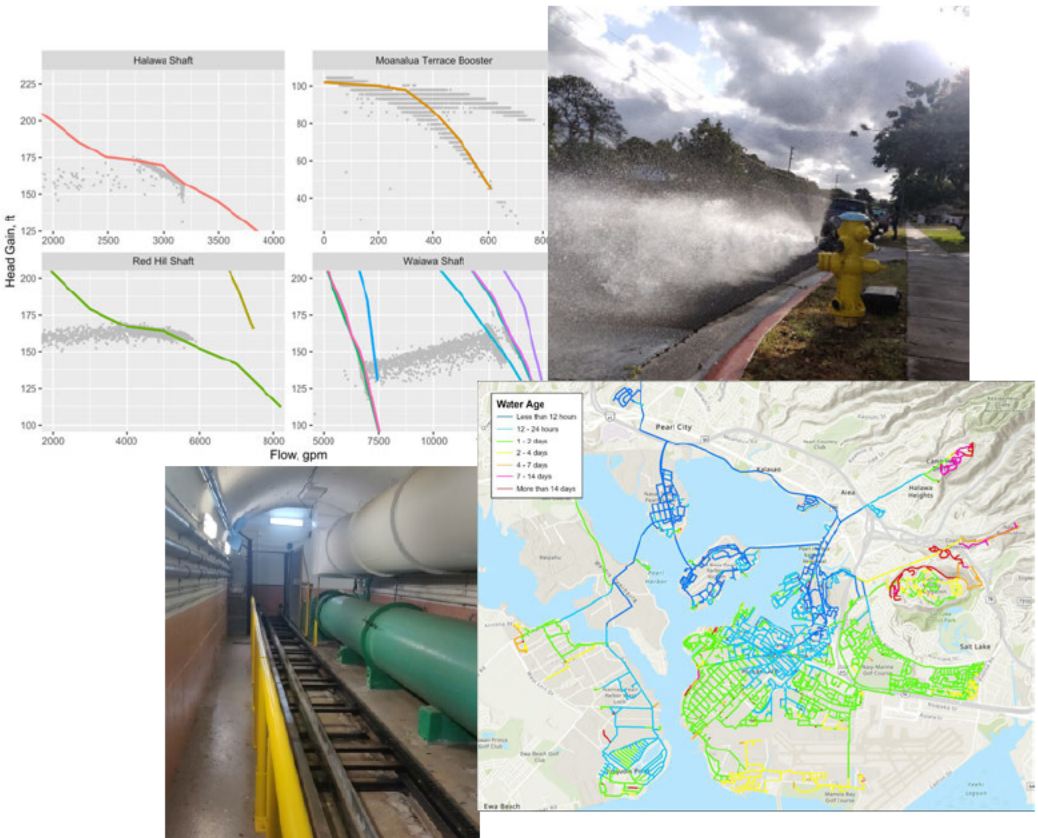
Final

HYDRAULIC MODELING STUDY



Joint Base Pearl Harbor – Hickam, Hawaii

Naval Facilities Engineering Systems Command Pacific

Contract Number: N62470-19-D-4001
Task Order Number: N6274222F0108

November 2022

HYDRAULIC MODELING STUDY

JOINT BASE PEARL HARBOR – HICKAM, HAWAII

Prepared For:

NAVAL FACILITIES ENGINEERING SYSTEMS COMMAND PACIFIC

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November 2022

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EXECUTIVE SUMMARY

The Joint Base Pearl Harbor Hickam (JBPHH) water system serves approximately 93,000 people through over 400 miles of water mains. Water originates from three underground sources: the Waiawa, Aiea-Halawa, and Red Hill Shafts, with a combined production capacity of up to [redacted] gallons per day. In November 2021, the Red Hill Shaft was contaminated with jet fuel and was subsequently shut down and physically disconnected from the distribution system. Out of an abundance of caution, use of the Aiea-Halawa Shaft was also discontinued.

To assess the existing water system capacities and plan for future emergencies, AH/BC Navy JV, LLC (AH/BC) was retained to develop a hydraulic model of the Navy water system and the consecutive system owned by the US Army. AH/BC conducted several field visits to gather infrastructure data and perform field testing. The water system model was developed using Bentley Systems, Inc. WaterGEMS® V10 software (WaterGEMS) and calibrated using both field and historical operation data.

AH/BC modeled the system under its design configuration and its existing configuration, and investigated additional scenarios involving potential emergency events, including loss of storage or the loss of the Waiawa shaft. System performance was assessed based on water pressures, tank levels, available fire flow (FF), and water age.

Based on the modeling results, AH/BC determined that the water system is hydraulically sound and not in any need of distribution system capacity improvements. Existing system limitations are primarily due to inadequate water production capacity. Without supplemental sources, the system cannot sustain the historical maximum day demand (MDD). Other than bringing the Aiea-Halawa Shaft back online during peak periods, JBPHH may want to investigate means of conserving water. A comprehensive water use study and a leak detection survey should be performed to help identify excessive water losses.

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1. INTRODUCTION

The Naval Facilities Engineering Systems Command (NAVFAC) Pacific retained AH/BC Navy JV, LLC (AH/BC) to develop a hydraulic model of the drinking water system at the Joint Base Pearl Harbor-Hickam (JBPPH) in Hawaii. The JBPHH was formed by the merger of Naval Station Pearl Harbor and Hickam Air Force Base (AFB) in 2010. The JBPPH drinking water system serves approximately 70,000 people, including a consecutive water system operated by the Army. Raw water for the system comes from three groundwater sources, which are chlorinated and fluoridated before distribution. One of the groundwater sources, the Red Hill Shaft, was contaminated with jet fuel in November 2021, and the contaminated water entered the distribution system. As a result, the Red Hill Shaft and the Aiea-Halawa Shaft discontinued production shortly after this discovery. The purpose of this hydraulic modeling study is to evaluate water production, distribution, and storage capacities under normal and emergency conditions, as well as to assess water travel times in the system and delineate areas served by each of the three water sources under typical operating conditions.

This report is organized as follows:

- Section 2 details the water system
- Section 3 includes a review of available historical data
- Section 4 describes on-site field testing
- Section 5 discusses the development of the hydraulic model
- Section 6 provides results and an evaluation of the hydraulic model
- Section 7 summarizes the findings and provides recommendations

Appendix A contains the Statement of Work for this task order. Appendix B defines abbreviations and acronyms used within this report. Appendix C includes detail maps for C-factor test locations. Appendix D provides an overview of hydraulic modeling and a description of the software used for this project. Hydraulic model input files are provided on the included compact disc (read-only memory).

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2. WATER SYSTEM DESCRIPTION

This section describes the base's water production, storage, and distribution system. Figure 2-1 provides a map of the water system. Figure 2-2 illustrates the system schematically. Raw water originates from three shafts drilled horizontally into the volcanic rock, skimming water from near the top of the fresh water lens. The western-most shaft, Waiawa, produces up to [redacted] gallons per day (MGD) using [redacted] vertical turbine pumps. [redacted]. The Red Hill Shaft is located furthest east of the three sources, and historically produced approximately [redacted] MGD, with [redacted] vertical turbine pumps. [redacted] The Aiea-Halawa Shaft is located west of Red Hill and produces approximately [redacted] MGD with [redacted] pump is undergoing repair.

After chlorine and fluoride have been added at the sources, water flows into a distribution system comprising over 400 miles of mains ranging from 4 to 42 inches in diameter and made from the following materials (in order of decreasing total length): cast iron (CI), polyvinyl chloride (PVC), ductile iron (DI), asbestos-cement (AC; Transite), and high-density polyethylene (HDPE). The lining materials, if any, for the cast iron pipes are not known. The ductile iron pipes are likely to be cement-lined. Most of the Navy water system is within one pressure zone, ranging in elevation from near sea level to approximately 100 feet (ft). Storage in the main pressure zone includes two [redacted] (MG) ground storage reservoirs, Halawa Tanks S1 and S2.

Areas of the Navy system above 100 ft elevation are supplied by booster pump systems. These include the Moanalua Terrace Housing Area, the Marine Corps Housing Area at Manana, the Marine Corps Base Hawaii at Camp Smith (at over 600 ft elevation), and two water storage tanks at Red Hill (at over 550 ft elevation). Moanalua Terrace Housing receives water through [redacted]

[redacted] The Manana booster pump station has [redacted]. Camp Smith is supplied by [redacted]. Water storage at Camp Smith includes one [redacted]-gallon ground storage tanks at elevation 850 ft (Tanks 325, 326, 327). Camp Smith spans an elevation range of nearly 400 ft; thus, there are several automatic control valves limiting the pressure to approximately [redacted] per square inch (psi) at the furthest downhill locations.

At the Red Hill Shaft, there are [redacted] booster pumps that supply water to two [redacted]n (Tanks 316 and 685).

The Navy also serves a consecutive water system owned by the Army through two interconnections: one serving the Red Hill housing area and one serving the Aliamanu Military Reservation (AMR), comprising of Army housing within the Aliamanu Crater and the former Coast Guard Reservation. The Army distribution system includes over 30 miles of mains, up to 16 inches in diameter, that are primarily made from PVC. The Red Hill Housing area receives water from Navy Tanks 316 and 685. There are several pressure reducing valves set at [redacted] psi to compensate for the elevation differences. AMR is supplied through a metered connection adjacent to the Halawa Tanks and comprises three pressure zones. A portion of the water received from the Navy is pumped to the Army's South Tank 182 using [redacted] gpm vertical turbine pumps ([redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] in Figure 2-2). The [redacted]-gallon South Tank is located [redacted] and serves elevations within the Army housing areas above 100 ft. Water can also flow by gravity to the [redacted]-gallon Middle Tank 2070, which serves the low-lying areas in the Aliamanu Crater. [redacted]-gpm vertical turbine pumps ([redacted] fill the [redacted]gallon North Tank 181, which is located [redacted] and serves the former Coast Guard Reservation on the northern flank of the crater rim.

(b) (3) (B)

[redacted]

Figure 2-1 JBPHH Water System Map

(b) (3) (B)

[redacted]

Figure 2-2 JBPHH Water System Schematic

3. HISTORICAL DATA REVIEW

This section describes the historical data reviewed to determine and validate hydraulic model parameters.

3.1 WATER PRODUCTION AND CONSUMPTION

Figure 3-1 displays historical water production data based on hourly supervisory control and data acquisition (SCADA) data provided by the Navy. There has been an increasing trend in both average and maximum daily water production through 2021. The average daily water production for the 2015 – 2022 period was [redacted]. The maximum daily water production was [redacted].

Peak hourly water production has remained at approximately [redacted], with the higher values in 2015 and 2019 representing rare situations when all three water sources were operated simultaneously.

[redacted]

Figure 3-1 Historical Water Production Data

Water consumption was derived by adding hourly changes in SCADA tank levels to the hourly water production data. Tank level fluctuations cancel out when averaged over longer periods of time. Therefore, average and maximum daily water consumption (also termed "demands," ADD and MDD, respectively) were expected to be similar to average and maximum day water production data. Figure 3-2 shows the ADD and MDD data for the years 2018 – 2022. (No Army SCADA data was available before 2018; therefore, demands were only evaluated for the 2018 – 2022 period). Given the similar results for daily production and consumption data, the ADD for the hydraulic model was set to [redacted] based on the 2015-2022 data. The MDD was set to [redacted].

[redacted]

Figure 3-2 Daily Water Demand (Consumption) Data

Water in storage tanks satisfies peak demands; therefore, the maximum (or peak) hourly demand is an important metric for sizing distribution systems. Figure 3-3 presents hourly water demand data for each year since 2018 as a normality plot, where the abscissa indicates the percentage of hourly readings not exceeding the water demand on the y-axis. Hourly demands above the black horizontal line, indicating the peak hourly demand, were identified as outliers. The outliers were due to events not likely to be related to increases in water demand, such as sudden drops in the Halawa tank levels when the Waiawa shaft was shut down, or re-alignment or calibration of the level sensors evidenced by tank level changes not associated with pressure drops elsewhere. Therefore, [redacted], indicated by the black horizontal line in Figure 3-3, was adopted as the peak hourly demand for this study.

[redacted]

Figure 3-3 Hourly Water Demand Data

3.2 SOURCE WATER PUMP OPERATION

Raw water at JBPHH is produced primarily at the Waiawa Shaft, which has the largest capacity of the three sources. The source water pumps are operated manually. Based on the 2018-2022 flow data from the three sources, AH/BC concluded the following:

- At least one pump has been in operation at Waiawa 99% of the time.
- The Red Hill and Aiea-Halawa Shafts have rarely been operated simultaneously (approximately 2.5% of the time), and no more than one pump has been used at Red Hill and Aiea-Halawa Shafts simultaneously.
- The remaining source/pump combinations comprise 97% of the time, and they are depicted in the pie chart in Figure 3-4:
- (b) (3) (B) [redacted]
- [redacted]
- The Aiea-Halawa Shaft has been used infrequently to supplement the Waiawa source (< 5% of the time).
- The Red Hill source has been used 40% of the time to supplement the Waiawa source.

(b) (3) (B) [redacted]

Figure 3-4 Common Source Water Pump Combinations

3.3 HISTORICAL PUMP PERFORMANCE DATA

Where SCADA provided upstream and downstream pressure (or water level) as well as flow data, AH/BC computed the pumps' head gain to confirm performance curves. Pump curves were obtained from design documentation or manufacturer's publications based on the pumps' name plate information and serial numbers. The original pump curves as well as pump curves resulting from operating two pumps simultaneously were then overlaid onto measured head gain versus flow data. Due to impeller and motor wear, as well as miscellaneous friction losses resulting in a reduction of actual pump performance, or because of inaccurate pump impeller information, AH/BC shifted the pump curves to obtain a proper fit to clusters of SCADA data points. Measured data points that did not align with pump curves represented instances where a pump did not operate for an entire hour. Figure 3-5 shows the results of this analysis using calendar year 2021 and 2022 data. Complete sets of flow and head gain data were only available for the source water pump stations and the Moanalua Terrace booster pump station.

The pump curves for the Aiea-Halawa Shaft main pumps [redacted] were adjusted by subtracting [redacted] of head. The pump curves for the Red Hill Shaft main pumps [redacted] were adjusted by subtracting [redacted] of head. The Red Hill shaft has not been operated since November 2021. Red Hill main pump [redacted] was not adjusted; based on the 2021 SCADA data, it appeared that it had not been operated. The Moanalua Terrace Booster pump station data exhibited clusters that appeared to represent one or two pumps running in parallel. The pump curves' head gain was reduced by [redacted] and flows were halved to fit the single-pump head-flow rate data.

The heads for the Waiawa Shaft main pumps [redacted] were reduced by [redacted]. The heads for the Waiawa Shaft main pumps [redacted] were reduced by [redacted]. The data show that in 2021 and 2022, mostly [redacted] operated as the lead pump, while [redacted] operated in lag mode. It appeared that [redacted] never operated simultaneously.

(b) (3) (B)

[redacted]

Figure 3-5 Pump Performance Analysis

3.4 TANK OPERATION

The water tanks at Camp Smith, Red Hill, and AMR are filled automatically based on water level. AH/BC determined the tanks' historical operating ranges (i.e., the levels at which the pump stations are turned on and off), based on daily minimum and maximum water levels measured hourly (Navy data) or every minute (Army data). There have been changes in the operating ranges of all tanks, and time series plots of hourly data may obscure this information. However, the prevailing values became apparent using histograms. Figure 3-6 shows histograms of daily minimum and maximum water levels by year for Red Hill Tank 685. The data show the tank used to operate between approximately 20 and 28 ft. Given the most recent data, the Red Hill booster pumps turn on when the level drops below 25 ft and turn off at 29 ft. Similarly, water levels in Camp Smith Tank 325 used to drop to 11 ft, but the tank currently operates typically between 13 and 14.5 ft (Figure 3-7).

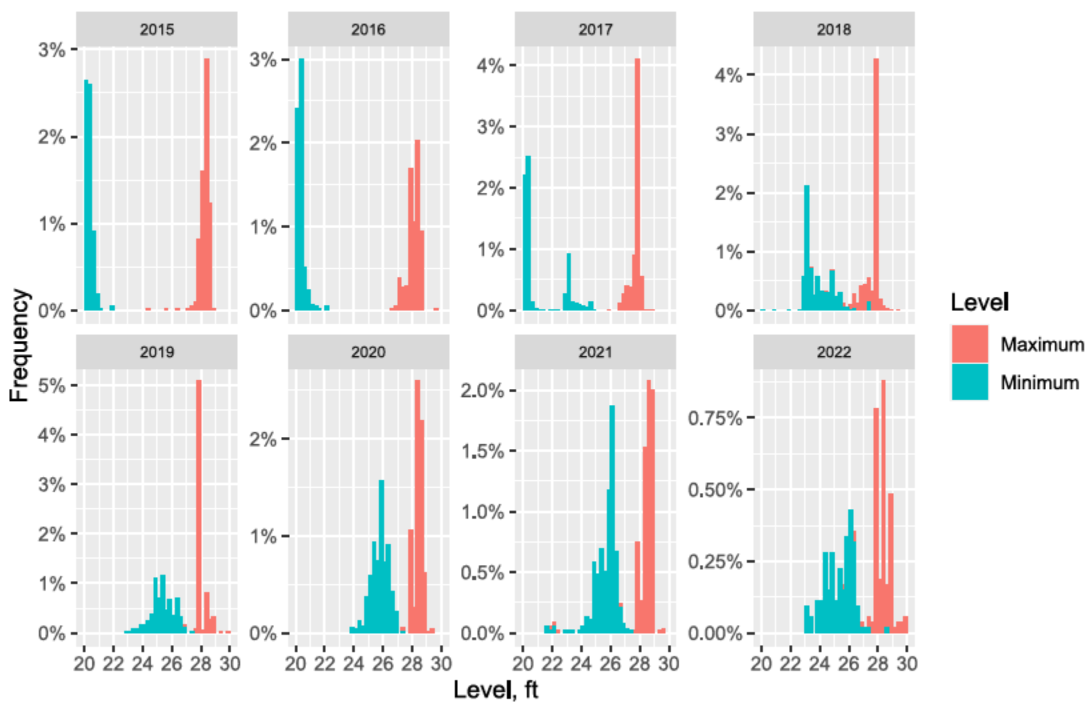

Figure 3-6 Red Hill Tank 685 Daily Operating Levels

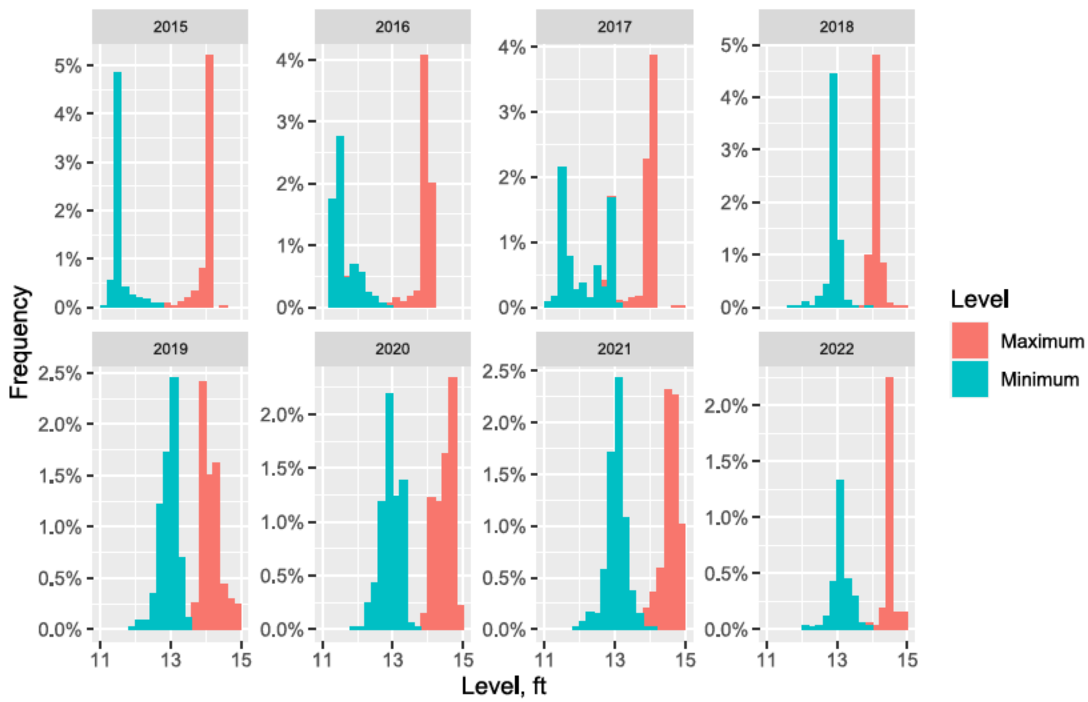

Figure 3-7 Camp Smith Tank 325 Daily Operating Levels

Water levels in the Halawa S1/S2 tanks were less predictable because the source water pump stations are operated manually, with one pump at the Waiawa Shaft in service at all times. Additionally, the two tanks provide substantial equalization storage and, therefore, the levels fluctuate significantly in response to demand variations (e.g., due to nighttime irrigation). To obtain water level controls to simulate human operation in the model, the historical source pump status (based on flow rates) and S1/S2 tank level data were reviewed and summarized in the box-and-whisker plot[1] in Figure 3-8.

These data show that the pumps at the Aiea-Halawa or Red Hill Shaft, or the second pump at the Waiawa Shaft, usually turn on when the S1/S2 tank levels drop below the range of 33 to 35 ft, with a median of approximately 34.3 ft. The Aiea-Halawa Shaft,

[1] In box-and-whisker plots, the box encompasses the central half of the data points, i.e., the height represents the range of values between the 25th and 75th percentile. The horizontal line in the center of the box indicates the median or 50th percentile. The whiskers above and below the box extend to the data points that are not outliers. The dots indicate statistical outliers.

Red Hill Shaft, or supplemental pump at the Waiawa Shaft usually turn off between 35 and 37 ft, with median levels of 35.6, 36.2, and 36.3 ft, respectively.

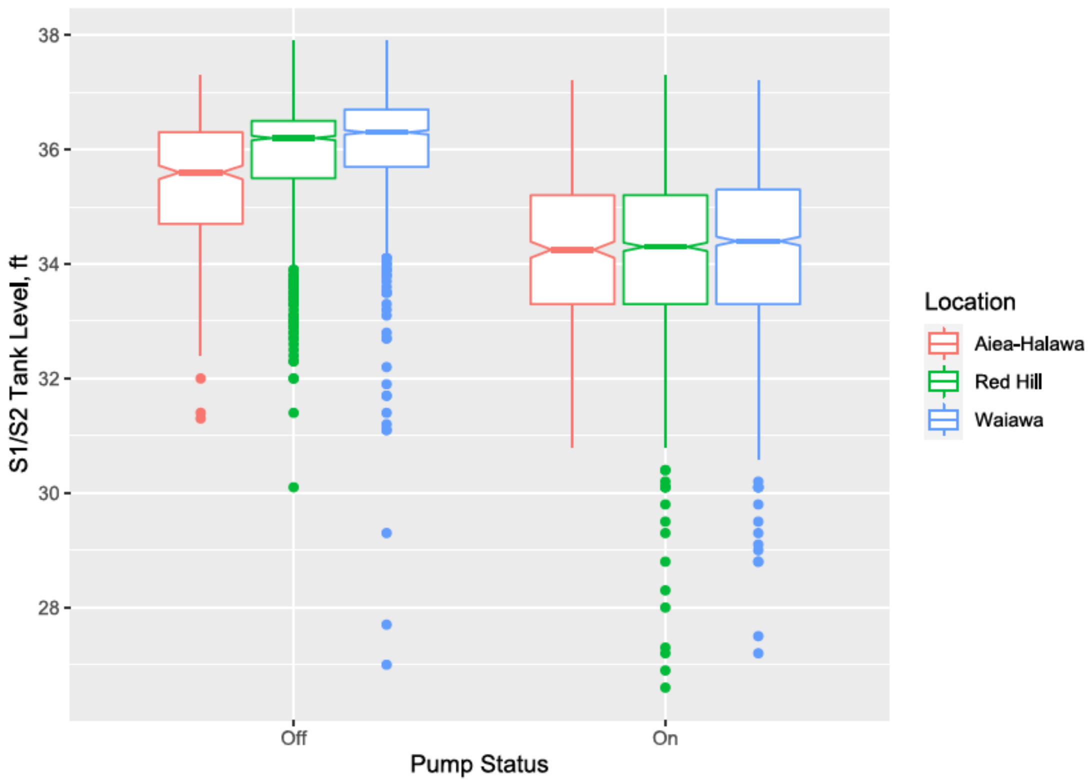

Figure 3-8 Typical Pump On/Off Water Levels for the Halawa S1/S2 Tanks

Historical operating levels for the Army tanks were easily discernible because the data was available in 1-minute intervals. Figure 3-9 shows the operating range of the North Tank (181), and Figure 3-10 provides the data for the South Tank (182). For both tanks, the operating levels changed in 2019 from a range of 7 – 12 ft to 14 – 18 ft[2]. Most recently, both tanks have been kept nearly full, with levels being maintained between 16 and 18 ft.

No historical tank level data were available for Tank 2070. This tank is fed by gravity from the Halawa S1/S2 tanks, and its levels were expected to fluctuate in the same manner.

[2] This change could also be due to a new level datum set during re-calibration.

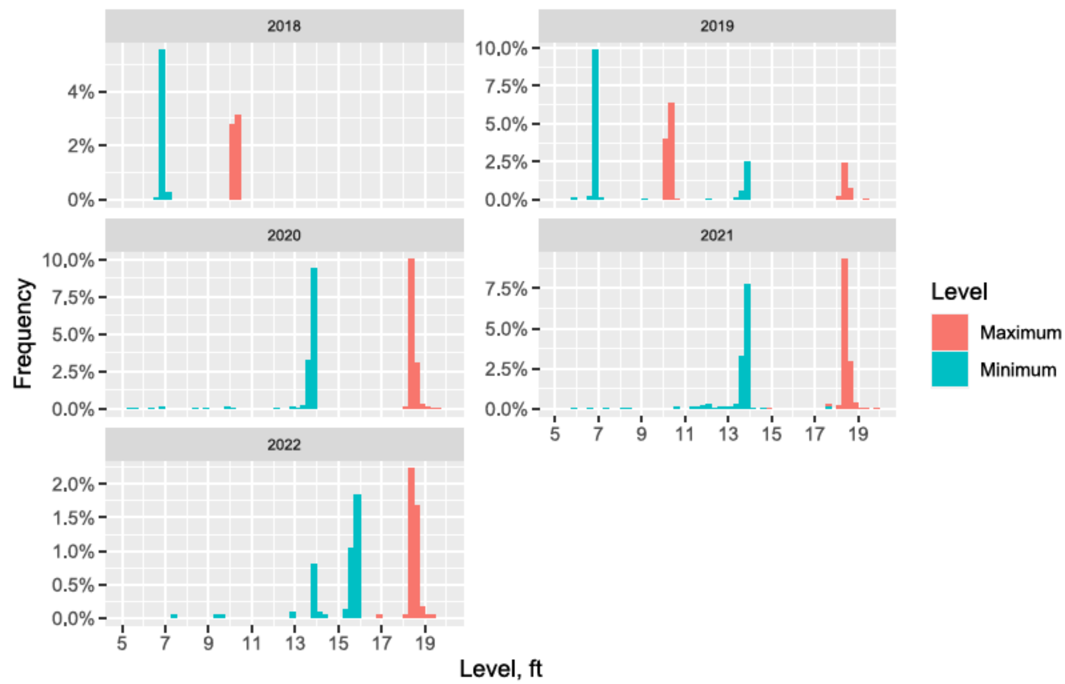

Figure 3-9 North Tank 181 Daily Operating Levels

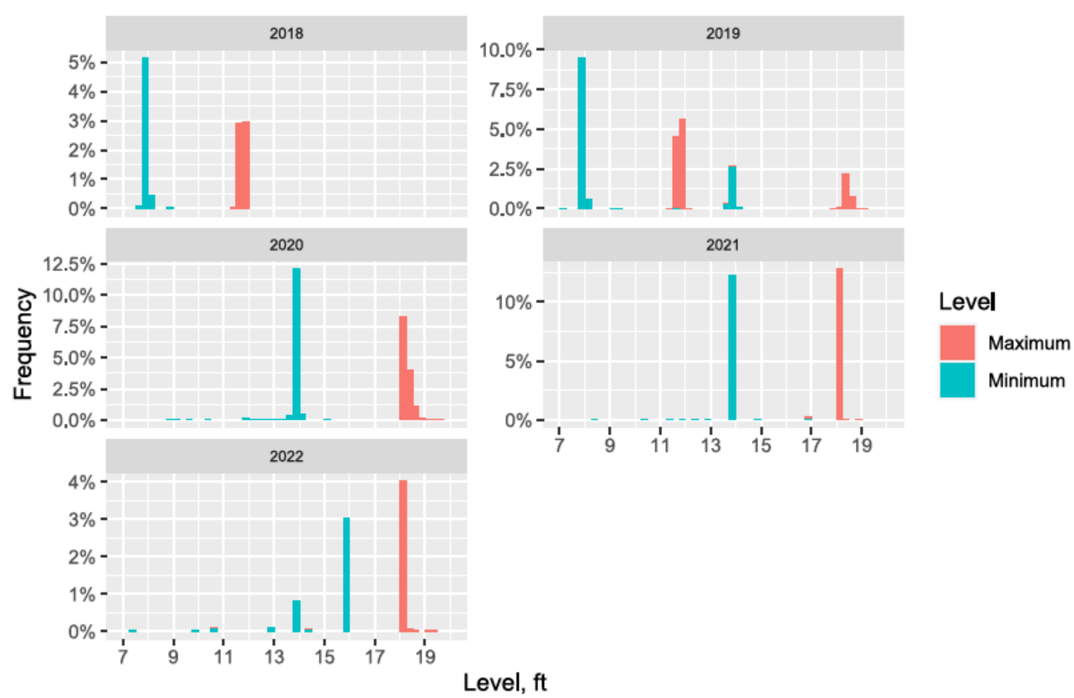

Figure 3-10 South Tank 182 Daily Operating Levels

3.5 DIURNAL DEMAND PATTERNS

The hourly variations in water demand were initially explored by determining the median demand exerted at each hour of the day by month and calendar year. The results are provided graphically in Figure 3-11. Note that the 2018 and 2022 data were incomplete.

(b) (3) (B)

[redacted]

Figure 3-11 Median Hourly Demands by Month and Year

Figure 3-11 reveals the following:

- Peak hourly demands (PHD) occur around midnight. The nighttime peaks are higher during the summer, presumably due to more extensive irrigation.
- The lowest demands typically occur in the evening hours.
- Water demands vary seasonally; both daytime and nighttime demands increase in the months from May to October. This contrast was most obvious in 2020 and 2021, and it may have been affected by tele-working and travel restrictions due to the COVID-19 pandemic.
- Following the shutdown of the Red Hill and Aiea-Halawa Shafts, the median hourly demands in January and February 2022 assumed a more "traditional" pattern with minimum water consumption occurring in the early morning hours and demand peaks during waking and evening hours.

At the end of December 2021, the Halawa S2 tank was taken out of service. Based on the observed demand patterns, little or no nighttime irrigation was performed through early March 2022. Based on the SCADA data from March and April 2022 (Figure 3-12 and Figure 3-13), nighttime irrigation resumed by mid-March causing two pumps at Waiawa to run continuously while the water level in the Halawa S1 tank kept declining. Irrigation ceased on April 8, and tank level, water production, and demand variations returned to the previously observed patterns.

(b) (3) (B)

[redacted]

Figure 3-12 March-April 2022 Tank Levels, Demand and Production

This information was used to extract the diurnal irrigation demand patterns from the SCADA data. For this purpose, median hourly data from 10 days before and 10 days after April 9 were aggregated daily and subtracted from one another. The extracted daily irrigation and non-irrigation pattern, when added back together, matched the actual SCADA water demand very well (Figure 3-13). The extracted patterns were subsequently scaled to total demands and utilized to develop water demand patterns for model validation and extended period simulations (refer to Section 4).

[redacted] (b) (3) (B)

Figure 3-13 March/April 2022 Extracted Water Demand Patterns

3.6 WATER METER DATA

JBPHH provided monthly water meter data covering the period from October 2020 to January 2022. The data included records from 1,556 meters, not all of which represented physical meters. Of the 1,556 meters, AH/BC was able to match 776 to physical locations using the JBPHH geographic information system (GIS) data via either the MAXIMOASSETIDFK or FEATURENAME attribute field. An additional 505 meters were located through the "facno1" or "facno2" attributes in the water meter data, which provided abbreviated meter zone designations or building numbers. The same field also indicated if the meter was an irrigation meter. Little or no meter data were available for Hickam Air Force Base, or the consecutive system operated by the Army. Collectively, AH/BC determined that only approximately 30% of the average daily water production was accounted for in the meter data. Refer to Section 5 for details on assigning demands to the water network.

4. FIELD TESTING

AH/BC conducted the following field testing of the JBPHH water system to generate the performance data used to calibrate and verify the hydraulic model:

- C-factor and fire hydrant flow testing (11 locations)
- Pressure monitoring (21 locations)
- Fluoride tracer study (20 locations)

This section summarizes field test results; for detailed field work procedures, refer to the project's Work Plan.

4.1 C-FACTOR AND HYDRANT FLOW TESTING

The general procedure for a C-factor and fire hydrant flow test is to create a dead-end pipe system by closing valves and then flowing a hydrant within that system at a specified rate and measuring the pressure drop between two (or more) upstream hydrants. The pipe friction or "C" factor, which is inversely proportional to the measured pressure differential, can then be determined using the Hazen-Williams equation. Between 12 and 18 April 2022, AH/BC collected representative data on pipe quality throughout the entire JBPHH water system by conducting C-factor testing on a variety of different pipe sizes, materials (CI, DI, PVC, and AC pipe), and ages. Each test was conducted multiple times at varying flow rates and using different flow nozzles.

The C-factor test locations are listed in Table 4-1, which also presents the estimated C-factors and confidence intervals for each test location. Figure 4-1 provides an overview map of the locations. Refer to Appendix C for detail maps. An unrealistically high C-factor was found at the Tenth Street location. It is likely that the 6-inch pipe diameter shown on the GIS maps was incorrect. If the actual diameter were 8 inches, the computed C-factor would be 141, which is more realistic. Also, an extremely low C-factor was determined at Salvor Street. This could be due to a highly tuberculated pipe, a partially closed valve, or an incorrect pipe diameter of 8 inches. If the actual pipe size at this location were 6 inches, the computed C-factor would be 82.

Table 4-1 C-Factor Test Results

No.	Location Description	Pipe Size (inch)	Pipe Material	Installation Year	Estimated C-Factor	95% Confidence Interval
1	Catlin Drive	12	PVC	2008	145	134 - 156
2	Gordon Street	12	CI	1960	155	112 - 197
3	Gemini Avenue	8	AC	1943	134	128 - 140
4	Porter Avenue	6	AC	1943	144	136 - 152
5	Seventeenth Street	8	PVC	2006	151	146 - 155
6	Tenth Street	6	PVC	2006	300*	245 - 356*
7	Worchester Avenue	10	PVC	2006	101	96 - 106
8	Hale Alii Avenue	10	CI	1943	67	50 - 84
9	Salvor Street	8	CI	1943	38*	36 - 40*
10	McGrew Loop	6	CI	1959	105	51 - 160
11	Victor Wharf Road	12	DI	1988	159	153 - 165

* Potential outlier; see text.

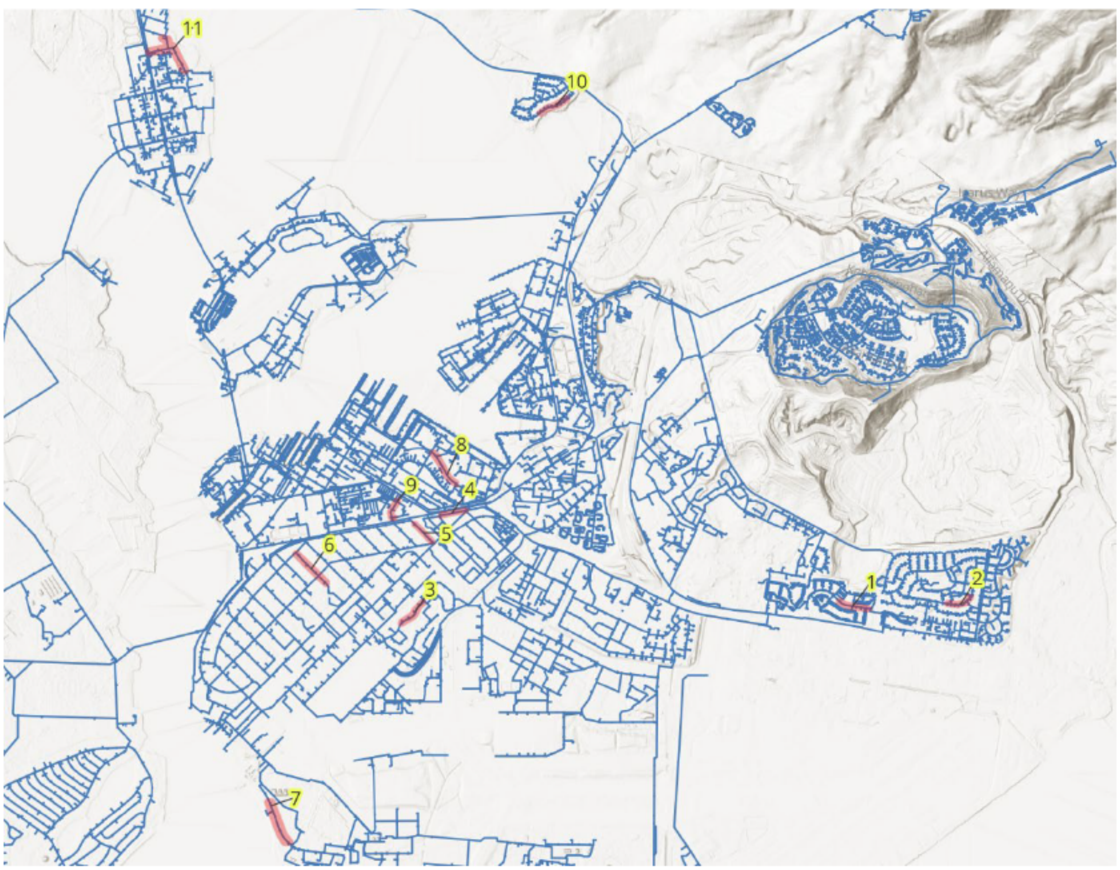

Figure 4-1 C-Factor Test Locations

4.2 PRESSURE MONITORING

AH/BC monitored distribution system pressures at multiple locations for 12 days. In addition to SCADA data, the pressure logs were used to verify that the hydraulic model reasonably represents the real-world system. Figure 4-2 provides a map of the logger locations. The numbered locations refer to Table 4-2, which summarizes the measured pressures.

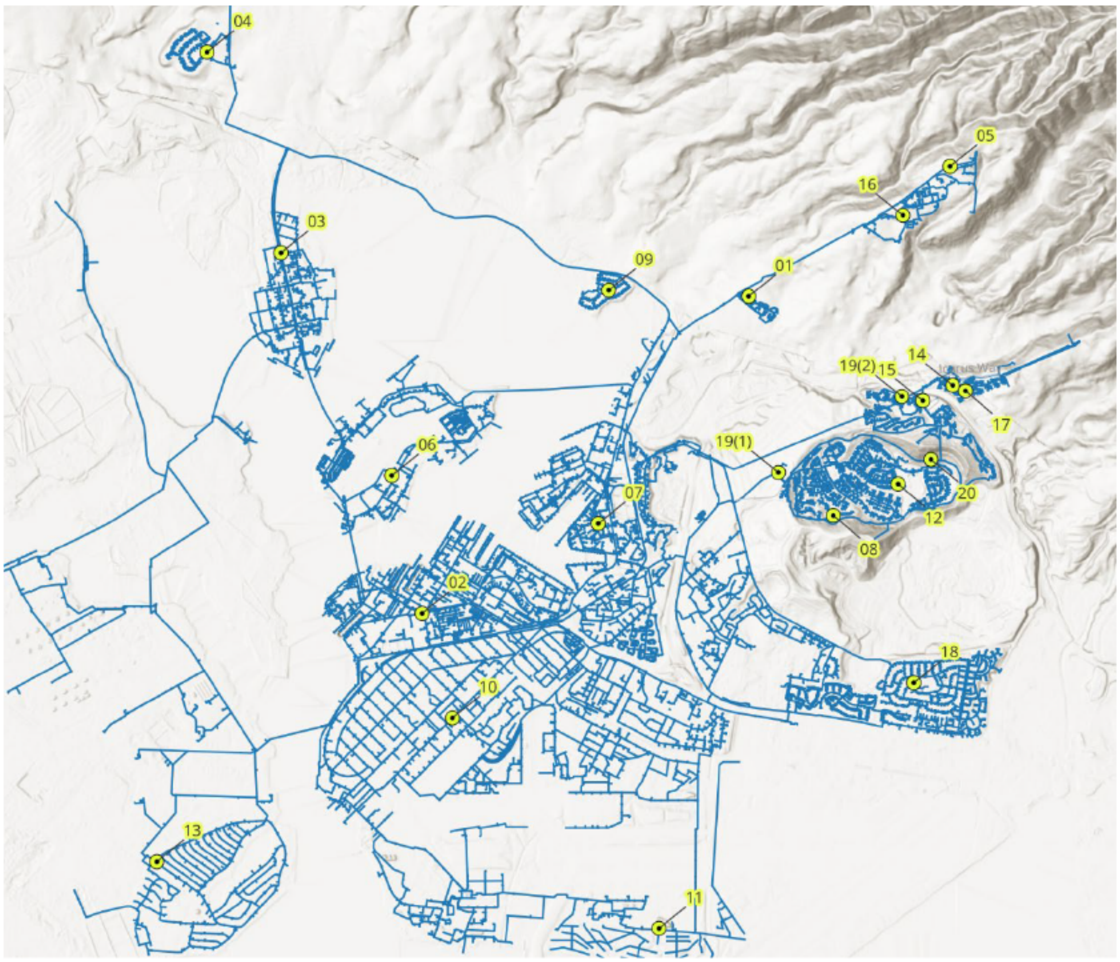

Figure 4-2 Pressure Logger Locations

Table 4-2 Pressure Logger Locations and Data Summary

Logger No.	Location Description	Minimum Pressure (psi)	Maximum Pressure (psi)
01	Halawa housing, center of Kaee Loop, fire hydrant #1420	[redacted]	[redacted]
02	Shipyard, north side of Bldg. 394, corner of Port Royal St. and Central Ave., fire hydrant #1536	[redacted]	[redacted]
03	Pearl City Peninsula, east side of the corner of Leahua Ave. and Farm St., fire hydrant #2319	[redacted]	[redacted]
04	Manana Housing community center, fire hydrant #147	[redacted]	[redacted]
05	Top of Camp Smith near the playground area, fire hydrant #878	[redacted]	[redacted]
06	Ford Island, at the corner of Enterprise St. and Lexington Blvd., fire hydrant #2216	[redacted]	[redacted]
07	Submarine Base (SUBASE), on the other side of Pierce St. from Bldg. 1736 (bowling center), fire hydrant #50	[redacted]	[redacted]
08	AMR Housing, on the corner of Skyview Loop and Crossandra St., fire hydrant #1343 (High elevation pressure zone, served by the South Tank 182)	[redacted]	[redacted]
09	McGrew Housing, located on McGrew Loop across from the community center, fire hydrant #1511	[redacted]	[redacted]
10	Hickam AFB, located in front of Bldg. 1168H off of Hangar Ave., fire hydrant #1819	[redacted]	[redacted]
11	Located across from Mamala Bay Dr., directly in front of the golf course, fire hydrant #2148	[redacted]	[redacted]
12	AMR, southeast corner of Begonia Loop, fire hydrant #1471 (Low elevation pressure zone, served by the Middle Tank)	[redacted]	[redacted]
13	Iroquois Point Housing, corner of Ibis Ave. and Iroquois Ave., fire hydrant #1298	[redacted]	[redacted]
14	Red Hill Housing, corner of Forward Ave. and Conifer Pl., fire hydrant #1317	[redacted]	[redacted]
15	AMR, corner of Sassafras Dr. and Red Hill Terrace, fire hydrant #291 (High elevation pressure zone, served by the North Tank 181)	[redacted]	[redacted]
16	Camp Smith, parking lot off Bailey Rd., directly across the recreation field, fire hydrant #1642	[redacted]	[redacted]
17	Red Hill Housing, off Tampa Dr. across from community center, fire hydrant #1315	[redacted]	[redacted]
18	Eastern Housing, west of the community center (Bldg. 606-POO), fire hydrant #2224	[redacted]	[redacted]
19 (1)	Downstream of AMR South Tank pump station (removed 15 April)	[redacted]	[redacted]
19 (2)	AMR, near the bottom of Sassafras Dr., fire hydrant #1656 (installed 15 April) (High elevation pressure zone, served by the North Tank 181)	[redacted]	[redacted]
20	Downstream of the Middle Tank 2070 pump station.	[redacted]	[redacted]

(b) (3) (B)

4.3 FLUORIDE TRACER STUDY

AH/BC conducted a fluoride tracer study to collect data on water travel times throughout the distribution system. Beginning at 8 am on 11 April 2022, the fluoride feed at the Waiawa shaft was turned off. AH/BC then collected multiple samples per day from 20 locations throughout the water system. The fluoride concentration in each sample was measured and recorded. At 8 am on 14 April 2022, the fluoride feed was turned back on, while sampling continued at the same frequency. Water was typically collected after 5 minutes of flushing from hose bibbs or other high-flow outlets, to ensure that the sample was representative of the water quality in the main pipes. The sample locations are listed in Table 4-3 and shown in Figure 4-3. Results are discussed in Section 5.6.

Table 4-3 Tracer Study Sampling Locations

Building No.	Location Description
1756H	Army & Air Force Exchange Service (AAFES) Mini Mall
3584H	Golf Clubhouse
794	Pearl City Navy Exchange (NEX) Mini-Mart
6890	Halsey Terrace NEX Mini-Mart
13	Camp Smith Semper Fit Center
2647	7-11 Convenience Store
388A	Makalapa Gym
55	Ford Island Fitness Center
487	McGrew Community Center
3455H	Outdoor Recreation Center
N/A	Manana Community Center
880	AMR Mini Mart
662	Navy Gateway Inns & Suites (NGIS)
150	Administrative Office*
1058H	Public Bathroom
1	Administrative Office
6882	Iroquois Point NEX Mini Mart
N/A	Halawa Tanks
N/A	Red Hill Community Center

* The adjacent Building 1719 (McDonald's) was sampled initially.

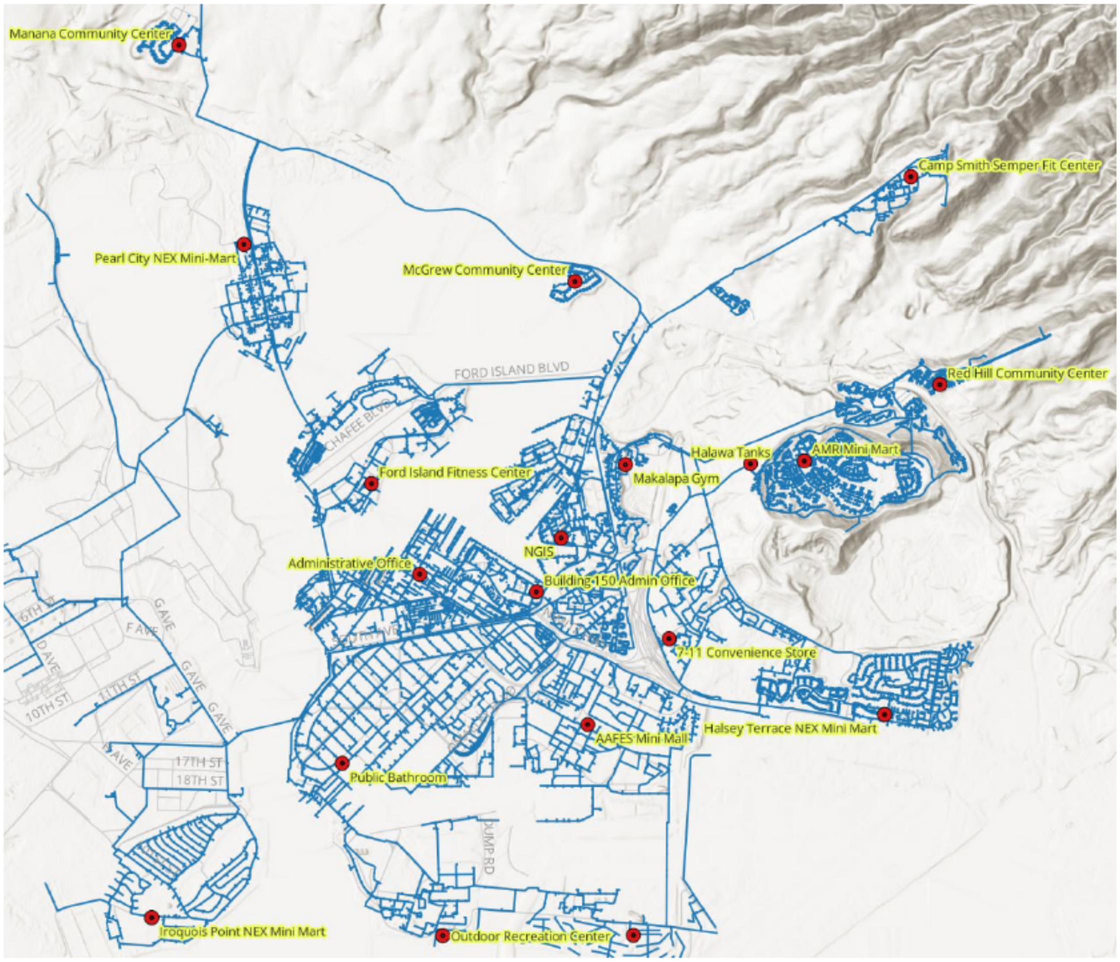

Figure 4-3 Tracer Study Sampling Locations

4.4 SEWER PUMP STATION MONITORING

AH/BC staff deployed event loggers at five sewer pump stations capable of recording pump cycles by monitoring the alternating current-induced magnetic field at the electrical conduits powering the station. Sewer pump station runtimes are proportional to sewer flow rates and, during dry weather, allow the determination of domestic water use patterns.

The five event loggers were installed at sewer pump stations selected to represent different uses at the base, as shown in Figure 4-4, including residential use (McGrew Point, Catlin Park), mixed barracks, recreational, industrial use (Hale Moku Housing, SUBASE), and office/non-residential use (NAVFAC Hawaii). The loggers installed at McGrew Point and SUBASE did not yield meaningful data. Refer to Section 5.5.1 for discussion of the recorded data.

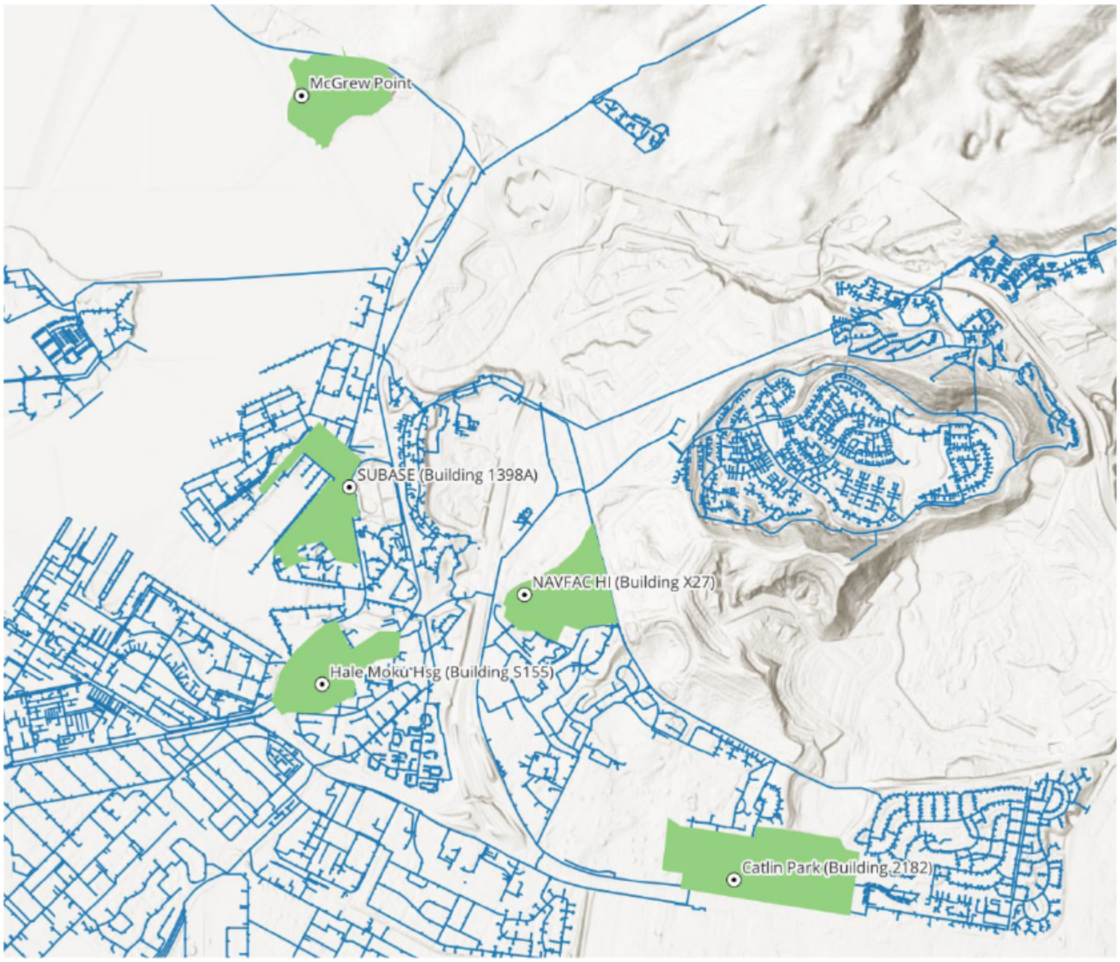

Figure 4-4 Sewer Pump Station Monitoring Locations

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5. HYDRAULIC MODEL DEVELOPMENT

This section provides background on the model representation of the distribution system network and a summary of model development efforts.

5.1 HYDRAULIC MODELING OVERVIEW

WaterGEMS is a computer program that performs steady-state and extended period simulations (EPS) of hydraulic and water quality behavior within pressurized pipe networks. A network consists of pipes, nodes (pipe junctions), pumps, valves, and storage tanks or reservoirs. The model tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period comprised of multiple time steps. In addition to chemical species, water age and source tracing can also be simulated.

WaterGEMS is GIS-based and interfaces to the “EPANET 2” analysis engine, which was developed and distributed by the Risk Reduction Engineering Laboratory of the United States Environmental Protection Agency. EPANET 2 is a well-known computer program that is widely used and tested in hydraulic modeling. Appendix D contains a detailed description of WaterGEMS including its physical and non-physical network model components, and its simulation of a distribution system with respect to hydraulics and water quality.

Developing a hydraulic model consists of four basic steps:

- Creating the model representation of the physical infrastructure
- Applying operational controls (e.g., pump controls)
- Applying water demands and time patterns
- Calibration and verification of the model

The following sections detail the steps performed for developing the JBPHH hydraulic model.

5.2 PHYSICAL NETWORK COMPONENTS

AH/BC imported the GIS data from the JBPHH and Army water utility databases using the WaterGEMS “ModelBuilder” tool to create a current representation of the water system framework of pipes and junctions. Pipes with WATERTYPE attributes other than “Potable Water” and WATERLINETYPE other than “Main” were excluded.

After the data were imported, AH/BC verified topology and connectivity by ensuring all junctions and pipes were properly connected and, in instances where they were not, connecting them based on available as-built drawings or other relevant information. AH/BC also removed duplicate pipes and nodes and, utilizing the WaterGEMS “Skeletonizer” tool, merged pipes of the same material, size, and age. This approach greatly reduced the number of model nodes.

Friction factors (C-factors) were assigned to pipes by material and diameter based on field test results and literature values as follows:

Pipe Material	Pipe Sizes	Assigned C-Factor
PVC or HDPE	All sizes	150
DI	All sizes	140
CI	Up to 10 inches	80
	12 – 20 inches	100
	> 20 inches	130
AC	All sizes	130

Where the pipe material was unknown, it was either assumed to be CI, if installed before 1960, or the same material as nearby pipes. Small-diameter CI pipe was assumed to be un-lined, resulting in lower C-factors.

AH/BC then added reservoirs, pumps, and tanks, defining each component using as-built or design drawings, specifications, or manufacturers’ data. Each pump was assigned head gain versus flow curves, some of which were corrected to match available measured data (refer to Section 3.3). Pressure reducing valves (PRVs) with appropriate settings were added at locations provided by Navy and Army staff. To assign elevations to the hydraulic network junctions and confirm elevations from drawings, AH/BC imported publicly available contour elevation data from the Hawaii Statewide GIS

Program using the WaterGEMS built-in "Trex" tool. The assigned elevations for pumps, tanks, and reservoirs were compared to as-built drawings for verification. Node elevations for underground locations (e.g., at the three shafts) were assigned based on drawings.

5.3 OPERATIONAL CONTROLS

Operating rules were set up based on observed pump operation and tank levels (Section 3.4). As stated earlier, the pumps at the three shafts are operated manually. The median water levels at which the second pump turns on or off (supplementing the lead pump at the Waiawa Shaft), were used as the trigger levels for EPSs (Table 5-1). Note that for model calibration and verification runs, the three sources were operated as recorded by the SCADA system.

Table 5-1 Pump Operational Controls

Pump	Controlling Tank	Pump ON Setting (ft)	Pump OFF Setting (ft)
Red Hill Booster Pump	Red Hill Tank 685	25.0	29.0
Camp Smith Booster Pump	Camp Smith Tank 325	13.0	14.5
(b) (3) (B) [redacted]	South Tank 182	16.0	18.0
	North Tank 181	16.0	18.0
	Halawa S1	34.4	36.3
	Halawa S1	34.3	36.2
	Halawa S1	34.2	35.6

5.4 WATER DEMAND ALLOCATION

In a typical water system model, not every service connection is represented. Rather, demands from multiple services are lumped together and assigned to the nearest network node. In WaterGEMS this task can be performed automatically using the "LoadBuilder" tool. Unlike in a municipal utility, not every service at JBPHH is metered. Thus, AH/BC assigned estimated water usage rates to each non-metered building.

ADDs were developed for each building based on a combination of water meter usage data and industry-approved water use coefficients based on building use type and square footage. JBPHH provided recent monthly water meter usage data (starting from fiscal year (FY) 2020) for individual facilities, irrigation areas, and master meters for neighborhoods. After review of the data, AH/BC determined that the metered data accounted for less than 30% of the ADD ([redacted]).

To account for the remainder of the demand, AH/BC generated a list of all facilities from the GIS data including relevant information such as coordinates, square footage of the building footprint, and the name of the facility. After filtering out the buildings that were already accounted for using meter data and those not expected to have any water demand (e.g., garages, warehouses), AH assigned a use type for each remaining building (i.e., Administration/Operations, Community Buildings, Gymnasium, etc.). Each use type has an associated, industry-determined mean water use coefficient that, when multiplied by the square footage of the building, gives an estimate of water usage in gallons per day (gpd). Mean water use coefficients were retrieved from literature[3], and they are presented in Table 5-2. To account for buildings with multiple stories, AH/BC assumed an average of 3 floors per facility on base, which was then multiplied by the demand to generate the total demand for each facility. The estimated facility demand was [redacted]. The total, including [redacted] of metered facilities, was [redacted].

To estimate residential demand, AH/BC divided master meter data by the number of residences and compared the result to typical residential demand. The calculated average of [redacted] per residence was then applied to unmetered homes. To account for multifamily dwellings (duplexes, etc.), AH/BC examined GIS data and aerial imagery to count the number of driveways or garage ports at each building. The estimated residential demand at JBPHH water system totaled approximately [redacted].

[3] Baumann D, Boland J, Hanemann W (1998). Urban Water Demand Management and Planning. McGraw-Hill, New York, 1998.

Table 5-2 Water Use Coefficients by Building Use and Type

Facility Use	Water Use Coefficient (gpd/ft²)
Administration/Operations	[redacted]
Reserves/National Guard	
Barracks	
Bowling Center	
Bank/Credit Union	
Bachelor Officers Quarters	
Community Building	
Commissary	
Dining	
Family Housing	
Gymnasium	
Guest Housing	
Health/Dental Clinic	
Hospital	
Laundromat	
Maintenance	
Restaurant	
School	
Service Station	
Warehouse	
Exchange	

A large fraction of water demand at JBPHH is attributed to irrigation. Available meter data indicated that approximately [redacted] MGD of water was used for irrigation throughout the base. AH/BC scaled this estimate up based on the land area for zones that appeared to be missing irrigation meter data, including Red Hill, Halawa Heights, and Manana Housing, which had no irrigation records. Estimated irrigation demand in these three neighborhoods was set to [redacted] gpd, respectively, based on data for neighborhoods of similar size. Lastly, we scaled the available irrigation meter data for Hickam AFB by a factor of 30 to account for the multiple residential areas, industrial facilities, golf course area, and additional irrigation uses. This brought the total irrigation demand to approximately [redacted] or 33.5% of ADD.

The approximately [redacted] (23%) of the ADD of [redacted] that remained unaccounted for, was distributed as constant leakage demand among the dense, central areas of the Fleet and Industrial Supply Center (FISC), the SUBASE, the Naval Station and shipyard, and Ford Island. Table 5-3 summarizes the demand allocation.

Table 5-3 Demand Allocation Summary

Demand Type	Metered, MGD	Estimated, MGD	Total, MGD
Facilities	[redacted]	[redacted]	[redacted]
Residential	[redacted]	[redacted]	[redacted]
Irrigation	[redacted]	[redacted]	[redacted]
Leakage	[redacted]	[redacted]	[redacted]
Total	[redacted]	[redacted]	[redacted]

5.5 TIME PATTERNS

A time pattern is a collection of multipliers that can be applied to a quantity to allow it to vary over time. For demands at network nodes, they are called water demand patterns. Reservoir heads, pump schedules, and water quality source inputs can all have time patterns associated with them.

The time interval used in all patterns is a fixed value, typically 1 hour, as in the present work. Within this interval a quantity remains at a constant level, equal to the product of its nominal value and the pattern's multiplier for that time period. Although all time patterns must utilize the same time interval, each can have a different number of periods. When the simulation clock exceeds the number of periods in a pattern, the pattern starts at its first period again.

5.5.1 Water Demand Pattern

Where no hourly water consumption data is available, water demand patterns for various uses can be based on literature data. Oftentimes, a single demand pattern can be utilized for all uses (residential, industrial, commercial, etc.) if the overall water demand is dominated by a particular use. As discussed in Section 3.5, irrigation demand apparently comprises a significant portion of the overall water consumption, and it exhibits a time pattern distinct from typical water use. Therefore, at least two water use patterns had to be developed for the JBPHH water system (irrigation and non-irrigation), in addition to a constant use pattern representing leakage.

To aid in developing a non-irrigation water use pattern, AH/BC reviewed sewer pump station (SPS) runtime data collected during the on-site visit in April 2022. Figure 5-1 presents the data both as time series graphs and as boxplots by hour.

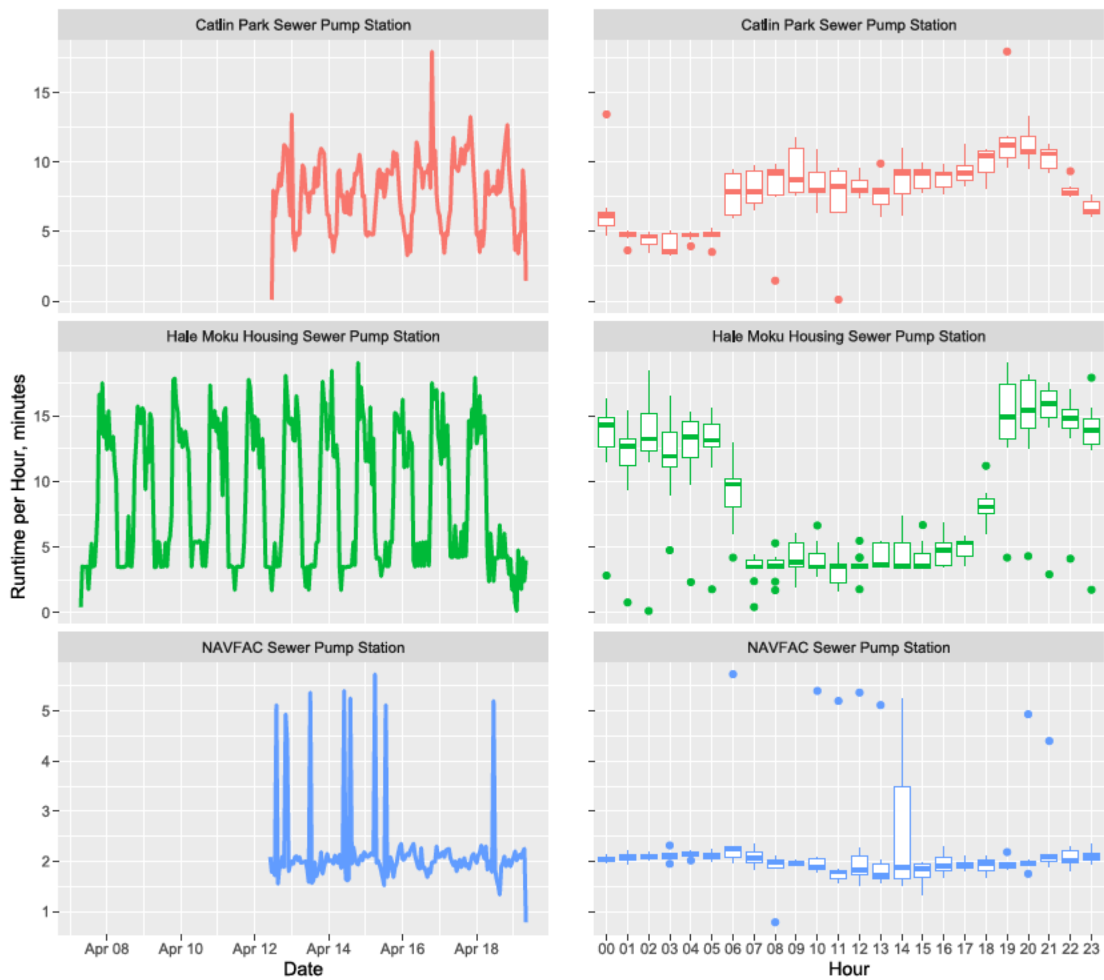

Figure 5-1 Sewer Pump Station Runtime Data

The data from the Catlin Park and Hale Moku SPSs exhibited consistent, repeating patterns, while the pump station at NAVFAC had little and intermittent use. The Catlin Park SPS runtime data look like typical domestic water use patterns, with minimum usage in the midnight to early morning and peaks around waking and evening hours.

After normalizing the data[4], the hourly runtime pattern closely resembles the system-wide water consumption pattern in January 2022, when little or no irrigation was performed (Figure 5-2).

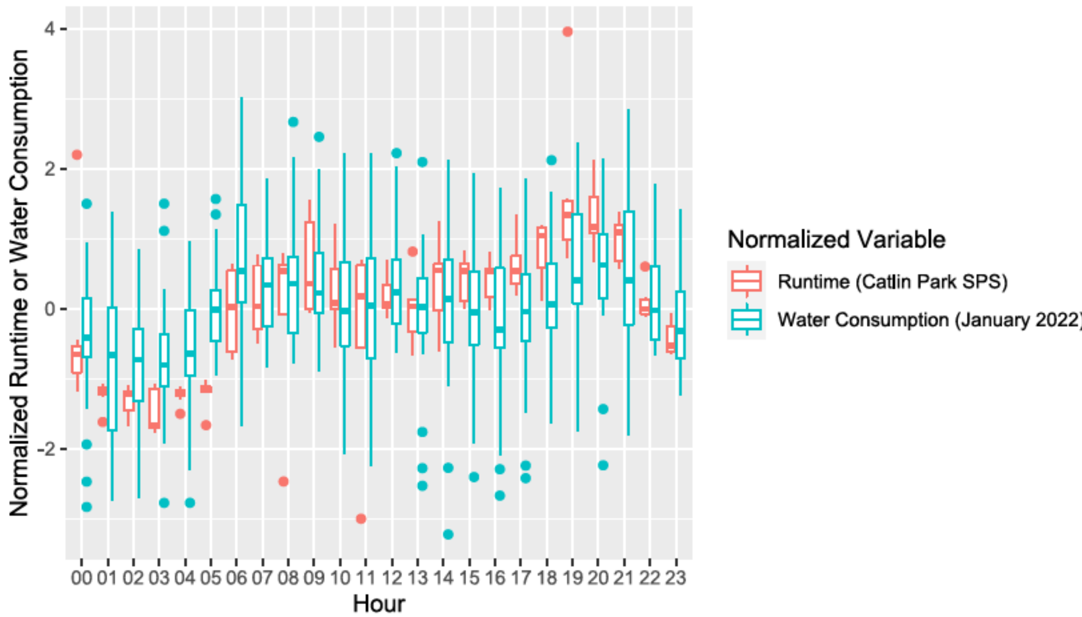

Figure 5-2 Normalized Runtime and Water Consumption Data

The Hale Moku SPS showed substantially increased flows during night-time hours. Based on the GIS data provided by JBPHH, the sewer service area contains primarily barracks and recreational facilities, including the field house, fitness centers, Club Pearl, and ball fields. Nighttime irrigation could explain the observed pattern, but irrigation should not affect sewer flows unless considerable infiltration and inflow occurred. This may be possible given the age of the sewer collection pipes in the area, most of it dating back to 1942. In addition, while irrigation on base was largely suspended on April 9, it may have continued in selected areas. Whatever the cause of the high nighttime flows may be, the similar pattern observed in base-wide water consumption justifies utilizing separate domestic and outdoor use patterns. Therefore, the following process was adopted to develop water demand patterns:

- Compute the average water demand of the simulation period.

[4] Data normalization was performed by subtracting the arithmetic mean and dividing by the standard deviation.

- Based on the water demand allocation (Section 5.4), the constant "leakage" demand is 23% of the observed average water demand.
- The irrigation demand pattern is equal to the observed irrigation demand pattern (Section 3.5), repeated for each simulation day.
- The domestic demand pattern is obtained by subtracting the leakage and irrigation demand from the observed water consumption.

The three demand patterns were then divided by their respective base demands (domestic: [redacted], leakage [redacted], irrigation: [redacted]) to obtain multipliers for use during extended period simulations for calibration and verification. This method ensured that calibration and verification results were not impacted by mass balance errors.

A standard 24-hour demand pattern for use in predictive simulations was developed in the same manner using FY 2020 and 2021 data. After subtracting leakage and irrigation demands from the observed hourly water consumption as described above, the domestic demand pattern was aggregated to a 24-hour pattern by computing the median demand for each hour of the day. Figure 5-3 shows the resulting patterns.

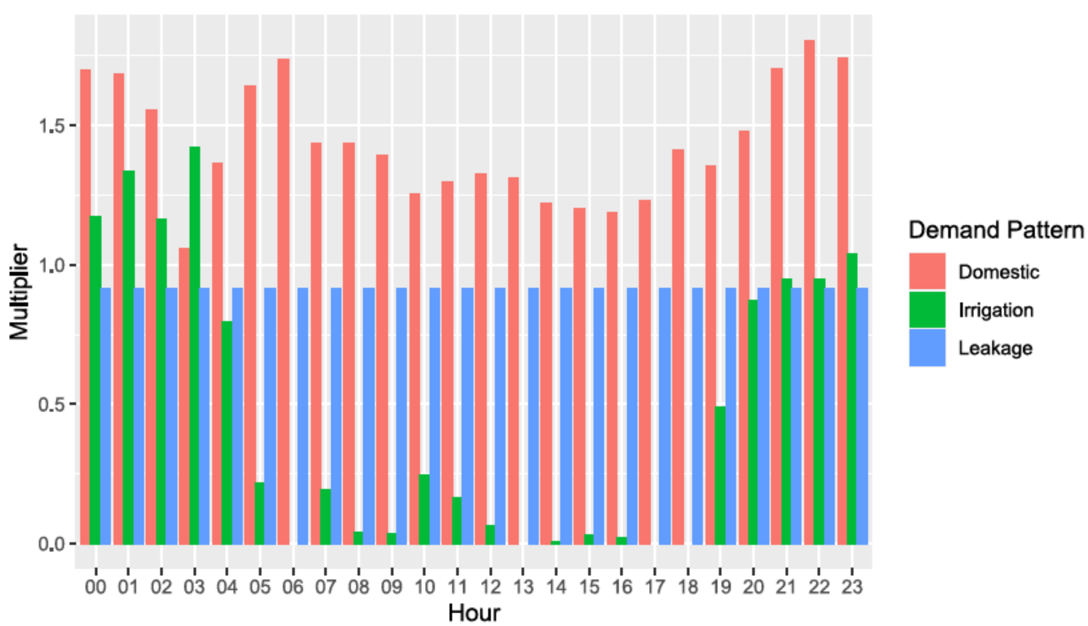

Figure 5-3 Standard Demand Patterns

5.5.2 Pump On/Off Time Patterns

For predictive simulations, source water pumps were actuated based on tank levels as described in Section 5.3. To minimize mass balance errors during calibration and verification simulations, the source water pumps for the three shafts were turned on based on actual observed flow rates. One Red Hill Shaft or one Aiea-Halawa Shaft pump was turned on when the observed hourly flow exceeded [redacted], respectively. At the Waiawa Shaft, one pump [redacted] remained in operation at all times. A second pump [redacted] was turned on based on predictable pressure and flow combinations as observed in Section 3.3. In instances where it was ambiguous if [redacted] was running, the pump that operated last in lag mode was turned on.

5.6 MODEL CALIBRATION

Model calibration involves the adjustment of model parameters so that model-predicted flow, pressures, tank levels, and water quality parameters (if included in the model) match the measured variables.

Initially, AH/BC performed cursory steady-state calibrations runs under both low-flow and high-flow conditions. With little variation in the hydraulic grade lines across each pressure zone, this approach helped identify errors in tank levels, reference elevations, control valve settings, pressure zone boundaries, pump status and speed, and demands.

The PRVs in the model set the downstream pressures to a constant value, and they were not capable of replicating the observed variable pressures at the downstream logger locations. Therefore, PRVs at Red Hill Housing, where pressure fluctuated along with the upstream tank levels, were replaced by general-purpose valves (GPVs) with head loss-flow curves chosen to match the observed pressures.

Flows through the Moanalua Terrace booster pump station were considerably higher than SCADA data. While the GIS did not indicate any normally closed valves, we found that recirculation in the neighborhood network caused the pump to run out of the end of the curve. After closing a connection between the Moanalua Terrace and Catlin Park neighborhoods on Tomich Ct, the flows decreased substantially. The connection remained closed for all mode simulations.

After the initial adjustments, AH/BC simulated the 12-day period of the on-site visit in April 2022, during which 20 pressure loggers were deployed throughout the Navy and Army water systems. AH/BC performed dozens of model simulations with various adjustments of global C-factors and relative contributions of domestic, irrigation, and leakage demand and found that the overall model fit was not very sensitive to the C-factors of pipe less than 24 inches in diameter. However, reducing the relative irrigation demand by 20% and increasing domestic demand accordingly for the calibration period resulted in a reasonable fit of both SCADA and pressure logger data. Table 5-4 summarizes the model-fit for SCADA data parameters including the root mean squared error (RSME) between model-predicted and measured parameter values, as well as the RSME relative to the mean of the data.

Table 5-4 Model Calibration Statistics for SCADA Parameter Data

Location	RSME	Mean	%RSME
North Tank 181 Level, ft	(b) (3) (B) [redacted]	(b) (3) (B) [redacted]	7%
South Tank 182 Level, ft	[redacted]	[redacted]	7%
Camp Smith Tank 325 Level, ft	[redacted]	[redacted]	4%
Halawa Booster Pump Station Pressure, psi	[redacted]	[redacted]	6%
Halsey Terrace Flow Rate, gpm	[redacted]	[redacted]	34%
Manana Pump Station Discharge Pressure, psi	[redacted]	[redacted]	9%
Manana Pump Station Suction Pressure, psi	[redacted]	[redacted]	11%
Moanalua Terrace Discharge Pressure, psi	[redacted]	[redacted]	7%
Moanalua Terrace Pump Station Flow Rate, gpm	[redacted]	[redacted]	120%
Moanalua Terrace Suction Pressure, psi	[redacted]	[redacted]	8%
Red Hill Booster Pump Flow Rate, gpm	[redacted]	[redacted]	423%
Red Hill Pump Station Pressure, psi	[redacted]	[redacted]	8%
Red Hill Tank 685 Level, ft	[redacted]	[redacted]	5%
S1 Tank Level, ft	[redacted]	[redacted]	21%
Waiawa Pump Station Discharge Pressure, psi	[redacted]	[redacted]	4%
Waiawa Pump Station Flow Rate, gpm	[redacted]	[redacted]	10%

Model-predicted pressures and tank levels were usually within a few psi or ft of the observed values. Large relative deviations from measurements were usually found with flow rates (shown in gpm). This may partly be due to inaccuracies in pump curve data as well as the hourly discretization of the model runs. At the Manana Pump Station, with the assumption that one pump was running continuously, the model did not simultaneously match pressure and flows without assuming complex operation patterns, (e.g., lead/lag operation, PRVs, etc.). Verification simulations yielded more satisfactory results (Section 5.7), so no further changes were made at that location. The large relative discrepancies in the Red Hill Booster flow rates are due to the intermittent operation of the pump. The mismatch was deemed inconsequential because the model adequately represented the receiving tank levels. The model-predicted pressures were generally within 5 psi of measured data (Table 5-5).

Table 5-5 Model Calibration Statistics for Pressure Logger Data

Location	RSME	Mean	%RSME
Pressure Logger 01 Halawa Housing, psi	(b) (3) (B) [redacted]	(b) (3) (B) [redacted]	9%
Pressure Logger 02 Naval Shipyard, psi	[redacted]	[redacted]	4%
Pressure Logger 03 Pearl City, psi	[redacted]	[redacted]	4%
Pressure Logger 04 Manana Housing, psi	[redacted]	[redacted]	7%
Pressure Logger 05 Camp Smith (high), psi	[redacted]	[redacted]	2%
Pressure Logger 06 Ford Island, psi	[redacted]	[redacted]	4%
Pressure Logger 07 SUBASE, psi	[redacted]	[redacted]	3%
Pressure Logger 08 AMR (high), psi	[redacted]	[redacted]	4%
Pressure Logger 09 McGrew Point Housing, psi	[redacted]	[redacted]	4%
Pressure Logger 10 Hickam, psi	[redacted]	[redacted]	5%
Pressure Logger 11 Mamala Golf Course, psi	[redacted]	[redacted]	5%
Pressure Logger 12 AMR (low), psi	[redacted]	[redacted]	9%
Pressure Logger 13 Iroquois Point, psi	[redacted]	[redacted]	6%
Pressure Logger 14 Red Hill (low), psi	[redacted]	[redacted]	4%
Pressure Logger 15 Sassafras Drive (high), psi	[redacted]	[redacted]	3%
Pressure Logger 16 Camp Smith (low), psi	[redacted]	[redacted]	2%
Pressure Logger 17 Red Hill (high), psi	[redacted]	[redacted]	2%
Pressure Logger 18 Eastern Housing, psi	[redacted]	[redacted]	5%
Pressure Logger 19(1) AMR South Tank Pump Station, psi	[redacted]	[redacted]	5%
Pressure Logger 19(2) Sassafras Drive (low), psi	[redacted]	[redacted]	2%
Pressure Logger 20 AMR Tank 2070, psi	[redacted]	[redacted]	3%

Figure 5-4 shows time-series plots of model-predicted and measured SCADA pressures, tank levels, and they generally followed the observed trend. Figure 5-5 presents the pressure logger data and model predictions for the same period.

[redacted]

(b) (3) (B)

Figure 5-4 Model-Predicted versus SCADA Pressures, Tank Levels, and Flows

(b) (3) (B)

[redacted]

Figure 5-5 Measured and Model-Predicted Pressure Logger Data

Within the Army's consecutive water system, the model could not adequately match the recurring mid-day pressure drops. AH/BC attempted to rectify the discrepancy by imposing a mid-day high-demand pattern but was not able to do so without incurring a significant drop in tank levels that was not observed in the SCADA data. It is noted that the Army installed granular activated carbon (GAC) adsorbers at the interconnections from the Navy system. While the granular media could incur some additional head loss, it would not explain the daily pressure drops downstream of the tanks. Using the changes in tank levels and pump status data, AH/BC also verified that the water demand allocated to the pressure zones was correct. Possible causes for the observed discrepancy may be connections between the three pressure zones and/or unknown PRVs, requiring further field investigation. No water meter or sewer flow data were available for the Army system to further investigate demand allocation and use patterns.

After the calibration runs, AH/BC simulated the tracer study by imposing a constant addition of fluoride to the Waiawa Shaft to a set point of 0.7 milligrams per liter (mg/L). The background fluoride concentration was assumed to be 0.1 mg/L. The chemical feed was then discontinued from April 11, 8 am to April 14, 8 am. Figure 5-6 shows the model-predicted fluoride concentrations, overlaid with data points from the tracer study sample collection. At locations close to the source and those not expected to receive water from storage tanks, the model-predicted drop and rise in fluoride concentrations is generally within a few hours of the actual observed changes. Camp Smith and the Army's service areas receive stored water when the booster pumps are not operating. Similarly, the eastern-most areas of the Navy system are expected to receive water from the Halawa storage tank when demands exceed water production. In these cases, the fluoride concentration would fluctuate accordingly: the stored water would still contain fluoride while the pumped water contains fluoride only at natural background concentrations. The graphs in Figure 5-6 show that the model adequately mimics the expected behavior and therefore, there are no gross demand allocation errors.

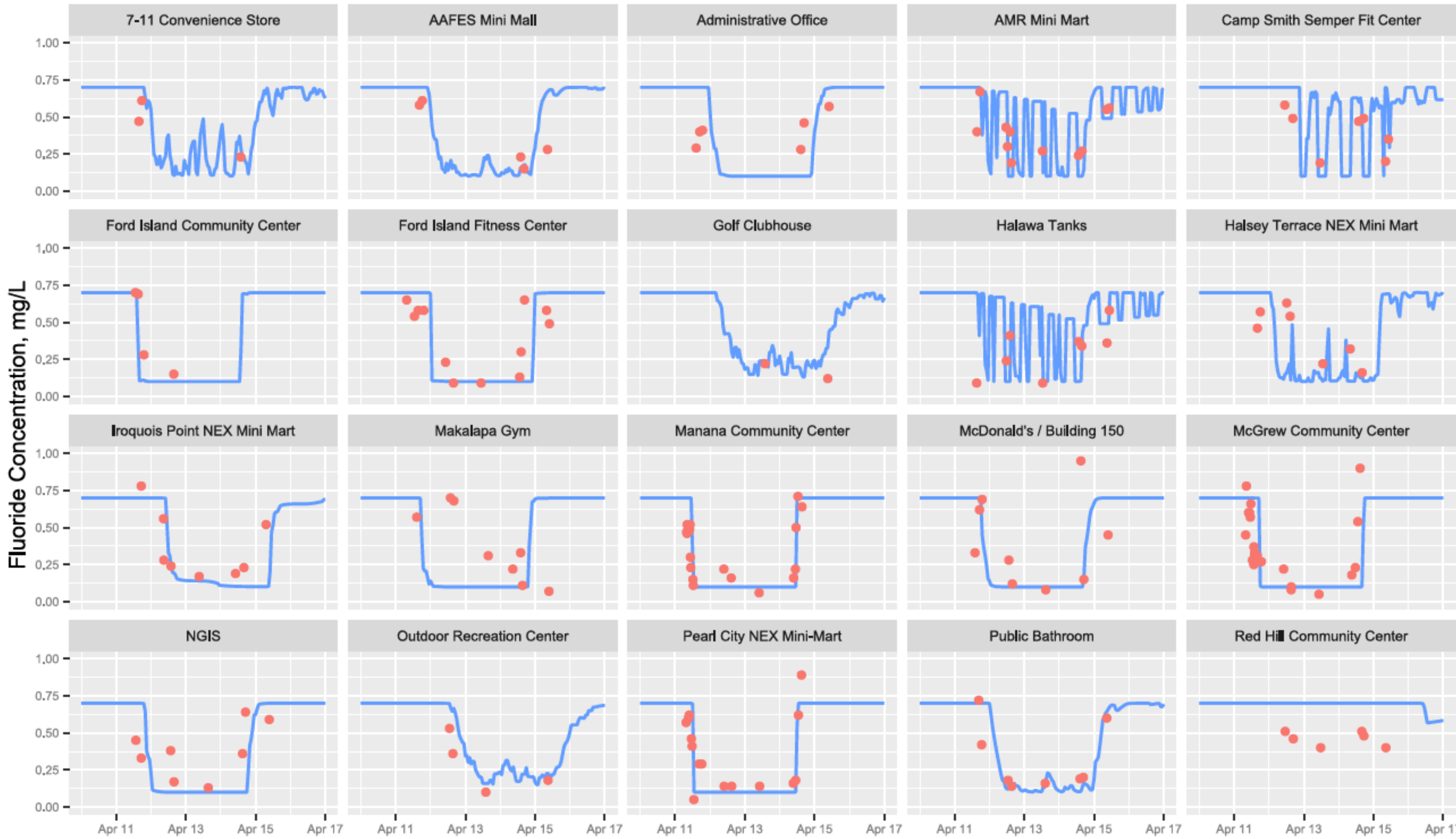

Figure 5-6 Measured and Model-Predicted Fluoride Tracer Concentrations

5.7 MODEL VERIFICATION

AH/BC performed additional simulations using the calibrated model configuration for two time periods before the Red Hill Shaft contamination event. The model was operated with demand and pump status patterns derived for each period as described in Section 5.5. The 12-day period starting on 1 June 2020 was chosen because the Red Hill Shaft was not in operation, and water production from the Waiawa source was supplemented by the Aiea-Halawa Shaft. The second 12-day verification period started on 1 September 2021 when the Waiawa and Red Hill Shafts were both in operation. Table 5-6 provides summary statistics for the model verification runs. The data indicate an overall good model fit, noting the exceptions observed for calibration. The match for pressures and flows at the Moanalua Terrace Pump Station was acceptable.

Table 5-6 Model Verification Statistics

	1 – 12 June 2020		1 – 12 Sept. 2021	
Location	**RSME**	**%RSME**	**RSME**	**%RSME**
North Tank 181 Level, ft	(b) (3) (B) [redacted]	10%	(b) (3) (B) [redacted]	10%
South Tank 182 Level, ft	[redacted]	10%	[redacted]	11%
Camp Smith Tank 325, Level, ft	[redacted]	7%	[redacted]	5%
Halawa Booster Pump Station Pressure, psi	[redacted]	7%	[redacted]	6%
Aiea-Halawa Pump Station Discharge Pressure, psi	[redacted]	6%	[redacted]	2%
Aiea-Halawa Pump Station Flow Rate, gpm	[redacted]	27%	[redacted]	N/A
Halsey Terrace Flow Rate, gpm	[redacted]	45%	[redacted]	47%
Manana Pump Station Discharge Pressure, psi	[redacted]	35%	[redacted]	19%
Manana Pump Station Suction Pressure, psi	[redacted]	10%	[redacted]	15%
Moanalua Terrace Discharge Pressure, psi	[redacted]	10%	[redacted]	11%
Moanalua Terrace Pump Station Flow Rate, gpm	[redacted]	39%	[redacted]	28%
Moanalua Terrace Suction Pressure, psi	[redacted]	10%	[redacted]	14%
Red Hill Booster Pump Flow Rate, gpm	[redacted]	398%	[redacted]	368%
Red Hill Pump Station Flow Rate, gpm	[redacted]	N/A	[redacted]	14%
Red Hill Pump Station Pressure, psi	[redacted]	4%	[redacted]	3%
Red Hill Tank 685 Level, ft	[redacted]	5%	[redacted]	5%
S1 Tank Level, ft	[redacted]	9%	[redacted]	3%
Waiawa Pump Station Discharge Pressure, psi	[redacted]	3%	[redacted]	5%
Waiawa Pump Station Flow Rate, gpm	[redacted]	9%	[redacted]	9%

Figure 5-7 provides time series graphs for the 1 – 12 June 2020 verification period. Graphs for the 1 – 12 September 2021 model simulation are shown in Figure 5-8. The figures indicate an overall excellent match between model-predicted and SCADA-recorded patterns of pressure, flows, and tank levels.

(b) (3) (B)

[redacted]

Figure 5-7 Model Verification versus SCADA Data (June 2020)

(b) (3) (B)

[redacted]

Figure 5-8 Model Verification versus SCADA Data (September 2021)

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6. DISTRIBUTION SYSTEM HYDRAULIC EVALUATION

This section provides the results of hydraulic evaluations performed with the model developed under this task order. AH/BC performed 18 model simulations, listed in Table 6-1, to identify performance issues under ADD, MDD, and PHD conditions, with and without fire flow (FF). Simulations included both steady-state (SS) and EPS analyses.

Table 6-1 Overview of Model Scenarios

No.	Demand	Purpose of Evaluation	Type	System Configuration
1	ADD	Performance under normal operation	SS	Design configuration (three water sources available, all tanks and mains in service)
2	MDD	Production and pumping requirements		
3	PHD			
4	PHD+FF	Sizing of mains		
5	MDD+FF			
6	ADD	Water age, travel time analysis	EPS	
7	ADD	Performance under normal operation	SS	Current configuration (April 2022, Waiawa Shaft online, S2 Tank out of service, Iroquois Point – Shipyard and Ford Island – Shipyard mains closed)
8	MDD	Production and pumping requirements		
9	PHD			
10	PHD+FF	Sizing of mains		
11	MDD+FF			
12	ADD	Water age, travel time analysis	EPS	
13	MDD	Assess sustainability of supply		
14	ADD	Sustainability of supply	EPS	Emergency configuration 1 – design configuration but with Waiawa Shaft offline, supply from Aiea-Halawa & Red Hill Shafts only
15	MDD			
16	ADD	Sustainability of supply	EPS	Emergency configuration 2 – design configuration but with S1/S2 tanks offline.
17	MDD			
18	ADD	Delineate Aiea-Halawa Shaft service area (source tracing)	EPS	Current configuration, plus Aiea-Halawa Shaft online

6.1 DESIGN CONFIGURATION

This section presents the results of the six model analyses representing the water system as designed. That is, both Halawa tanks are in operation, and the mains connecting Iroquois Point and Hickam AFB as well as Ford Island and the shipyard are active. All three water sources are available. SS analyses were performed with two Waiawa Shaft pumps, one Aiea-Halawa pump, and one Red Hill pump. FF evaluations were conducted with the Waiawa and Aiea-Halawa sources only, representing a conservative scenario. For the water age simulations, AH/BC evaluated three common variations of utilizing the water sources (Waiawa and Aiea-Halawa, Waiawa and Red Hill, or all three).

6.1.1 Water Pressure

Color-coded maps at ADD (Figure 6-1), MDD (Figure 6-2), and PHD (Figure 6-3) show that the system in its design configuration can sustain adequate pressures above [redacted] psi throughout most of the base. Waterfront pressures are above [redacted] psi at ADD. Pressures can reach more than [redacted] psi (and up to [redacted] psi) in areas supplied by booster pumps and not controlled by PRVs including sections of Moanalua Terrace, Camp Smith, and AMR.

While the pressures remained above the minimum required 20 psi[5] at all model nodes under the three demand scenarios, there are areas at higher elevation where pressures are below [redacted] psi[6]. These include Halawa Housing, areas in Eastern Housing along Salt Lake Boulevard, Makalapa Housing, and elevated areas in the Aliamanu Crater supplied directly by the Halawa tanks. At PHD, pressures also drop below [redacted] psi in Manana Housing. However, when the second pump is activated at Manana, pressures remain above [redacted] psi (not shown).

[5] Most plumbing codes require a 20-psi minimum pressure for bathroom fixtures.
[6] Minimum pressures of over [redacted] psi may be required for flushometer valves. Systems with pressures below [redacted] psi may not be able to supply sprinkler systems without booster pumping.

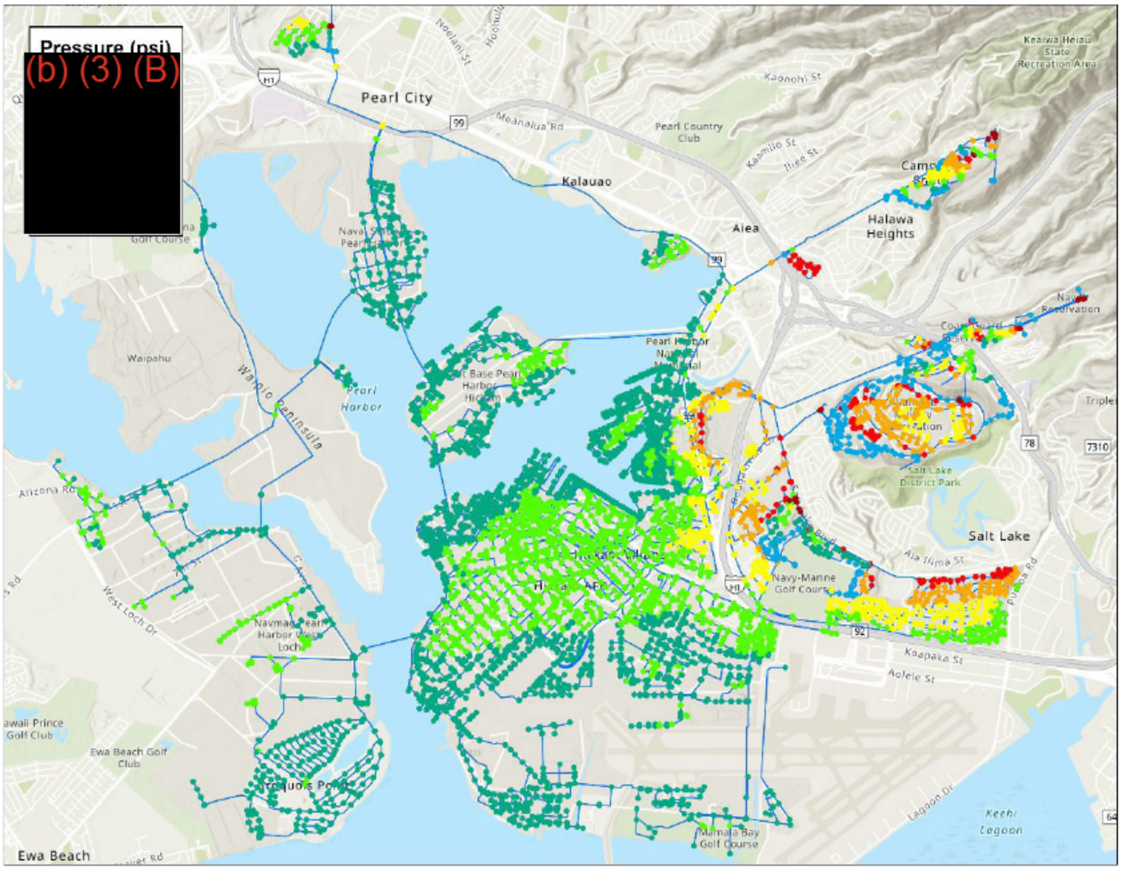


Figure 6-1 Pressures at ADD (Design Configuration)

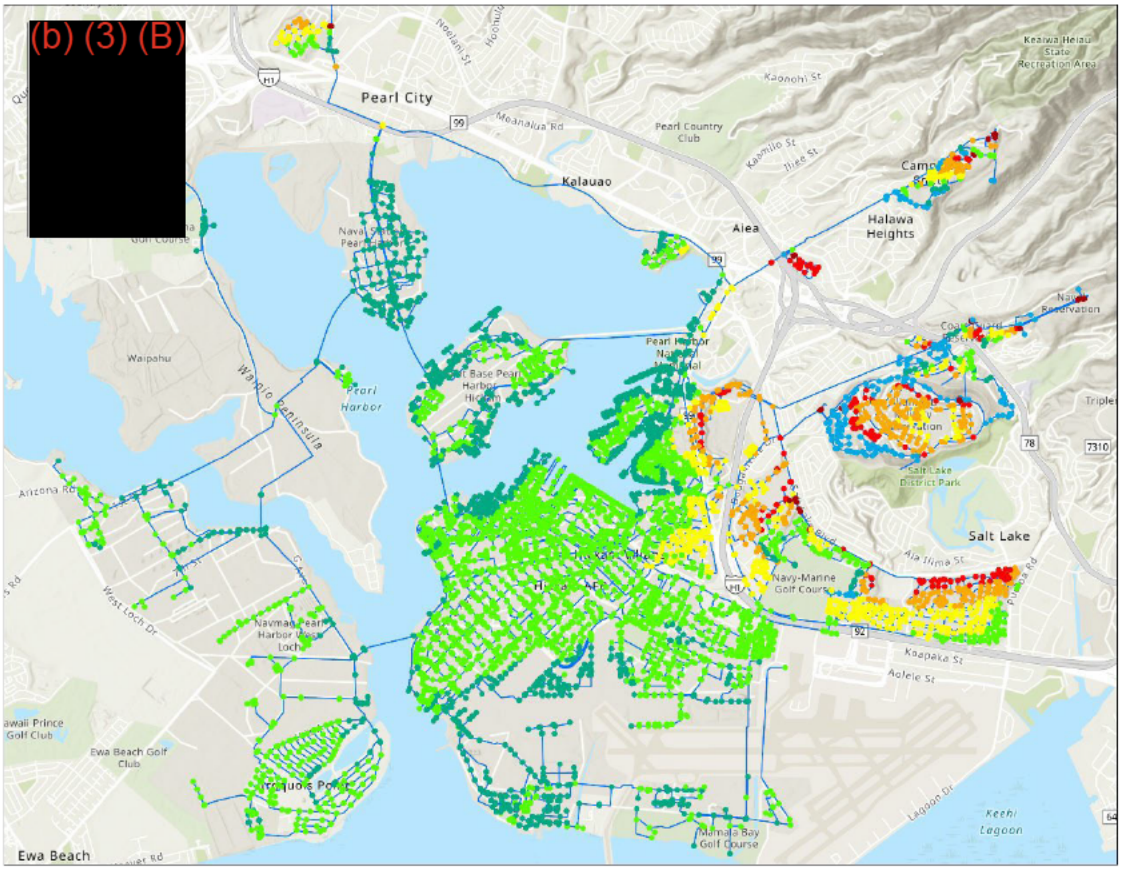


Figure 6-2 Pressures at MDD (Design Configuration)

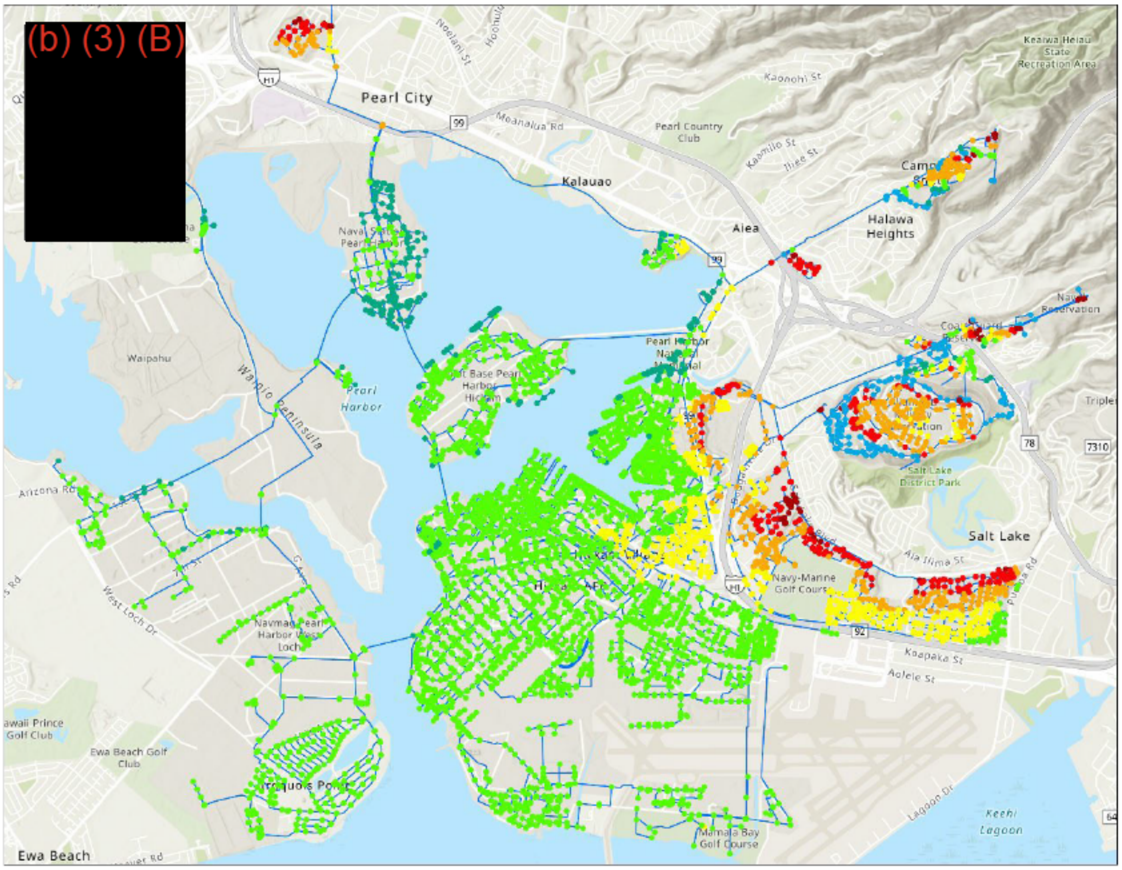


Figure 6-3 Pressures at PHD (Design Configuration)

6.1.2 Available Fire Flows

Color-coded maps at PHD (Figure 6-4) and MDD (Figure 6-5) show that the system in its design configuration can provide FF above [redacted] gpm throughout most of the base under high water demand conditions. FF below [redacted] gpm, a typical minimum for single-family residential structures, may be encountered at Manana Housing, the lower elevation areas of Red Hill Housing, and at Moanalua Terrace (at PHD only). None of the FF limitations appear to be due to undersized water pipes. FF limitations at Red Hill Housing may be an artifact of modeling the PRVs as GPVs; however, the Army is aware of actual issues due to the GAC adsorbers at the interconnection to the Navy system.

FFs at Moanalua Terrace greatly improve at PHD with the second pump online (not shown). Operating a second pump at Manana Housing has only a small effect on FF.

However, there is a dedicated diesel-driven fire pump at the pump station that was not included in the hydraulic model, which would likely provide sufficient capacity.

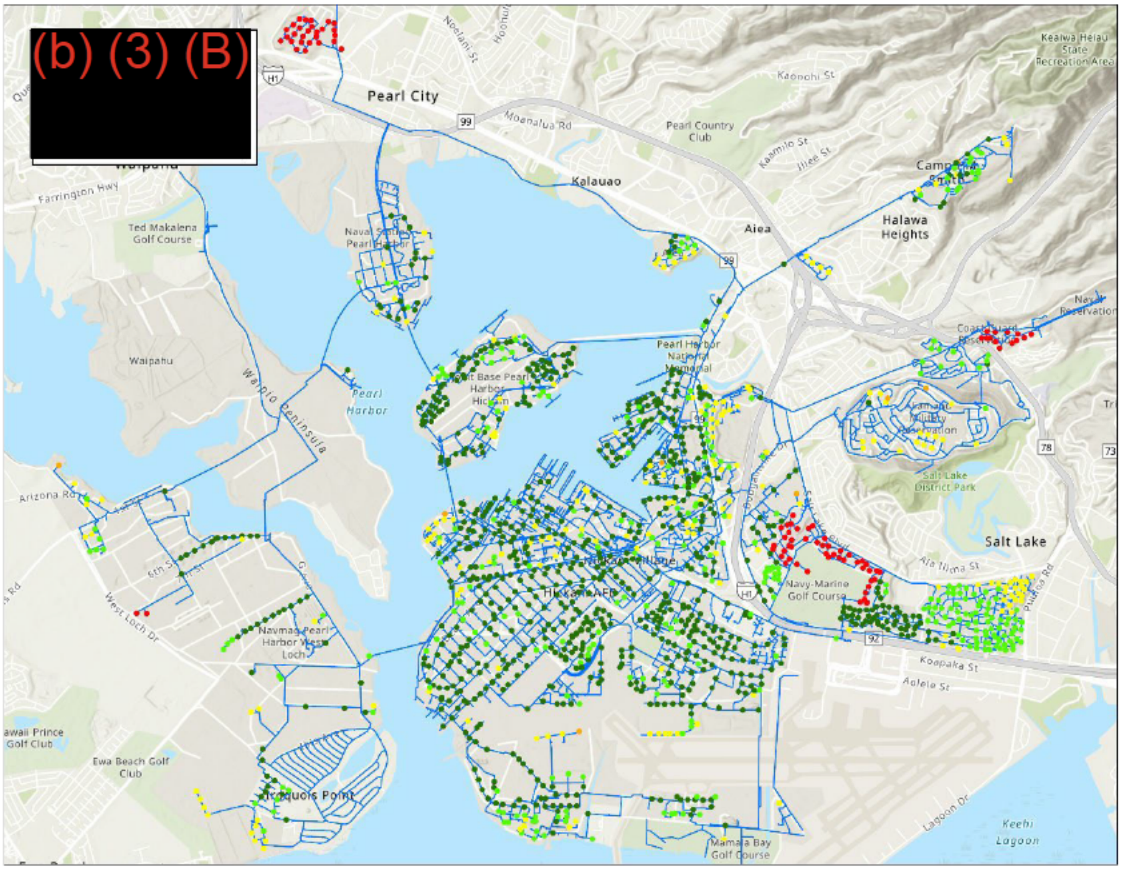


Figure 6-4 Available FF Rates at PHD (Design Configuration)

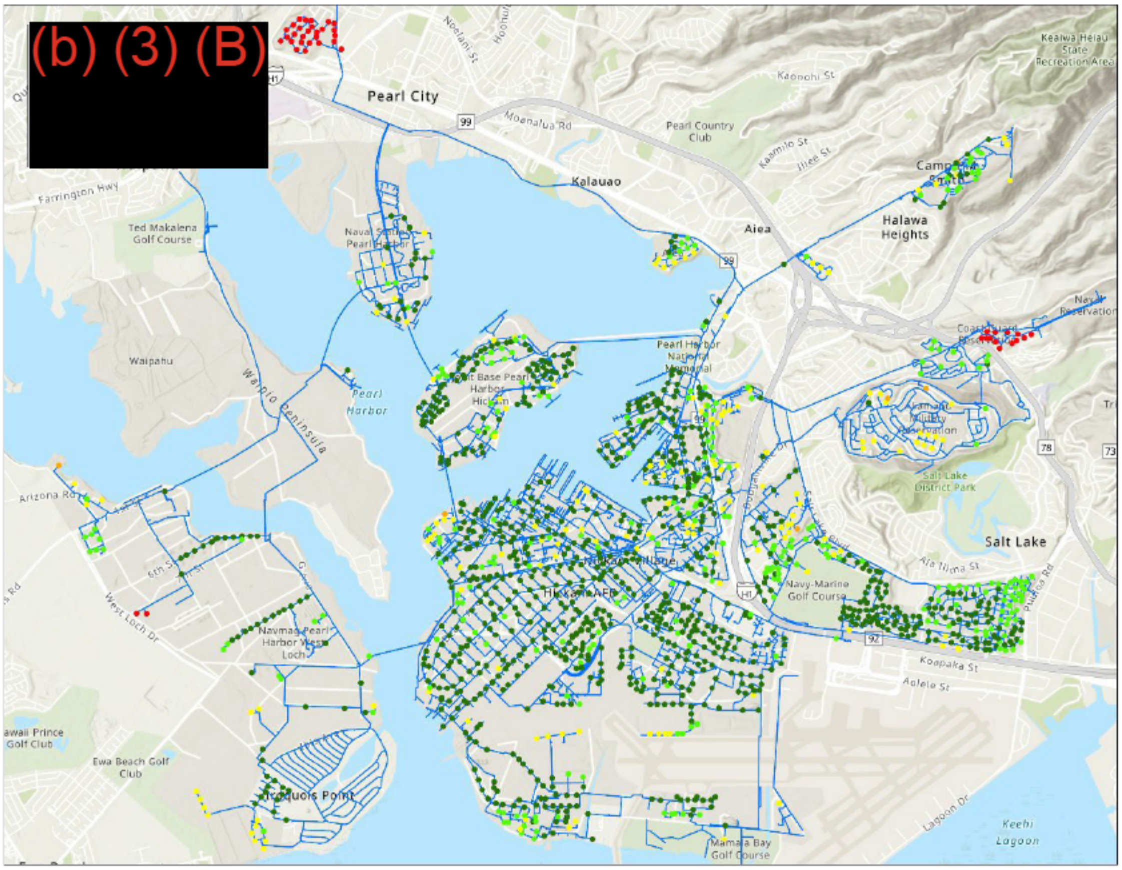


Figure 6-5 Available FF Rates at MDD (Design Configuration)

6.1.3 Water Age

The average water age in the distribution system on the last day of a 720-hour simulation is depicted in the color-coded maps in Figure 6-6 (three sources online), Figure 6-7 (Waiawa and Aiea-Halawa Shafts operating), and Figure 6-8 (Waiawa and Red Hill Shaft online). Most of the westerly parts of the base receive water from the highest producing source, Waiawa, and therefore, have the lowest water age, usually below 2 days. Water of moderate age may be encountered in southerly parts of Hickam AFB and in the Eastern Housing area.

The oldest water is found in areas that are supplied wholly or in part by water storage tanks, including Camp Smith and the Army water system. When the Red Hill Shaft is operating, water older than 14 days may also be encountered in the Eastern Housing area. This is due to peak demands not being attenuated by the Halawa S1/S2 tanks as much as when only Waiawa and Aiea-Halawa Shafts are online.

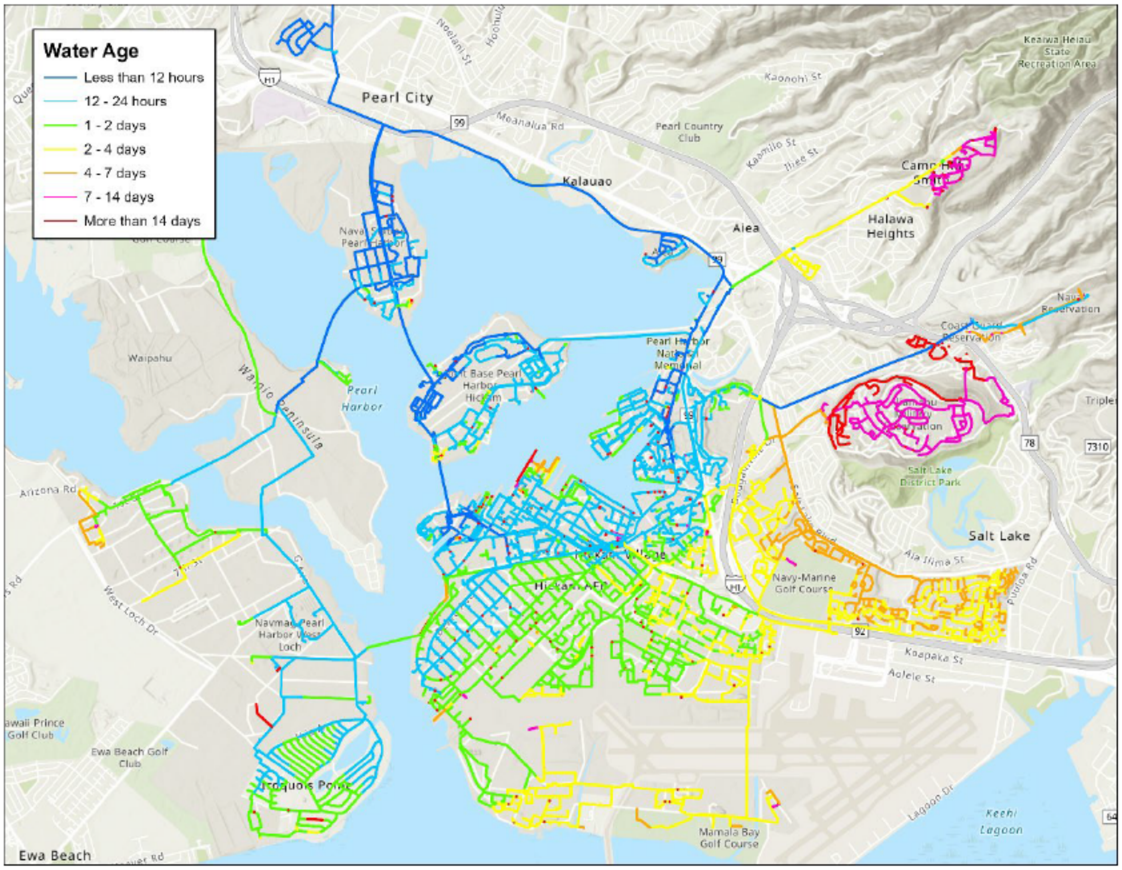


Figure 6-6 Water Age at ADD (Design Configuration, Three Sources)

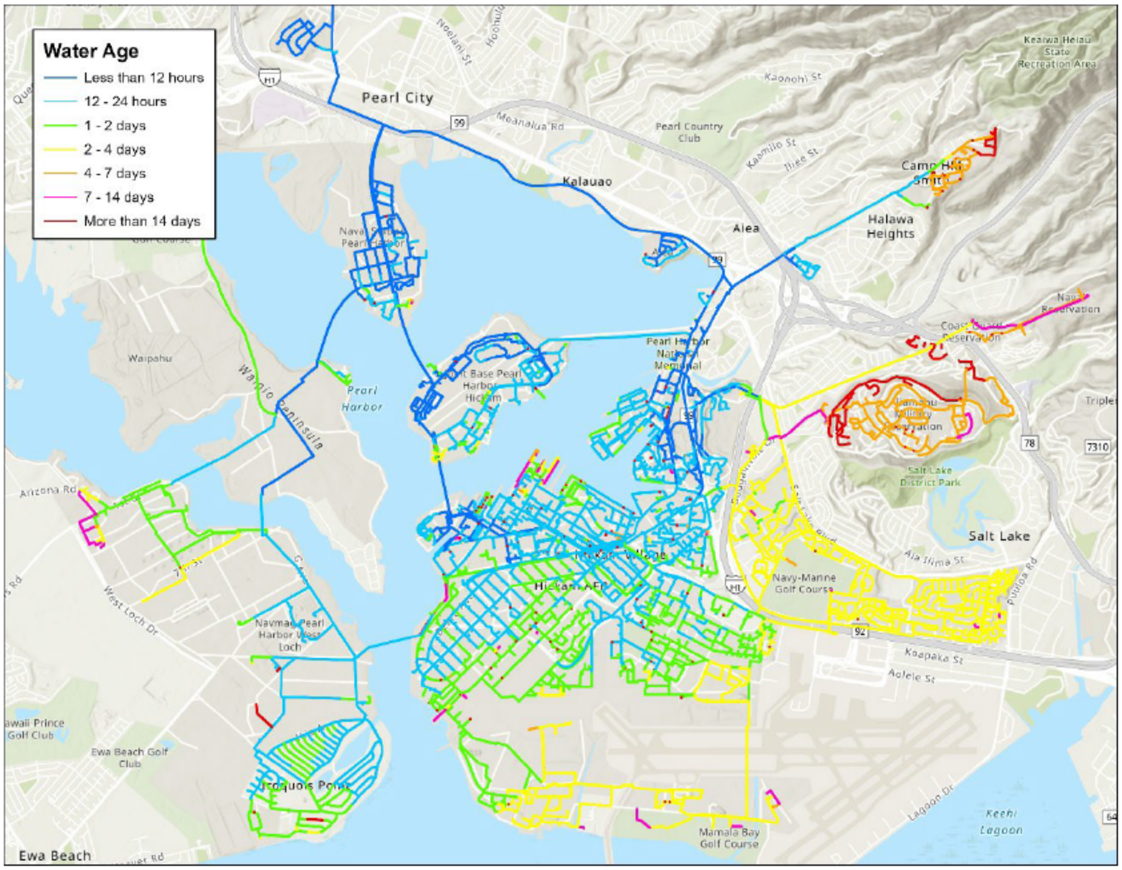


Figure 6-7 Water Age at ADD (Design Configuration, Waiawa & Aiea-Halawa)

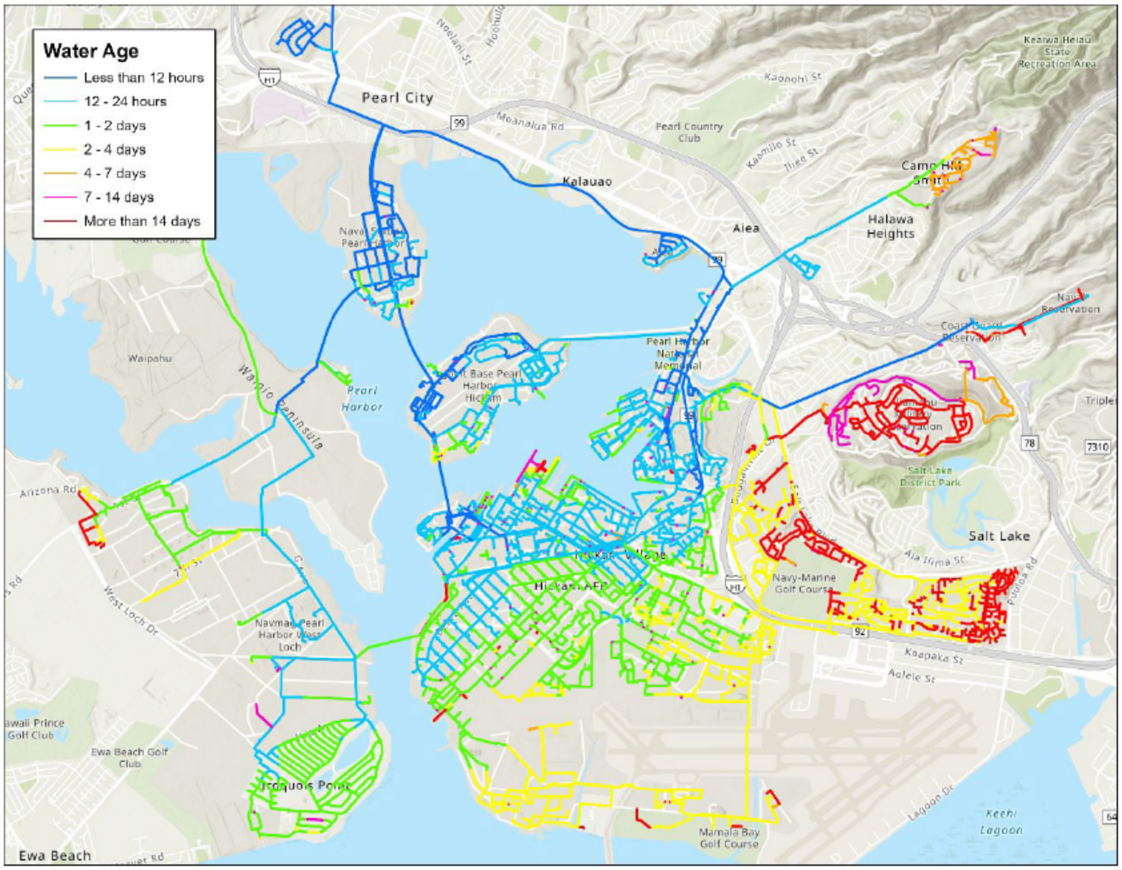


Figure 6-8 Water Age at ADD (Design Configuration, Waiawa & Red Hill)

6.2 CURRENT CONFIGURATION

AH/BC conducted seven model analyses for the water system as it has been operating in 2022: the Waiawa Shaft is the sole water source, and Halawa Tank S2 is offline. Additionally, the underwater crossings between Iroquois Point and Hickam AFB and between Ford Island and the shipyard are valved off. At steady state, [redacted] (b) (3) (B) are operating at the Waiawa Shaft. For the EPS, the Waiawa Pumps were activated based on the water levels in Halawa Tank S1 (Section 5.3).

6.2.1 Water Pressure

AH/BC created color-coded pressure maps under ADD (Figure 6-9), MDD (Figure 6-10), and PHD (Figure 6-11). As in the design configuration, pressures ranged from [redacted] psi up to the low [redacted] with additional higher pressures observed at the high-pressure pump stations. At ADD and MDD, the main differences compared to the design configuration are slightly lower pressures ([redacted] psi) in the low-lying areas along the water front and in Hickam. At PHD, Iroquois Point and the central areas of JBPHH experience lower pressures, in the range of [redacted] psi, compared to the design configuration. In addition, Halawa Housing, with pressures generally below [redacted] psi in the design configuration, incurs a pressure decrease below [redacted] psi under current conditions (as was observed during the field work in April 2022).

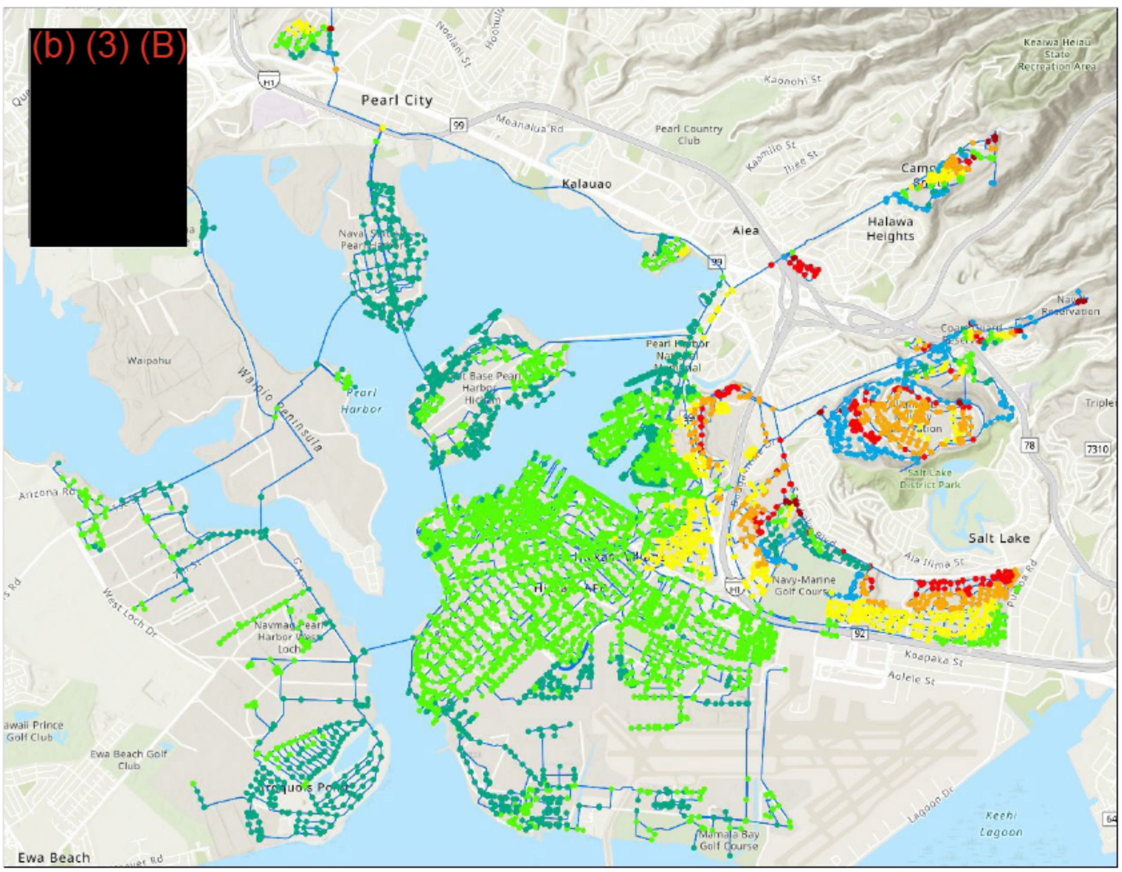


Figure 6-9 Pressures at ADD (Current Configuration)

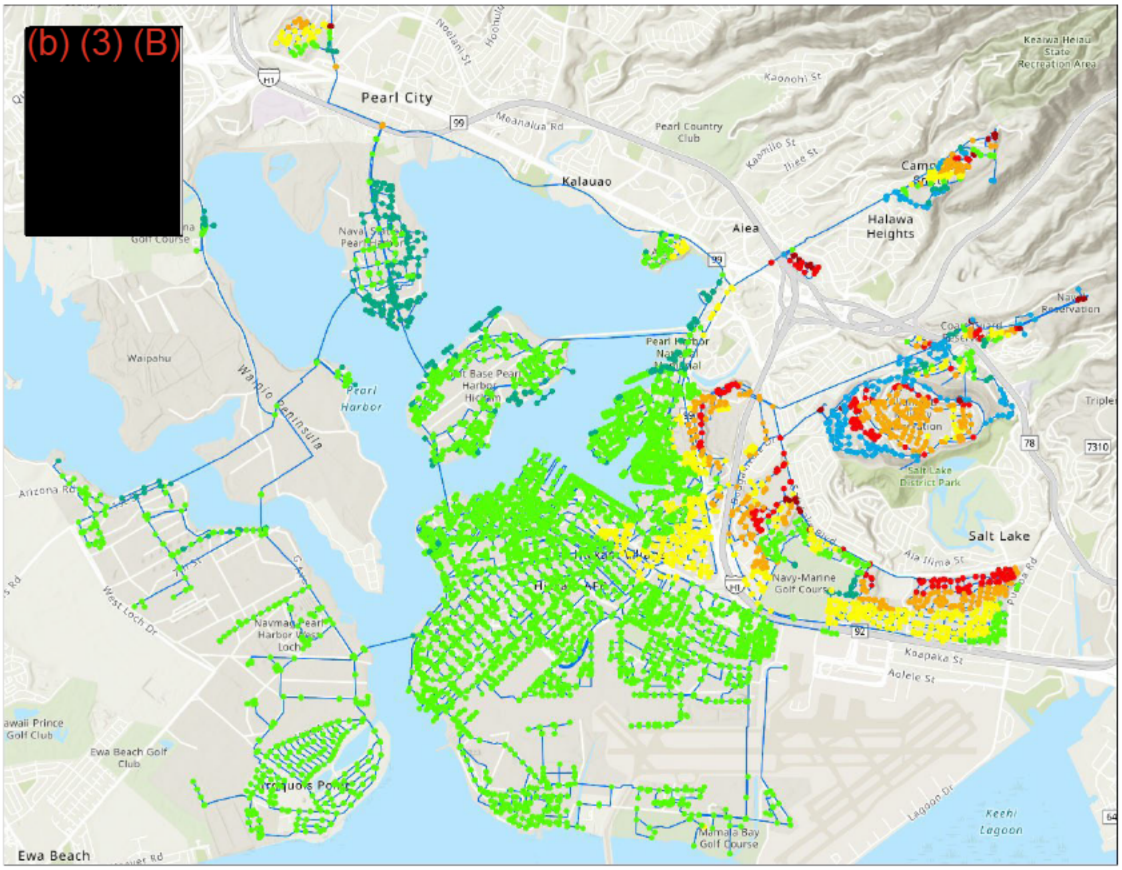


Figure 6-10 Pressures at MDD (Current Configuration)

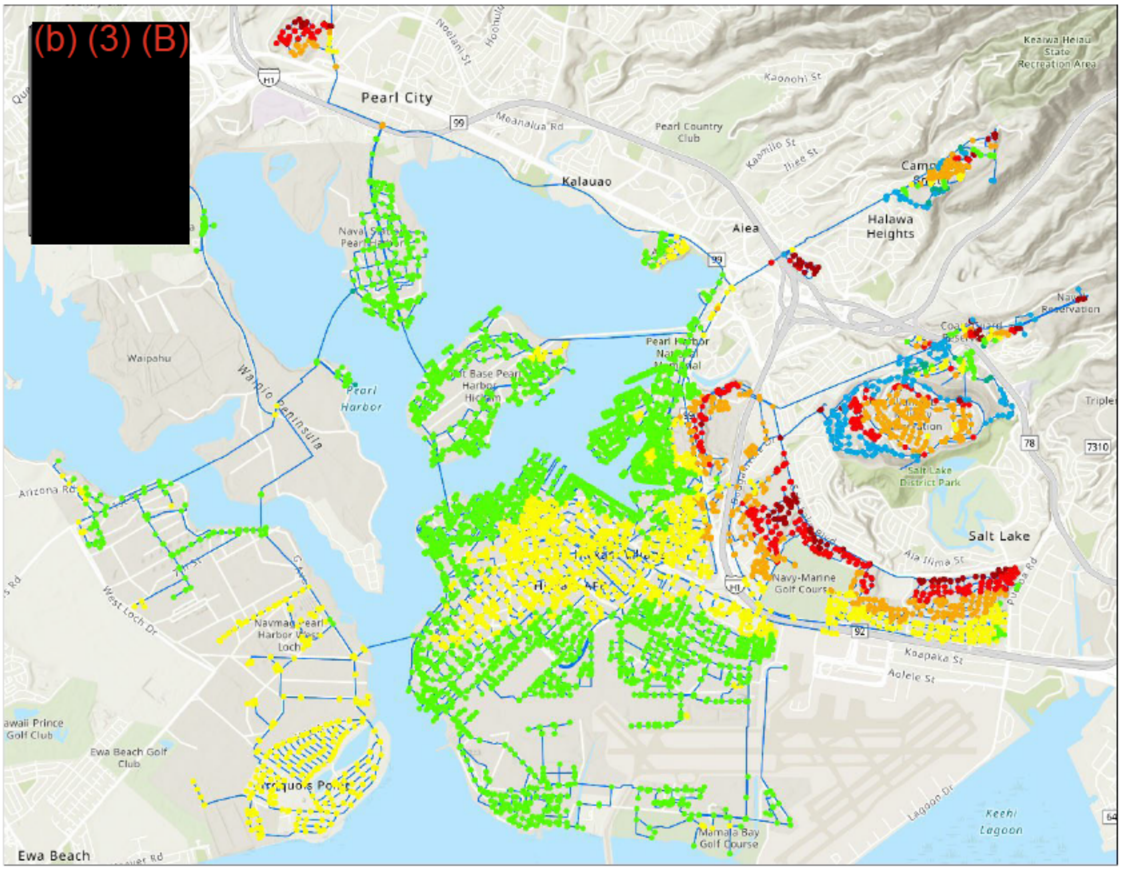


Figure 6-11 Pressures at PHD (Current Configuration)

6.2.2 Available Fire Flows

Color-coded maps at PHD (Figure 6-12), and MDD (Figure 6-13) show that the system in the current configuration can still provide FF above [redacted] gpm throughout most of the base under high water demand conditions. As in the design configuration, FF below [redacted] gpm may be encountered at Manana Housing, the lower elevation areas of Red Hill Housing, and at Moanalua Terrace (at PHD only). FFs at Moanalua Terrace greatly improve at PHD with the second pump online (not shown).

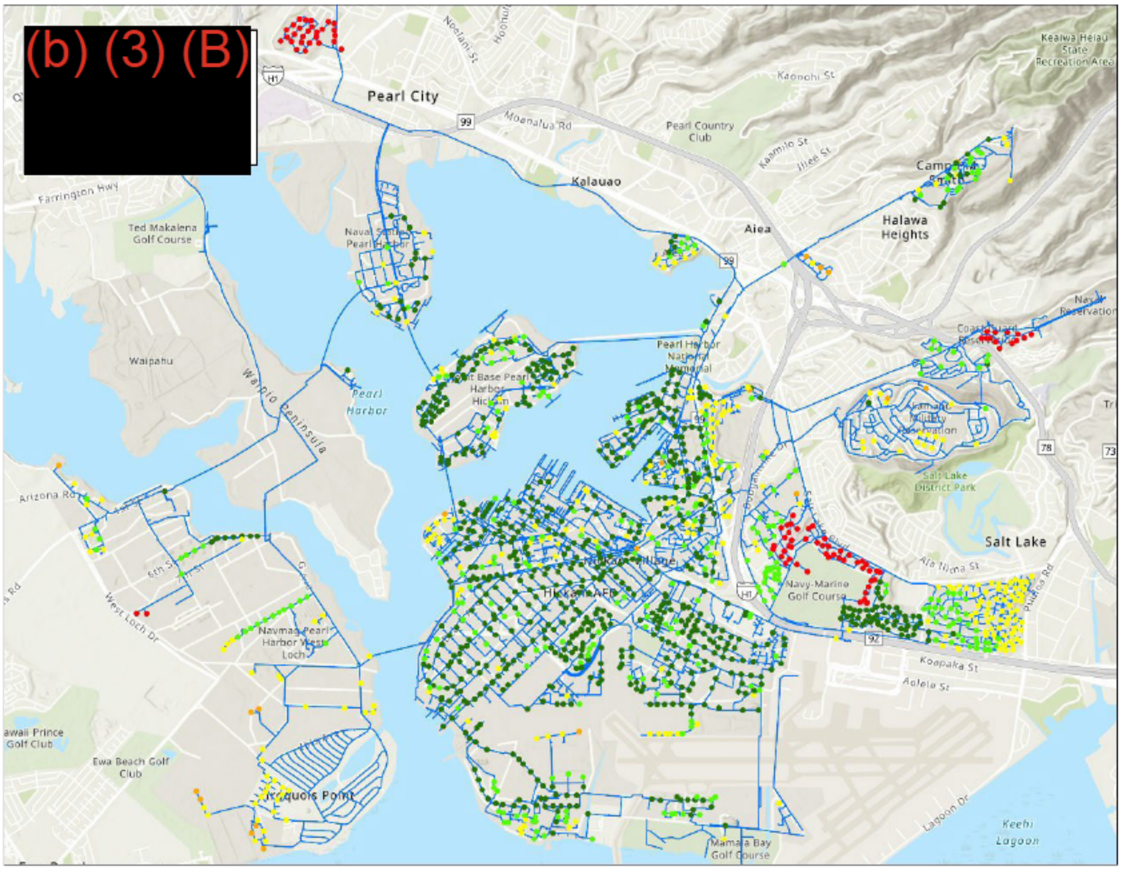


Figure 6-12 Available FF Rates at PHD (Current Configuration)

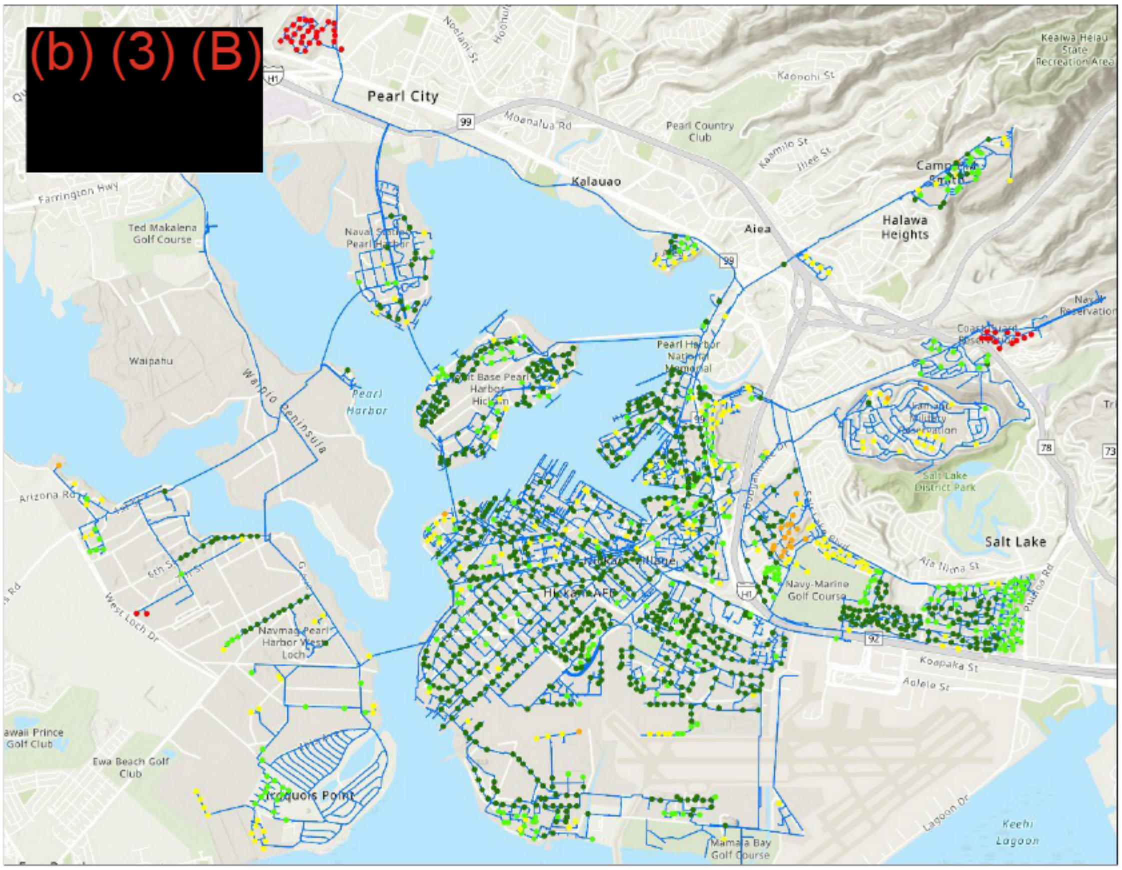


Figure 6-13 Available FF Rates at MDD (Current Configuration)

6.2.3 Water Age

Figure 6-14 provides a color-coded map depicting the average water age in the current distribution system at ADD on the last day of a 720-hour simulation. Compared to the design configuration, there remain only a few areas in the system with water age above 4 days. With the Waiawa Shaft operating by itself, peak water demands must be satisfied by stored water, resulting in less stagnation within reservoirs and lower water age system-wide.

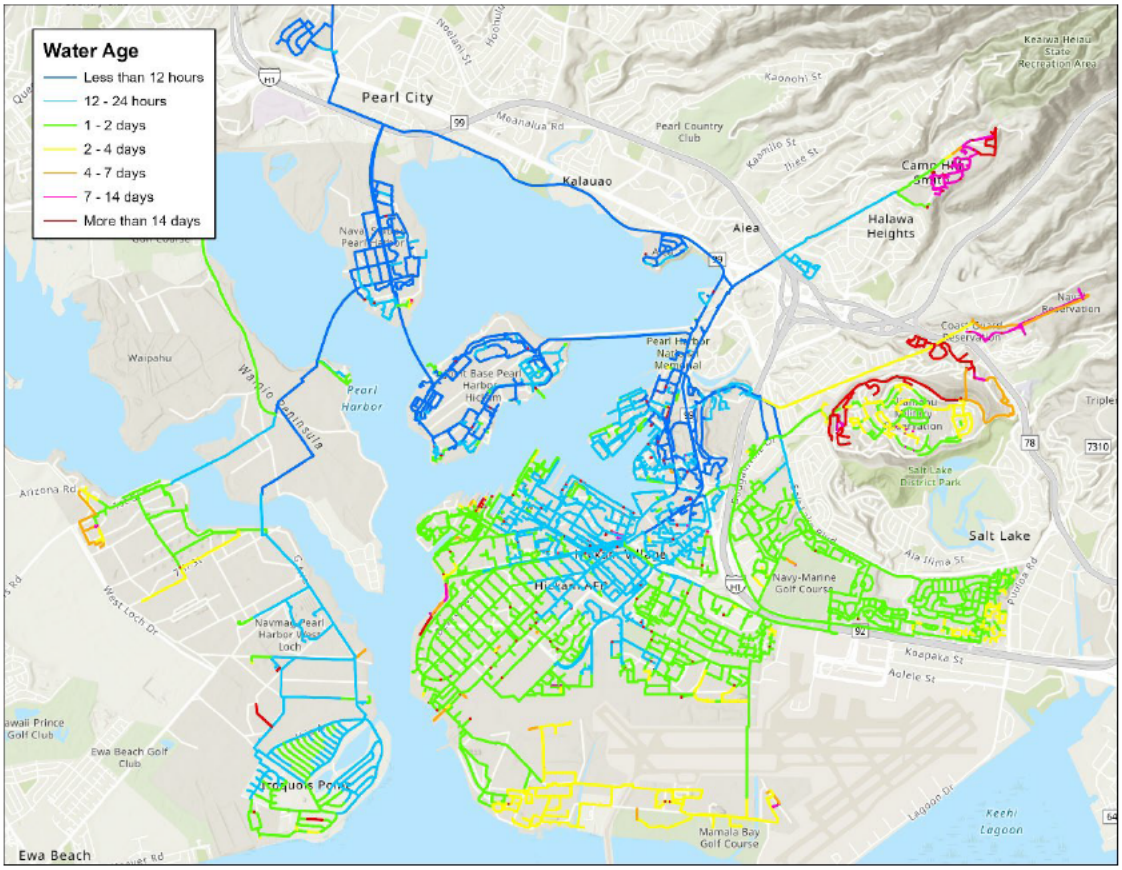


Figure 6-14 Water Age at ADD (Current Configuration)

6.2.4 Water Supply Sustainability

Unlike the SS simulations performed for pressure and FF analyses, an EPS can predict how long if a water system's production or storage capacities are sufficient. Based on Waiawa Shaft's production capacity of approximately (b) (3) (B) [redacted], it was anticipated that the JPBHH system cannot sustain the MDD of (b) (3) (B) [redacted]. We performed a 168-hour EPS at MDD (b) (3) (B) [redacted] Therefore, curtailment of irrigation and other non-essential demands will be necessary during periods of high domestic water use.

6.3 EMERGENCY CONFIGURATION 1

This section presents the results of one of two model configurations to study the sustainability of the water supply under emergency conditions. For each emergency configuration, AH/BC performed a 168-hour EPS both at ADD and MDD and evaluated the evolution of tank levels and pressures in the system. The present scenario assumed an extended shutdown of the Waiawa Shaft. The remainder of the system was operated as designed with the Red Hill and Aiea-Halawa Shafts each operating with one pump controlled by the Halawa S2 tank level (Section 5.3). Because the nominal capacity of the two remaining water sources is less than the ADD, it was anticipated that the model would predict the system to eventually drain.

It is noted that WaterGEMS (and EPANet), as typically utilized, will continue the model simulation even if network nodes experience significant negative water pressures. Because of the physical impossibility of large, sustained negative gauge pressures and the reality that water demands are dependent upon supply pressures[7], the model runs were terminated when any node pressure decreased below zero, which typically happened soon after the Halawa S1/S2 tanks were empty. Figure 6-15 shows that the level of the Halawa S2 Tank reaches zero after approximately (b) (3) (B) [redacted] at ADD. The model predicted that booster pump-supplied areas at Camp Smith and the Army housing areas would continue to receive water until that point. At MDD, the Halawa S1/S2 tanks (b) (3) (B) [redacted] Figure 6-16).

[7] Newer model software versions allow performing model calculations using pressure-dependent node demands. This relatively new software feature would decrease nodal demands in accordance with predefined functions. However, due to the complexity of the JPBHH water system and the wide range of pressures in various zones, as well as additional computational challenges, WaterGEMS was not capable of hydraulically balancing the system.

[redacted]

Figure 6-15 Tank Levels with Waiawa Shaft Offline at ADD

[redacted]

Figure 6-16 Tank Levels with Waiawa Shaft Offline at MDD

6.4 EMERGENCY CONFIGURATION 2

In this configuration, the system was operated as designed, with two out of three water sources in service (Waiawa plus Aiea-Halawa or Red Hill), but without the two [redacted] tanks Halawa S1 and S2. The source water pumps in the model were originally setup to be triggered by the S1 tank; for the scenarios with the tank out of service, they were configured to run continuously. Alternatively, they could operate based on pressures at a node adjacent to the tanks. However, this approach was not further explored because initial test runs yielded significant negative pressures and frequent pump cycles.

The model predicted that the water system could be operated this way at ADD, but would produce extremely large pressure swings, regardless of whether the Aiea-Halawa Shaft (Figure 6-17) or the Red Hill Shaft (Figure 6-18) supplemented the primary water source. This is not likely sustainable because of the high risk of damage to the water system. [redacted]

At MDD, the model showed negative pressures when water was supplied by Waiawa and Aiea-Halawa. With the Red Hill Shaft, pressure swings at MDD were even larger than at ADD (Figure 6-19).

[redacted]

Figure 6-17 Pressures without Halawa Tanks (Waiawa & Aiea-Halawa Shafts Online) at ADD

[redacted] (b) (3) (B)

Figure 6-18 Pressures without Halawa Tanks (Waiawa & Red Hill Shafts Online) at ADD

[redacted] (b) (3) (B)

Figure 6-19 Pressures without Halawa Tanks (Waiawa & Red Hill Shafts Online) at MDD

6.5 AIEA-HALAWA SOURCE TRACE

Due to the jet fuel spill, there are concerns that contaminated water may migrate from Red Hill to the Aiea-Halawa Shaft. To determine which areas in the distribution system would be supplied by the Aiea-Halawa Shaft if it were operating, AH/BC performed a 720-hour EPS with source tracing in WaterGEMS. The system was configured as it is currently operated (with the Halawa S2 tank out of service) plus one pump at the Aiea-Halawa Shaft, triggered by tank levels as described previously.

The color-coded map in Figure 6-20 depicts the percentage of water supplied from the Aiea-Halawa Shaft in this scenario. The Pearl City Peninsula, Ford Island, most of the Navy base, Waipio, West Loch, and Iroquois Point receive nearly exclusively Waiawa water. Aiea-Halawa Shaft water may contribute up to 25% of water supplied to Hickam AFB. Eastern Housing and the Army's consecutive system may receive up to 50% water from the Aiea-Halawa Shaft. Due to the proximity to the source, Halawa Housing and Camp Smith receive mostly Aiea-Halawa Shaft water.

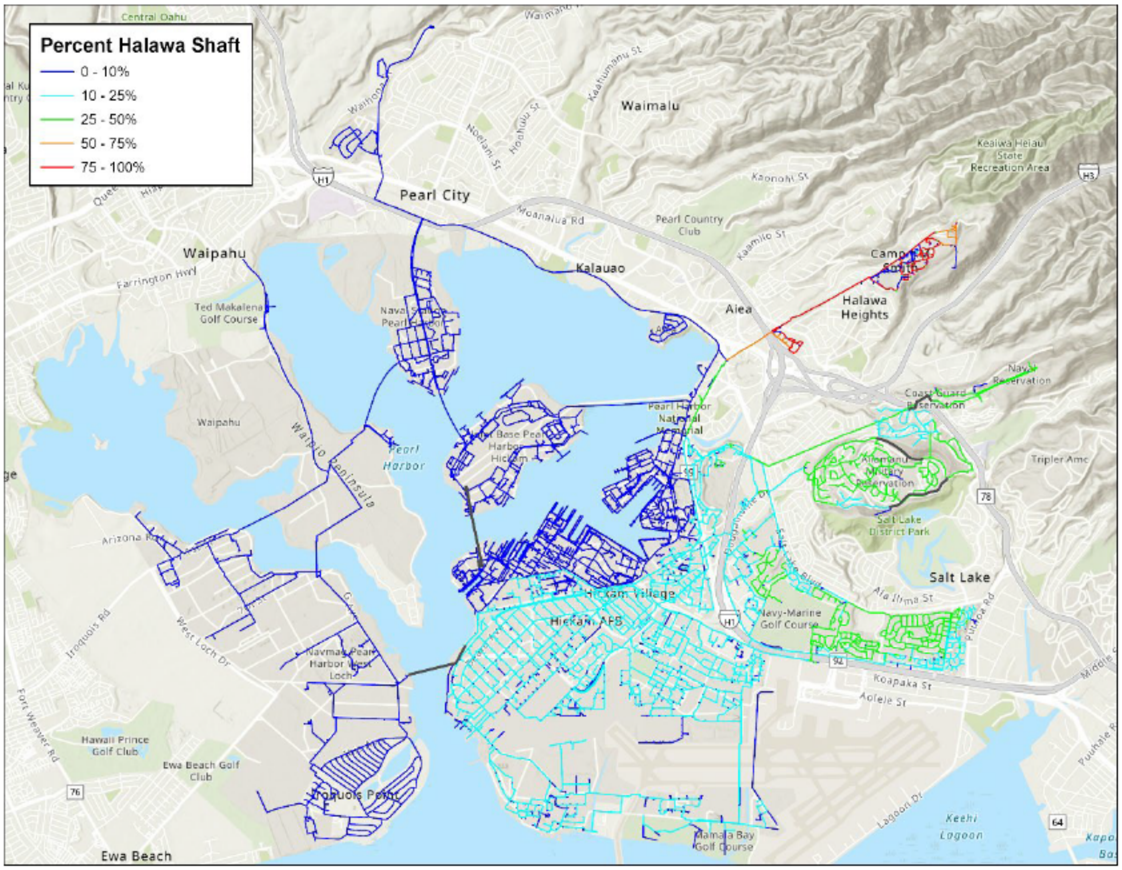


Figure 6-20 Aiea-Halawa Shaft Source Trace

7. SUMMARY AND RECOMMENDATIONS

This section summarizes the findings and recommendations from the modeling study.

7.1 SUMMARY OF FINDINGS

The JBPHH water system can adequately serve average day, maximum day, and peak hourly demands, when operated as designed, with all tanks and transmission mains in service, and typically supplying water from at least two sources (Waiawa plus Aiea-Halawa or Red Hill). The system can provide FF above [redacted] gpm throughout most of the base under high water demand conditions. FF below [redacted] gpm may be encountered at Manana Housing (without use of the fire pumps), the lower elevation areas of Red Hill Housing, and, under some circumstances, at Moanalua Terrace.

EPS data showed that the water age throughout most of the installation is four days or less. Water age up to 14 days may occur in AMR and Camp Smith, both of which, due to the distance from the water sources and high elevations, are served by their own water tanks. Additionally, water age above four days may occur in the Eastern Housing area when the Red Hill Shaft operates to supplement the Waiawa Shaft.

Currently, the JBPHH water system operates only with the Waiawa Shaft. Additionally, the Halawa Tank S2 has been offline since December 2021 and transmission mains connecting Hickam AFB and Iroquois Point and between Ford Island and the shipyard are valved off. The model predicted that, compared to the design configuration, pressures throughout the system are generally lower for all existing demands, but remained above 20 psi. The impacts on available FF were minimal. While the system can hydraulically satisfy instantaneous demands at MDD or PHD, the existing production and storage capacities cannot sustain such high flow requirements for more than a [redacted]. SCADA data from April 2022 support this finding.

AH/BC also modeled potential emergency scenarios, including the loss of both Halawa Tanks (S1 and S2) or the sole reliance on the Red Hill and Aiea-Halawa Shafts, in case the Waiawa Shaft is out of service. Operation of the system without the Waiawa Shaft results in draining the S1/S2 tanks [redacted] at ADD or [redacted] at MDD. Without the S1/S2 tanks, it was observed that the system could continue to operate, albeit with extremely large, potentially damaging, pressure fluctuations.

7.2 RECOMMENDATIONS

The obvious shortcomings in the existing system are due to the shutdown of two of the three water sources, aggravated by one of the two large storage reservoirs being out of service. Other than bringing the Aiea-Halawa Shaft back online to supplement peak demands, JBPHH may want to investigate means of conserving water. Aside from curtailing various outdoor uses, there may be opportunities to minimize unintended water loss.

AH/BC recommends that JBPHH perform a comprehensive water use study and a leak detection survey to identify excessive water losses. Additionally, such studies can provide refined data for allocating water demands in the hydraulic model.

APPENDIX A

Statement of Work

(8 PAGES)

NAVAL FACILITIES ENGINEERING SYSTEMS COMMAND PACIFIC (NAVFAC PAC)

STATEMENT OF WORK

DATE: 26 April 2022

A/E CONTRACT NO.: N62470-19-D-4001

STATEMENT OF WORK NO.: Modification No. 1

MODIFICATION NO. 1
The execution of this task order modification removes the remaining Task 3 – Flushing and Incident Response Support, which were not utilized in emergency response activities, and adds Task 5 – Training.

I. PROJECT IDENTIFICATION

Project Title: Hydraulic Water Modeling

Project Location: Joint Base Pearl Harbor Hickam (JBPPH), Hawaii

II. REFERENCES:

The Contractor selected for this contract is expected to have a great wealth of industry knowledge and common practices. In addition, the following should be referenced for this project:

a. Hawaii Administrative Rules (HAR), Title 11, Chapter 20, Public Water Systems
b. Unified Facilities Criteria, UFC 3-230-01, Water Storage and Distribution, 1 September 2018.
c. Unified Facilities Criteria, UFC 3-230-02, Operation and Maintenance: Water Supply Systems, 10 December 2019.
d. Utility System Assessment (USA) of the Joint Base Pearl Harbor-Hickam Potable Water System, May 2015

III. BACKGROUND/OBJECTIVE:

The JBPPH drinking water system serves approximately 70,000 people, including a consecutive water system operated by the Army. The water sources for the system are three groundwater sources, which are disinfected and fluoridated before distribution to Navy customers.

One of the groundwater sources, Red Hill Shaft, was contaminated with jet fuel in November 2021, and the contaminated water entered the distribution system. Red Hill Shaft and Halawa

Shaft discontinued production shortly after this discovery. Residents in affected areas of the distribution system have been displaced, and the ultimate goal is to be able to declare the drinking water safe and return families to their homes. Efforts are currently underway to flush the distribution system utilizing the main Waiawa Shaft source, which supplies the majority of the water system and is not contaminated.

~~The objective of this project is to support flushing and other urgent incident response activities related to the contamination of the JBPPH drinking water system through hydraulic model simulations, data analysis and the creation of visual presentations.~~ The ~~secondary~~ objective of this project is to develop a hydraulic model of the current JBPPH drinking water system for capacity and emergency response planning purposes.

The deliverables will be ~~hydraulic model output data, graphics and analysis summaries to support the incident responses team on-base, including progress of flushing the distribution system, as well as,~~ a new hydraulic model provided in digital format and summary report.

IV. SPECIAL INSTRUCTIONS

A. The fee proposal shall be submitted with a separate breakdown of costs by work efforts and by personnel in order to facilitate the review of the proposal.

B. The A/E shall record minutes of all meetings and phone conversations and shall forward a copy of the minutes to the Engineer-in-Charge (EIC) within seven calendar days.

C. The A/E shall forward submissions directly to those concerned as specified in Section VIII. Reports shall be submitted by first class mail. Meeting minutes and the Work Plan shall be submitted electronically.

D. The A/E shall coordinate all field evaluations and inspections with activity personnel and obtain all necessary clearances from the appropriate activity personnel to enter and perform all required fieldwork. The A/E shall inform the EIC and the installation Point of Contact (POC) of the field work schedule.

E. All field work shall be coordinated through the installation POC.

F. All text shall use Microsoft Word. Provide all spreadsheets using Microsoft Excel and drawings using Adobe pdf. GIS data acquired during the field evaluation shall be submitted for incorporation into the installation GIS mapping program. Provide ArcGIS mxd map files for drawings implementing GIS data. Final documents shall also be provided electronically in Adobe Acrobat PDF format to ensure a single file that is an "exact" duplicate of what was provided as a deliverable including all tables, maps, appendices, etc. Other formats (i.e., Word, Excel, etc.) shall also be provided, but shall be in addition to the PDF file.

   Each CD shall be labeled with contract and delivery order number, document title, activity name, and final document approval date. Each CD shall include all correspondence, meeting minutes, project documentation, etc. in the project file denoted with the contract number and delivery order number, activity name and location. Upon completion of the project, the entire project file shall be included on a CD (excluding GIS data which is a separate deliverable).

G. OPSEC requirements are applicable when contractor personnel have access to or generate covered defense information (CDI) as defined in DFARS 225.204-7012. As such, OPSEC Measures (i.e., the planned action to conceal or protect identified critical information and indicators from disclosure, observation, or detection and to protect the same from collection) are applicable to this requirement. Contractor employees shall not discuss or disclose any information provided to them in the performance of their duties to parties other than authorized Government and/or Contractor personnel who have a "need to know" in accordance with the "Authorized Use and Non-Disclosure Agreement & OPSEC Certification of Understanding" executed by the Contractor which is incorporated in full by reference herein. Contractor shall not use any information or documentation provided by the Government or developed under this requirement for other purposes without the consent of the Government Contracting Officer IAW DFARS 252.204-7000. Contractor shall not release to anyone outside the Contractor's organization any unclassified information, regardless of medium (e.g., film, tape, document, etc.), pertaining to any part of this contract or any program related to this contract, unless the Contracting Officer has given prior written approval IAW DFARS 252.204-7000.

   Markings: All deliverables/submittals generated by the Contractor shall be properly marked. Technical information shall also be marked with appropriate Distribution Statements and Export Control warnings in accordance with DoDD 5230.24 and program Security Classification Guidance. Certain information provided by the government may require unique handling, storage and or release/dissemination procedures. Contractors are cautioned to study “Authorized Use and Non-Disclosure Agreements & OPSEC Certification of Understanding" and comply accordingly.

   Note: the following clauses have been incorporated in this solicitation/contract - DFARS 252.204.7000 Disclosure of Information, 252.204-7008 Compliance with Safeguarding Covered Defense Information Controls, and 252.204-7012 Safeguarding Covered Defense Information and Cyber Incident Reporting. DFARS Clause 252.204-7000 restricts the release of unclassified information outside contractor's organization without prior Contracting Officer permission, with exceptions; DFARS Clause 252.204-7008 requires contractor compliance with Safeguarding Covered Defense Information Controls; and DFARS 252.204-7012 requires contractor to provide adequate security for all covered contractor information systems (including implementation of NIST 800-171 CUI requirements) and to comply with cyber incident reporting requirements.

V. SCOPE OF WORK

The A/E shall be responsible for performing the following services under this delivery order:

<u>Task 1</u>: Kick-Off Meeting & Project Management

The Contractor project manager shall schedule a kickoff meeting conference call within one (1) week after the notice to proceed with the NAVFAC PAC Engineer in Charge (EIC) and Activity

POCs. The meeting will be no longer than one (1) hour in duration. The intent of the call will be to introduce the key project team members and explain their roles, establish the lines of communication, and review the project tasks to ensure a common understanding of the Navy's objectives and requirements under this task order.

The Contractor shall present a project schedule of critical project milestones, including a site visit schedule, for discussion and approval. The requirements for site and building access will also be discussed and confirmed during this call so that approvals can be arranged prior to the start of work. The Contractor will be responsible for preparing and submitting all required documentation prior to scheduling the site visits for Task 3 and 4. The Contractor shall coordinate with NAVFAC PAC and Activity POCs to obtain daily data for Task 3 and provide a request for information (RFI) that is needed for model development under Task 4, including but not limited to, current water utility GIS data, as-built drawings and specifications for water infrastructure, historical water meter readings and SCADA data, population and housing/building occupancy data.

The Contractor shall provide kickoff meeting minutes within three days of the kickoff meeting electronically to the EIC. The minutes will include action items assigned to designated personnel for comment and distribution.

The Activity POCs will provide a list of Government personnel and their contact information who will be providing input during the project.

Routine project management activities (e.g., reporting, invoicing, status calls and meetings, etc.) will be completed as part of this task.

Task 2: Develop Abbreviated Accident Prevention Plan and Project Work Plan

The draft plans will be submitted electronically to the EIC. The Contractor will incorporate all government comments prior to finalization. The final plans will also be submitted electronically. There will be no hard copy deliverables for this task.

Task 3: Flushing & Incident Response Support

Subtask 3A: Flushing of the JBPPH distribution system and laboratory testing is ongoing to ensure that contaminated water has been expelled from the system. The Contractor shall make the minimal necessary modifications to the existing 2014 WaterGEMS hydraulic model of the JBPHH drinking water distribution system, provided by the Government, to enable contaminant tracking in all housing areas, including but not limited to Aliamanu Military Reservations, Red Hill Housing, Hickam Housing and Airfield, and the Ft. Kamehameha/HIANG/Mamala areas, and provide graphical analyses of contaminant dispersal and removal from the system. ~~For this purpose, the Contractor shall perform up to 100 hydraulic model runs. The Contractor shall use GIS to provide up to 100 color-coded maps depicting the progress of daily flushing activities and laboratory test results with analysis summary narratives.~~

~~The Contractor shall provide intermediate updates to the existing hydraulic model to support these efforts, including a skeletonized representation of the water system in the Aliamanu Military Reservations, Red Hill Housing, Hickam Housing and Airfield, and the Ft. Kamehameha/HIANG/Mamala areas. The newly developed model in Task 4 shall be deployed for Task 3 purposes as soon as it is available. This will likely be an "interim" model since the field testing necessary for calibrating the updated model is a longer-term effort covered under Task 4.~~

~~Subtask 3B: The Contractor shall provide ad-hoc onsite support for up to two (2) weeks. Tasks include attendance of face-to-face meetings, providing technical expertise on water quality concerns, flushing activities, hydraulic modeling, data analysis and visualization, and related support at the discretion of the Activity POCs.~~

Task Order Modification No. 1 removes the remainder of Task 3 work from the Statement of Work.

Task 4: New Hydraulic Model

The Contractor shall develop a new model of the water distribution system using Bentley WaterGEMS software that is compatible on version 10.00.00.40. The new hydraulic model shall include representation of the entire water system consisting of mains 6 inches in diameter or greater, including in the Aliamanu Military Reservation, Red Hill Housing, Hickam Housing and Airfield, and the Ft. Kamehameha/HIANG/Mamala areas, and all areas represented in the existing 2014 hydraulic model.

The Contractor shall perform a field visit for up to 4 weeks to conduct model calibration activities, including inspection of all pump stations, tanks, valves, control systems, and other critical areas requiring field verification; determination of Hazen-Williams "C" factors for up to 10 representative water mains; hydrant flow testing at up to 10 locations to determine available firefighting capacities; pressure logging; and tracer studies to support all testing efforts and confirm flow paths, controls, and temporal and spatial consumption patterns. The Contractor shall then calibrate the WaterGEMS model by using available operational and field data.

The Contractor shall utilize the new WaterGEMS model to determine residual pressures under fire flow conditions and peak conditions, identify deficiencies, and evaluate the adequacy and improvements required – near-term and long-term – for the water distribution system to satisfy current and future water demand and fire flow requirements. This task will include modeling of twelve (12) scenarios including baseline conditions and seasonal variation in production capacity to evaluate options for future improvements.

The Contractor will describe all steps in developing the new WaterGEMS model, discuss identified deficiencies, and recommend improvements to the water distribution system in a Summary Report. The Contractor will submit the draft report electronically to the EIC for review and comment. The Contractor will incorporate government comments into the final draft. The final version shall be submitted in hard copy and electronic format to the EIC.

Task 5: Training

The Contractor will provide on-site training on the new WaterGEMS model to Government staff. Training will be up to one week in duration for up to six (6) persons. The training will, at a minimum, include a review of hydraulics, an introduction to the software, the specific assumptions used to develop the model, and demonstrations of how to update the model and run scenarios. A minimum of two (2) hands-on exercises will be included for students to practice how to update the model and run scenarios.

Draft training materials in electronic format will be provided to the EIC at least three (3) weeks before training begins. The Contractor will incorporate government comments into the final training materials. Final training materials will be provided to students in hard copy format and to the EIC in electronic format at the start of training.

On-site training will be conducted following delivery of the final hydraulic model report and updated model.

VI. MEETING AND REPORTS

A. **Task 1 Kickoff Meeting** – The A/E shall hold a kickoff meeting teleconference with the installation POC and EIC.

B. **Task 2 Accident Prevention Plan and Project Work Plan** – The A/E shall submit an accident prevention plan and project work plan.

~~C. **Task 3 Flushing and Incident Response Maps** – The A/E shall submit up to 100 color coded maps depicting progress of daily flushing activities, laboratory test results, hydraulic model outputs, and analysis summary narratives.~~

D. **Task 4 Draft Hydraulic Model Report** – This draft report will be provided in hard copies along with compact discs and distributed as shown below.

E. **Task 4 Final Hydraulic Model Report & Updated Model** – Final report will be provided in hard copies along with compact discs and distributed as shown below.

F. **Task 5 Draft Training Materials** – Draft training materials will be provided in electronic format and distributed as shown below.

G. **Task 5 Final Training Materials** – Final training materials will be provided in hard copy and electronic format and distributed as shown below.

VII. COMPLETION DATES

Kickoff Meeting Teleconference	No later than (NLT) one (1) week after notice to proceed

Accident Prevention Plan & Project Work Plan	NLT one (1) week after notice to proceed
~~Flushing Operations Data Analysis & Graphical Presentations~~	~~NLT 90 calendar days after notice to proceed~~
Draft Hydraulic Model Report	NLT October 15, 2022
Govt Review Meeting	NLT 14 calendar days after submittal of Hydraulic Model Report
Final Hydraulic Model Report & Updated Model	NLT 30 calendar days after Govt Review Meeting
Draft Training Materials	NLT three (3) weeks before training begins
Final Training Materials	NLT start of training
On-Site Training	NLT November 30, 2022

Work completion date shall be no later than December 30, 2022.

VIII. DISTRIBUTION OF DOCUMENTS

A. Submittals should be forwarded to the addresses below in accordance with the time frame established in Section VII of this document. The following distribution of documents will be made for each deliverable:

Work Plan

	Draft	Final
NAVFAC PAC EIC	1 electronic copy	1 electronic copy

Flushing Operations – Data Analysis & Graphical Representations

	Final
NAVFAC PAC EIC	1 electronic copy

Updated Hydraulic Model & Summary Report

	Draft	Final
NAVFAC PAC EIC	2 hard copies 1 electronic copy	2 hard copies 1 electronic copy

	Training Materials	
	Draft	Final
NAVFAC PAC EIC	1 electronic copy	6 hard copies 1 electronic copy

B. Addresses:

NAVFAC PAC, Engineer in Charge:
NAVFAC PAC
ATTN: [redacted]
258 Makalapa Drive Suite 100
JBPHH, HI 96860

APPENDIX B

Abbreviations and Acronyms

(2 PAGES)

ABBREVIATIONS AND ACRONYMS

°F	degrees Fahrenheit
AAFES	Army & Air Force Exchange Service
AC	asbestos-cement
ADD	average daily demand
AFB	Air Force Base
AH/BC	AH/BC Navy JV, LLC
AMR	Aliamanu Military Reservation
CDROM	compact disc, read-only memory
CI	cast iron
DI	ductile iron
EPS	extended period simulation
FF	fire flow
FIFO	first in first out
FISC	Fleet and Industrial Supply Center
Ft	feet
FY	Fiscal Year
GAC	granular activated carbon
GIS	geographic information system
gpm	gallons per minute
gpd	gallons per day
GPV	general purpose valve
HDPE	high-density polyethylene
JBPHH	Joint Base Pearl Harbor – Hickam
LIFO	last in first out
MDD	maximum daily Demand
mg/L	milligrams per liter
MG	million gallons
MGD	million gallons per day
MSL	mean sea level
NAVFAC	Naval Facilities Engineering Systems Command
NEX	Navy Exchange
NGIS	Navy Gateway Inns & Suites
PHD	peak hourly demand
PRV	pressure reducing valve
psi	pounds per square inch
PVC	Polyvinyl chloride
RMSE	root mean squared error

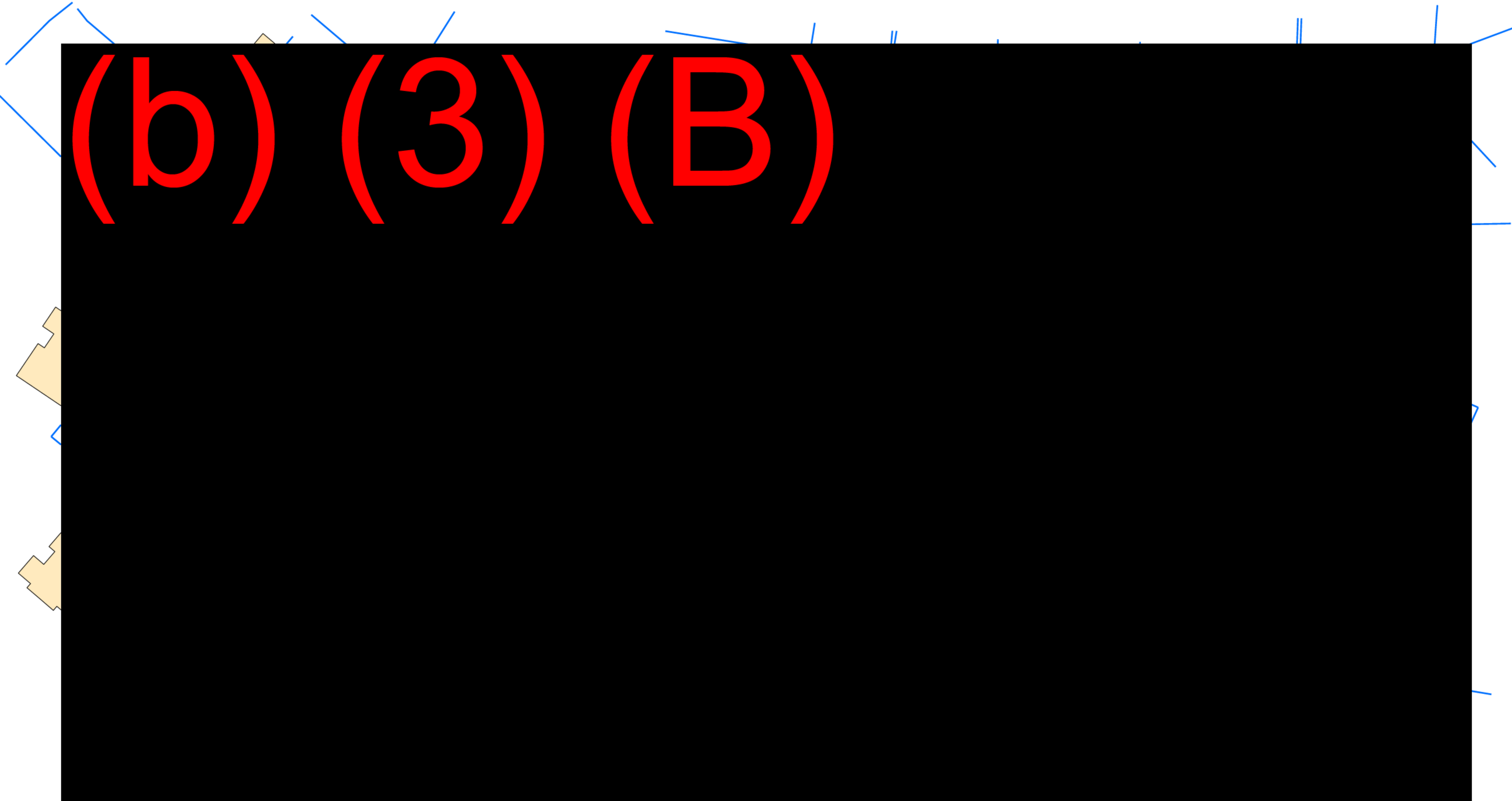
SCADA	supervisory control and data acquisition
SPS	sewer pump station
SS	steady state
SUBASE	Submarine Base
TDH	total dynamic head
US	United States
WaterGEMS	WaterGEMS® V10

APPENDIX C

C-Factor Test Location Maps

(12 PAGES)

Figure No.	Description	Pipe Diameter	Material	Year	Pipe Length	Closed Valve(s)	Flow Hydrant	Downstream Differential Pressure Hydrant	Upstream Differential Pressure Hydrant
C-1	Eastern Housing - Catlin Drive	[redacted]	PVC	2008	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-2	McGrew Housing - McGrew Loop	[redacted]	CI	1959	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-3	Pearl City Peninsula - Victor Wharf Road (2)	[redacted]	DI	1988	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-4	Eastern Housing - Gordon Street	[redacted]	CI	1960	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-5	Hickam - Gemini Avenue	[redacted]	AC	1943	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-6	Hickam - Porter Avenue	[redacted]	AC	1943	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-7	Hickam - Seventeenth Street	[redacted]	PVC	2006	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-8	Hickam - Tenth Street	[redacted]	PVC	2006	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-9	Hickam - Worchester Avenue	[redacted]	PVC	2006	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-10	JBPHH - Hale Alii Avenue	[redacted]	CI	1943	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
C-11	JBPHH - Salvor Street	[redacted]	CI	1943	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]



[redacted]

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: (b) (6) [redacted]

N

0 100 200
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - Catlin Drive

Hydraulic Modeling Study

Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-1

(b) (3) (B)

[redacted]

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: [redacted] (b) (6)

N

0 112.5 225
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - McGrew Loop

Hydraulic Modeling Study

Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-2

(b) (3) (B)

[redacted]

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: (b) (6) [redacted]

N

0 150 300
Feet

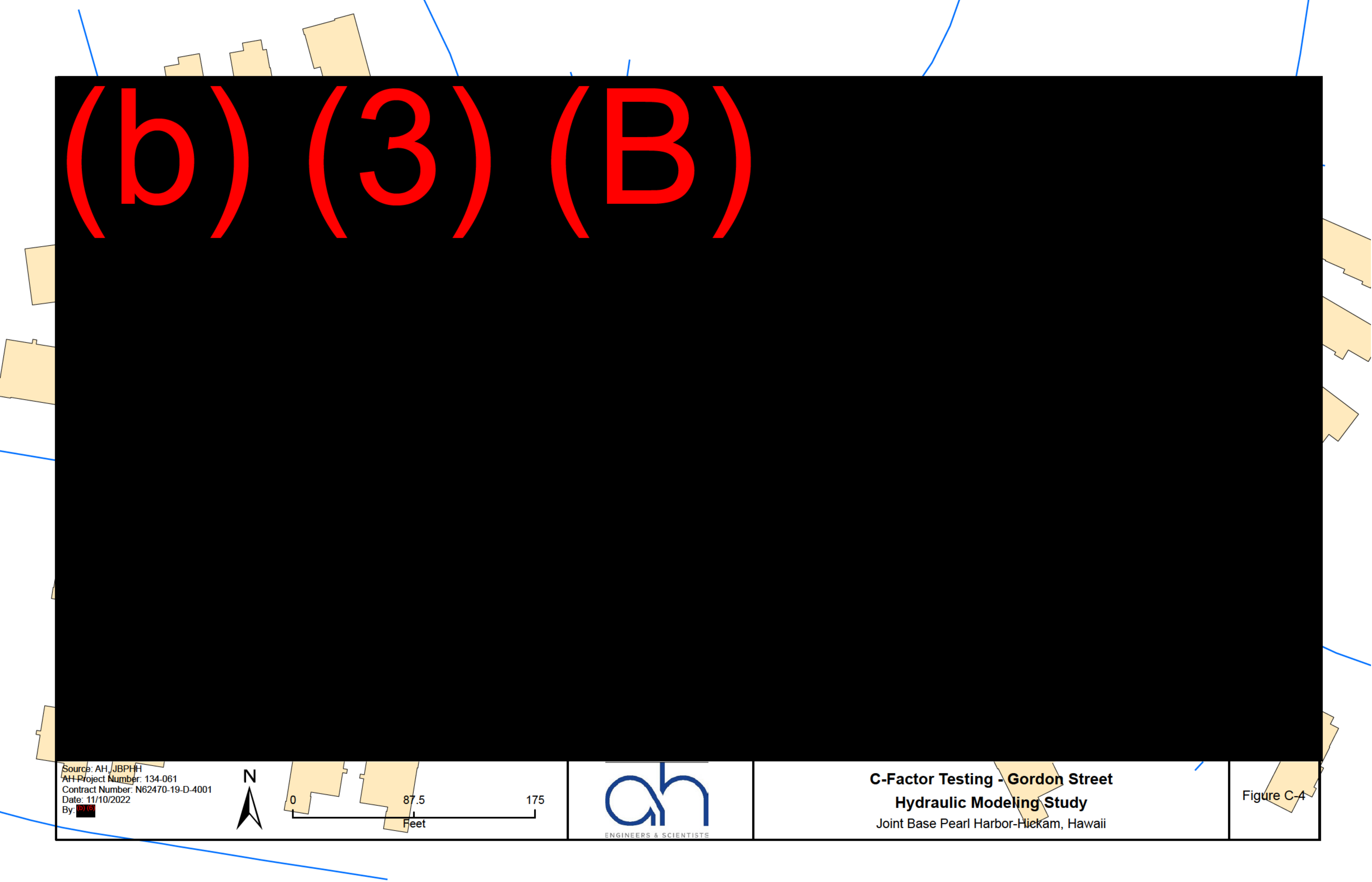
ENGINEERS & SCIENTISTS

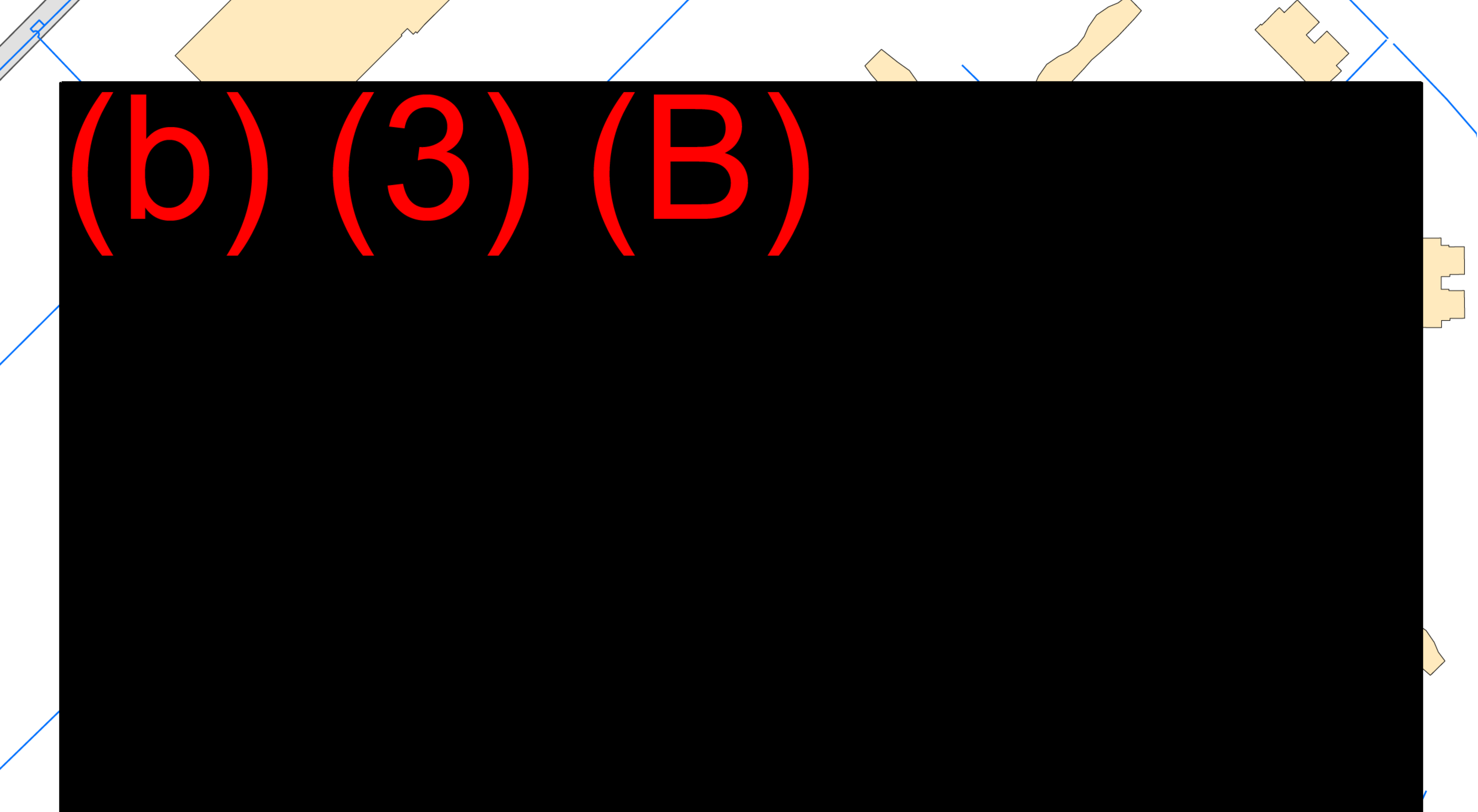
C-Factor Testing - Victor Wharf Road

Hydraulic Modeling Study

Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-3


(b) (3) (B)
[redacted]
Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: [redacted]
N
0
87.5
175
Feet
ENGINEERS & SCIENTISTS
C-Factor Testing - Gordon Street
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii
Figure C-4



(b) (3) (B) [redacted]

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: [redacted]

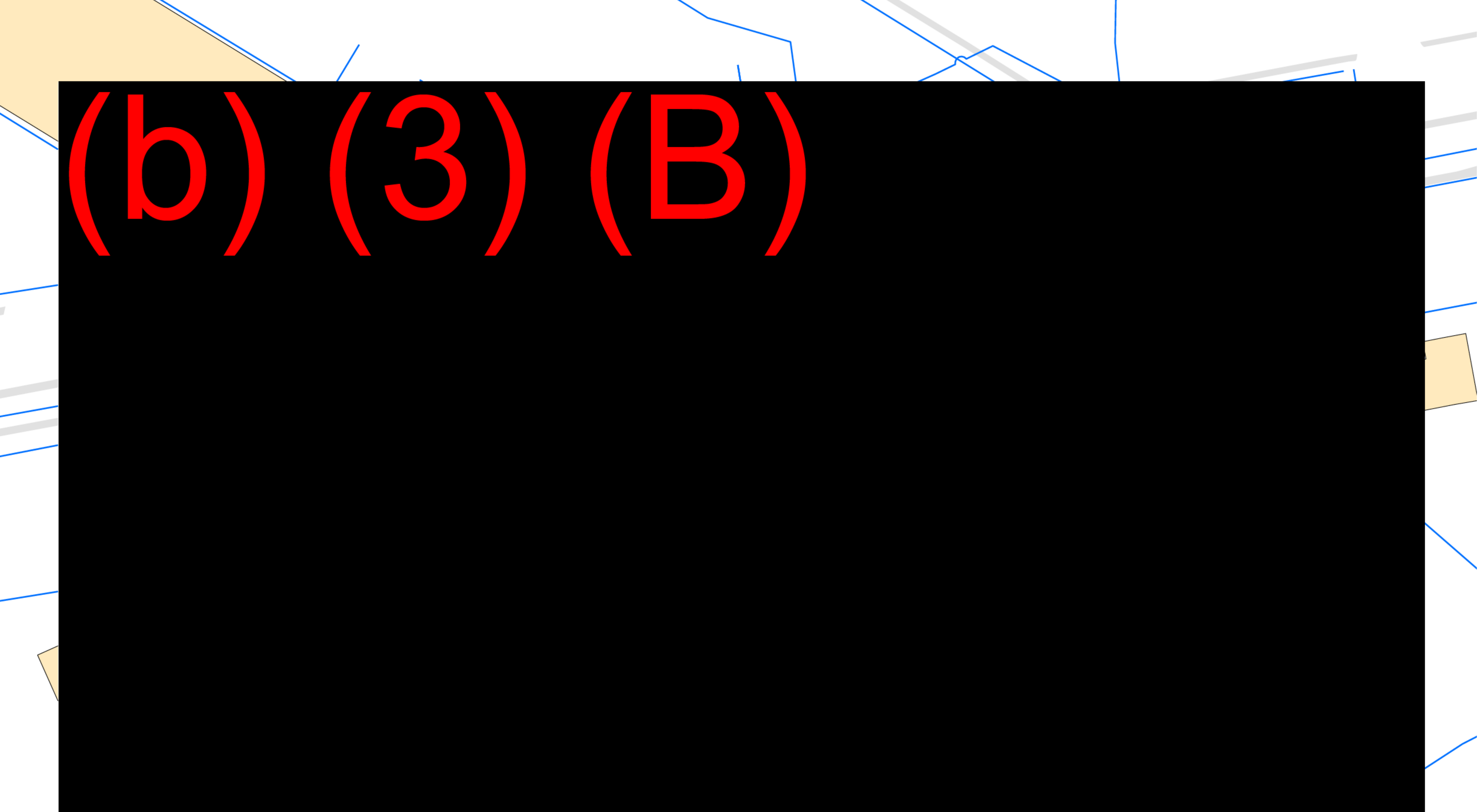
N

0 150 300
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - Gemini Avenue
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-5



(b) (3) (B) [redacted]

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: (b) (6) [redacted]

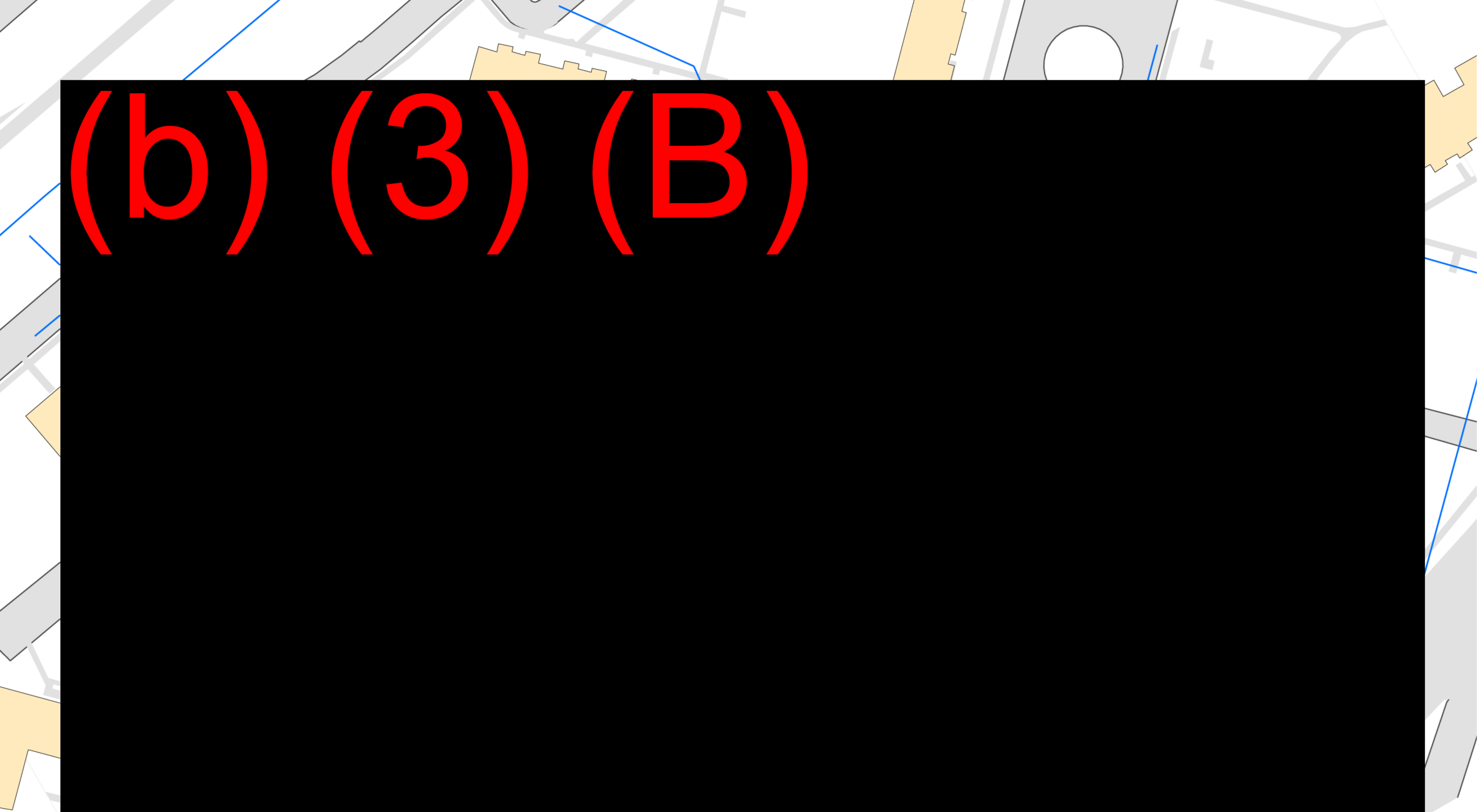
N

0 87.5 175
Feet

ah
ENGINEERS & SCIENTISTS

C-Factor Testing - Porter Avenue
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-6



[redacted] (b) (3) (B)

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: [redacted] (b) (6)

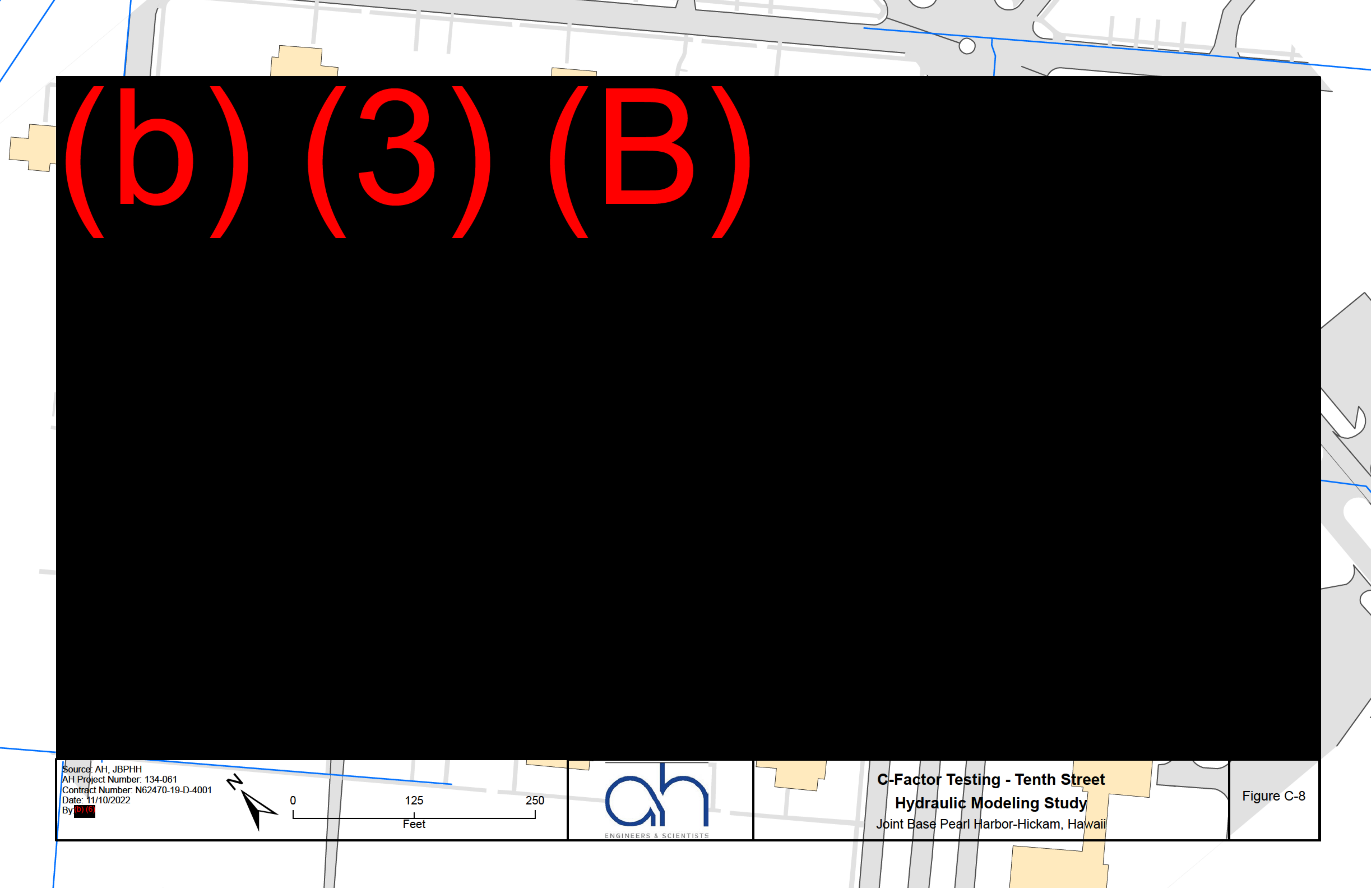
N

0 | 87.5 | 175
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - Seventeenth Street
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-7



Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: (b) (6) [redacted]

N

0 125 250
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - Tenth Street
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-8

[redacted] (b) (3) (B)

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: [redacted] (b) (6)

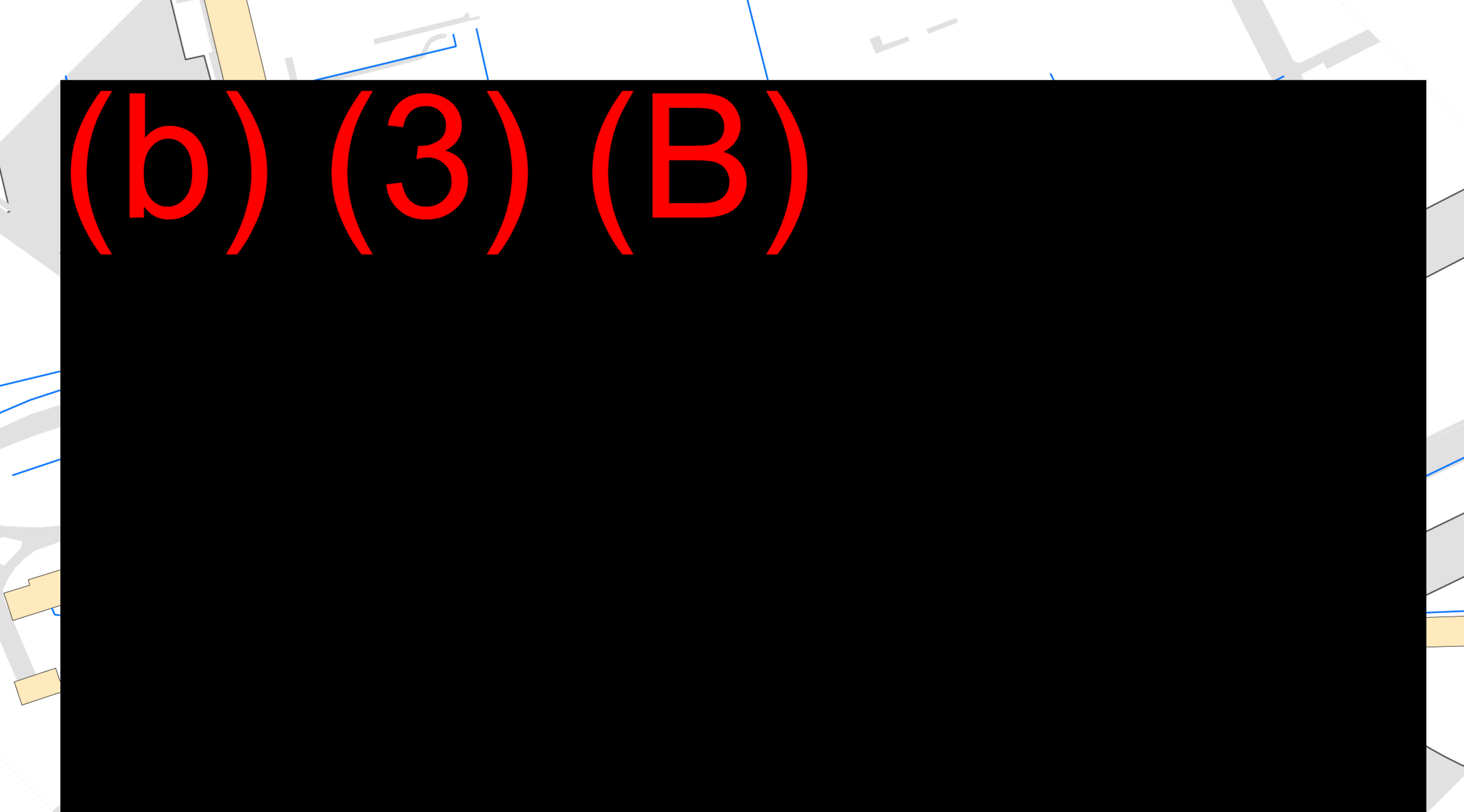
N

0 125 250
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - Worchester Avenue
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-9



[redacted]

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: (b) (6) [redacted]

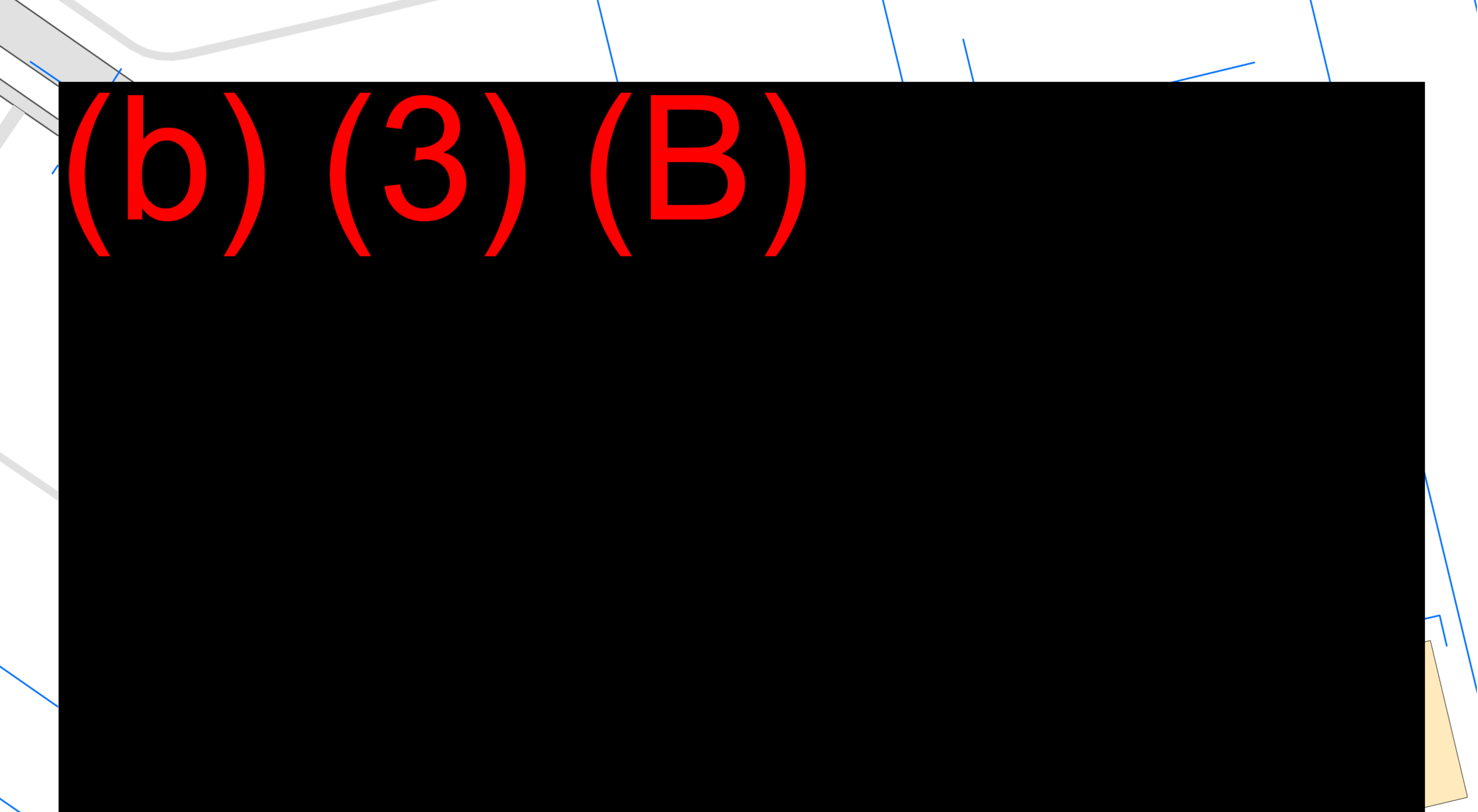
N

0 125 250
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - Hale Alii Avenue
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-10



[redacted] (b) (3) (B)

Source: AH, JBPHH
AH Project Number: 134-061
Contract Number: N62470-19-D-4001
Date: 11/10/2022
By: [redacted] (b) (6)

N

0 75 150
Feet

ENGINEERS & SCIENTISTS

C-Factor Testing - Salvor Street
Hydraulic Modeling Study
Joint Base Pearl Harbor-Hickam, Hawaii

Figure C-11

APPENDIX D

Hydraulic Model Description

(12 PAGES)

1. INTRODUCTION

AH developed the Joint Base Pearl Harbor-Hickam (JBPHH) water system hydraulic computer model using WaterGEMS® Version 10 software developed by Bentley Systems, Inc. (herein referred to as "WaterGEMS"). WaterGEMS is a computer program that performs both steady-state (SS) and extended period simulations (EPS) of hydraulic and water quality behavior within pressurized pipe networks. Networks can consist of any combination of pipes, nodes (also known as pipe junctions), pumps, valves, storage tanks, and reservoirs. WaterGEMS tracks the flow of water through each pipe, the pressure at each junction, the overflow elevation and volume of water available in each tank, and the water age throughout the network over user-defined simulation periods comprised of multiple time steps.

WaterGEMS is GIS-based software that interfaces with the "EPANET 2.2" analysis engine to determine the various hydraulic and water quality parameters of a modeled network. The United States (US) Environmental Protection Agency (EPA) developed and distributed the EPANET software package as a water supply network design and analysis tool (Rossman, 2020). EPANET 2.2 hydraulic modeling software is widely used and accepted public domain software that may be freely copied and distributed.

2. PHYSICAL MODEL COMPONENTS

WaterGEMS models a water distribution system as a collection of junctions, reservoirs, tanks, pipes, pumps, and valves as shown in Figure 2-1. The following sections describe each physical component used in the creation of the JBPHH hydraulic model.

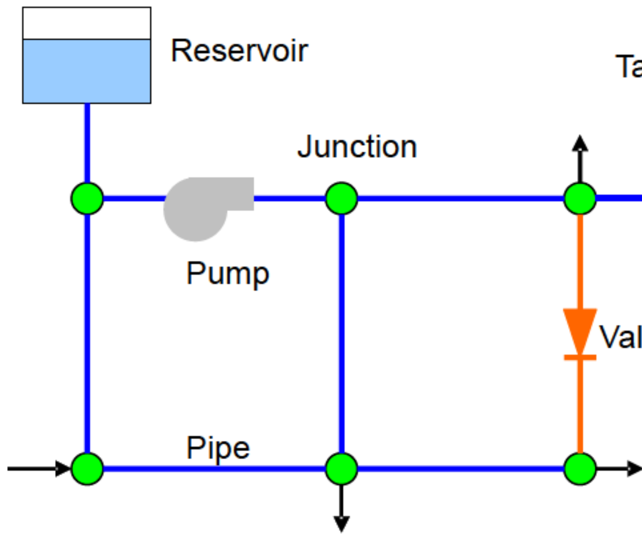


Figure 2-1 Physical Network Components

2.1 JUNCTIONS

Junctions are points in the network where pipes join together and water enters or leaves the network. Junctions are also located at pipe ends that do not intersect with other pipes. Junctions require the following basic input data:

- Elevation above some reference (usually mean sea level [MSL])
- Water demand (rate of withdrawal from the network) at the location of the junction
- Initial water quality value (water age or constituent concentration)

The model computes the following output results for junctions at all time periods of a simulation:

- Hydraulic grade line (internal energy per unit weight of fluid)
- Pressure
- Water quality value (water age or constituent concentration)

The model allows for the following data inputs at junctions:

- A demand that varies with time
- Multiple categories of demands assigned to a single junction

- Negative demands indicating water entering the network
- Influx of water quality constituents (such as chlorine)

2.2 RESERVOIRS

Reservoirs are junctions that represent an external and infinite source of water entering or leaving the network. Reservoirs are used to model water sources such as lakes, rivers, groundwater aquifers, and connections to other water systems. Reservoirs can also serve as water quality source points. The primary input properties for a reservoir are hydraulic grade line (equal to the water surface elevation if the reservoir is not under pressure) and initial concentrations of water quality parameters.

Processes within the network cannot affect a reservoir's head or water quality because it represents a boundary point to a network. Therefore, a reservoir has no computed output properties.

2.3 TANKS

Tanks are junctions with storage capacity, where the volume of stored water can vary with time during a simulation. Tanks require the following primary input properties:

- Bottom elevation (where the water storage volume is zero)
- Diameter (or shape, if non-cylindrical)
- Initial, minimum, and maximum water elevations
- Initial water quality value

The principal outputs computed over time are hydraulic grade line (water surface elevation) and water quality values. Tanks must operate within specified minimum and maximum elevations. WaterGEMS stops outflow from the tank when a tank is at its minimum elevation and stops inflow into the tank if it reaches its maximum elevation. Tanks can also serve as water quality source points.

Additional model inputs for tanks include the following:

- Inlet/outlet geometry (single pipe or separate pipes)
- Tank mixing model (Figure 2-2)
  - Complete mixing

– Two-compartment mixing
– First-in-first-out (FIFO) plug flow
– Last-in-first-out (LIFO) plug flow

The complete mixing model assumes that all water that enters a tank is instantaneously and completely mixed with the water already in the tank.

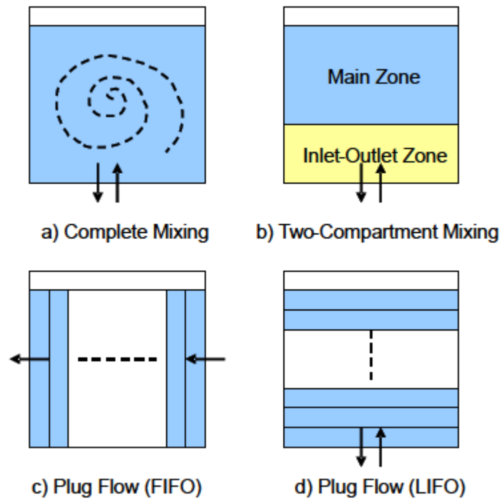


Figure 2-2 Tank Mixing Models

The two-compartment mixing model divides the available storage volume in a tank into two compartments, both of which are assumed completely mixed. The inlet/outlet pipes of the tank are assumed to be in the first compartment. New water that enters the tank mixes with the water in the first compartment. If this compartment is full, then it sends its overflow to the second compartment where it completely mixes with the water already stored there. When water leaves the tank, it exits from the first compartment, which, if full, receives an equivalent amount of water from the second compartment to make up the difference. The first compartment is capable of simulating short-circuiting between inflow and outflow while the second compartment can represent dead zones. The user must supply a single parameter, which is the fraction of the total tank volume devoted to the first compartment.

The FIFO plug flow model assumes that there is no mixing of water at all during its residence time in a tank. Water parcels move through the tank in a segregated fashion where the first parcel to enter is also the first to leave. Physically speaking, this model is most appropriate for baffled tanks that operate with simultaneous inflow and outflow. There are no additional parameters needed to describe this mixing model.

The LIFO plug flow model also assumes that there is no mixing between parcels of water that enter a tank. However, in contrast to FIFO plug flow, the water parcels stack up, one on top of another, where water enters and leaves the tank on the bottom. This type of model applies to elevated tanks with a single inlet/outlet pipe at the bottom of the bowl and a low momentum inflow. It requires no additional parameters.

2.4 PIPES

Pipes are links that convey water from one junction in the network to another. WaterGEMS assumes that all pipes are always full. Flow direction runs from the end with higher hydraulic grade line (internal energy per weight of water) to that of lower hydraulic grade line. The following parameters are the principal hydraulic inputs for pipes:

- Start and end junctions
- Diameter
- Length
- Roughness coefficient (for determining pipe friction head loss)
- Status (open, closed, or contains a one-way check valve)

The status parameter allows pipes to implicitly contain shutoff valves and check valves. Pipes can be set open or closed at preset times or under specific conditions, such as when tank levels or nodal pressures fall above or below certain values. The model limits water quality input for pipes to an initial water age.

The model computes outputs for the following pipe variables:

- Flow rate
- Velocity
- Head loss
- Average water quality value (over the pipe length)

The hydraulic grade line loss caused by the friction of water flowing in a pipe is typically computed using one of the following formulas:

- Hazen-Williams formula
- Darcy-Weisbach formula
- Chezy-Manning formula

The WaterGEMS software uses the empirically based Hazen-Williams formula, which is the most commonly used friction head loss formula in the US. The Hazen-Williams formula, developed for turbulent flow only, is accurate for water at 60 degrees Fahrenheit (°F). The viscosity of water is inversely proportional to temperature. Friction loss is directly proportional to viscosity. Therefore, friction loss is inversely proportional to temperature. The Hazen-Williams formula does not reflect this friction-temperature relationship. Field observed friction loss can be as much as 20 percent greater at 32°F and 20 percent less at 212°F than the calculated friction loss using the Hazen-Williams formula. The Hazen-Williams formula is as follows:

$$h_{L(ft)} = \frac{10.44 \cdot L_{ft} \cdot Q_{gpm}^{1.85}}{C^{1.85} \cdot d_{in}^{4.8655}} \quad \text{[US customary units]}$$

The variable h_L is the friction head loss (in feet [ft]), Q is the flow rate (volume/time), C is the unitless Hazen-Williams roughness coefficient (referred to as the Hazen-Williams C), d is the pipe diameter (inches), and L is the pipe length (ft).

2.5 PUMPS

Pumps are junctions in the model that impart energy to a fluid, thereby raising its hydraulic grade line. The principal input parameters for a pump are the start and end nodes, and the pump curve (the curve relating system head to the flow rate the pump can produce).

The principal output parameters are flow and head gain. Flow through a pump is unidirectional and WaterGEMS will not allow a pump to operate outside the range of its pump curve.

As with pipes, pumps can be turned on and off at preset times or under certain network conditions. Pump operation can also be described by assigning a time pattern of relative speed settings. WaterGEMS can also compute the energy consumption and cost of a pump. Each pump can be assigned an efficiency curve and schedule of energy prices.

When system conditions require more head than the pump can produce, WaterGEMS turns the pump off. If more than the maximum flow is required, WaterGEMS extrapolates the pump curve to the required flow, even if this produces a negative head. In both cases, the model issues a warning message.

2.6 VALVES

Valves are junctions that can limit the pressure or flow at a specific point in the network. Their principal input parameters include the following:

- Downstream pipe
- Diameter
- Open / closed setting

The computed outputs for a valve are flow rate and head loss. WaterGEMS incorporates the following types of valves:

- Pressure reducing valve (PRV): a simulated valve that limits the pressure downstream of the valve to a user defined pressure
- Pressure sustaining valve: a simulated valve that maintains a set pressure at a specific point in the pipe network. The valve can operate in the following states: (1) partially open to maintain pressure on the upstream side of the valve if the downstream pressure is below the valve's pressure setting; (2) fully open when the downstream pressure is above the valve's pressure setting; (3) closed when the downstream pressure exceeds the upstream pressure (i.e., not permitting reverse flow)
- Pressure breaker valve: a simulated valve that creates a specified pressure drop across the valve
- Flow control valve: a simulated valve that limits the maximum flow rate through the valve from upstream to downstream
- Throttle control valve: a simulated valve used for controlled minor loss
- General purpose valve (GPV): a simulated valve that can be assigned a friction head loss curve, commonly used to simulate the friction head losses associated with backflow prevention devices, turbines, or other similar devices
- Isolation valves: a simulated valve used to model devices that can be set to allow or disallow flow through a pipe (gate valve, butterfly valve, etc.)
- Check valves: a simulated valve used to prevent reverse flow through a pipe

3. NON-PHYSICAL MODEL COMPONENTS

In addition to physical components, WaterGEMS employs three types of informational objects: curves, patterns, and controls. Together, these objects describe the behavior and operational aspects of a distribution system.

3.1 CURVES

Curves are objects that contain data pairs representing a relationship between two quantities. Two or more objects can share the same curve. A WaterGEMS model can utilize the following types of curves:

- Centrifugal pump curve
- Efficiency curve
- Volume curve
- Head loss curve

A centrifugal pump curve represents the relationship between the total dynamic head (TDH) and the flow rate a pump can deliver at its nominal speed setting. TDH is the hydraulic grade line increase imparted to the water by the pump and is plotted on the vertical axis of the curve in feet or meters. The flow rate is plotted on the horizontal axis in flow units. A valid pump curve must have decreasing head with increasing flow. WaterGEMS will apply different shapes of pump curves depending on the number of input points (Figure 3-1).

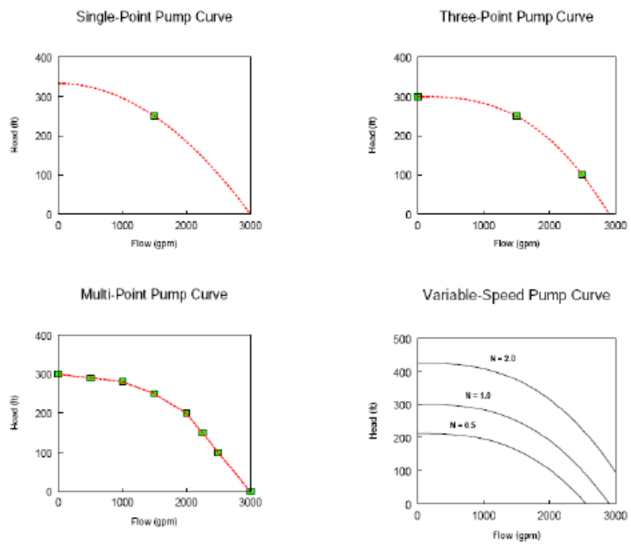


Figure 3-1 Pump Curve Representations

A single-point pump curve is defined by a single head-flow combination that represents a pump's desired operating point. WaterGEMS adds two more points to the curve by assuming a shutoff head at zero flow equal to 133% of the design head and a maximum flow at zero head equal to twice the design flow. It then treats the curve as a three-point curve.

A three-point pump curve is defined by three operating points: a low flow point (flow and head at low flow condition), a design flow point (flow and head at desired operating point), and a maximum flow point (flow and head at maximum flow). WaterGEMS attempts to fit a continuous function of the following form through the three points to define the entire pump curve:

$$h_G = A - B \cdot q^C$$

In this function, h_G is the TDH, q is the flow rate, and A, B, and C are constants.

A multi-point pump curve is defined by providing either a pair of head-flow points or four or more such points. WaterGEMS creates a complete curve by connecting the points with straight-line segments and then extrapolating a curve based on these line segments.

An efficiency curve determines pump efficiency as a function of pump flow rate. Efficiency curves are used only for energy calculations.

A volume curve determines how storage tank volume varies as a function of water level. It provides accurate storage volumes for tanks whose cross-sectional area varies with height.

A head loss curve describes the head loss through a model node (usually a GPV) as a function of flow rate. It provides the capability to model devices and situations with unique head loss-flow relationships, such as backflow prevention devices and turbines.

3.2 TIME PATTERNS

A time pattern is a collection of multipliers that, when applied to a baseline quantity, allow it to vary over time. Nodal demands, reservoir heads, pump schedules, and water quality source inputs can all have associated time patterns. The time interval used in all patterns is a fixed value. Within this interval, a quantity remains at a constant level equal to the product of its baseline value and the pattern's multiplier for that time period. Although all time patterns must utilize the same time interval, each can have a different number of periods. When the simulation clock exceeds the number of periods in a pattern, the pattern starts again at its first period.

As an example of how time patterns work, consider a junction node with an average demand of 10 gpm. Assume demand at this node follows a time pattern interval set to four hours and a pattern with the multipliers listed below. During the simulation, the node will experience the following actual demand:

Period	**1**	**2**	**3**	**4**	**5**	**6**
Multiplier	0.5	0.8	1.0	1.2	0.9	0.7
Hours	**0-4**	**4-8**	**8-12**	**12-16**	**16-20**	**20-24**
Demand (gpm)	5	8	10	12	9	7

These specific time patterns are referred to as demand patterns or diurnal curves. During an EPS, these curves help to accurately represent how the demand varies throughout the day.

3.3 CONTROLS

Controls are statements that determine how the network operates over time. They specify the status of selected junctions, valves, and pumps as a function of time, tank volumes, and pressures at select points within the network. Two categories of controls can be used:

- Simple controls
- Logic-based controls

Simple controls change the status or setting of a junction, valve, or pump based on the volume of water in a tank, the pressure at a junction, the time into the EPS, or the time of day. Logic-based controls allow junction, valve, and pump statuses and settings to depend on a combination of potential network conditions following computation of an initial hydraulic state.

3.4 HYDRAULIC SIMULATION MODEL

WaterGEMS's hydraulic simulation model computes junction pressures and pipe flows for a fixed set of reservoir levels, tank levels, and water demands over a succession of points in time. From one time step to the next, the model updates reservoir levels and junction demands according to their prescribed time patterns, while it updates tank levels using the current flow solution. The solution for pressures and flows at a particular point in time involves simultaneously solving the conservation of flow equation for each junction and the head loss relationship across each junction in the network. This process, known as "hydraulically balancing" the network, requires an iterative technique to solve the nonlinear equations involved. WaterGEMS employs the "Gradient Algorithm" for this purpose. For details, consult the user's manual for EPANET 2.2 (Rossman, 2020). The user can set the hydraulic time step used for an EPS. Unless otherwise specified, shorter than normal time steps will automatically occur during any of the following events:

- The next output reporting time period occurs
- The next time pattern period occurs
- A tank becomes empty or full
- A simple control or rule-based control is activated

3.5 WATER AGE MODELING

WaterGEMS can model the changes in water age throughout a distribution system. Water age is the time spent by a parcel of water in the network. New water entering the network from reservoirs or source nodes enters with an initial age of zero. Water age provides a simple, non-specific measure of the overall quality of delivered drinking water. Internally, WaterGEMS treats age as a reactive constituent whose growth follows zero-order kinetics with a rate constant equal to one (i.e., with each passing second the water becomes one second older).

Each water age simulation begins with an initial age of zero at all model nodes. The water age increases as the simulation time increases until fresh water from the source arrives at a given node. Nodes with zero or very small demand, especially at dead ends, will not receive fresh water and therefore will not have an accurate simulation of water age. Similarly, the water age for tanks will be equal to the simulation time until the entire volume of the tank has been refreshed with water from the source. Depending on operating conditions in the simulation, this may take as long as several weeks. To overcome the effects of the initial conditions in a water age analysis, the simulations are run for a sufficient length of time to fully turn over all water in all storage facilities.

4. REFERENCES

Rossman L.A. *et al* (2020). EPANET 2.2 User Manual (EPA/600/R-20/133). Water Infrastructure Division, Center for Environmental Solutions and Emergency Response, US Environmental Protection Agency, Cincinnati, Ohio 45268. Available online at: https://epanet22.readthedocs.io/_/downloads/en/latest/pdf/ (Accessed October 2022)