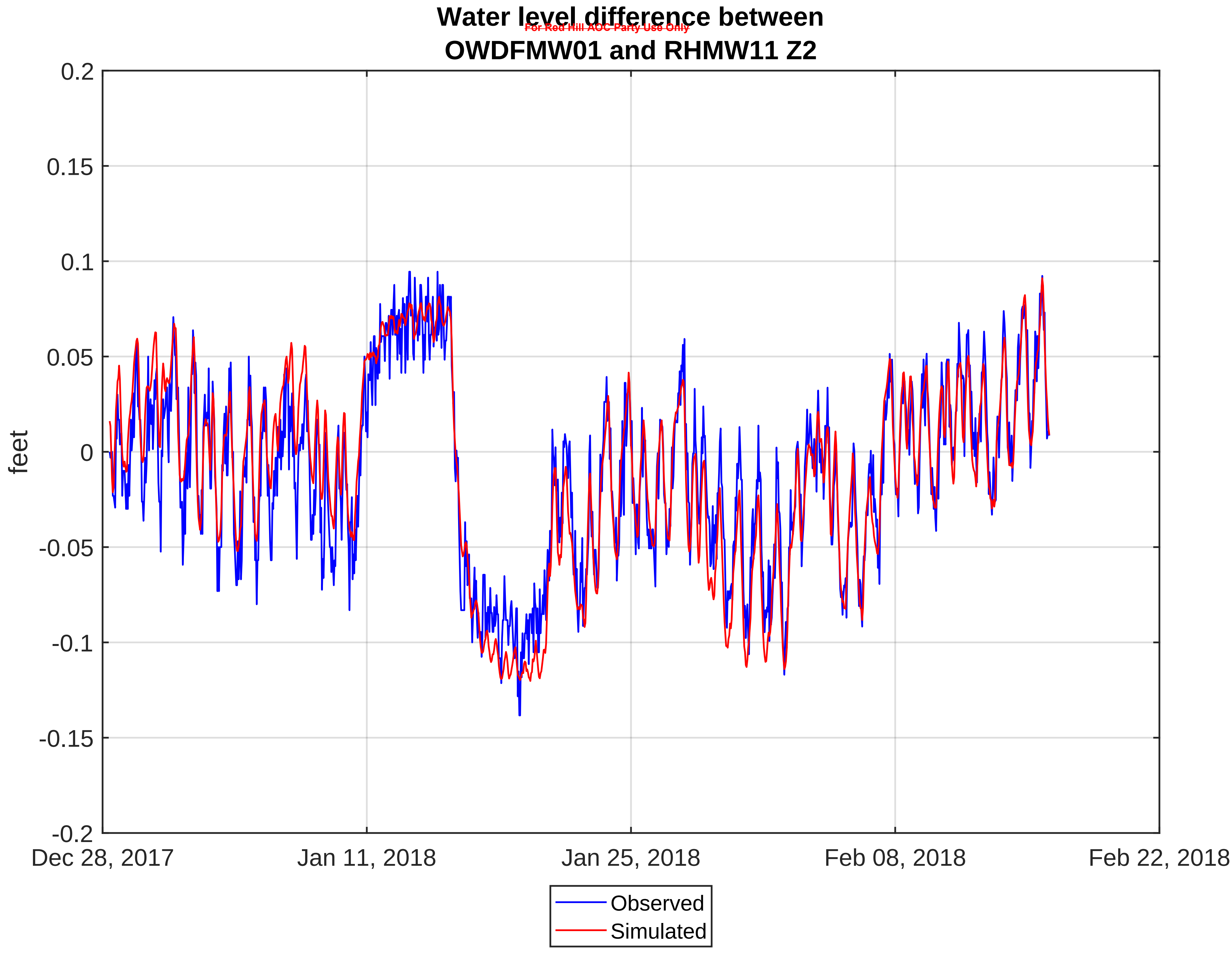

Water level difference between
OWDFMW01 and RHMW09
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



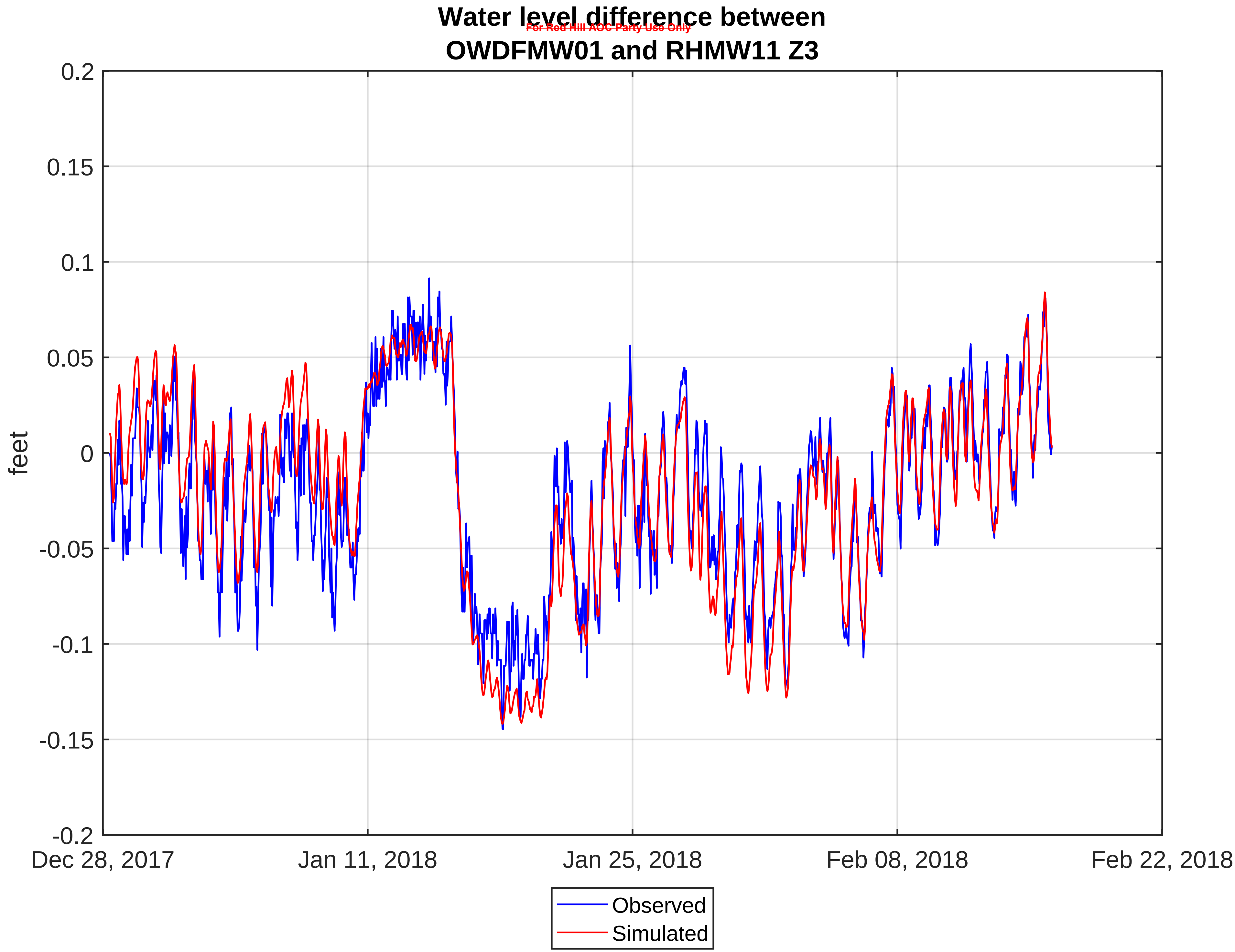
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW10
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



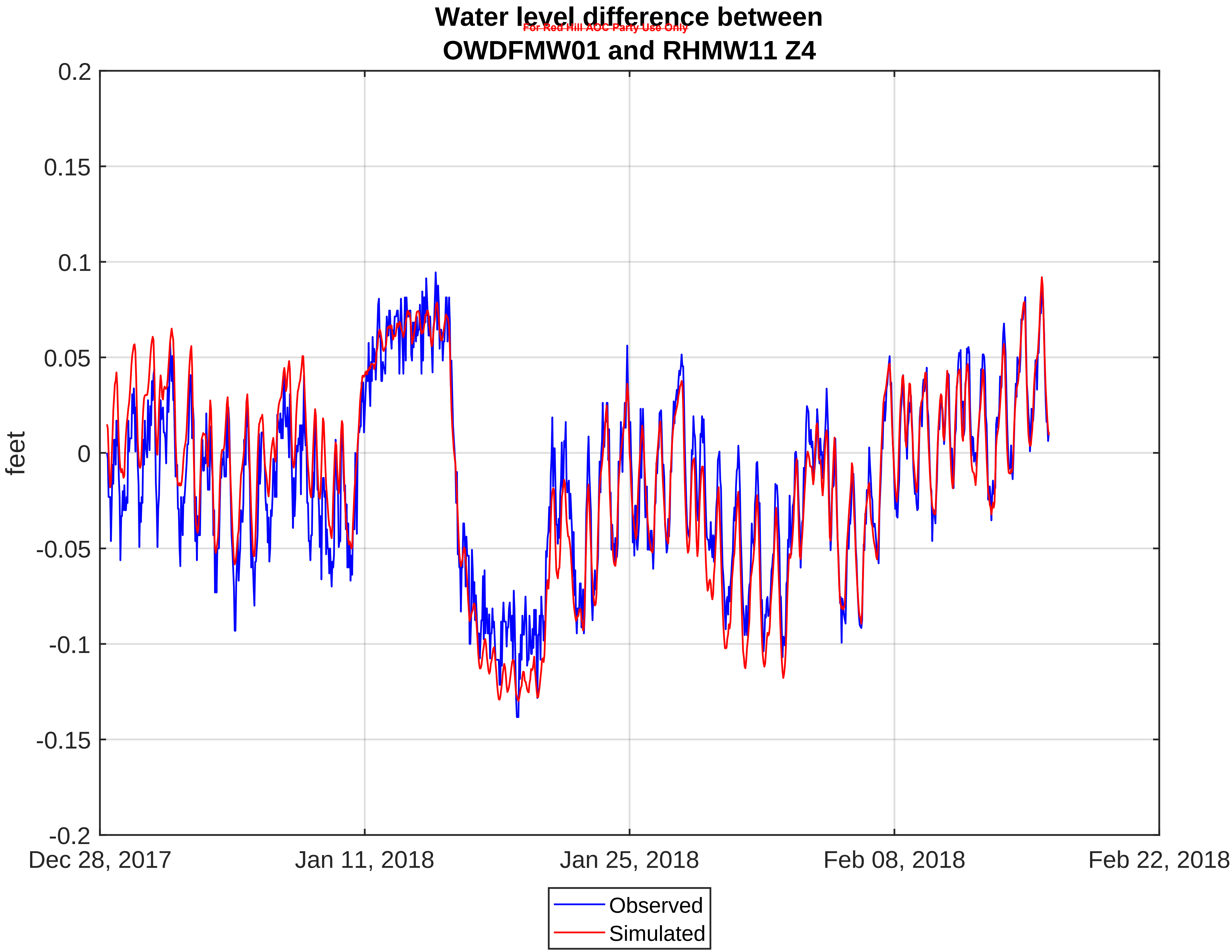
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW11 Z1
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



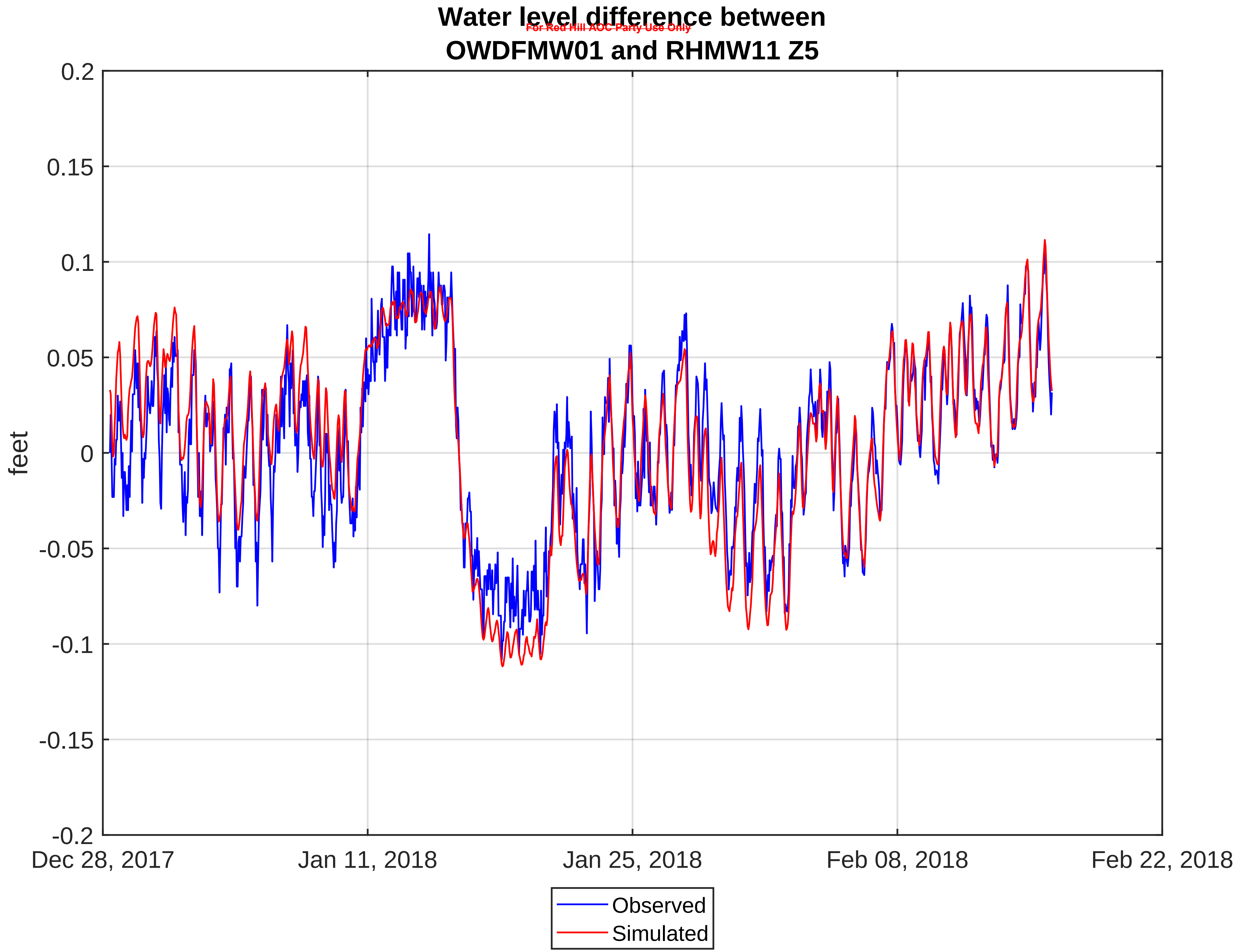
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW11 Z2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



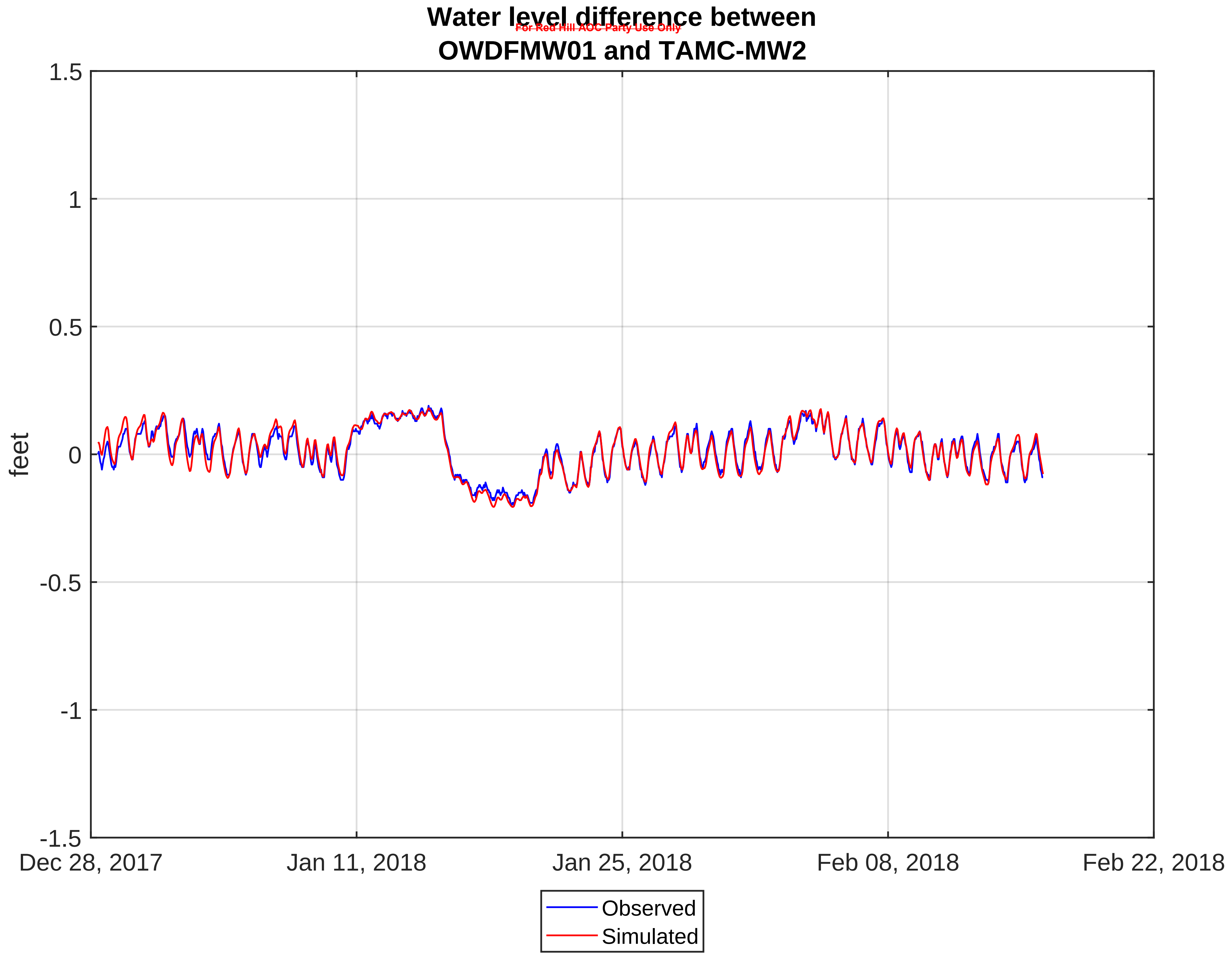
Water level difference between
OWDFMW01 and RHMW11 Z3
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



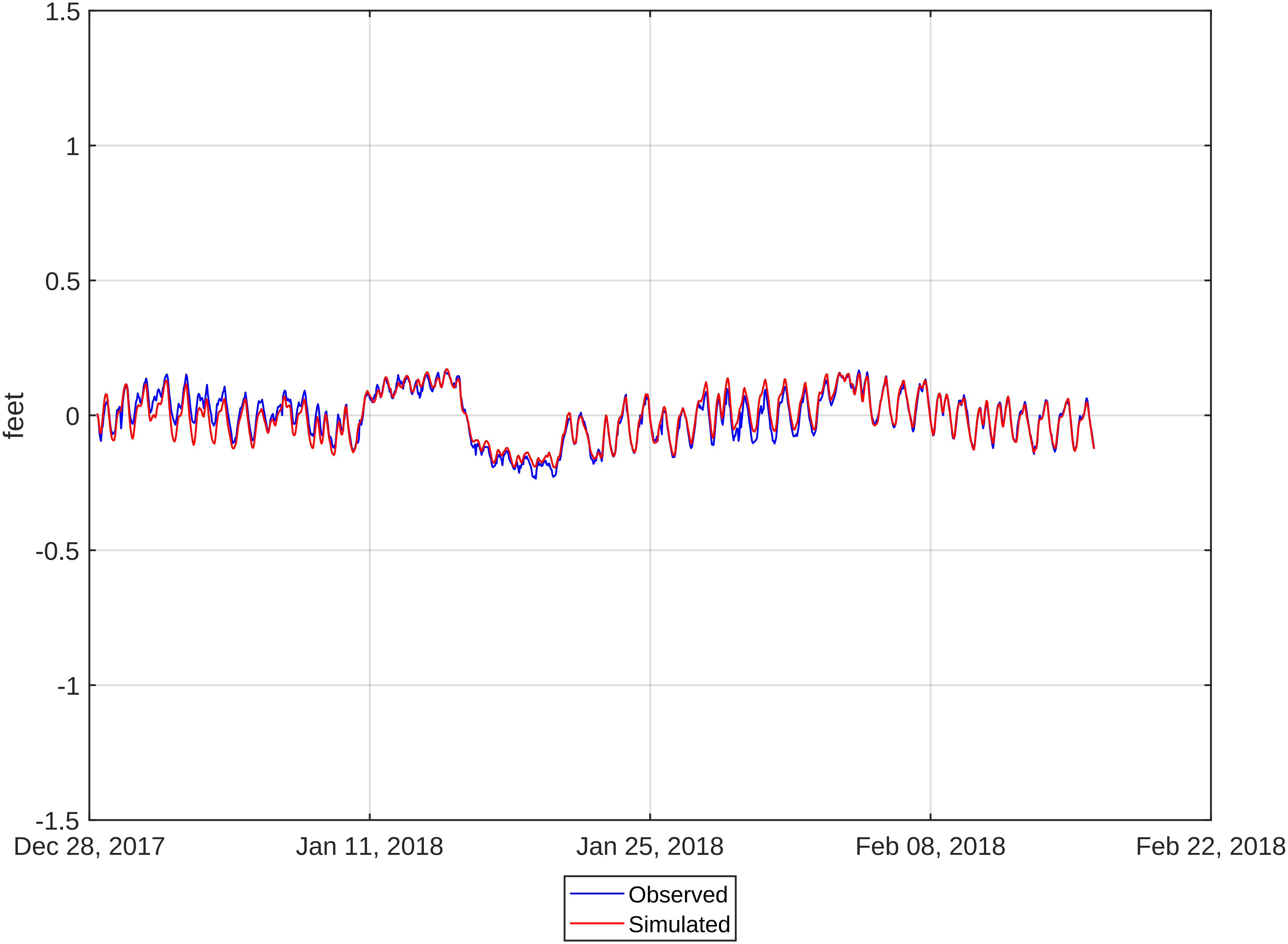
Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW11 Z4
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

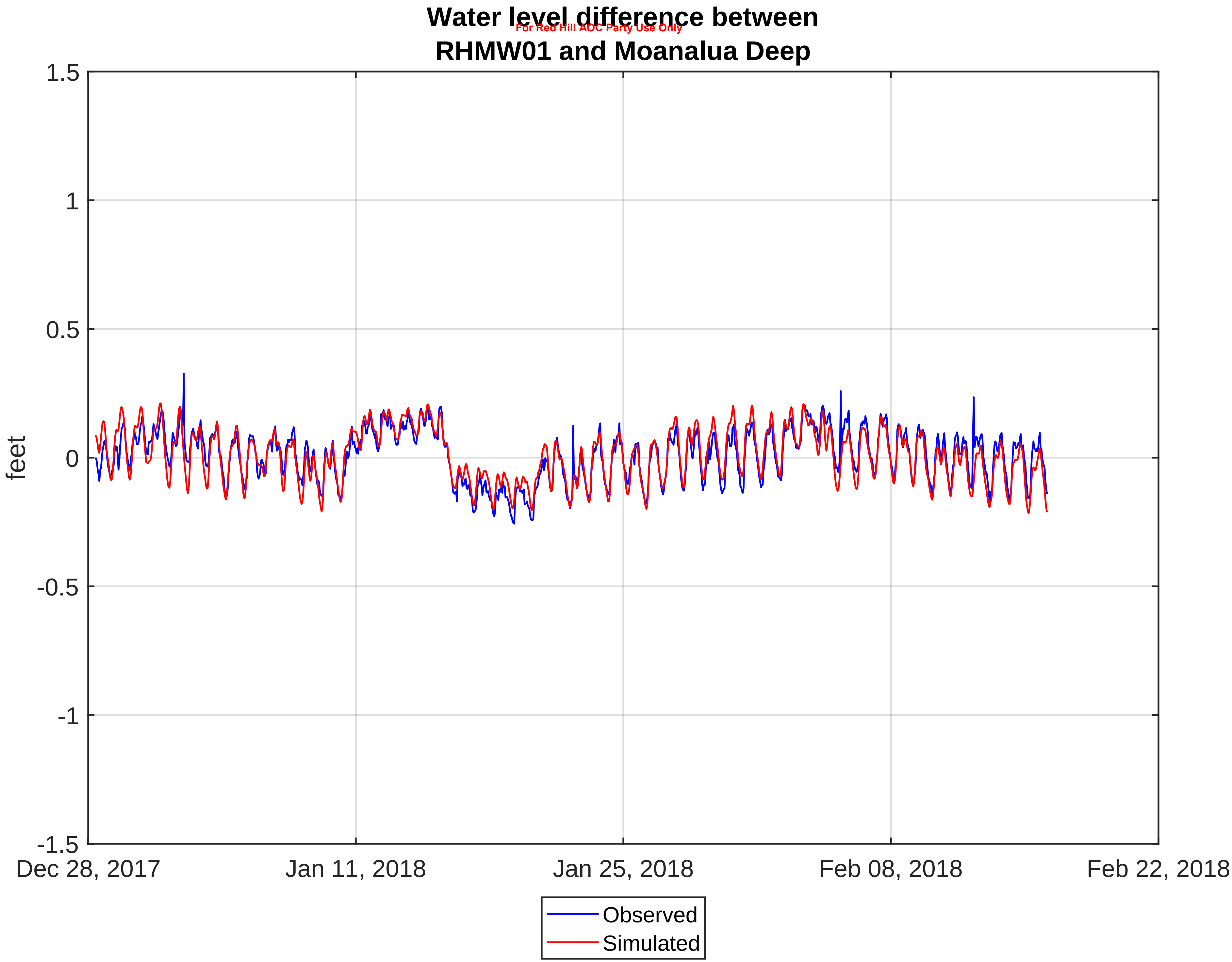


Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and RHMW11 Z5
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

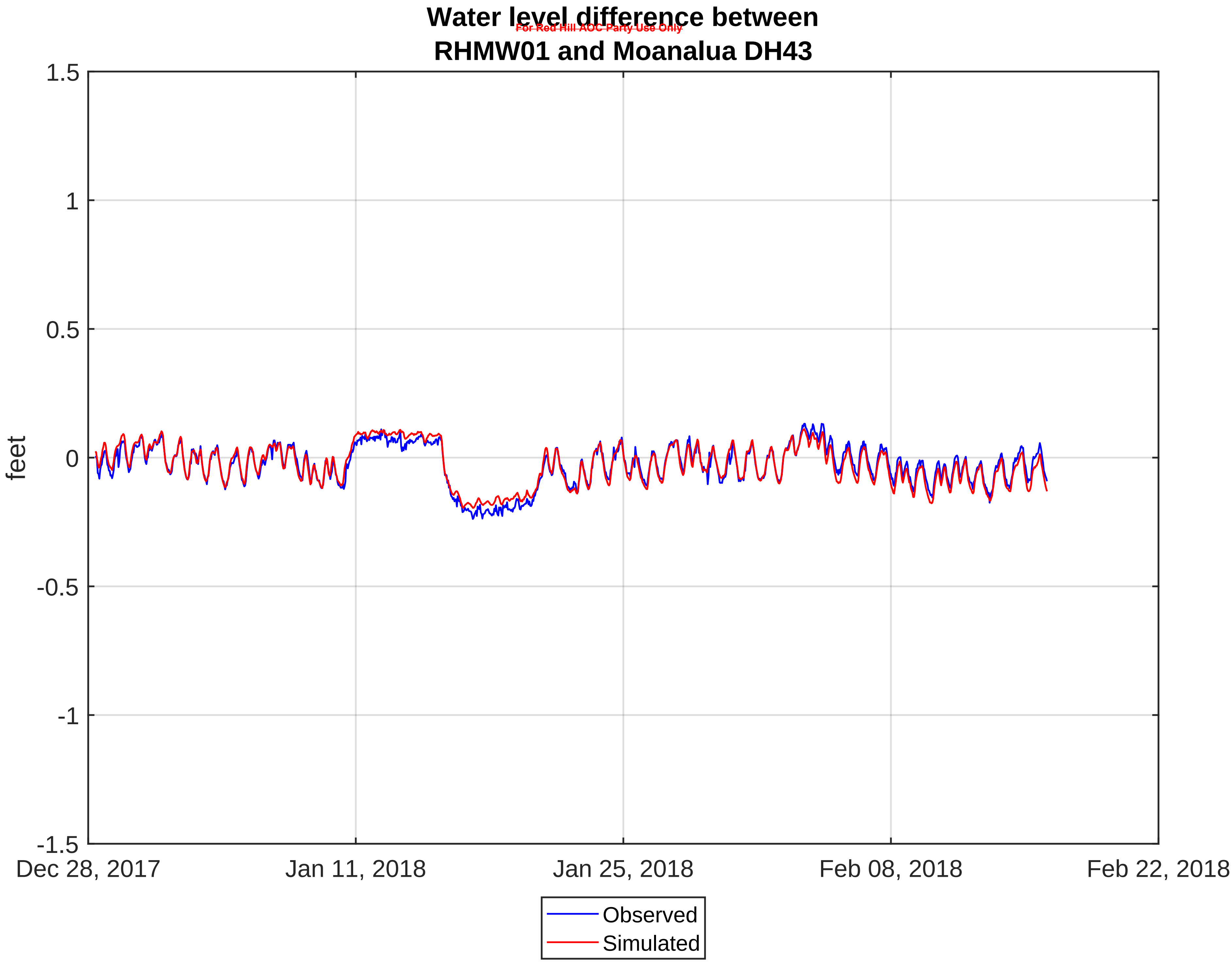

Water level difference between
For Red Hill AOC Party Use Only
OWDFMW01 and TAMC-MW2
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
RHMW01 and Manaiki T-24

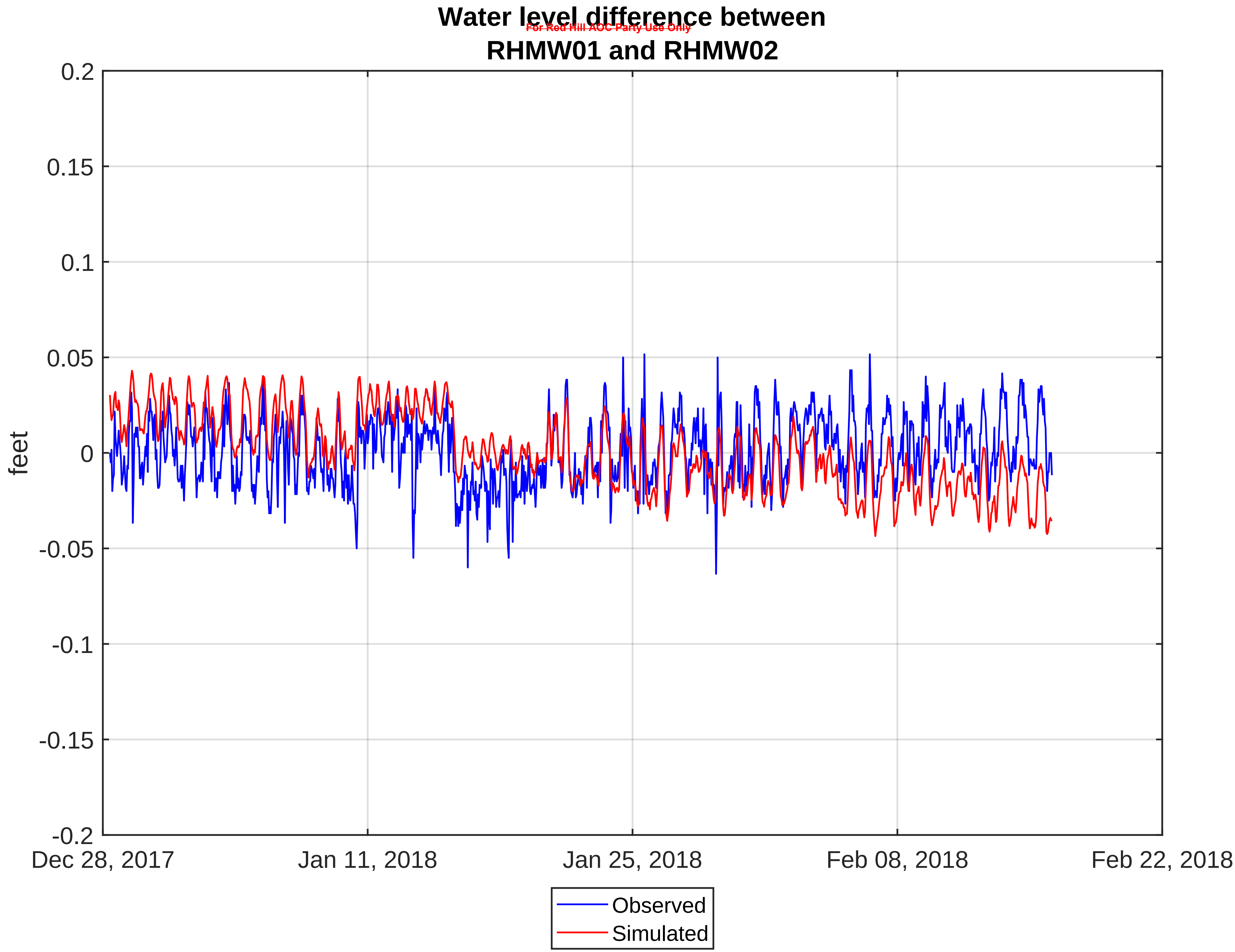




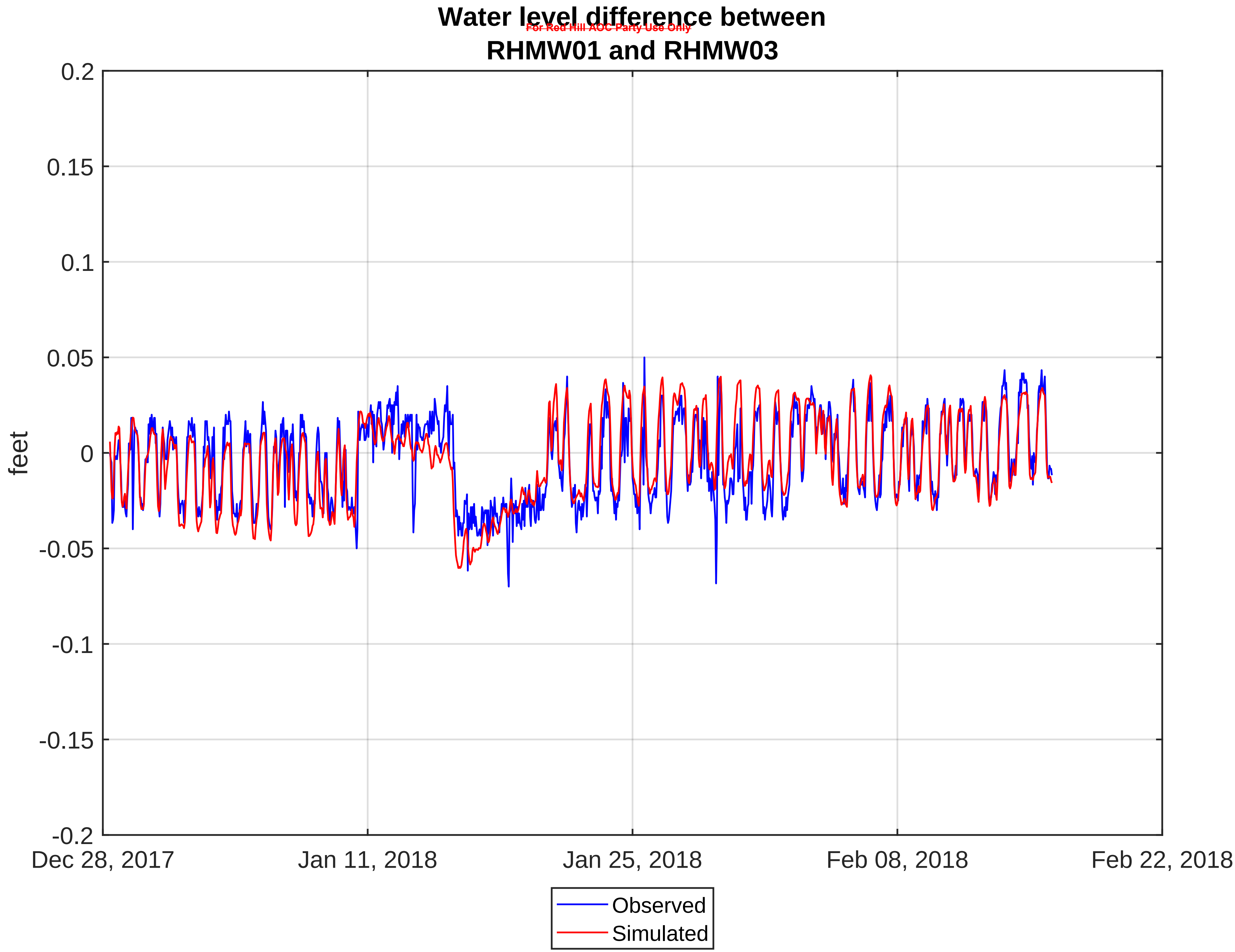
Water level difference between
RHMW01 and Moanalua Deep
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



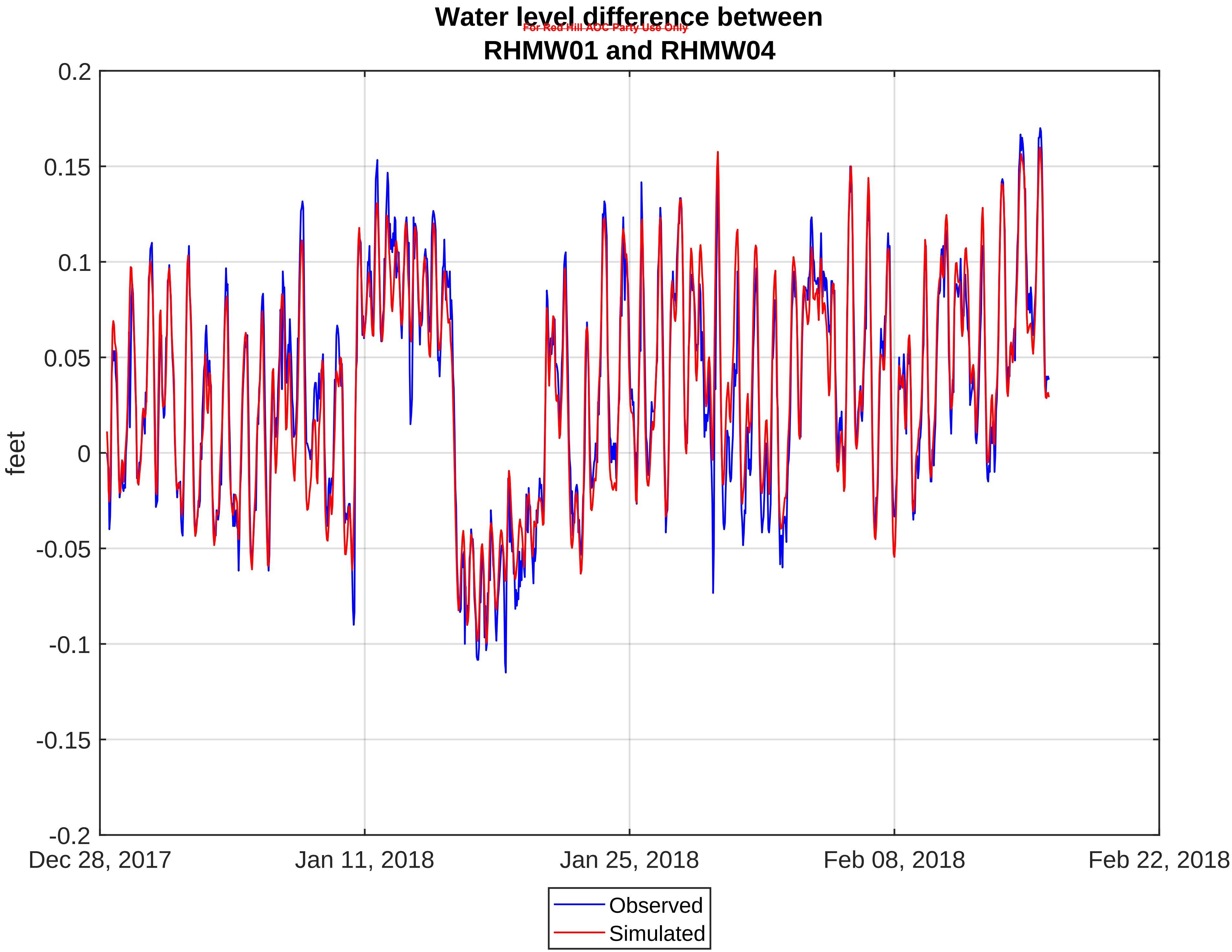
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and Moanalua DH43
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



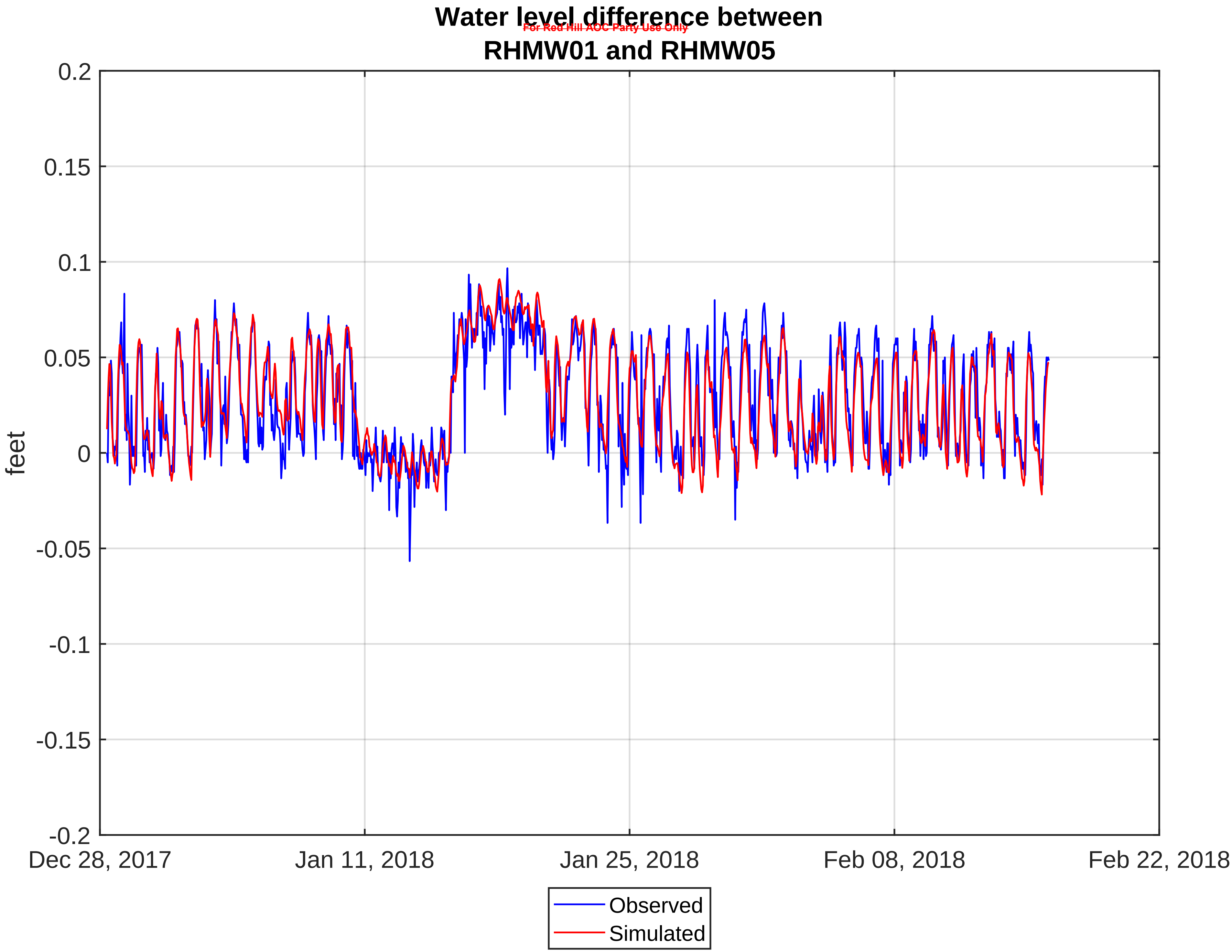
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW02
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



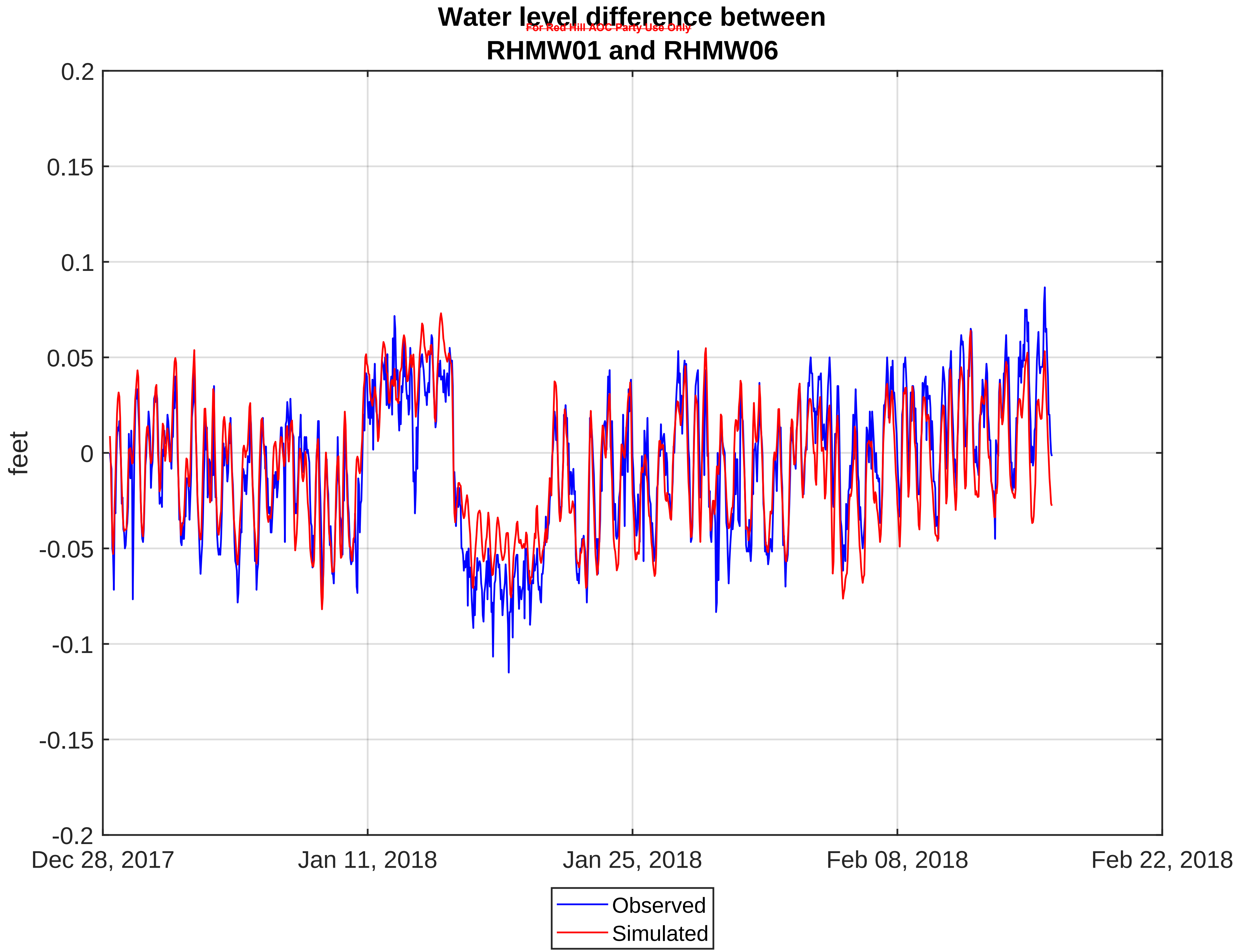
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW03
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



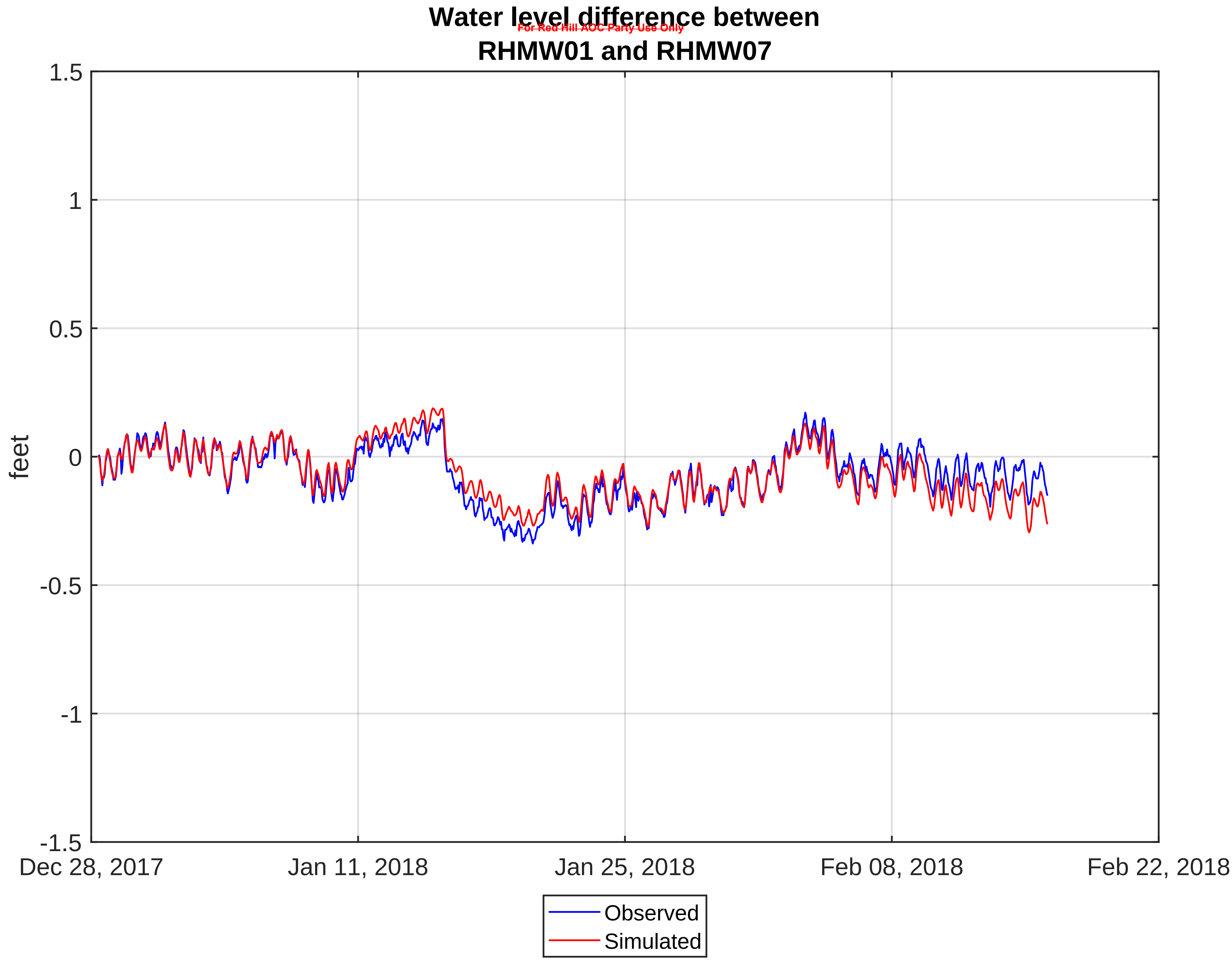
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW04
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



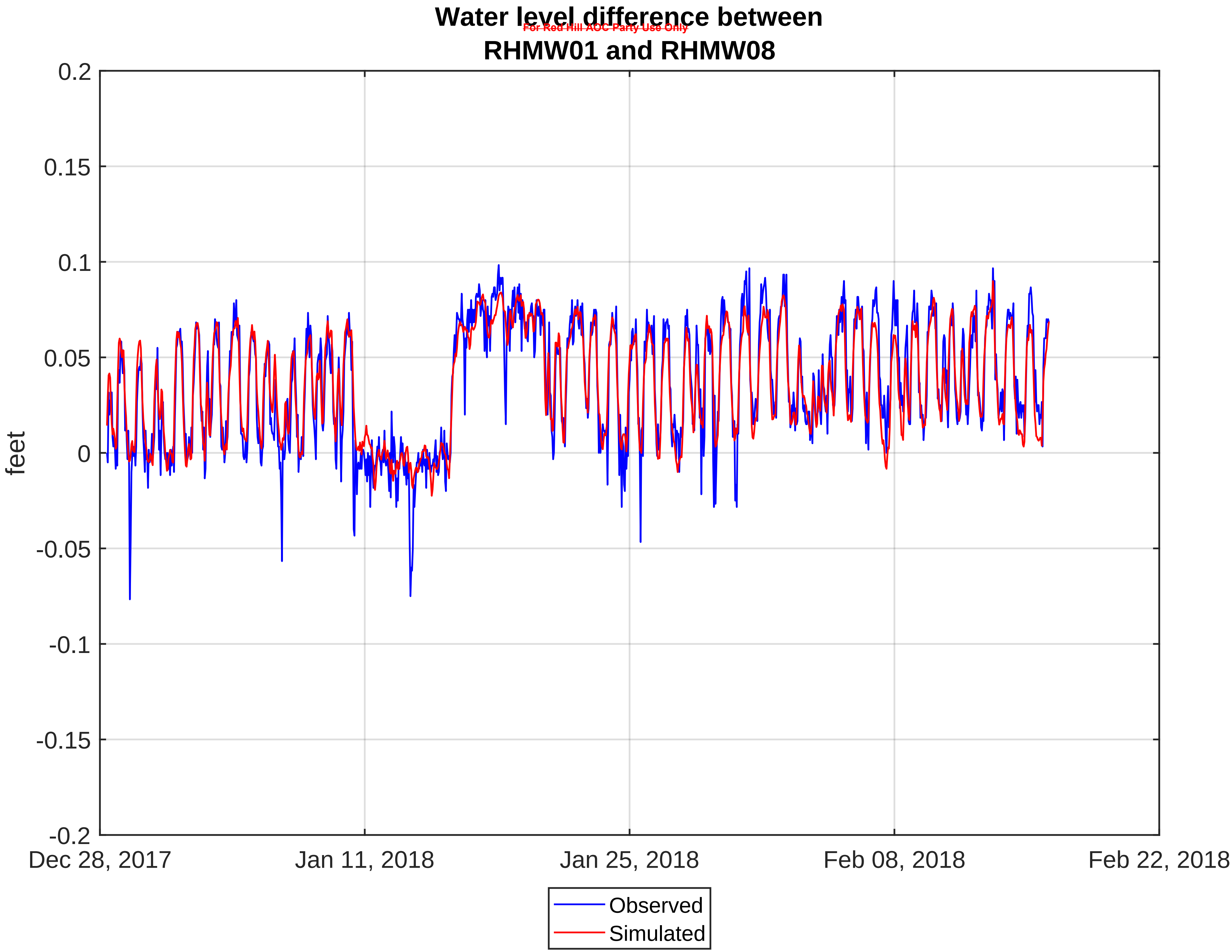
Water level difference between
RHMW01 and RHMW05
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

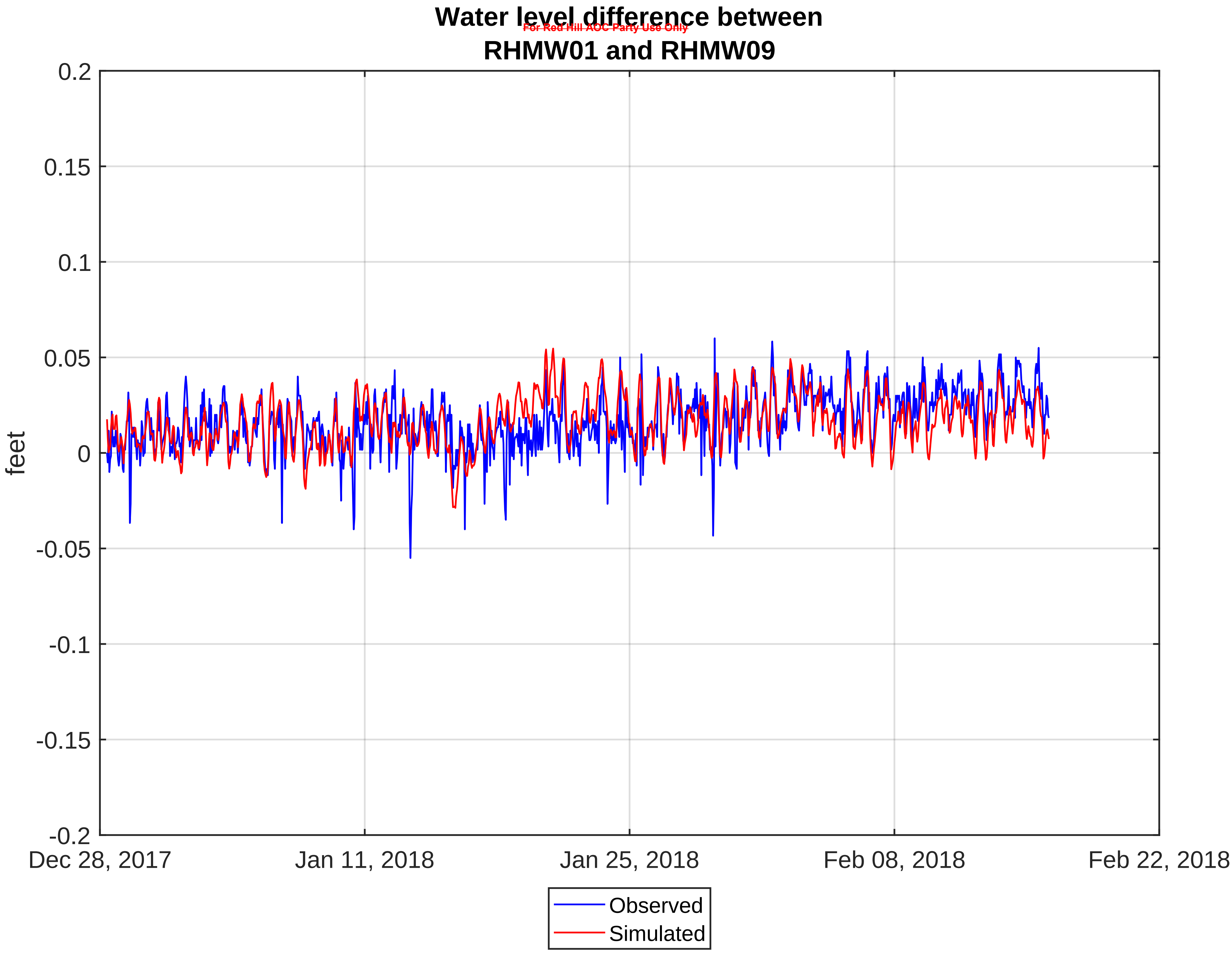


Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW06
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



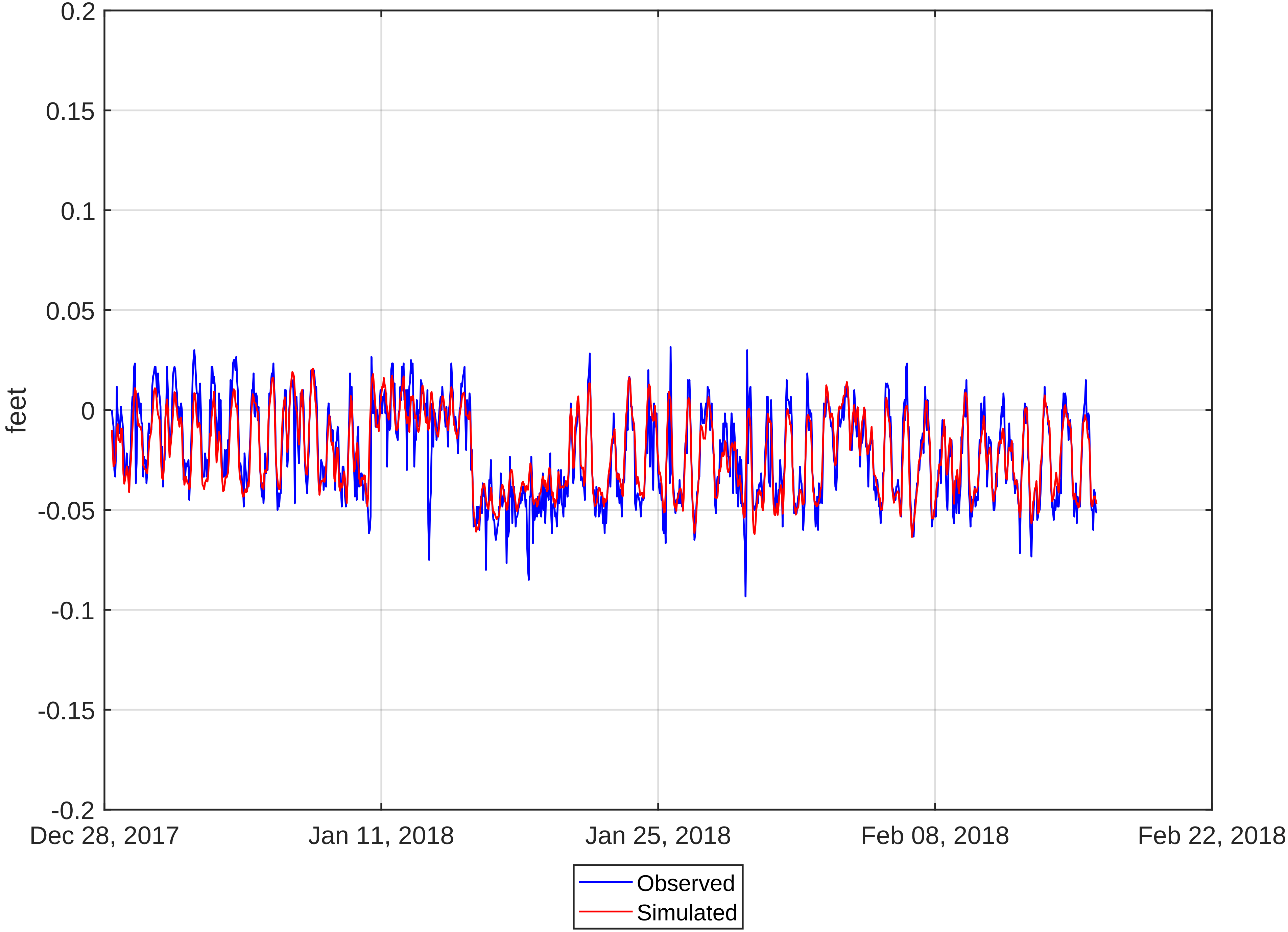
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW07
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

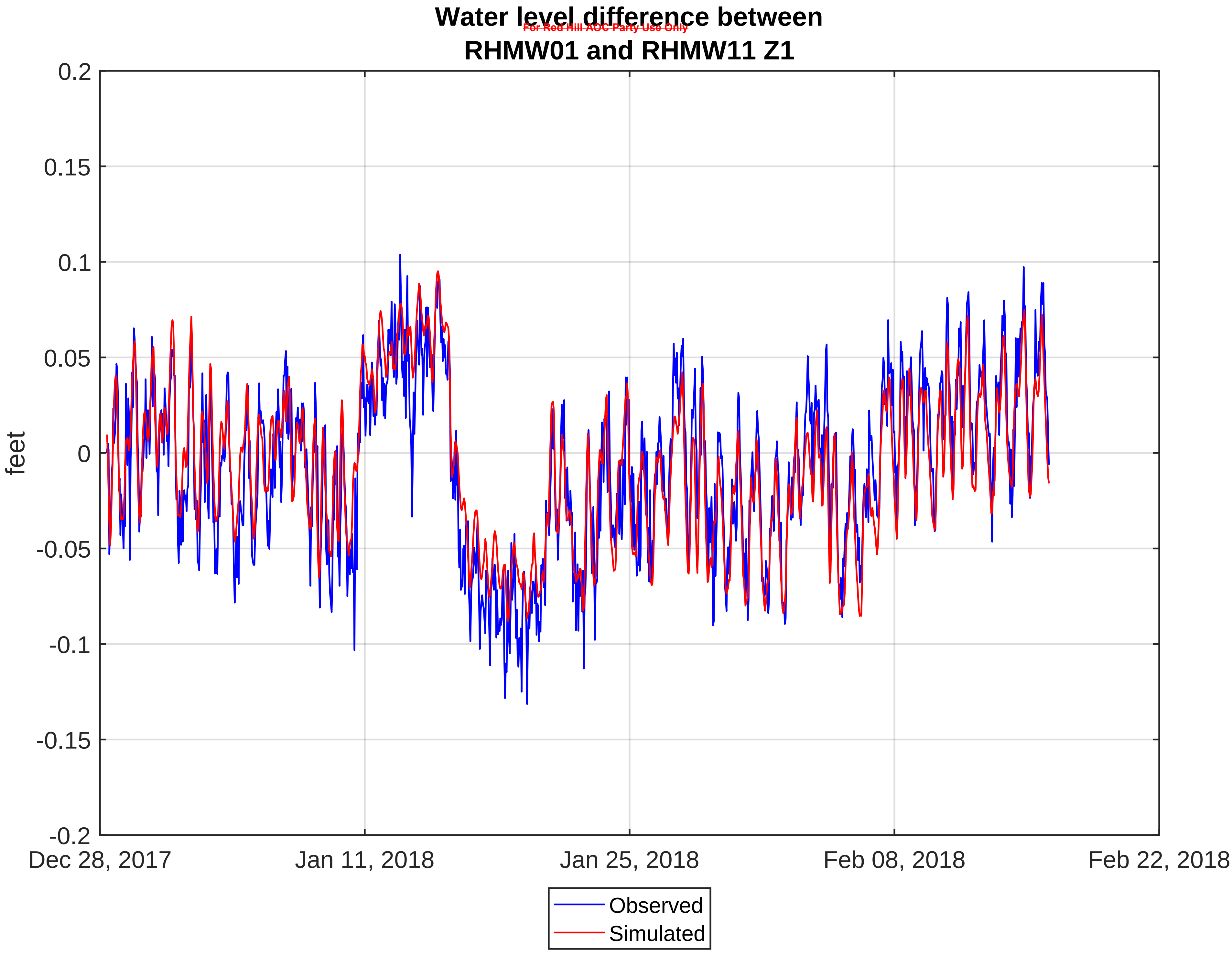

Water level difference between
RHMW01 and RHMW08
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

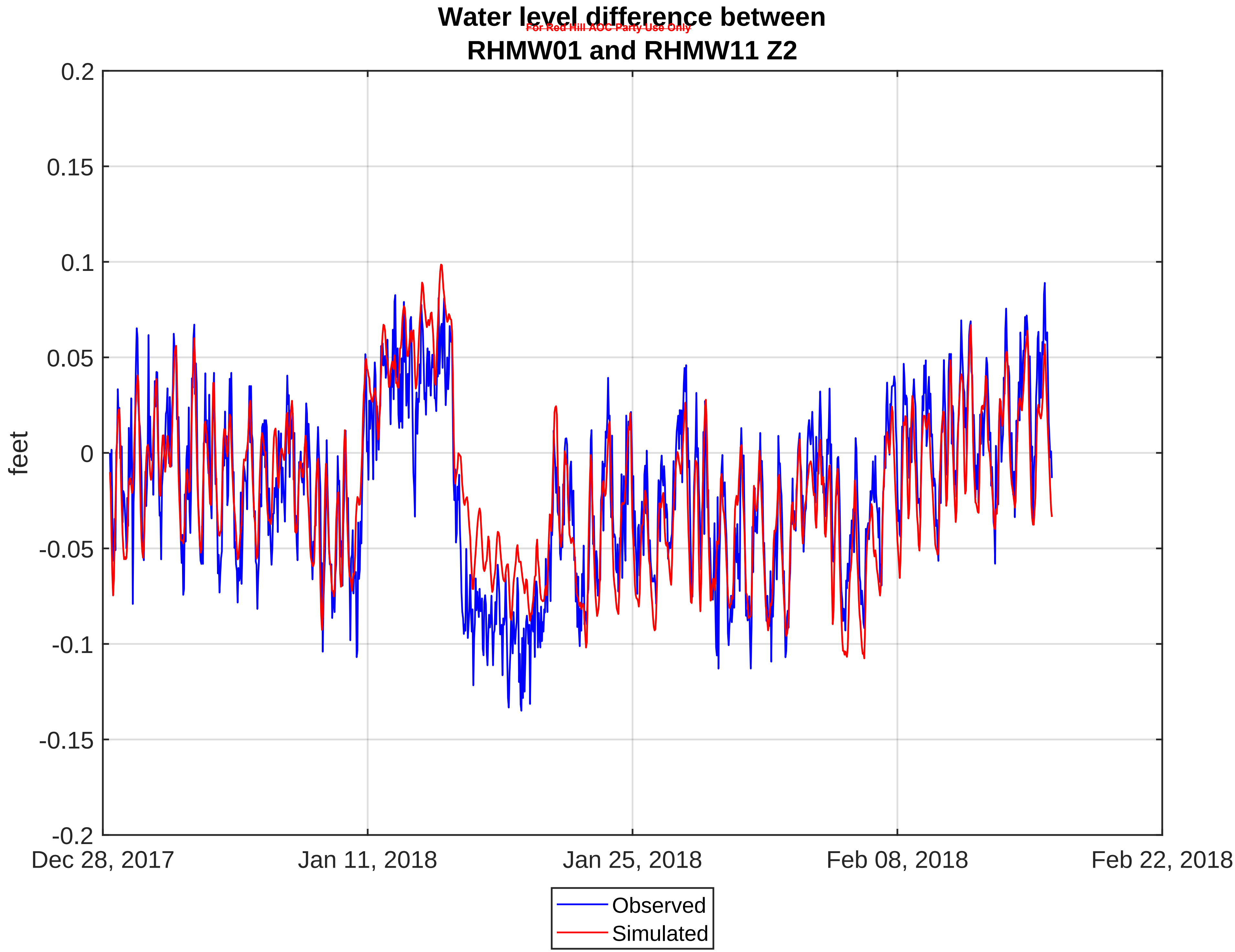


Water level difference between
RHMW01 and RHMW09
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

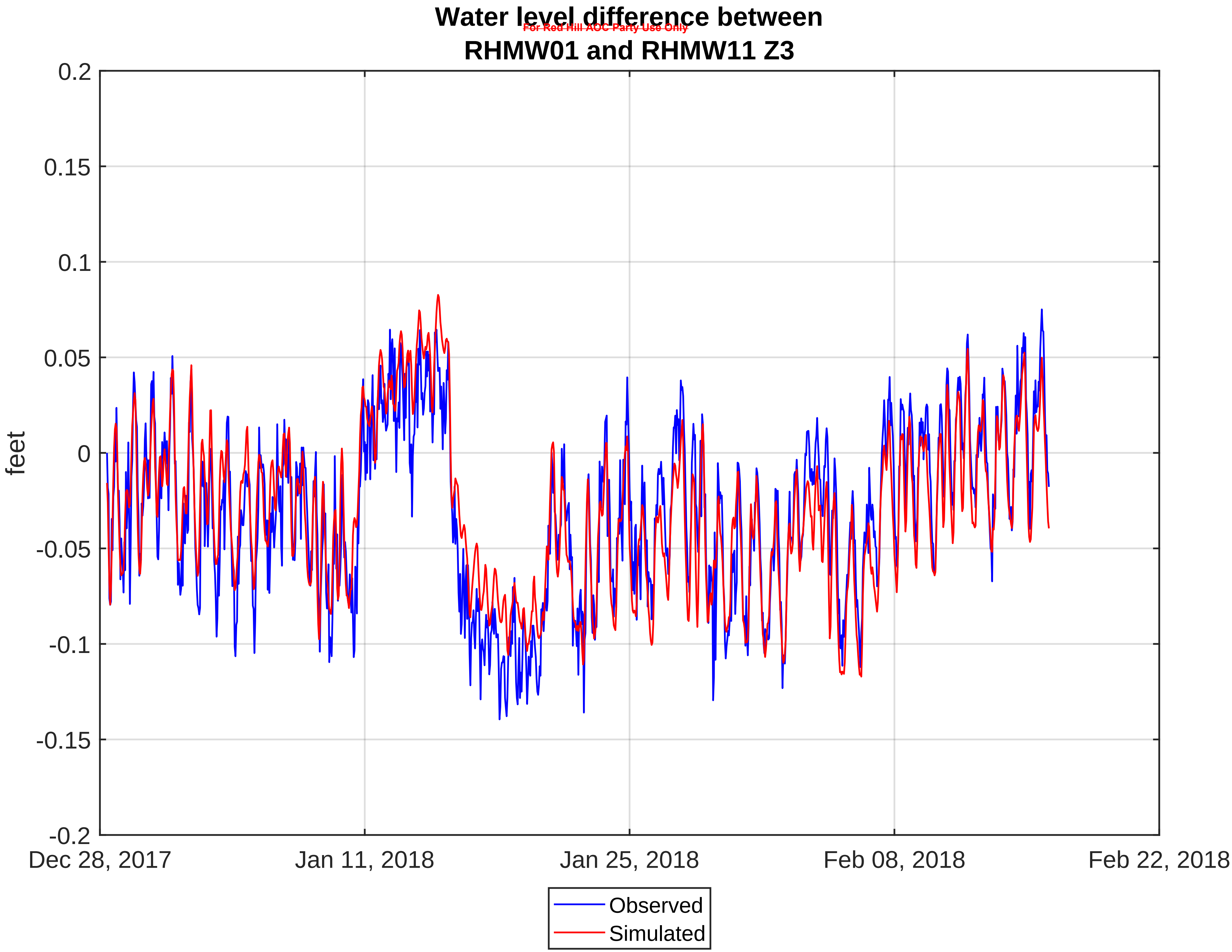
Water level difference between RHMW01 and RHMW10




Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW11 Z1
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

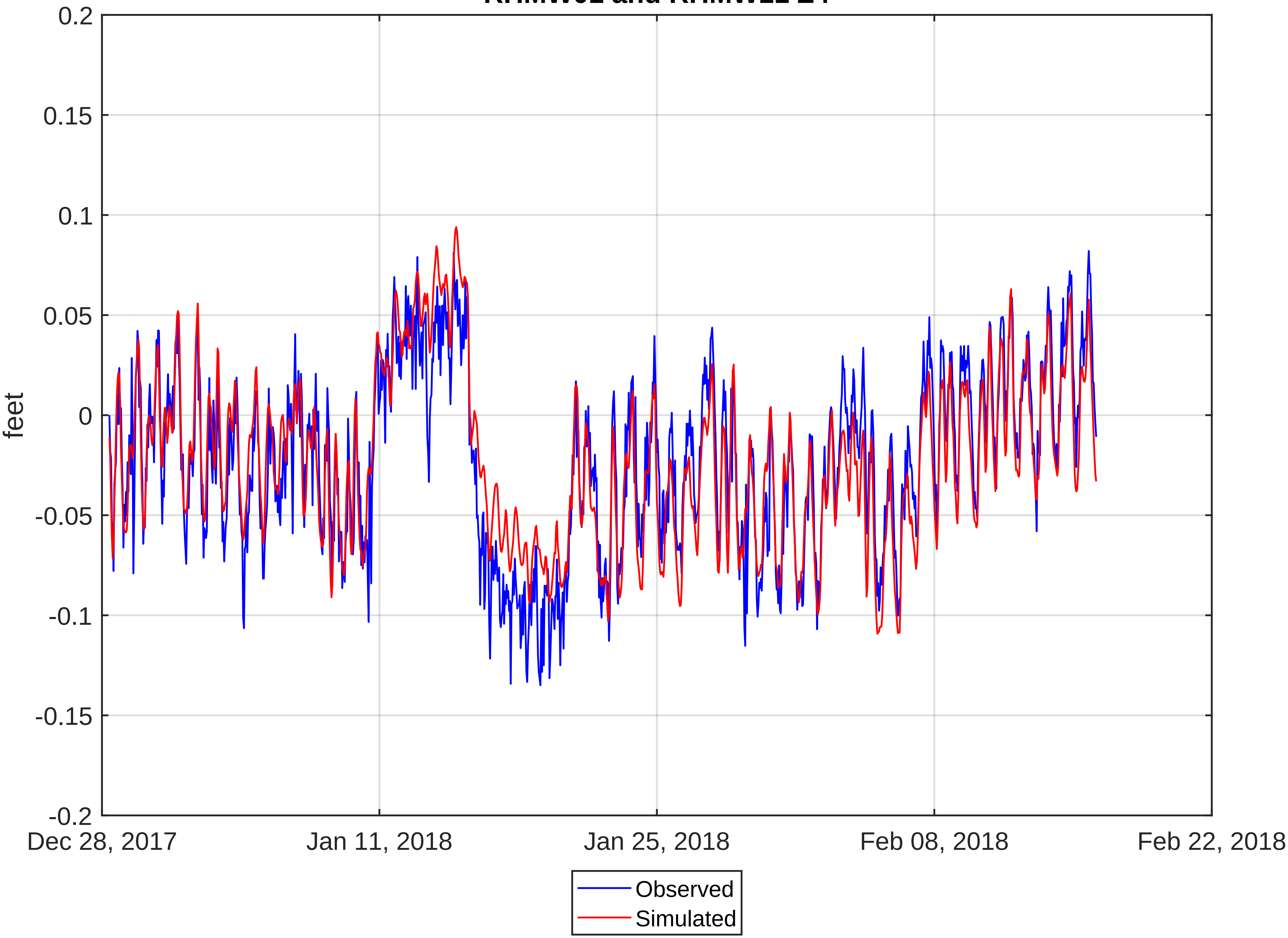


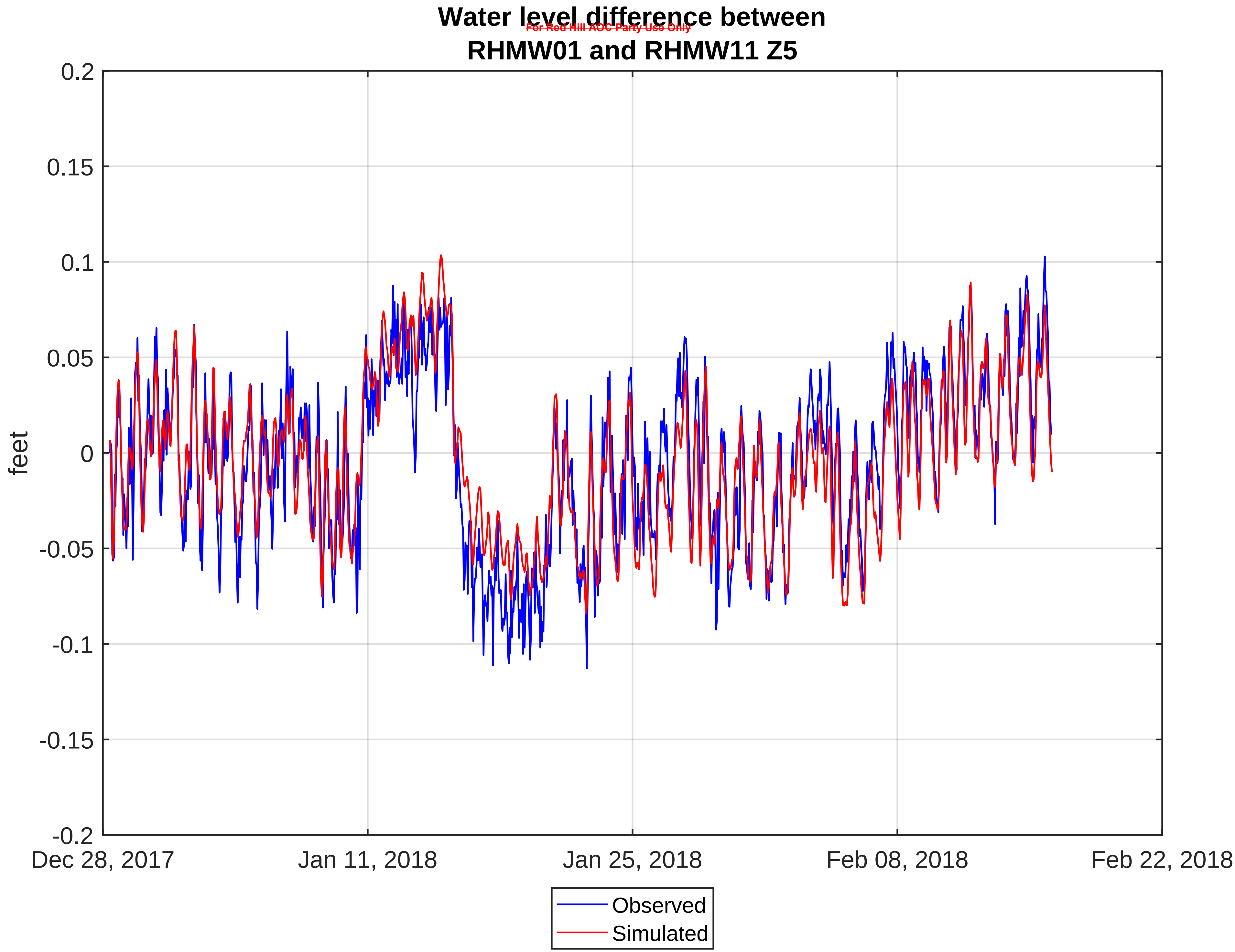
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW11 Z2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



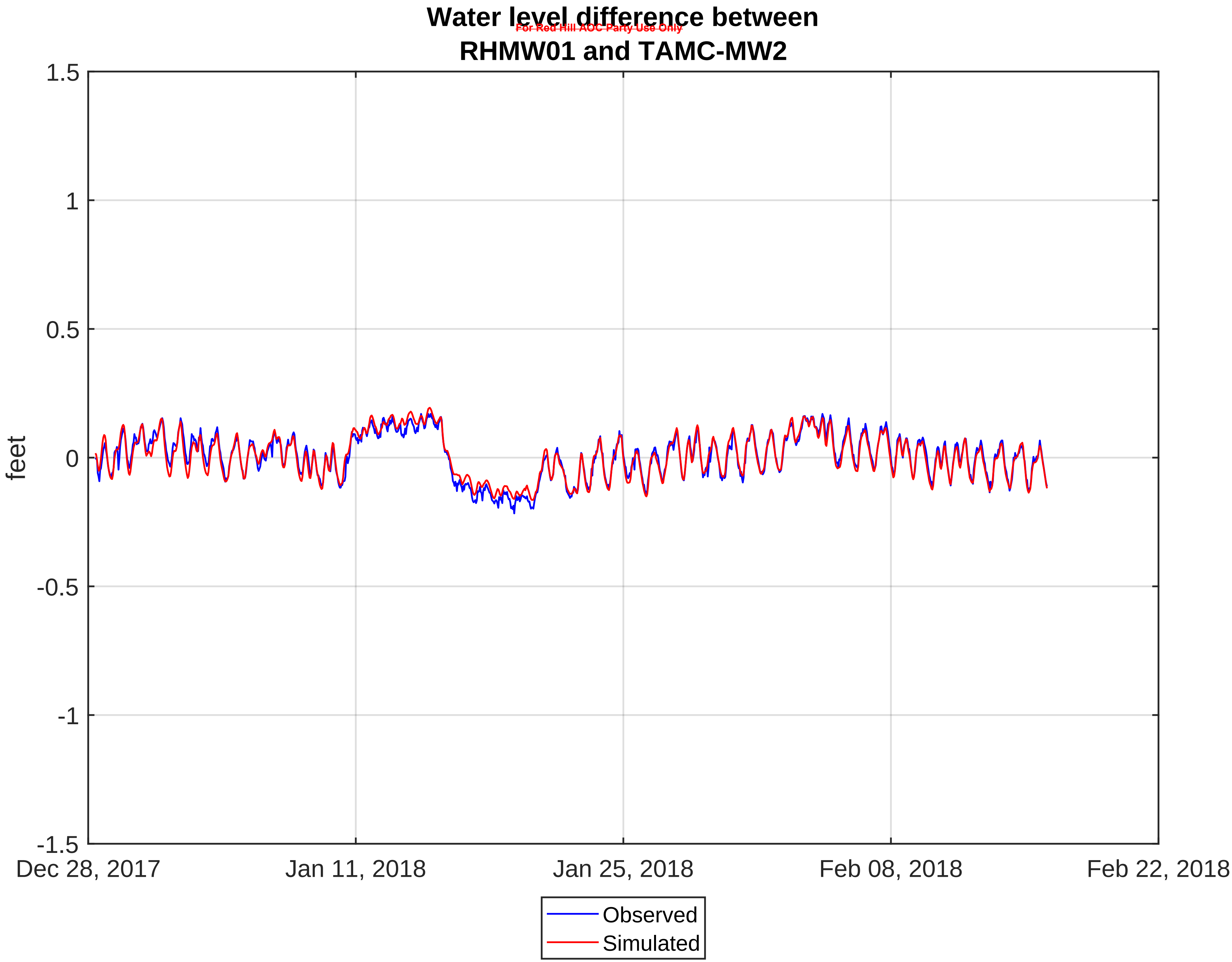
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW11 Z3
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
RHMW01 and RHMW11 Z4





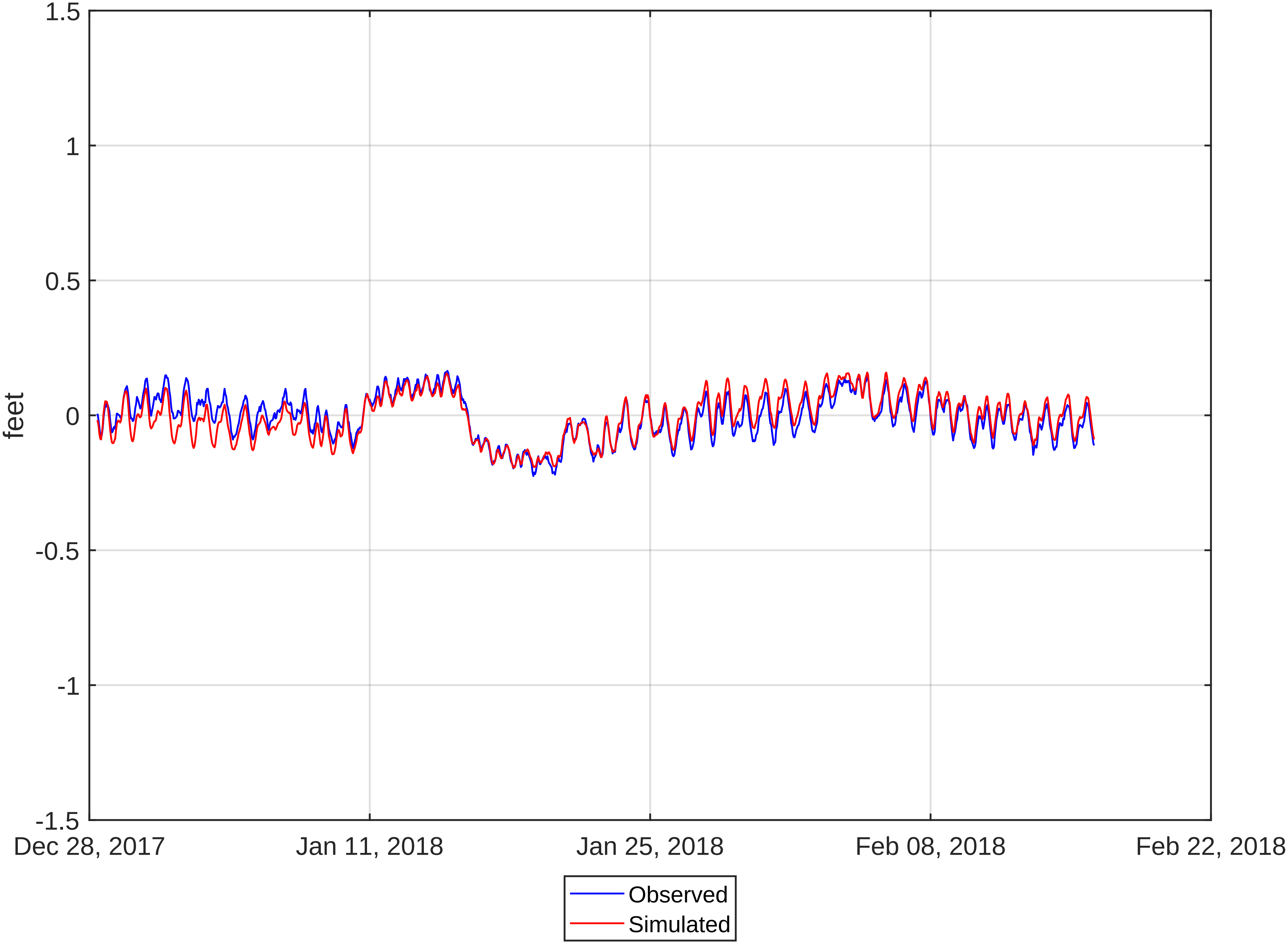
Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

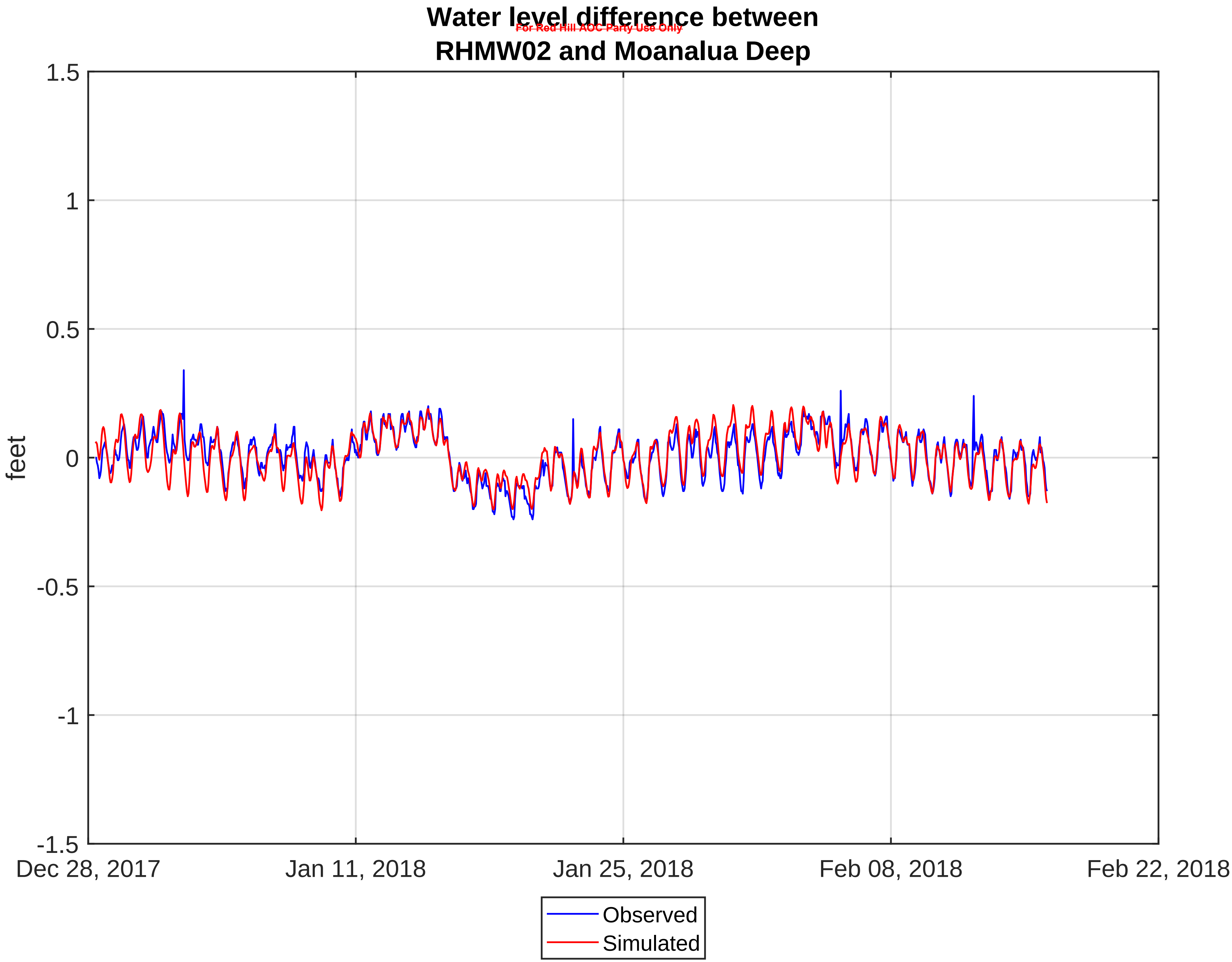


Water level difference between
For Red Hill AOC Party Use Only
RHMW01 and TAMC-MW2
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

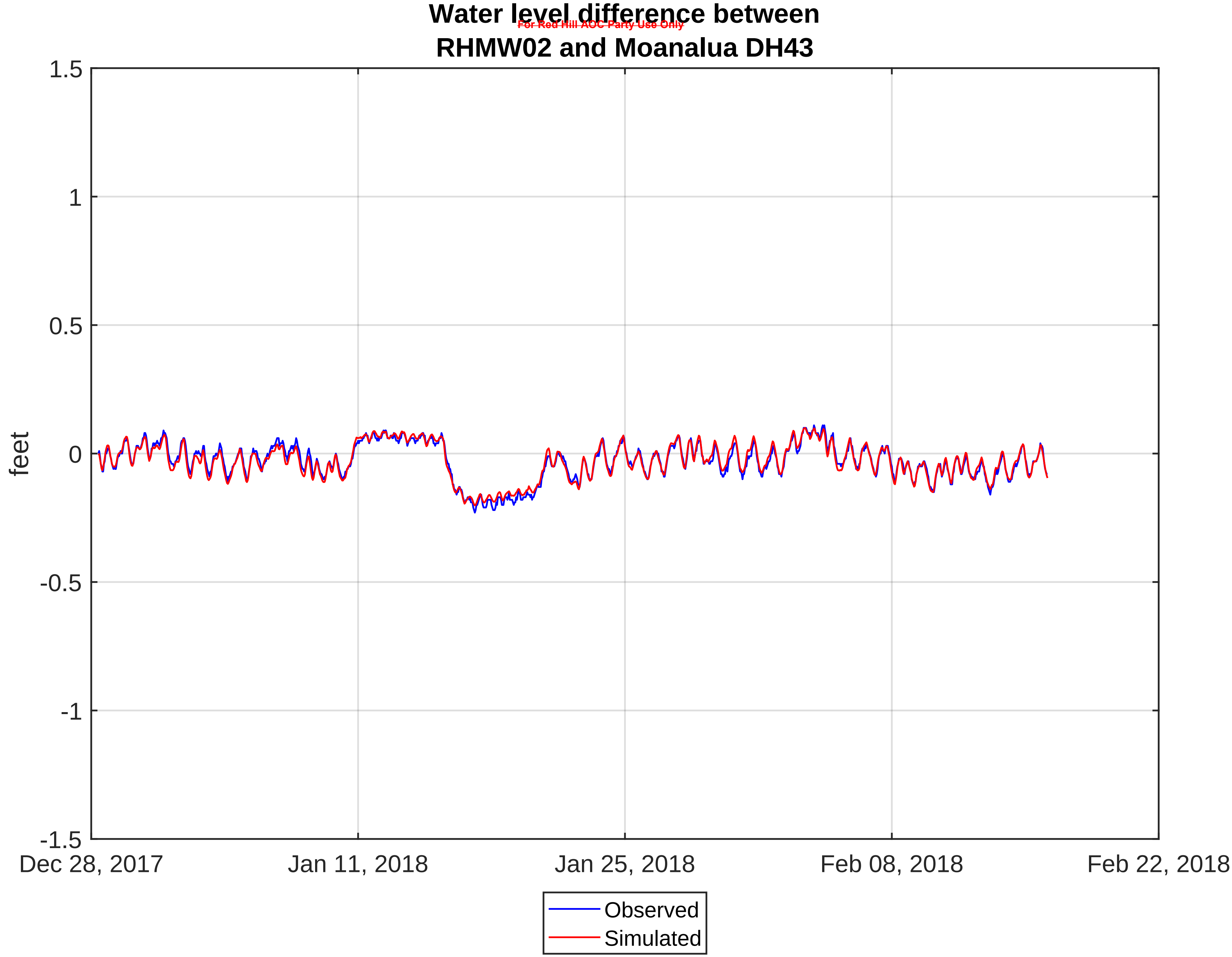
Water level difference between

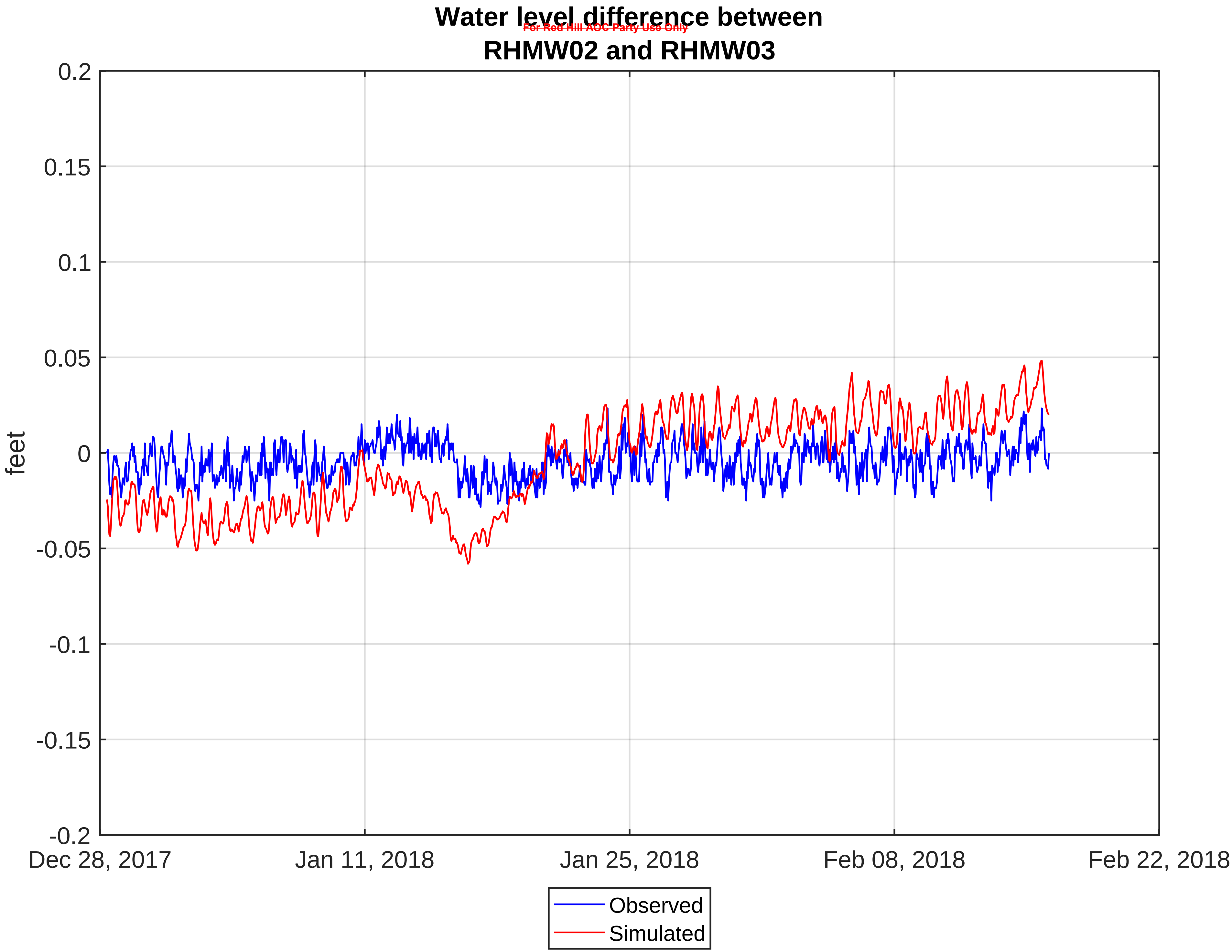
RHMW02 and Manaiki T-24



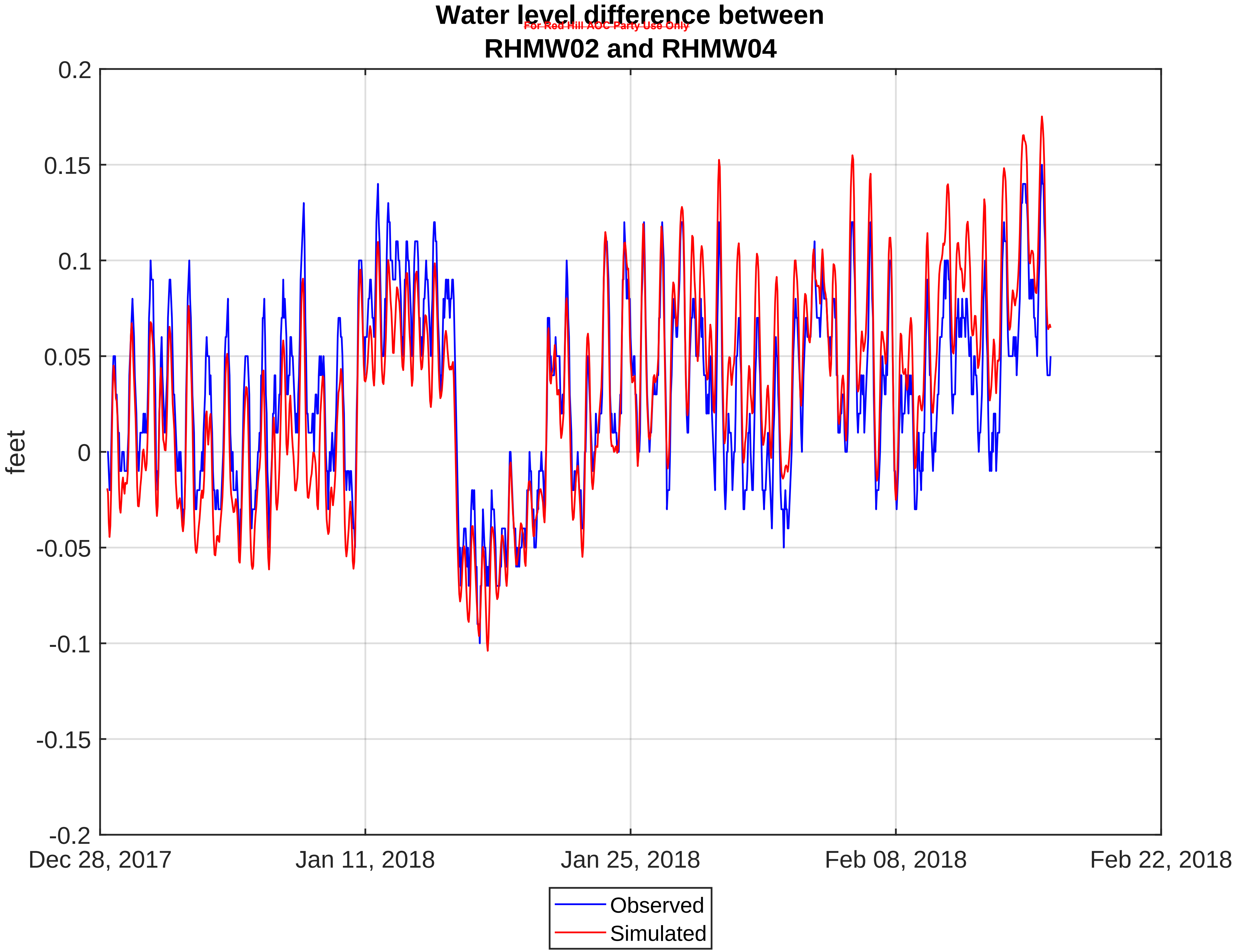


Water level difference between
RHMW02 and Moanalua Deep
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

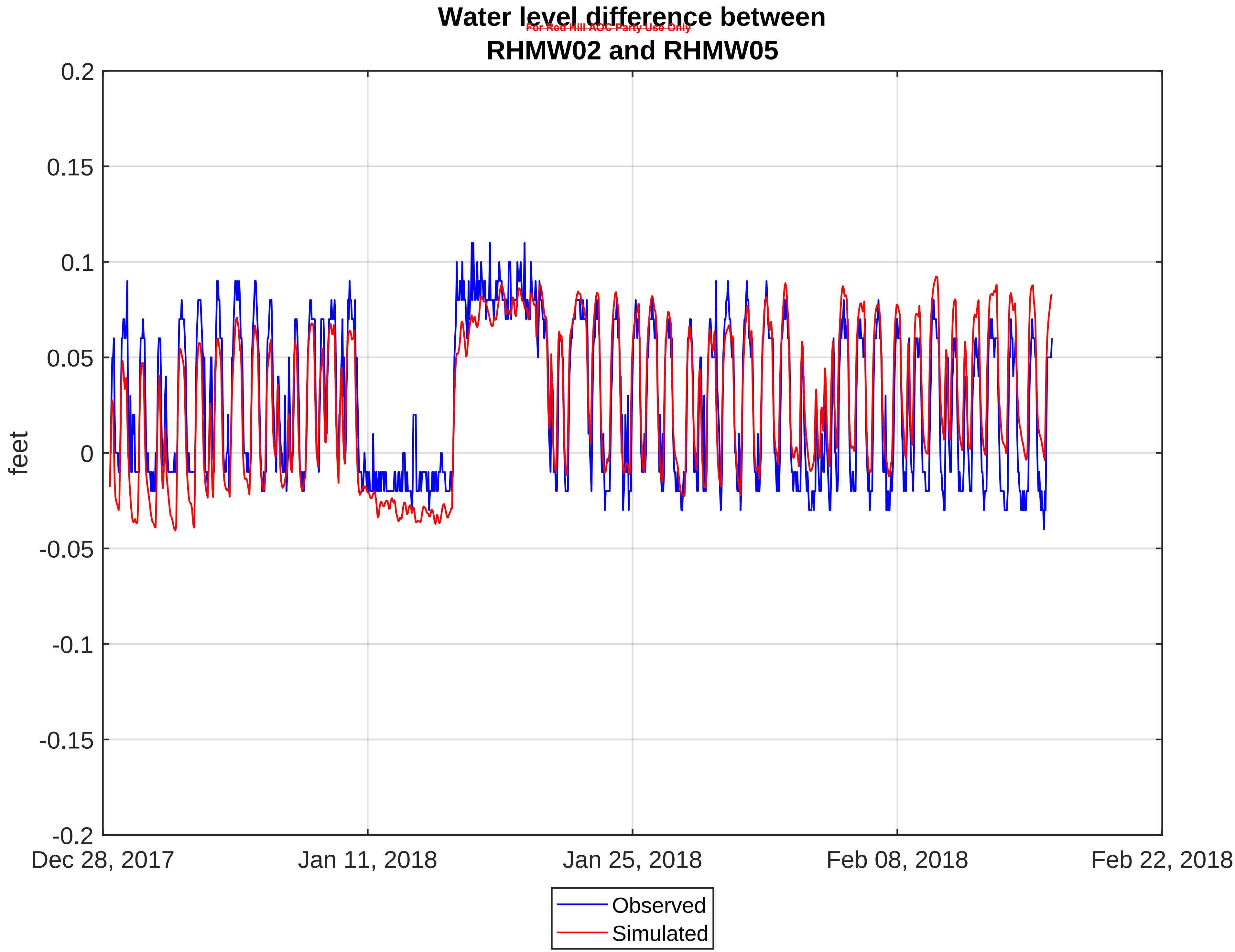

Water level difference between
RHMW02 and Moanalua DH43
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



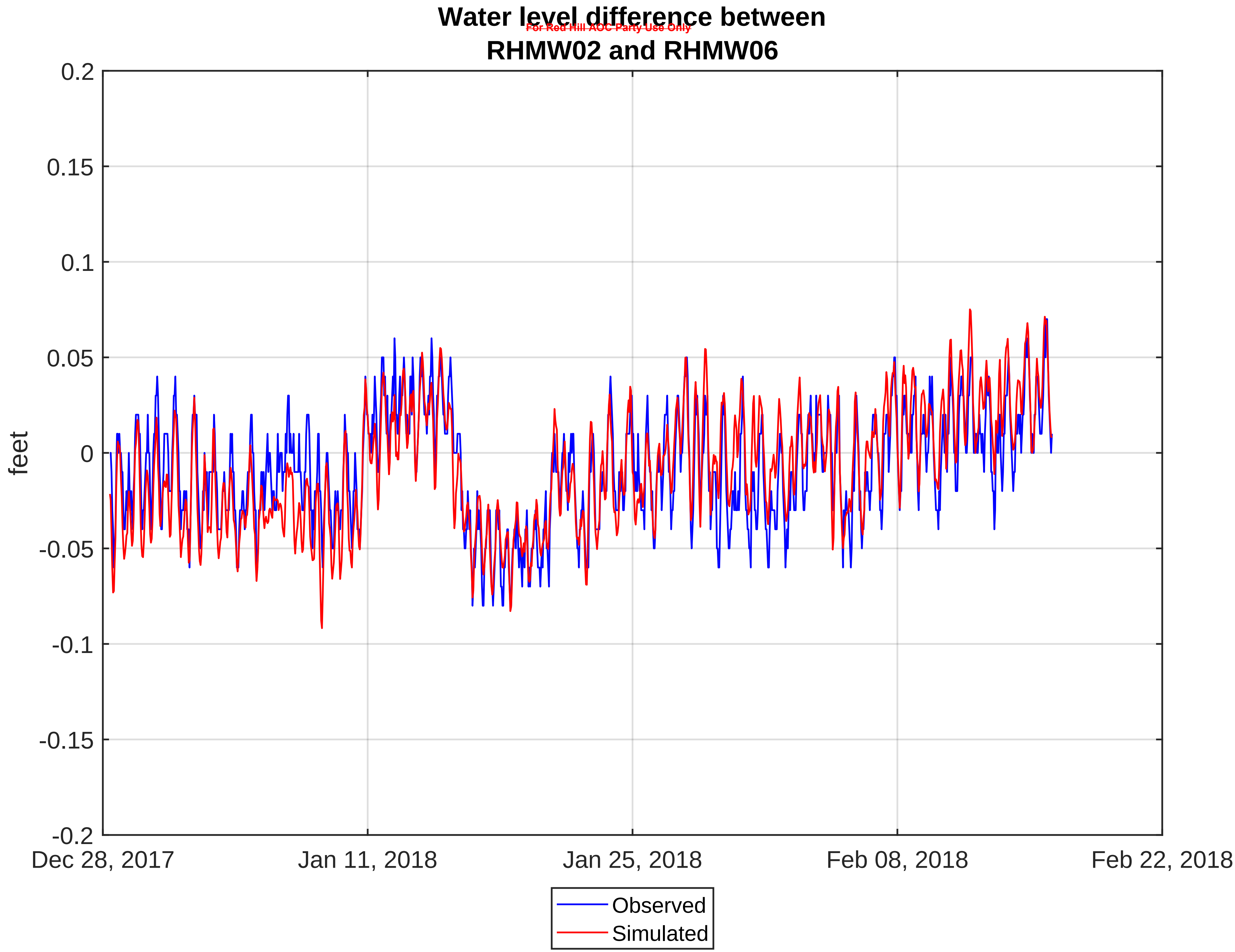
Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW03
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
RHMW02 and RHMW04
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

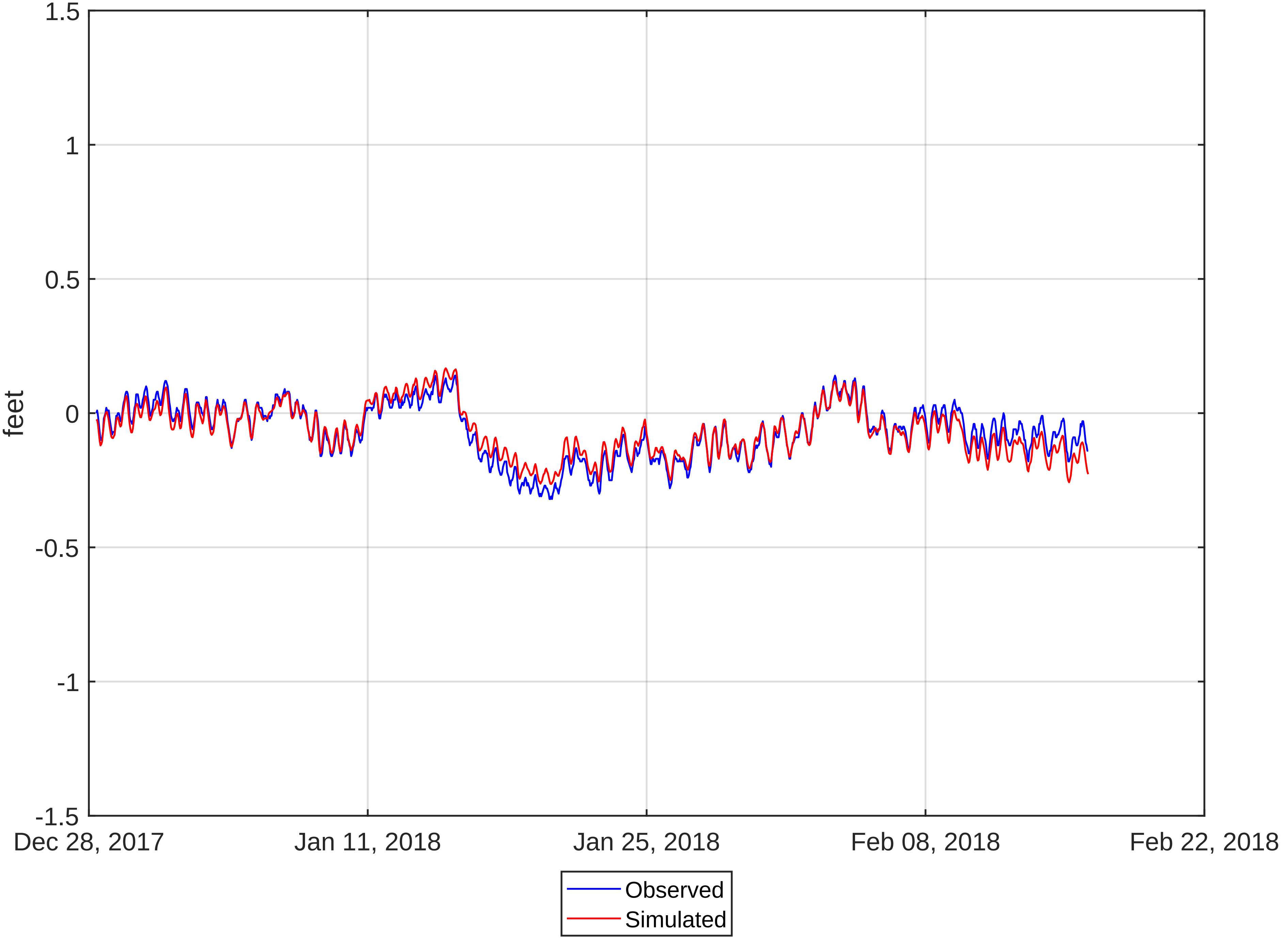


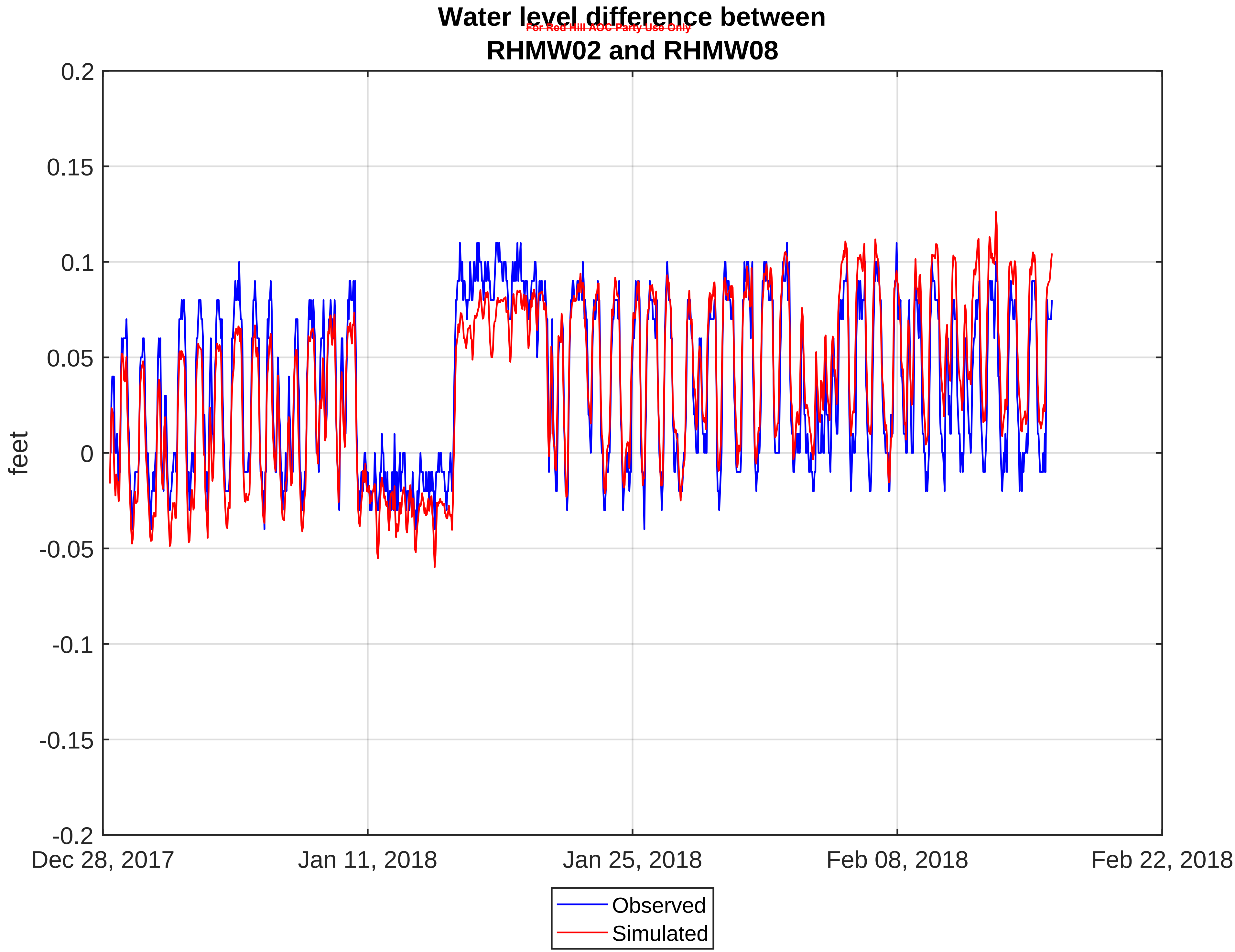
Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW05
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



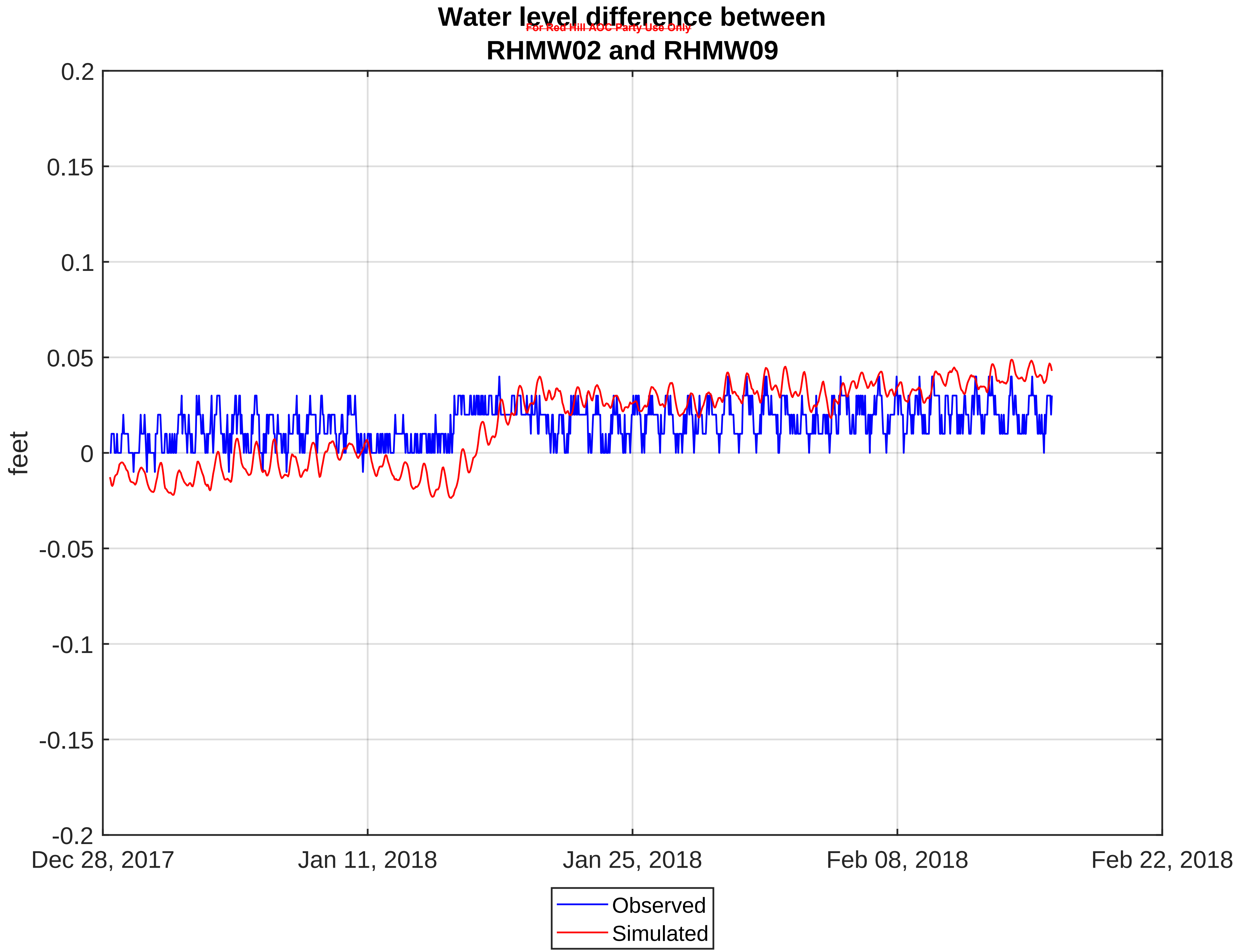
Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW06
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW02 and RHMW07

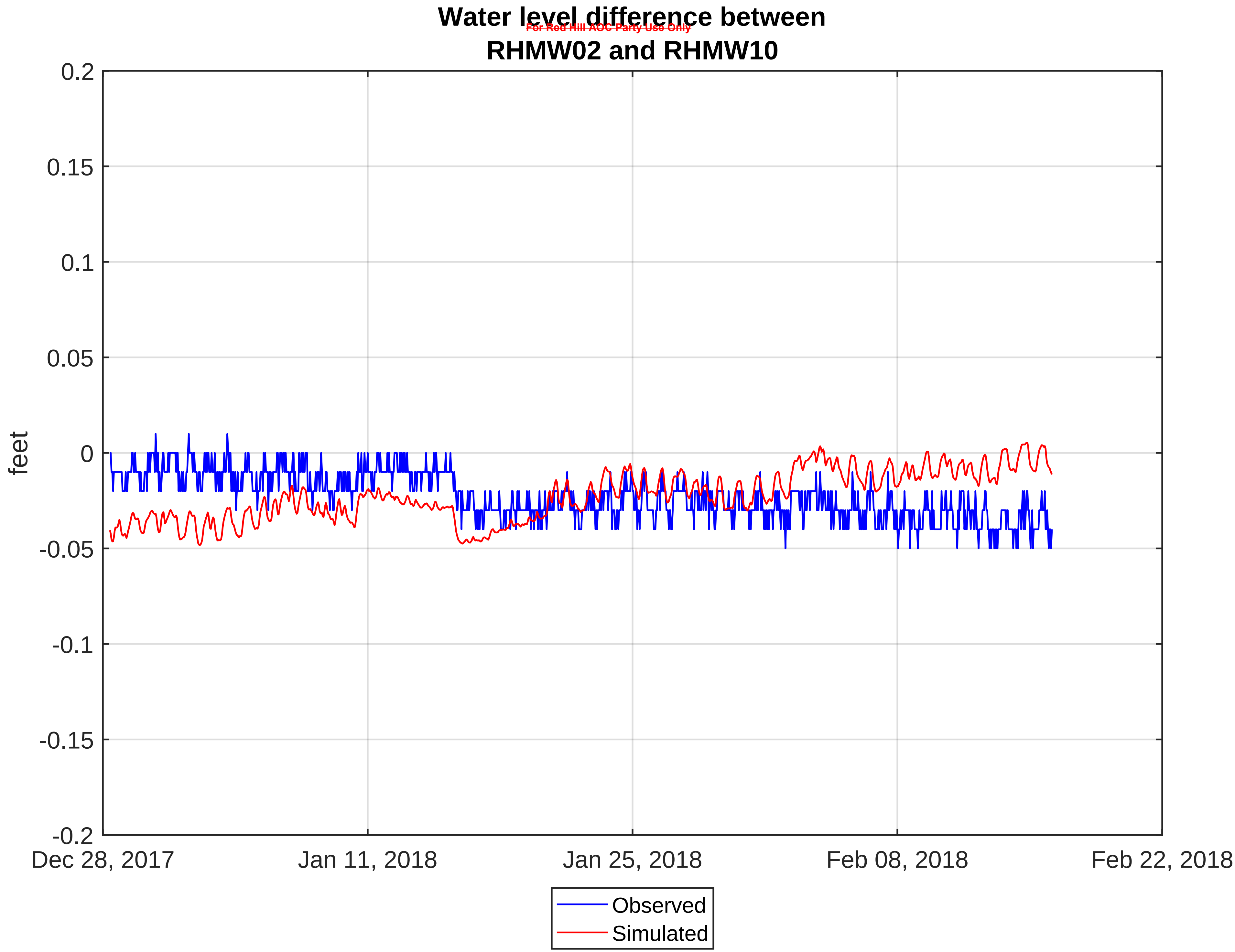




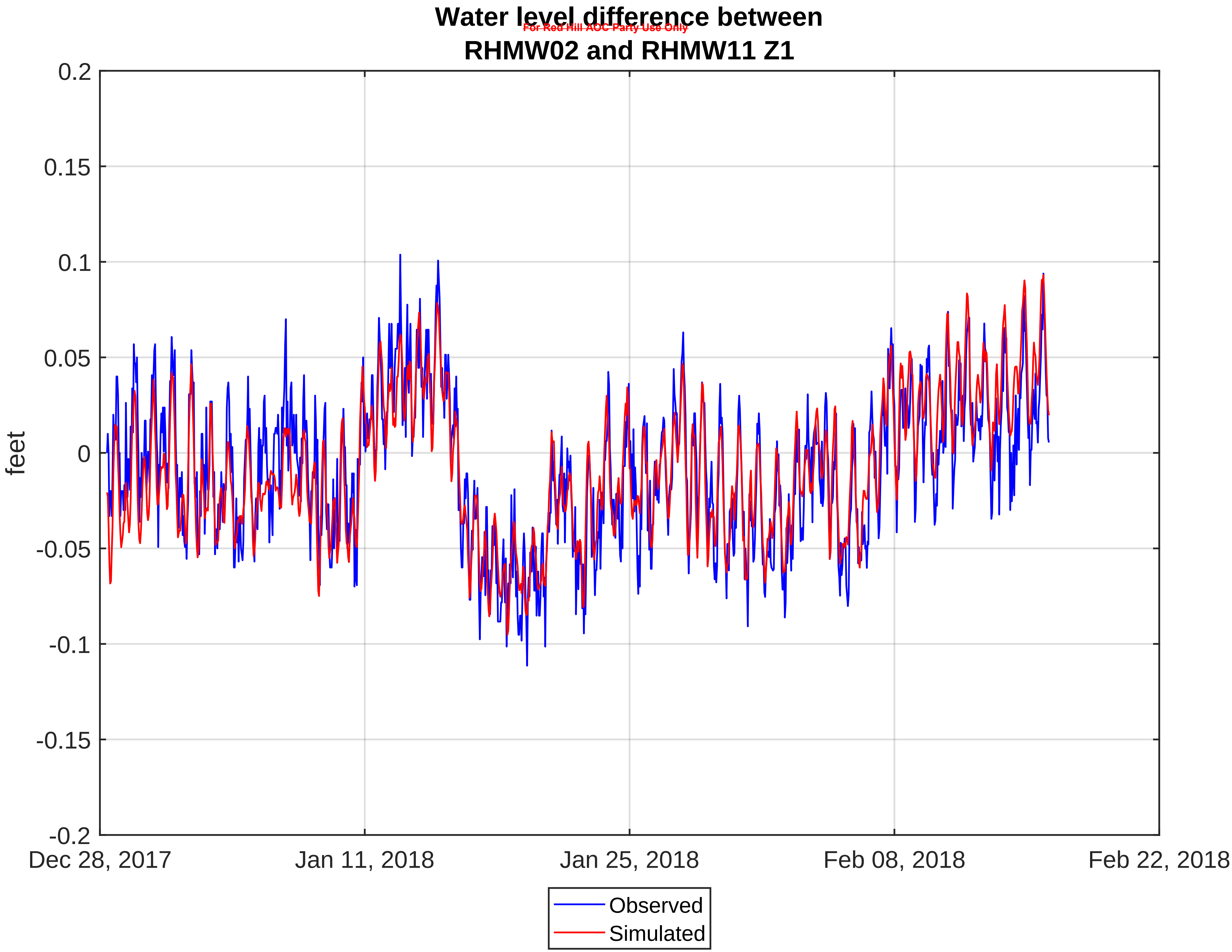
Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW08
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



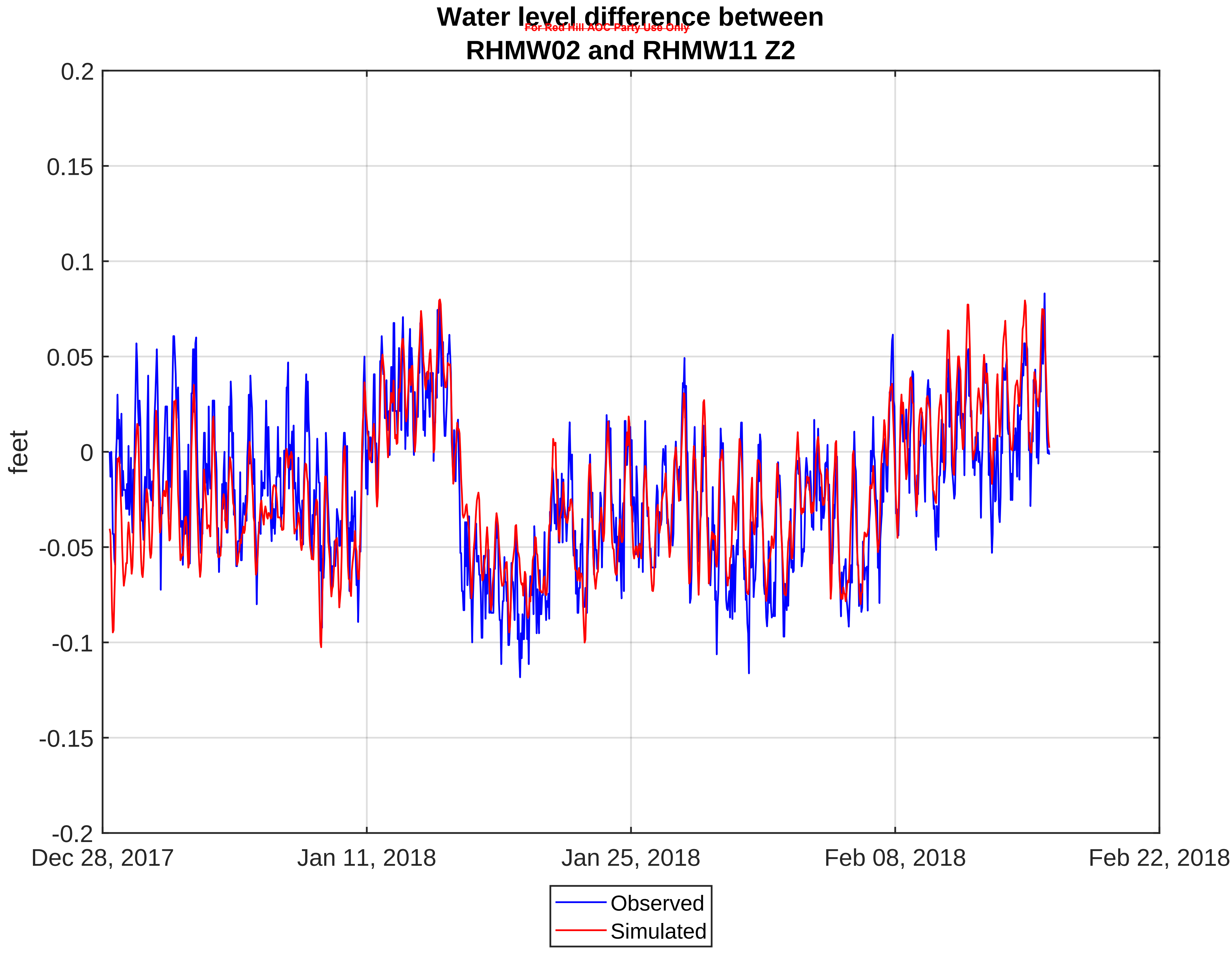
Water level difference between
RHMW02 and RHMW09
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

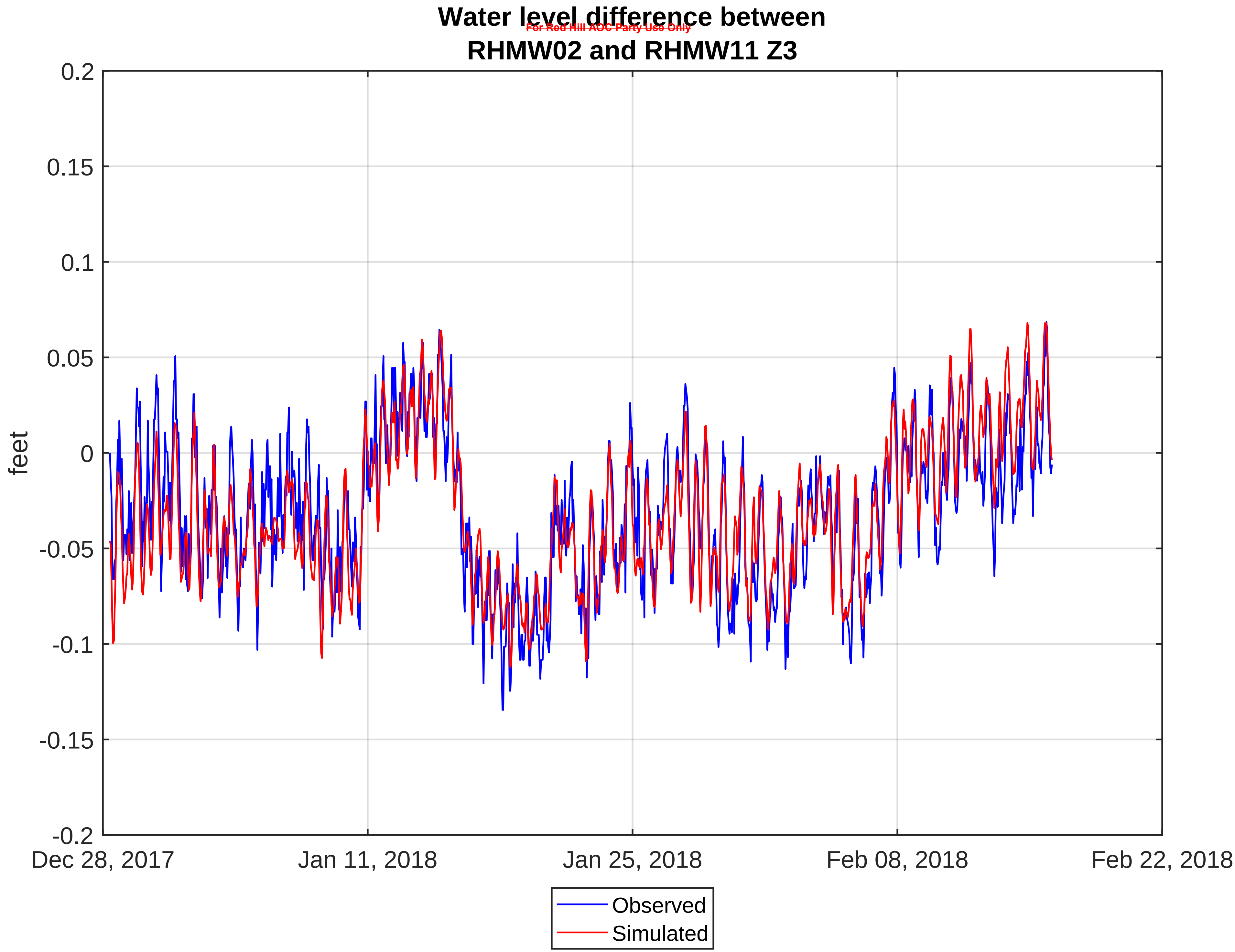


Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW10
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

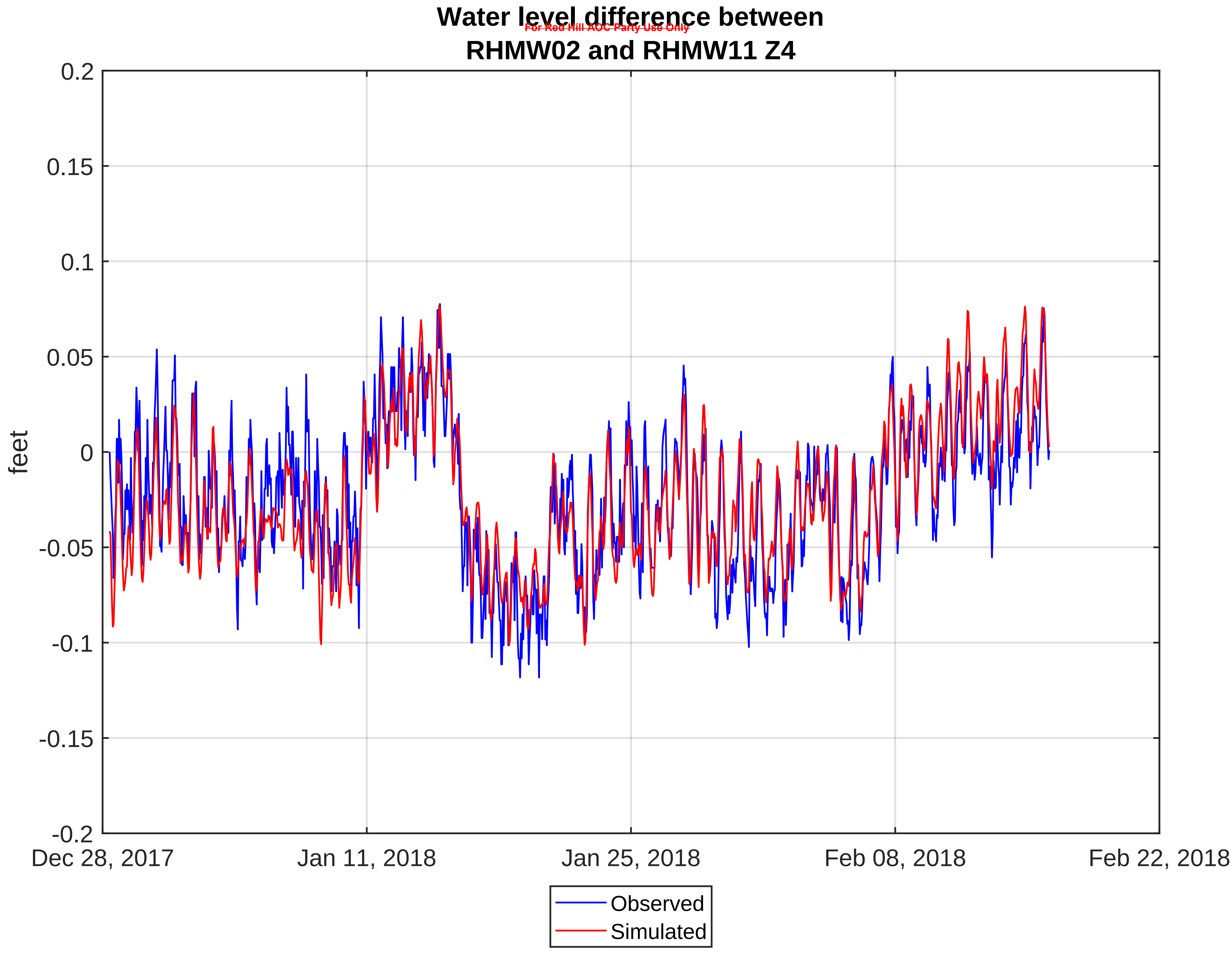


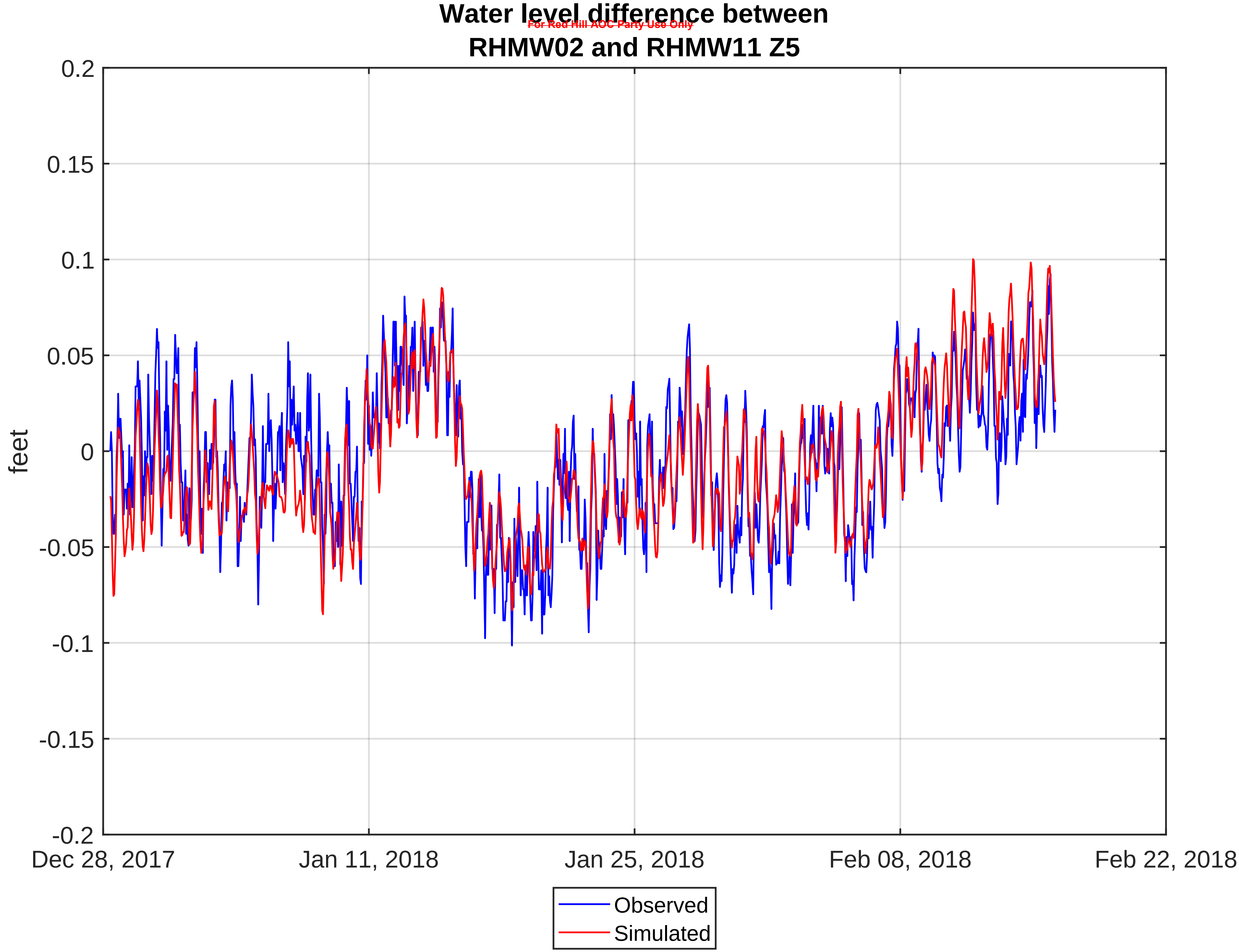
Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW11 Z1
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW11 Z2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

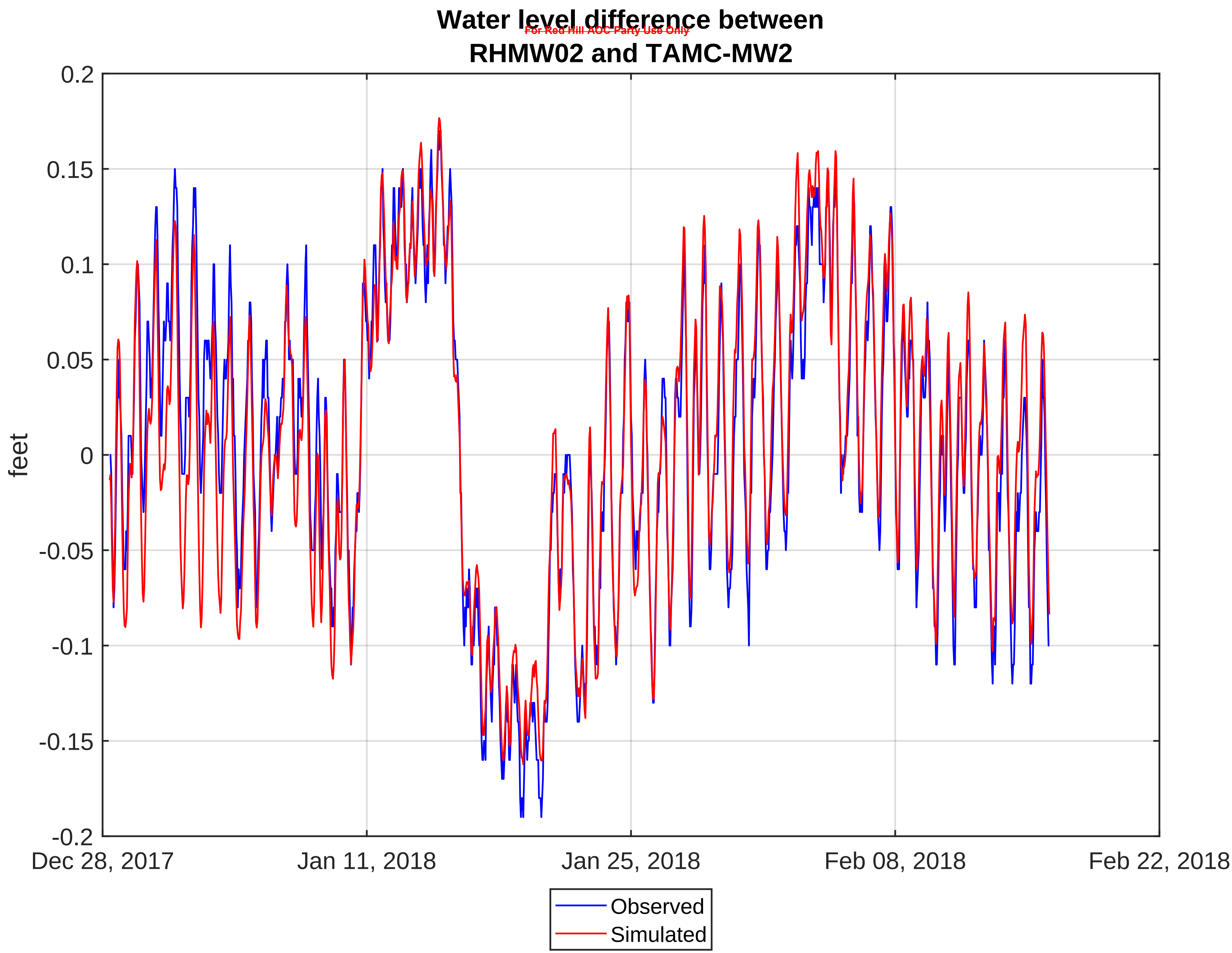


Water level difference between
RHMW02 and RHMW11 Z3
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

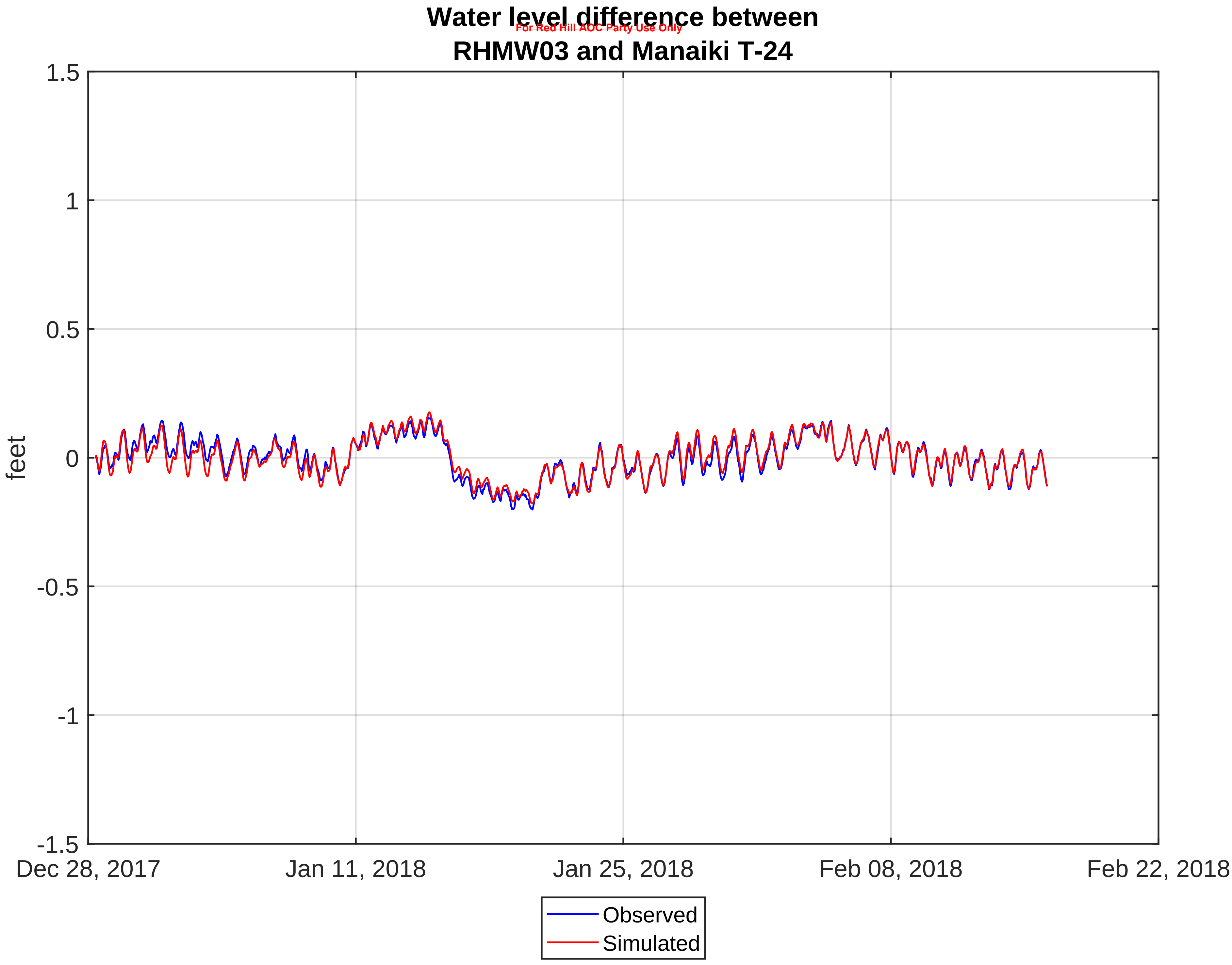

Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW11 Z4
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



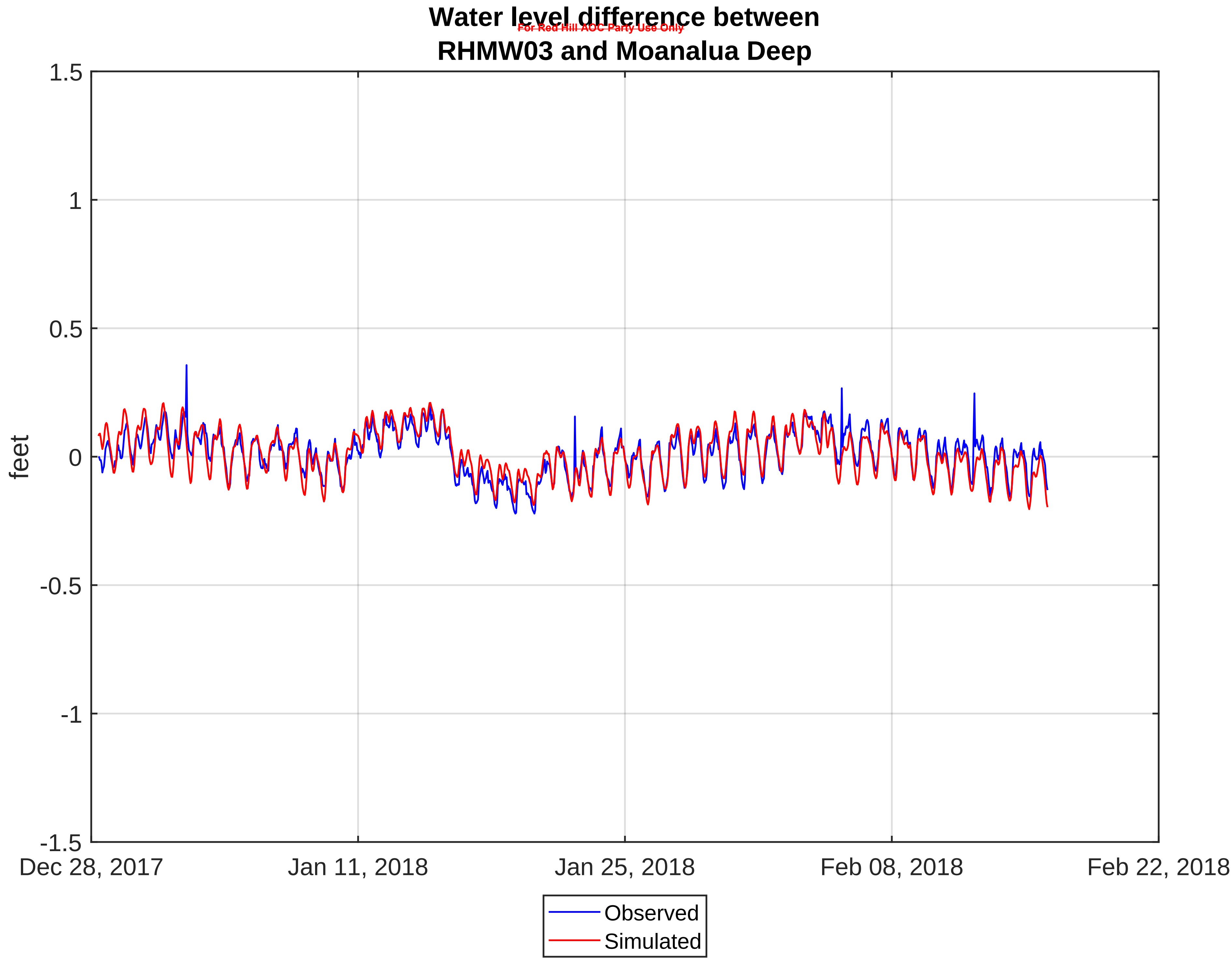
Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
RHMW02 and TAMC-MW2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

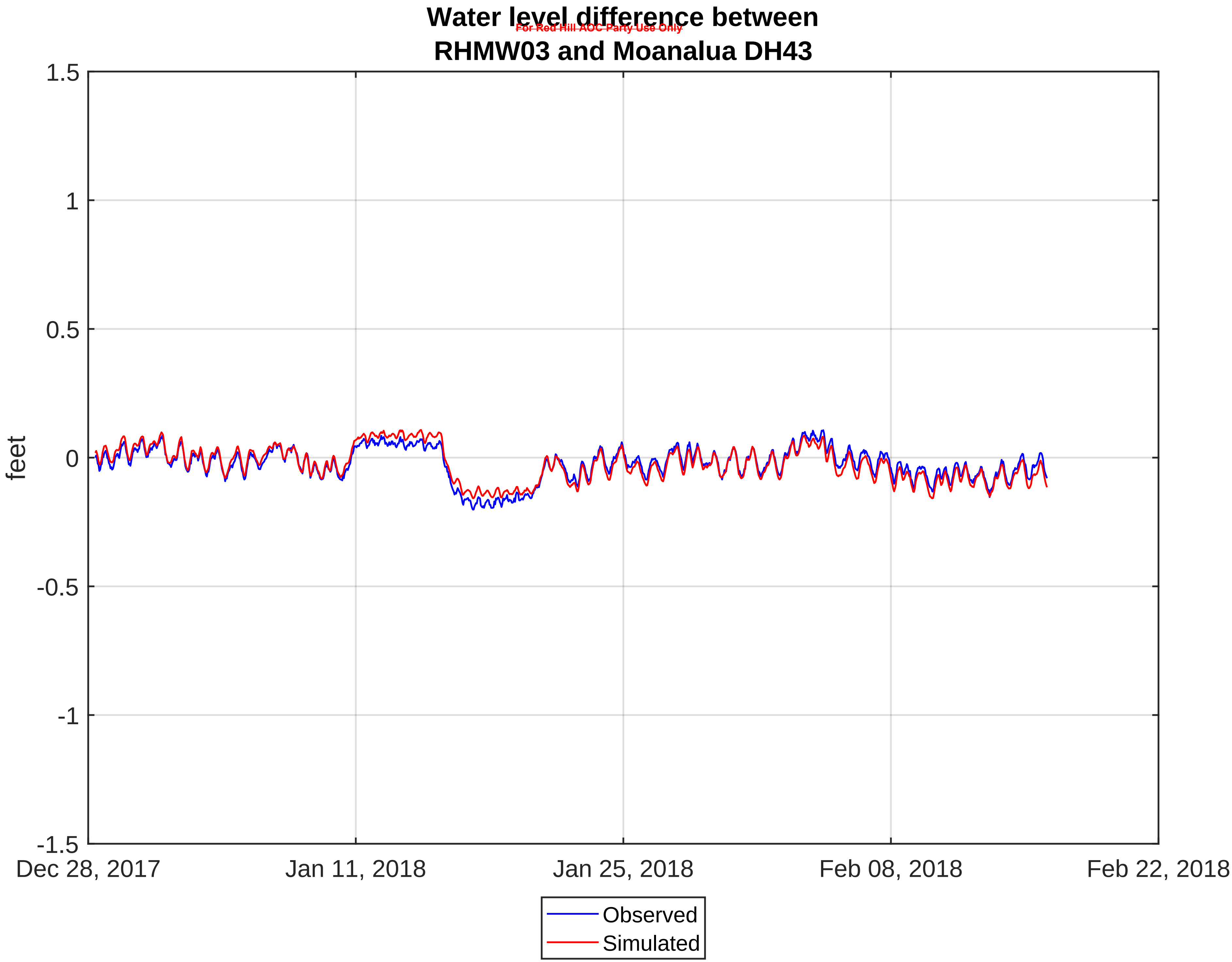


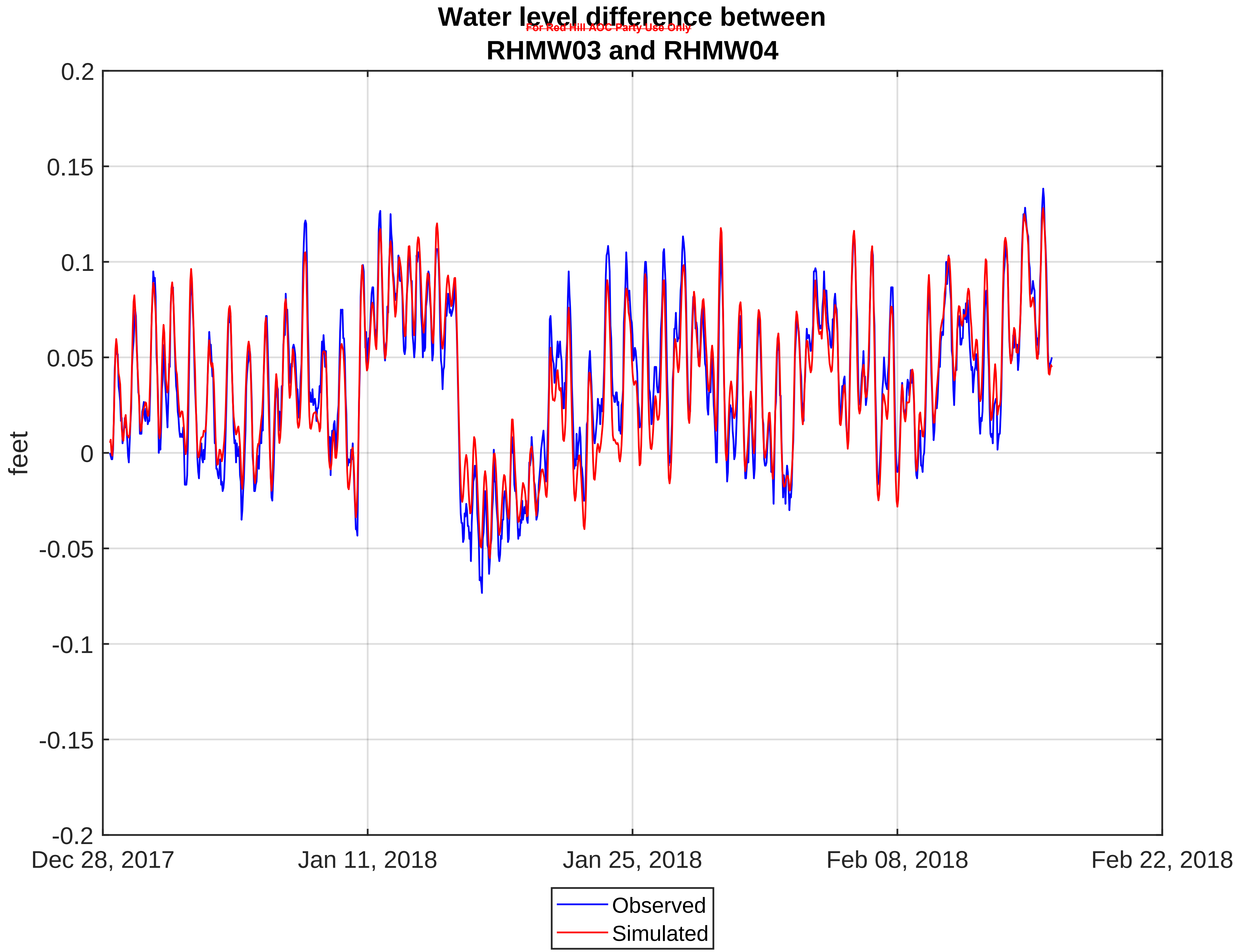
Water level difference between
For Red Hill AOC Party Use Only
RHMW03 and Manaiki T-24
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

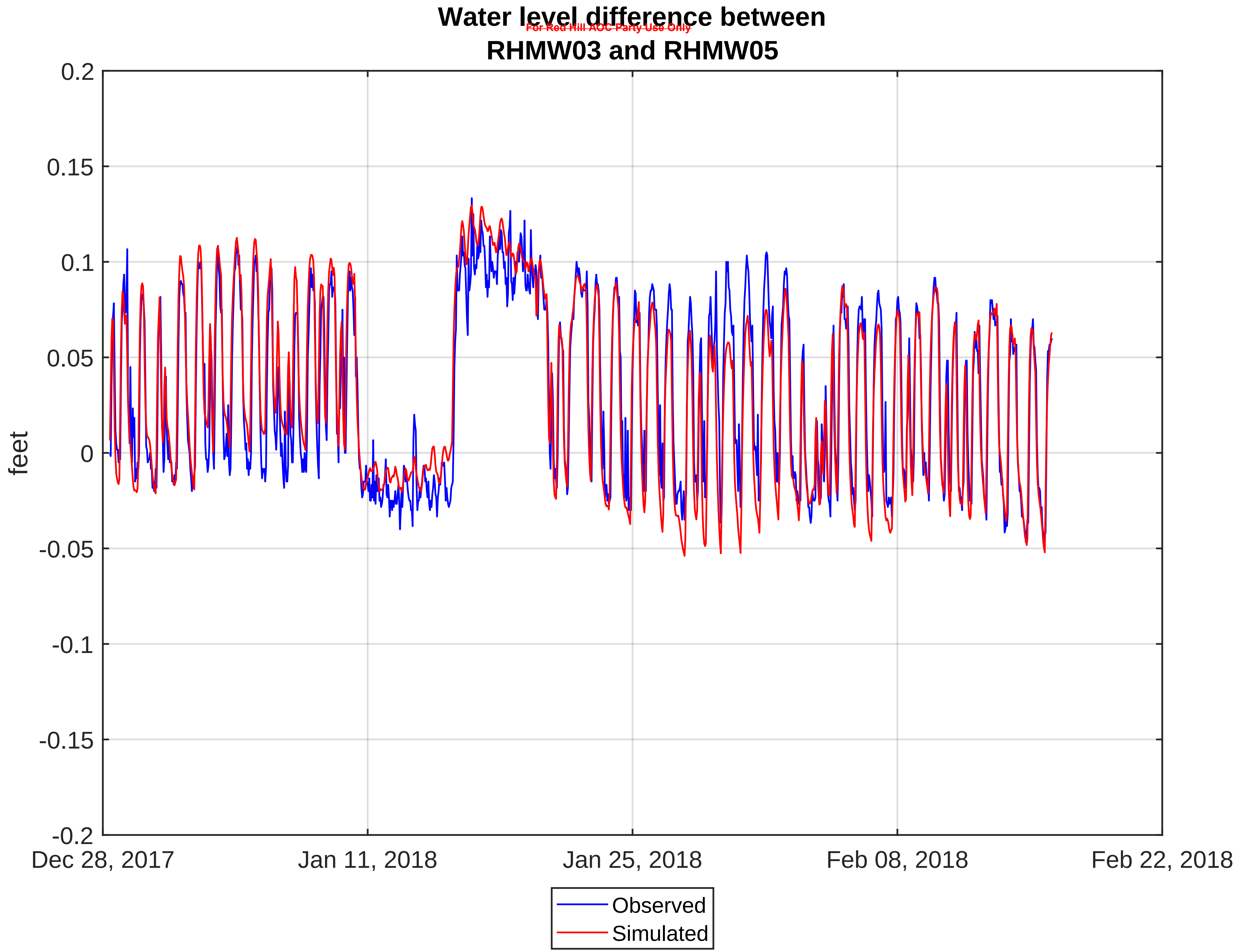


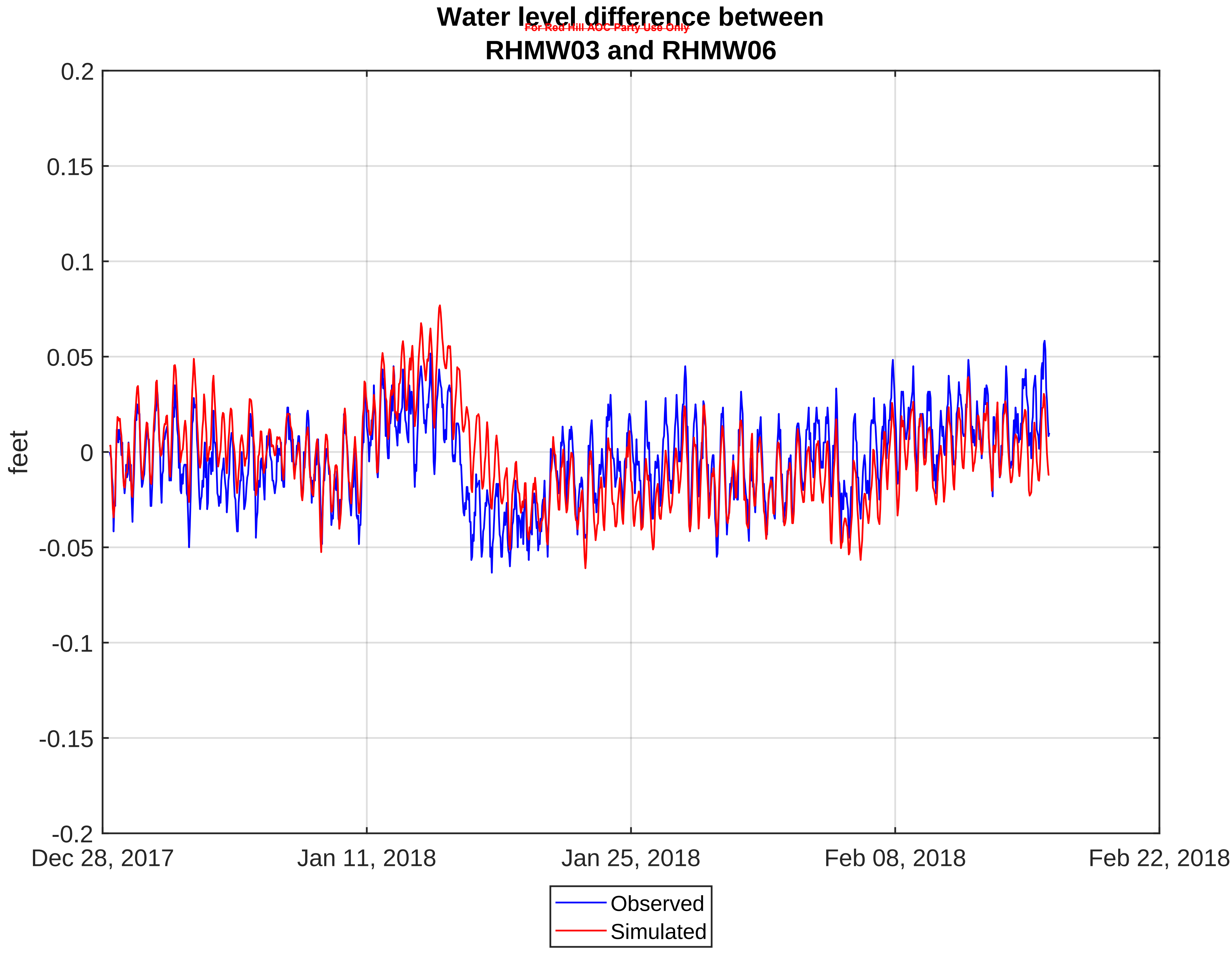
Water level difference between
For Red Hill AOC Party Use Only
RHMW03 and Moanalua Deep
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

For Red Hill AOC Party Use Only

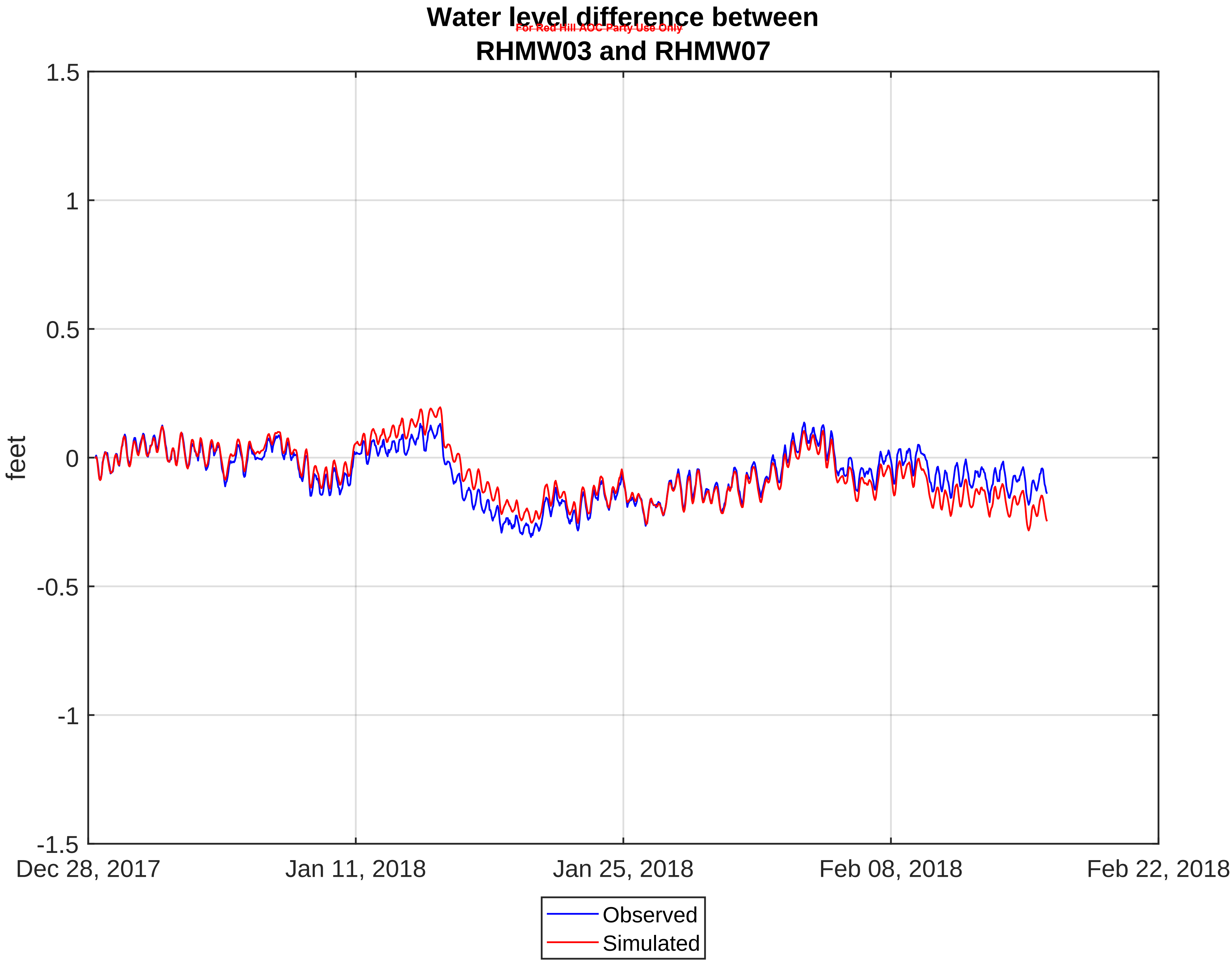



Water level difference between
RHMW03 and RHMW04
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

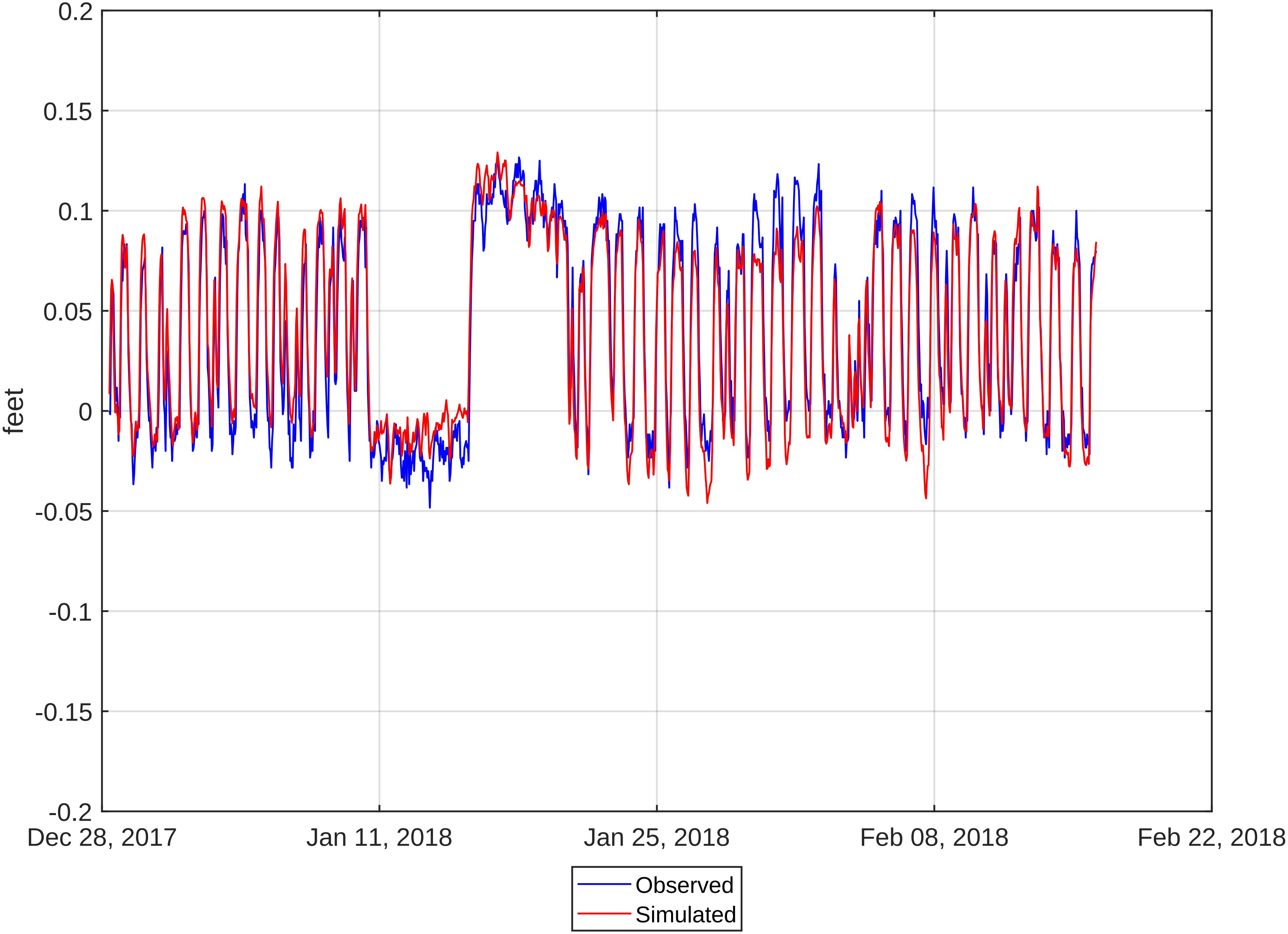

Water level difference between
For Red Hill AOC Party Use Only
RHMW03 and RHMW05
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

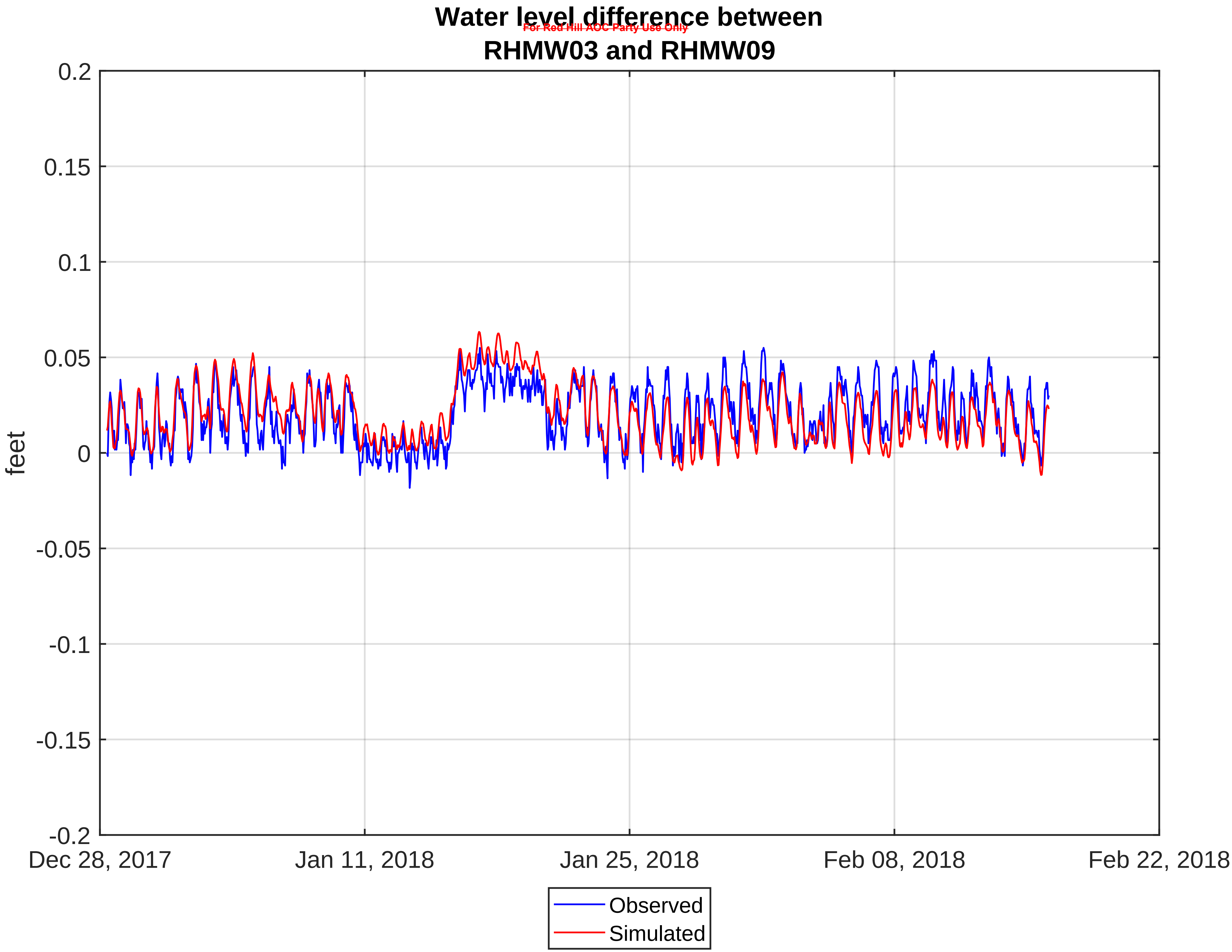


Water level difference between
RHMW03 and RHMW06
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

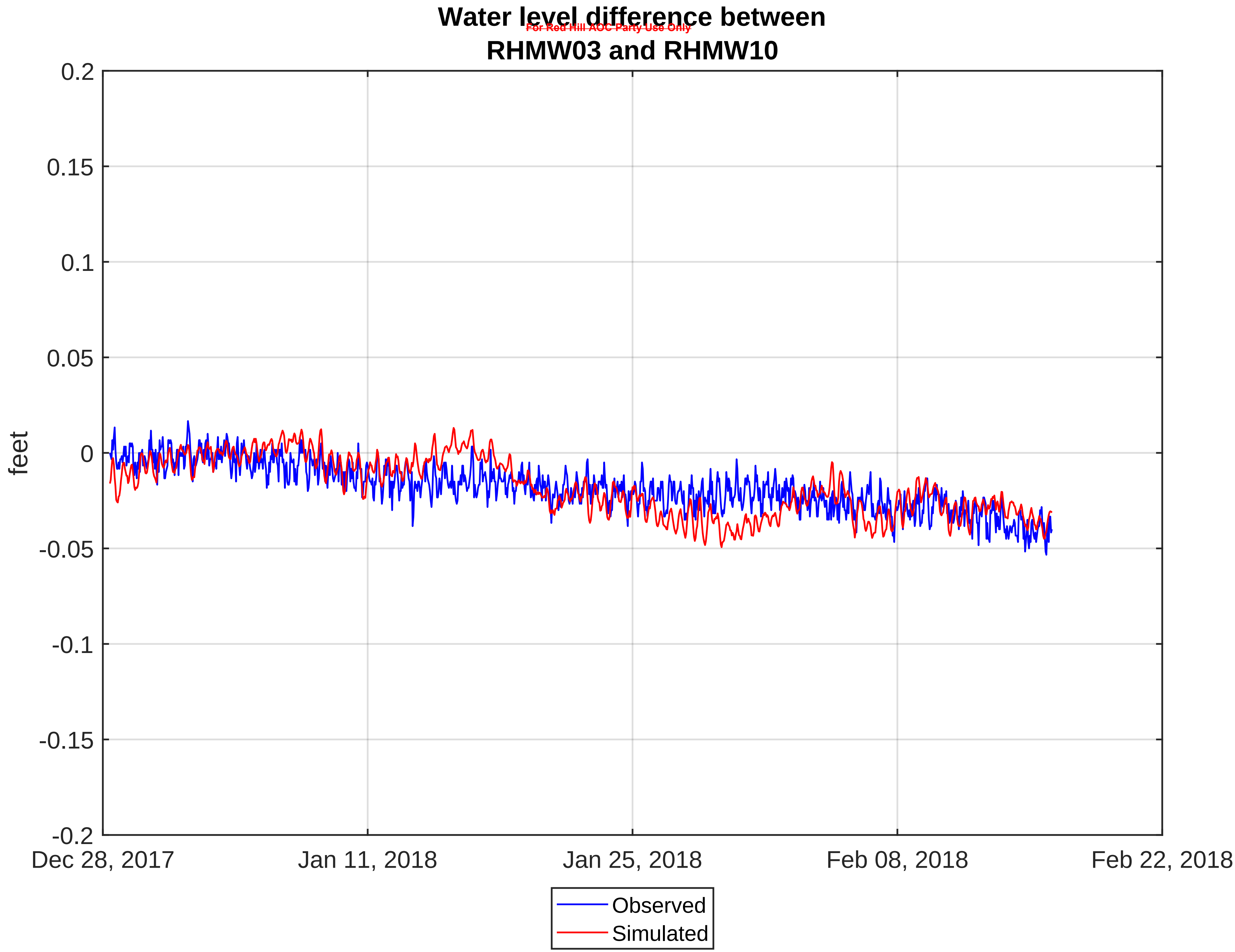

Water level difference between
RHMW03 and RHMW07
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
RHMW03 and RHMW08

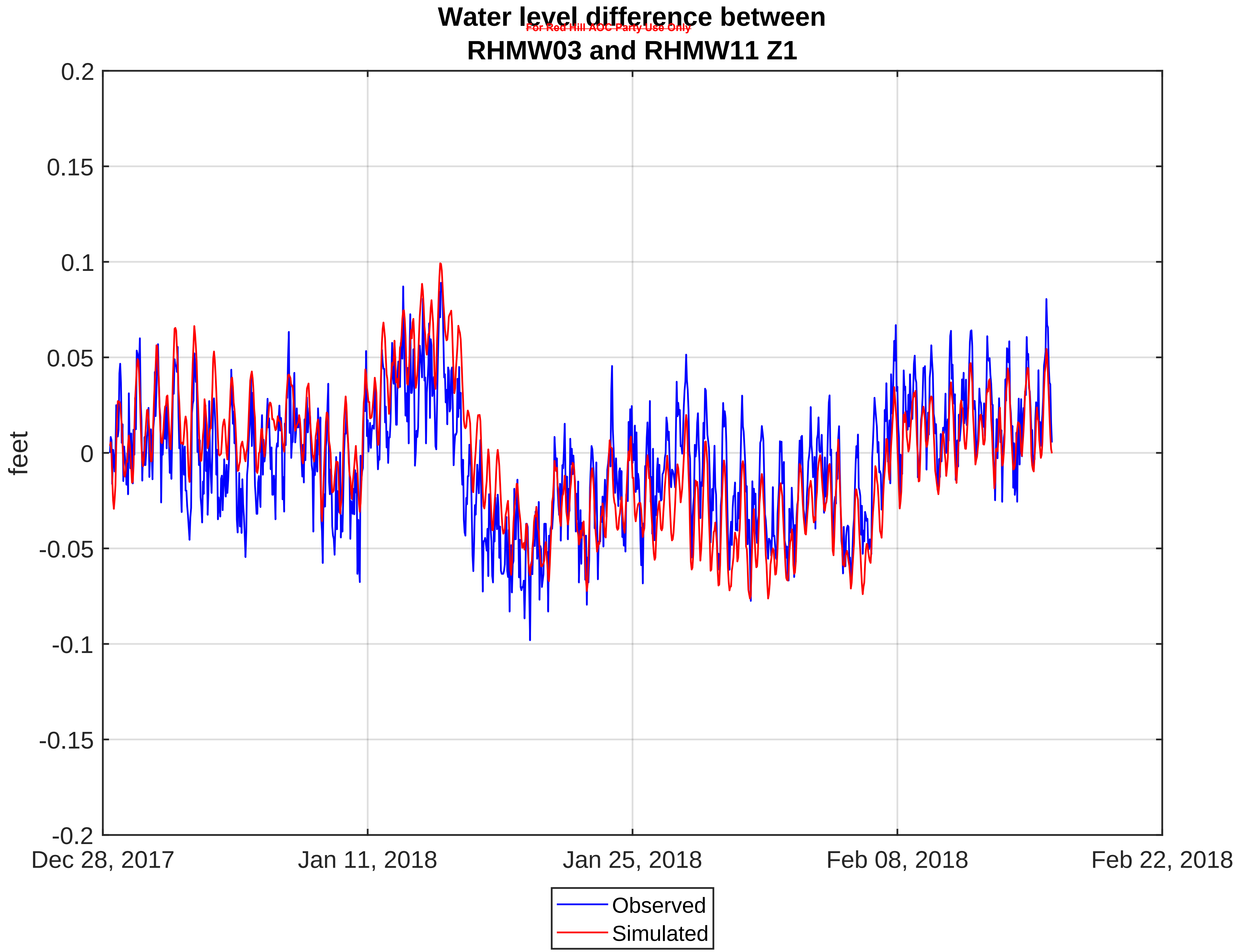




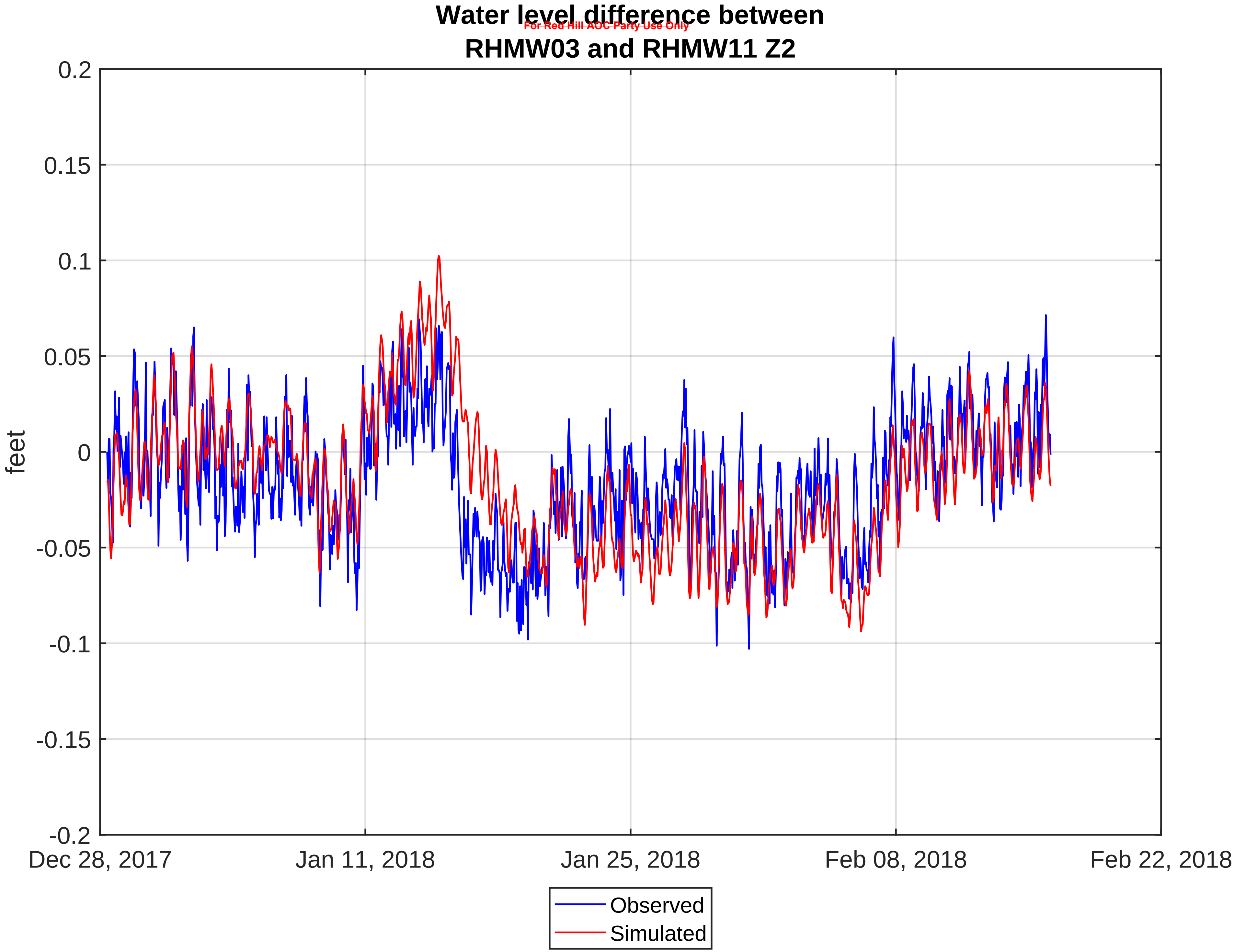
Water level difference between
RHMW03 and RHMW09
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
RHMW03 and RHMW10
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

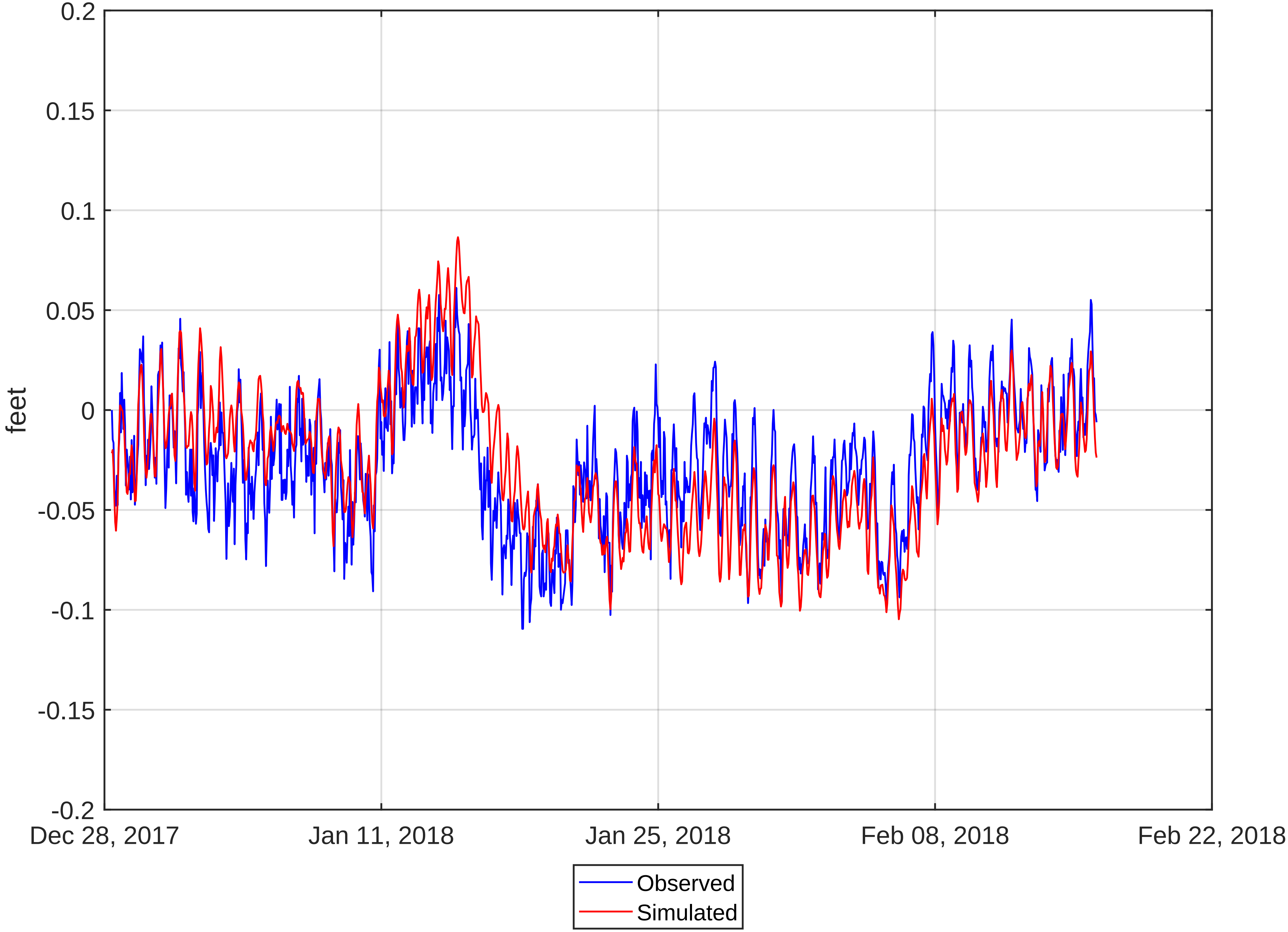


Water level difference between
For Red Hill AOC Party Use Only
RHMW03 and RHMW11 Z1
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

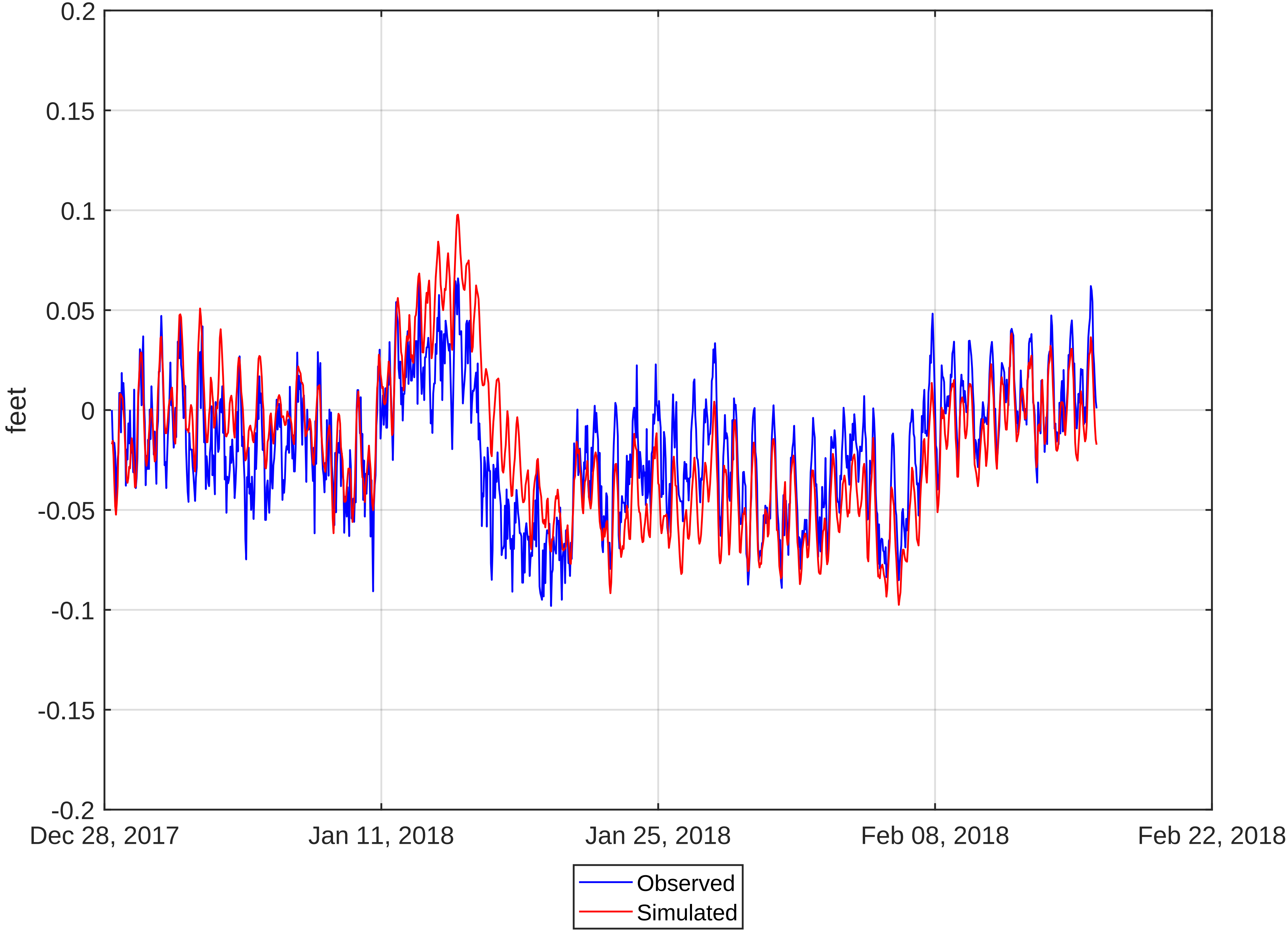


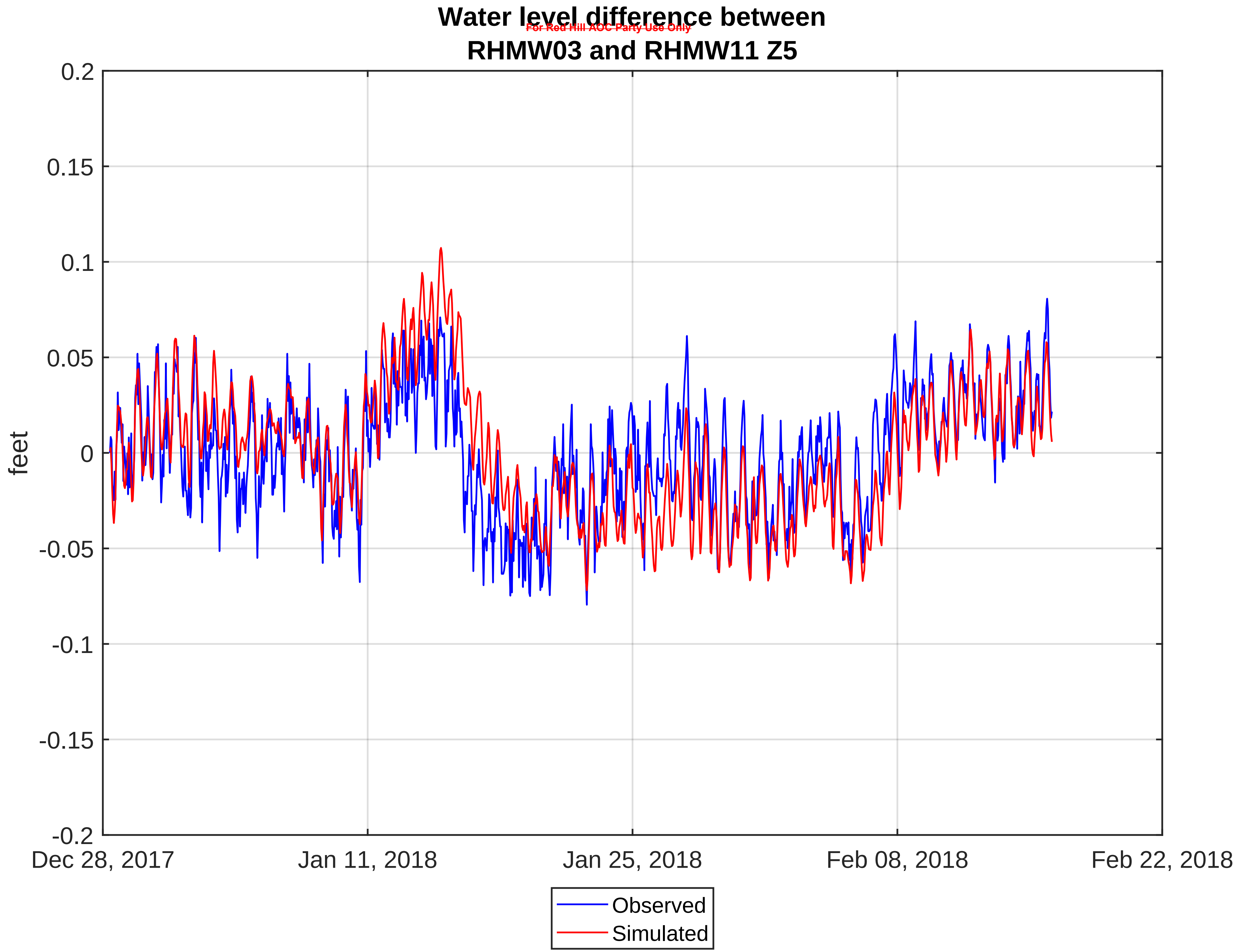
Water level difference between
For Red Hill AOC Party Use Only
RHMW03 and RHMW11 Z2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW03 and RHMW11 Z3

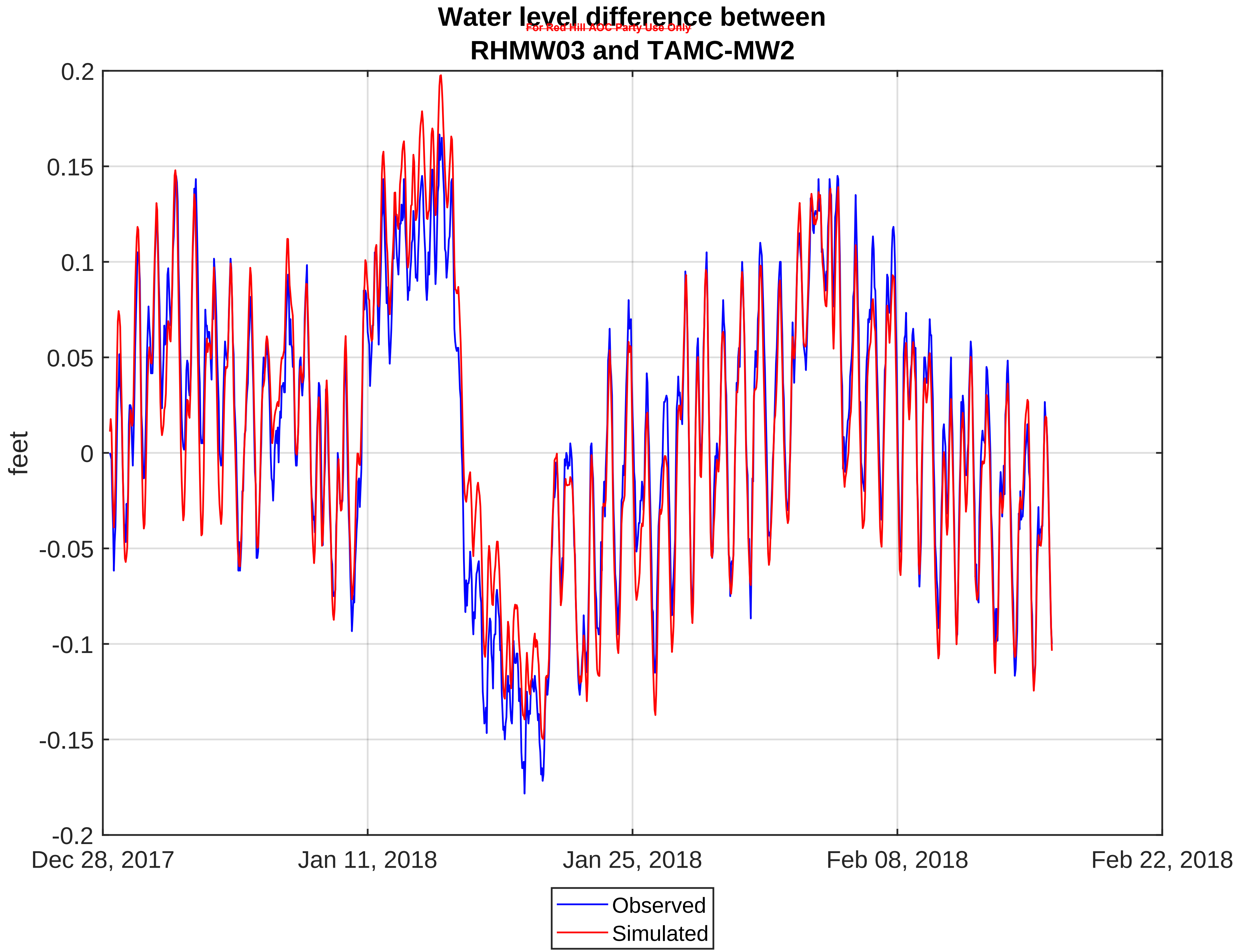


Water level difference between
RHMW03 and RHMW11 Z4

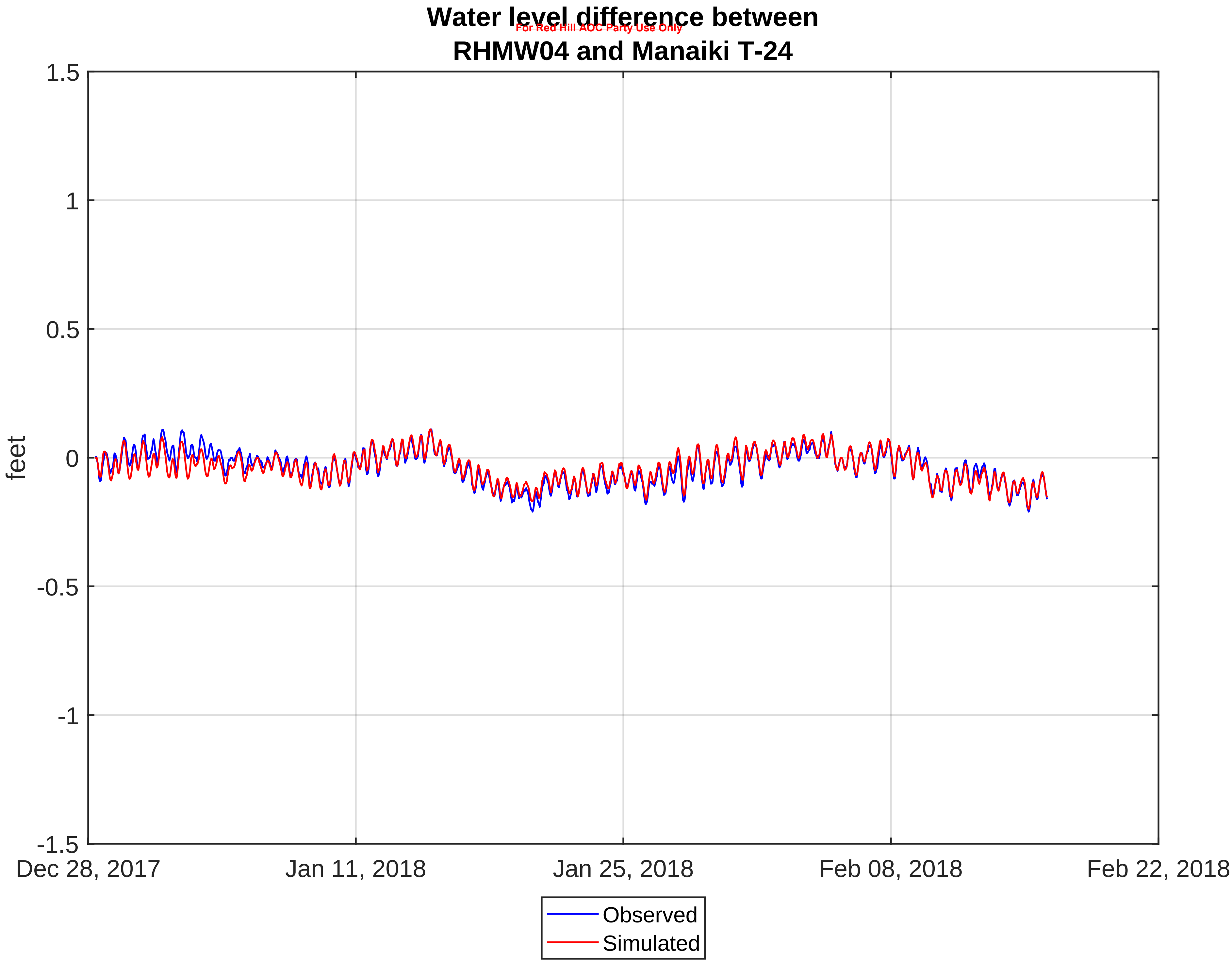




Water level difference between
For Red Hill AOC Party Use Only
RHMW03 and RHMW11 Z5
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

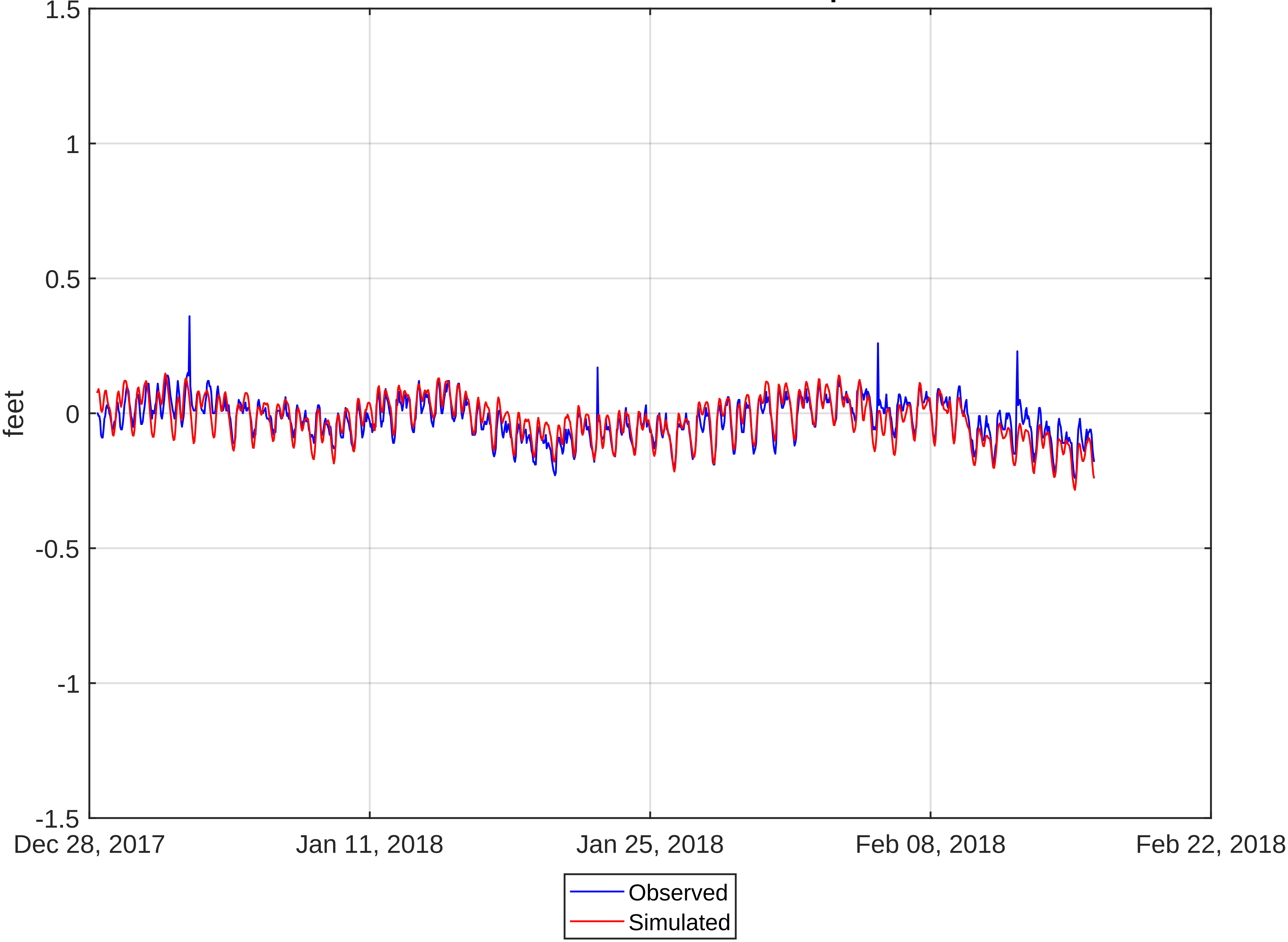


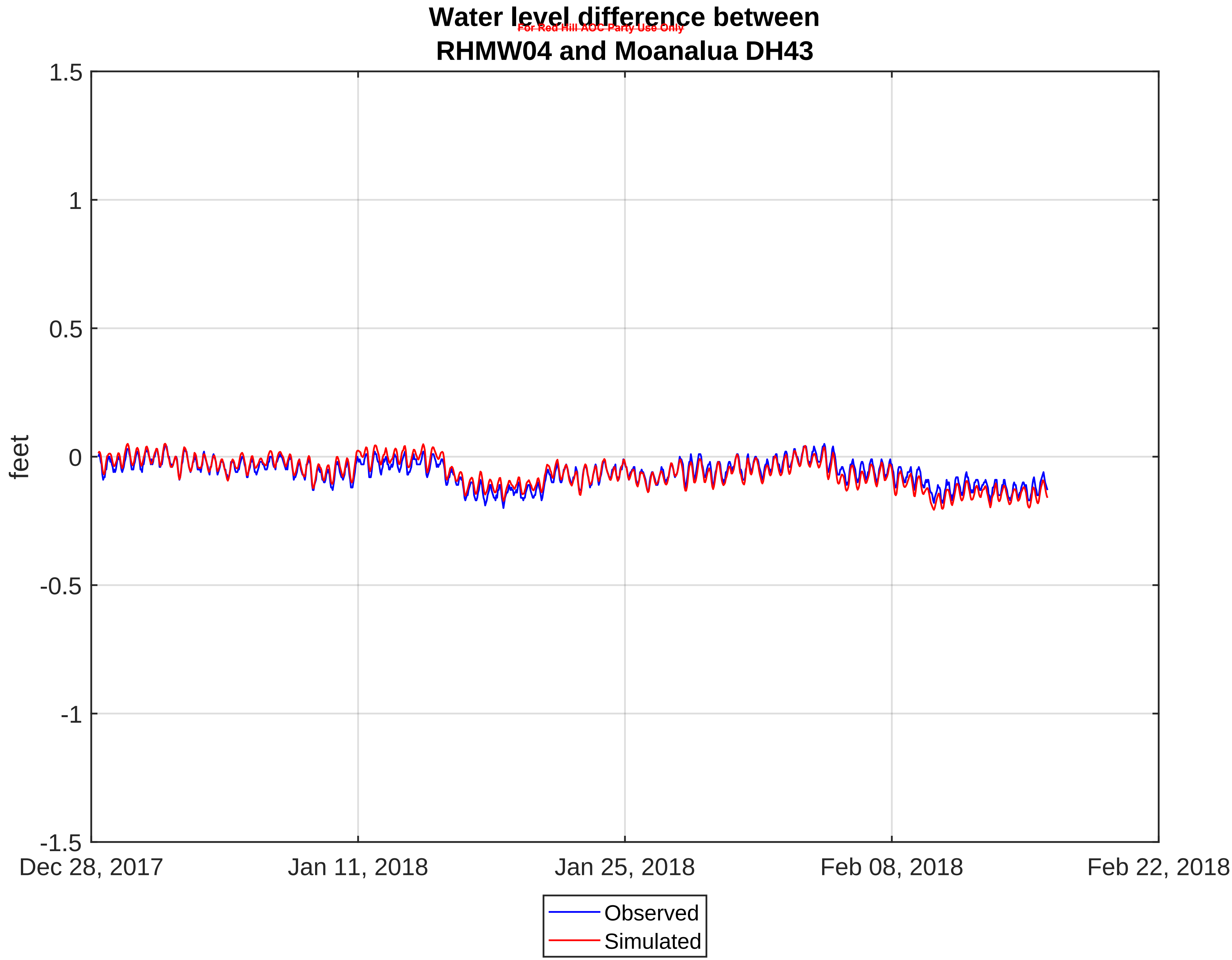
Water level difference between
RHMW03 and TAMC-MW2
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



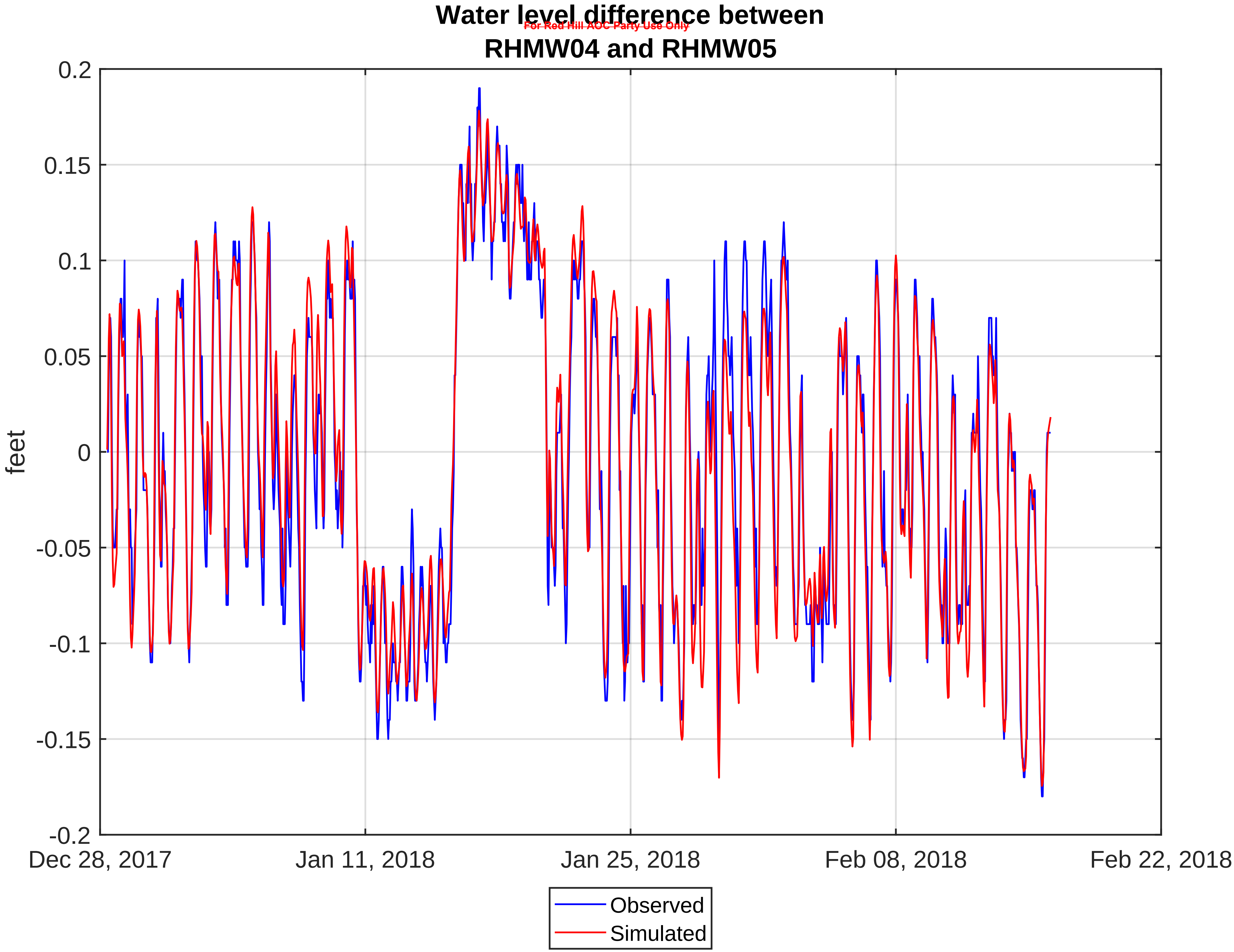
Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and Manaiki T-24
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW04 and Moanalua Deep

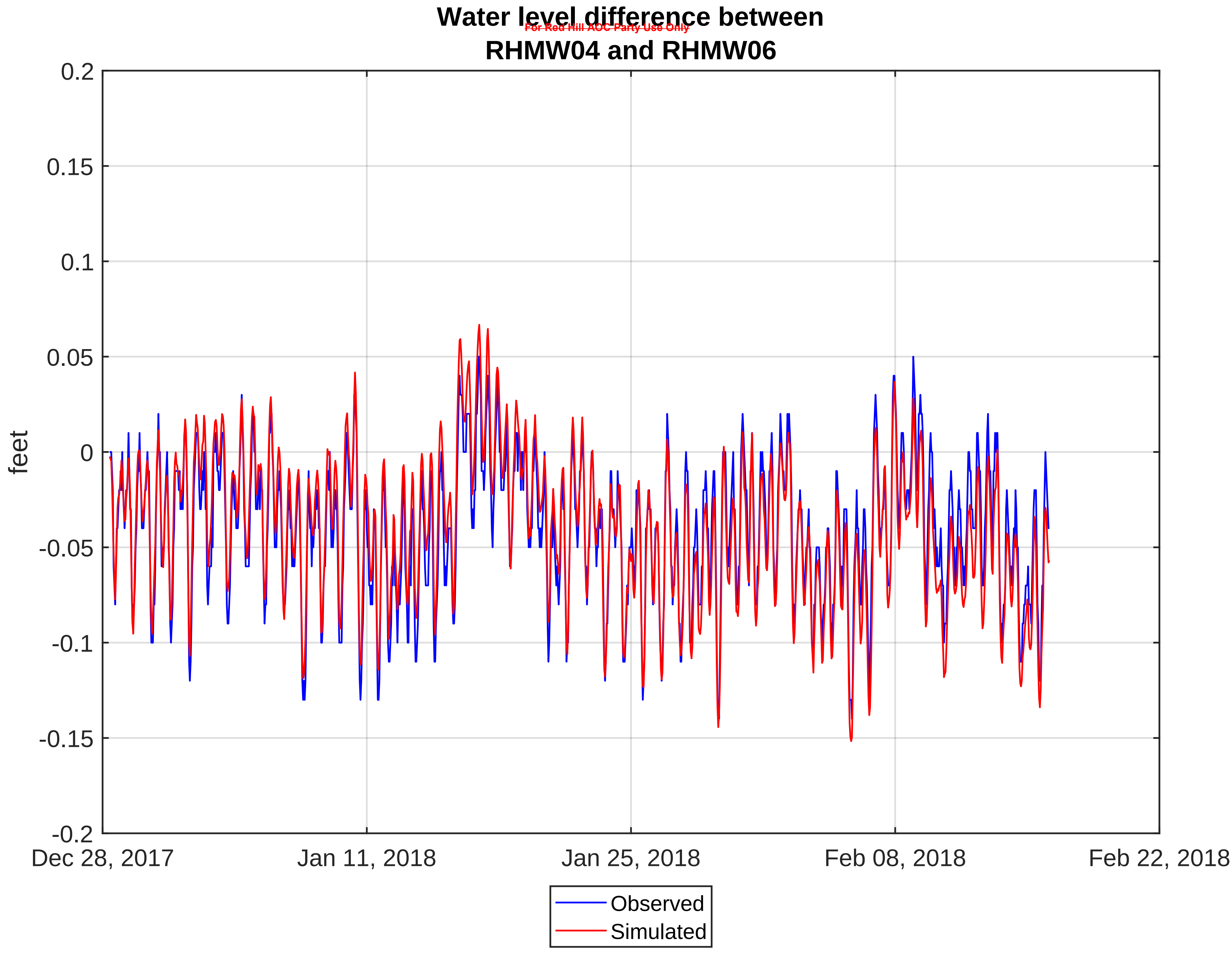




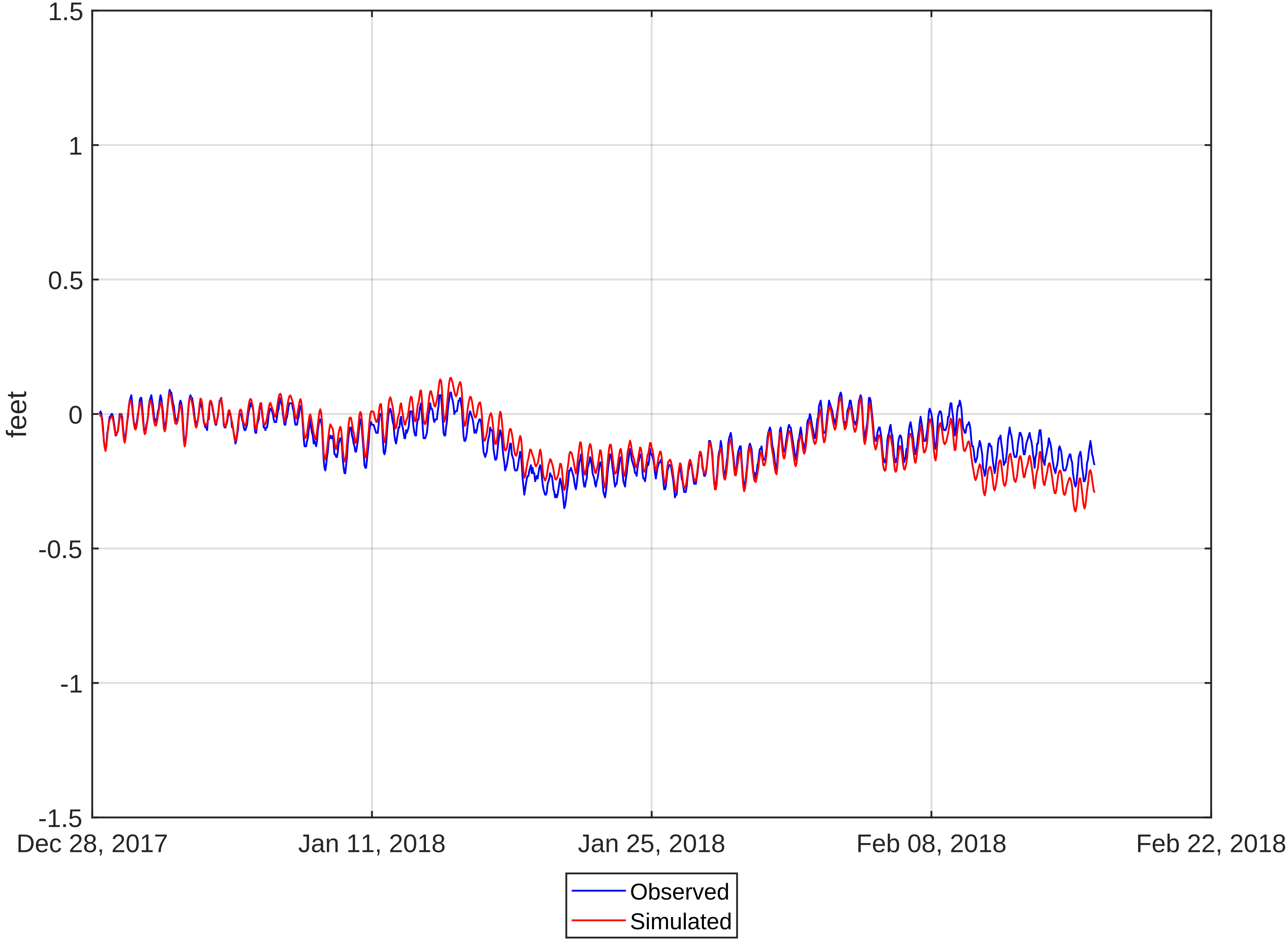
Water level difference between
RHMW04 and Moanalua DH43
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

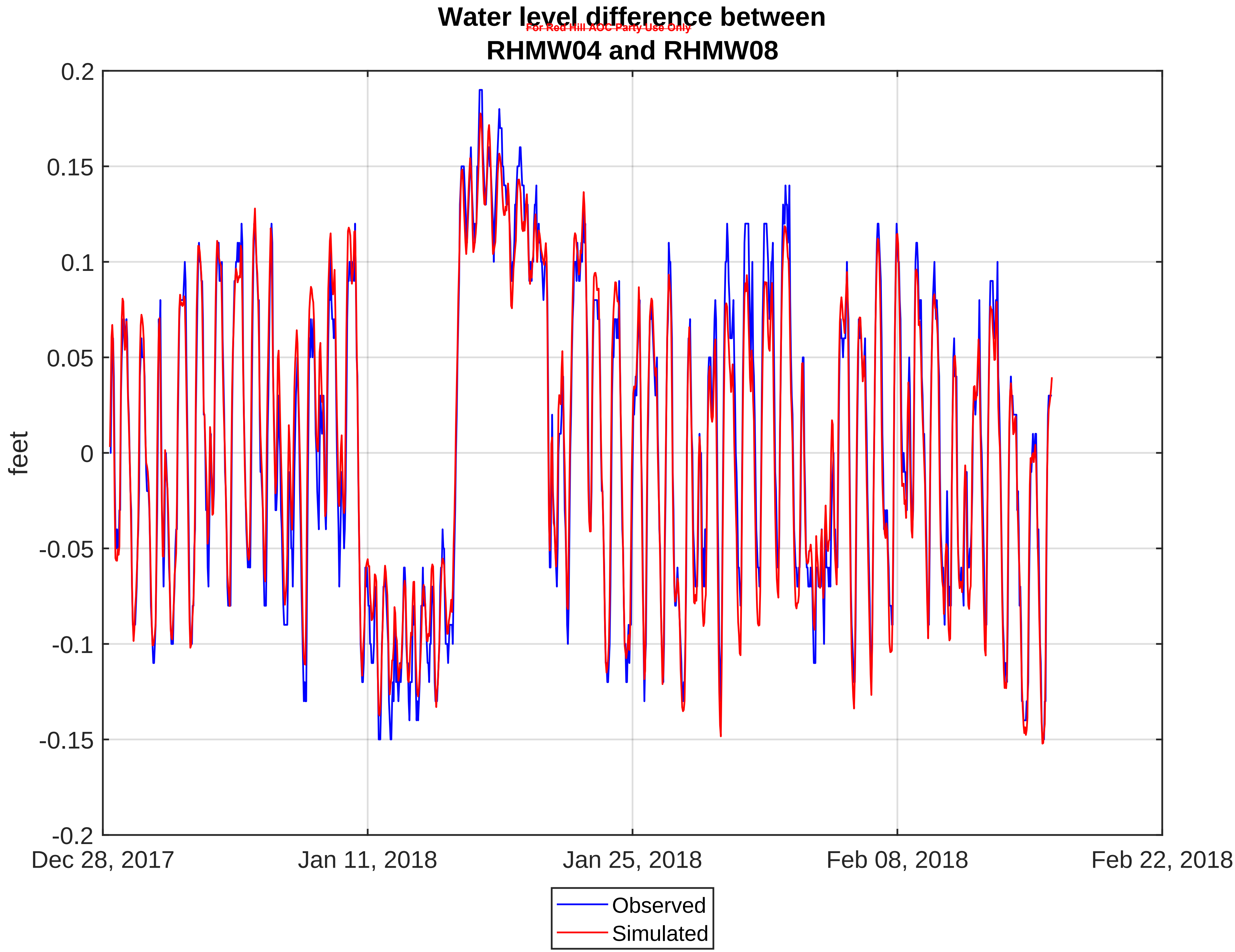


Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW05
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

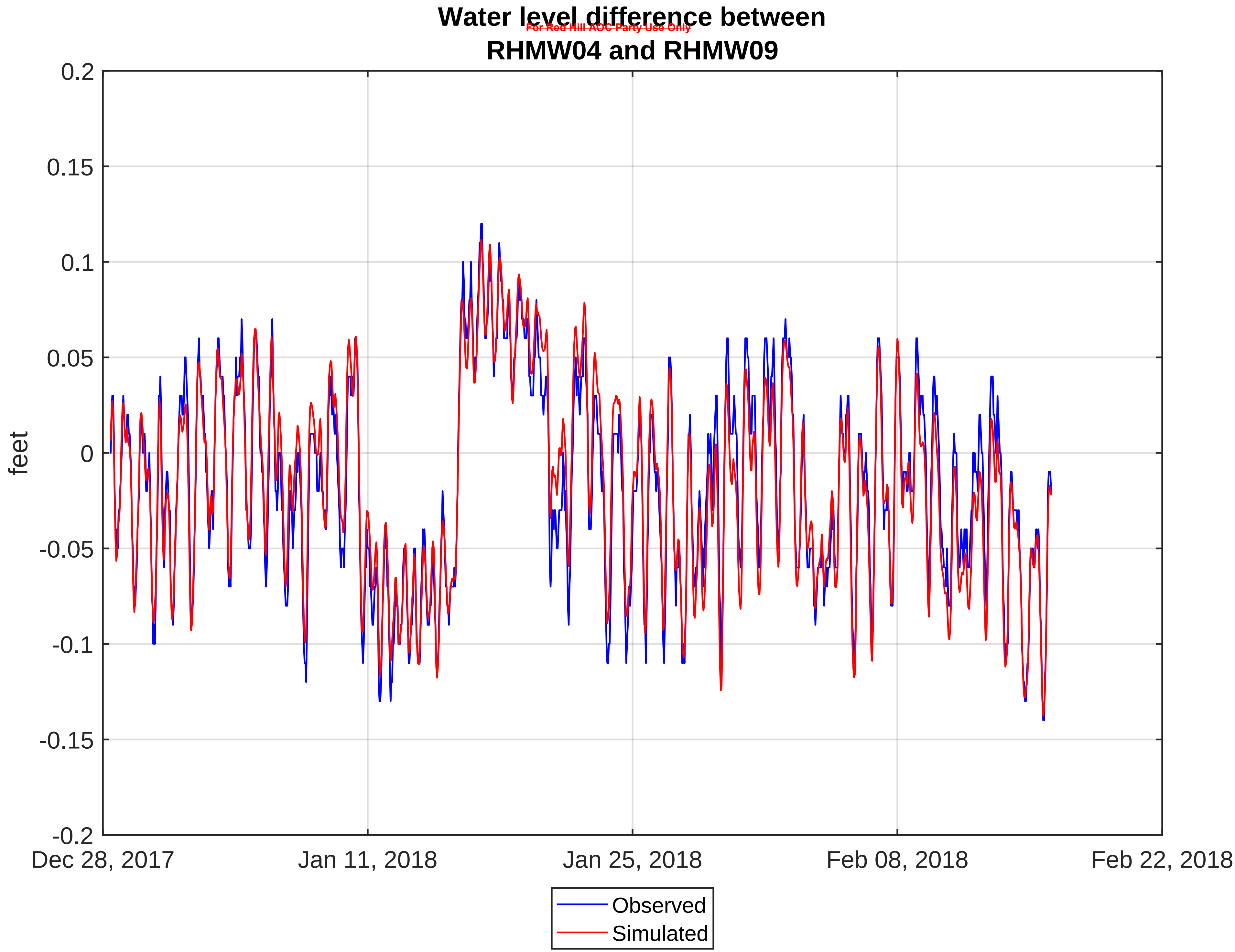

Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW06
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW04 and RHMW07

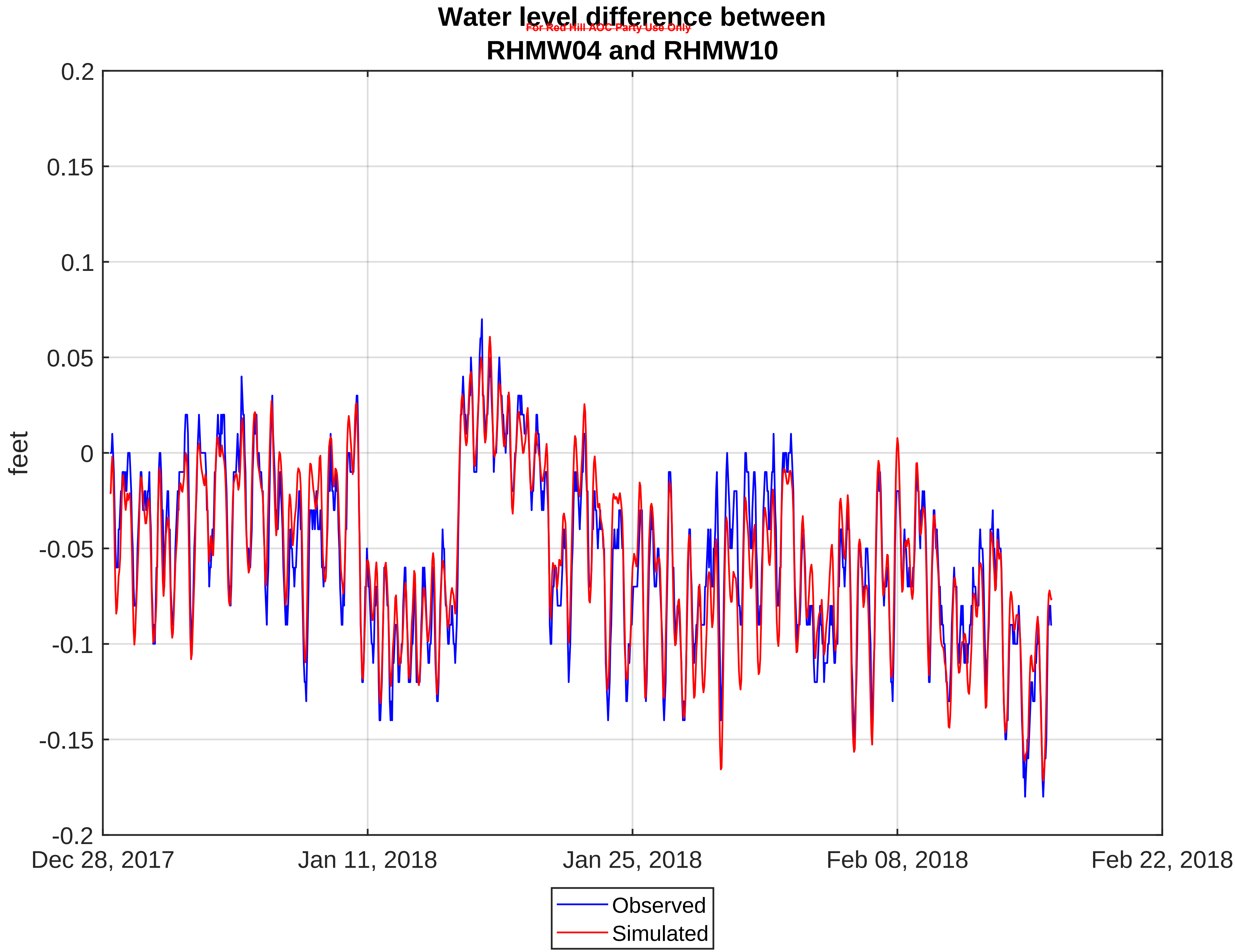


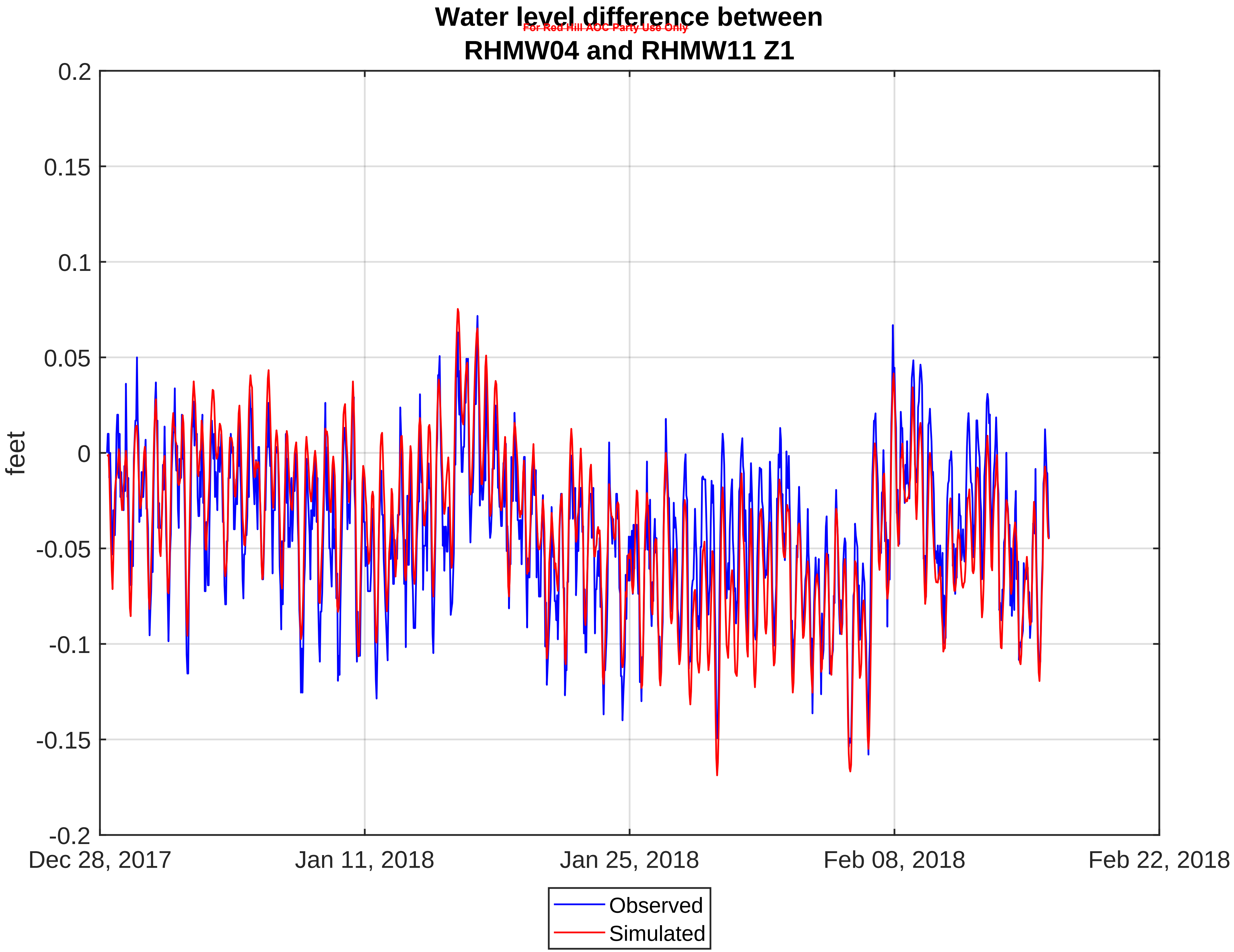


Water level difference between
RHMW04 and RHMW08
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



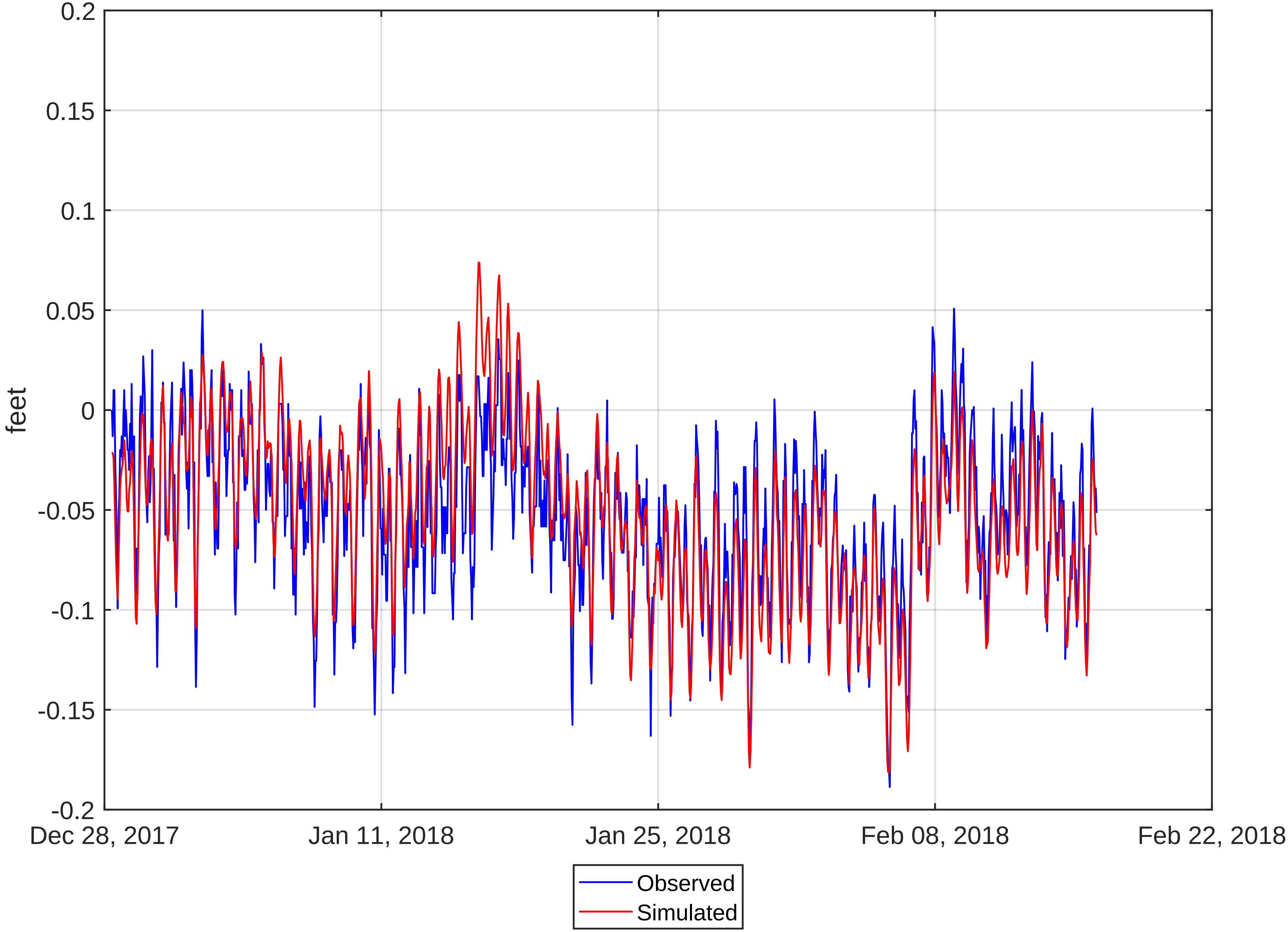
Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW09
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

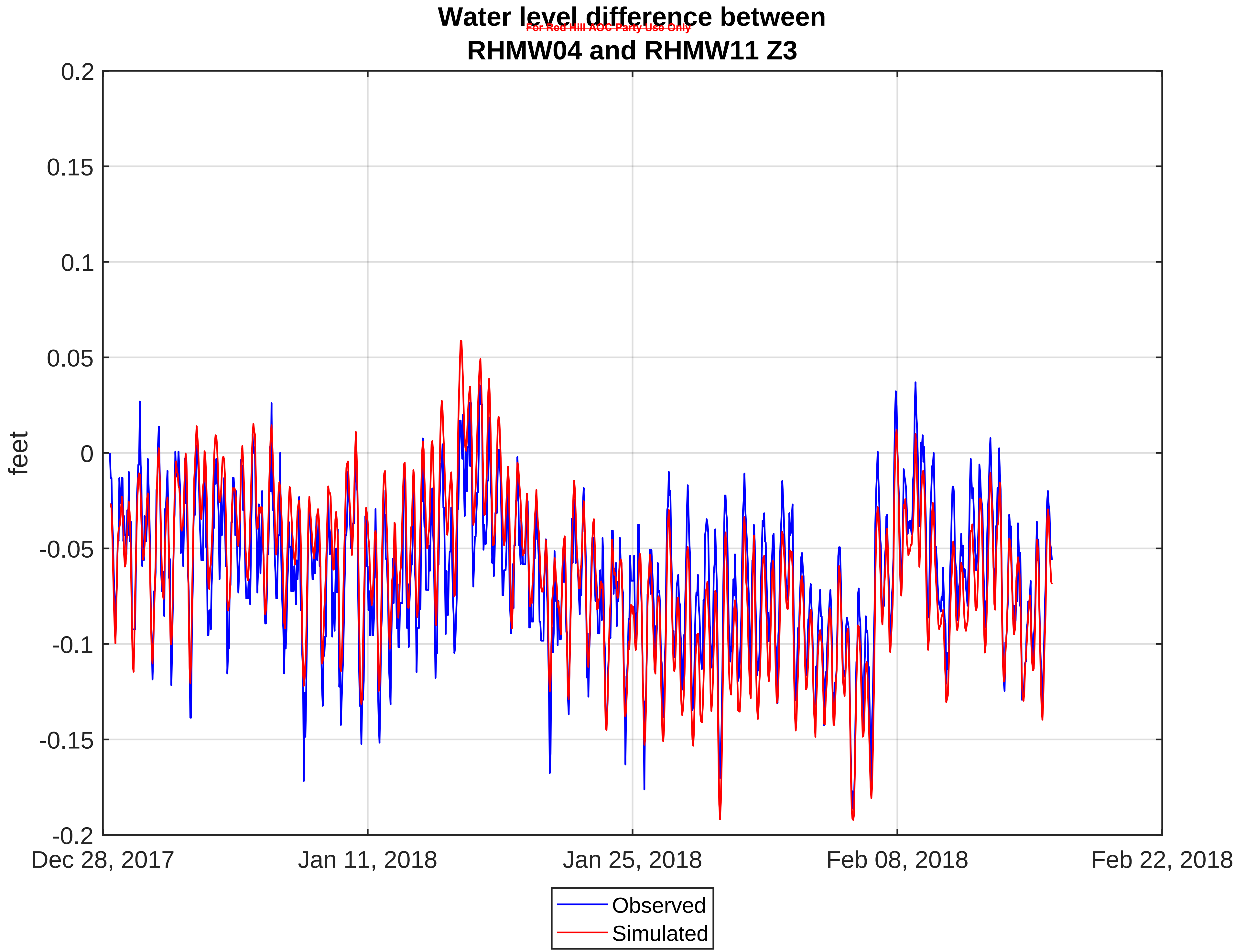

Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW10
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

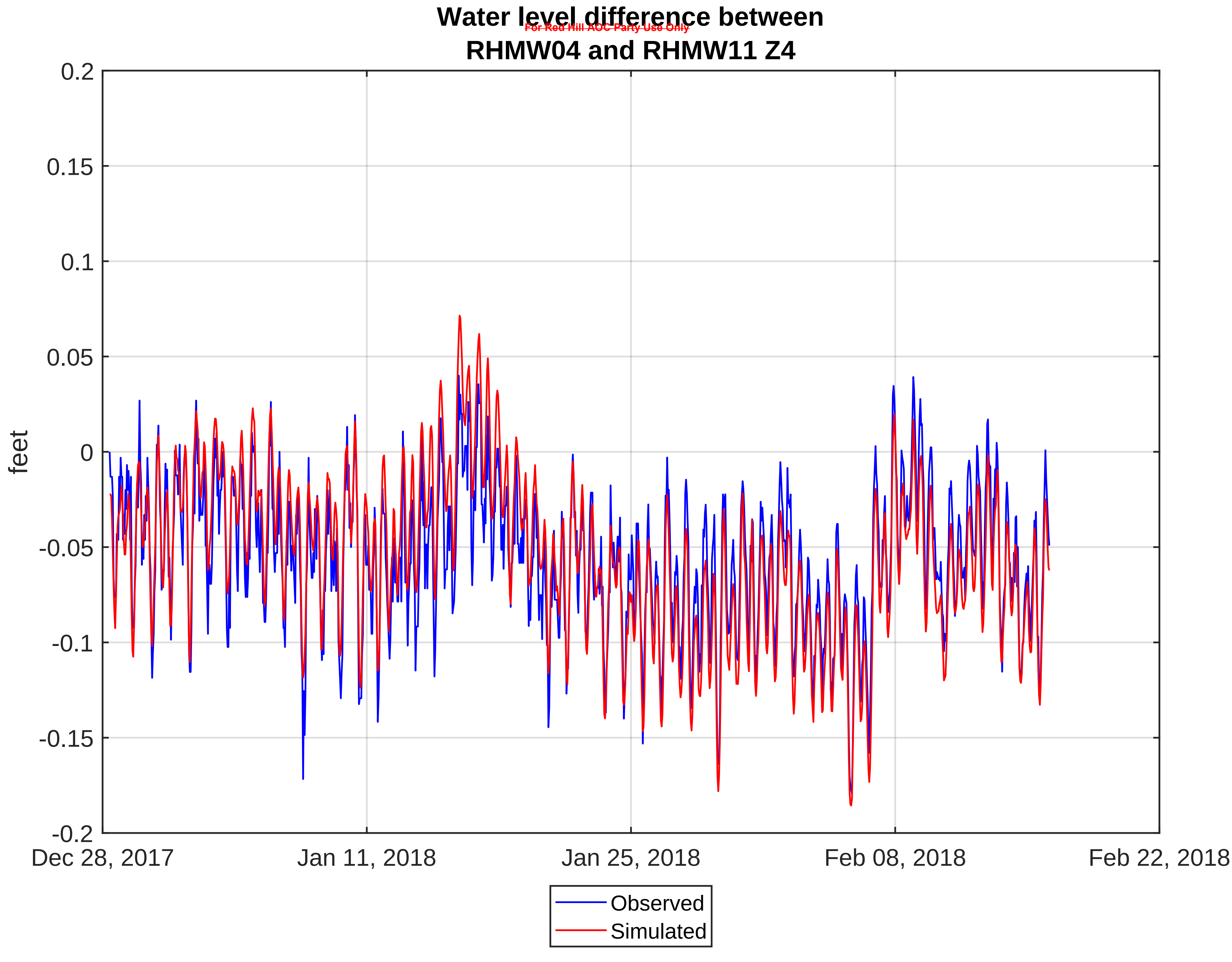


Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW11 Z1
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

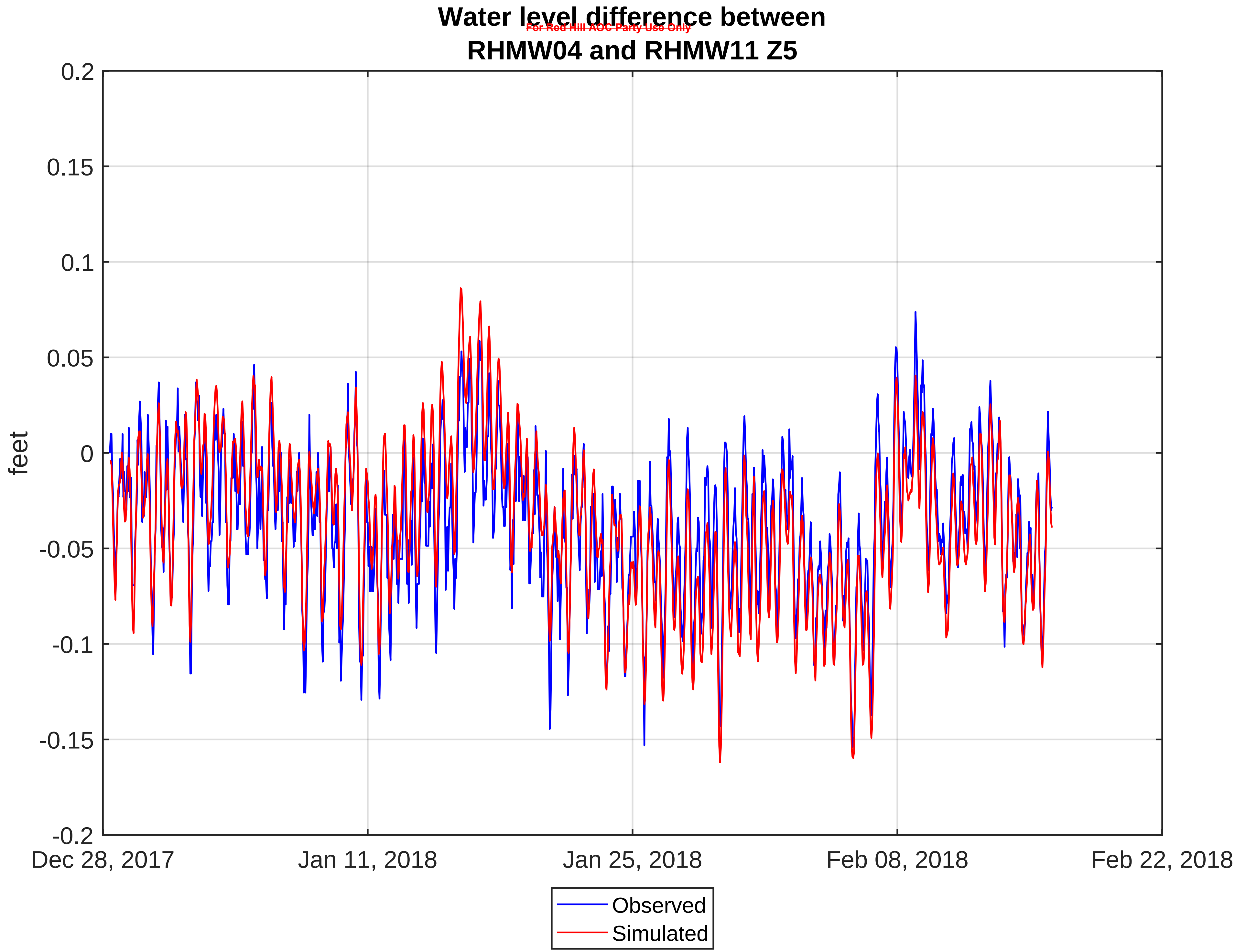
Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW11 Z2



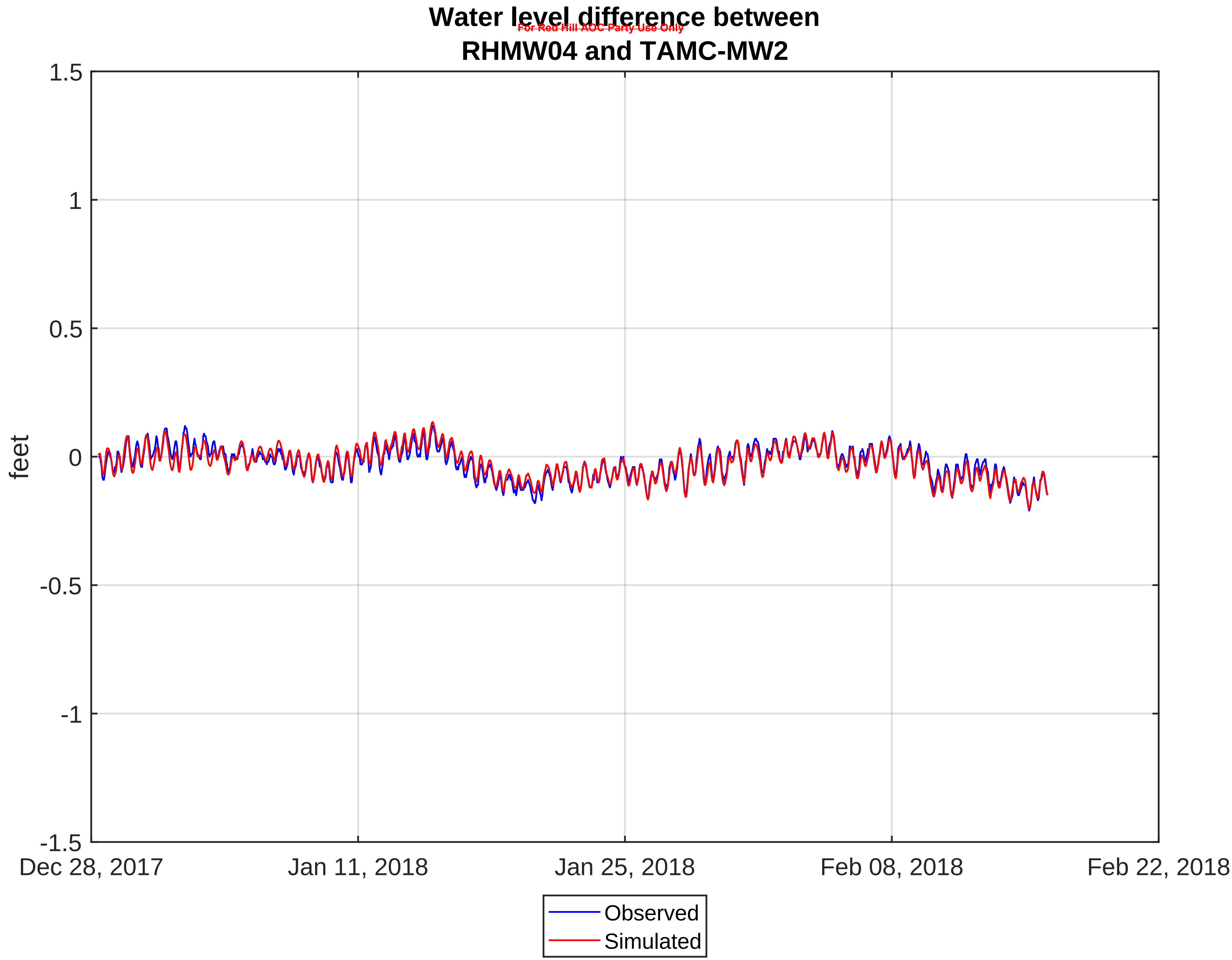

Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW11 Z3
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW11 Z4
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

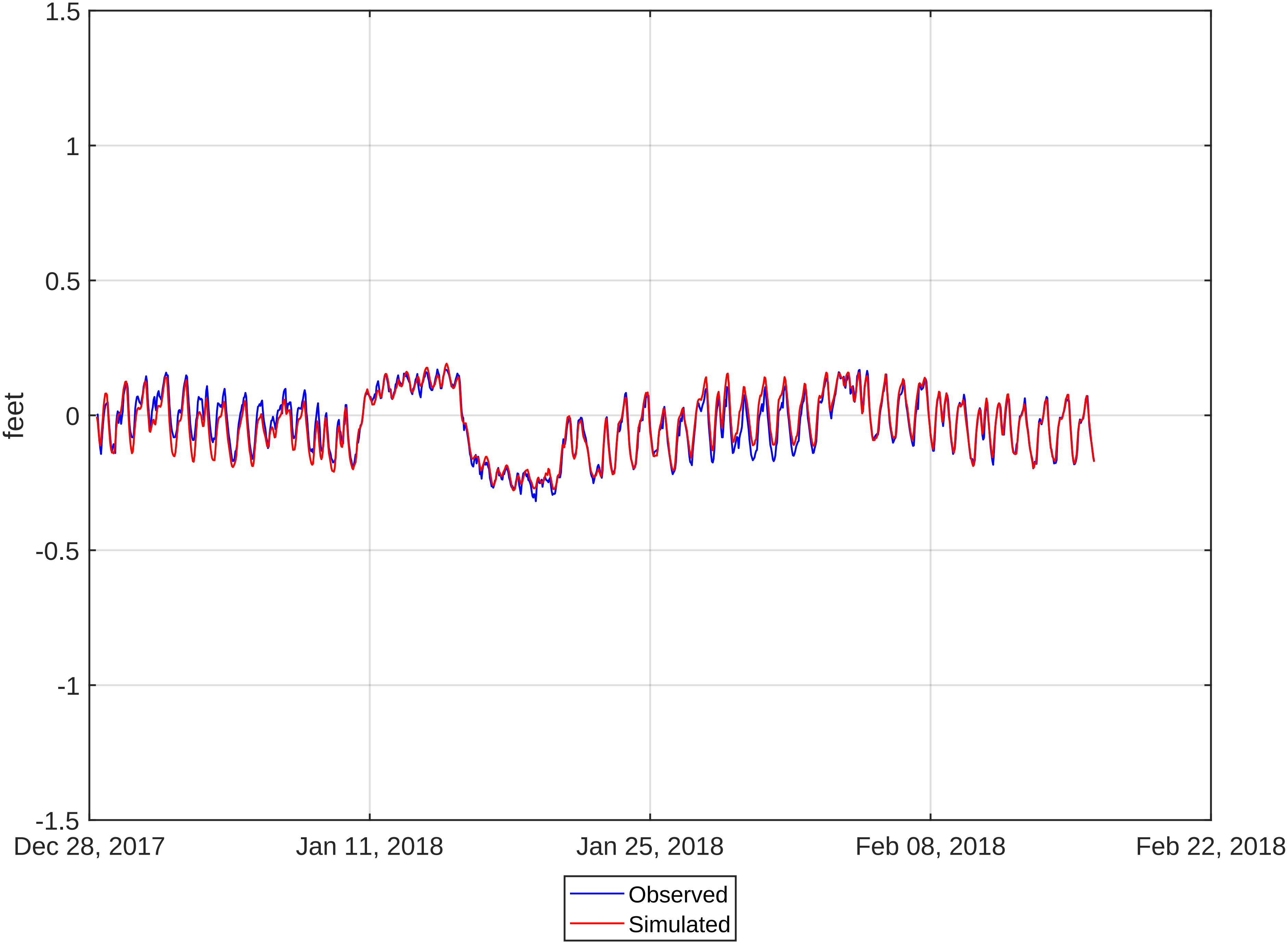


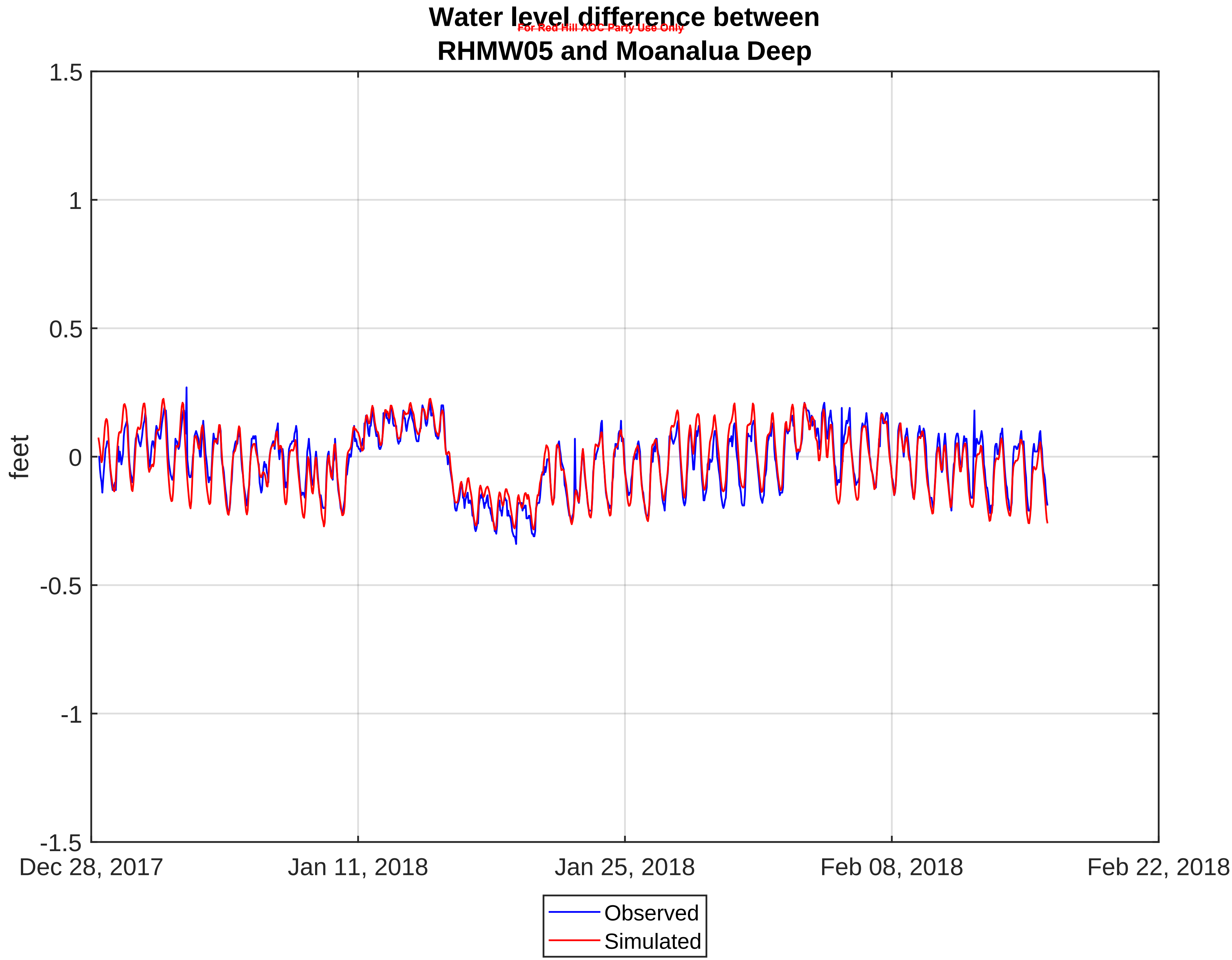
Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
RHMW04 and TAMC-MW2
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

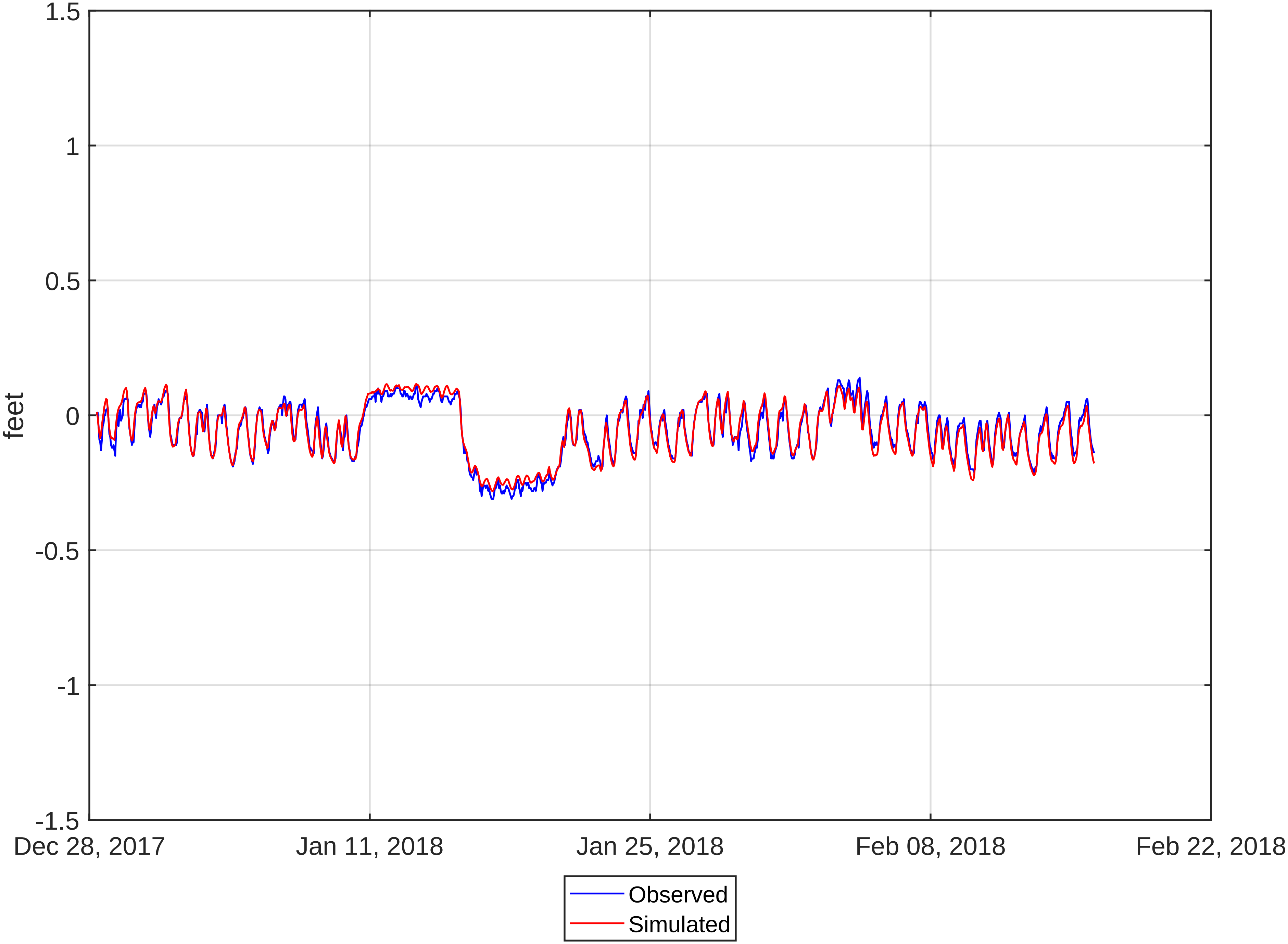
Water level difference between RHMW05 and Manaiki T-24

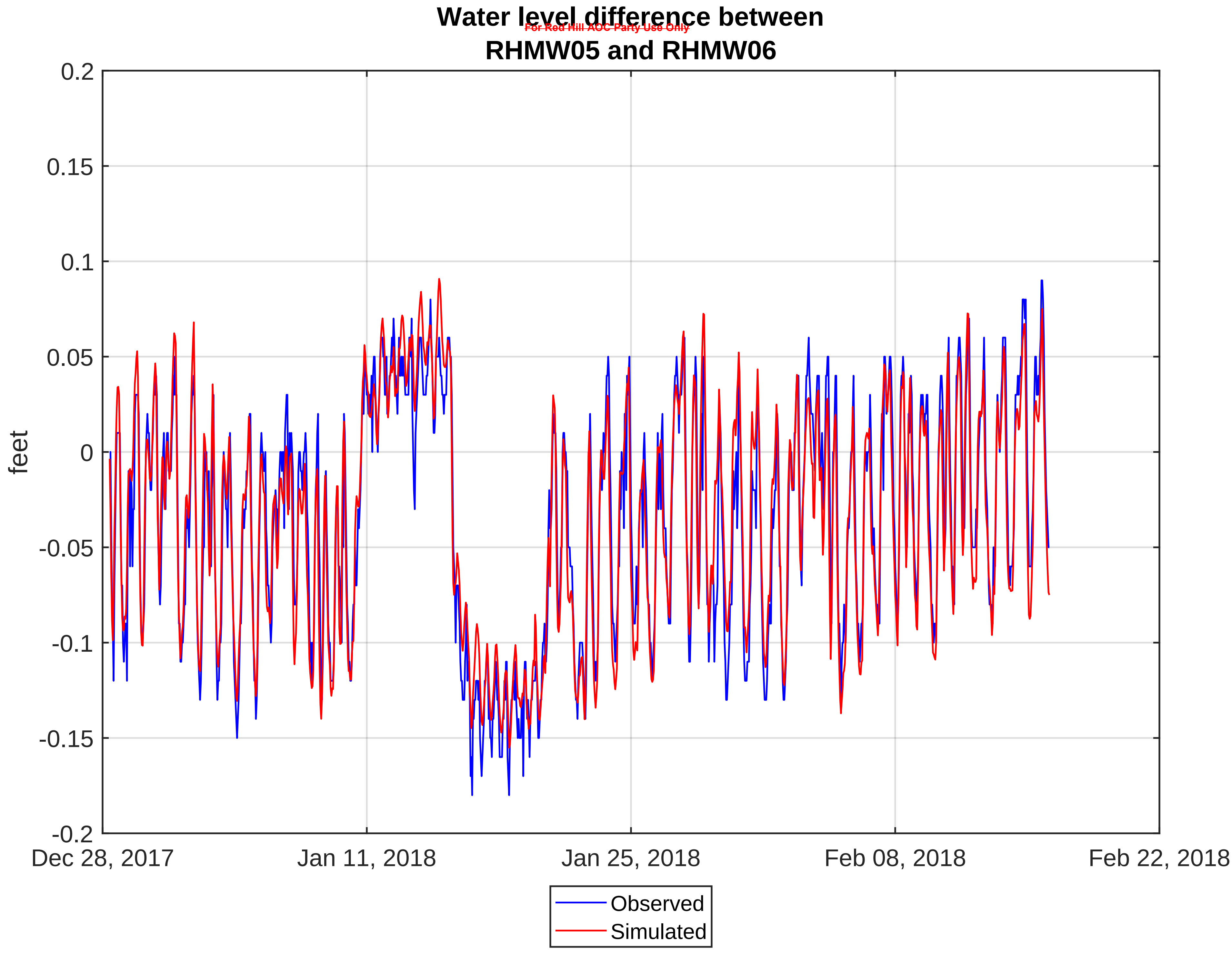




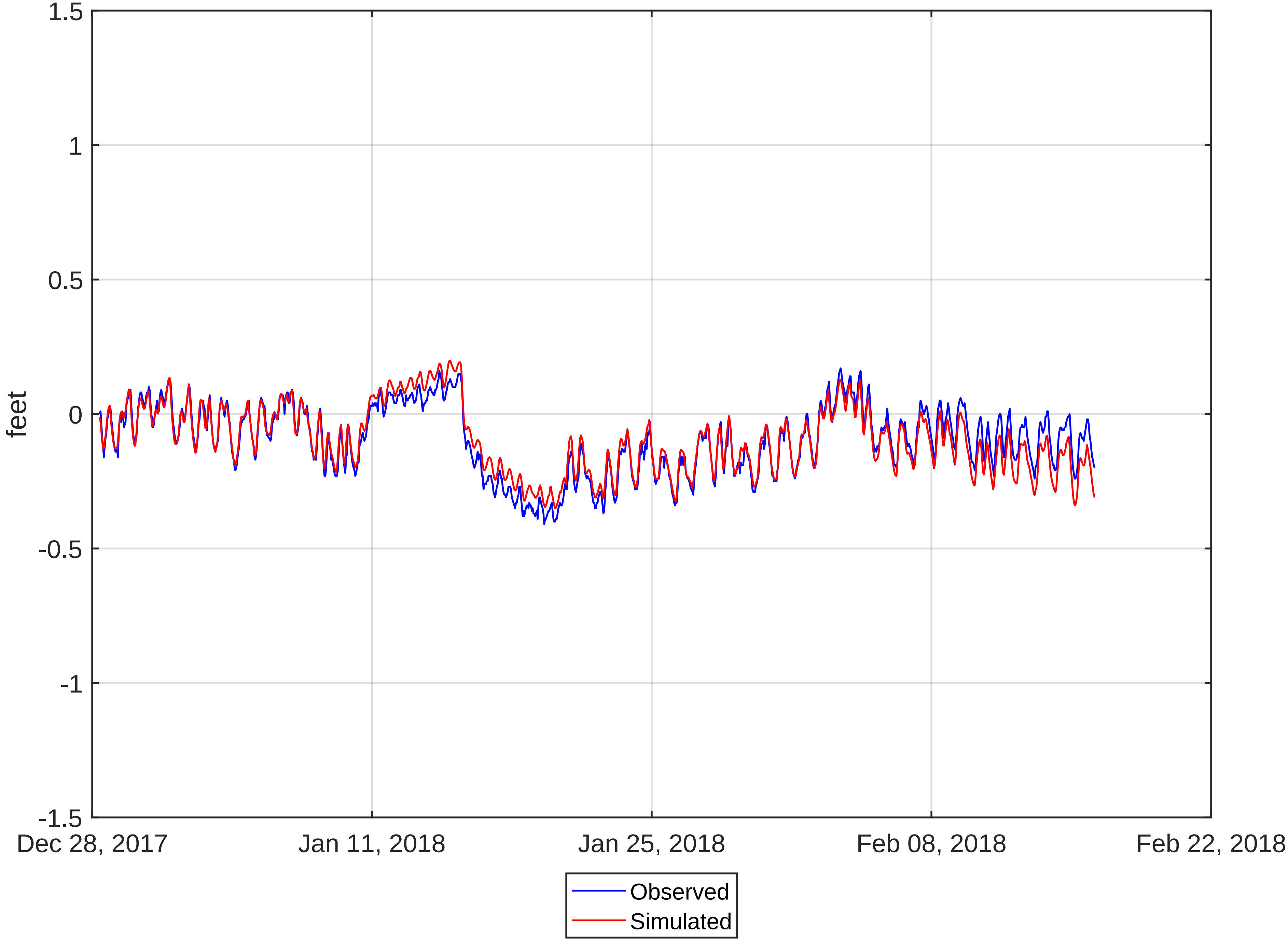
Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and Moanalua Deep
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and Moanalua DH43

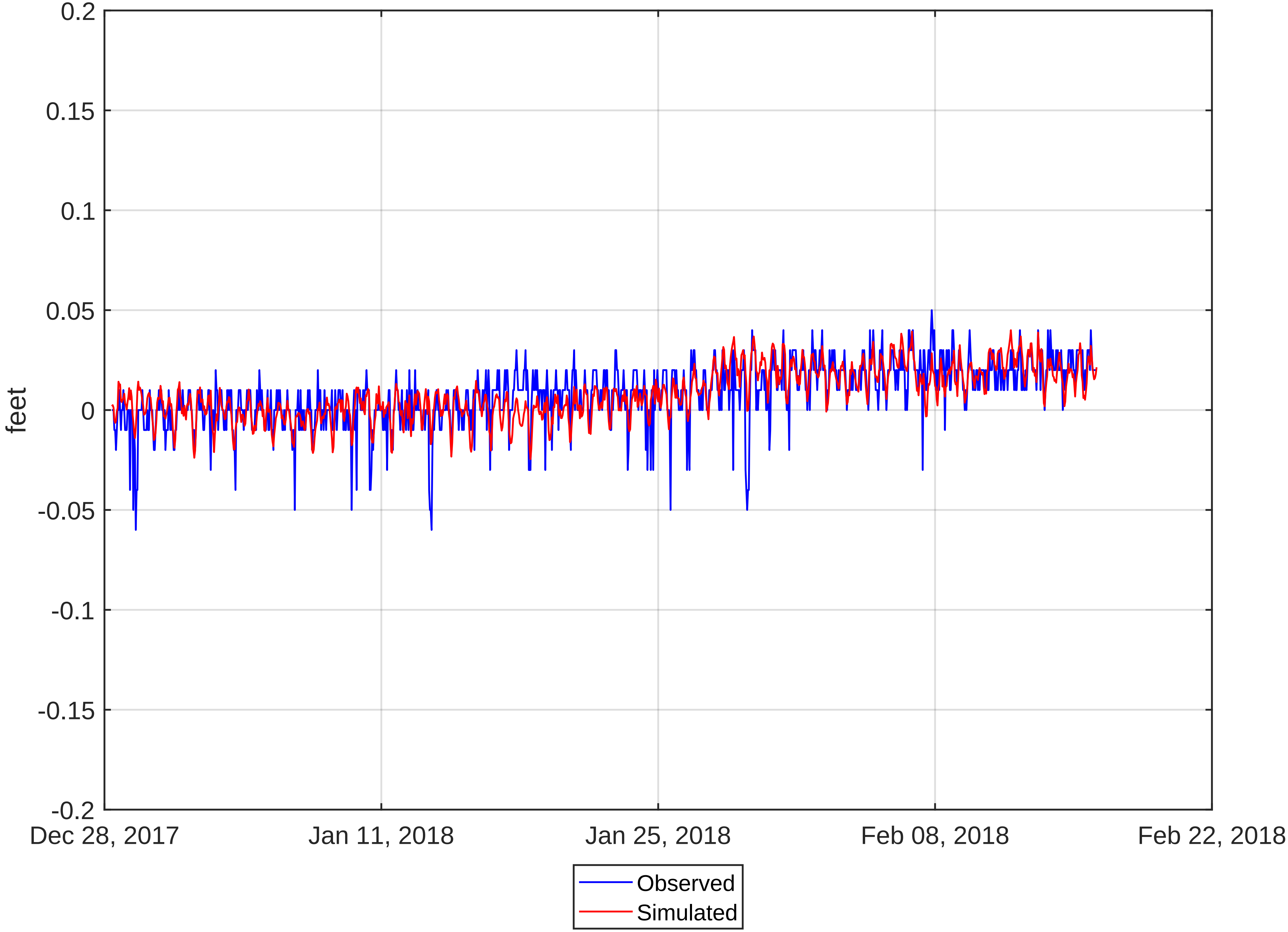


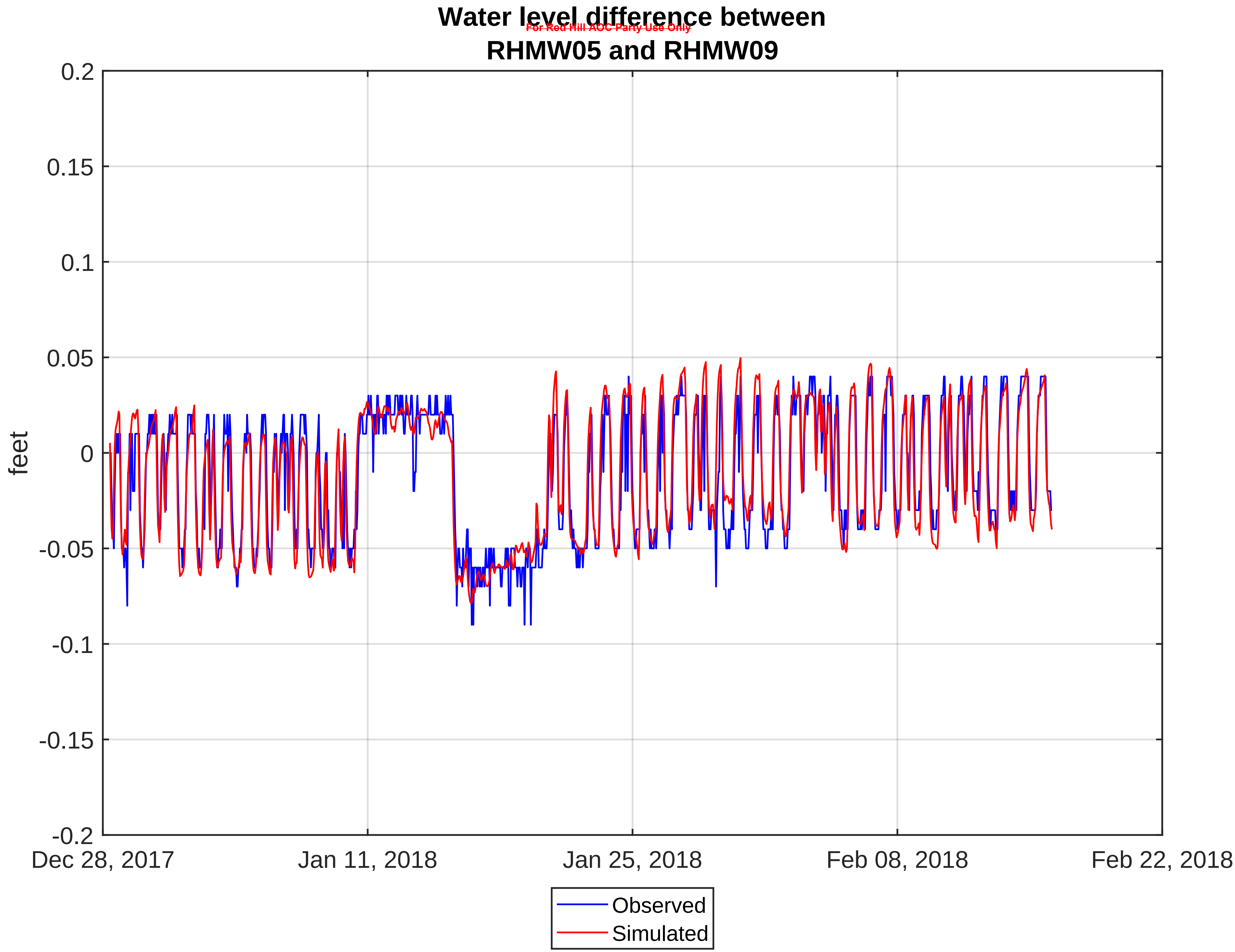

Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and RHMW06
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW05 and RHMW07

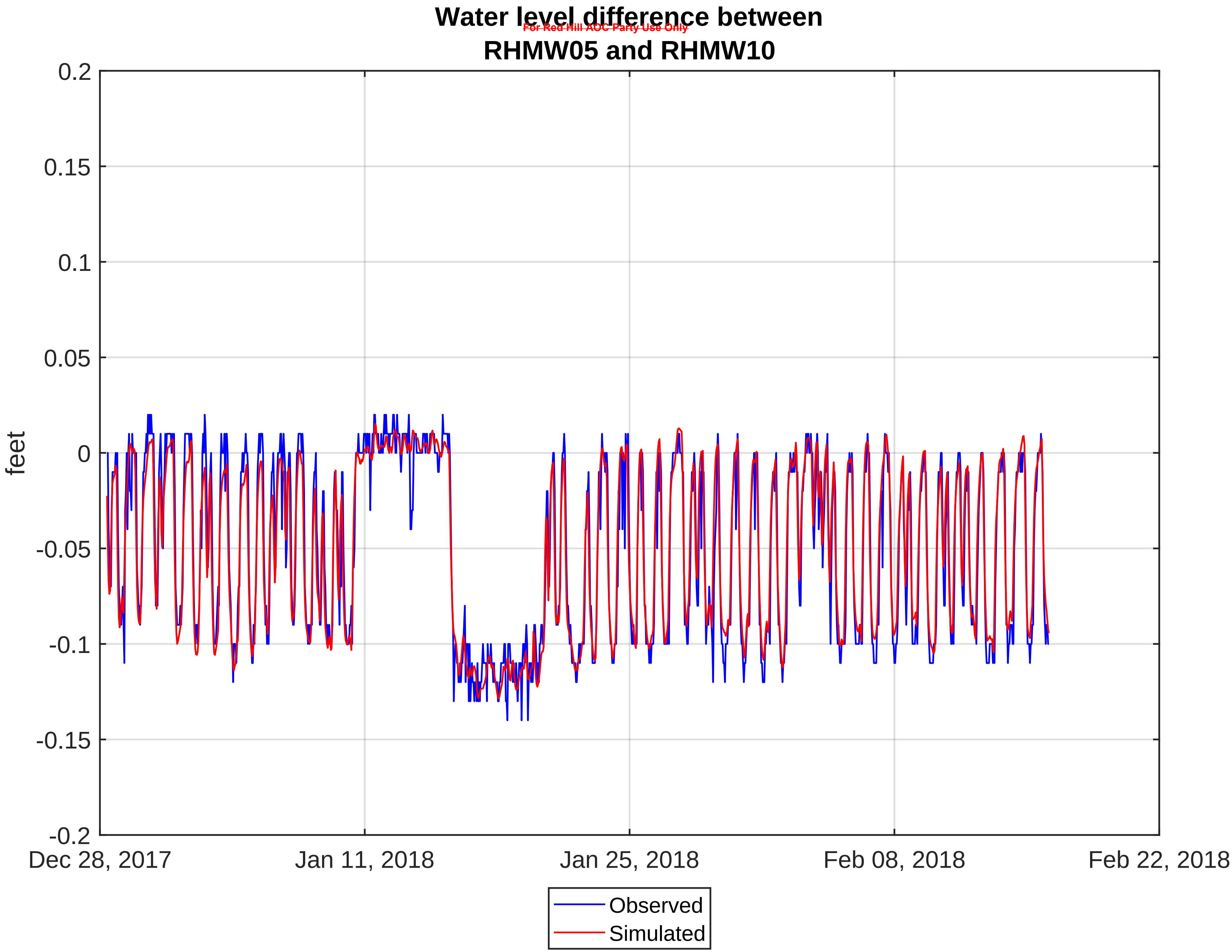


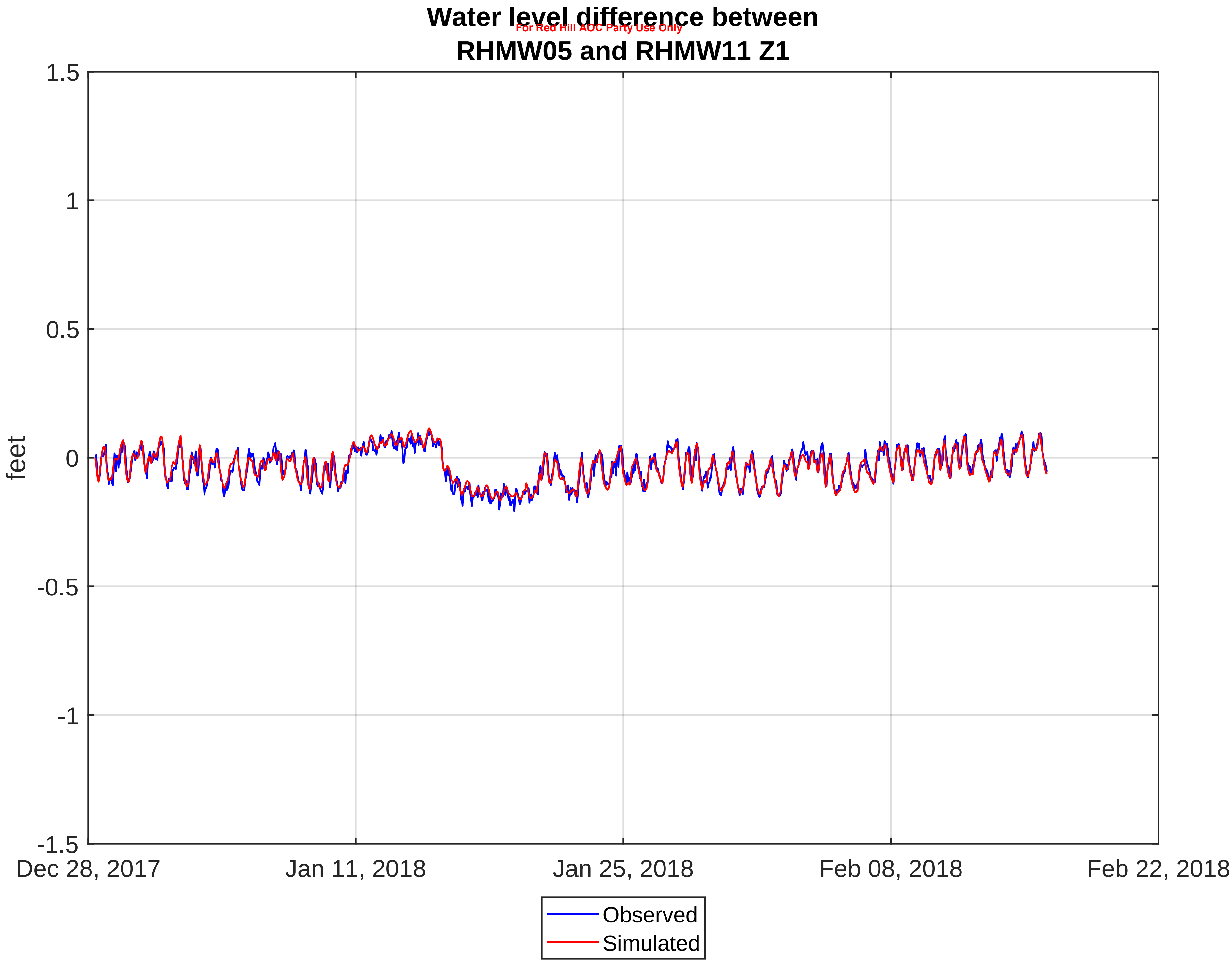
Water level difference between RHMW05 and RHMW08





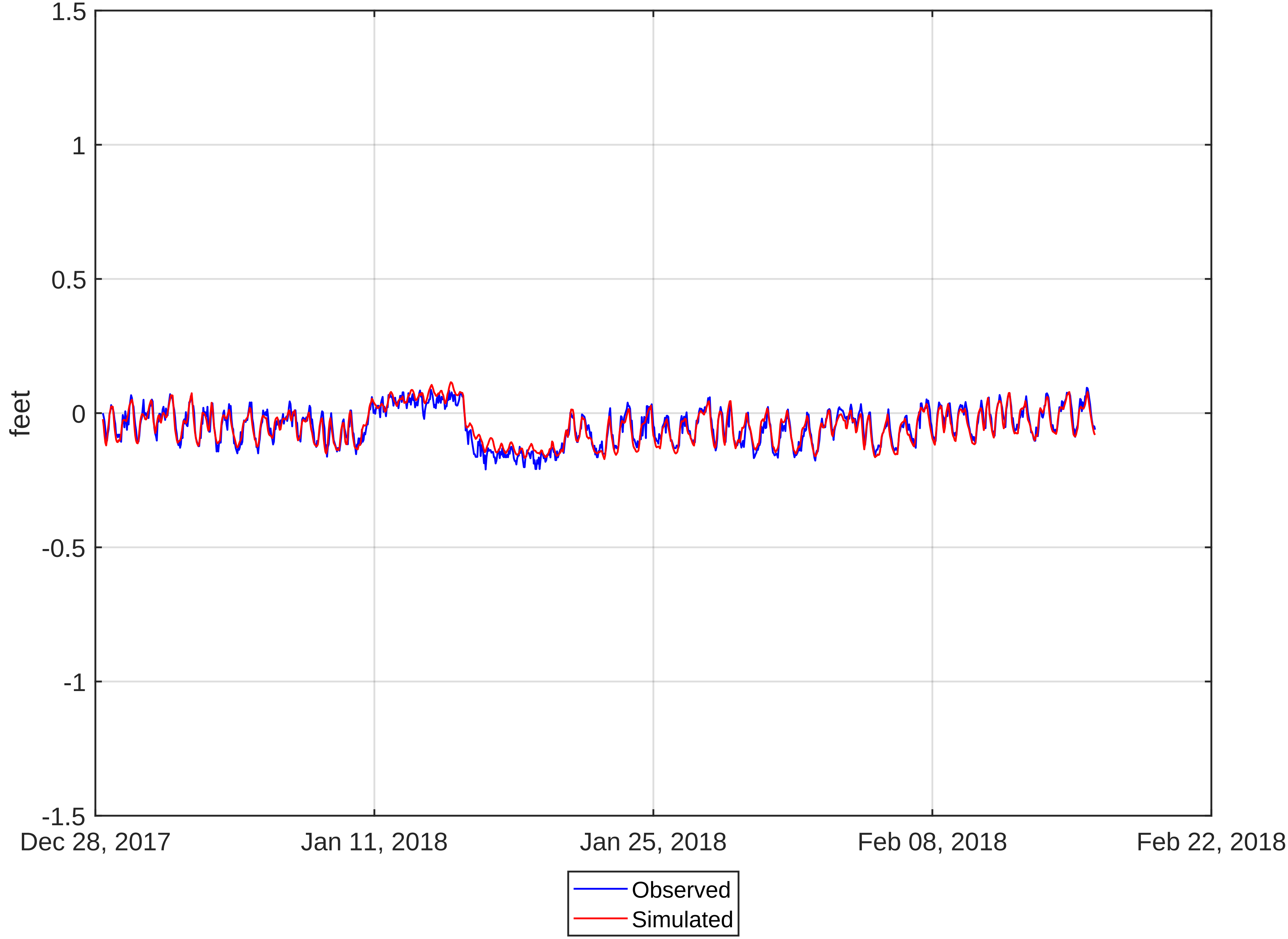
Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and RHMW09
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

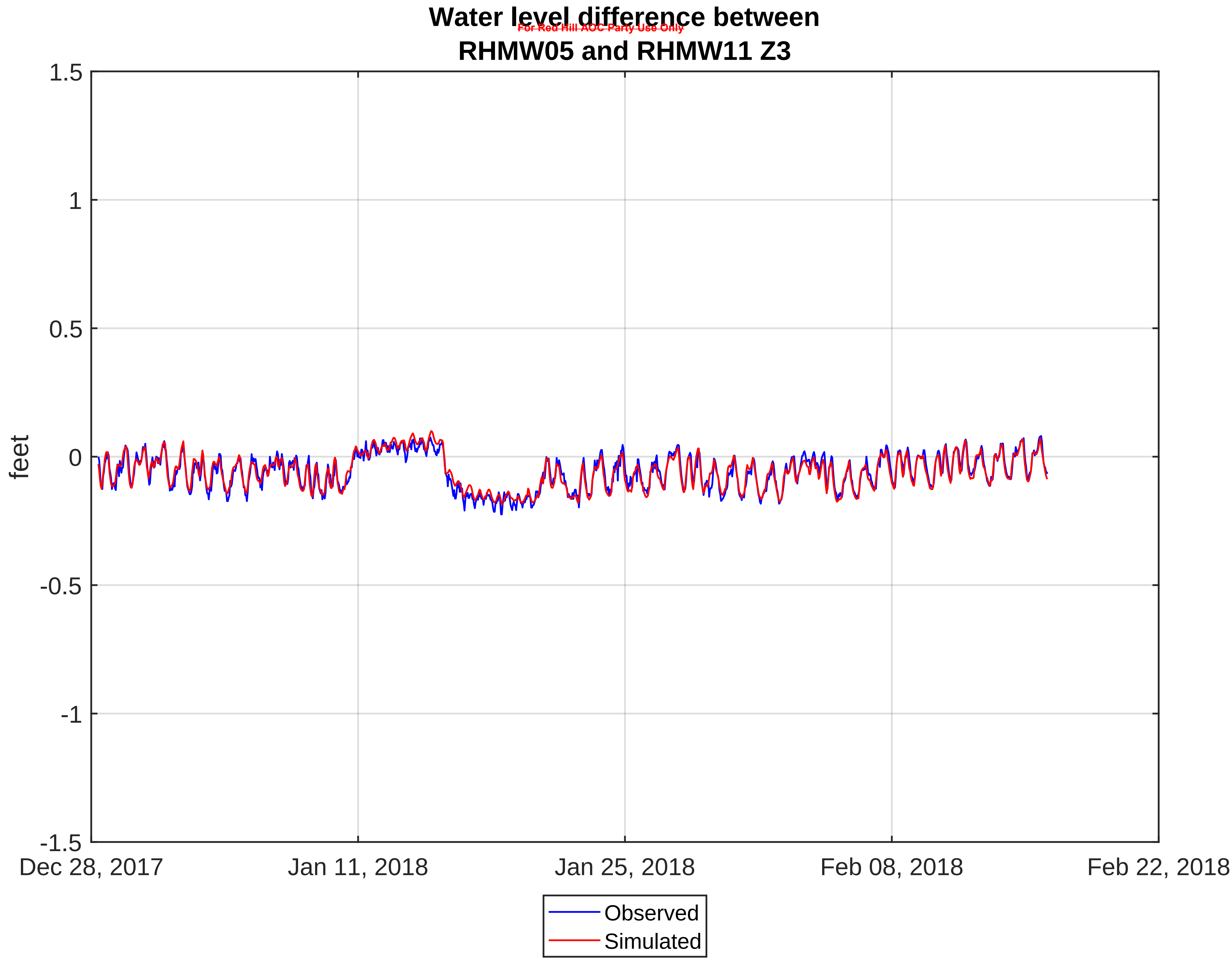

Water level difference between
RHMW05 and RHMW10
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



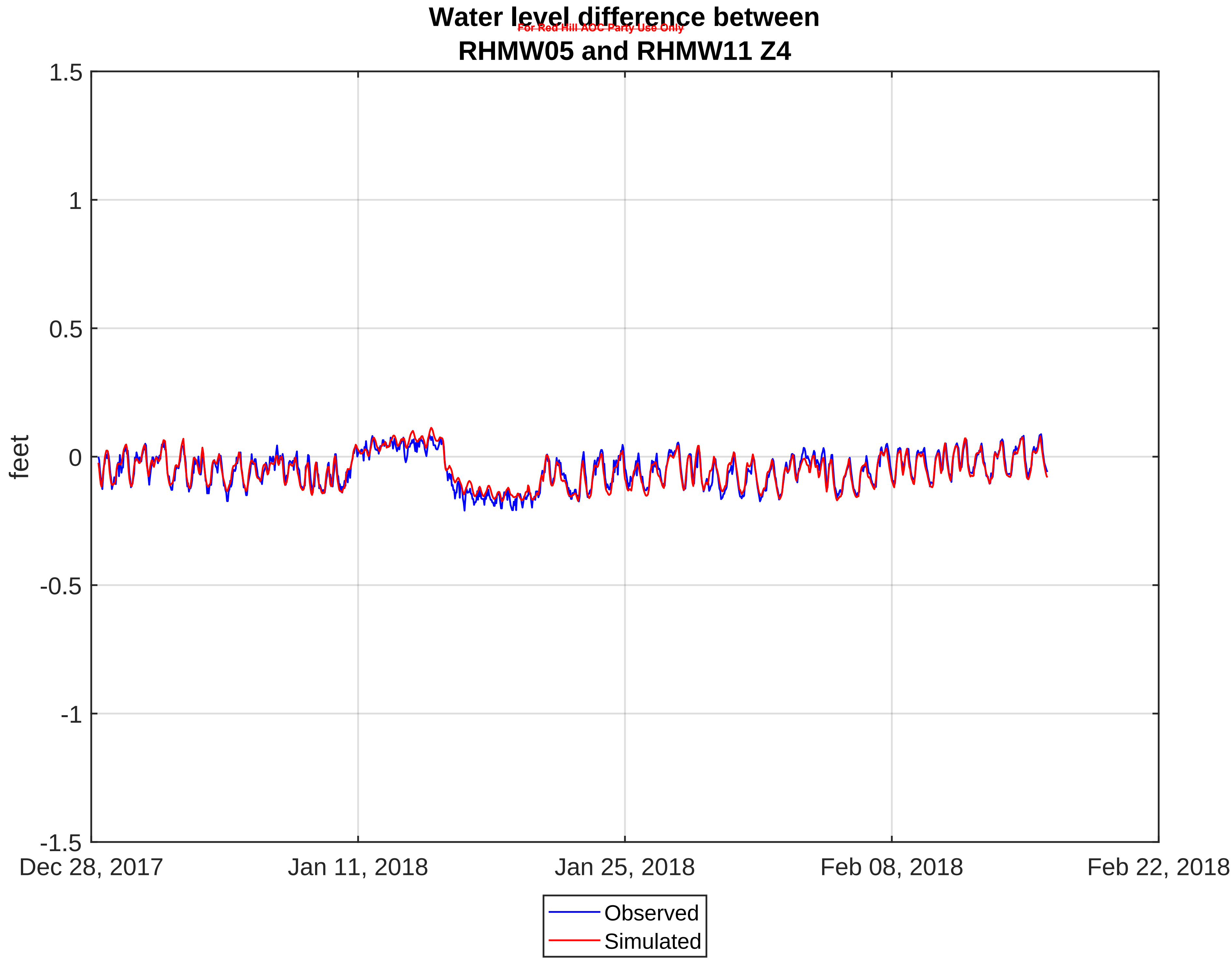
Water level difference between
RHMW05 and RHMW11 Z1
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW05 and RHMW11 Z2

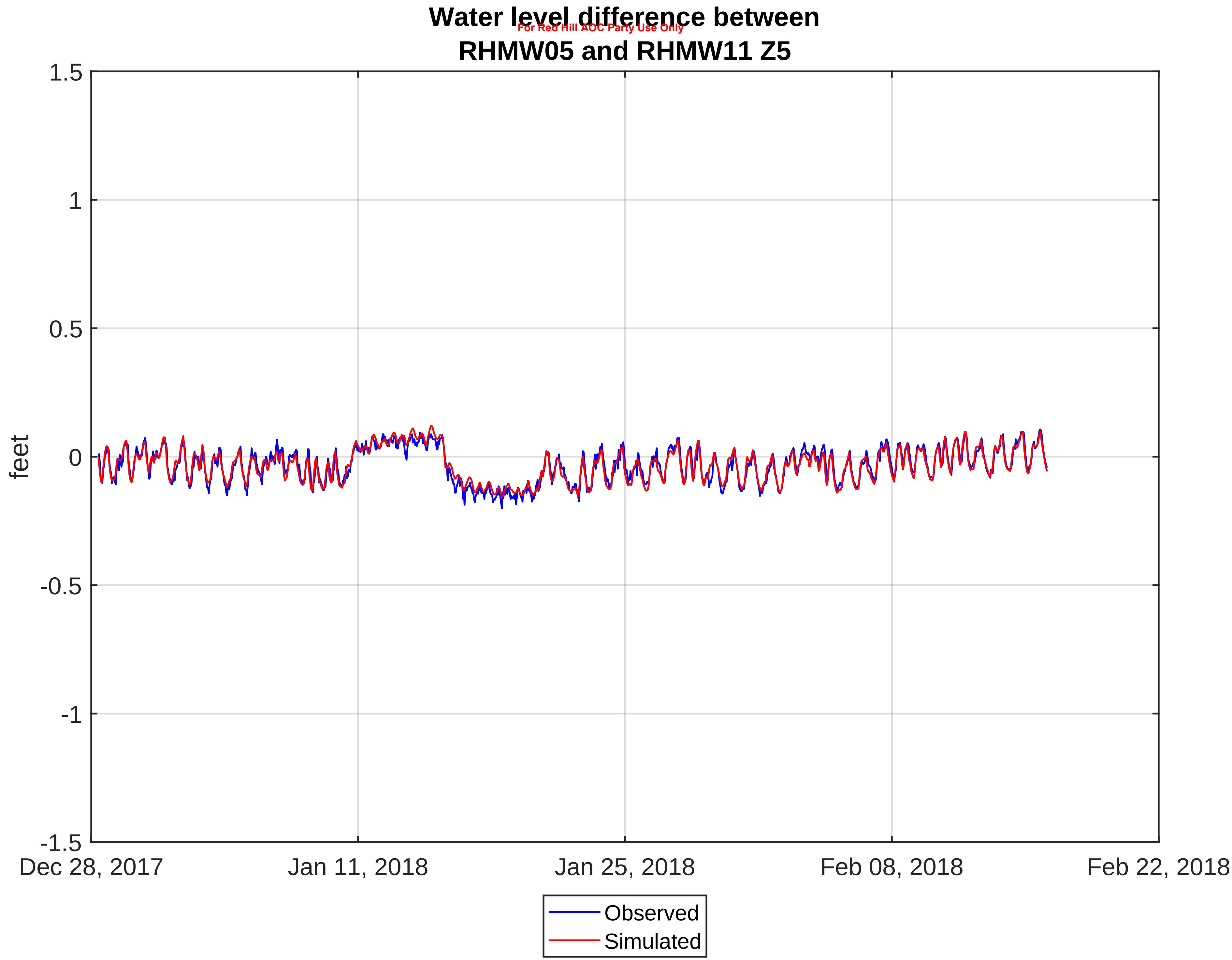




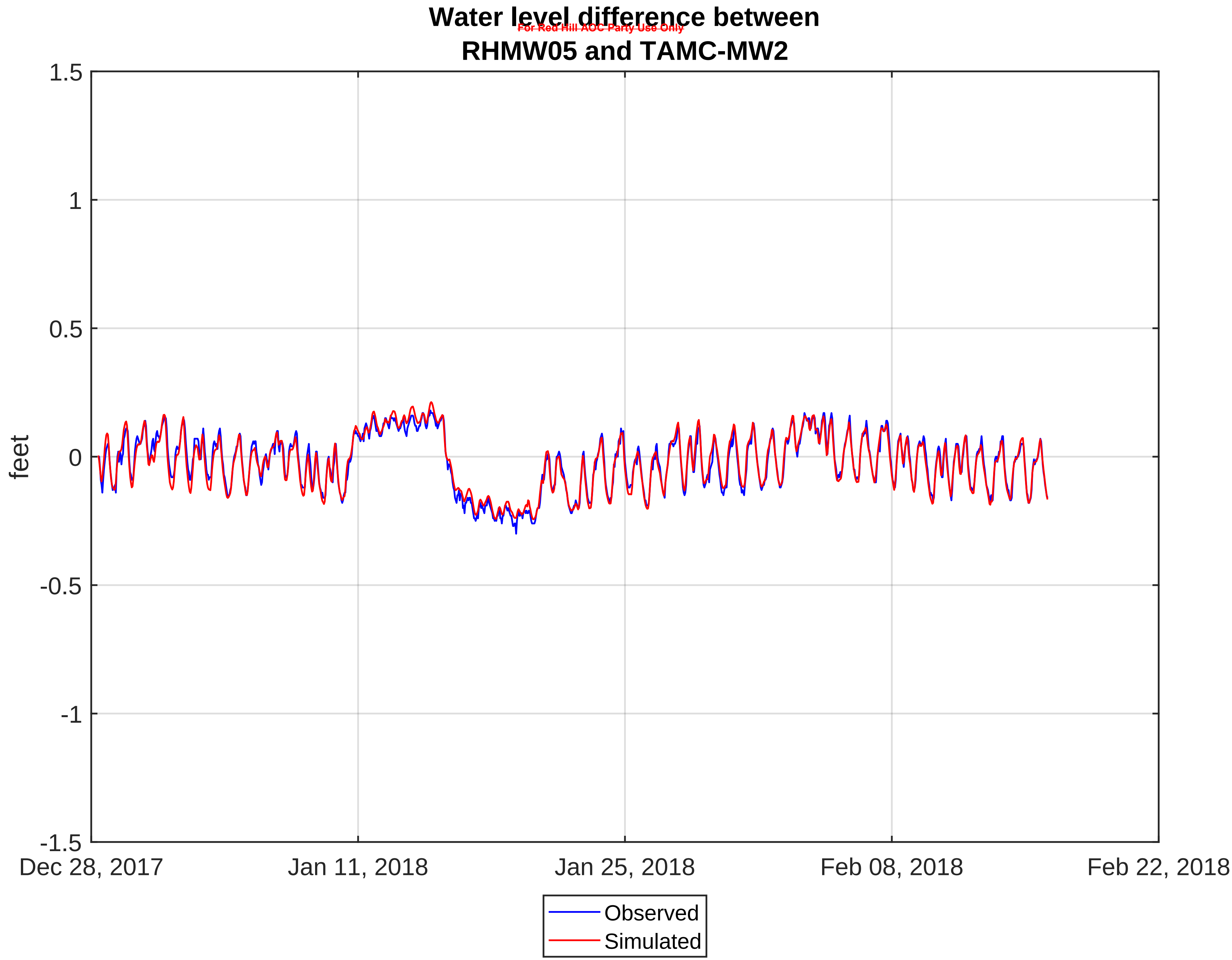
Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and RHMW11 Z3
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and RHMW11 Z4
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

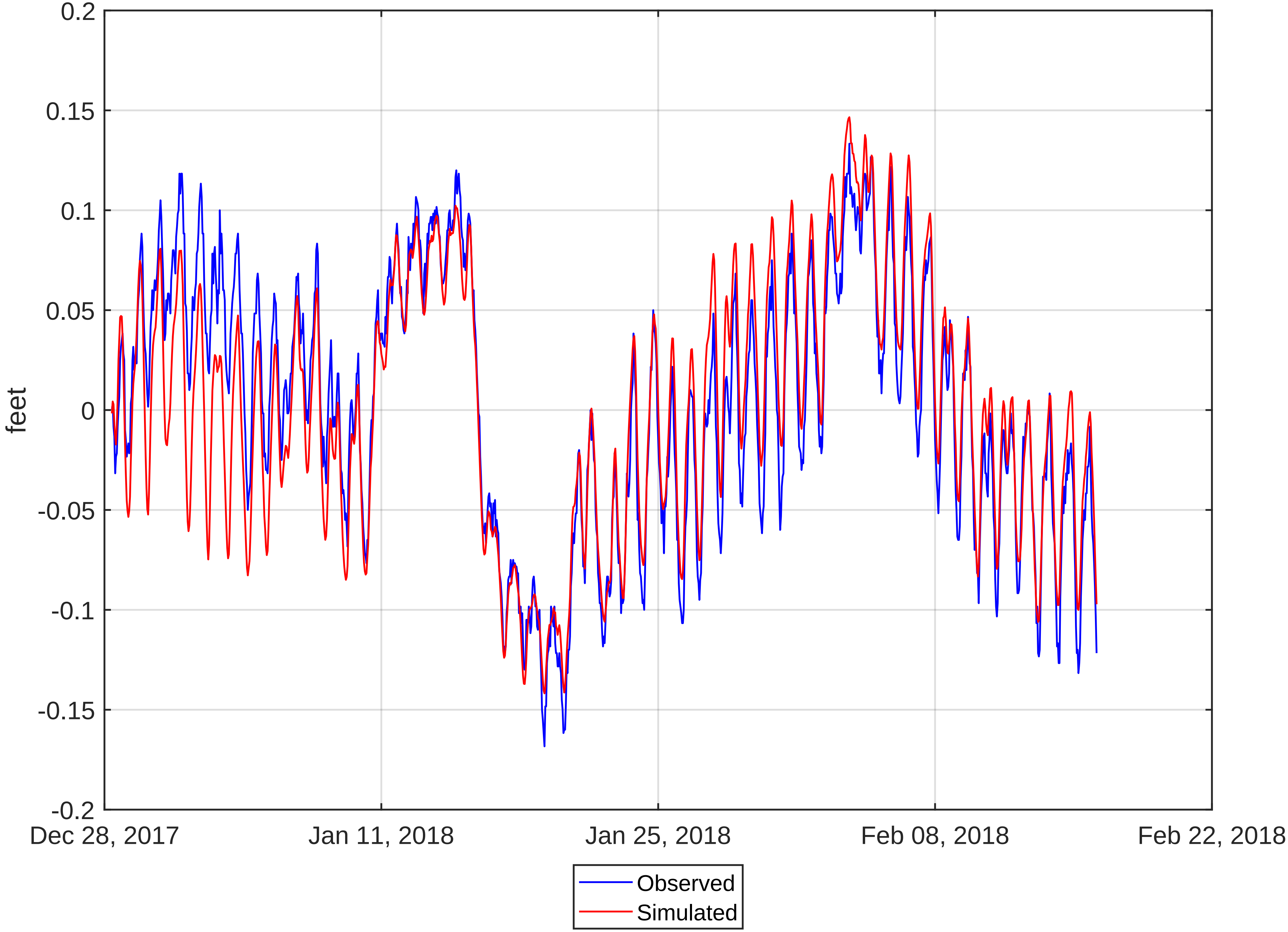


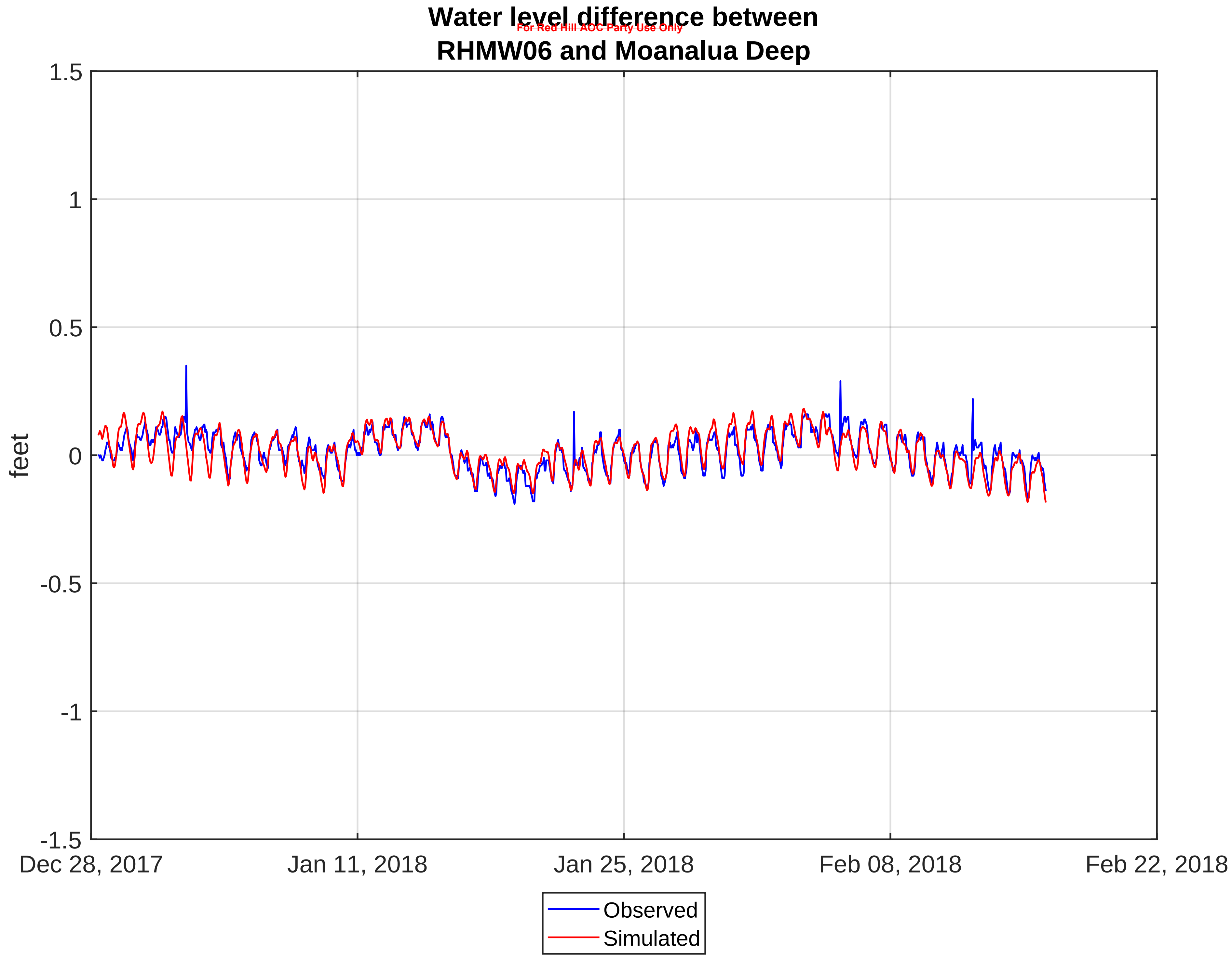
Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and RHMW11 Z5
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
RHMW05 and TAMC-MW2
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

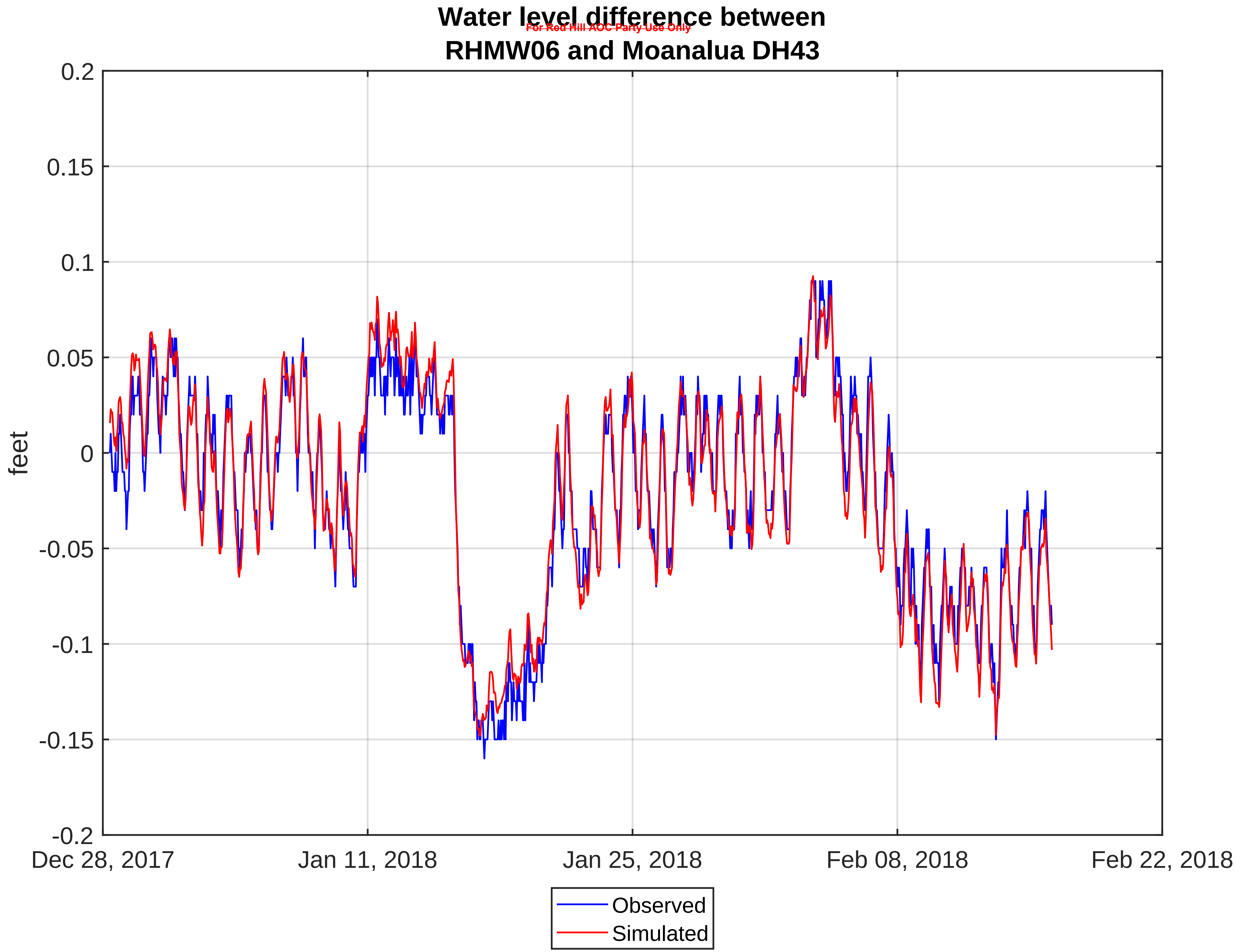
Water level difference between
RHMW06 and Manaiki T-24

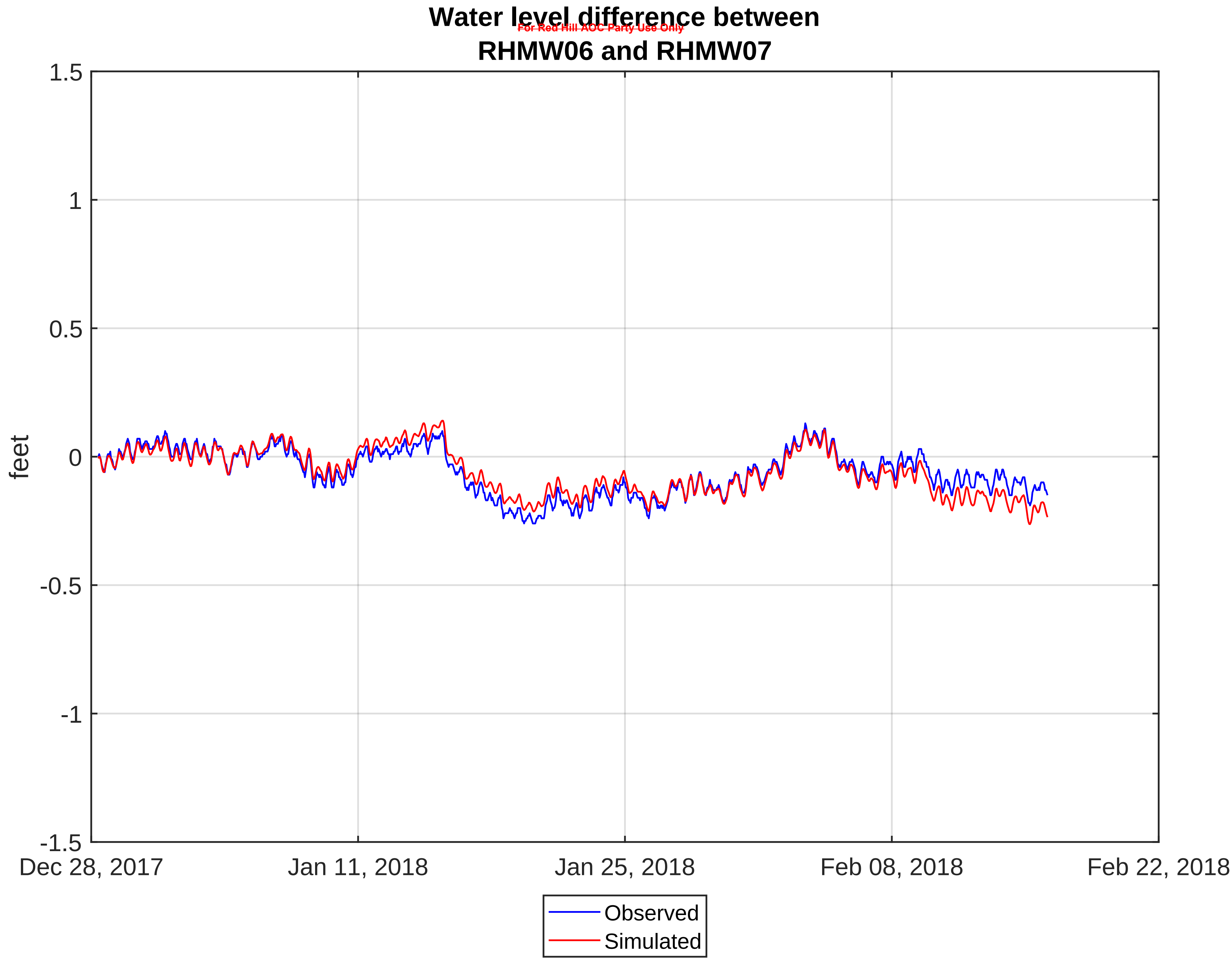


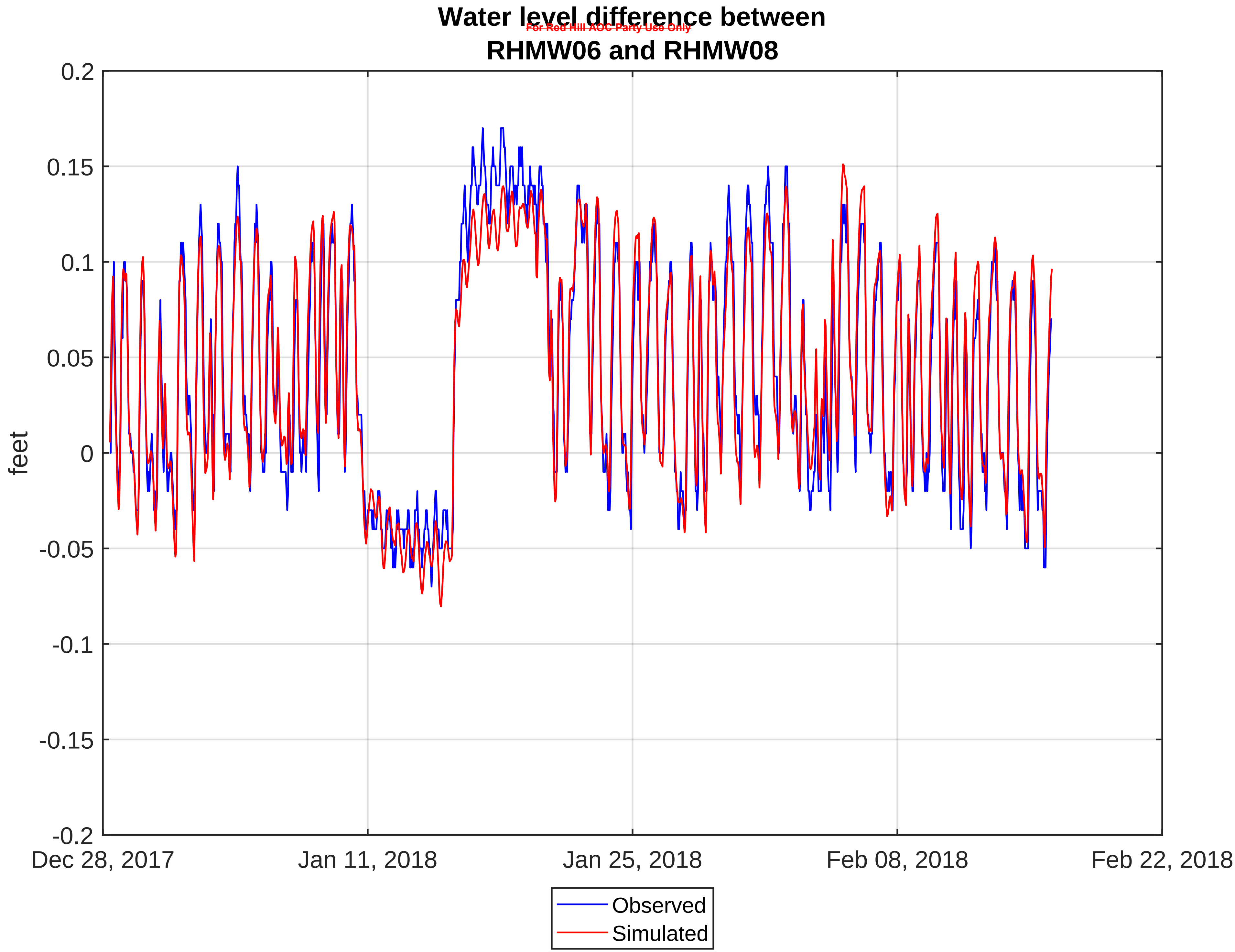


Water level difference between
RHMW06 and Moanalua Deep
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

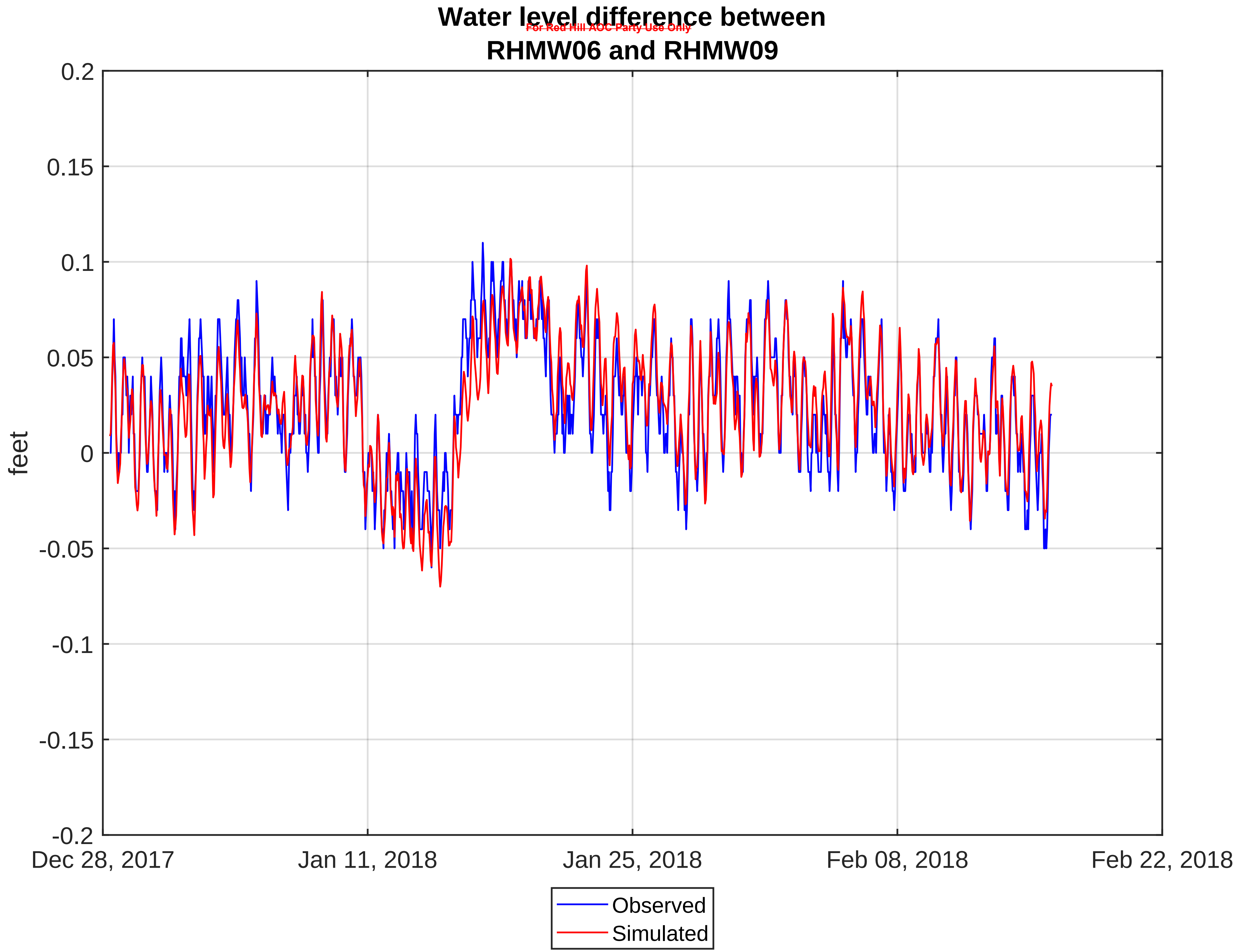
For Red Hill AOC Party Use Only

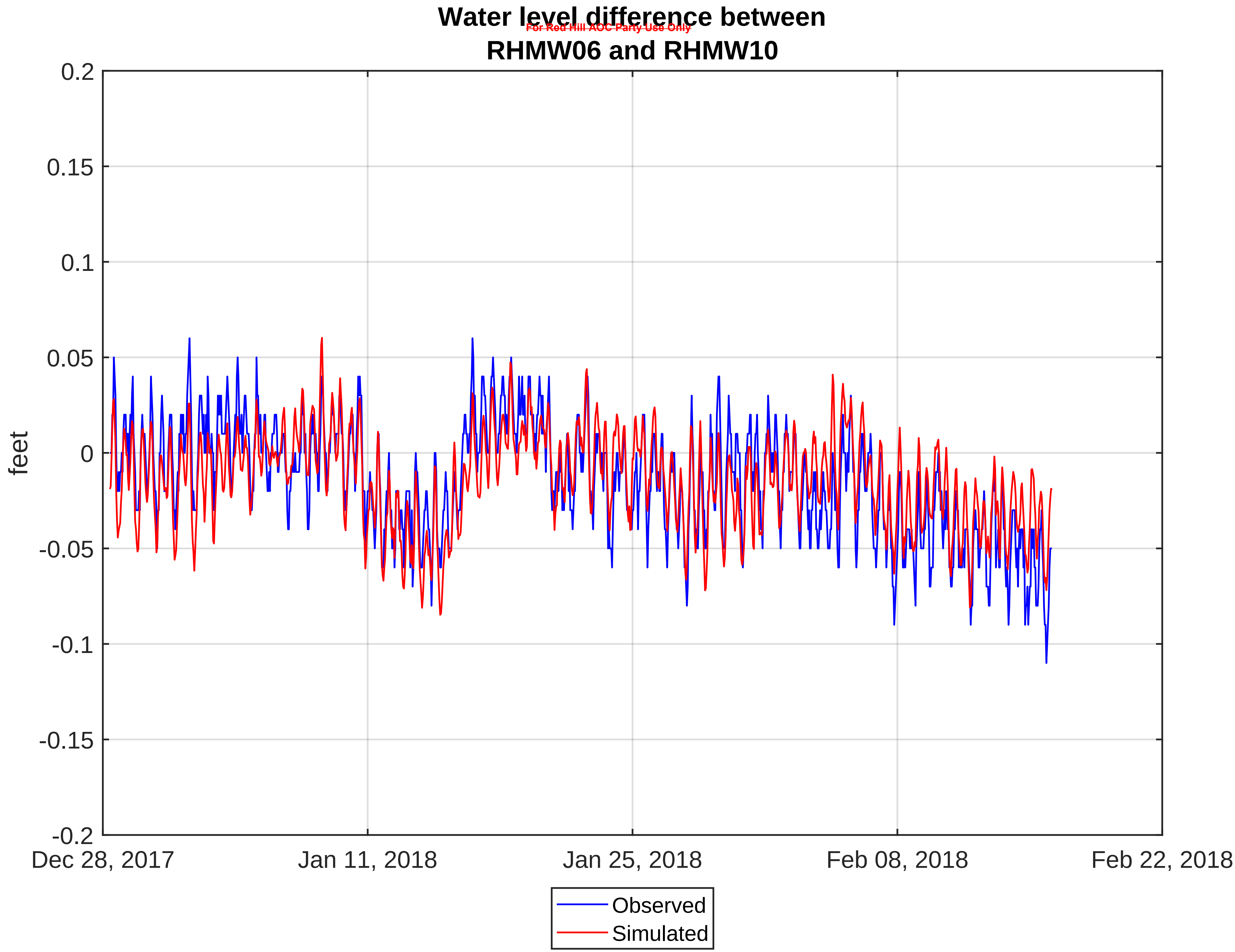



Water level difference between
RHMW06 and RHMW07
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



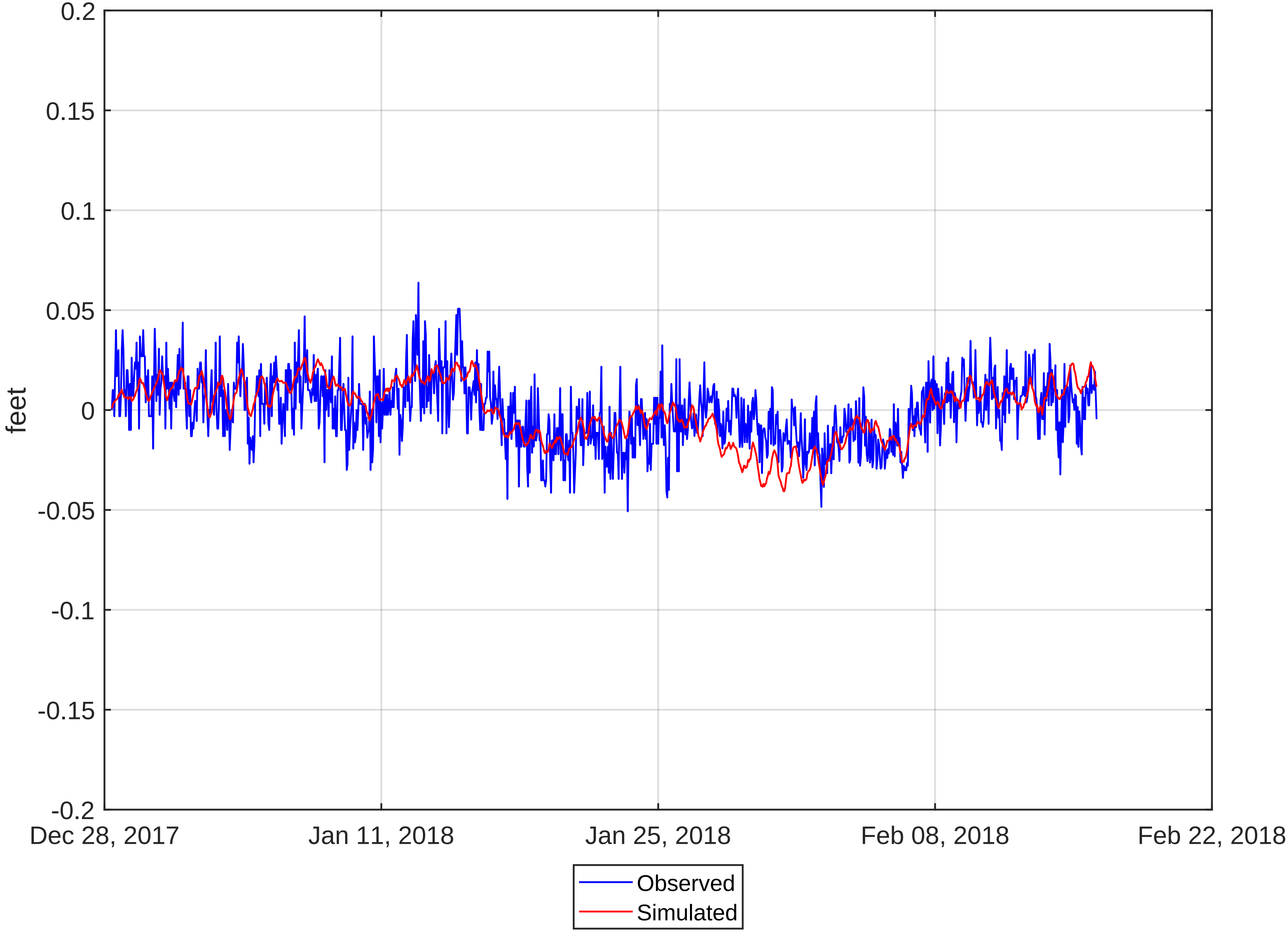
Water level difference between
RHMW06 and RHMW08
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

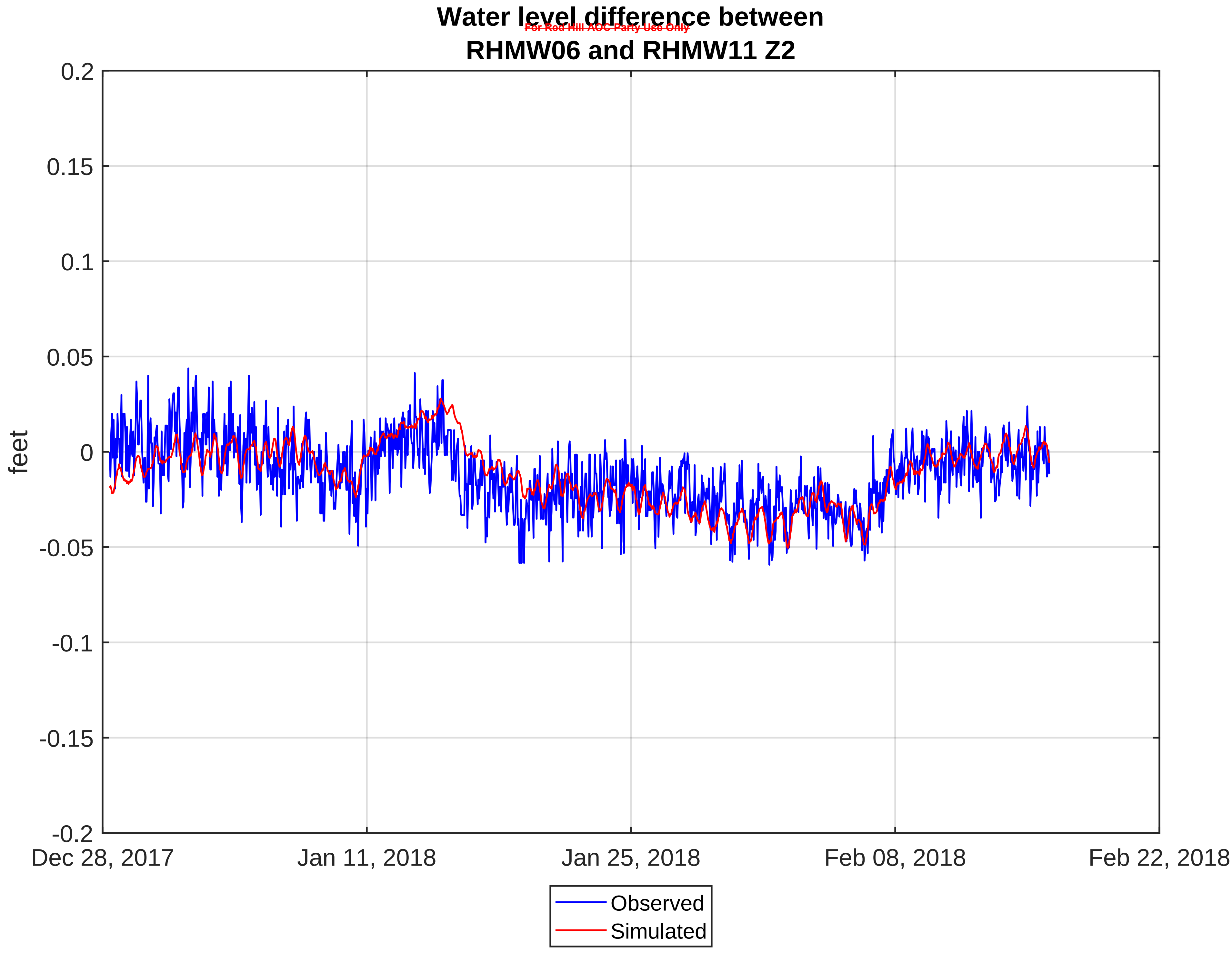

Water level difference between
RHMW06 and RHMW09
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

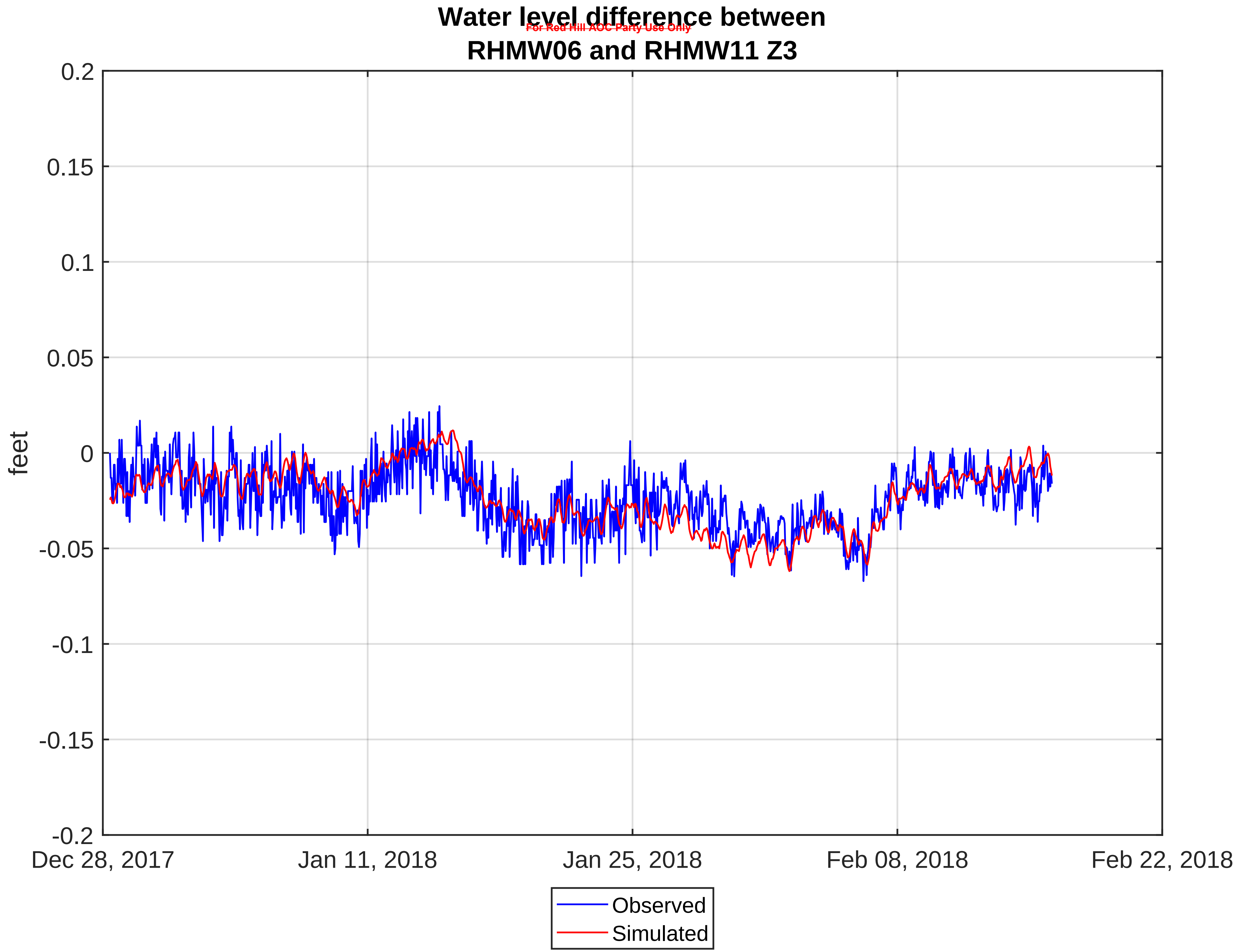


Water level difference between
For Red Hill AOC Party Use Only
RHMW06 and RHMW10
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

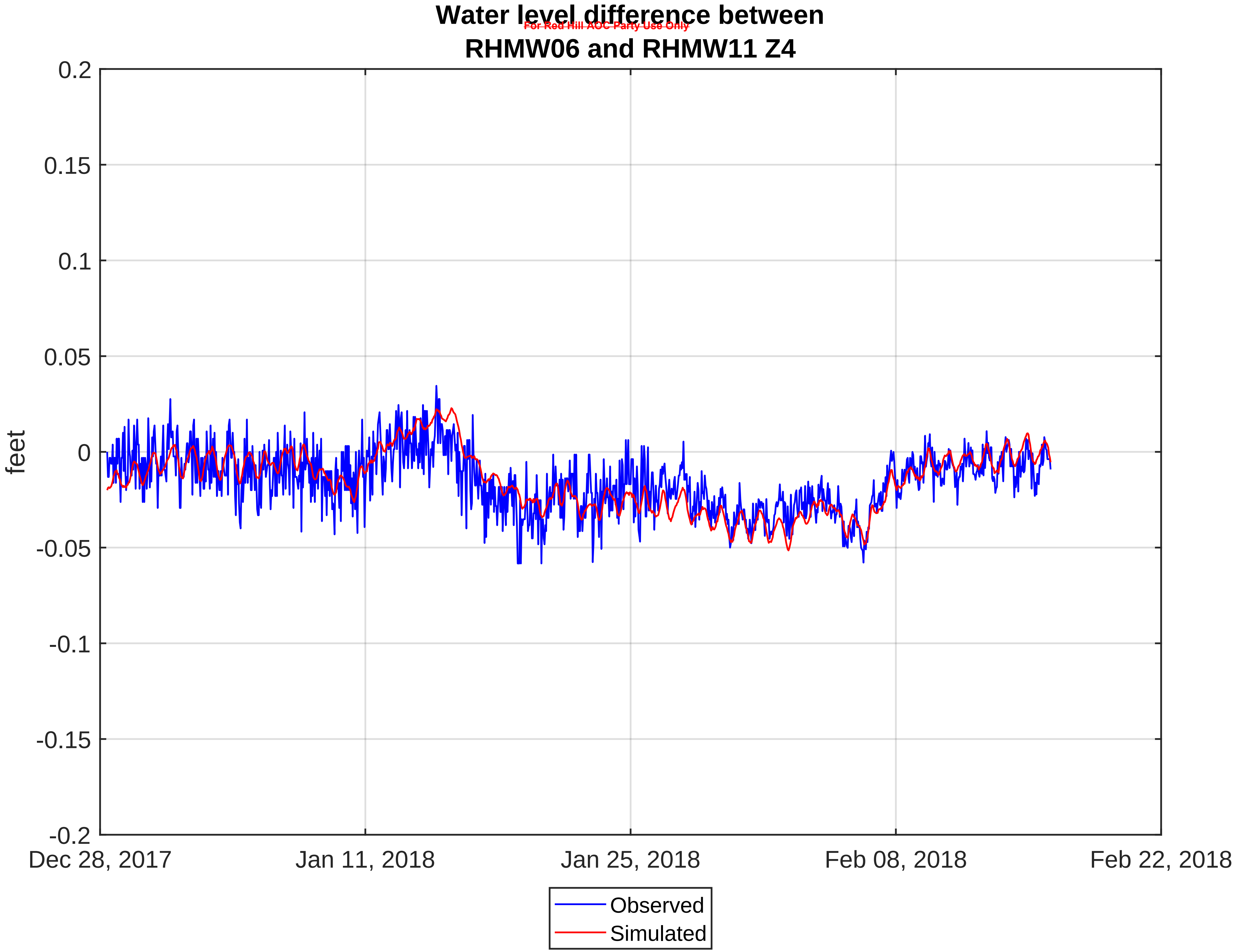
Water level difference between
RHMW06 and RHMW11 Z1



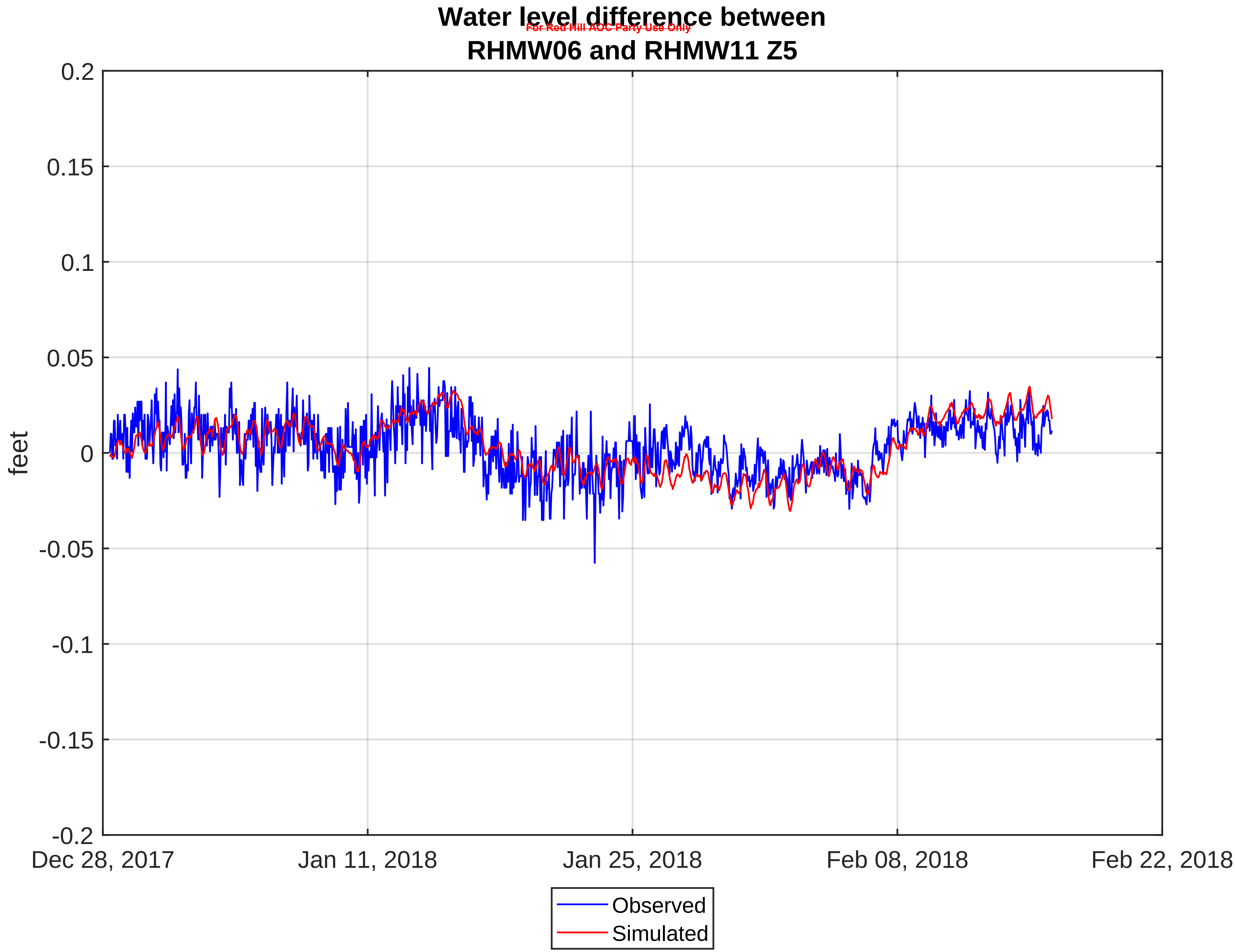

Water level difference between
For Red Hill AOC Party Use Only
RHMW06 and RHMW11 Z2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



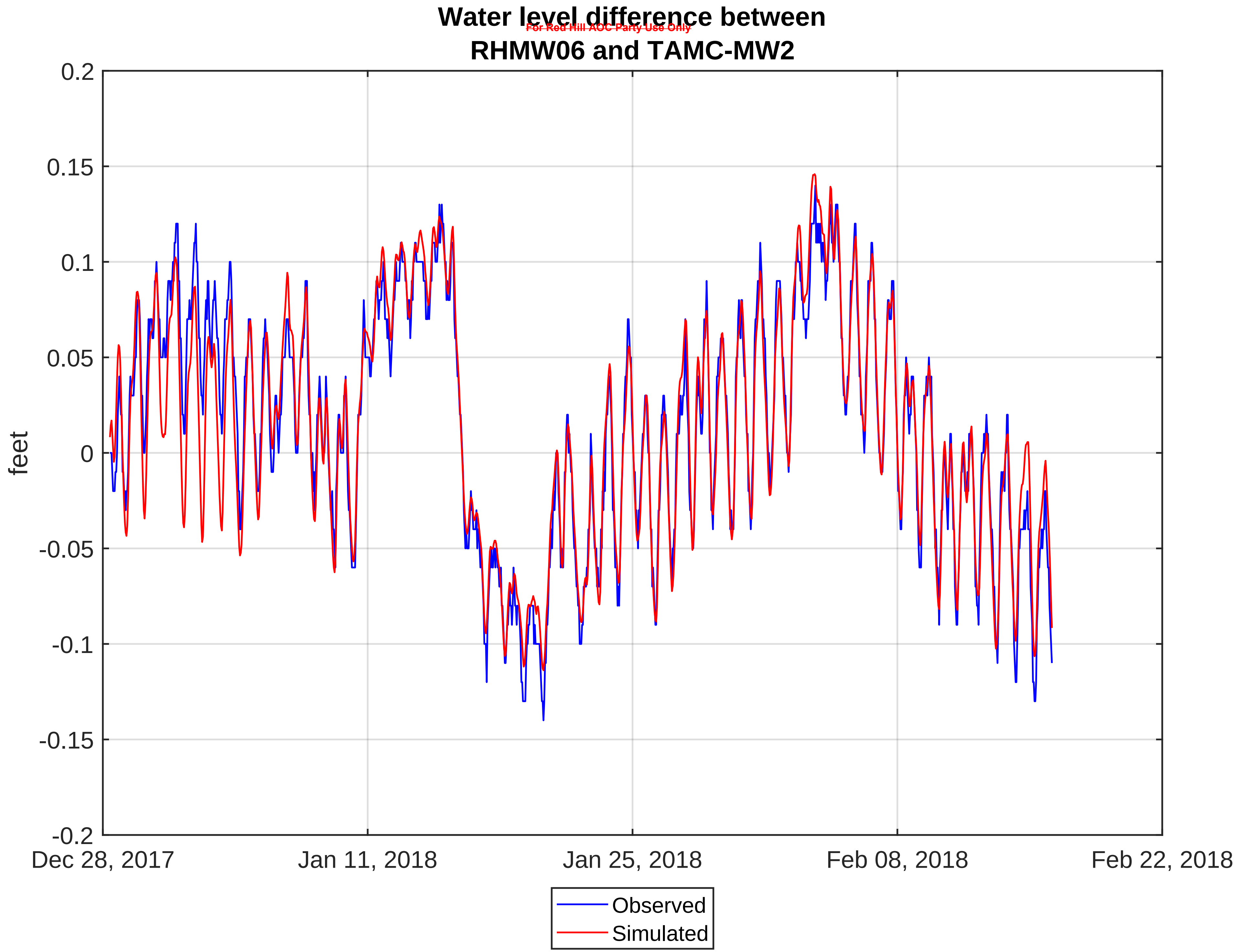
Water level difference between
For Red Hill AOC Party Use Only
RHMW06 and RHMW11 Z3
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



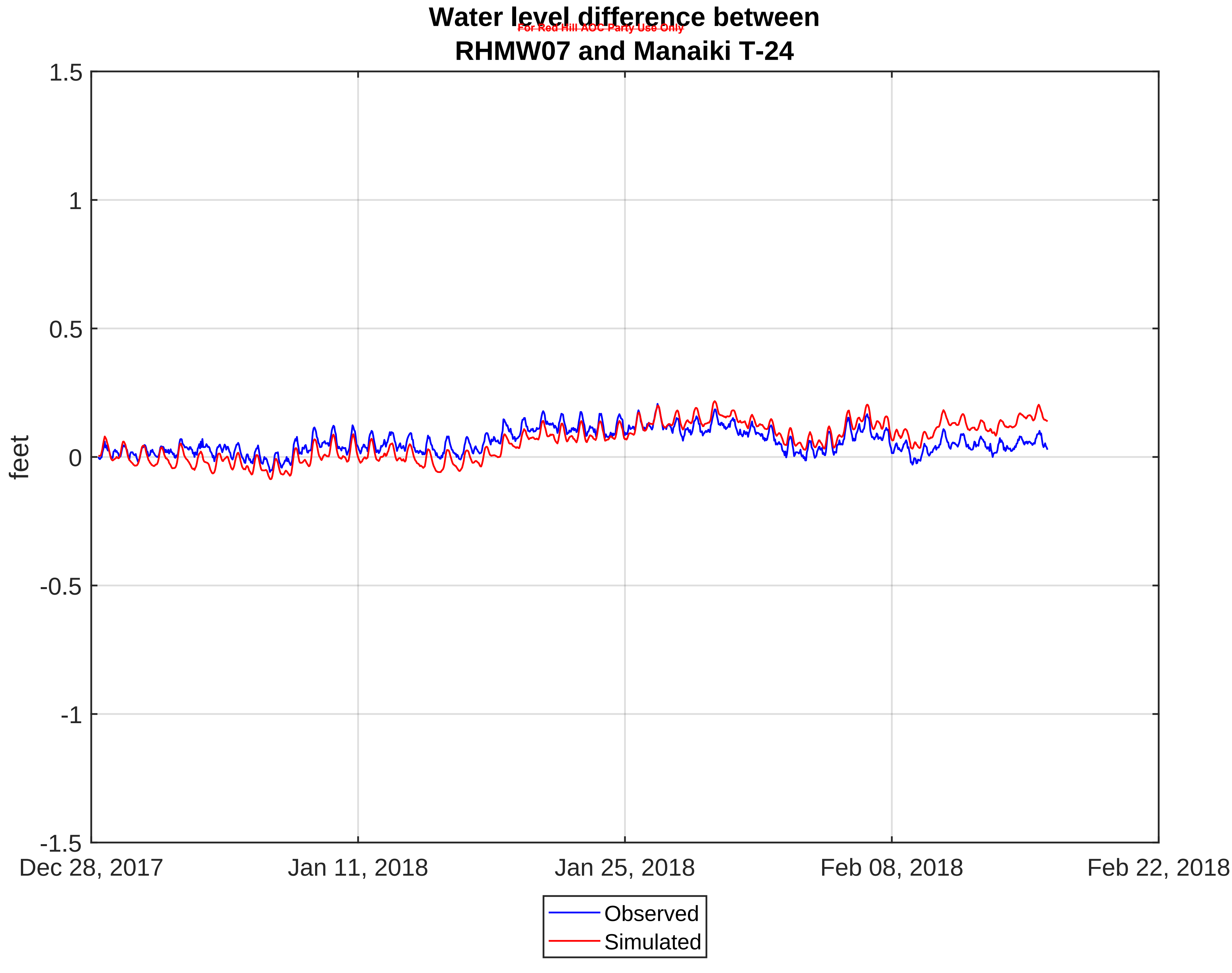
Water level difference between
For Red Hill AOC Party Use Only
RHMW06 and RHMW11 Z4
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

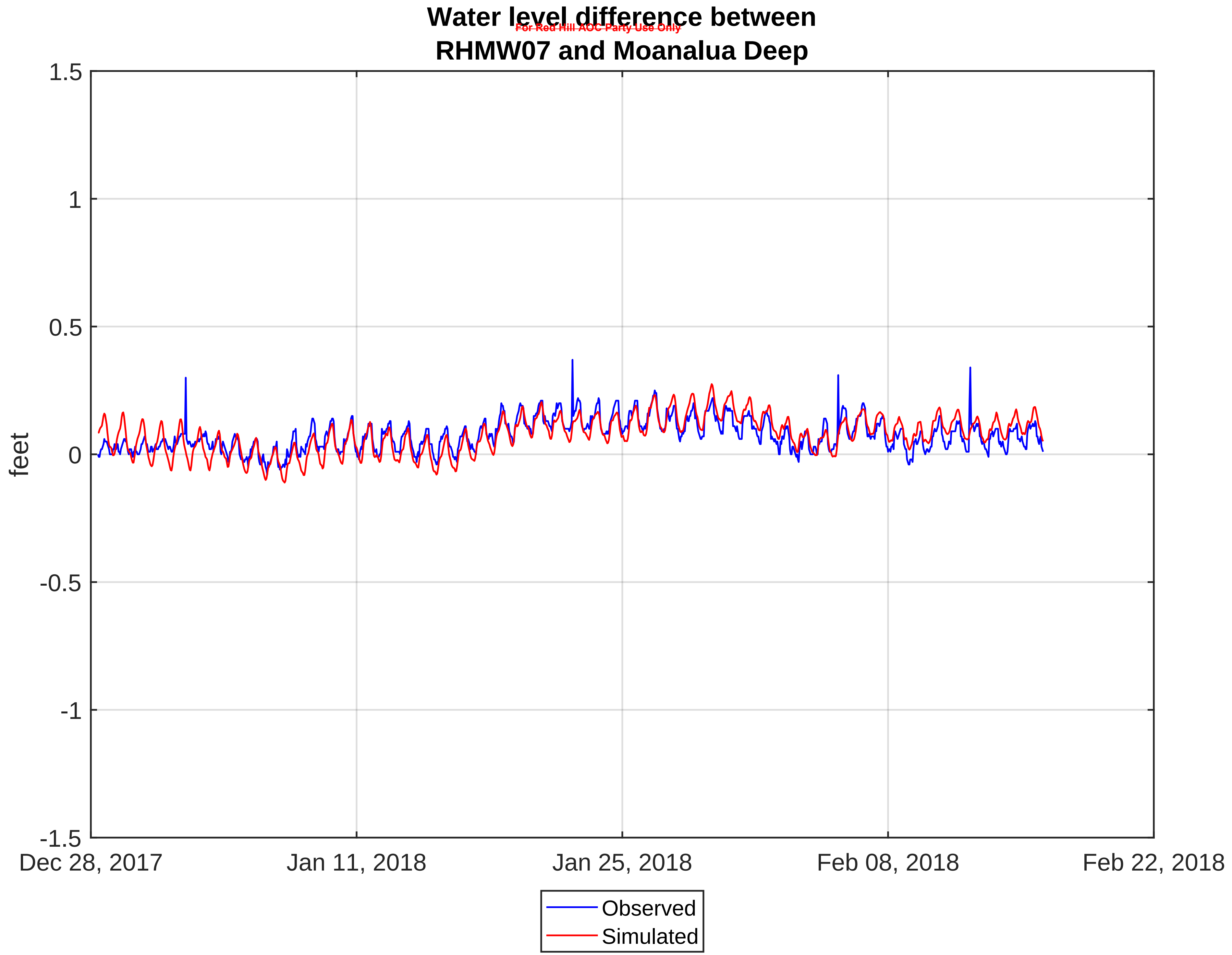


Water level difference between
For Red Hill AOC Party Use Only
RHMW06 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

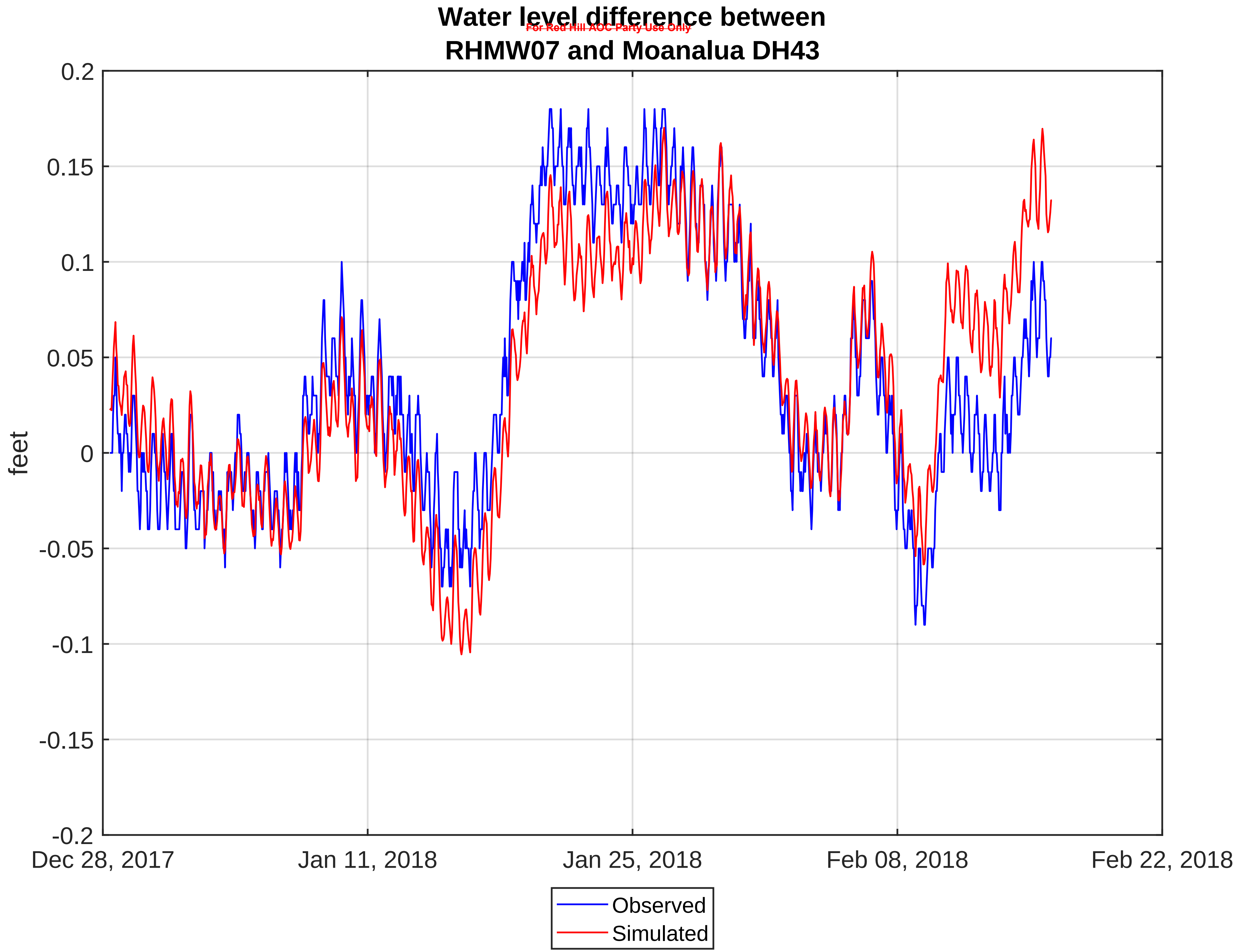


Water level difference between
For Red Hill AOC Party Use Only
RHMW06 and TAMC-MW2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

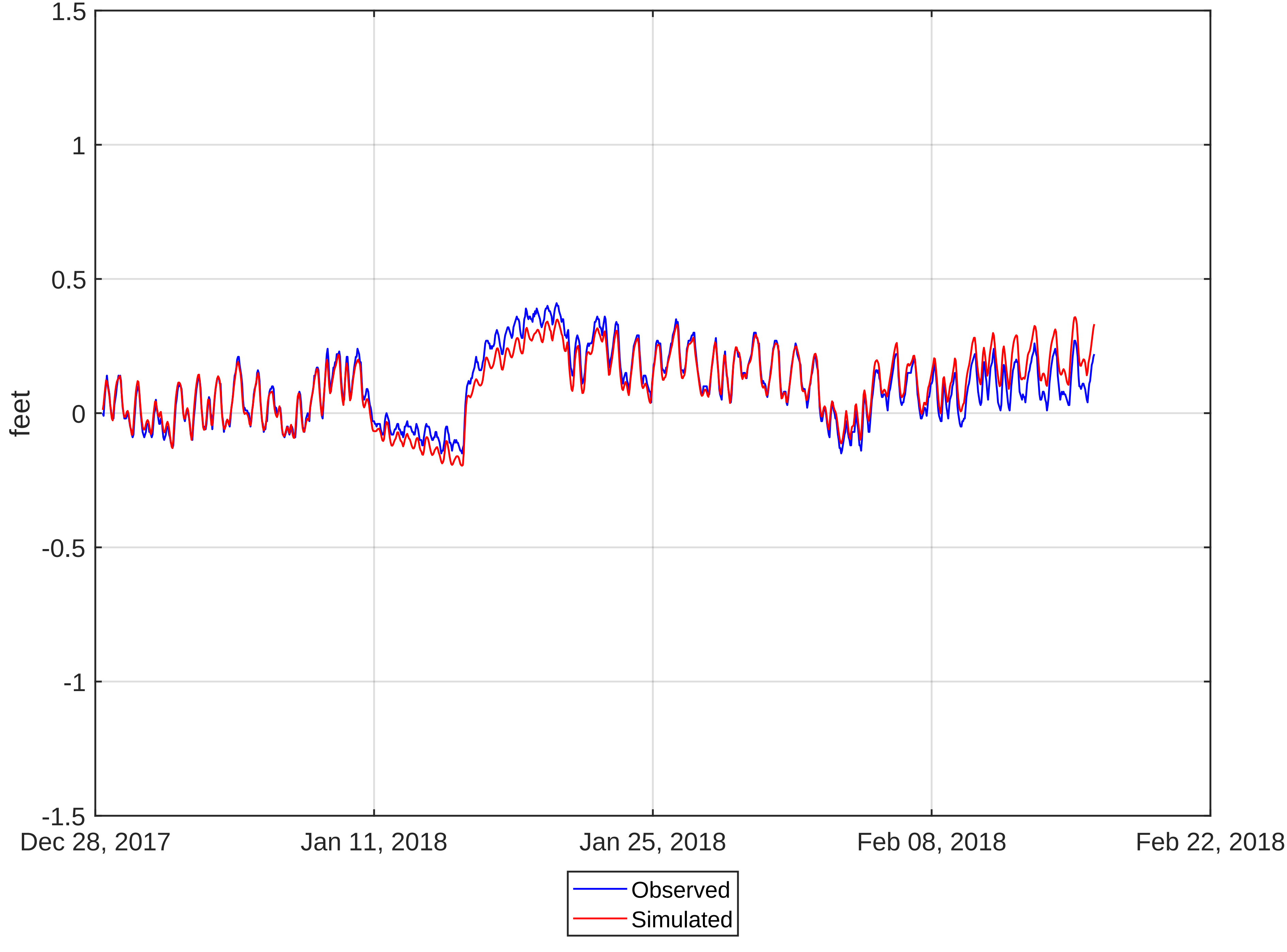

Water level difference between
RHMW07 and Manaiki T-24
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

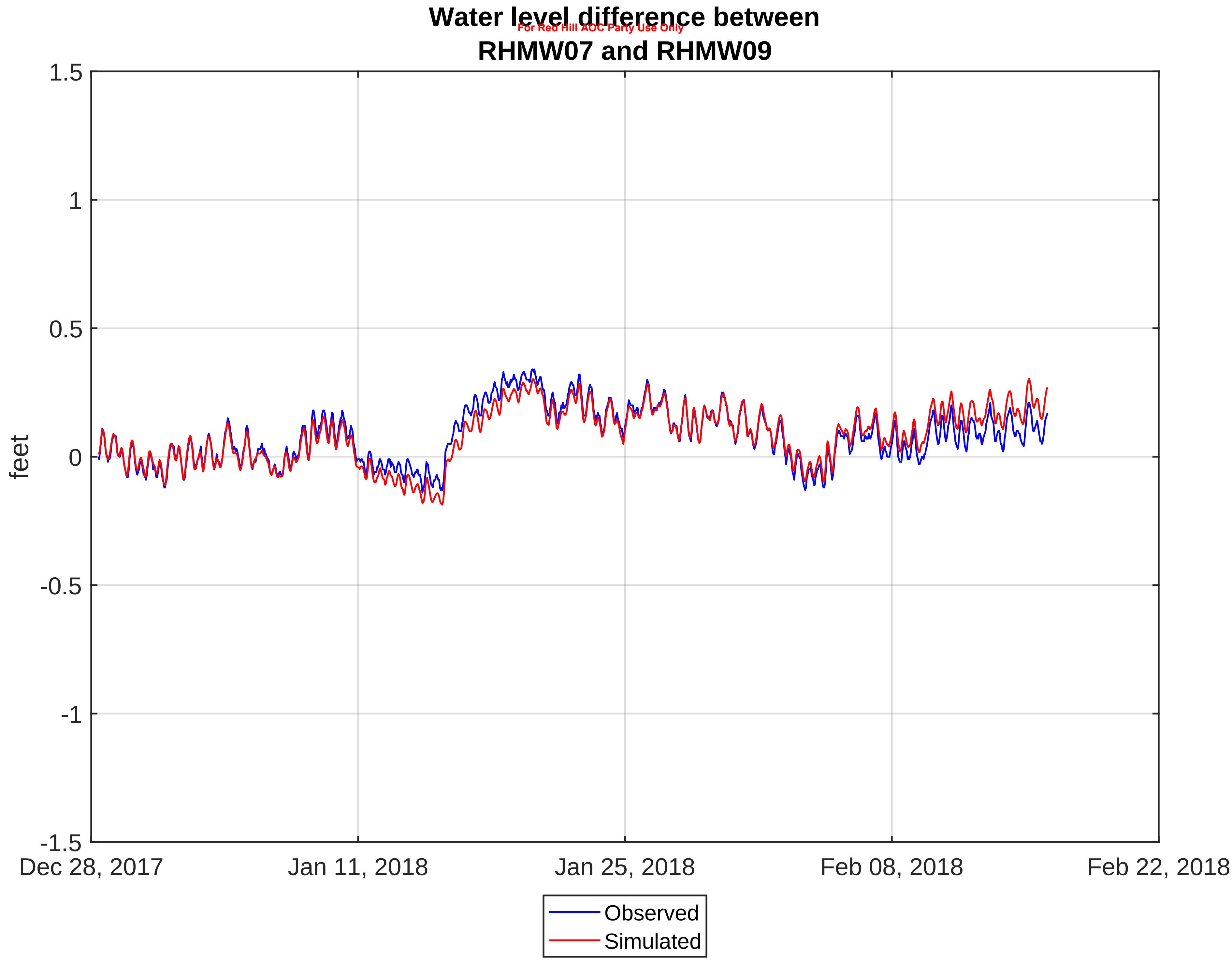


Water level difference between
For Red Hill AOC Party Use Only
RHMW07 and Moanalua Deep
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

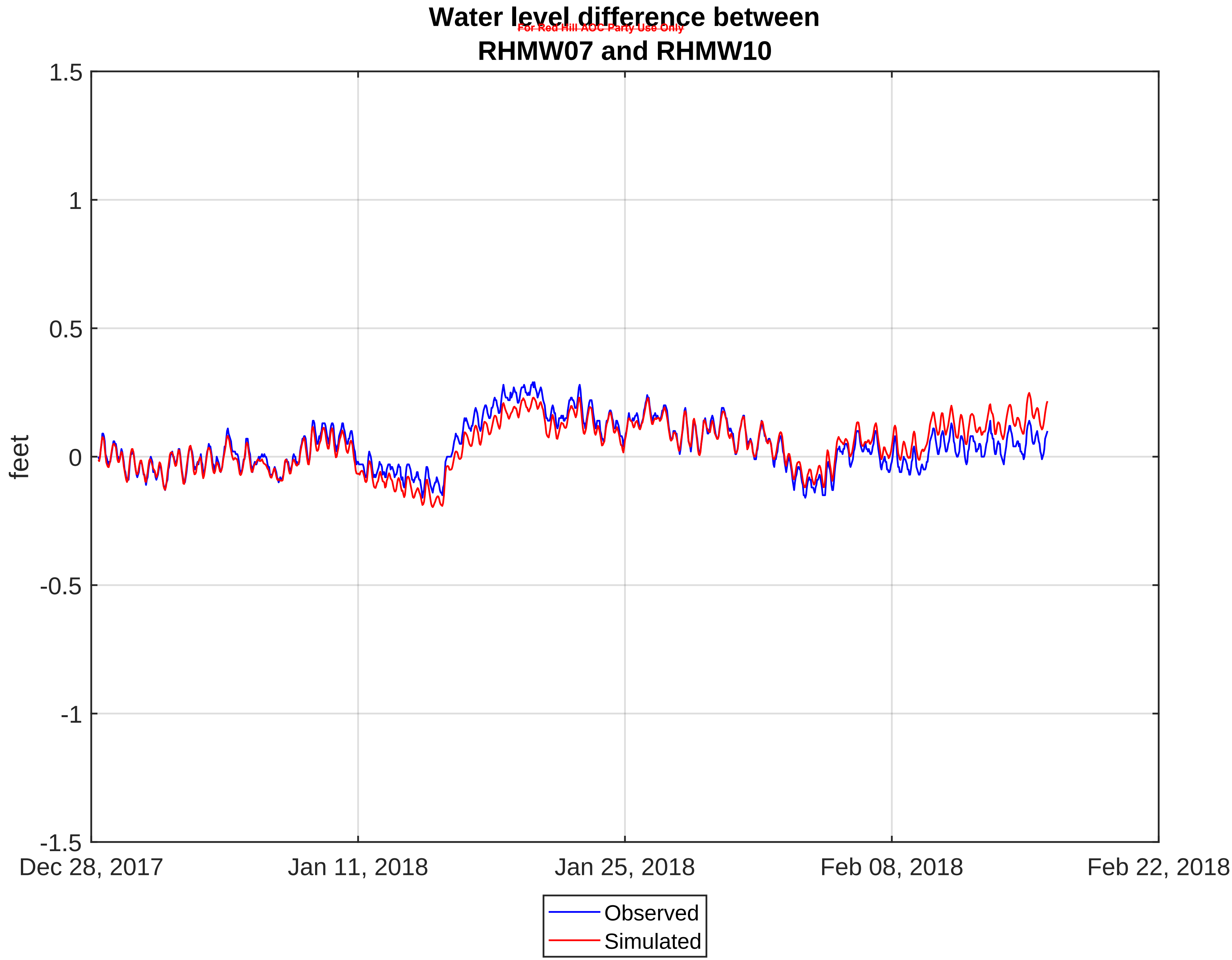

Water level difference between
RHMW07 and Moanalua DH43
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
RHMW07 and RHMW08

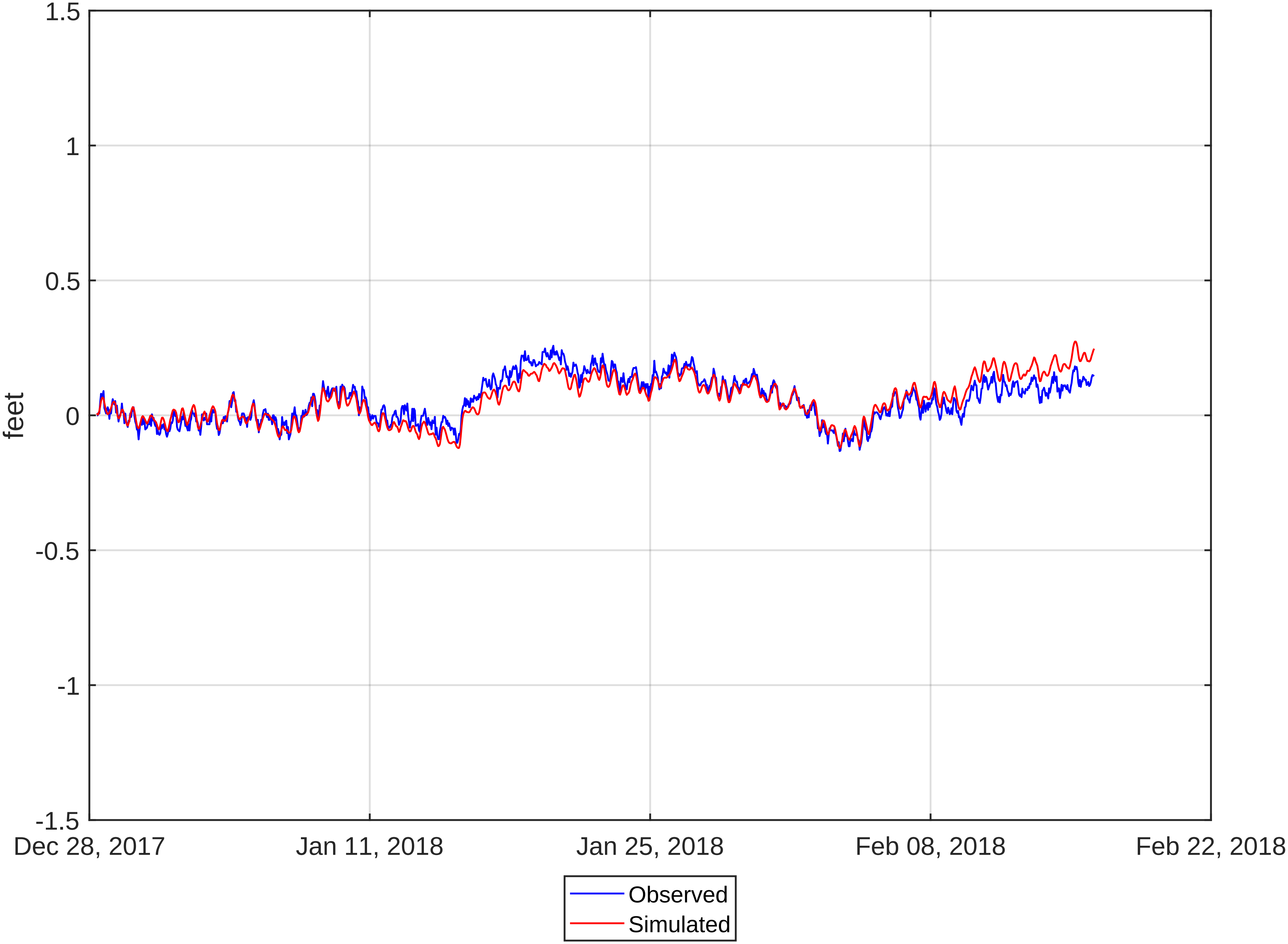


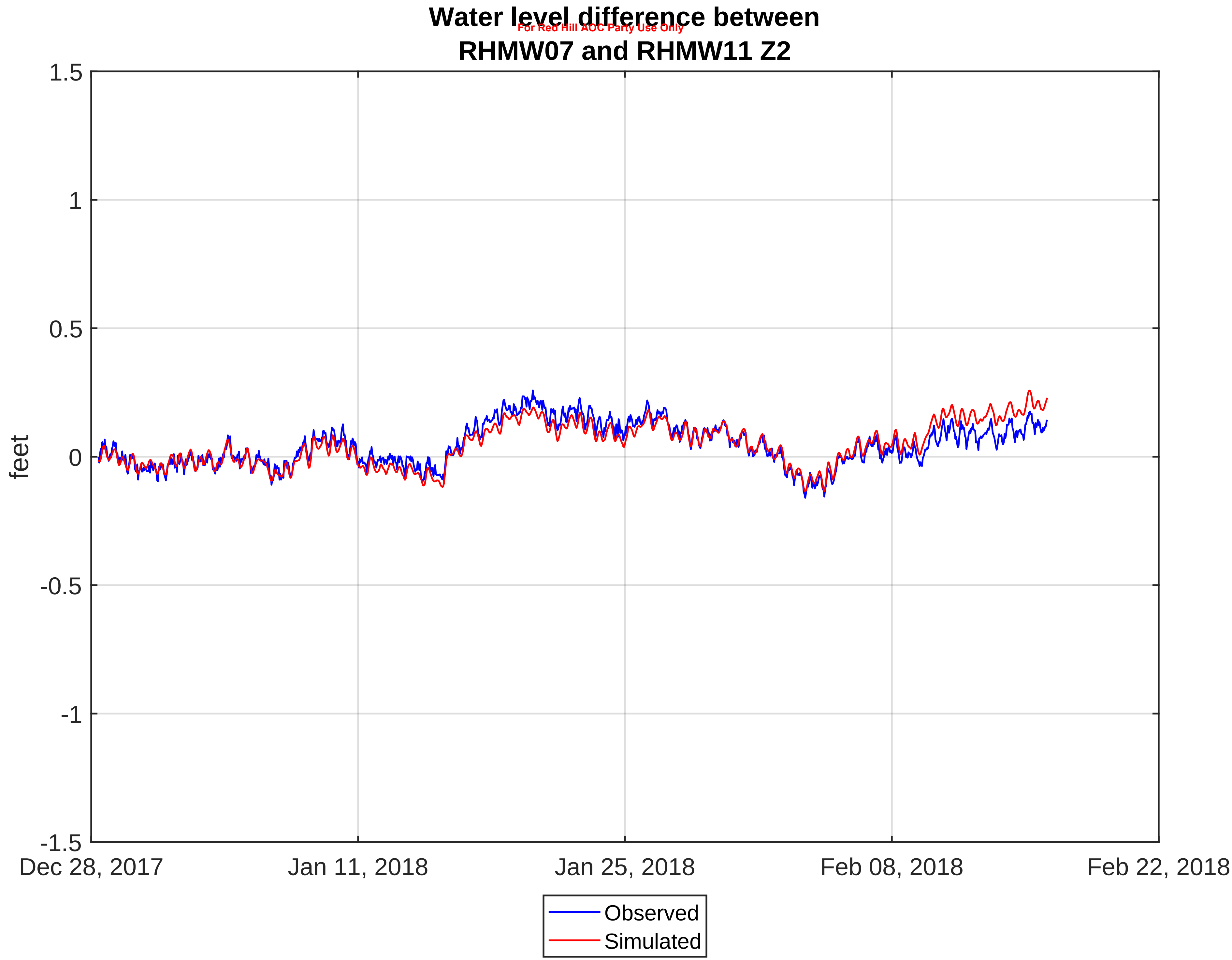


Water level difference between
RHMW07 and RHMW09
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

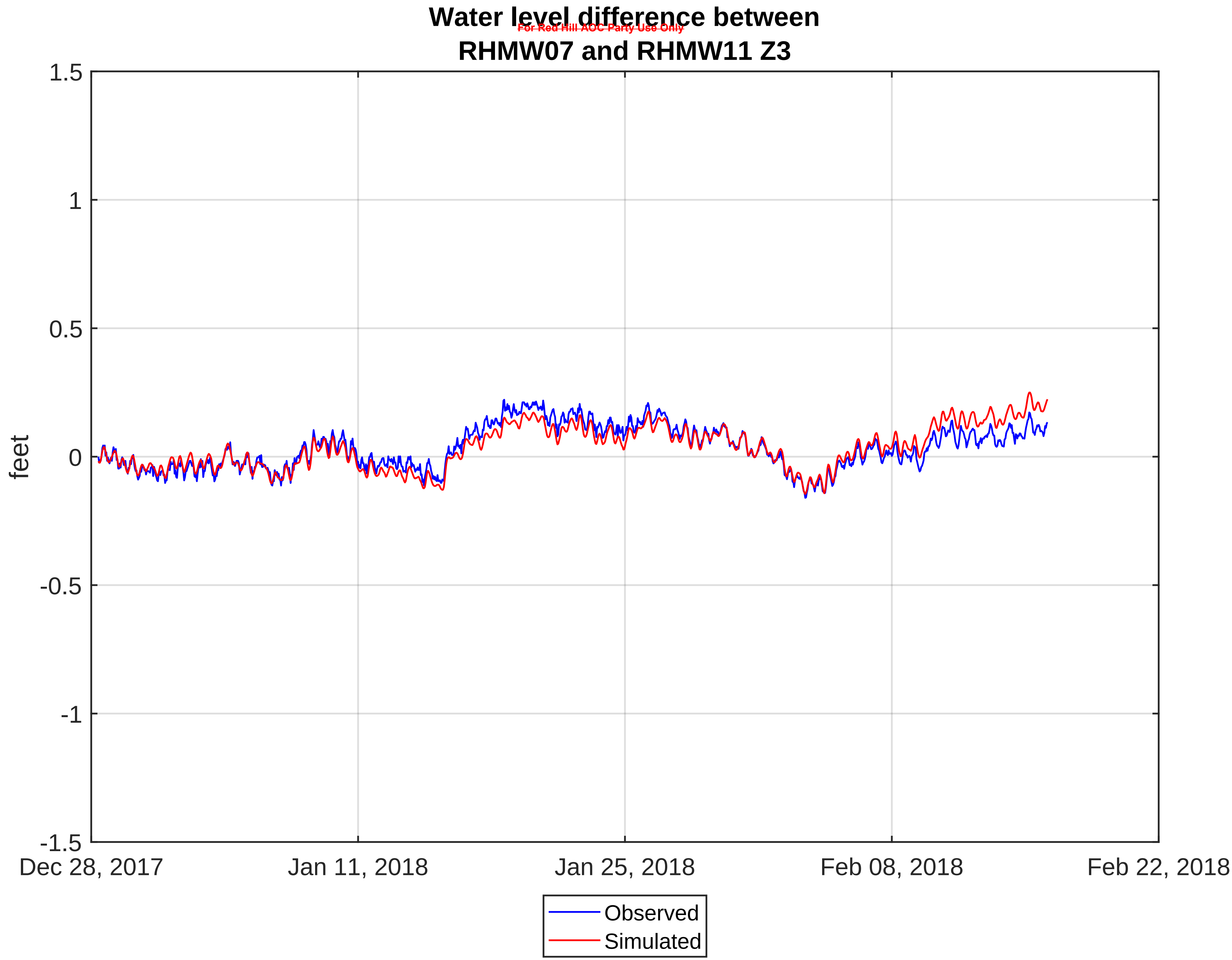

Water level difference between
RHMW07 and RHMW10
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW07 and RHMW11 Z1

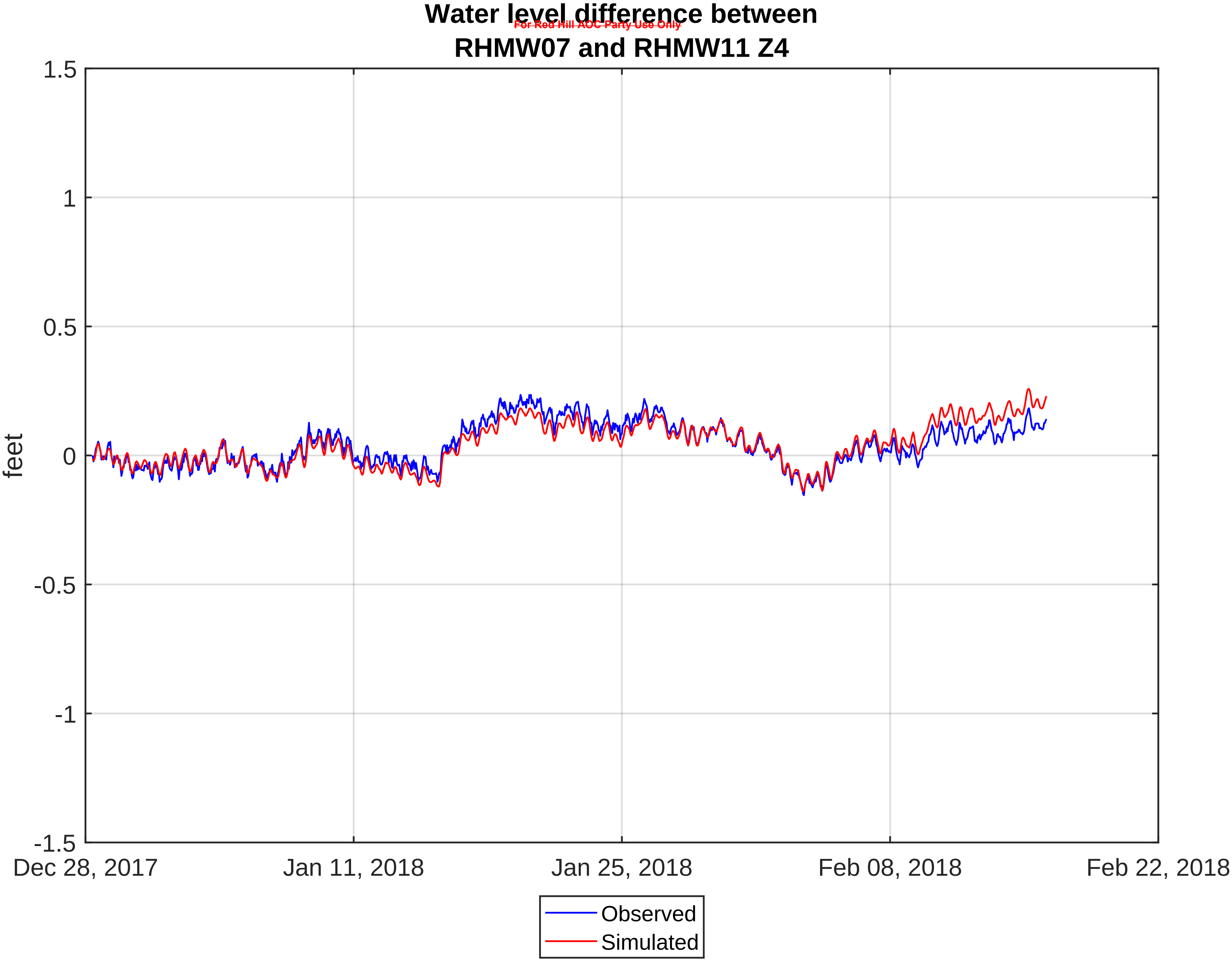




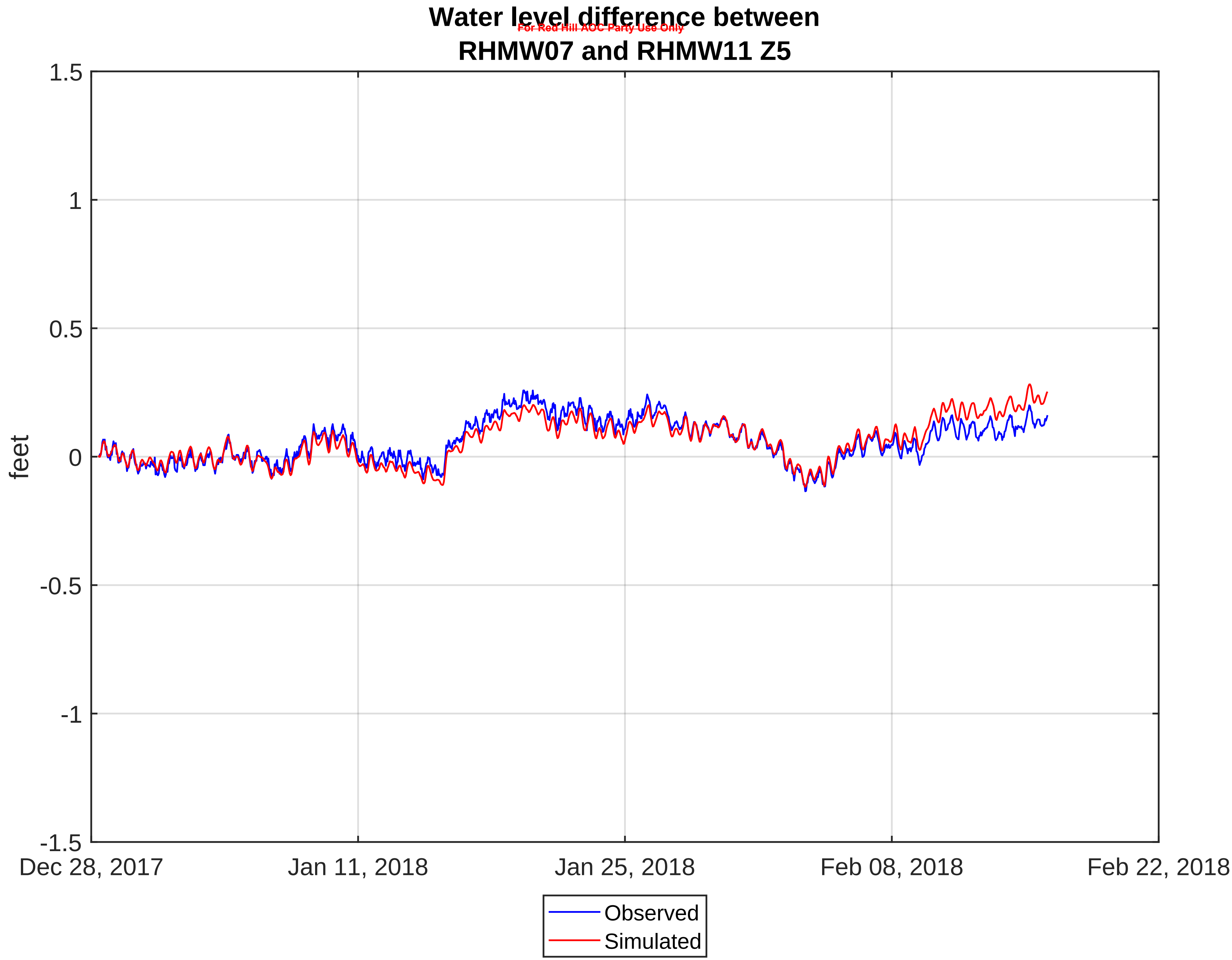
Water level difference between
RHMW07 and RHMW11 Z2
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



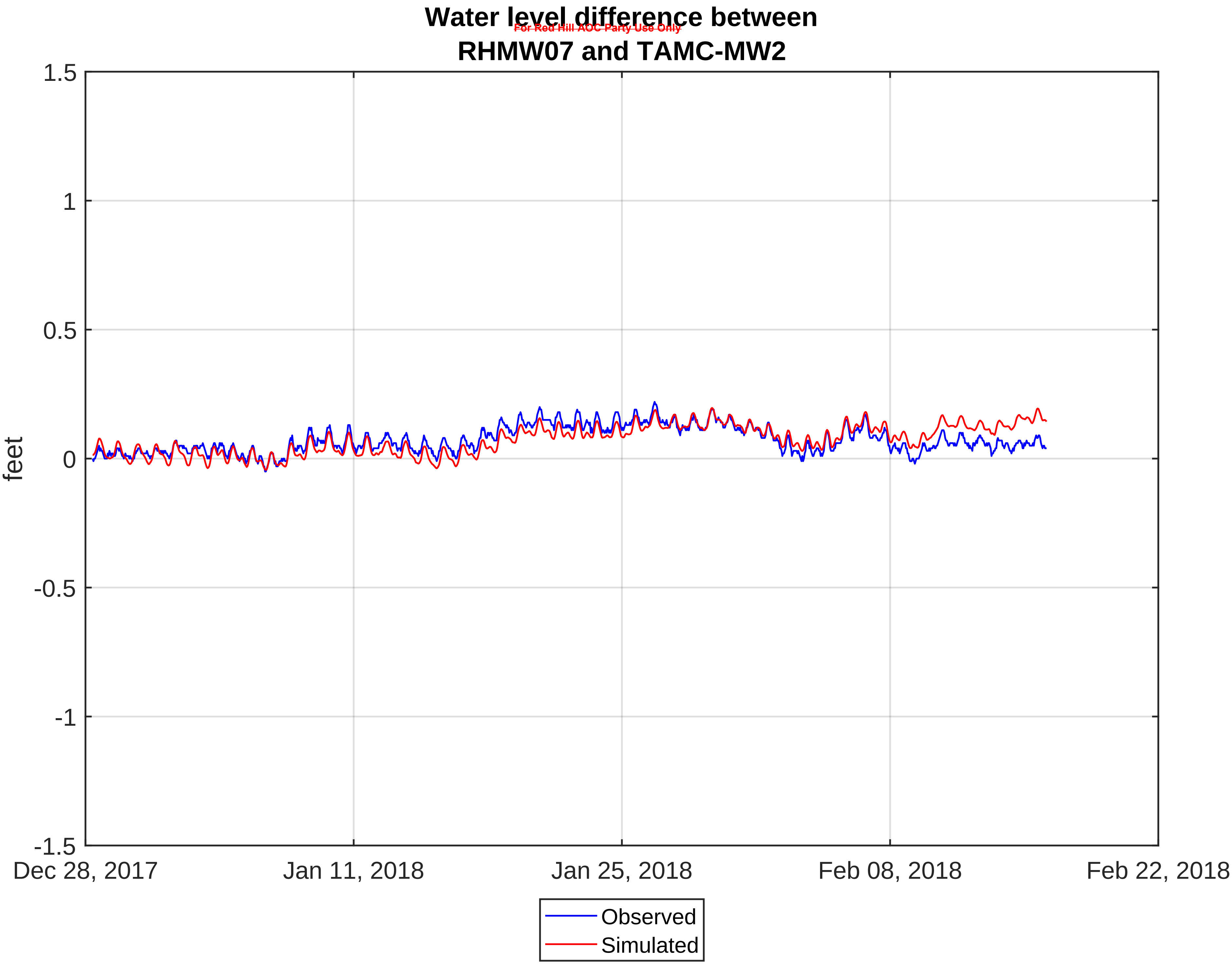
Water level difference between
For Red Hill AOC Party Use Only
RHMW07 and RHMW11 Z3
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

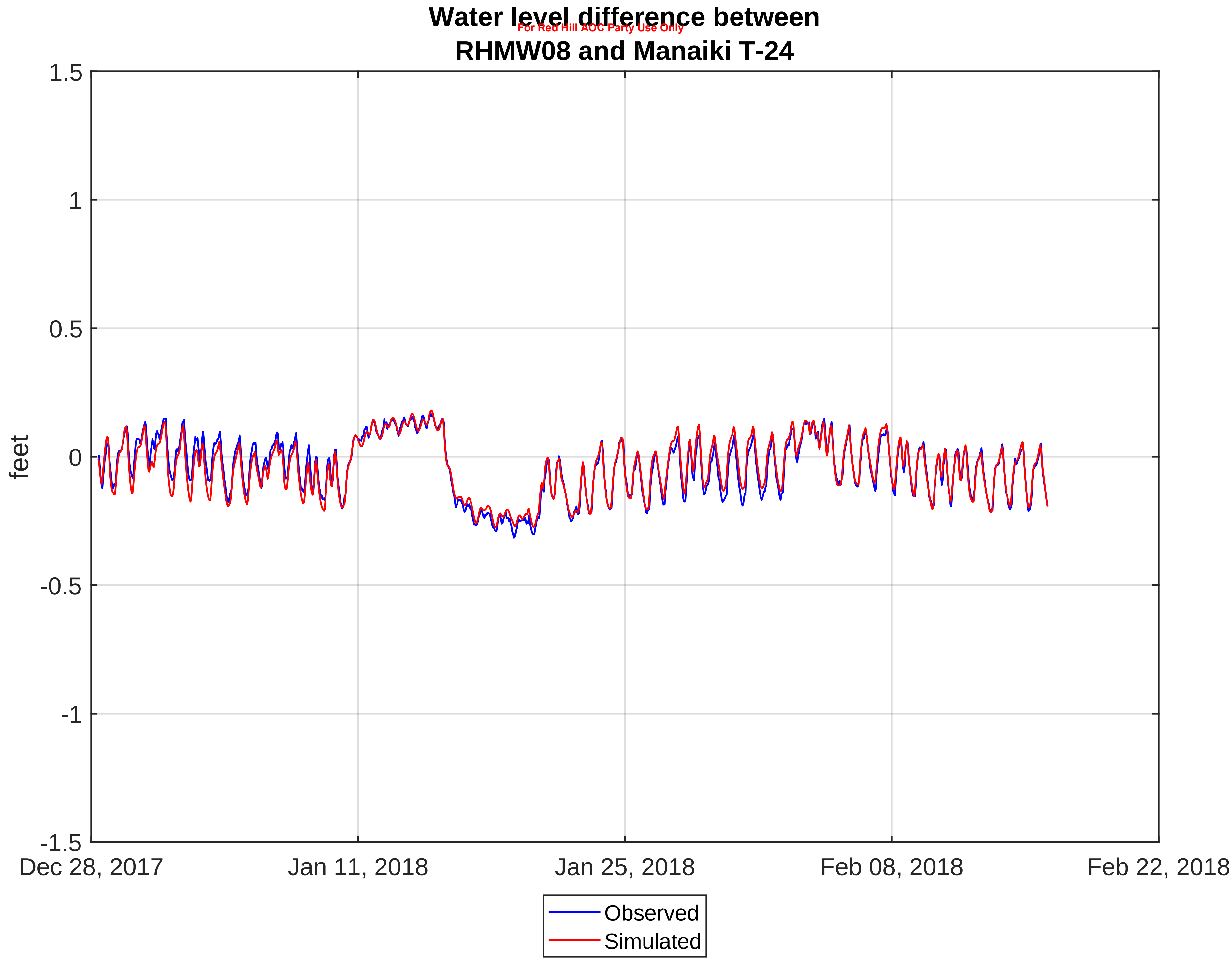


Water level difference between
For Red Hill AOC Party Use Only
RHMW07 and RHMW11 Z4
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

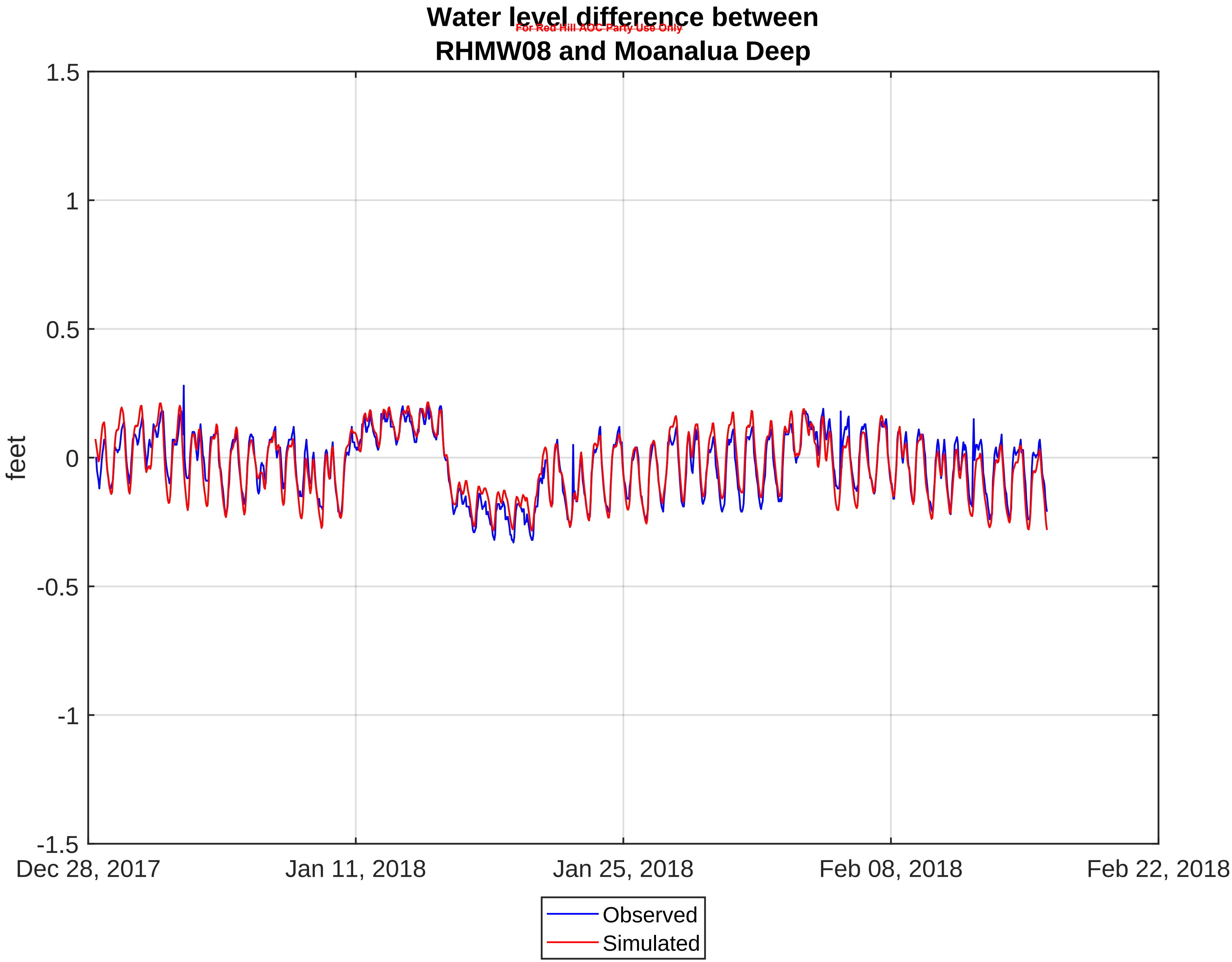


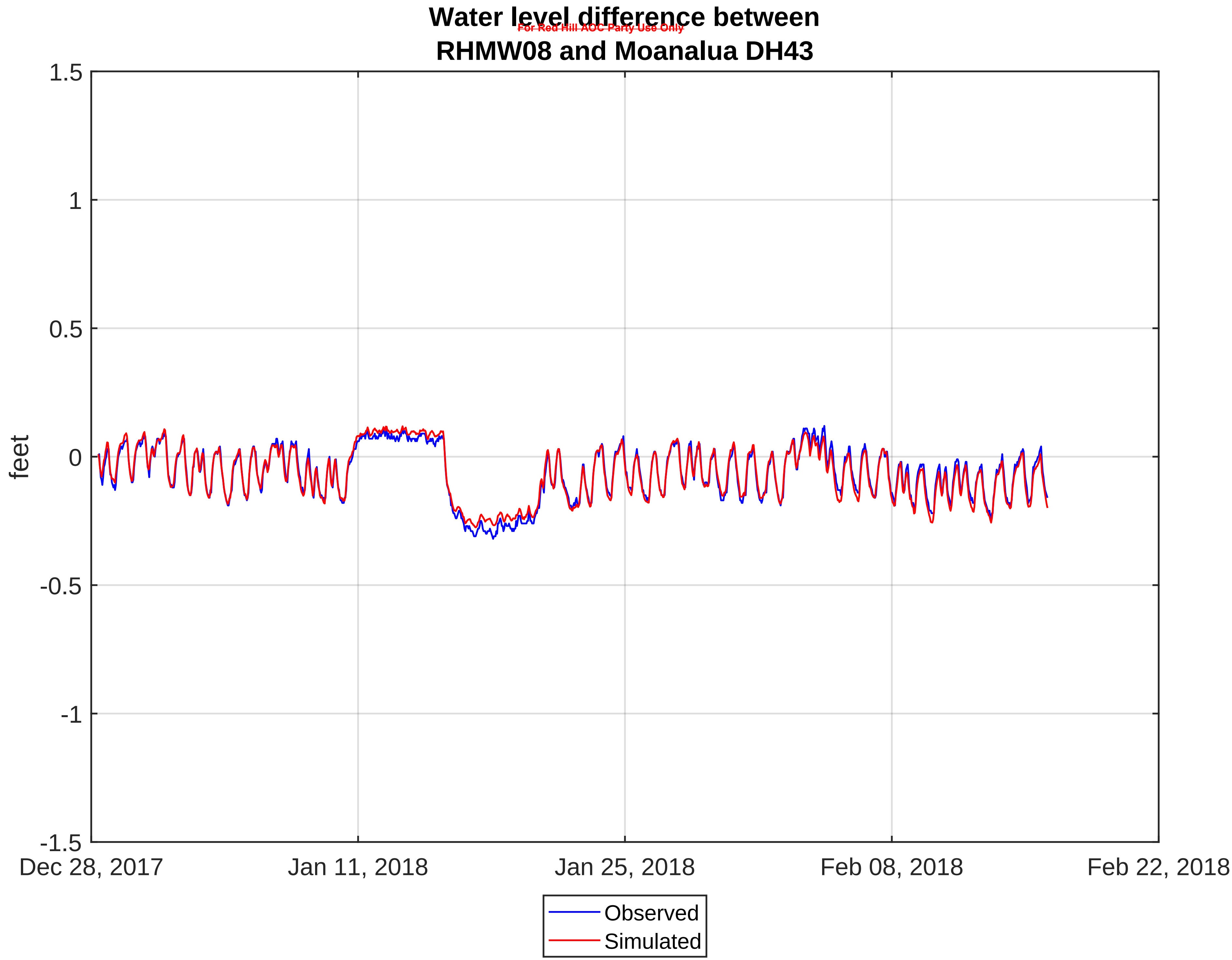
Water level difference between
For Red Hill AOC Party Use Only
RHMW07 and RHMW11 Z5
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
RHMW07 and TAMC-MW2
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

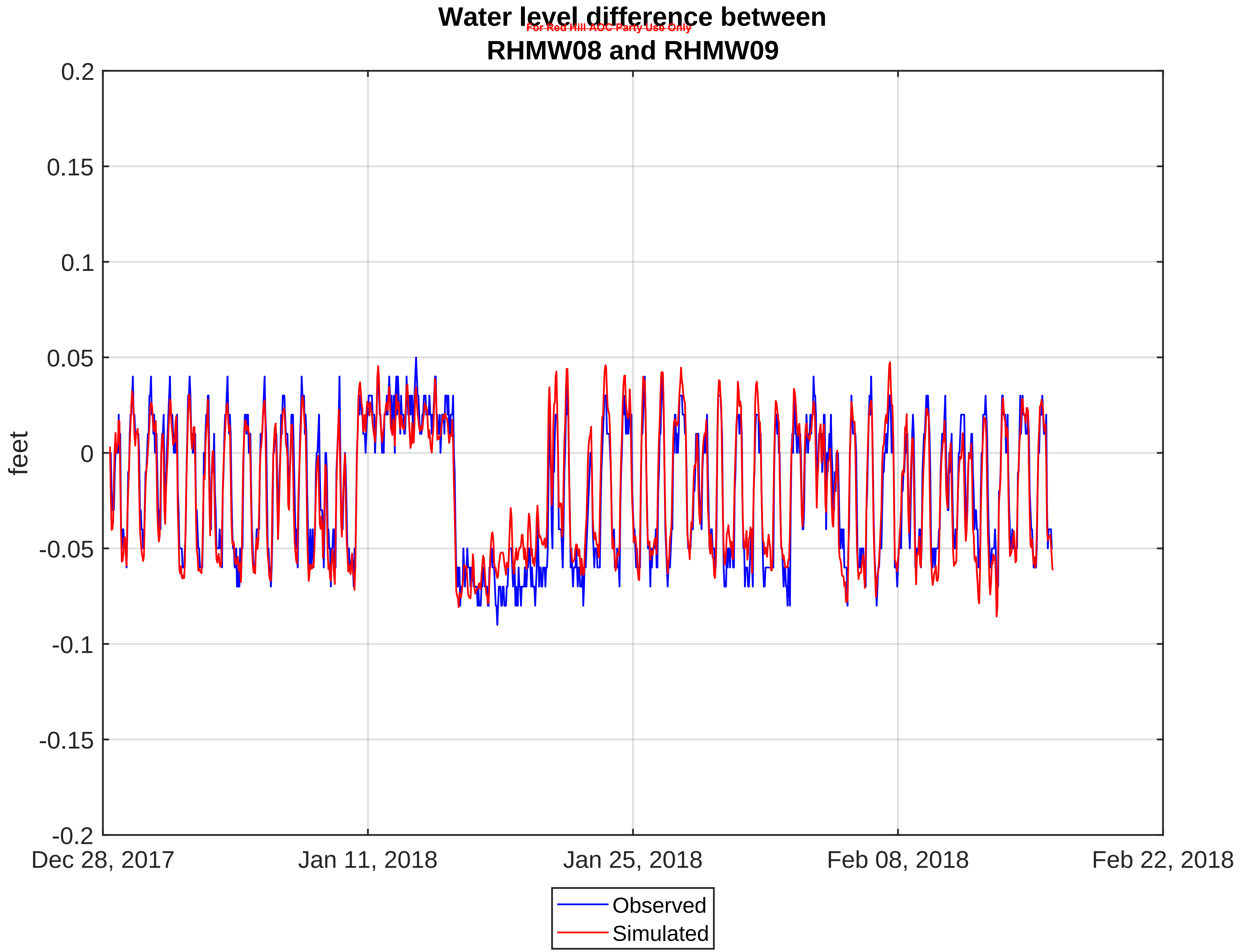


Water level difference between
RHMW08 and Manaiki T-24
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

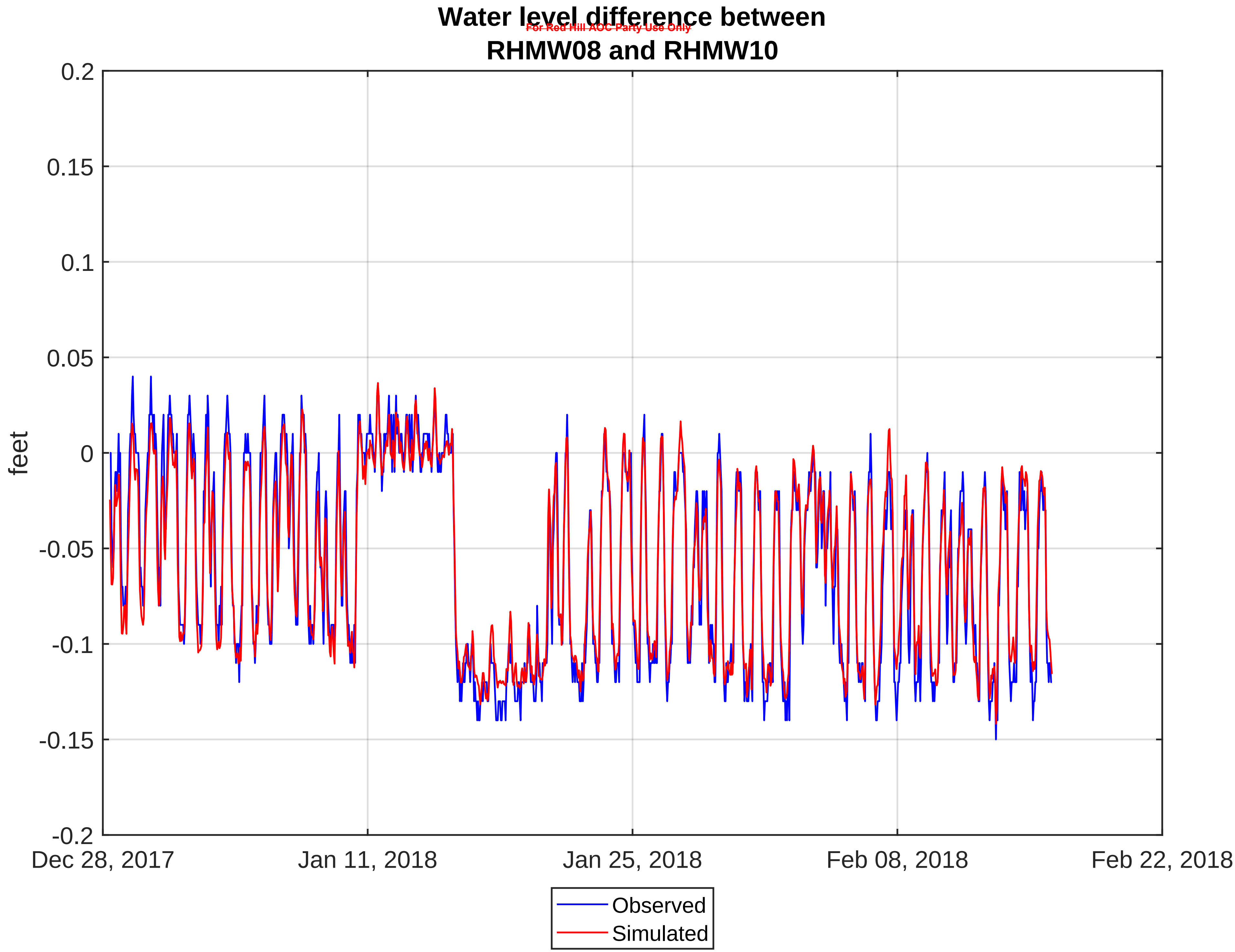

Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and Moanalua Deep
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

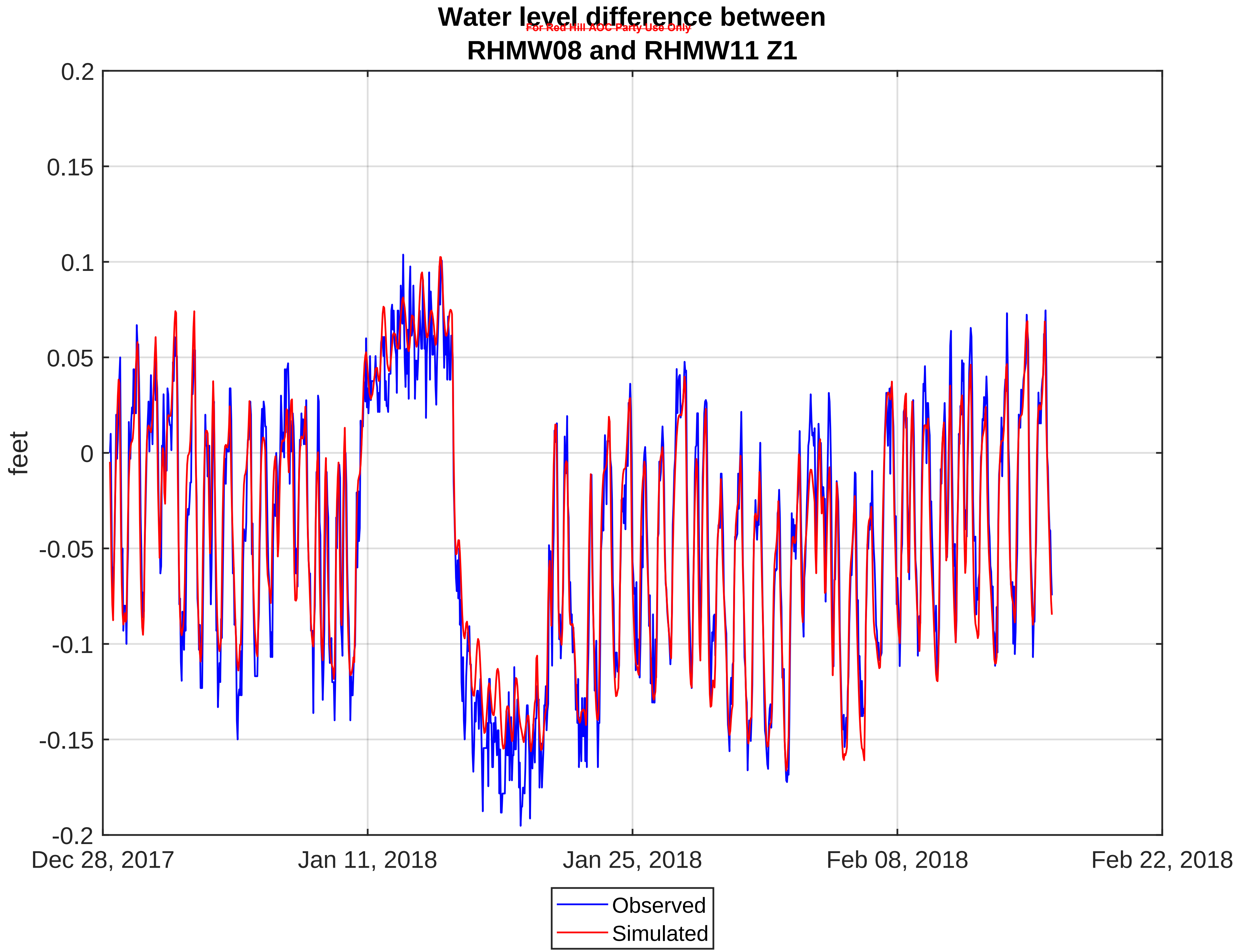


Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and Moanalua DH43
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

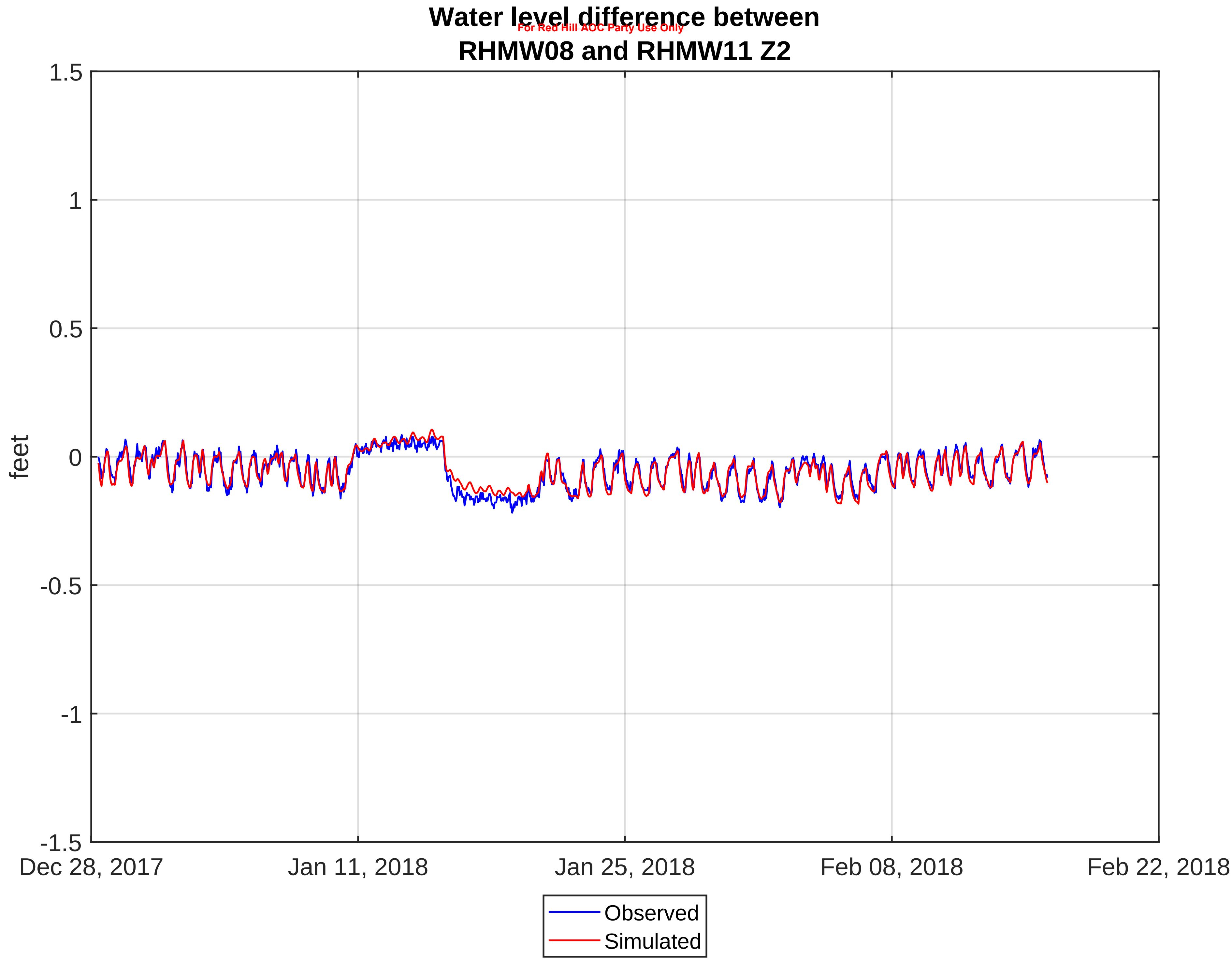


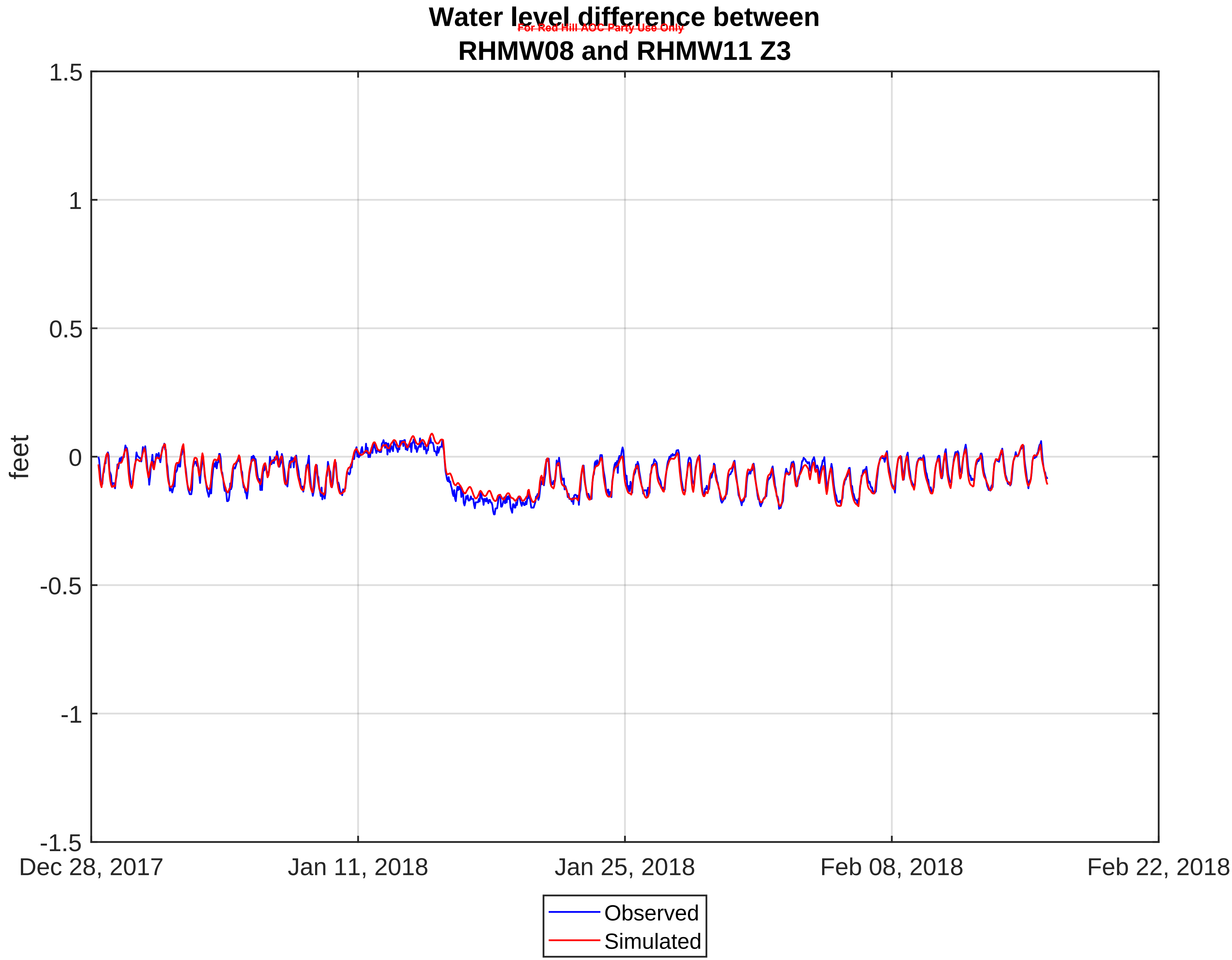
Water level difference between
RHMW08 and RHMW09
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

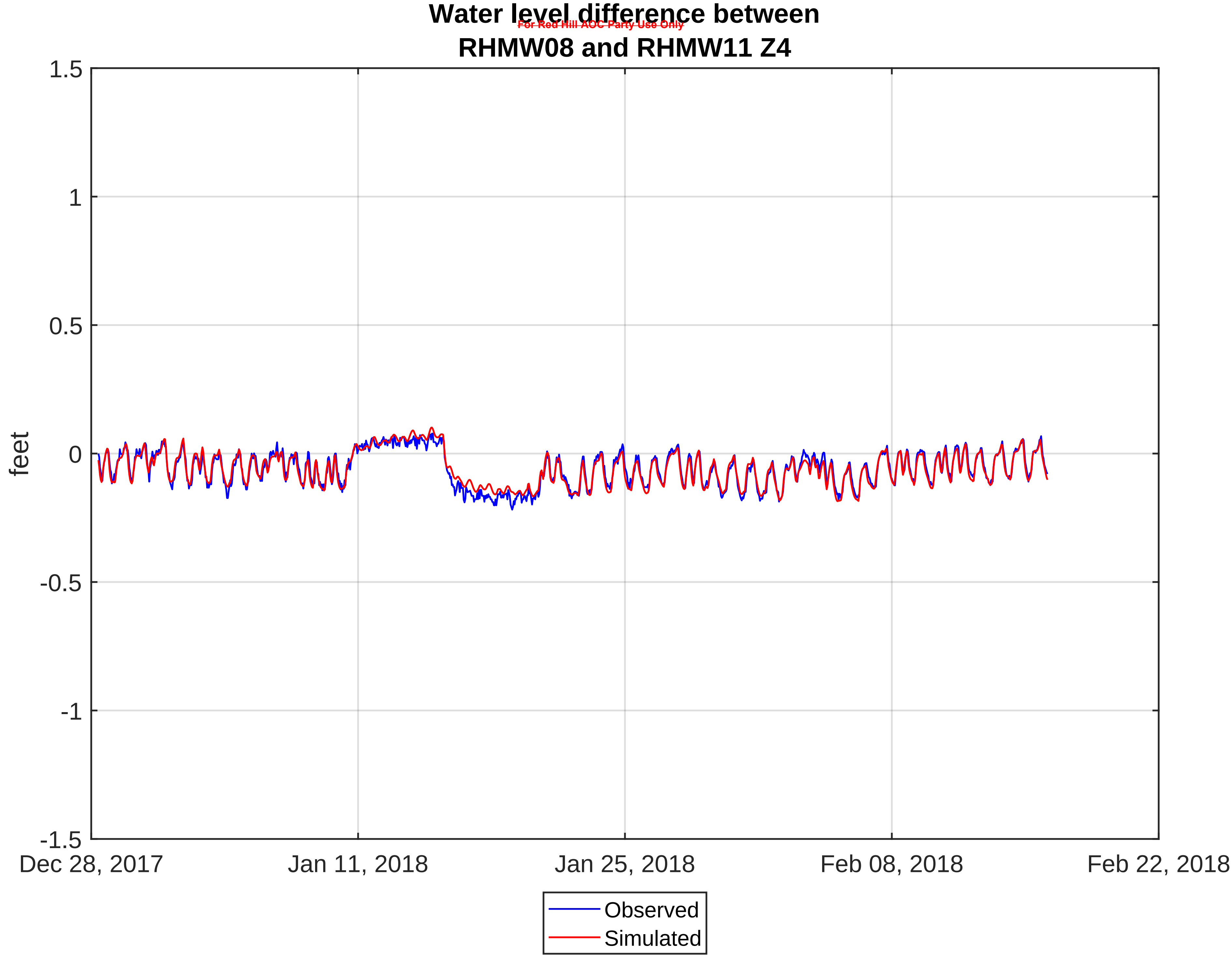

Water level difference between
RHMW08 and RHMW10
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



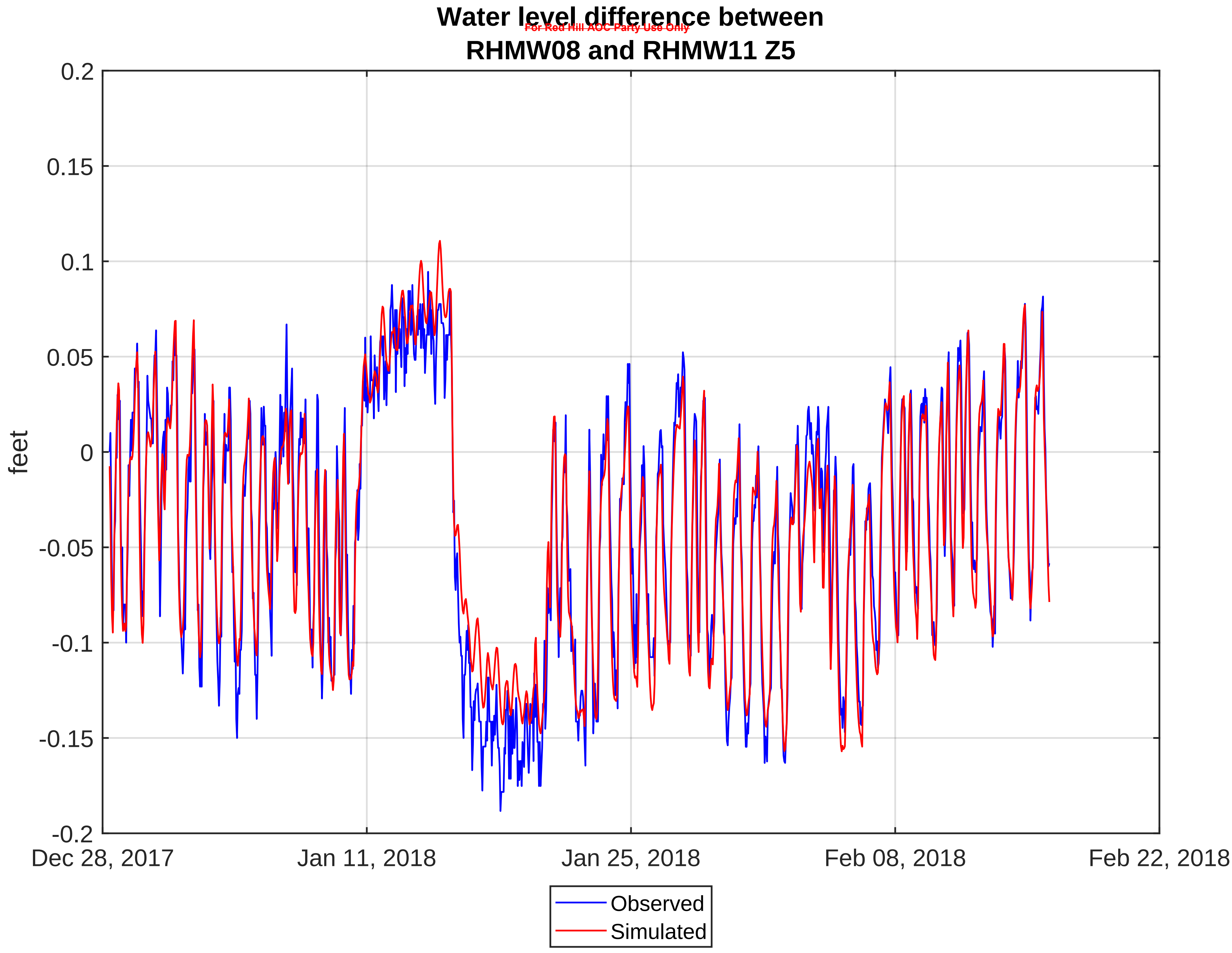
Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and RHMW11 Z1
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and RHMW11 Z2
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

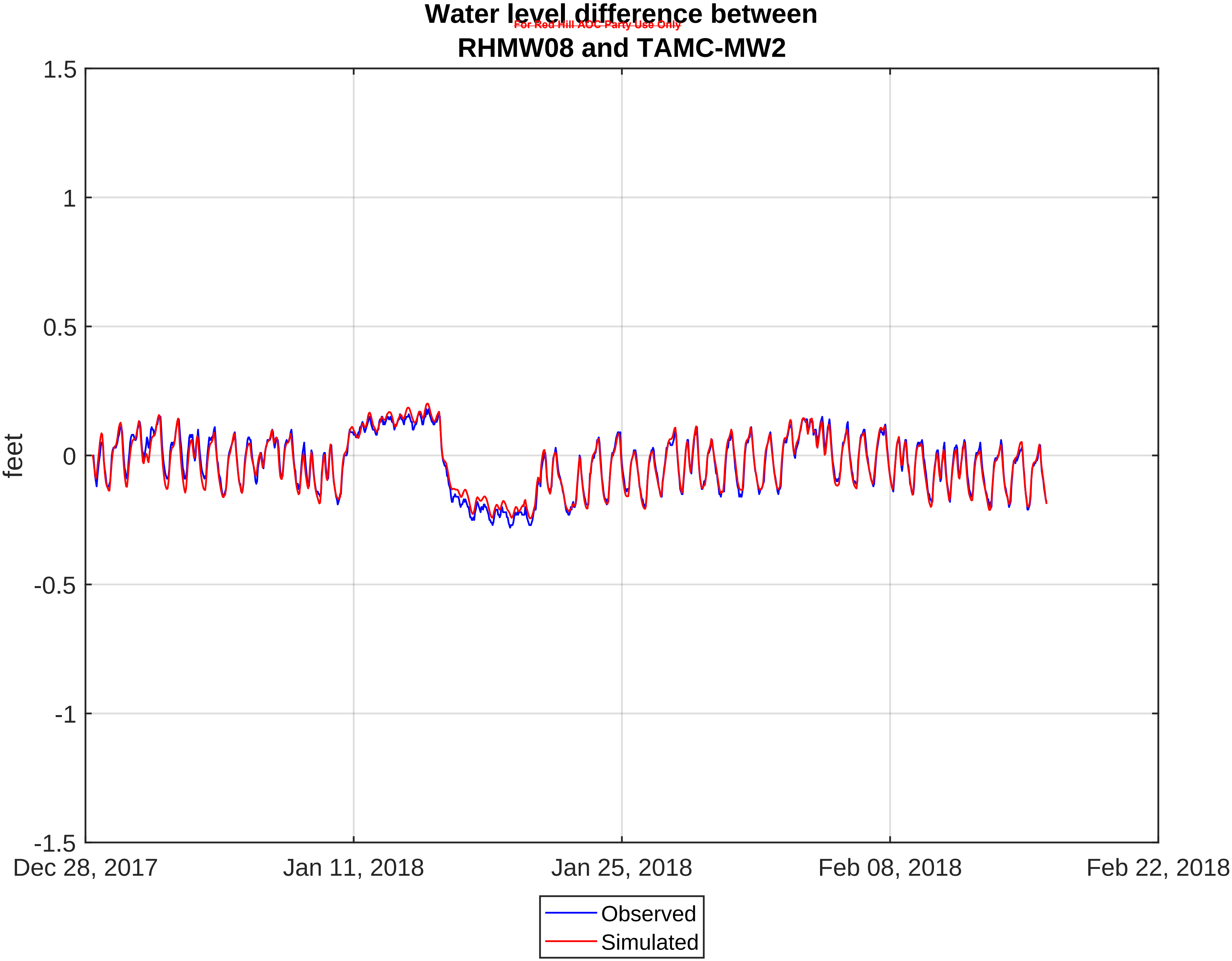

Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and RHMW11 Z3
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

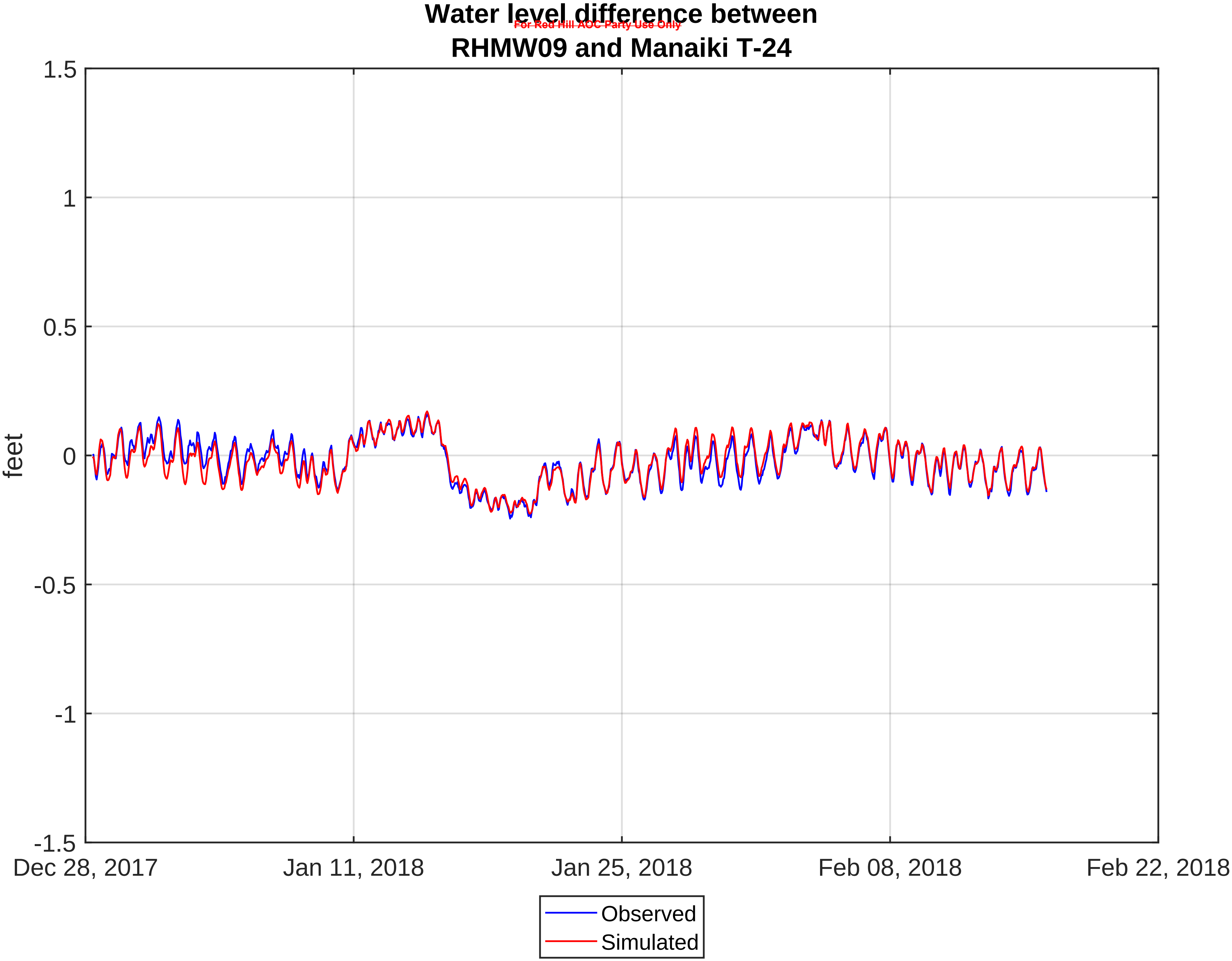


Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and RHMW11 Z4
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

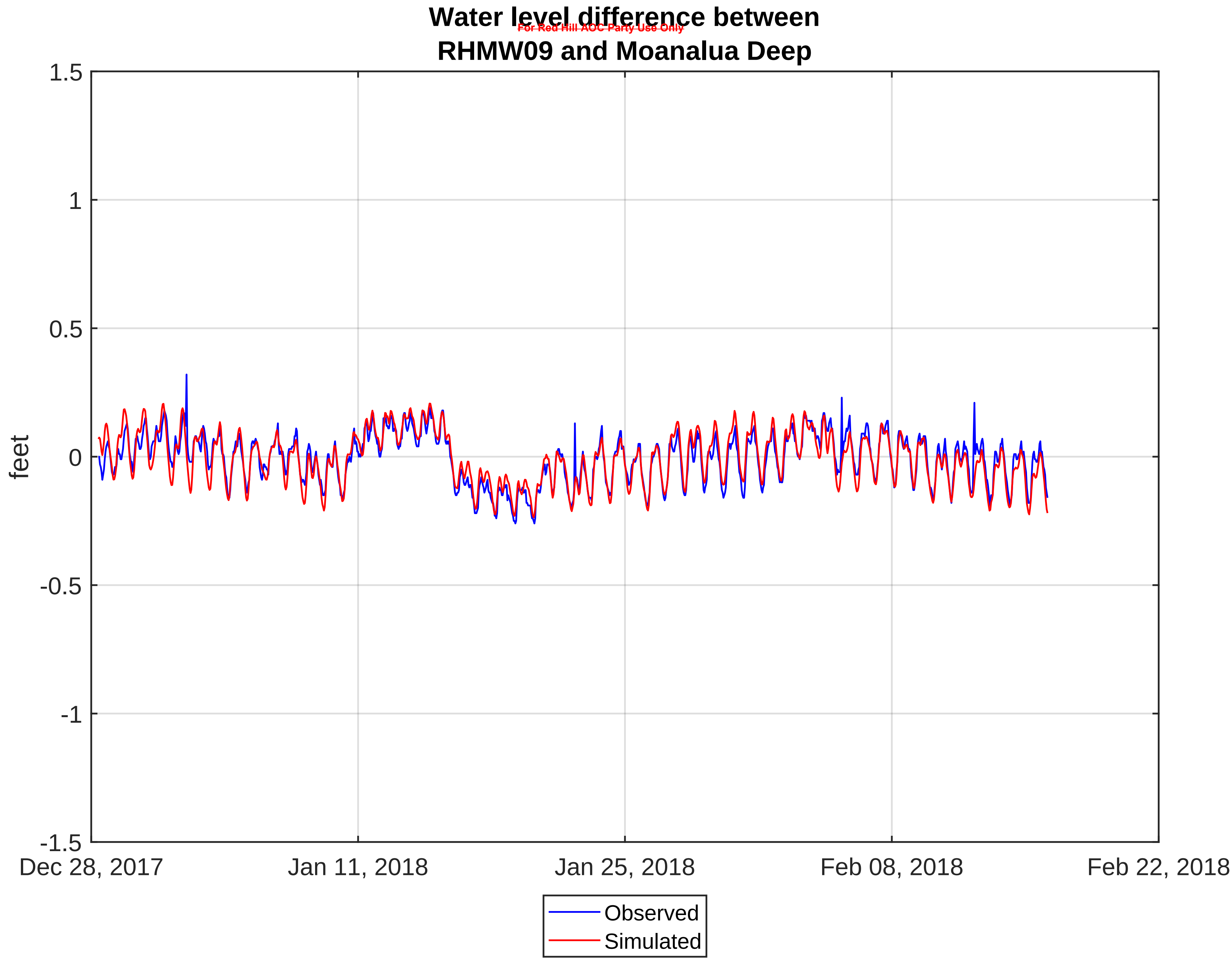


Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and RHMW11 Z5
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
RHMW08 and TAMC-MW2
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

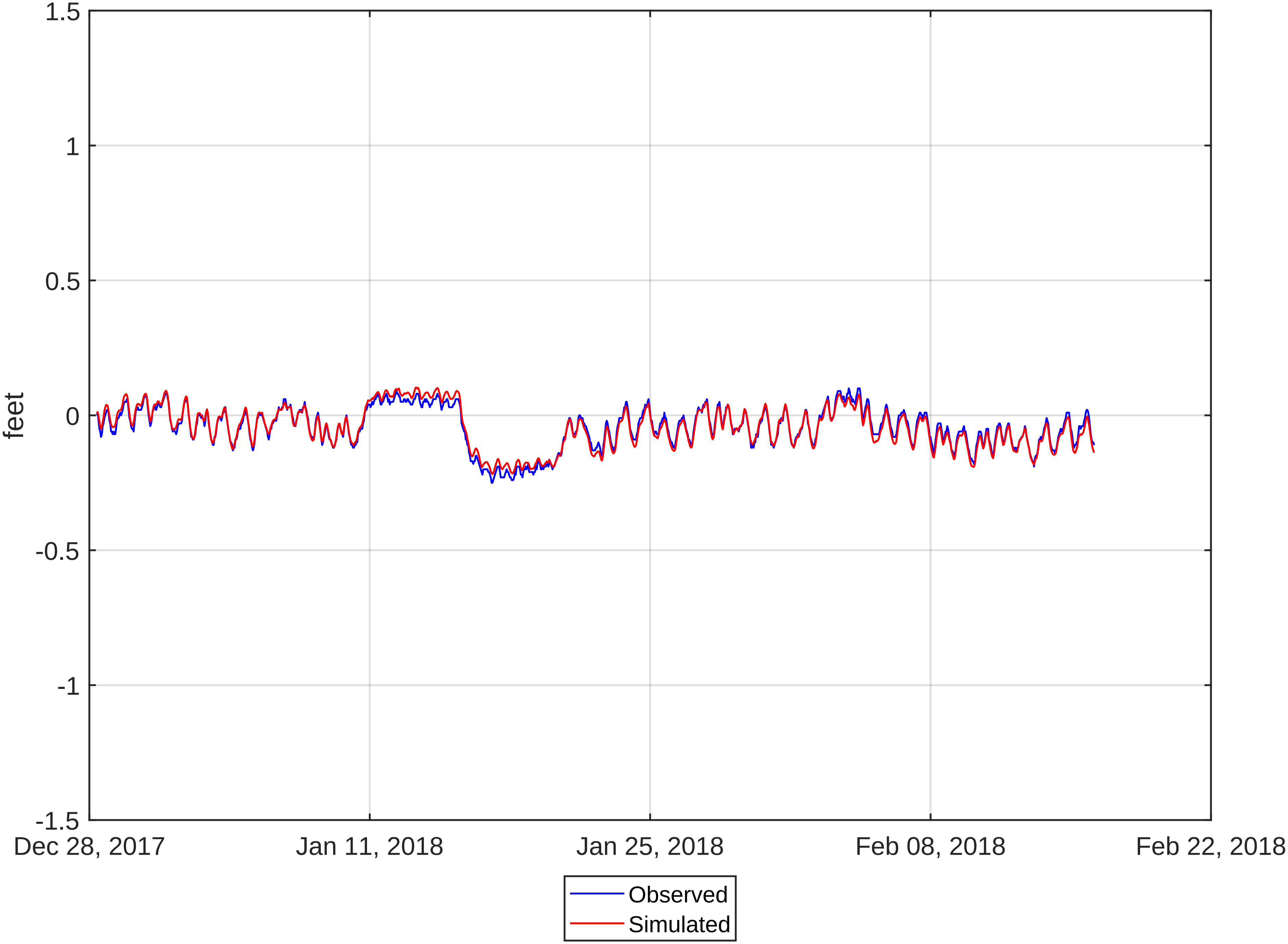


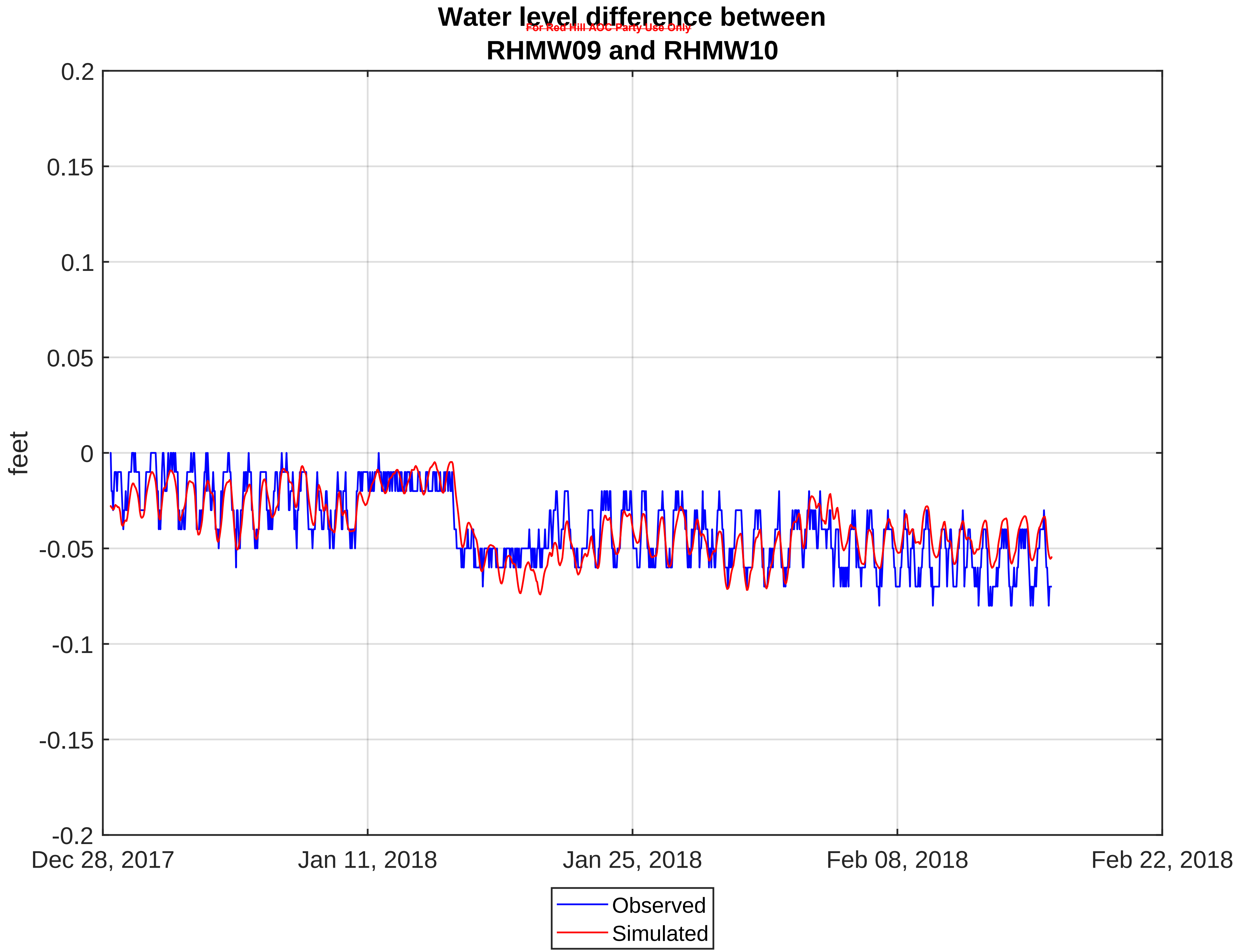
Water level difference between
For Red Hill AOC Party Use Only
RHMW09 and Manaiki T-24
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
RHMW09 and Moanalua Deep
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW09 and Moanalua DH43

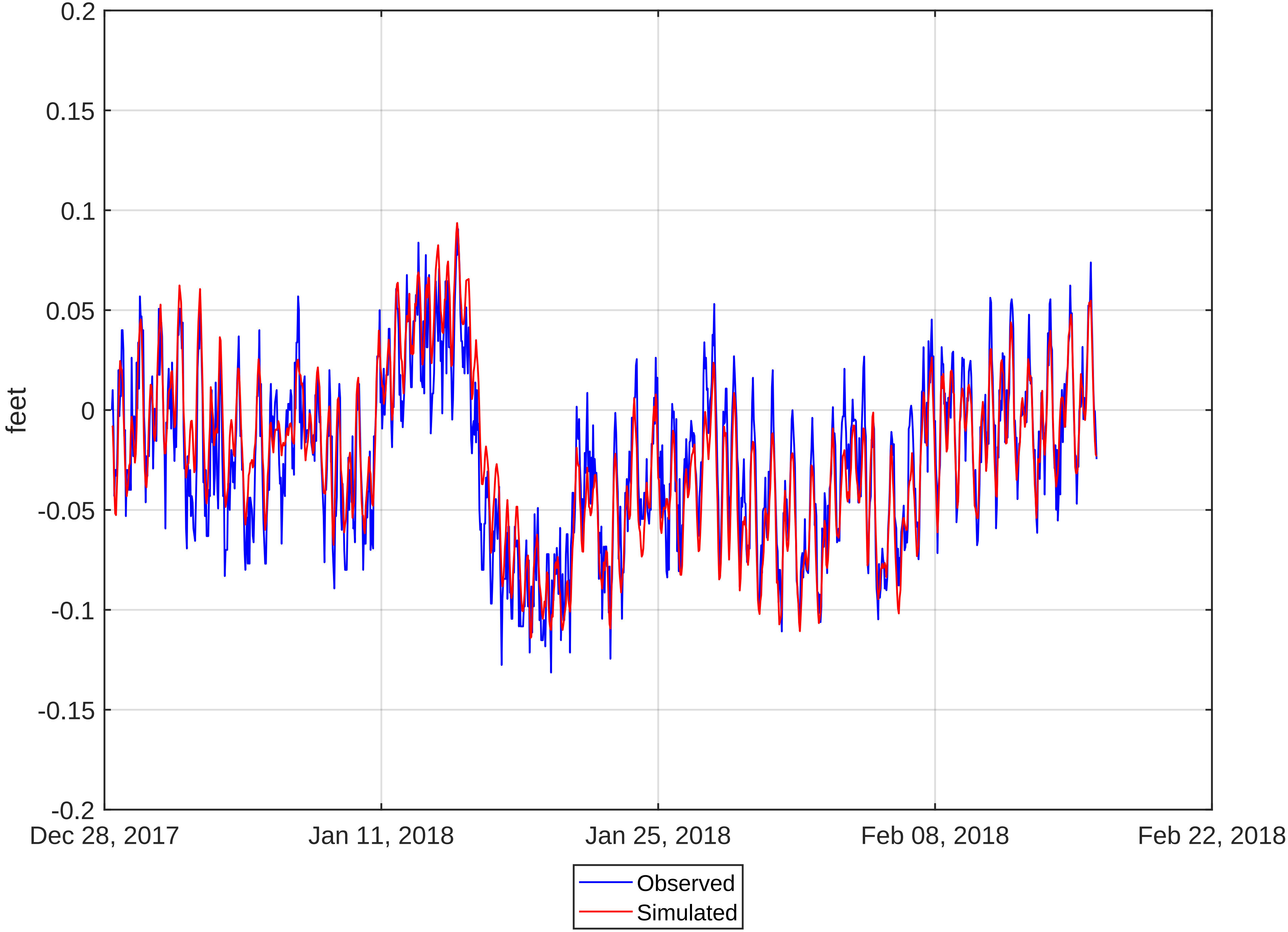
For Red Hill AOC Party Use Only



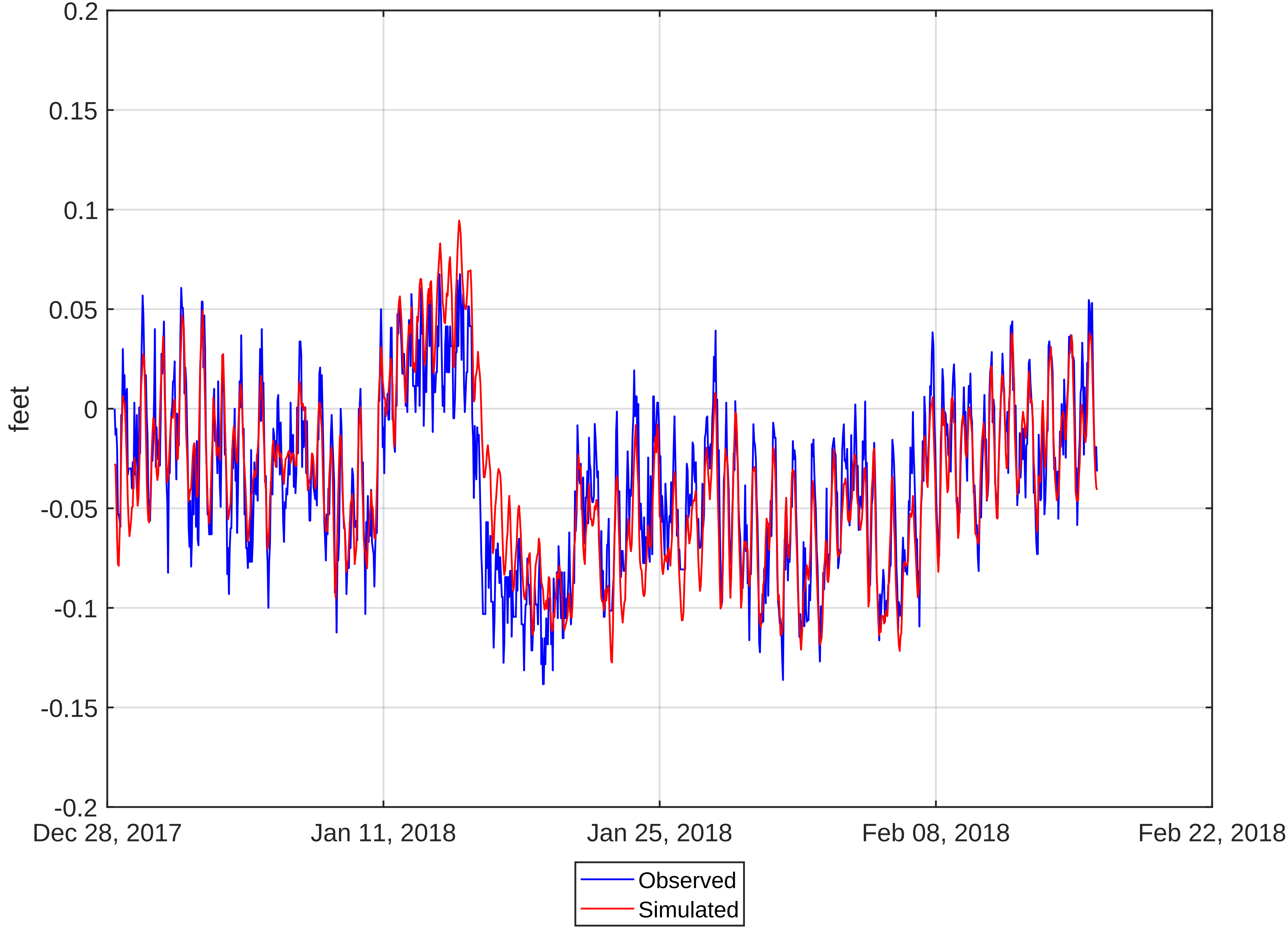


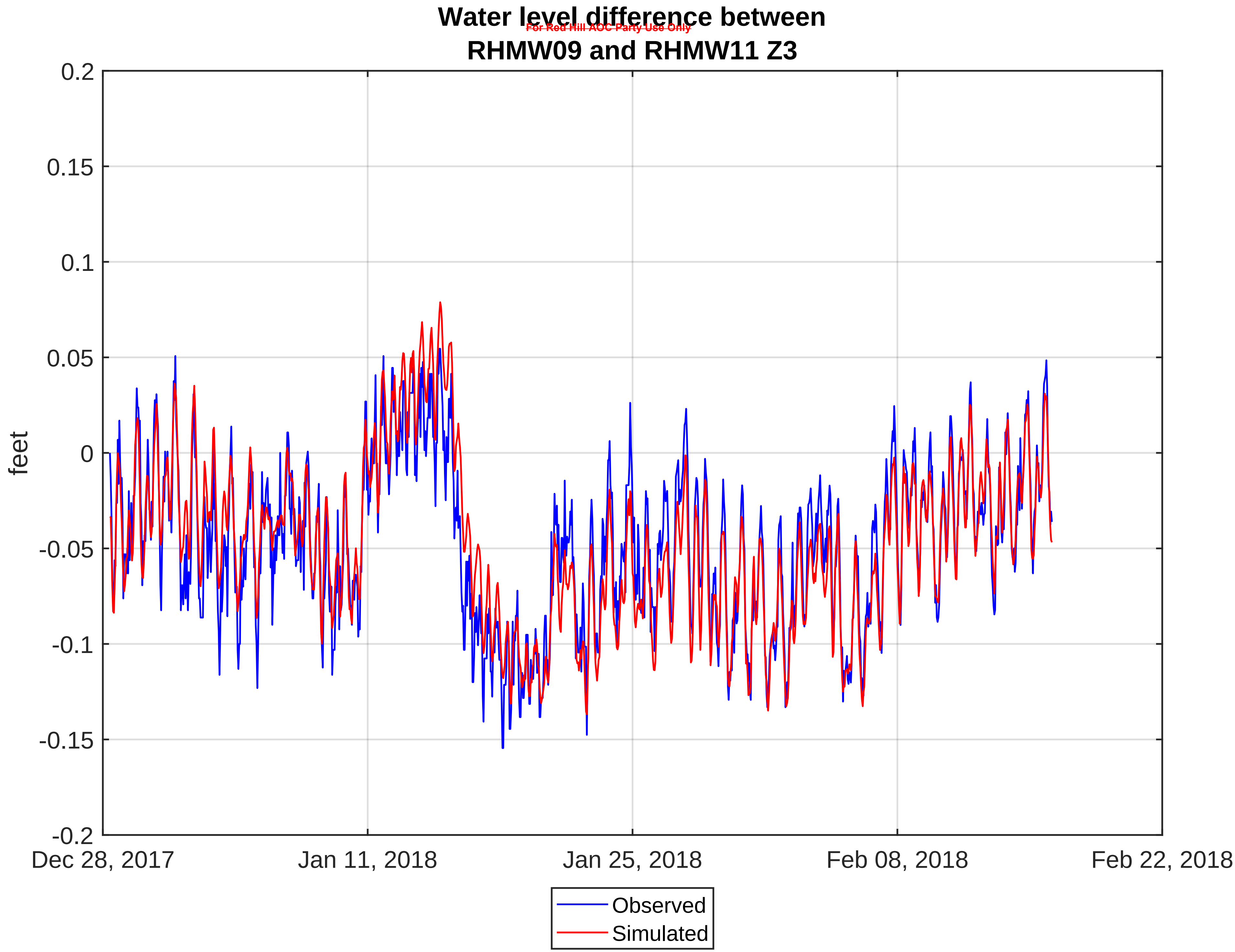
Water level difference between
RHMW09 and RHMW10
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW09 and RHMW11 Z1

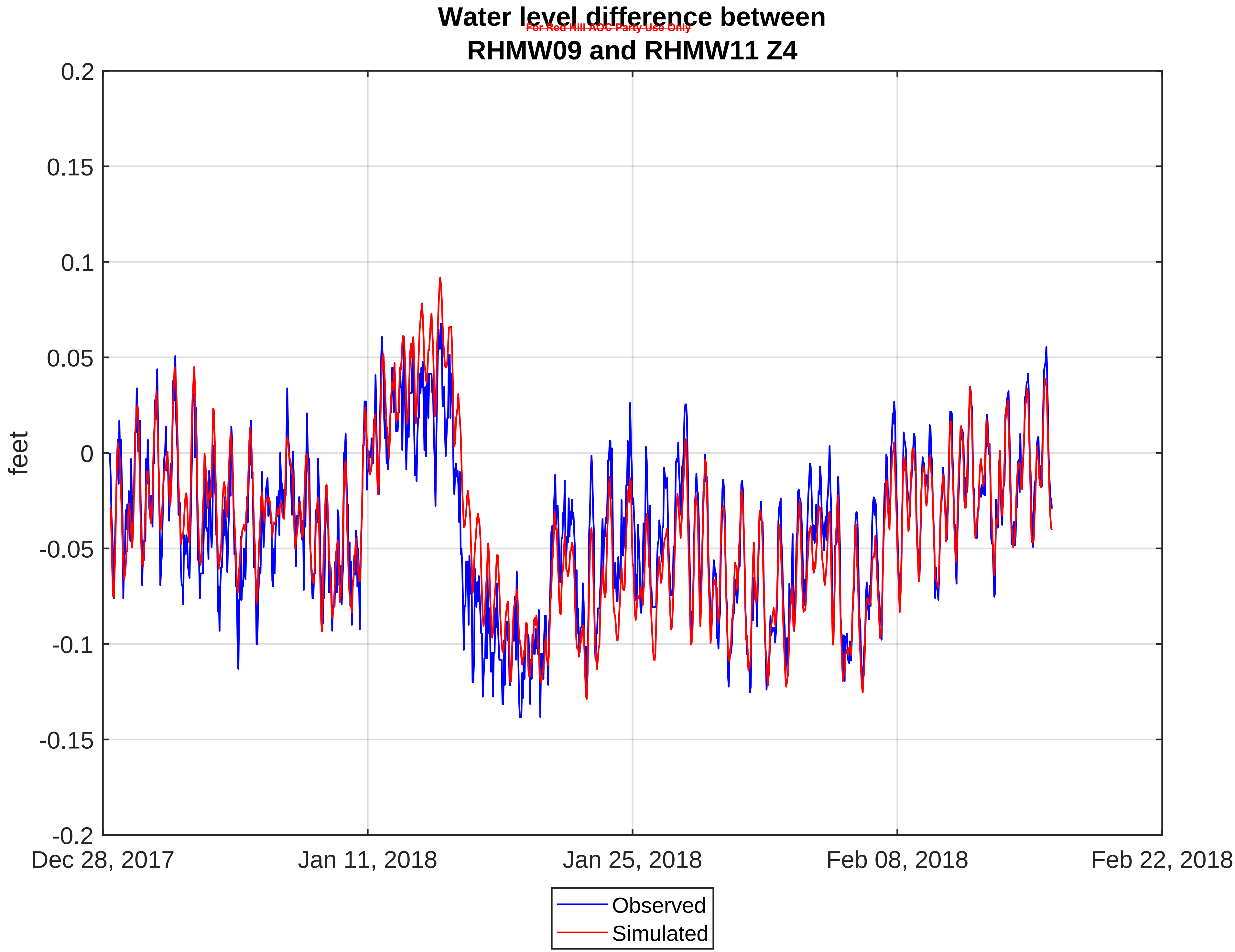


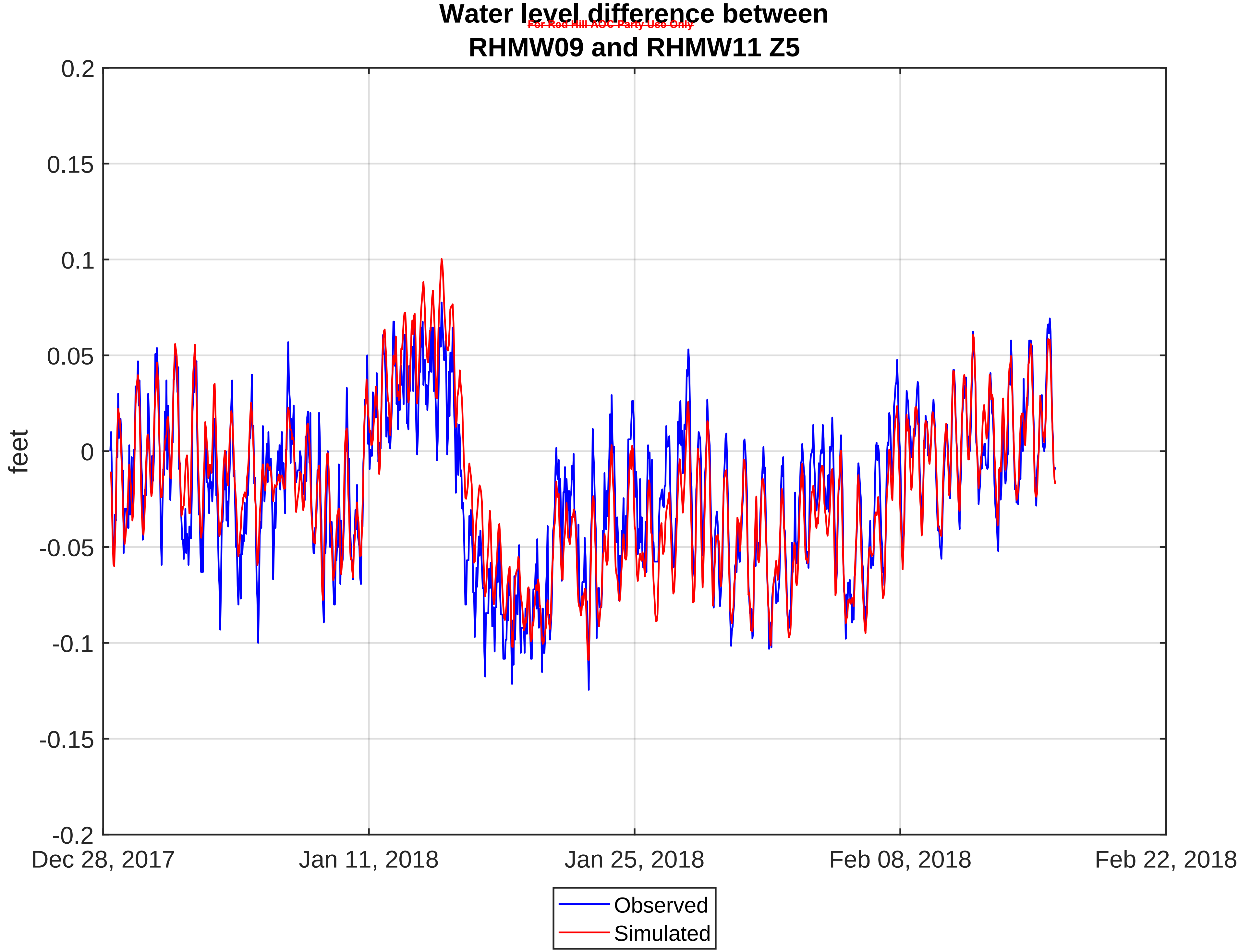
Water level difference between RHMW09 and RHMW11 Z2



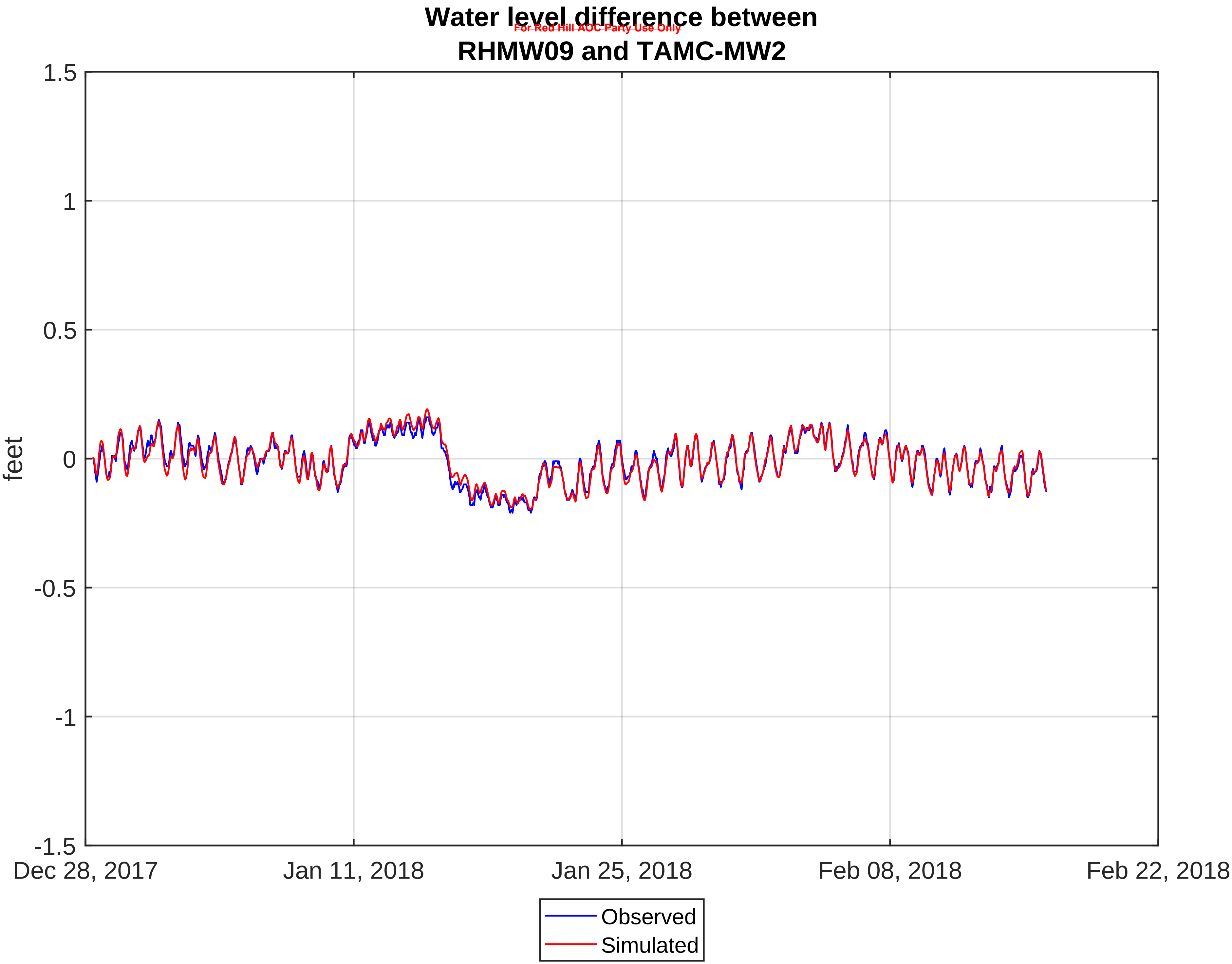


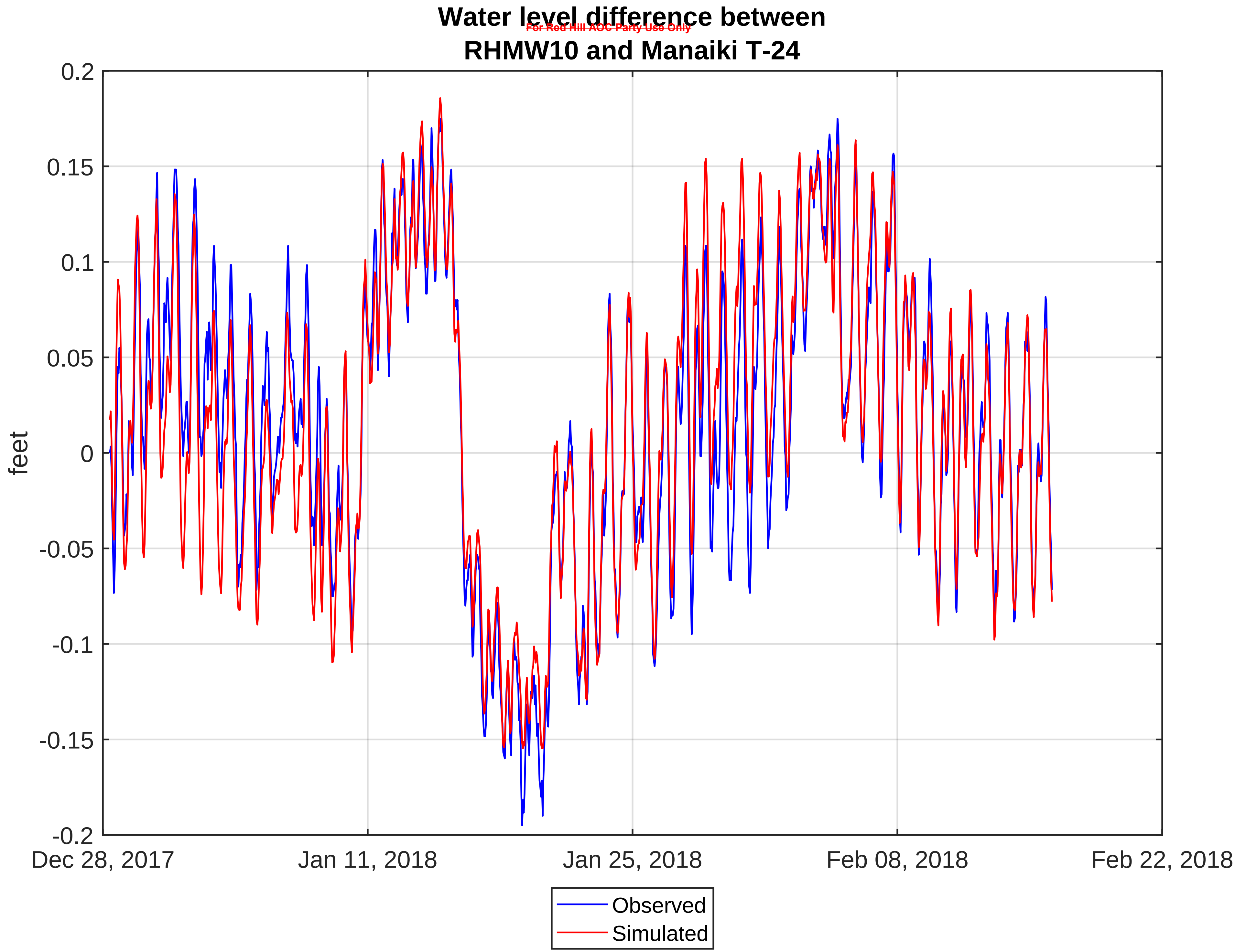
Water level difference between
For Red Hill AOC Party Use Only
RHMW09 and RHMW11 Z3
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
For Red Hill AOC Party Use Only
RHMW09 and RHMW11 Z4
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

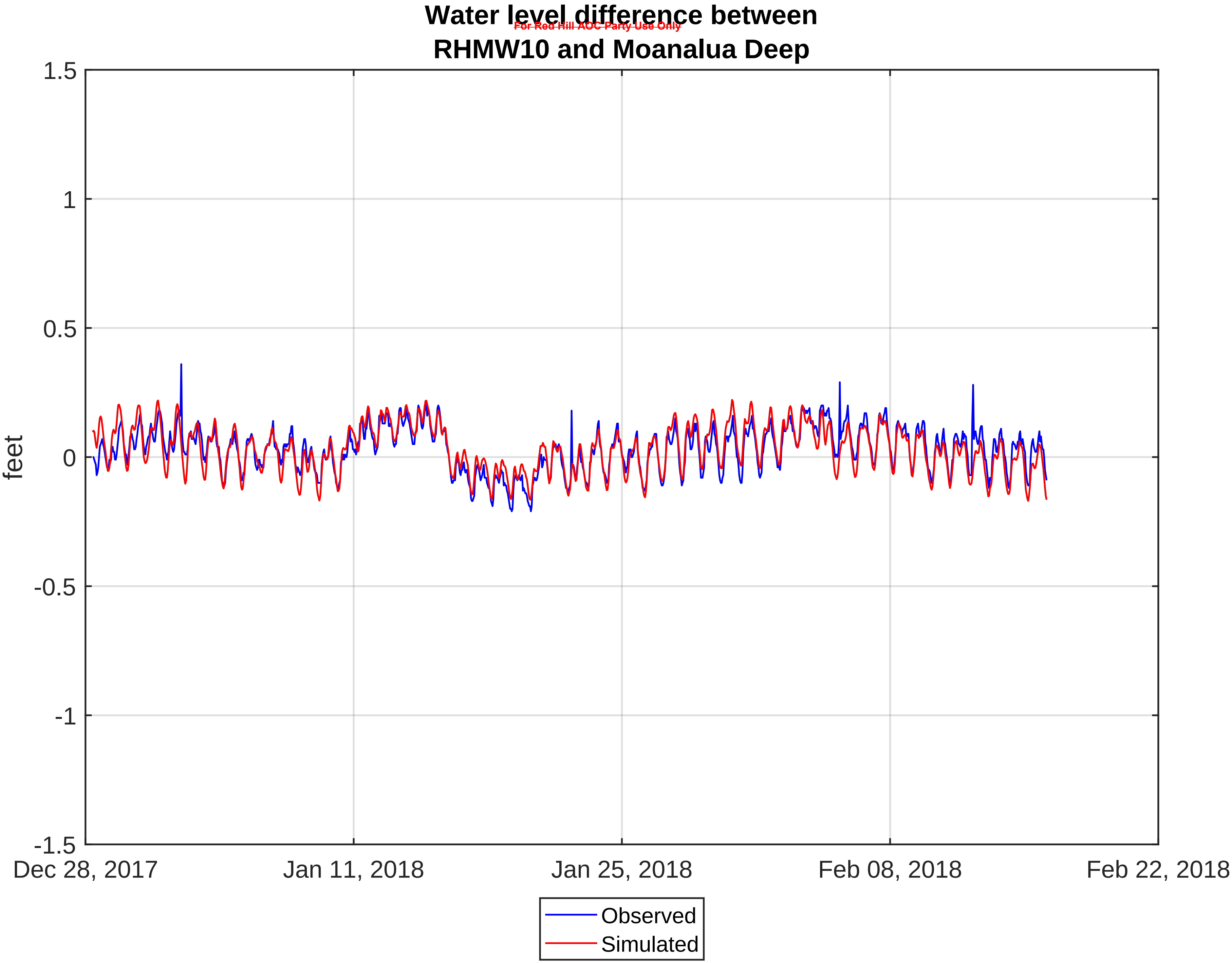


Water level difference between
For Red Hill AOC Party Use Only
RHMW09 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated


Water level difference between
RHMW09 and TAMC-MW2
For Red Hill AOC Party Use Only
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



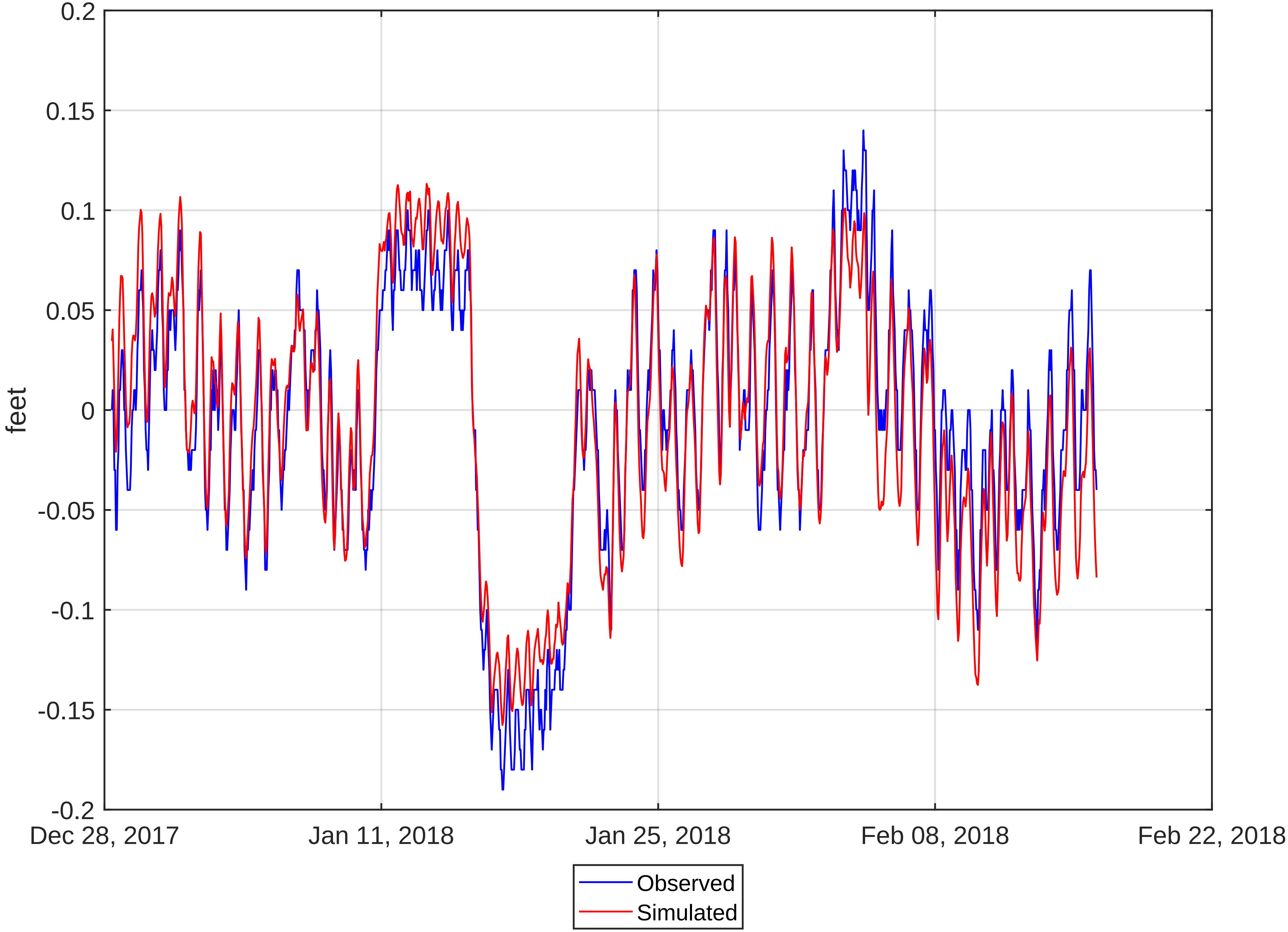
Water level difference between
RHMW10 and Manaiki T-24
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

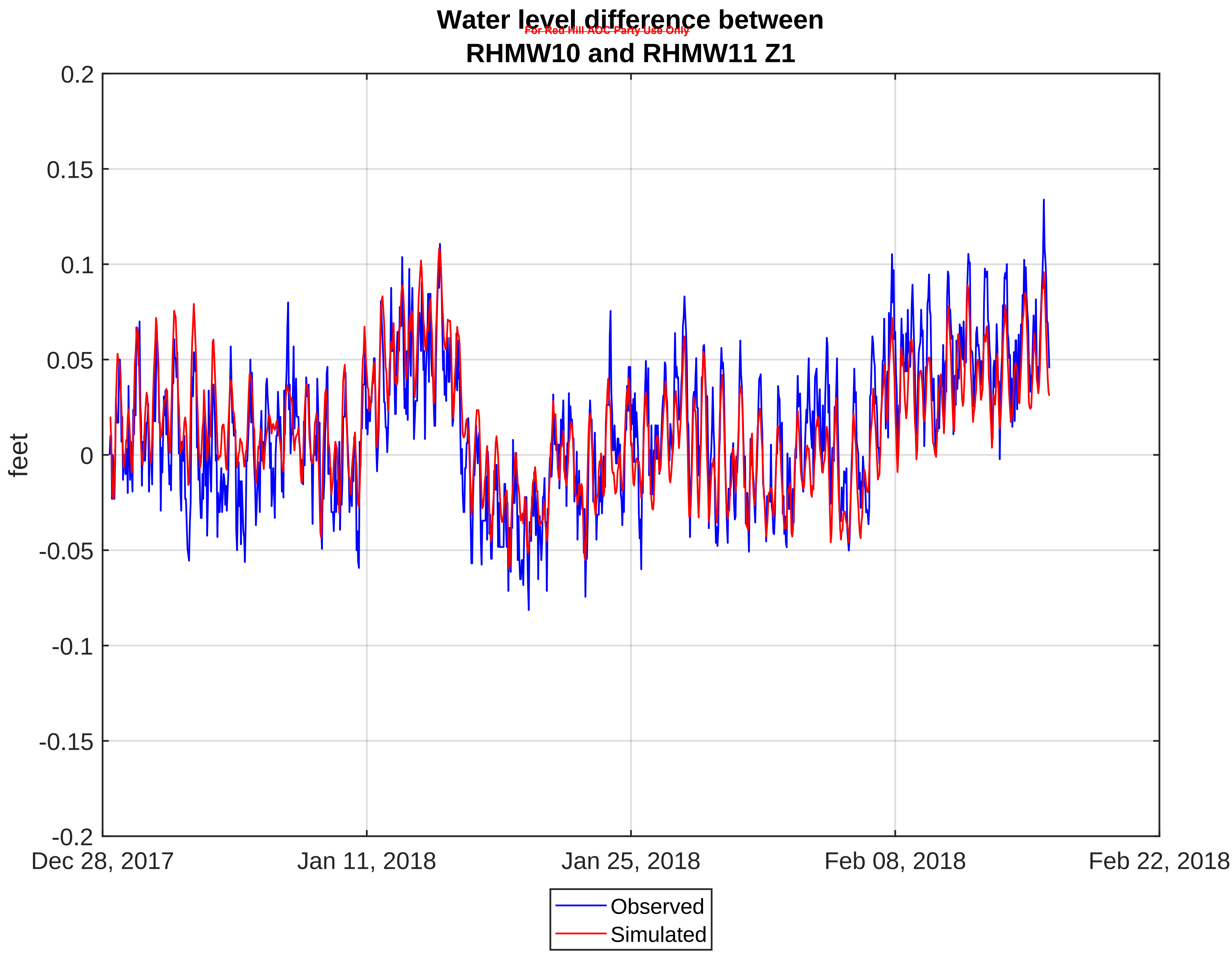


Water level difference between
For Red Hill AOC Party Use Only
RHMW10 and Moanalua Deep
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

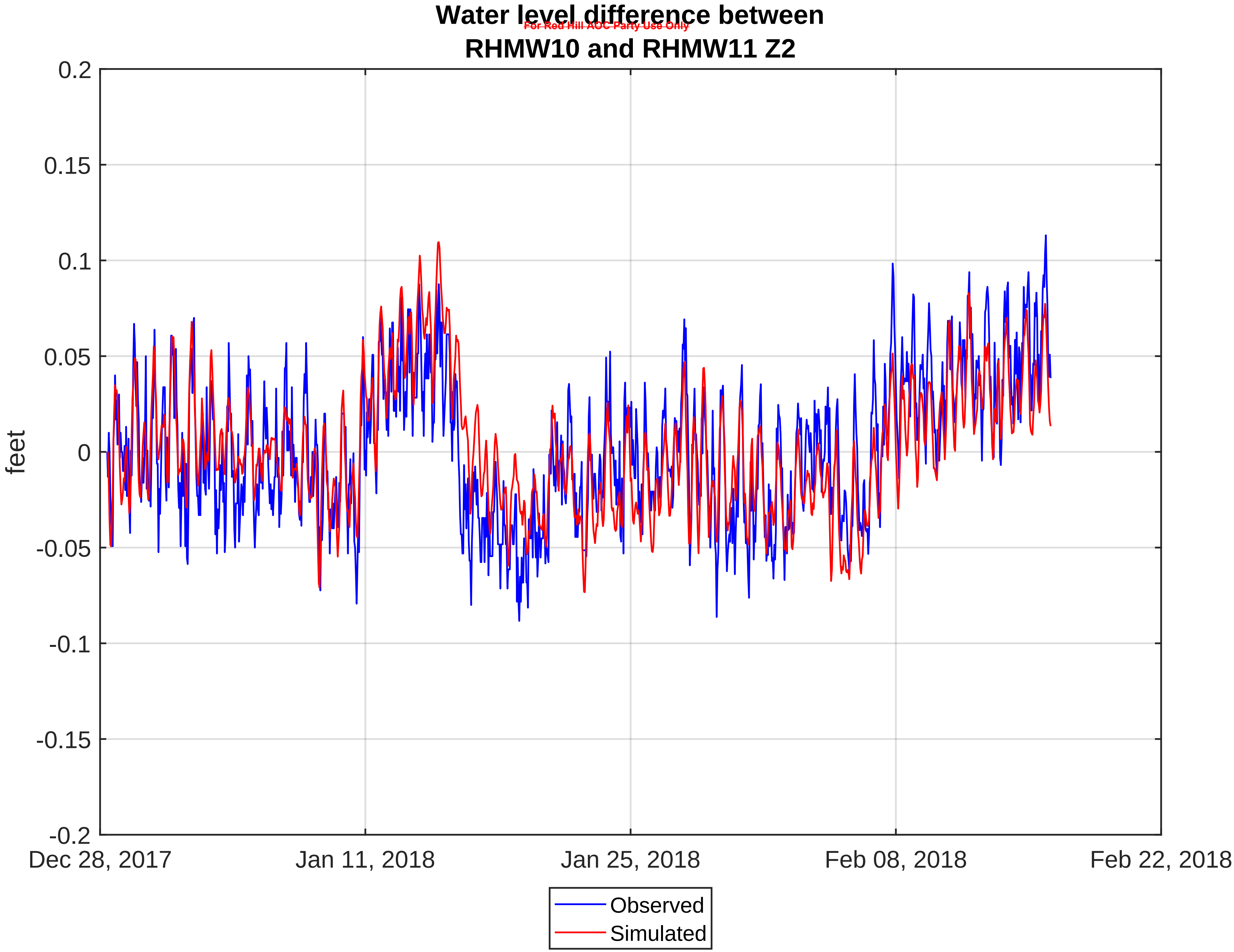
Water level difference between RHMW10 and Moanalua DH43

For Red Hill AOC Party Use Only

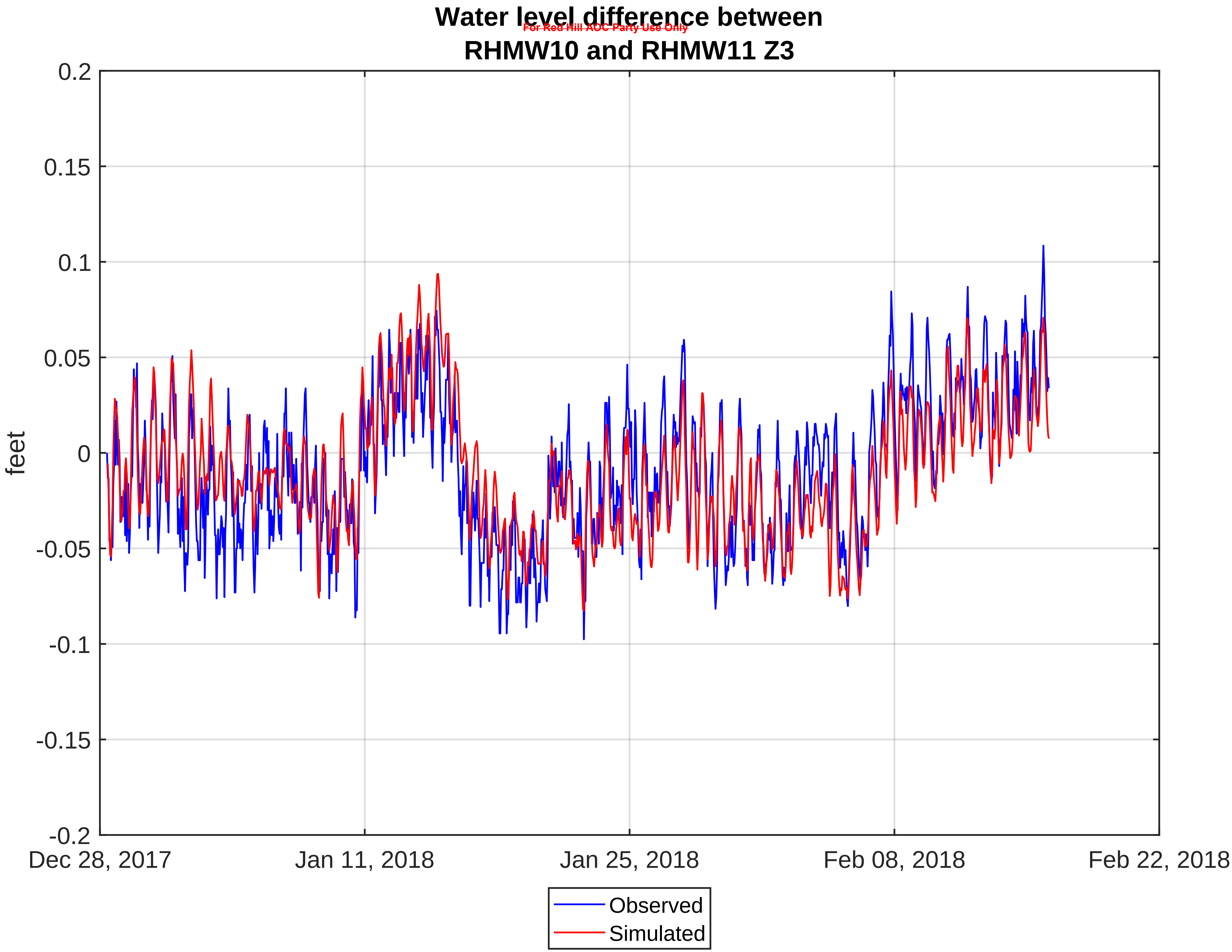




Water level difference between
RHMW10 and RHMW11 Z1
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

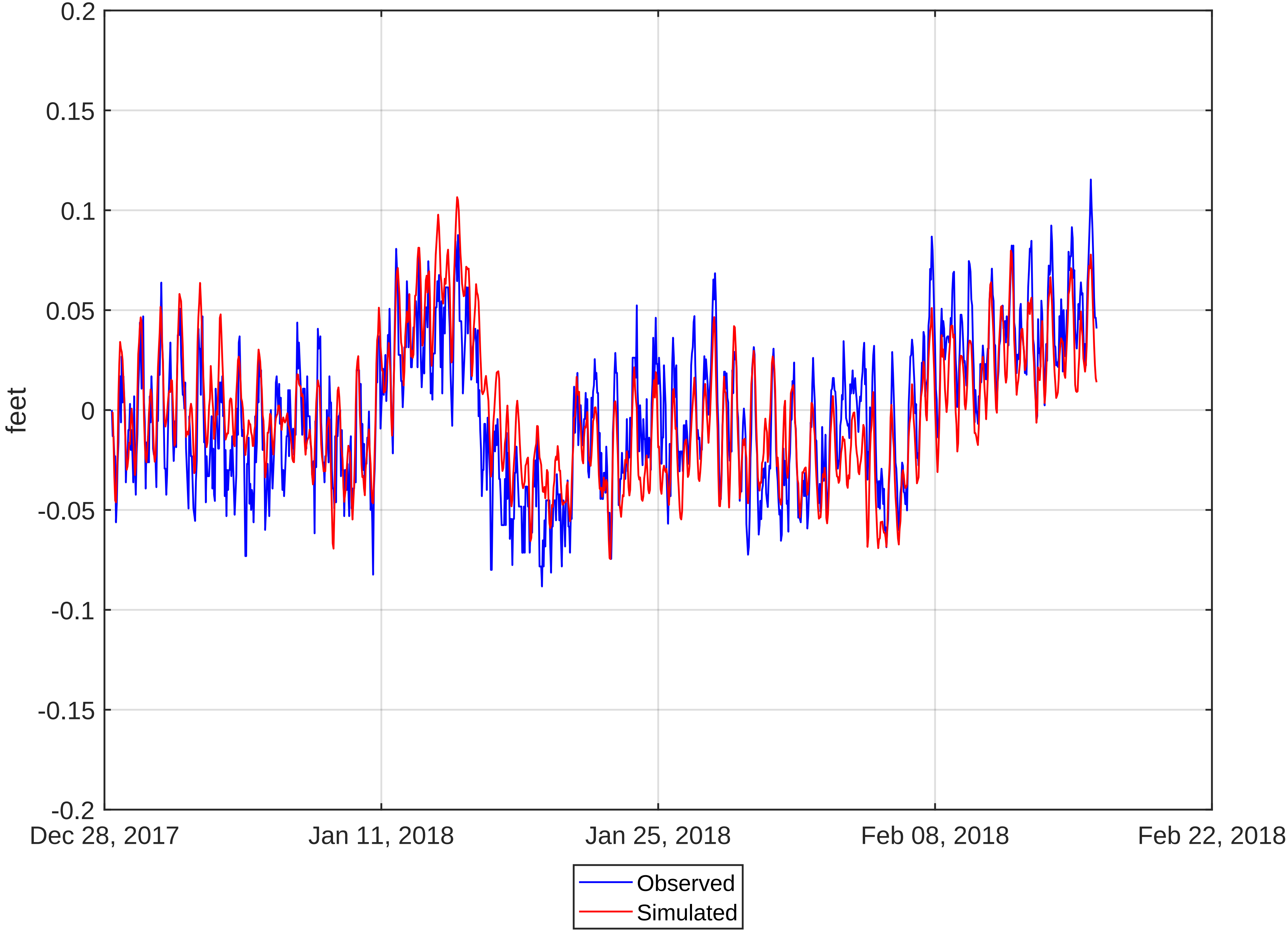


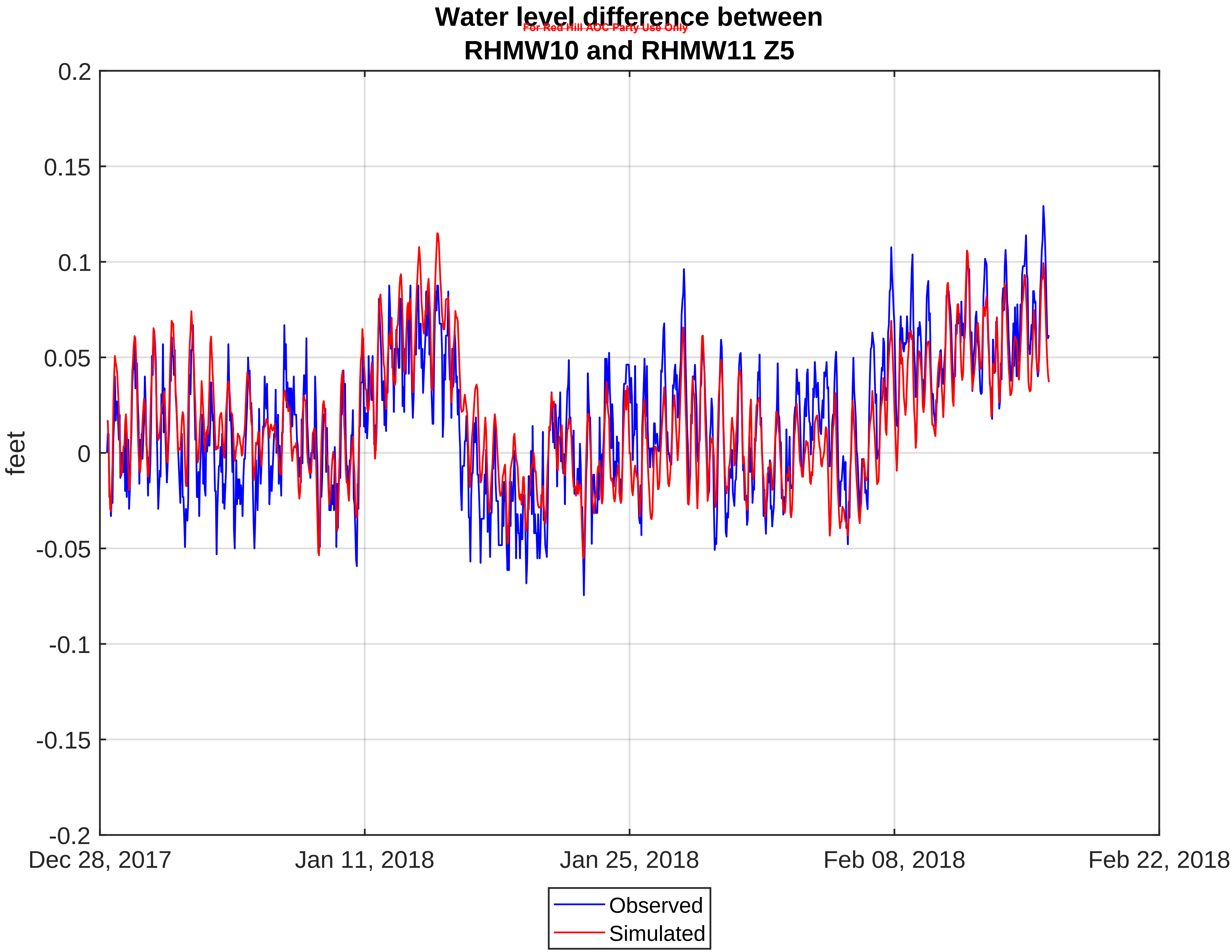
Water level difference between
For Red Hill AOC Party Use Only
RHMW10 and RHMW11 Z2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



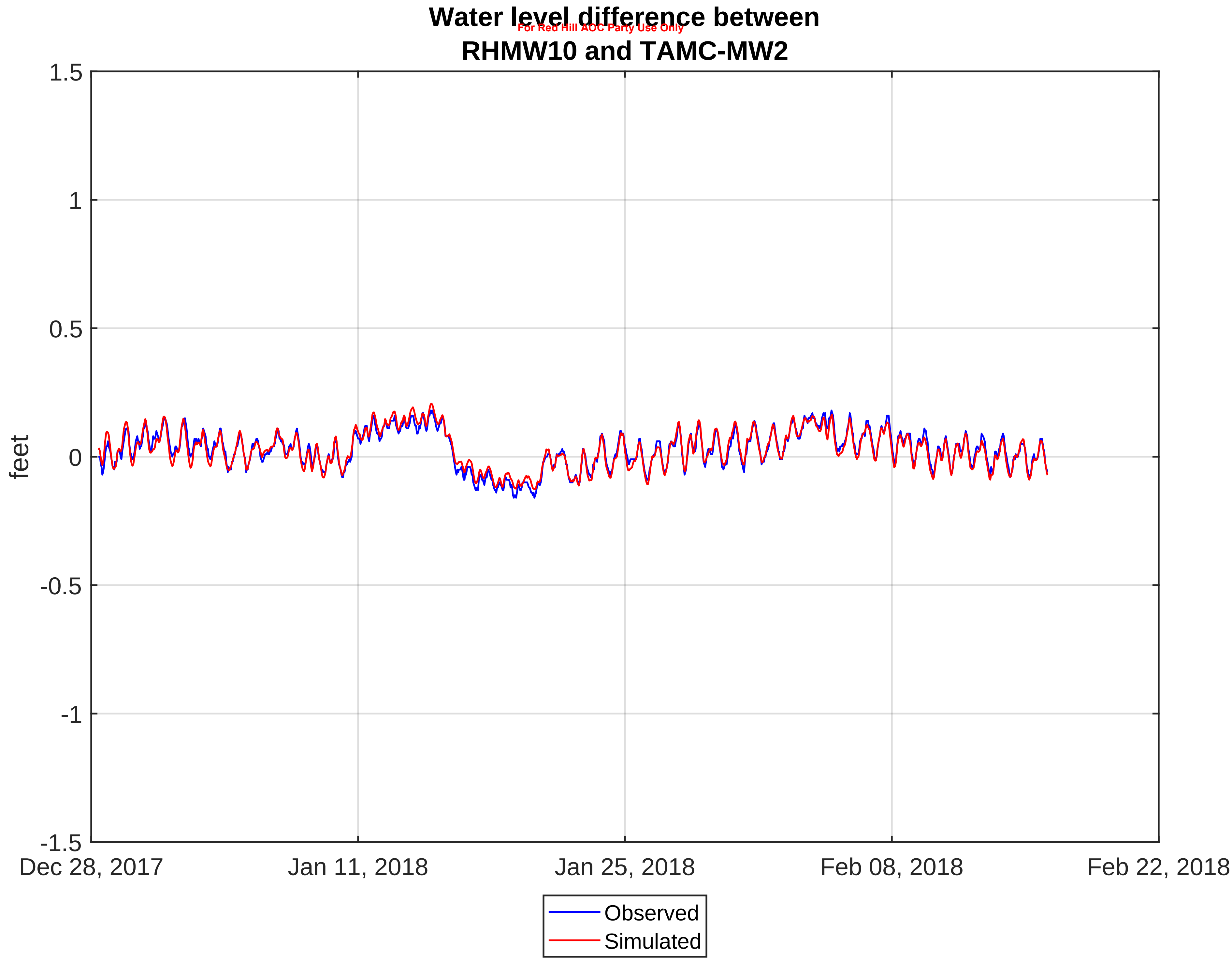
Water level difference between
For Red Hill AOC Party Use Only
RHMW10 and RHMW11 Z3
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
RHMW10 and RHMW11 Z4

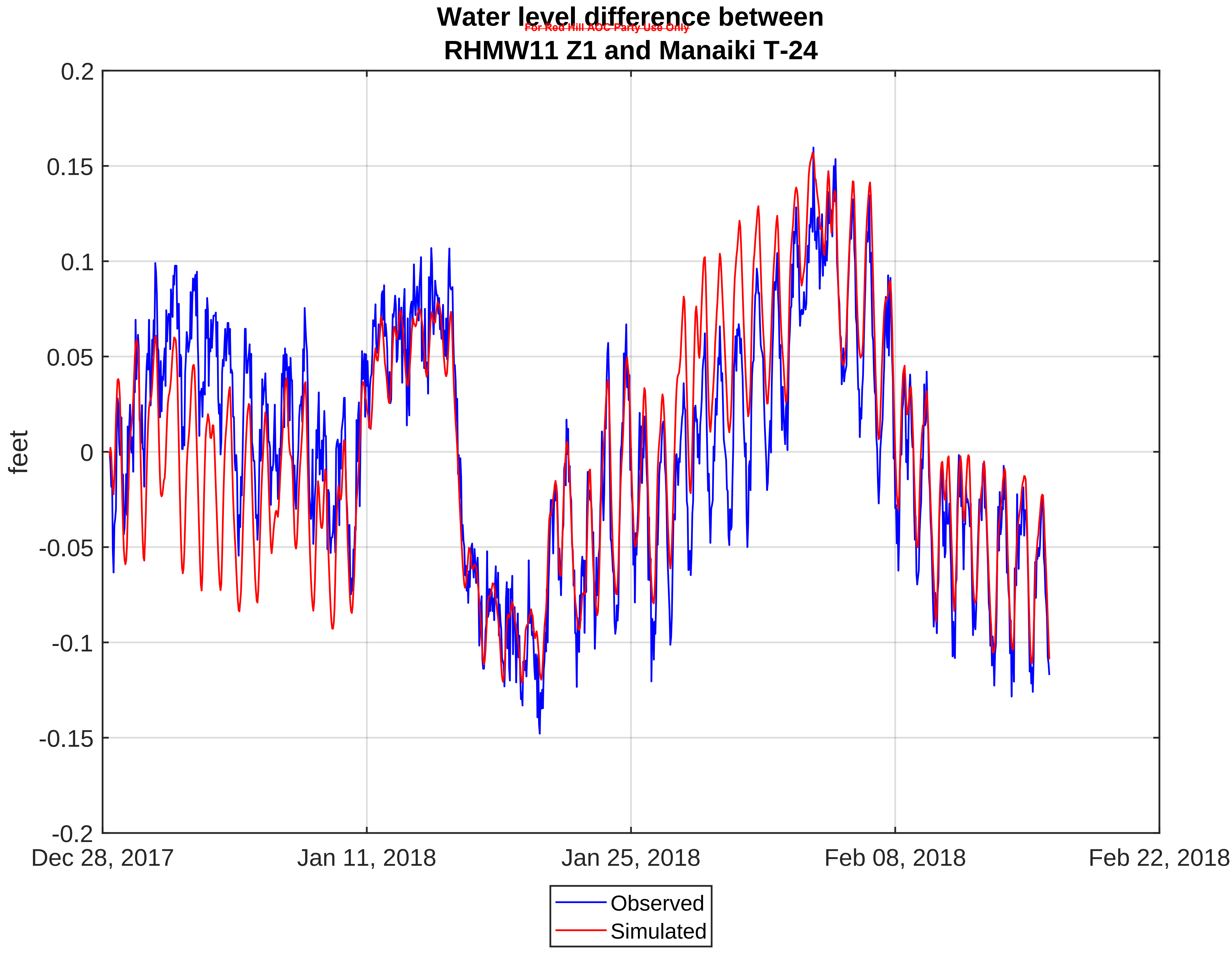




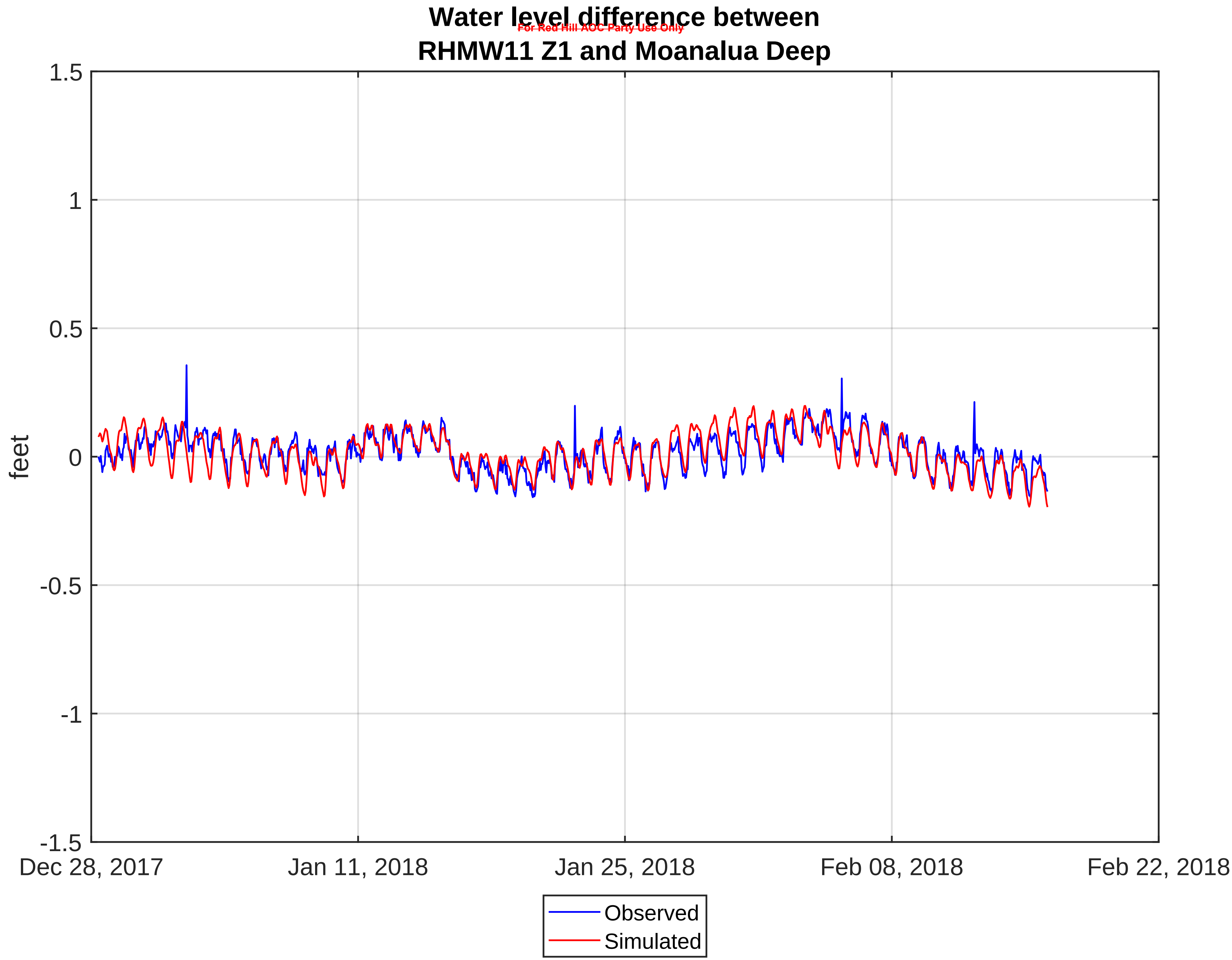
Water level difference between
For Red Hill AOC Party Use Only
RHMW10 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



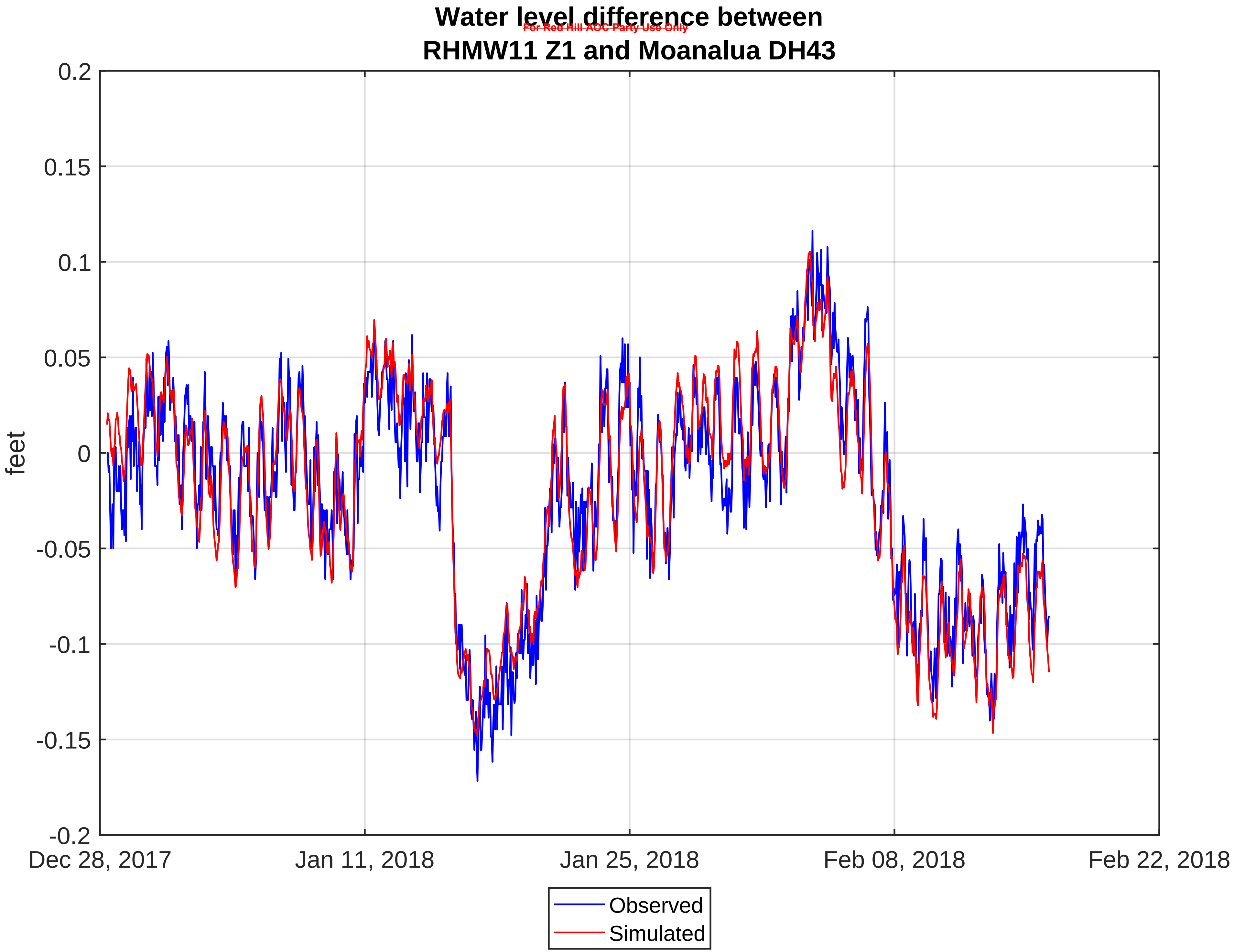
Water level difference between
For Red Hill AOC Party Use Only
RHMW10 and TAMC-MW2
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



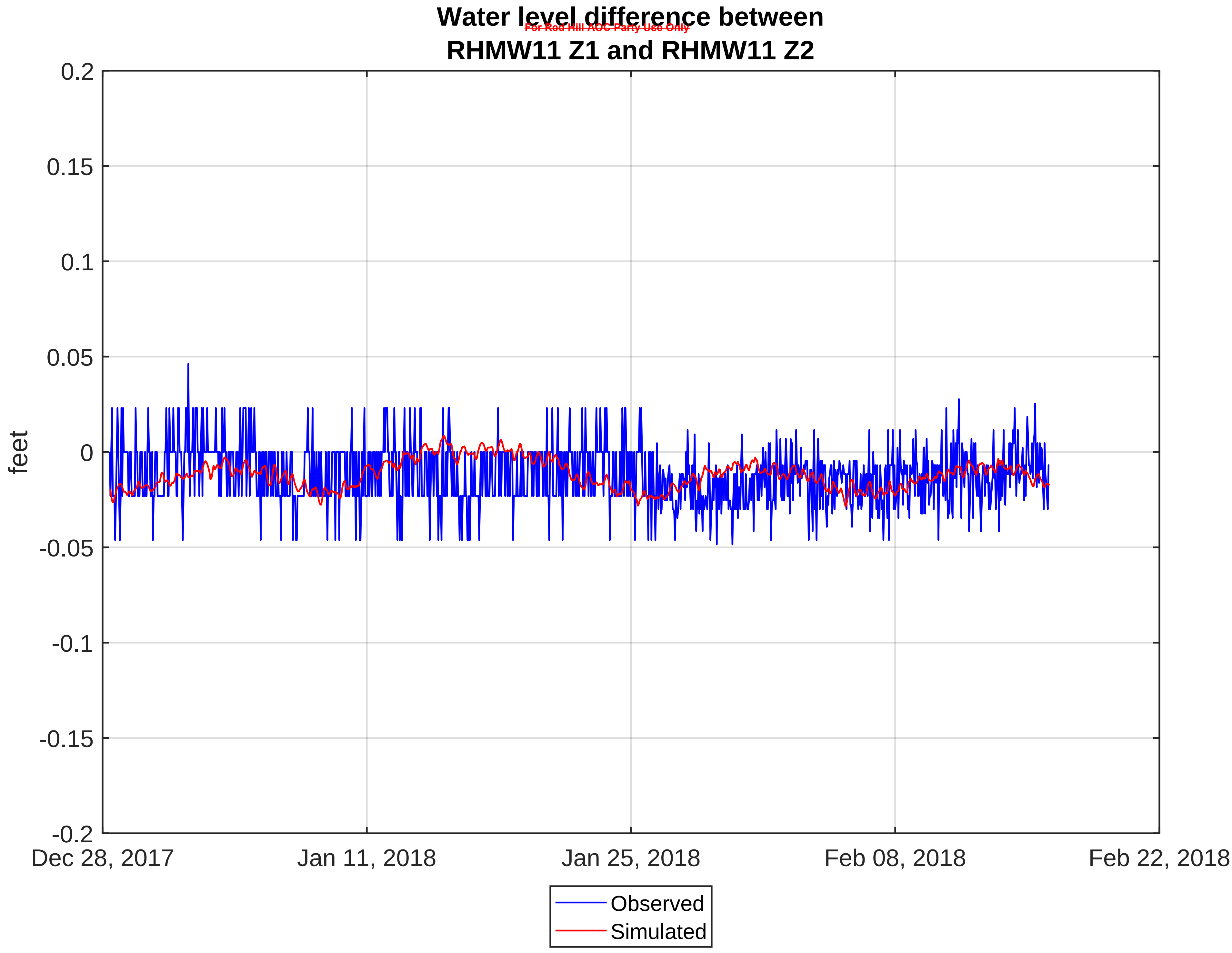
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z1 and Manaiki T-24
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



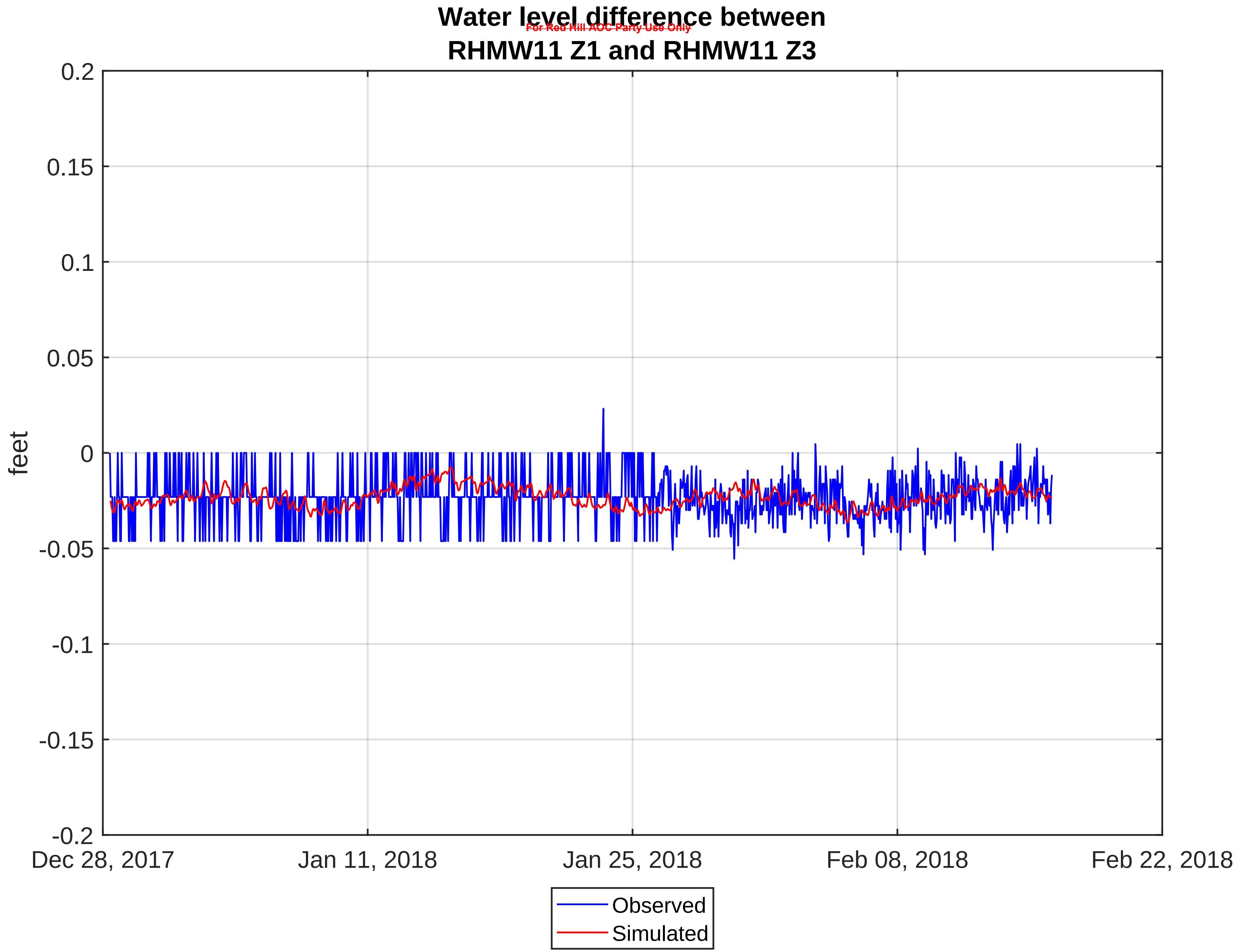
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z1 and Moanalua Deep
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



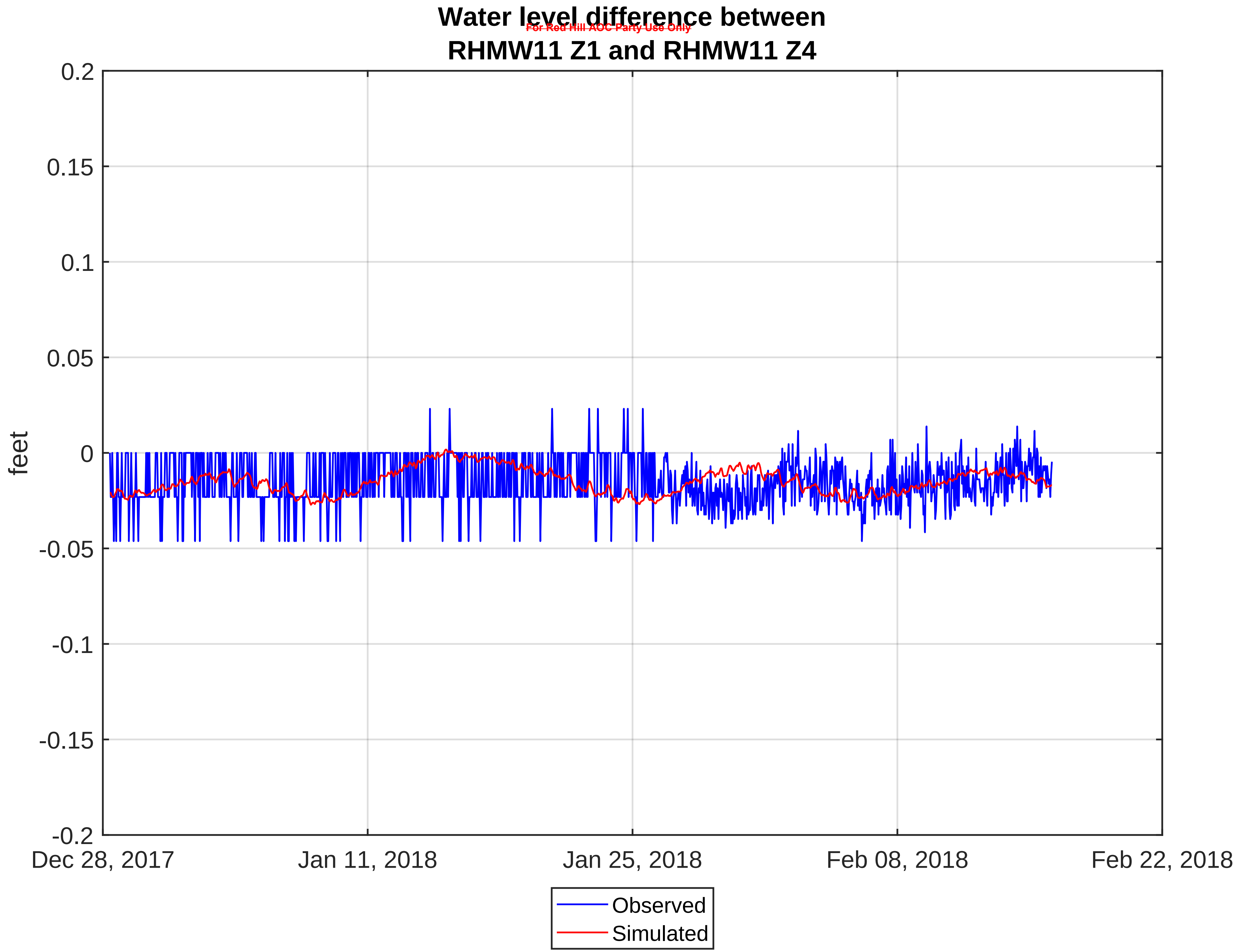
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z1 and Moanalua DH43
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

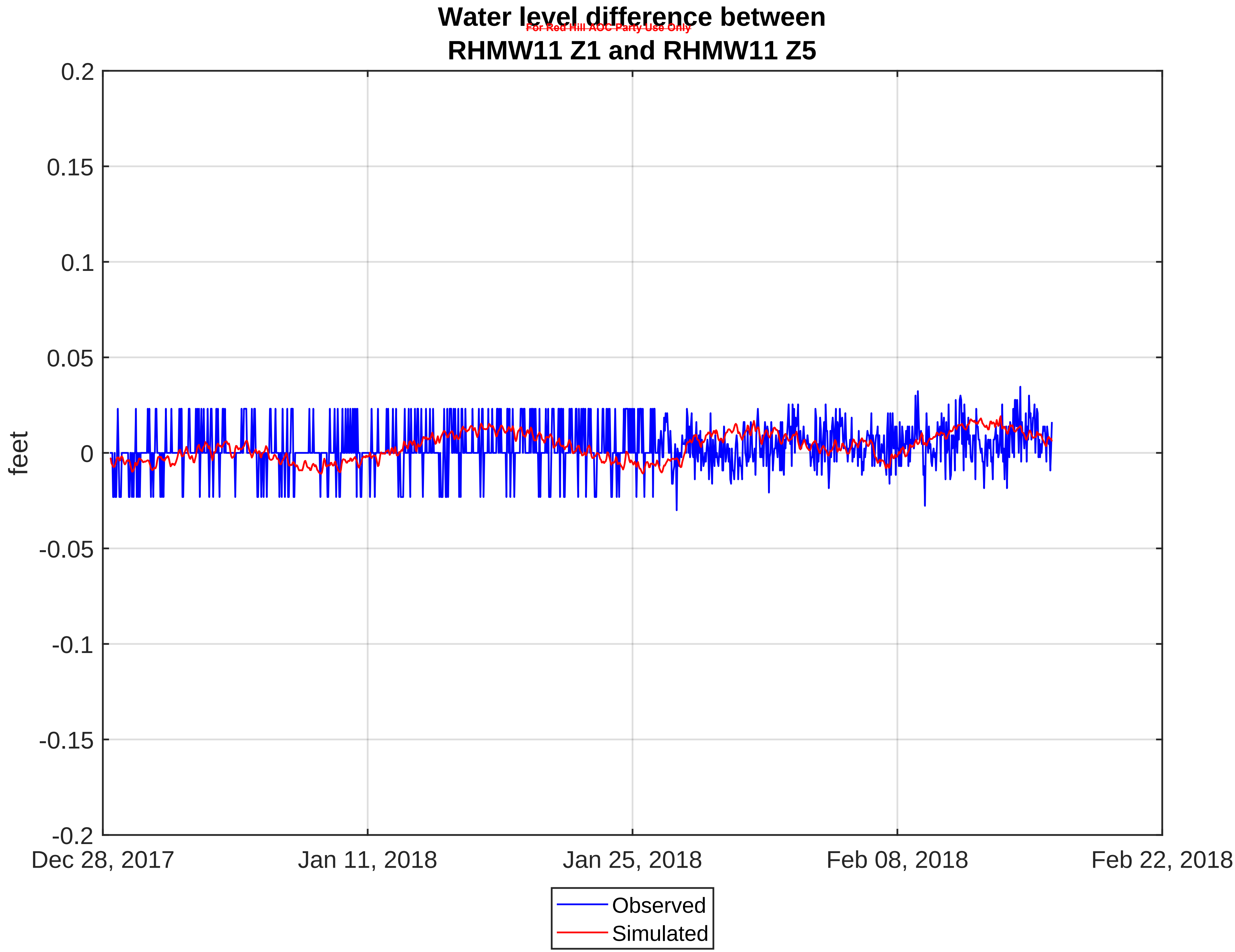


Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z1 and RHMW11 Z2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

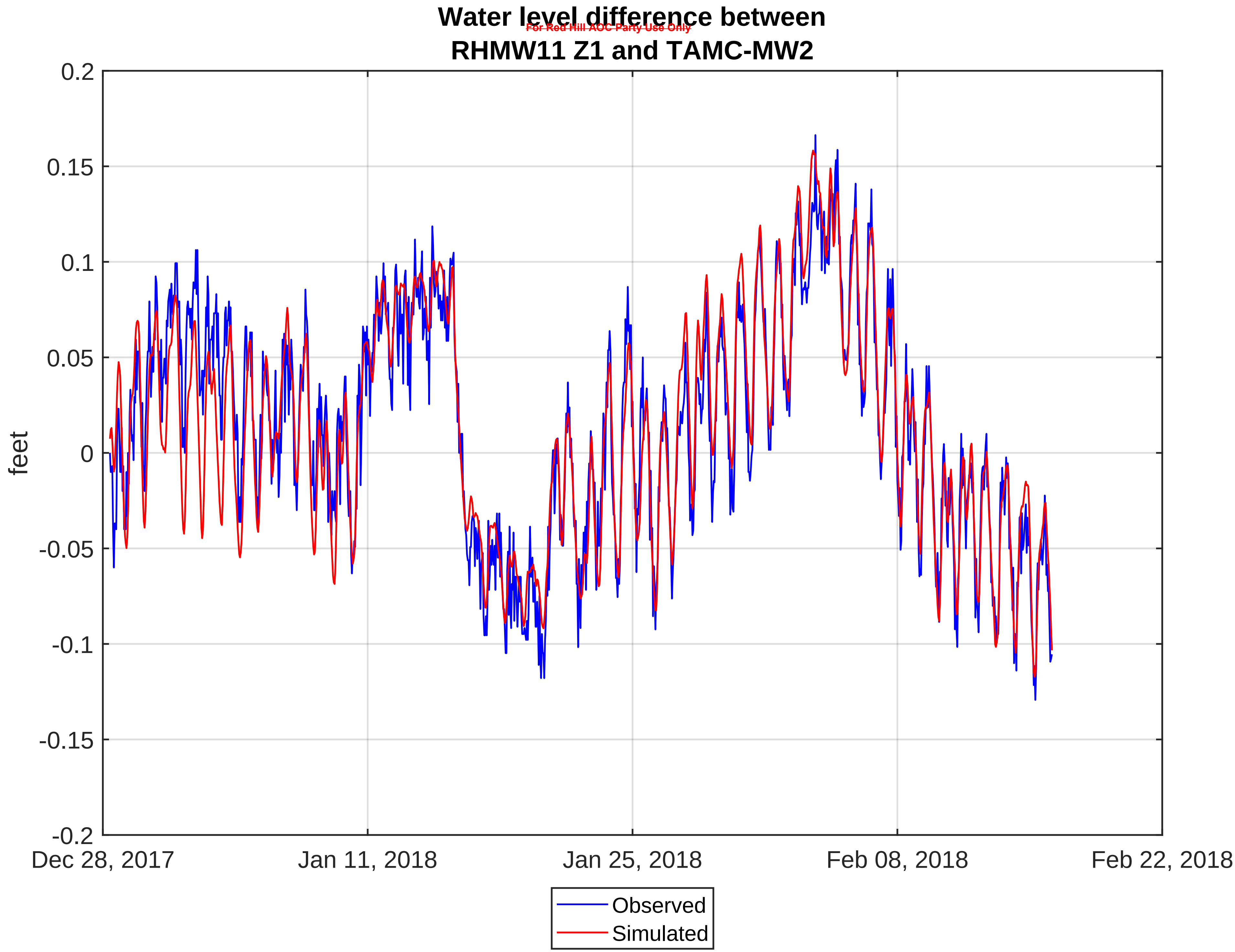


Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z1 and RHMW11 Z3
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

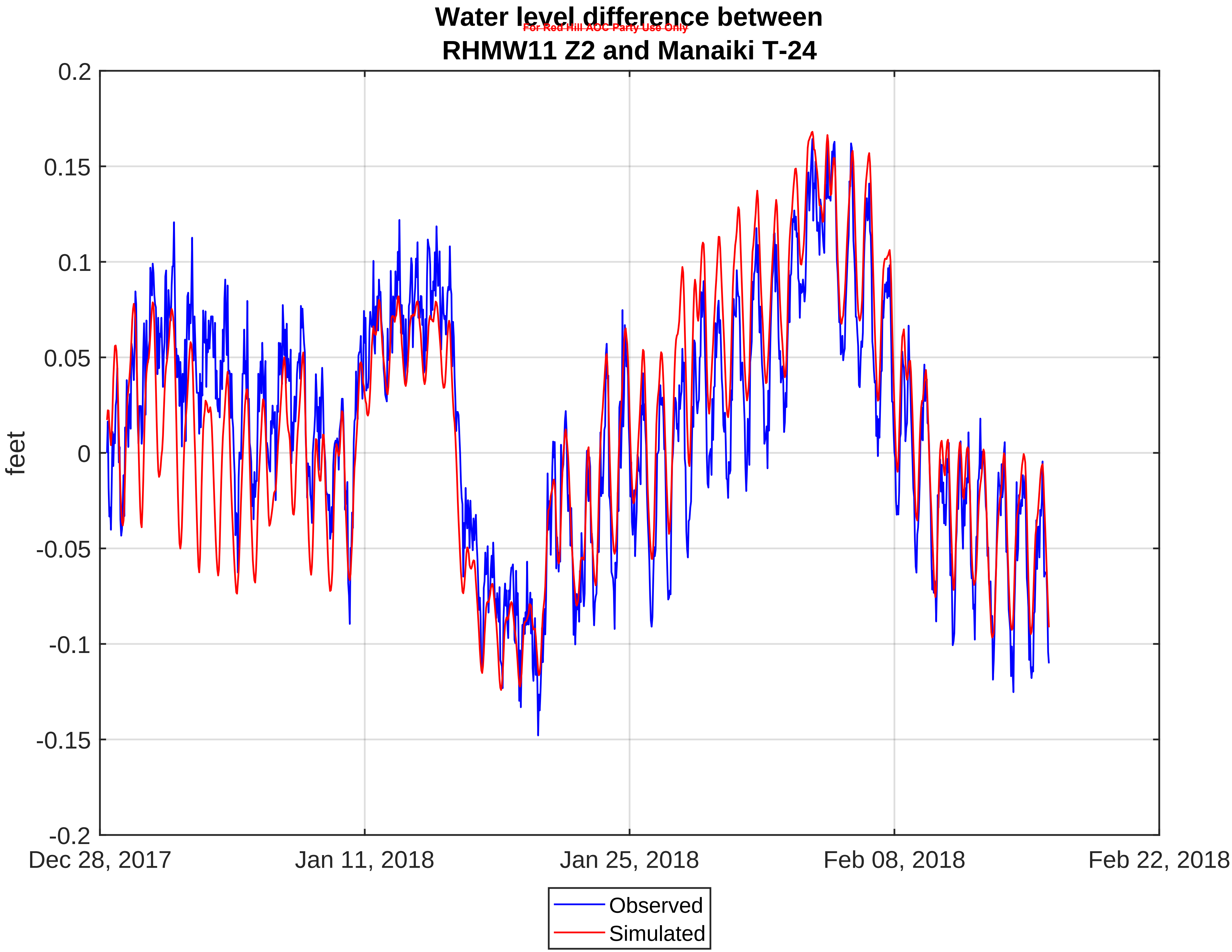

Water level difference between
RHMW11 Z1 and RHMW11 Z4
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z1 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

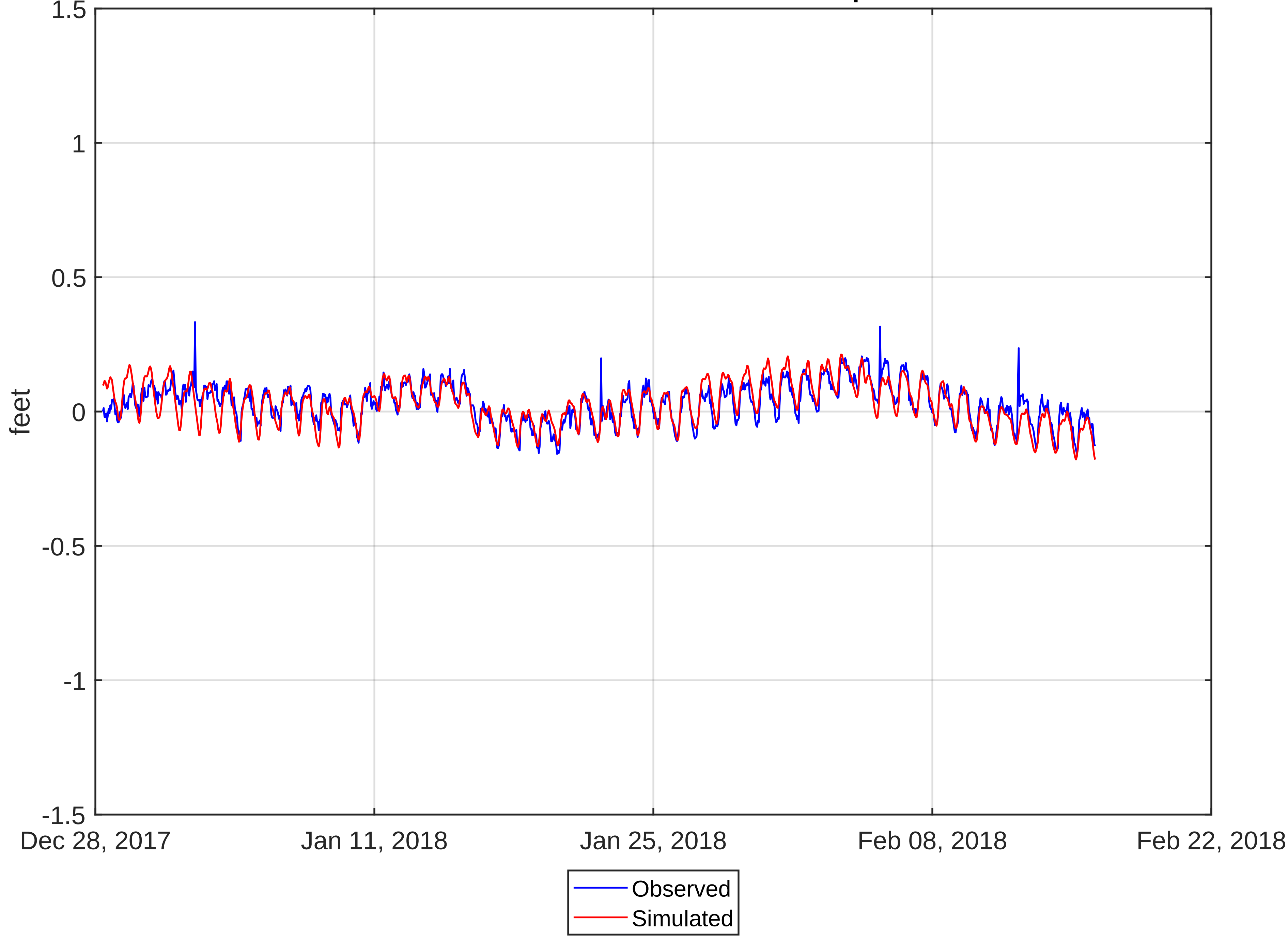


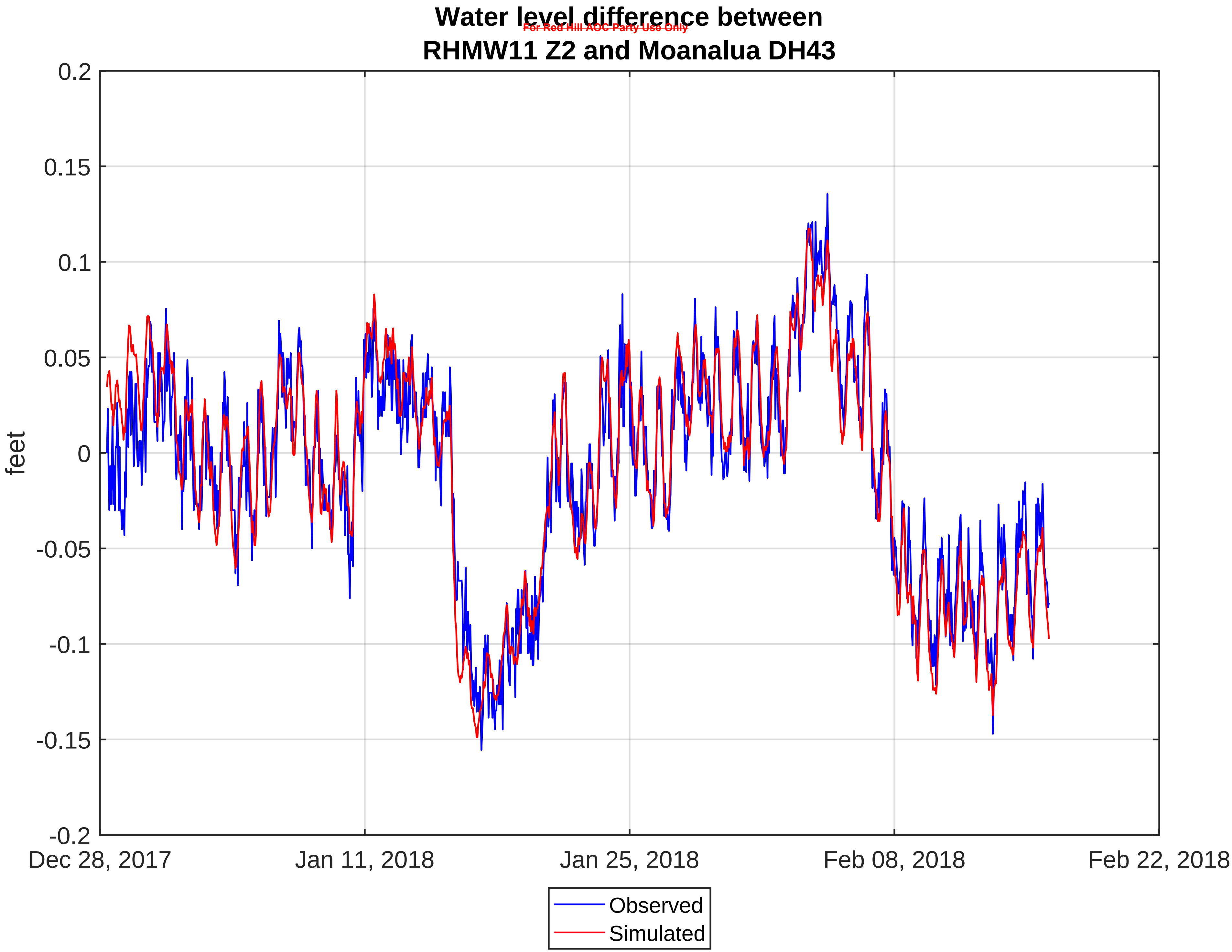
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z1 and TAMC-MW2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



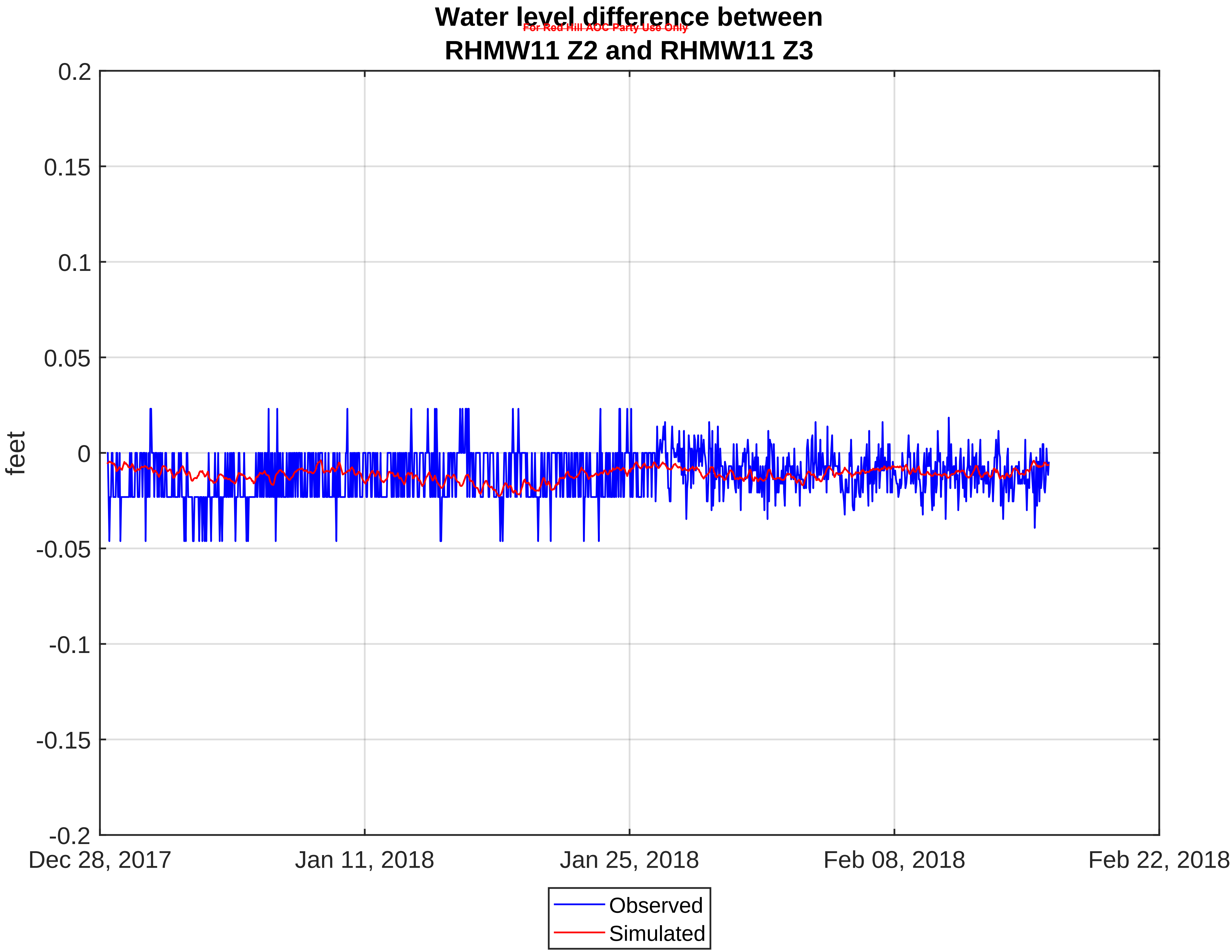
Water level difference between
RHMW11 Z2 and Manaiki T-24
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between RHMW11 Z2 and Moanalua Deep



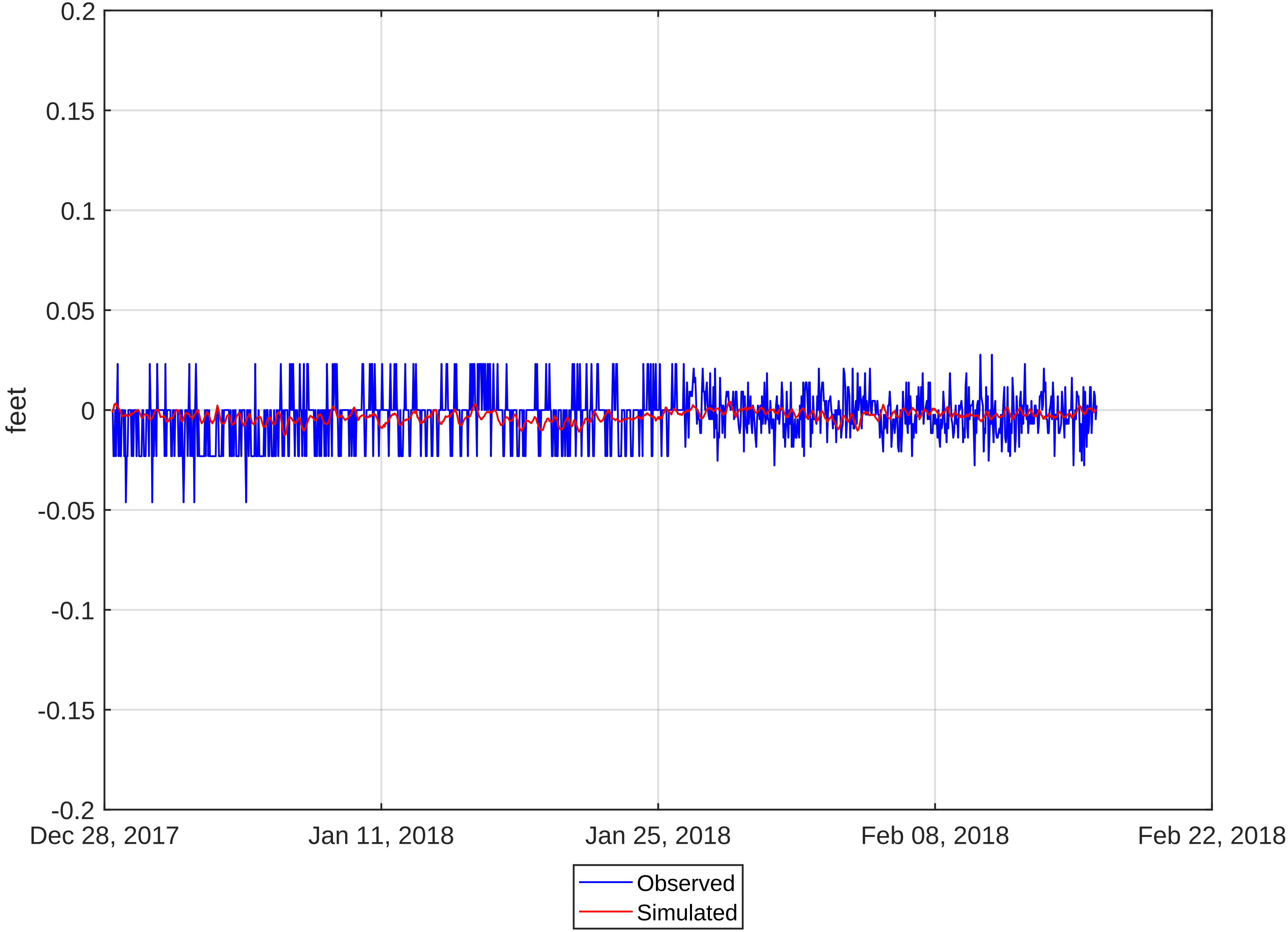


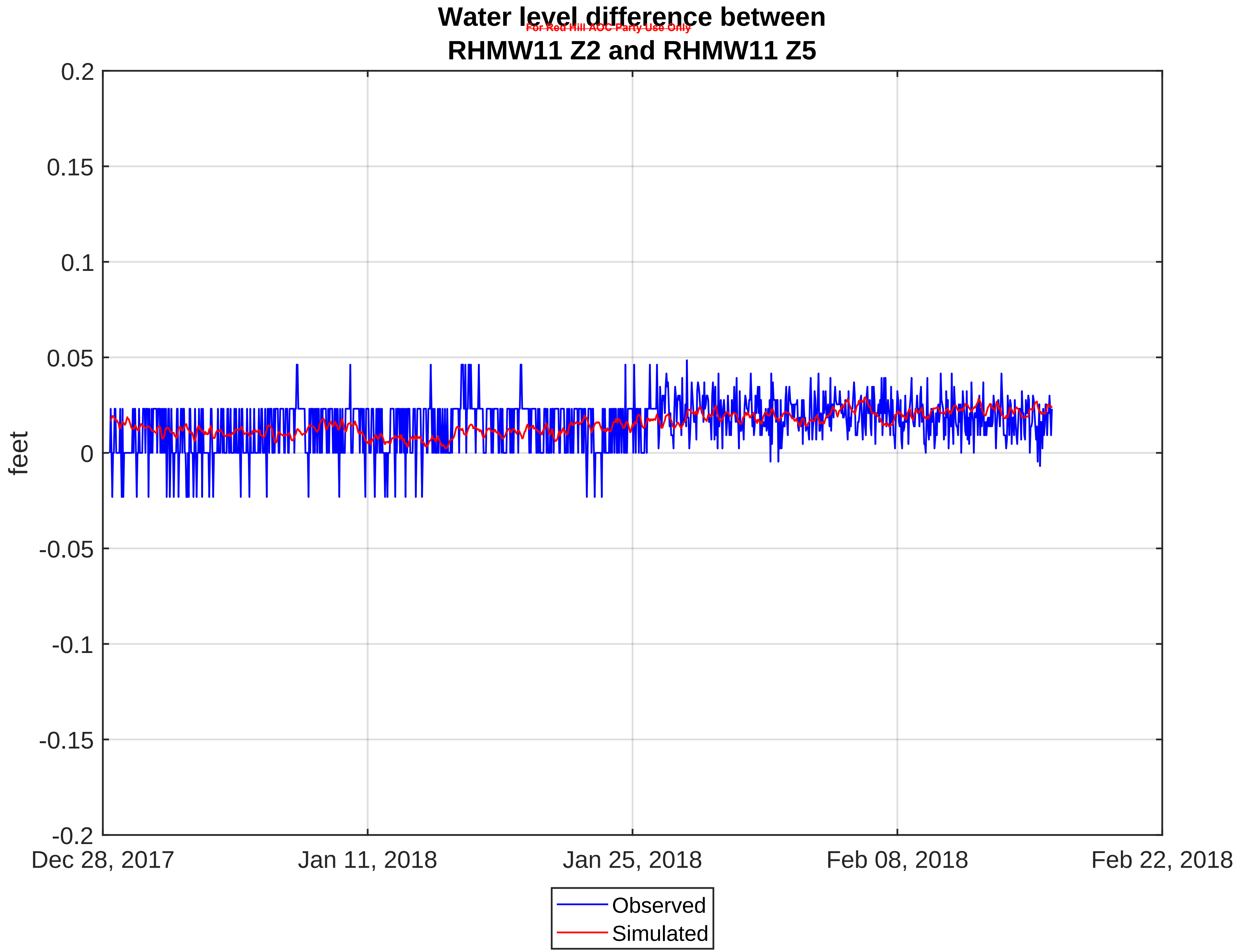
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z2 and Moanalua DH43
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



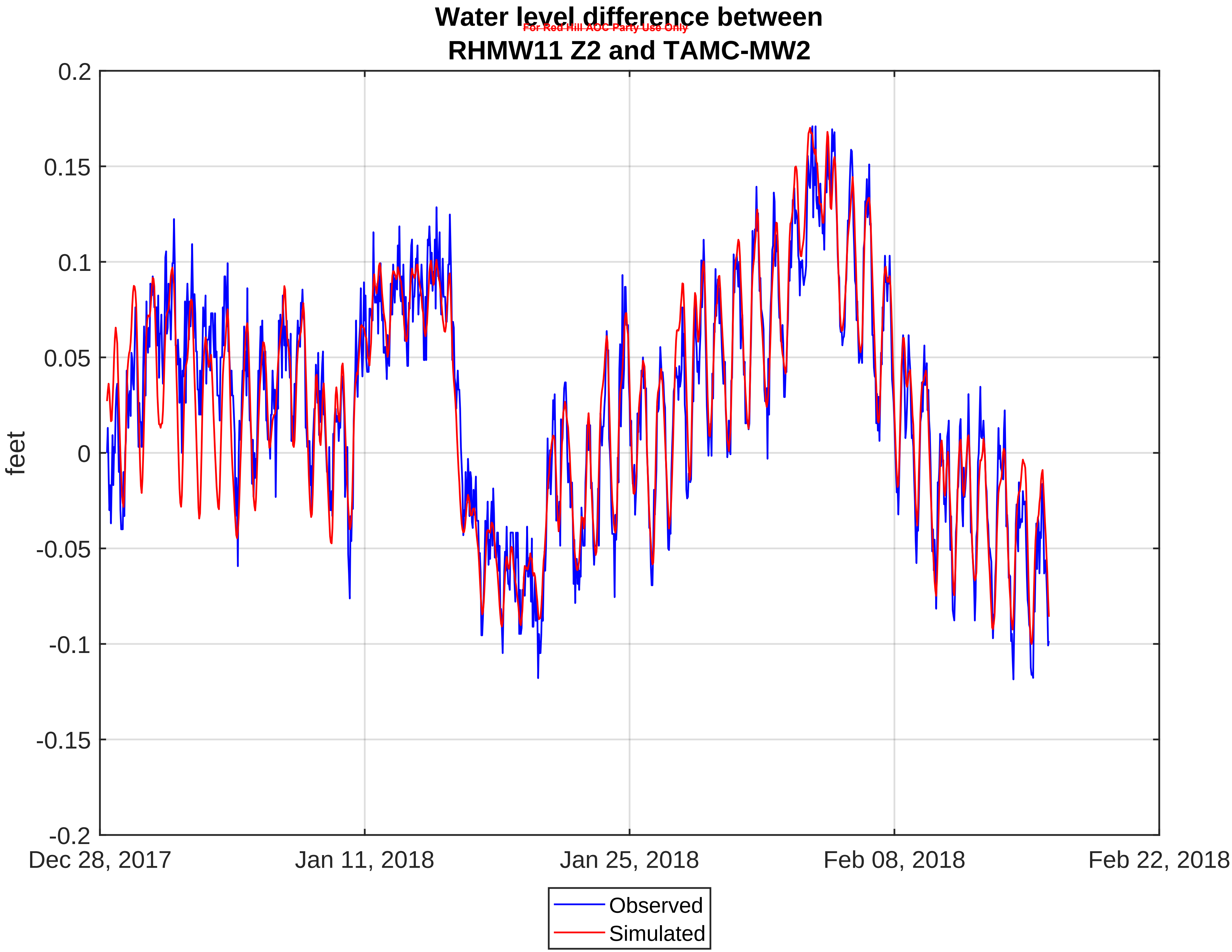
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z2 and RHMW11 Z3
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z2 and RHMW11 Z4

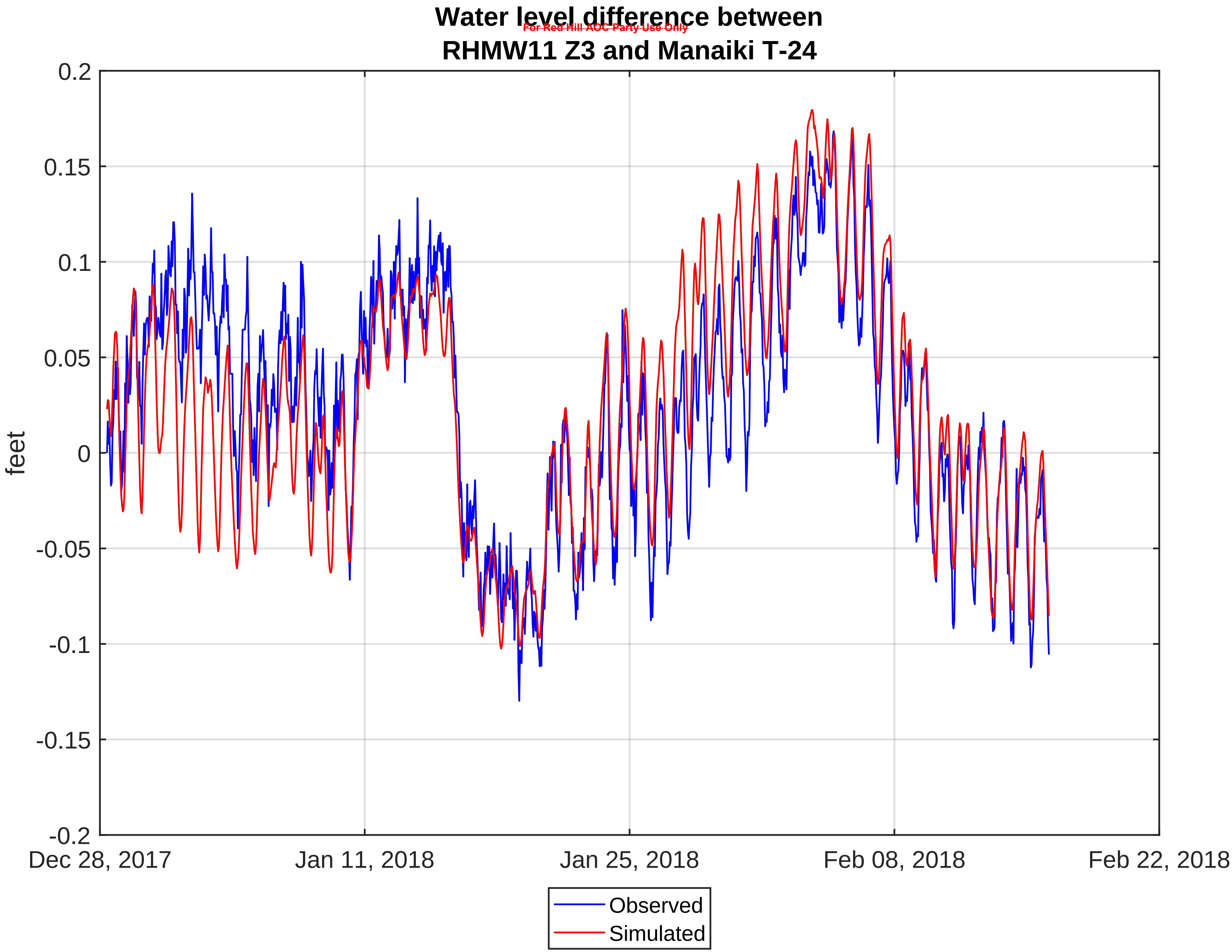




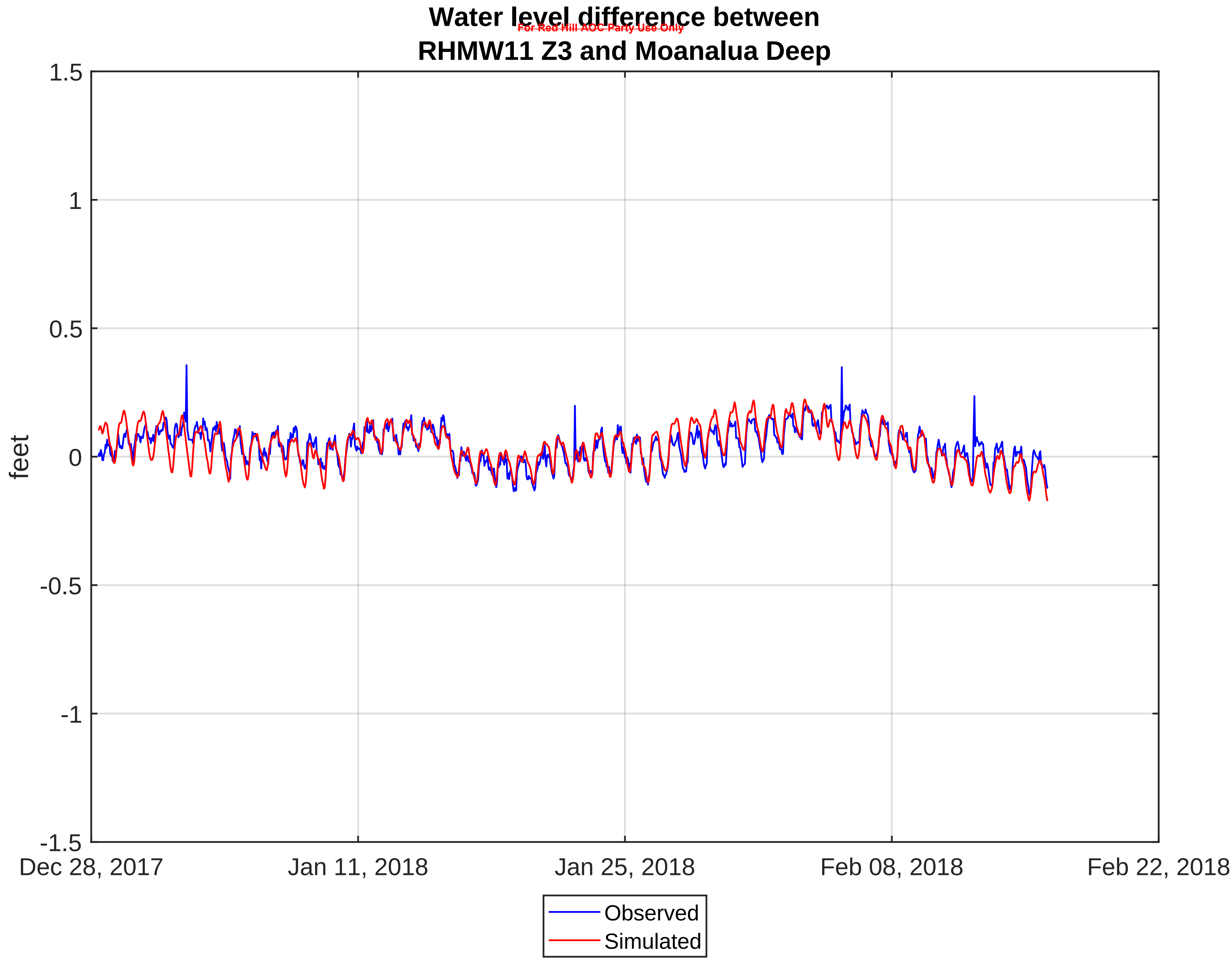
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z2 and RHMW11 Z5
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



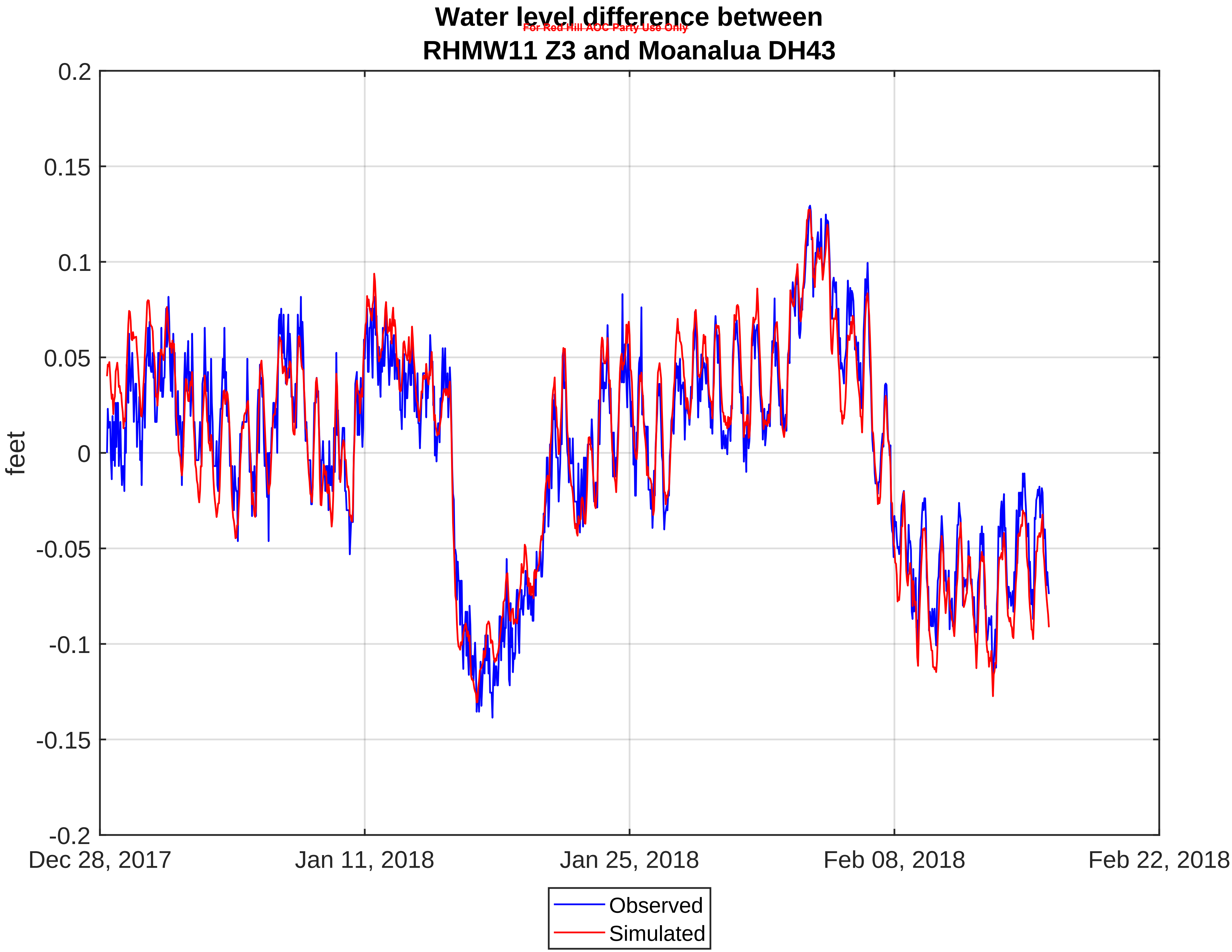
Water level difference between
RHMW11 Z2 and TAMC-MW2
For Red Hill AOC Party Use Only
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



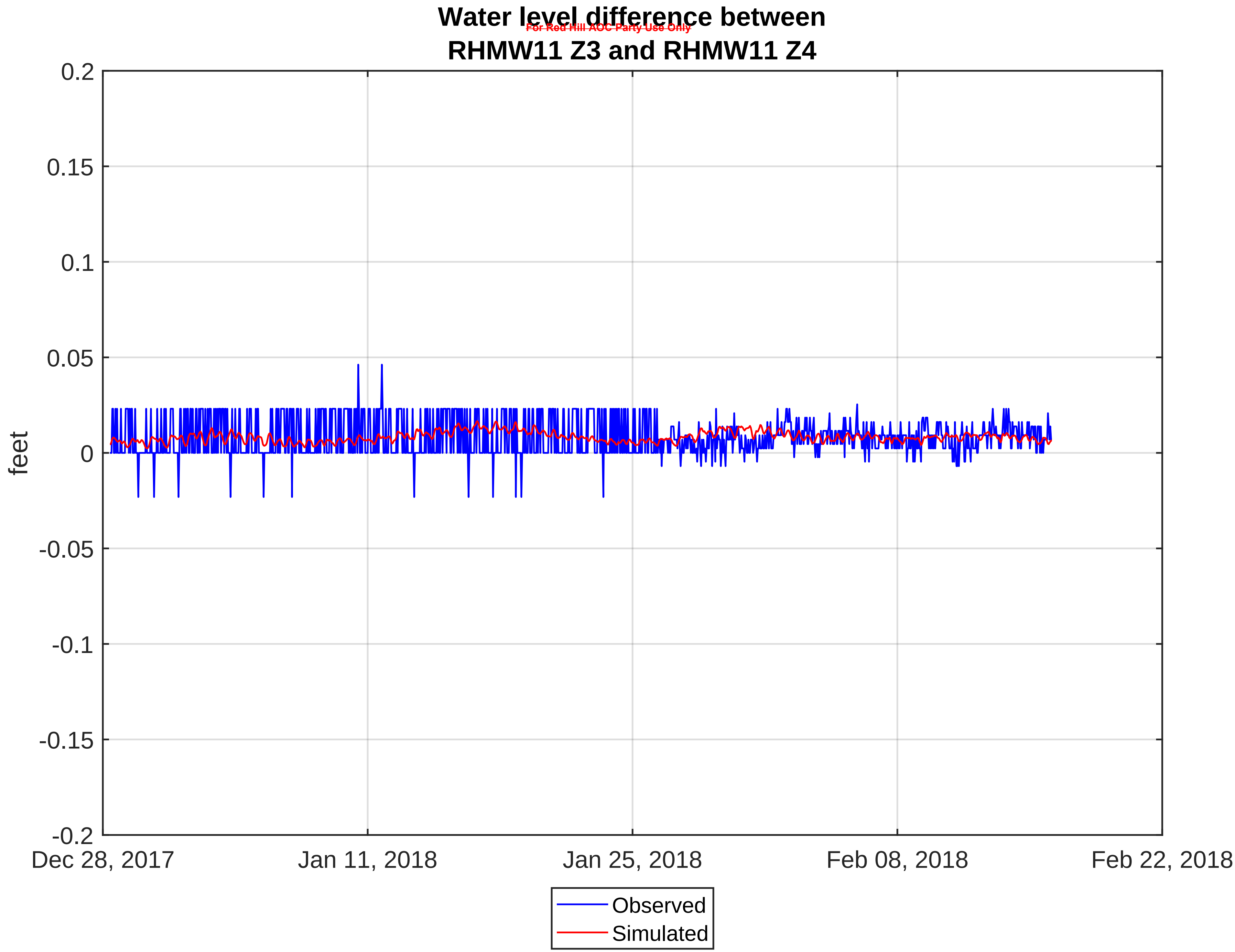
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z3 and Manaiki T-24
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



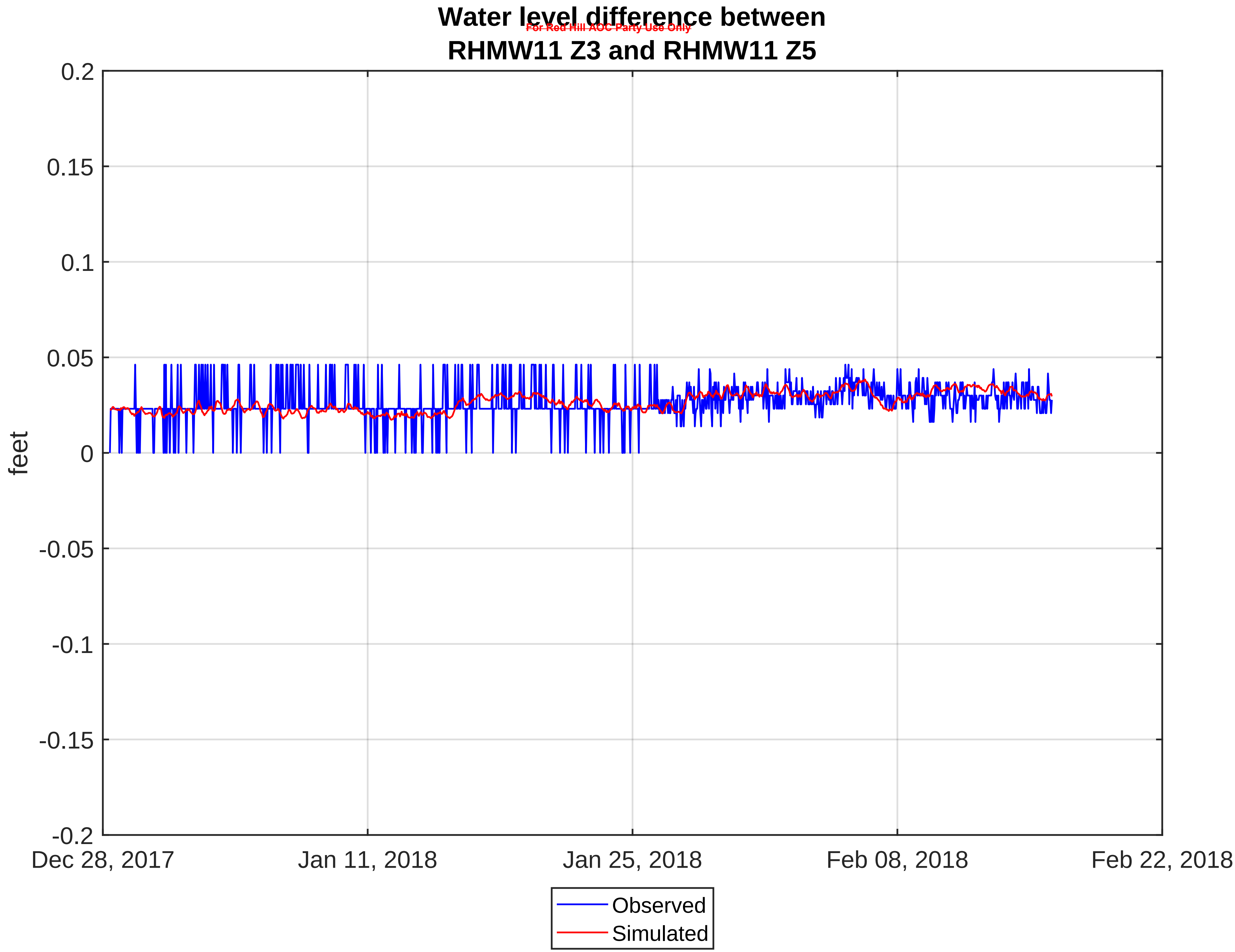
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z3 and Moanalua Deep
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



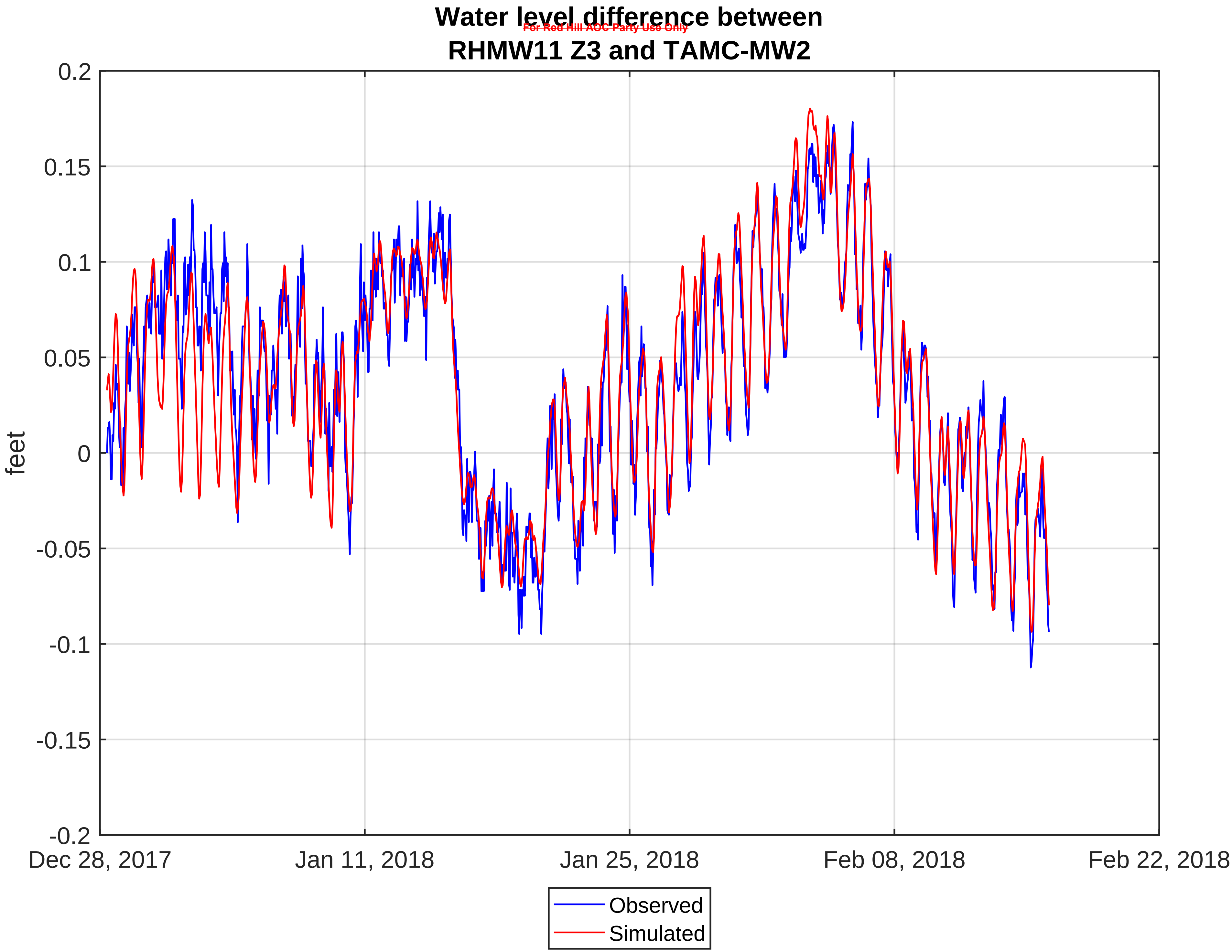
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z3 and Moanalua DH43
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



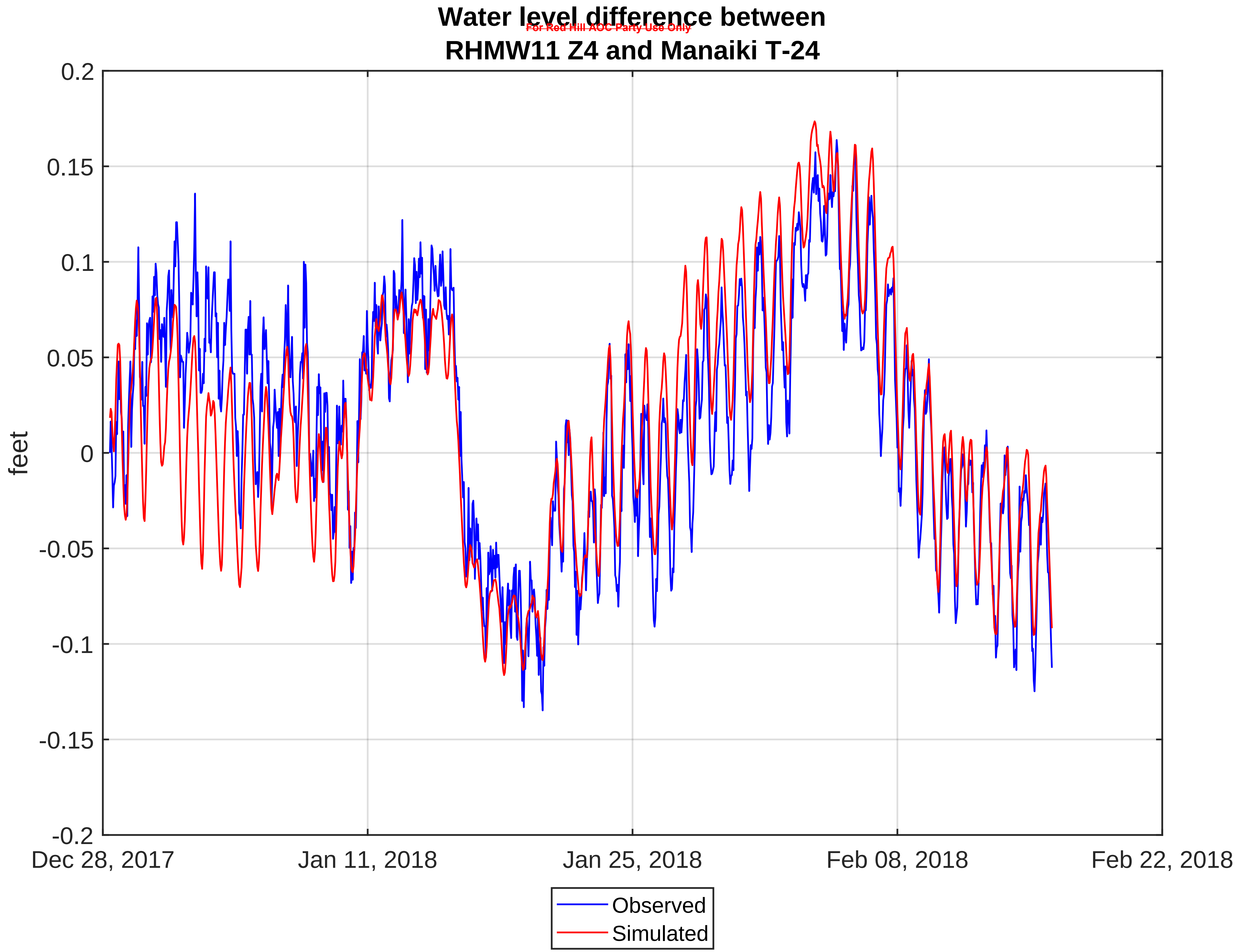
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z3 and RHMW11 Z4
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



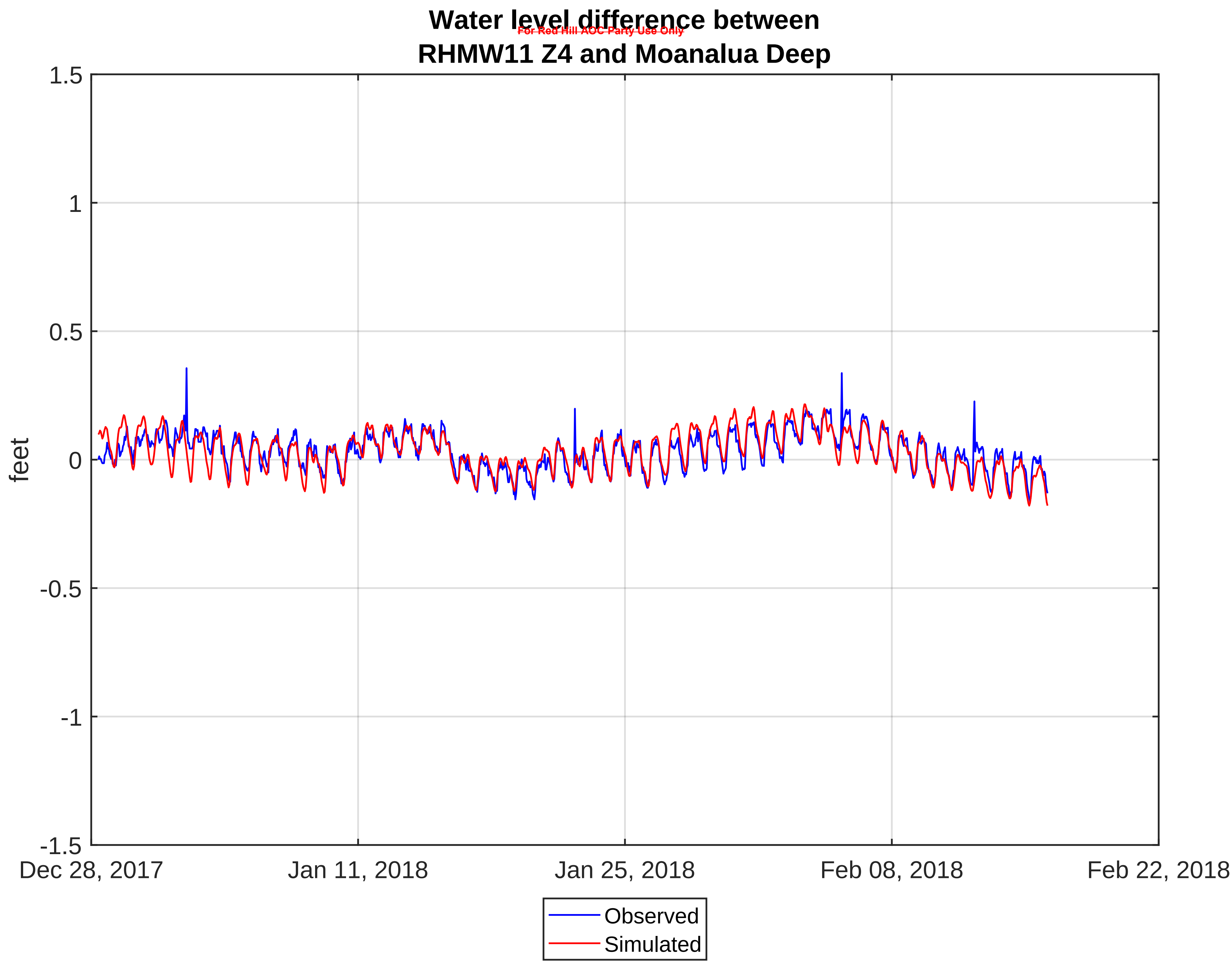
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z3 and RHMW11 Z5
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



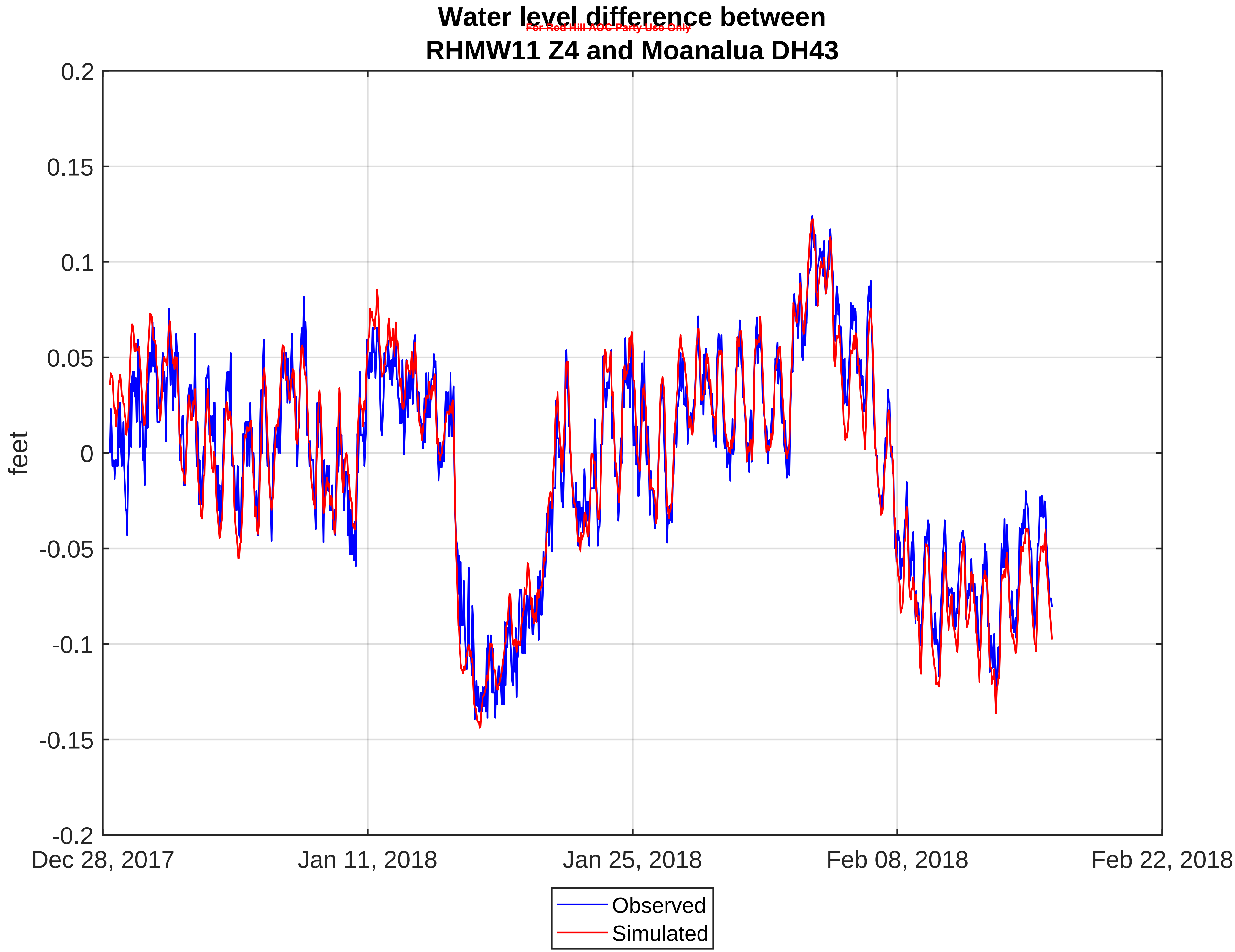
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z3 and TAMC-MW2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



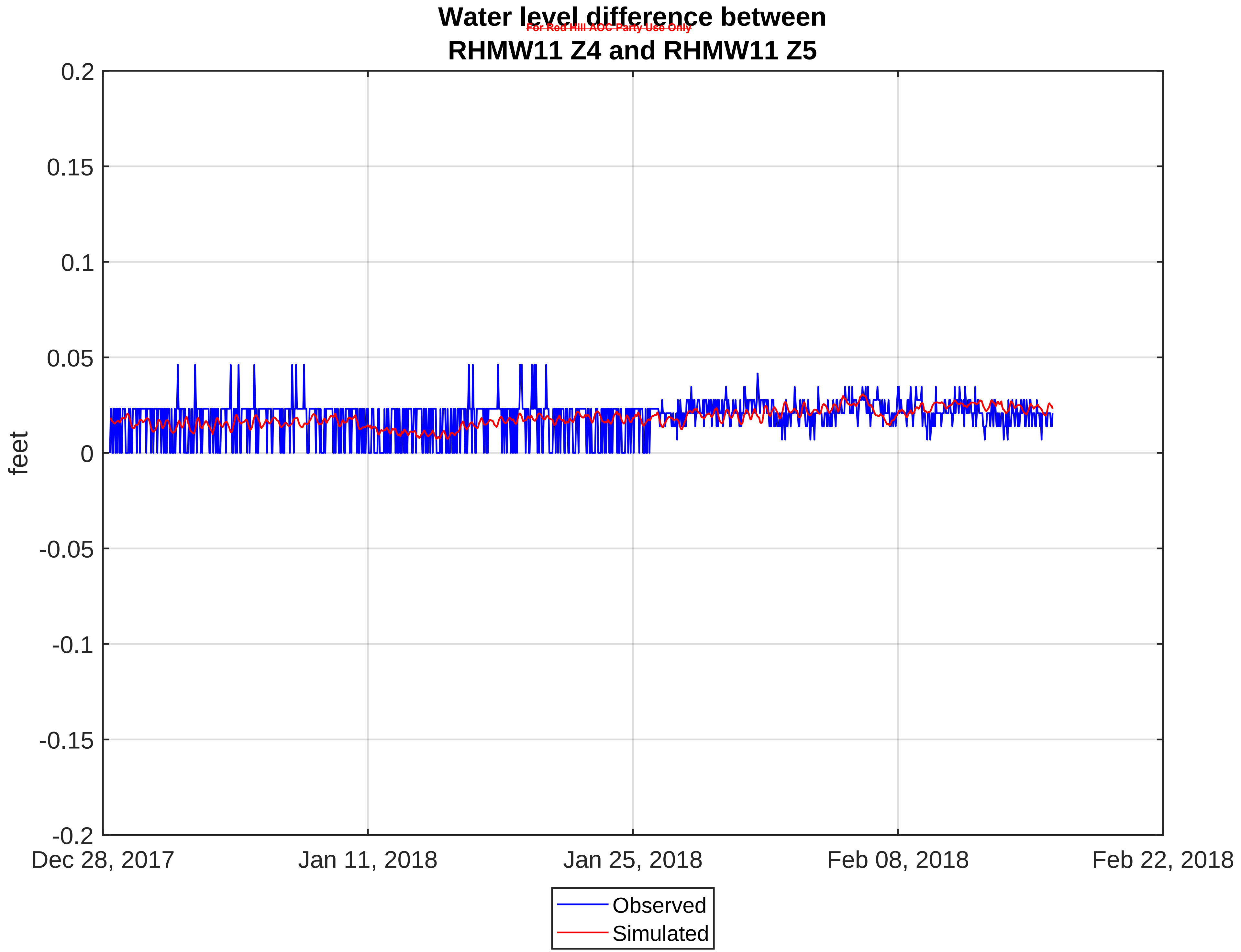
Water level difference between
RHMW11 Z4 and Manaiki T-24
For Red Hill AOC Party Use Only
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

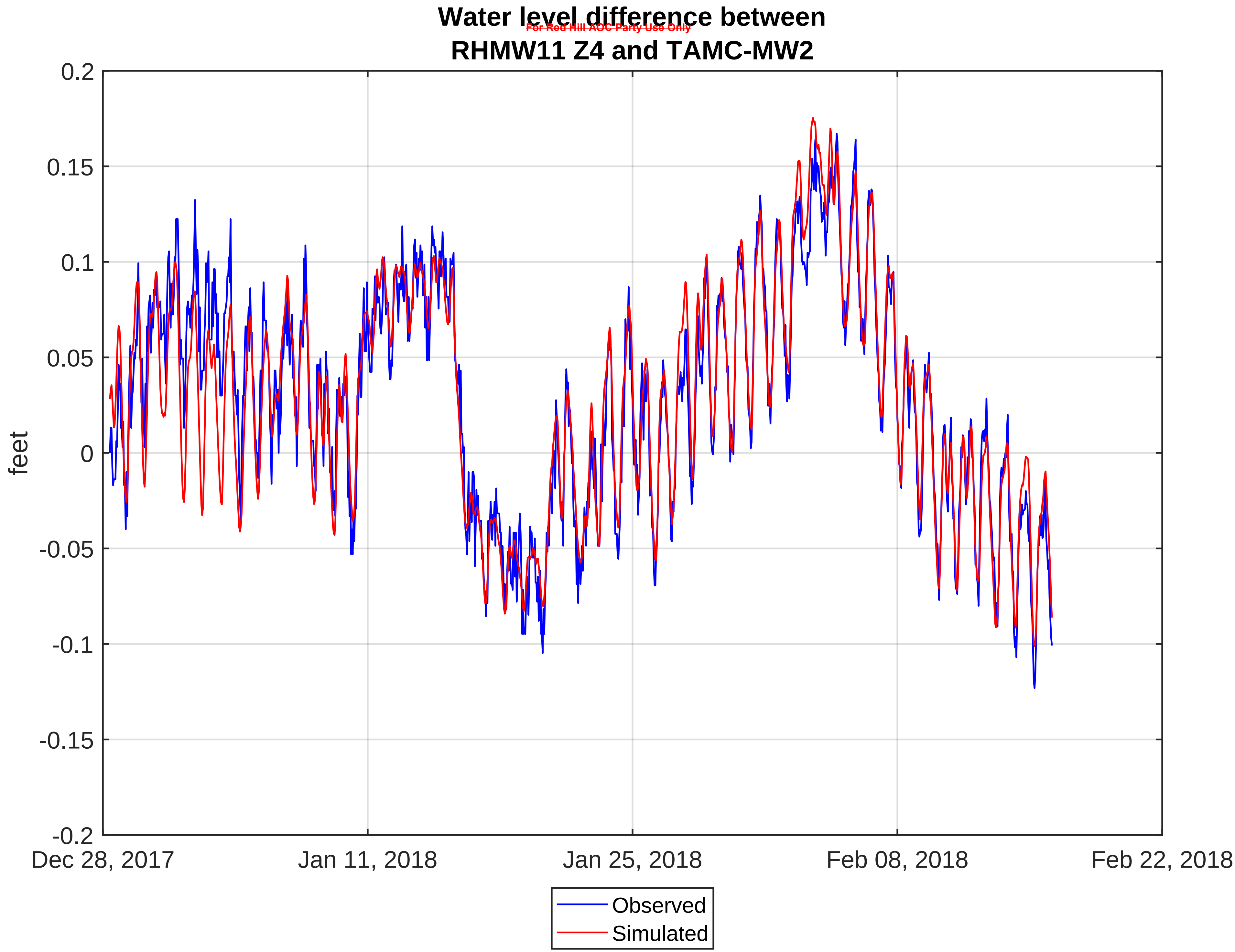


Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z4 and Moanalua Deep
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



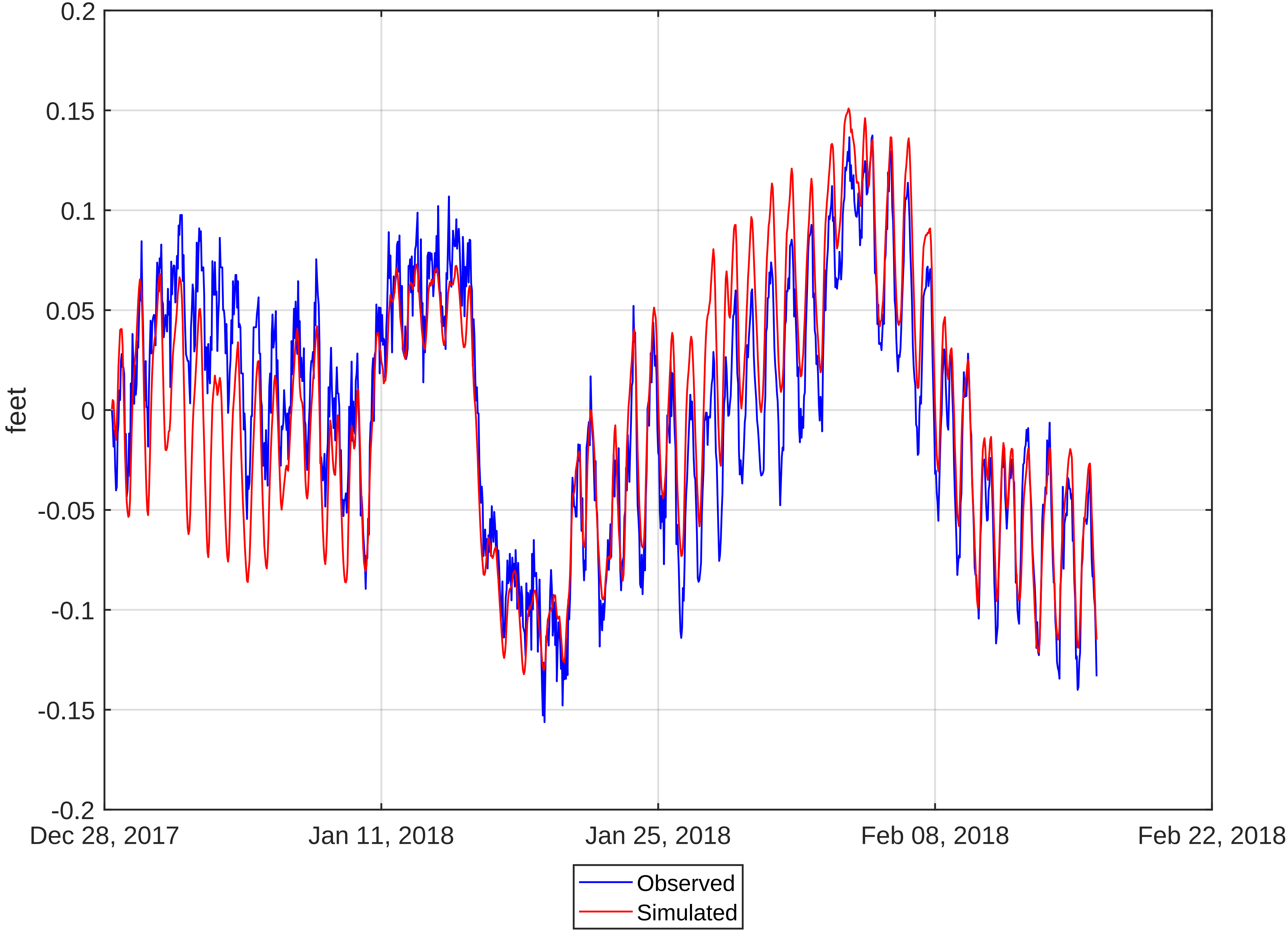
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z4 and Moanalua DH43
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

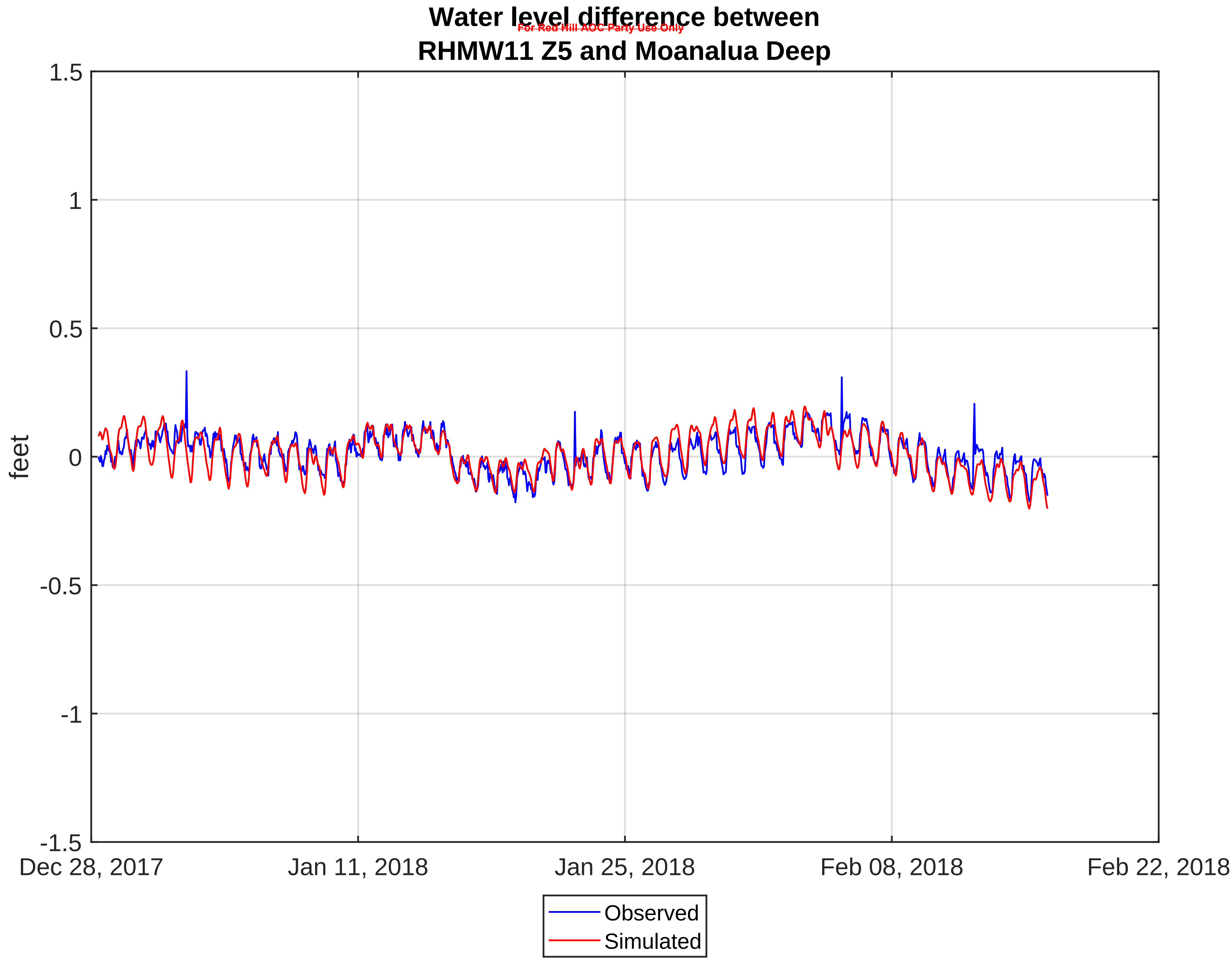

Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z4 and RHMW11 Z5
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z4 and TAMC-MW2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

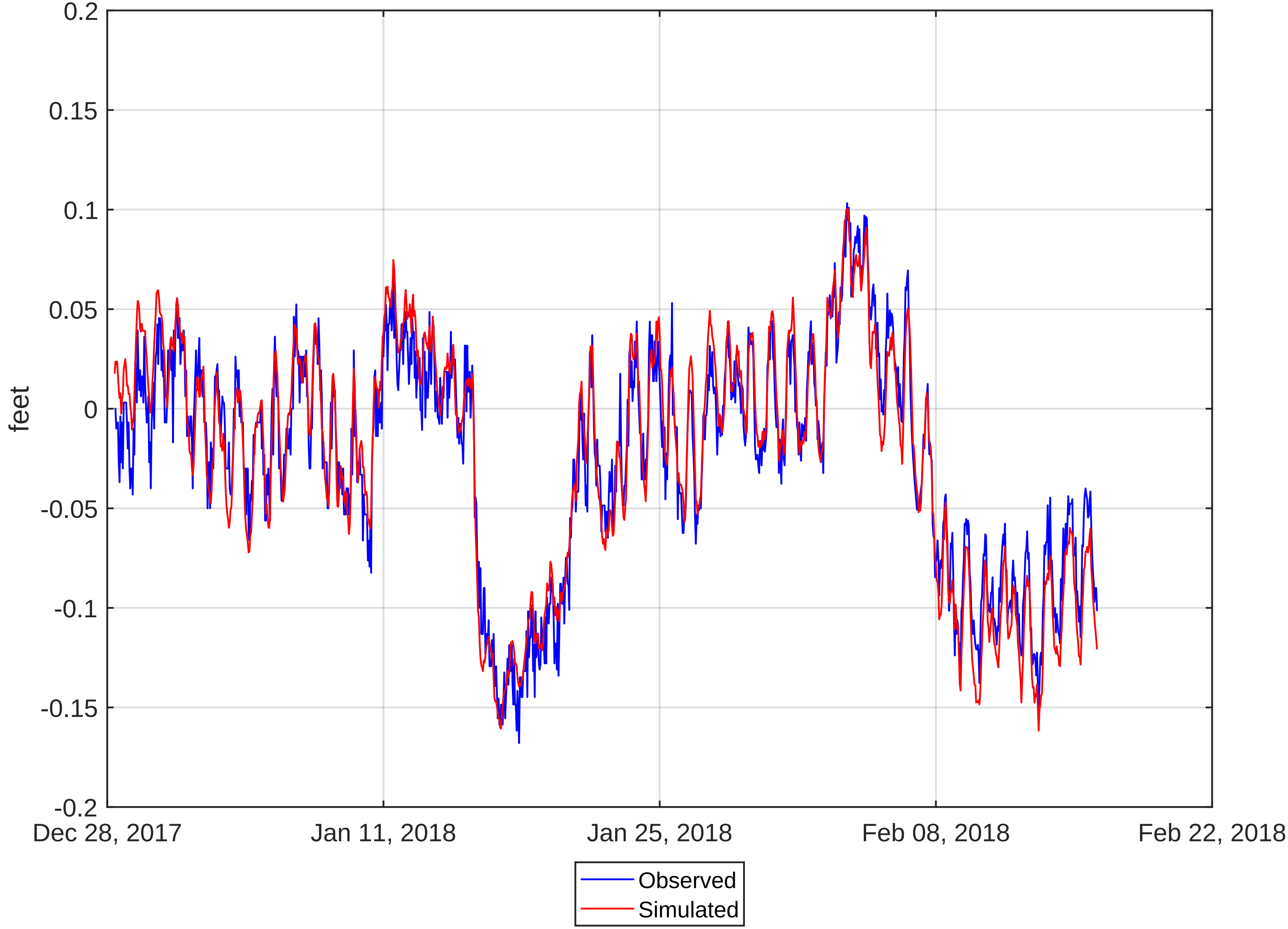
Water level difference between RHMW11 Z5 and Manaiki T-24

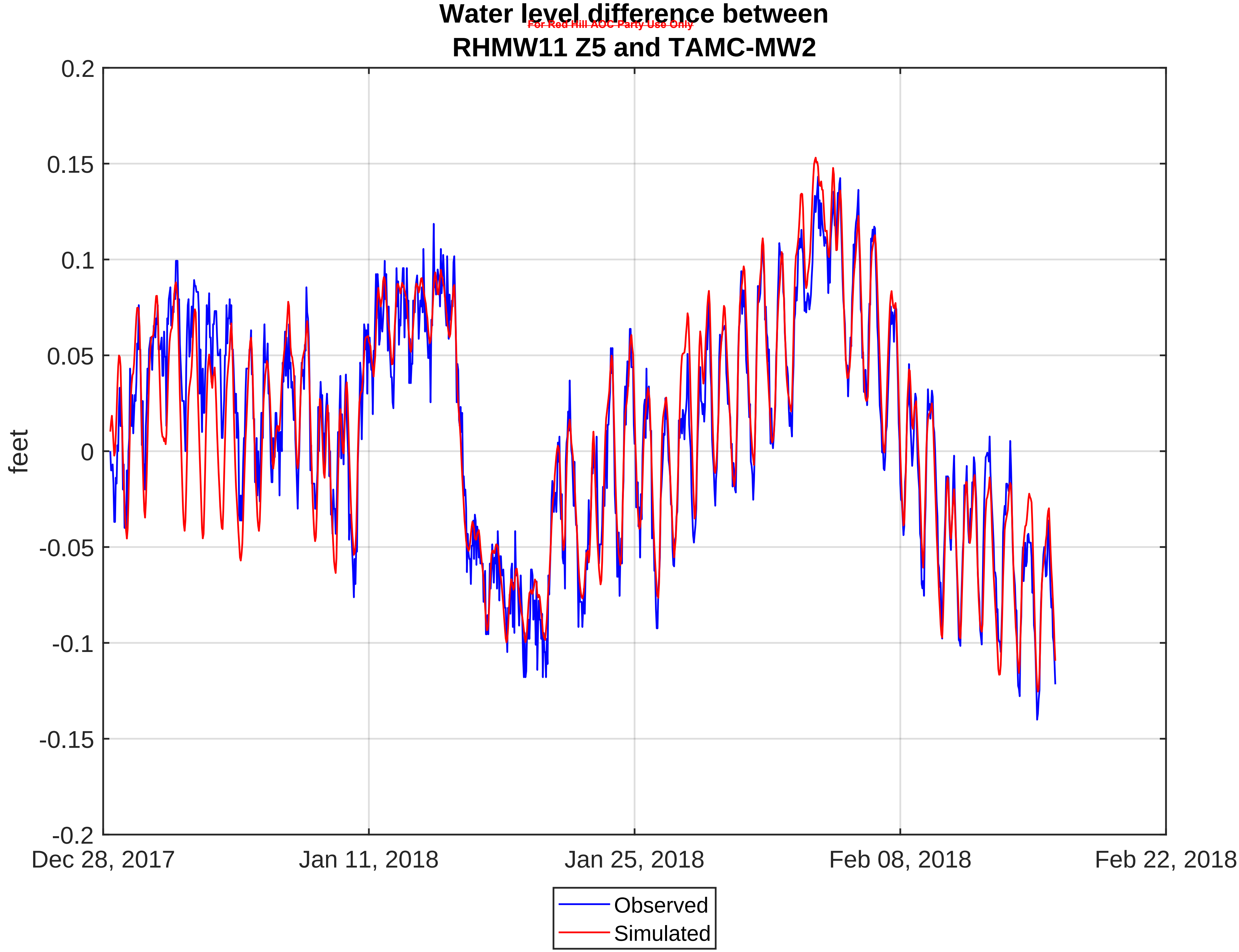


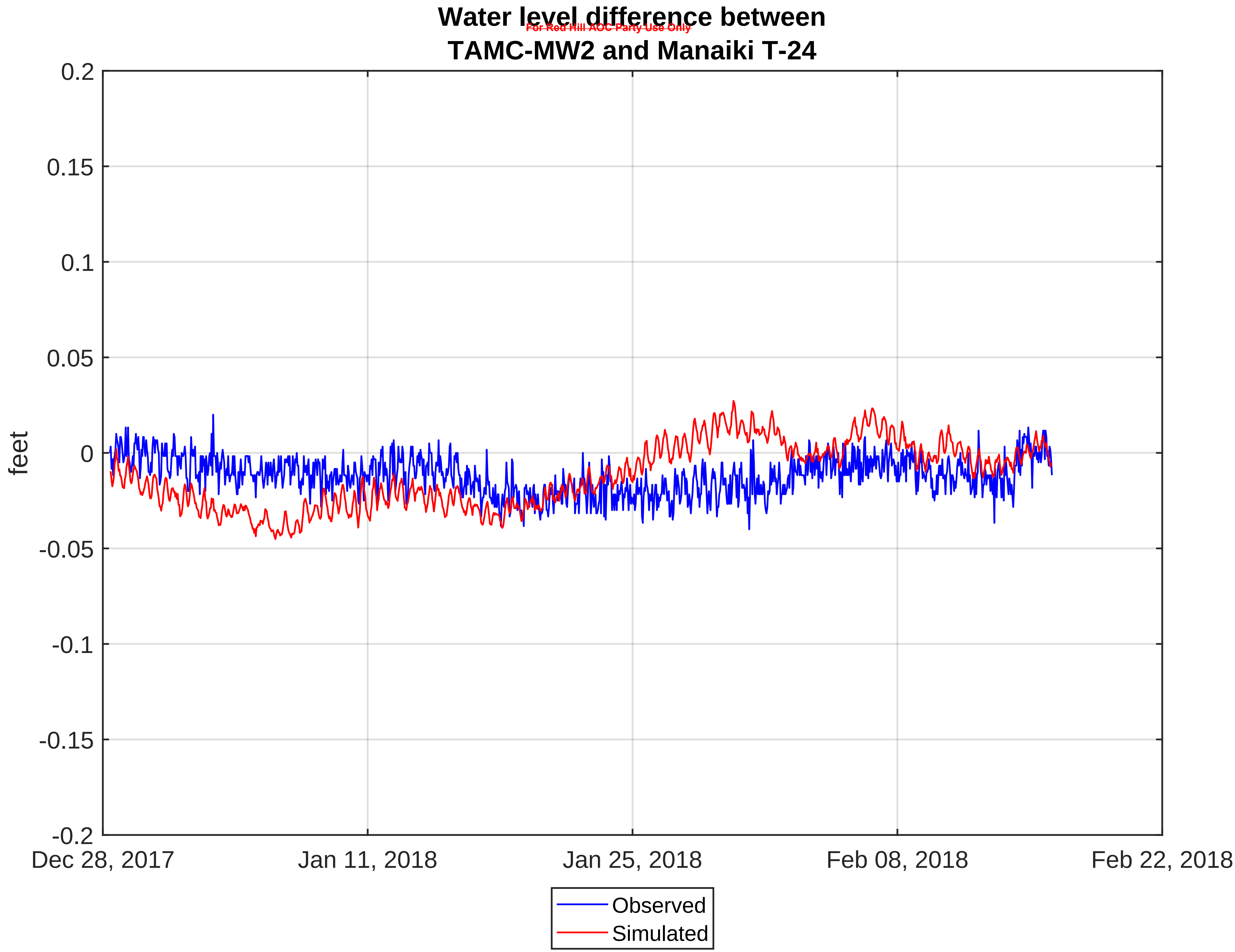


Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z5 and Moanalua Deep
feet
1.5
1
0.5
0
-0.5
-1
-1.5
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

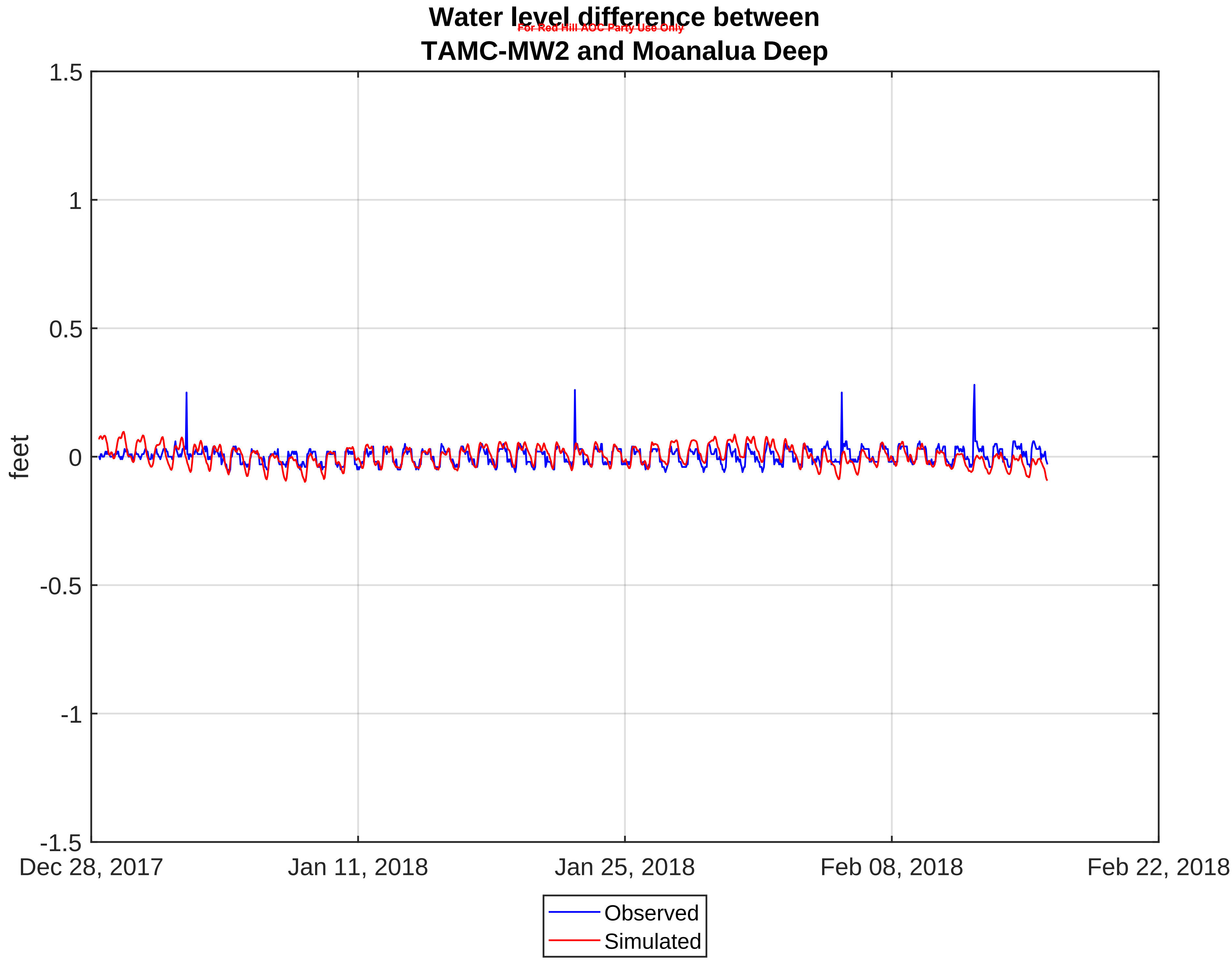
Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z5 and Moanalua DH43




Water level difference between
For Red Hill AOC Party Use Only
RHMW11 Z5 and TAMC-MW2
feet
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
For Red Hill AOC Party Use Only
TAMC-MW2 and Manaiki T-24
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated



Water level difference between
TAMC-MW2 and Moanalua Deep
For Red Hill AOC Party Use Only
1.5
1
0.5
0
-0.5
-1
-1.5
feet
Dec 28, 2017
Jan 11, 2018
Jan 25, 2018
Feb 08, 2018
Feb 22, 2018
Observed
Simulated

Appendix B:
Verification of Groundwater Flow Model Calibration Using Transfer Function Approach

The Red Hill numerical groundwater flow models were calibrated to the unit step response functions estimated by transfer function-noise (TFN) analysis for Red Hill Shaft and Hālawa Shaft. The concept and implementation of the TFN analysis have been presented in the Red Hill *Conceptual Site Model* (CSM) report (DON 2019). To evaluate the performance of the calibrated groundwater models, the unit step response functions simulated by the groundwater model were used as transfer functions to compute the resulting water level response to Red Hill Shaft and Hālawa Shaft pumping using the pumping rate time series associated with the two shafts.

The groundwater models were constructed with four stress periods. The first and third stress periods were treated as steady state. In the first stress period, both Red Hill and Hālawa Shaft pumped at their average extraction rate, simulating average conditions before the Red Hill shaft shutdown on January 10, 2018. In the second stress period, Red Hill Shaft was turned off and Hālawa Shaft stayed in operation at its average pumping rate for 15 days. In the third stress period, the pumping rate for Hālawa Shaft was slightly adjusted to the average pumping rate before Hālawa Shaft was turned off on January 26, 2018. In the fourth stress period, Hālawa Shaft was turned off. Red Hill shaft did not operate in Stress Periods (SPs) 3 and 4. The pumping rates of Red Hill Shaft and Hālawa Shaft for each model stress period are listed in Table B-1.

Table B-1: Pumping Rates in Groundwater Models (in million gallons per day)

Stress Period	Red Hill Shaft	Hālawa Shaft
1	[redacted]	6.64
2	0	6.64
3	0	6.40
4	0	0

The calibrated model responses for SP2 and SP4 were used as transfer functions associated with the Red Hill Shaft and Hālawa Shaft, respectively. Using a similar approach as in the TFN modeling, the water level response at each monitoring well due to a hydraulic stress was simulated in the hydraulic stress time series and the calibrated model unit step response function using convolution integration. The water level response to Red Hill Shaft pumping was calculated using the Red Hill pumping time series and the calibrated model unit step response function from SP2. Similarly, the water level response due to Hālawa Shaft was computed from the Hālawa Shaft pumping time series and the calibrated model unit step response function from SP4. The total water level change was modeled by superposition of the water level response time series due to Red Hill Shaft and Hālawa Shaft pumping, the barometric and tidal influences from TFN modeling, and the TFN model residual. The TFN model residuals represent the influences by sources other than Red Hill Shaft and Hālawa Shaft pumping, barometric influences, and tidal influences.

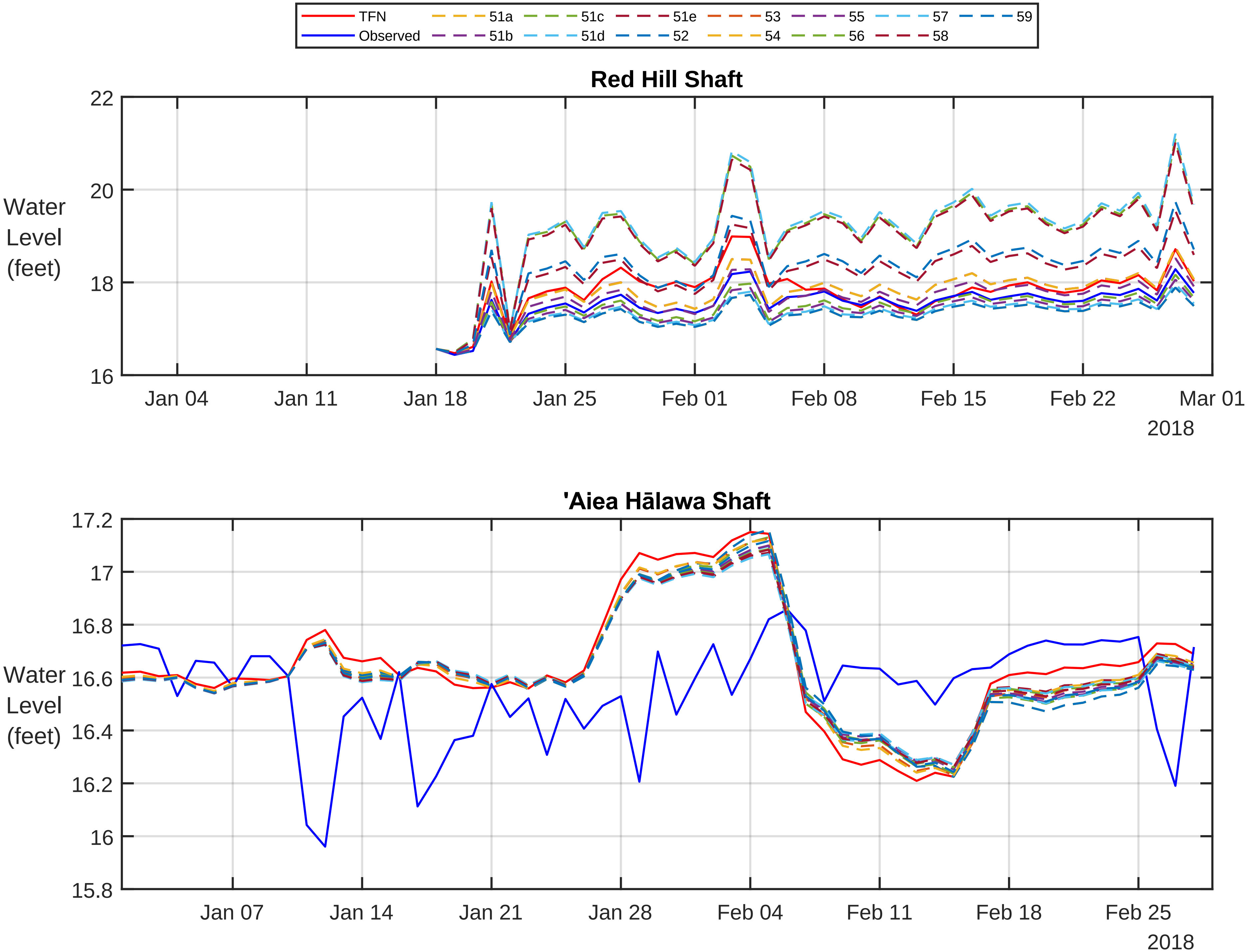
Attachment B.1 shows the results of verification using the TFN analysis approach at all synoptic study wells that were evaluated by the groundwater model. The blue line represents the observed water level, the red line represents the water level generated by the TFN analysis, and the other colors represent the model-generated water levels. In general, the water level characteristics generated from the model transfer functions bracket the major observed water level characteristics. For most of the monitoring wells, the response to the Red Hill Shaft shutdown/restart in January 2018 is simulated well by the models, and the response to the Hālawa Shaft shutdown/restart in January/February 2018 is represented reasonably well. There are marginal differences in the performance of the various models.

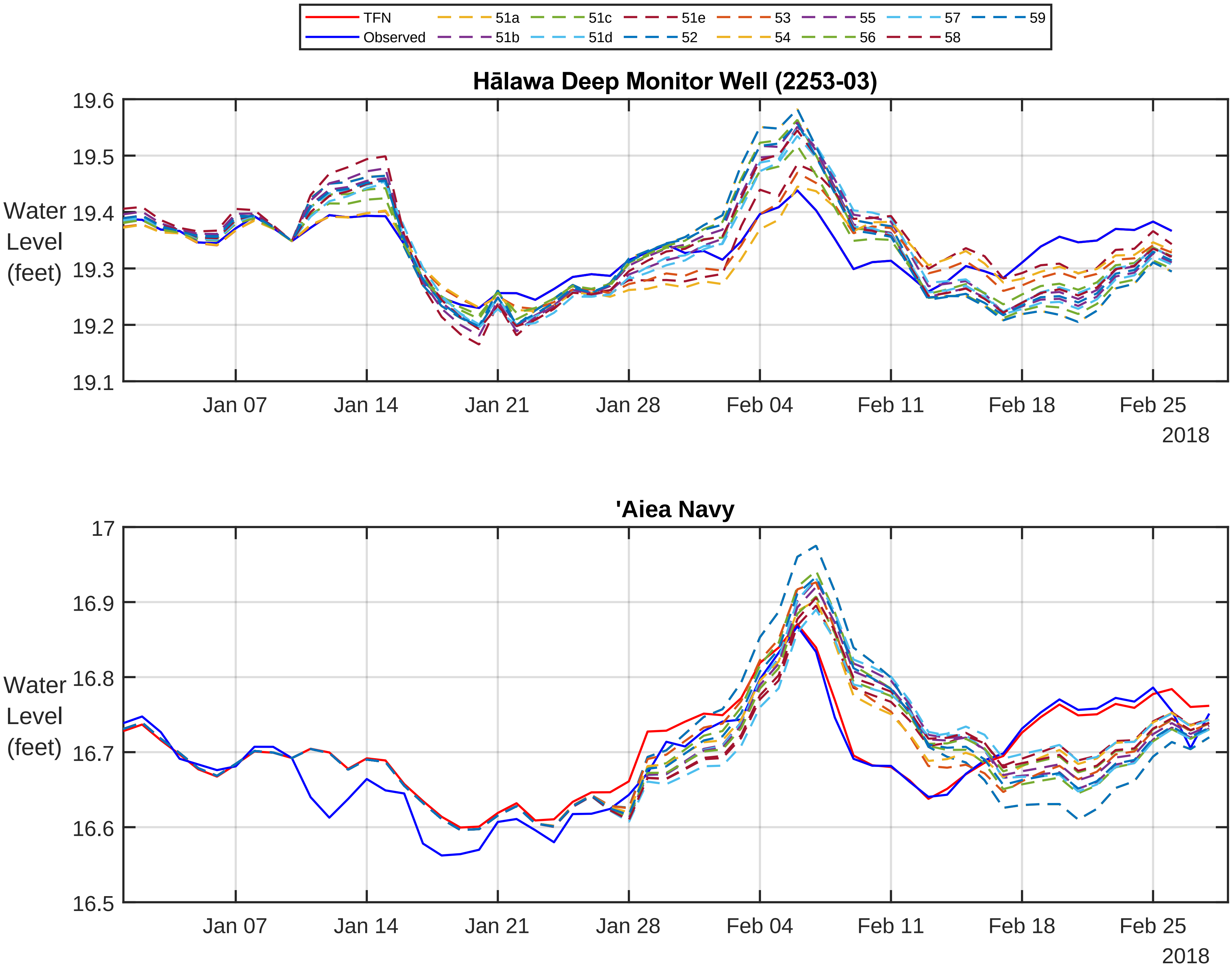
■ FOIA §(b)(3), Critical Infrastructure

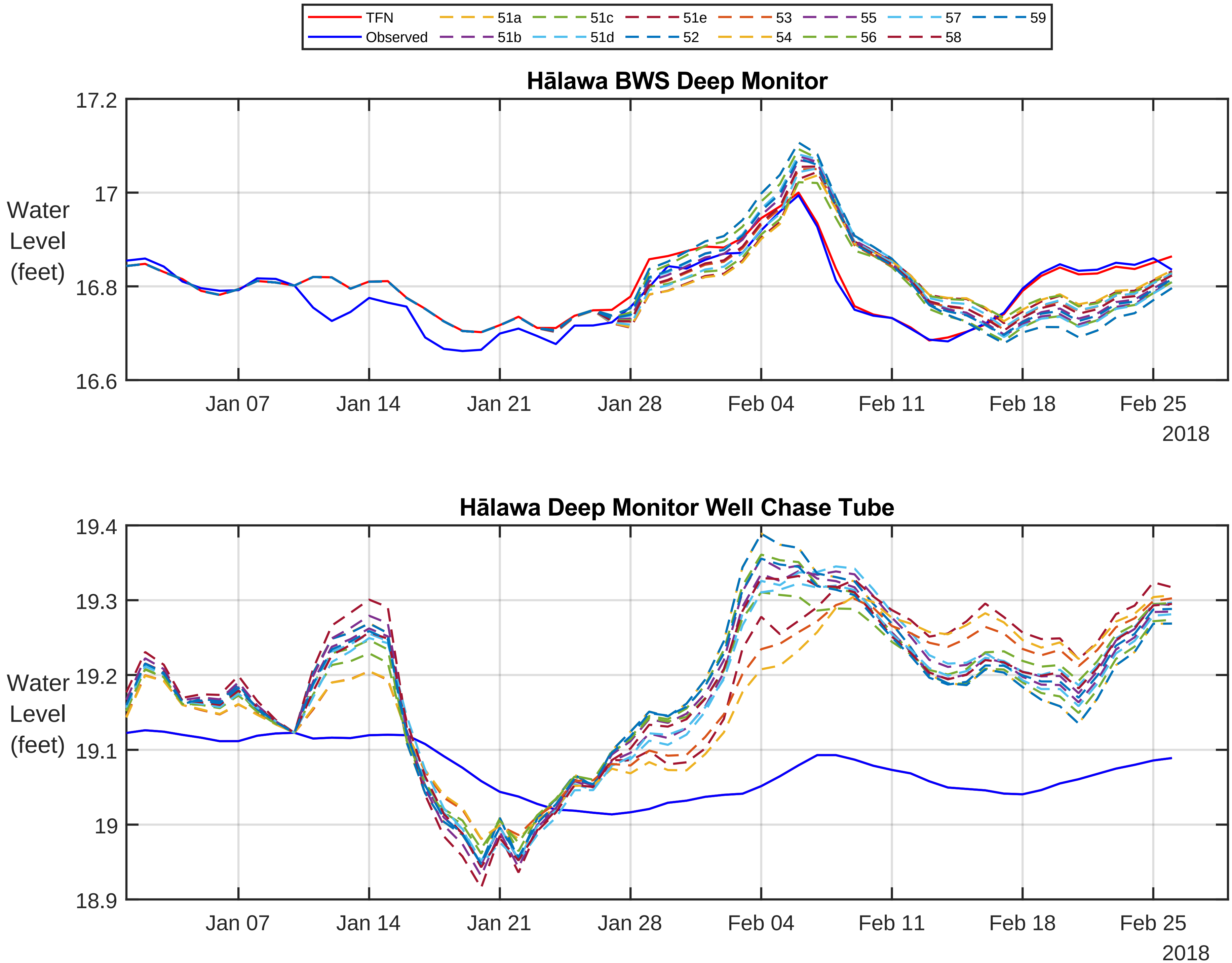
REFERENCES

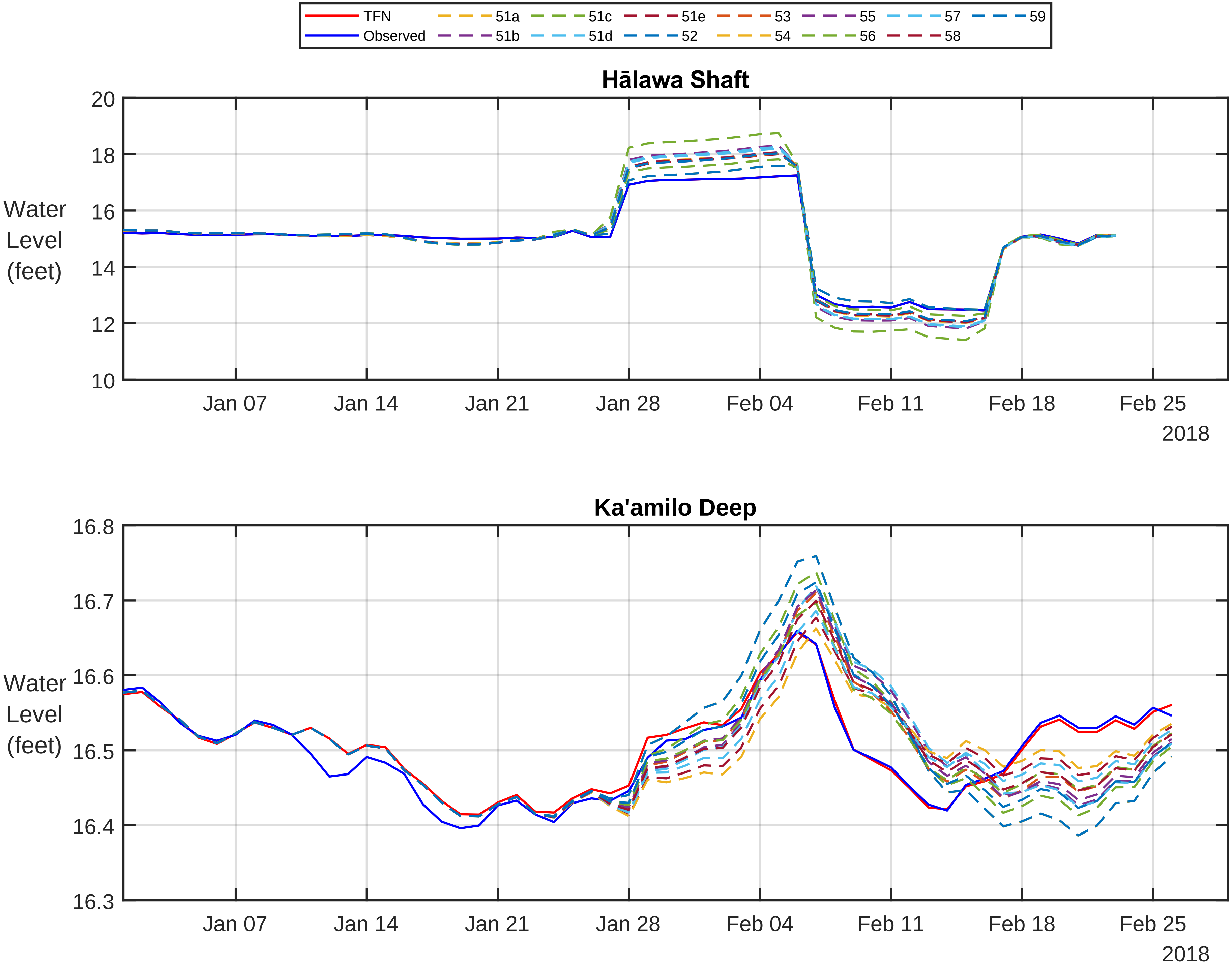
Department of the Navy (DON). 2019. *Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, O‘ahu, Hawai‘i; June 30, 2019, Revision 01*. Prepared by AECOM Technical Services, Inc., Honolulu, HI. Prepared for Defense Logistics Agency Energy, Fort Belvoir, VA, under Naval Facilities Engineering Command, Hawaii, JBPHH HI.

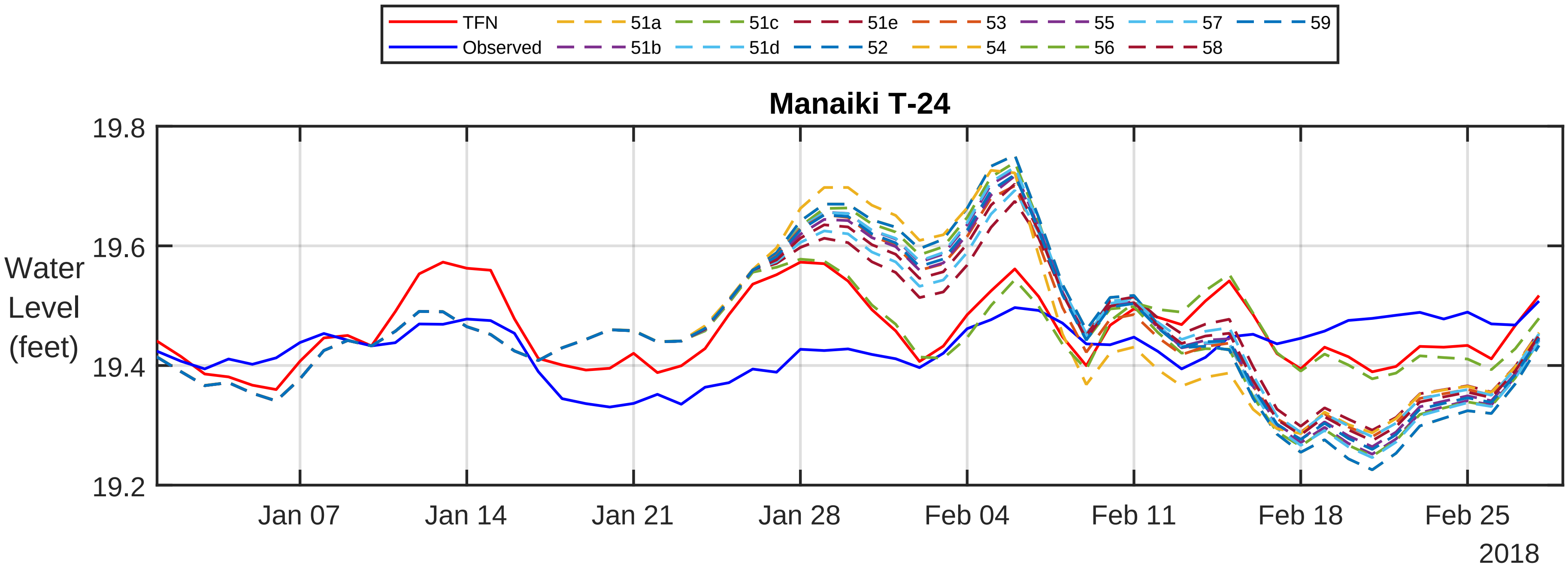
Attachment B.1
Comparison of Simulated and Observed Water Level Changes Using Transfer Functions from Groundwater Flow Models and Transfer Function-Noise Analysis

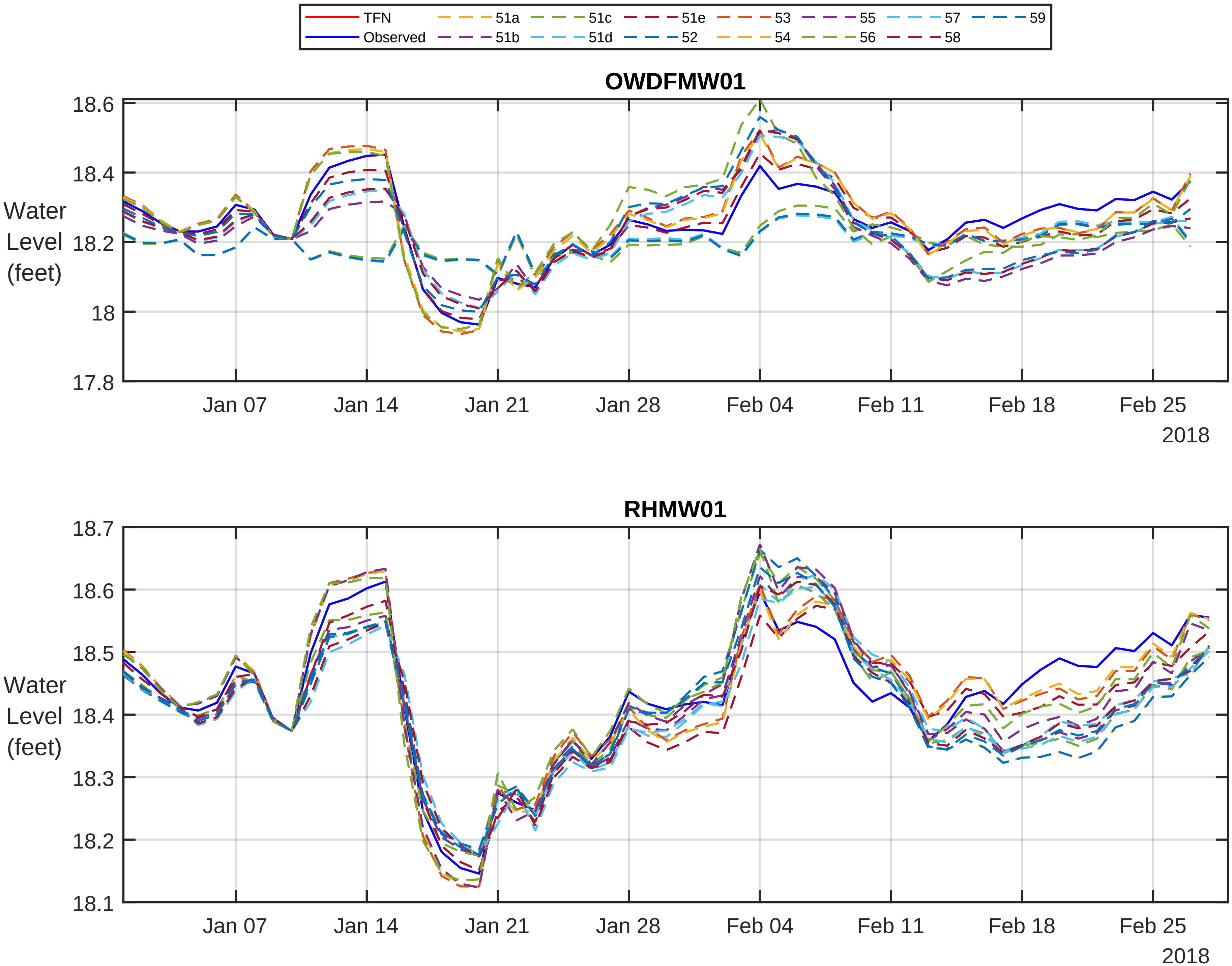

TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
Red Hill Shaft
Water Level (feet)
22
20
18
16
Jan 04
Jan 11
Jan 18
Jan 25
Feb 01
Feb 08
Feb 15
Feb 22
Mar 01
2018
'Aiea Hālawa Shaft
Water Level (feet)
17.2
17
16.8
16.6
16.4
16.2
16
15.8
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018

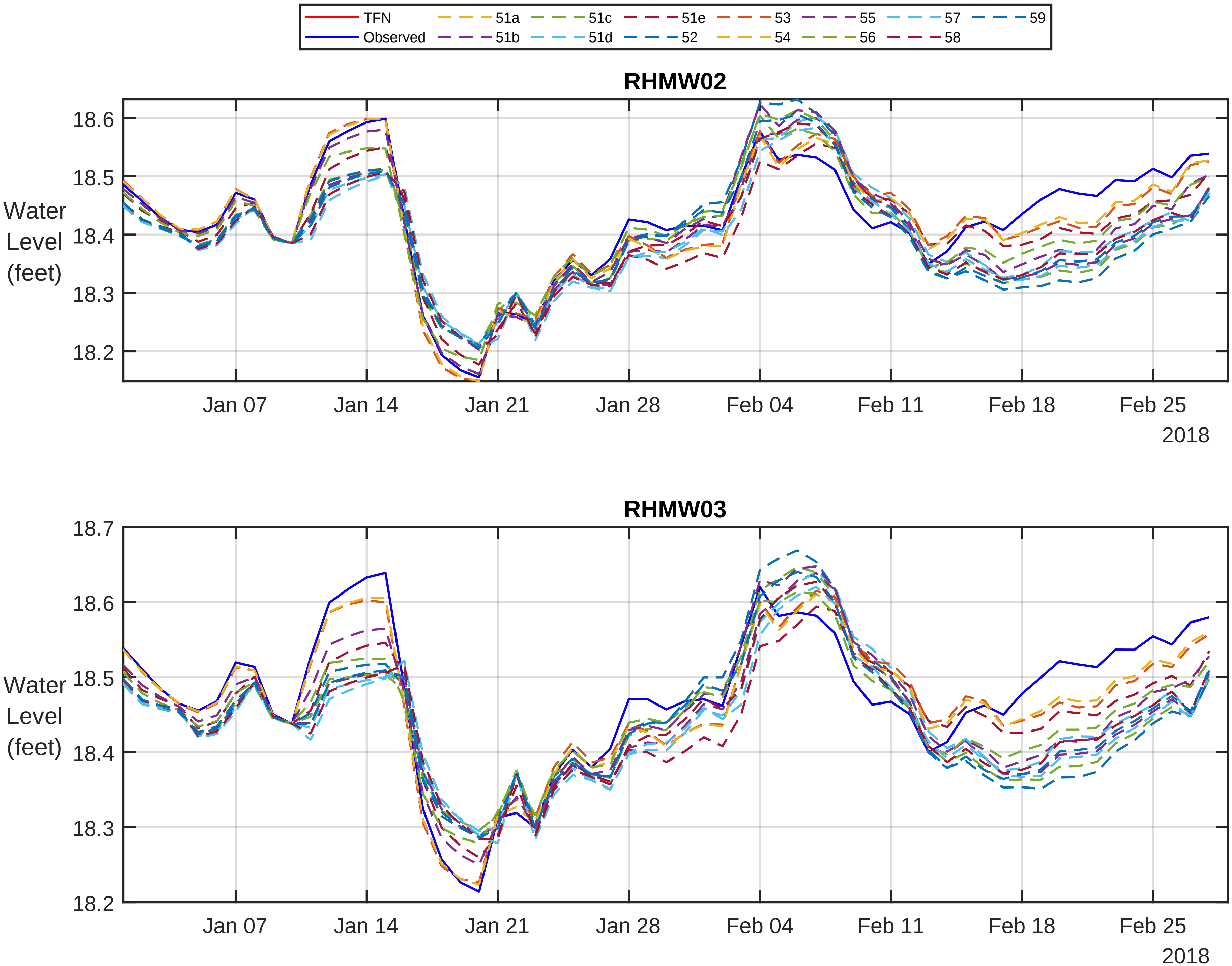

TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
Hālawa Deep Monitor Well (2253-03)
Water Level (feet)
19.6
19.5
19.4
19.3
19.2
19.1
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
'Aiea Navy
Water Level (feet)
17
16.9
16.8
16.7
16.6
16.5
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018

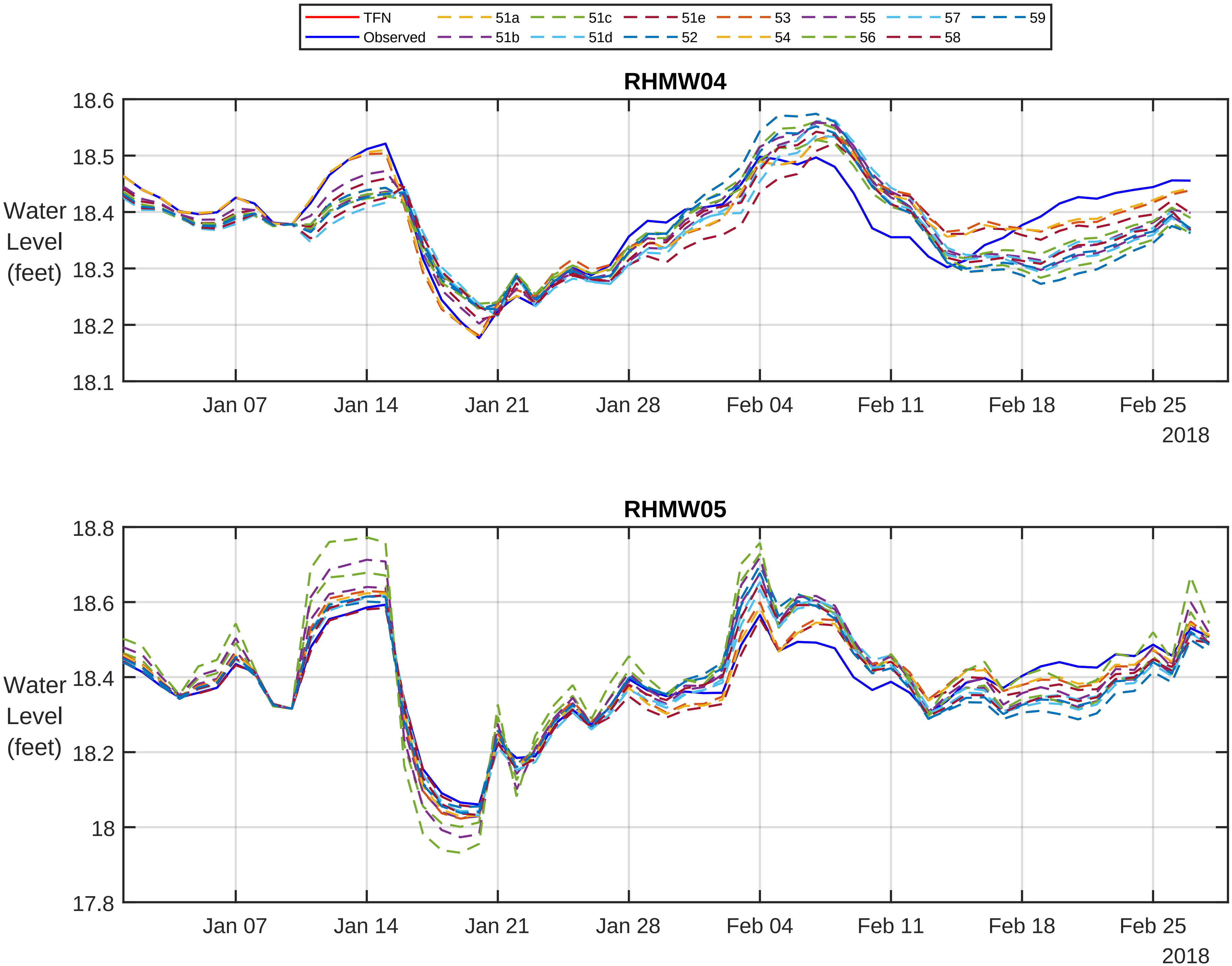

TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
Hālawa BWS Deep Monitor
Water Level (feet)
17.2
17
16.8
16.6
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
Hālawa Deep Monitor Well Chase Tube
Water Level (feet)
19.4
19.3
19.2
19.1
19
18.9
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018


TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
Hālawa Shaft
Water Level (feet)
20
18
16
14
12
10
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
Ka'amilo Deep
Water Level (feet)
16.8
16.7
16.6
16.5
16.4
16.3
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018

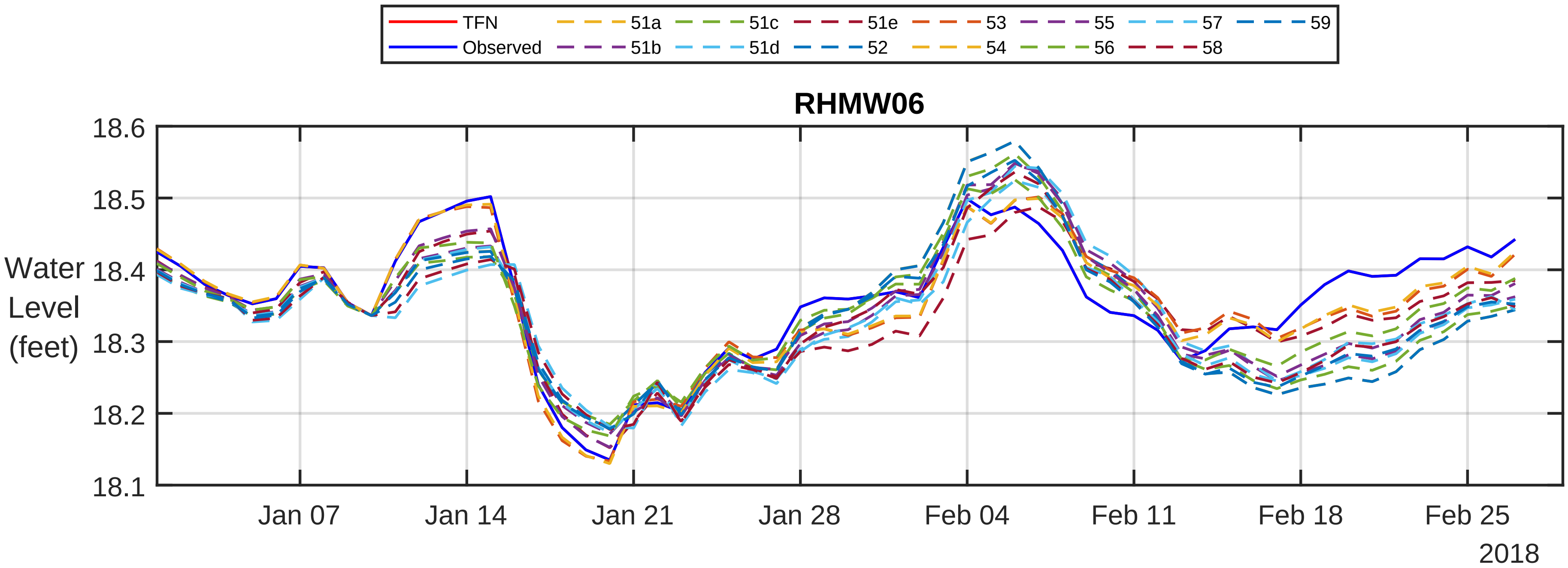

TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
Manaiki T-24
Water Level (feet)
19.8
19.6
19.4
19.2
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018


TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
OWDFMW01
Water Level (feet)
18.6
18.4
18.2
18
17.8
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
RHMW01
Water Level (feet)
18.7
18.6
18.5
18.4
18.3
18.2
18.1
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018

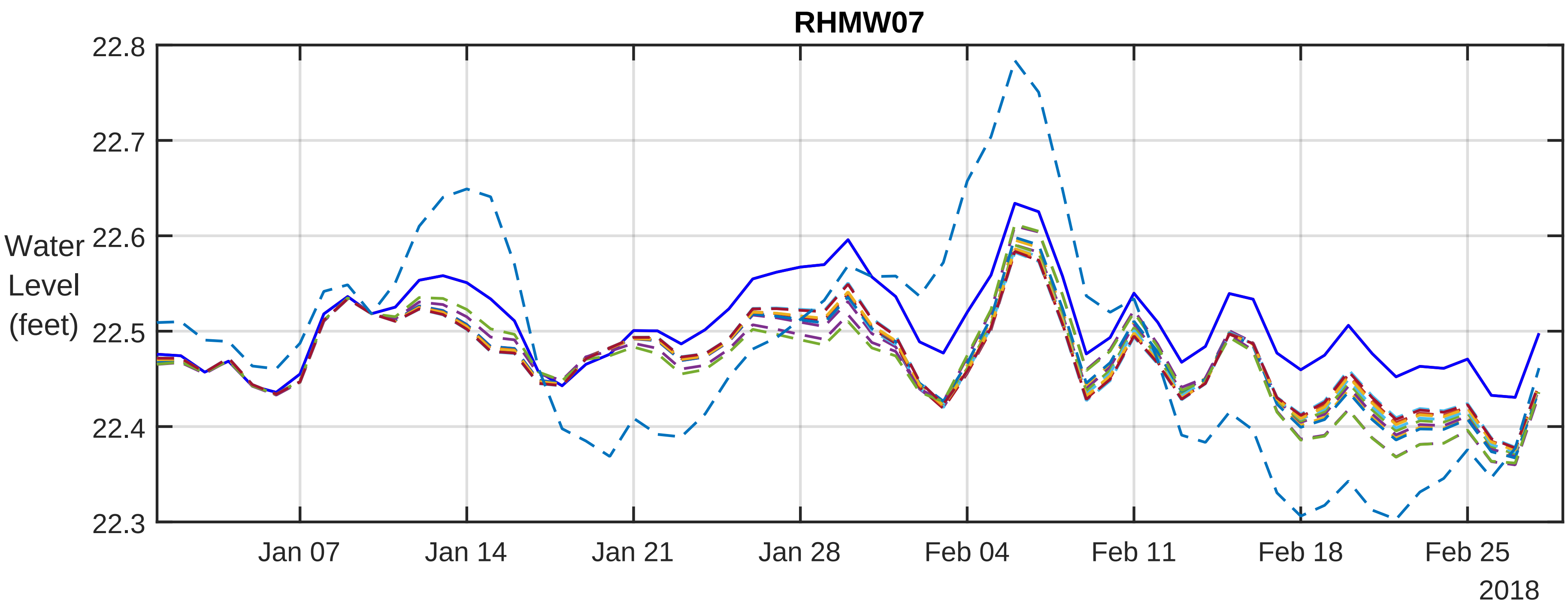

TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
RHMW02
Water Level (feet)
18.6
18.5
18.4
18.3
18.2
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
RHMW03
18.7
18.6
18.5
18.4
18.3
18.2



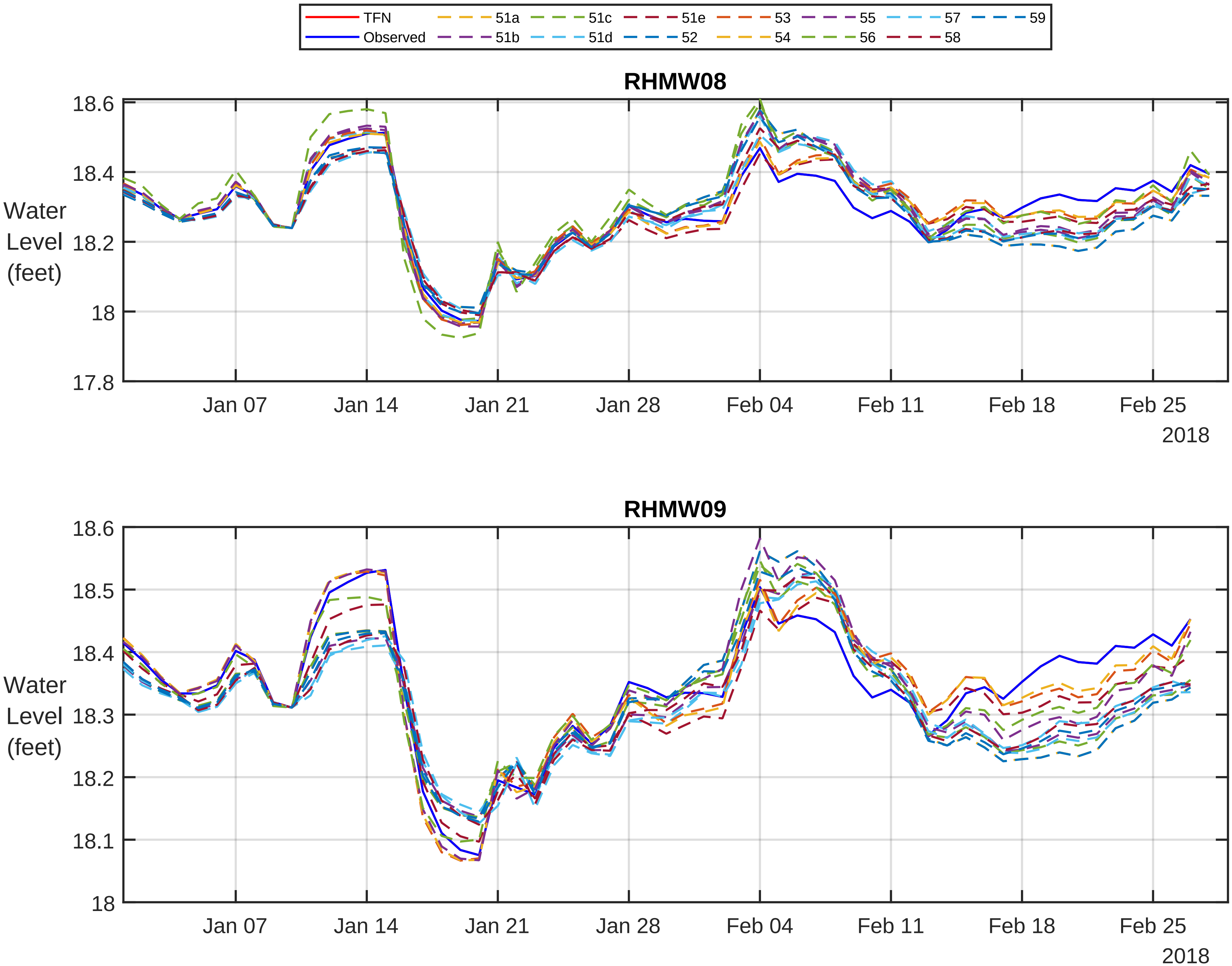
TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
RHMW04
Water Level (feet)
18.6
18.5
18.4
18.3
18.2
18.1
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
RHMW05
18.8
18.6
18.4
18.2
18
17.8



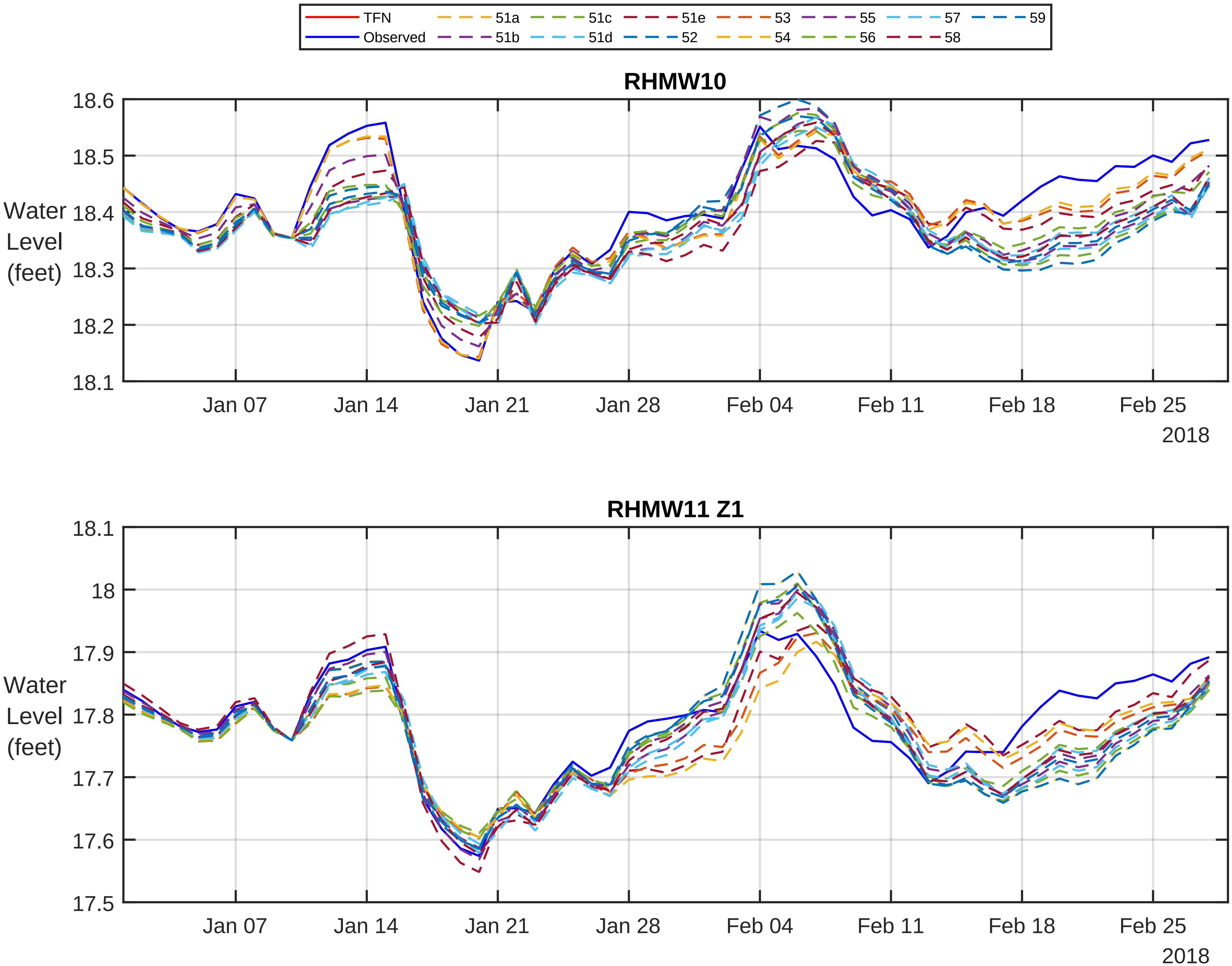
TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
RHMW06
Water Level (feet)
18.6
18.5
18.4
18.3
18.2
18.1
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018

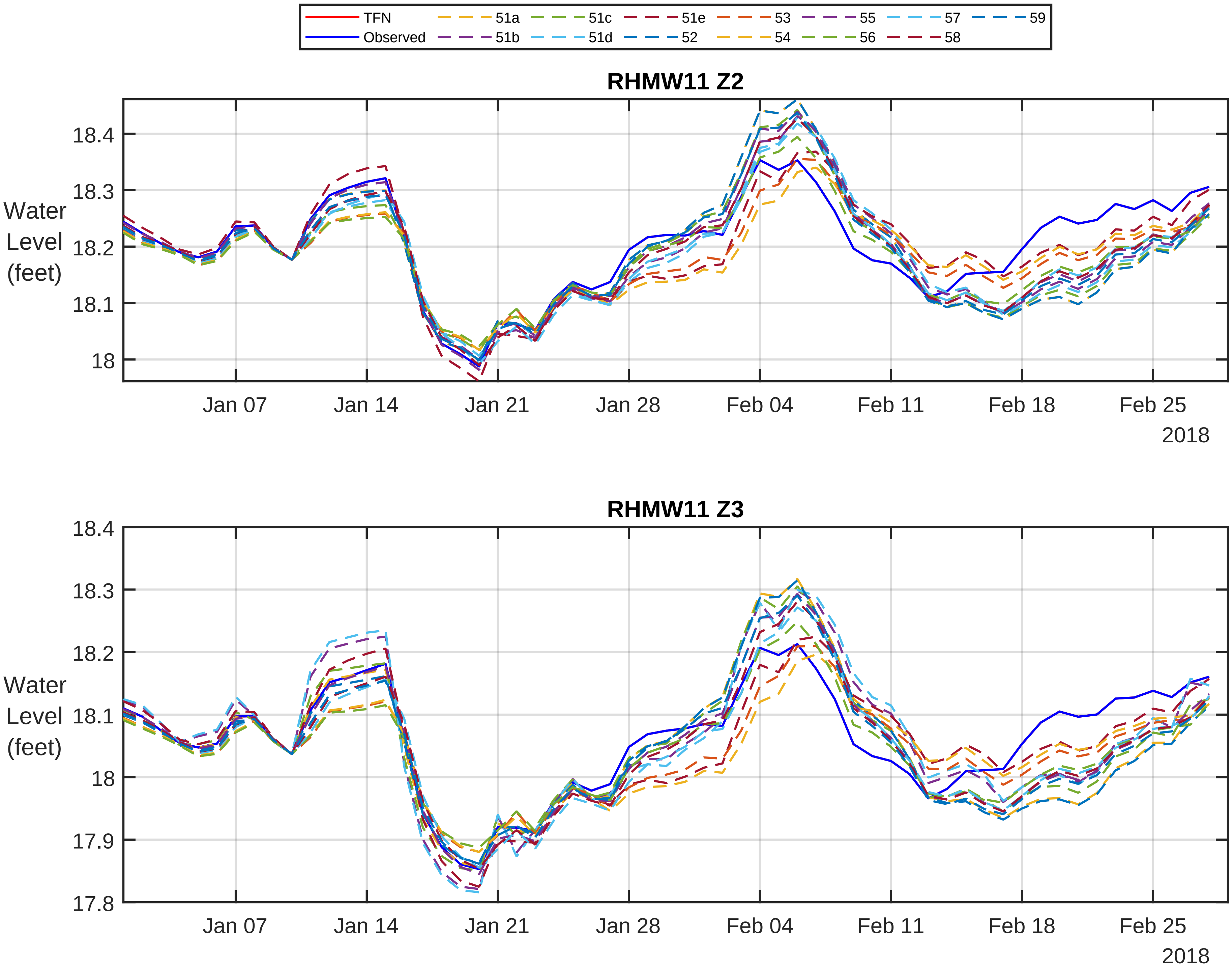


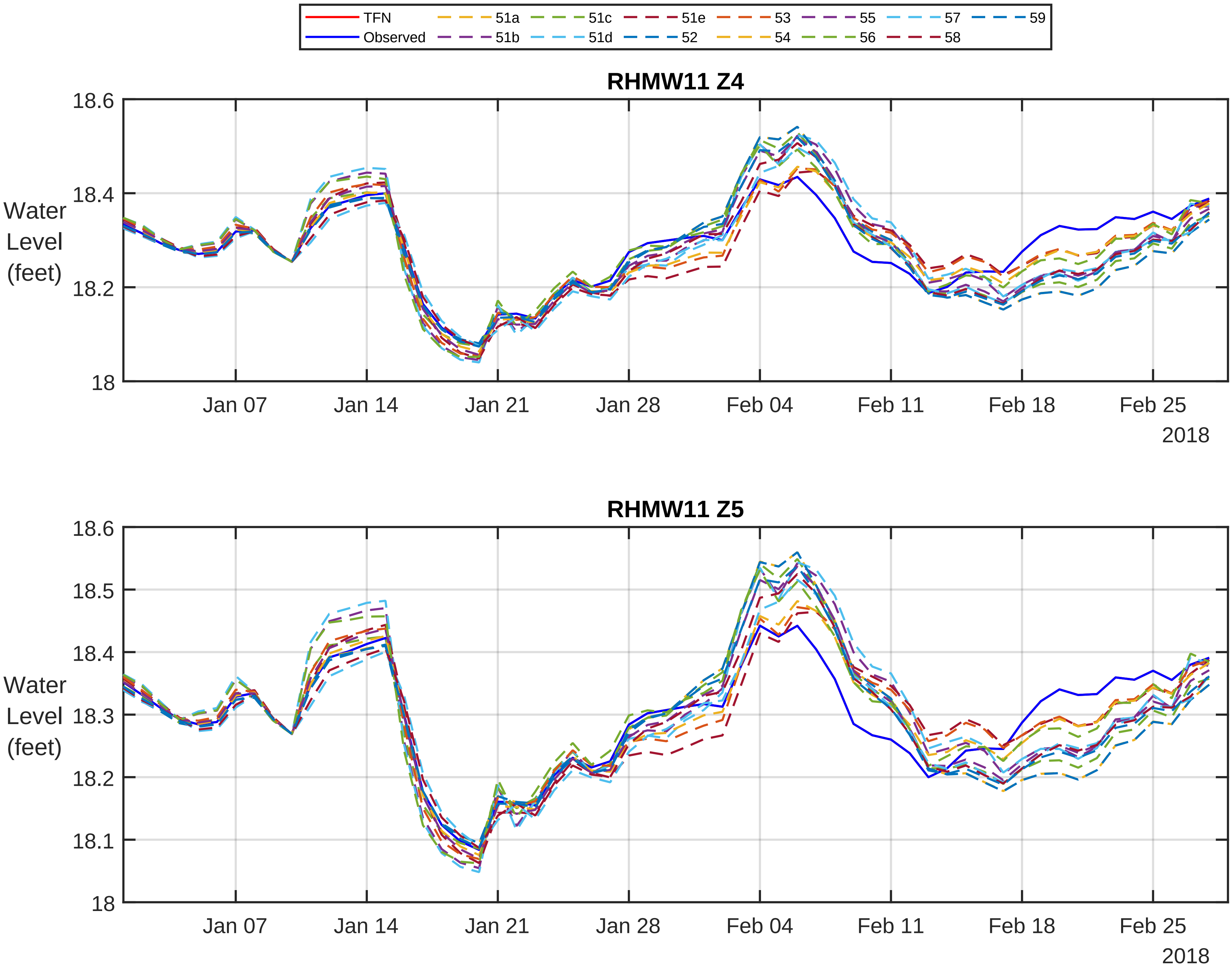
RHMW07
Water Level (feet)
22.8
22.7
22.6
22.5
22.4
22.3
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018

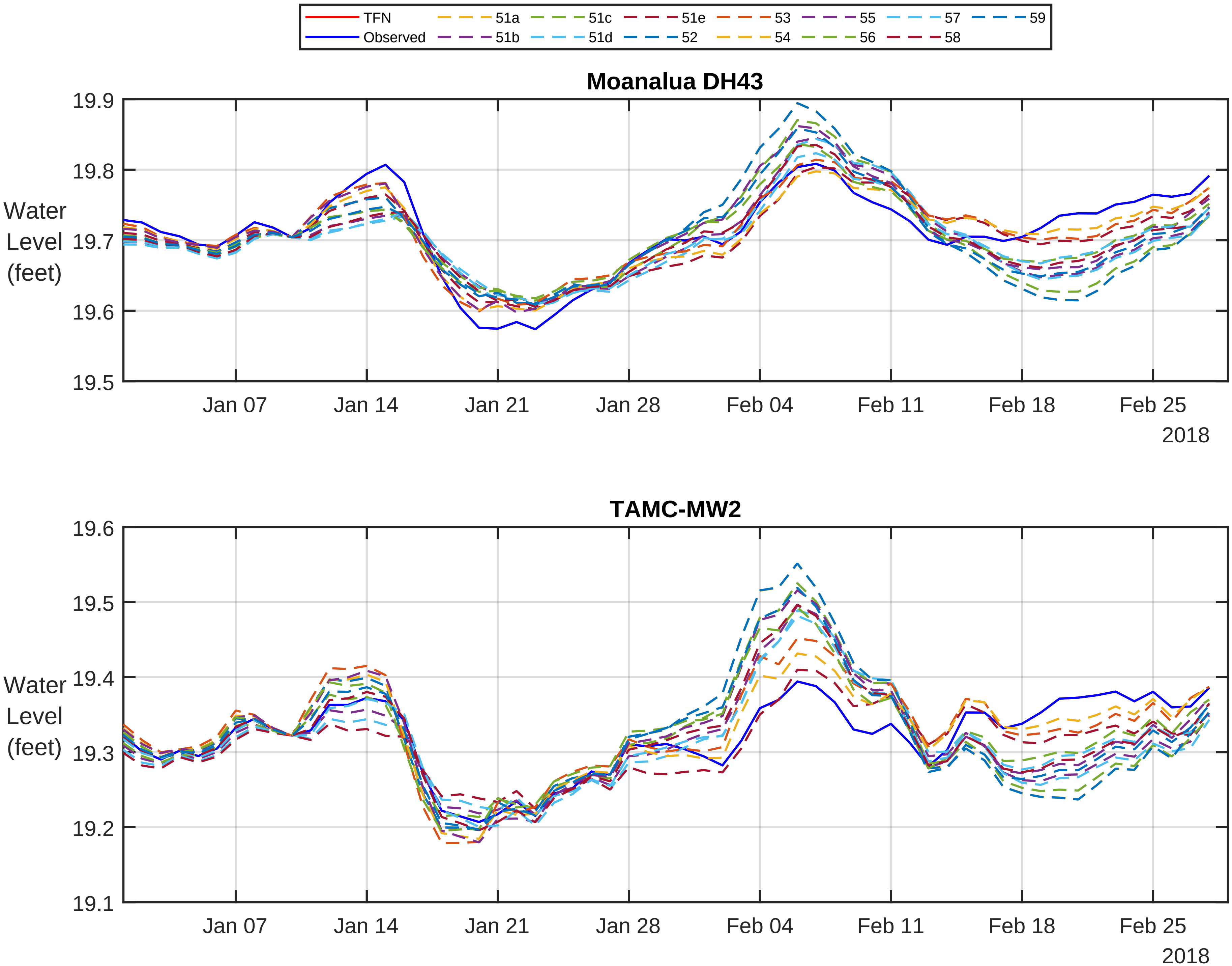


TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
RHMW08
Water Level (feet)
18.6
18.4
18.2
18
17.8
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
RHMW09
Water Level (feet)
18.6
18.5
18.4
18.3
18.2
18.1
18
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018


TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
RHMW10
Water Level (feet)
18.6
18.5
18.4
18.3
18.2
18.1
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
RHMW11 Z1
Water Level (feet)
18.1
18
17.9
17.8
17.7
17.6
17.5
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018


TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
RHMW11 Z2
Water Level (feet)
18.4
18.3
18.2
18.1
18
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
RHMW11 Z3
Water Level (feet)
18.4
18.3
18.2
18.1
18
17.9
17.8
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018


TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
RHMW11 Z4
Water Level (feet)
18.6
18.4
18.2
18
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
RHMW11 Z5
Water Level (feet)
18.6
18.5
18.4
18.3
18.2
18.1
18
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018


TFN
Observed
51a
51b
51c
51d
51e
52
53
54
55
56
57
58
59
Moanalua DH43
Water Level (feet)
19.9
19.8
19.7
19.6
19.5
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018
TAMC-MW2
Water Level (feet)
19.6
19.5
19.4
19.3
19.2
19.1
Jan 07
Jan 14
Jan 21
Jan 28
Feb 04
Feb 11
Feb 18
Feb 25
2018