# Waimānalo Community Flood Hazard Study

## Waimānalo, O‘ahu, Hawai‘i

**Final Report**
**31 January 2023**

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**Prepared for:**
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| | |
|---|---|
| 2D | two-dimensional |
| AEP | annual exceedance probability |
| cfs | cubic feet per second |
| DA | drainage area |
| F | Fahrenheit |
| FEMA | Federal Emergency Management Agency |
| ft | feet |
| GIS | geographic information system |
| HEC | Hydrologic Engineering Center |
| HMS | Hydrologic Modeling Software |
| HoLIS | Honolulu Land Information System |
| IfSAR | Interferometric Synthetic Aperture Radar |
| JALBTCX | Joint Airborne Lidar Bathymetry Technical Center of Expertise |
| LiDAR | Light Detection and Ranging |
| LMSL | local mean sea level |
| mi | mile |
| MG | million gallons |
| MRLC | Multi-Resolution Land Characteristics Consortium |
| MSL | mean sea level |
| NAD83 | North American Datum of 1983 |
| NLCD | National Land Cover Database |
| NOAA | National Oceanic and Atmospheric Administration |
| NWS | National Weather Service |
| RAS | River Analysis System |
| US | United States |
| USACE | U.S. Army Corps of Engineers |
| USGS | U.S. Geological Survey |
| WIS | Waimānalo Irrigation System |

# EXECUTIVE SUMMARY

The purpose of this study is to evaluate flood risk in the Waimanalo community from rainfall and riverine sources. This study provides community flood hazard maps, where the floodplain for the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) annual exceedance probability (AEP) flood events have been delineated. These maps are provided in Appendix A. This study was completed and funded through the Flood Plain Management Services (FPMS) Program, authorized by Section 206 of the Flood Control Act of 1960, as amended (33 U.S. Code § 709a).

A flow frequency analysis was performed to determine the magnitude of the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) annual exceedance probability (AEP) flood discharges for the Waimānalo community. Significant hydrologic changes have occurred in the watershed since improvements to the Waimānalo Irrigation System were made in the early 1980s, the Waimānalo 60 MG Reservoir was constructed in 1993, and the Kailua Reservoir was intentionally breached in 2006. A stream gage analysis on the older record (1963 – 1991) at USGS 16249000, *Waimanalo Stream*, results in a larger 1% annual exceedance probability (AEP) peak flow of about 7,652 $ft^3/s$. Performing a stream gage analysis on the recent record (2003 – 2021) results in a much smaller 1% AEP peak flow of about 1,850 $ft^3/s$. Final flow frequency estimates were determined by the development of a rainfall-runoff model, which was then calibrated to recent historical storm events. The details of the stream gage analysis, rainfall-runoff model, and overall flow frequency analysis are described in detail in Appendix B.

The results of this study make available the water surface profiles, flood elevations, and areal extent of the floodplain for the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) AEP flood events (5 profiles). A two-dimensional, unsteady flow hydraulic model was developed for this study, which is described in detail in Appendix C.

With several streams in the study area, many residential properties and commercial buildings are at risk of being flooded frequently. Kalanianaʻole Hwy near Sherwood Beach becomes flooded and unusable during the highest frequency event evaluated, the 10% AEP flood event (statistically, once every ten years). It likely floods more frequently given the extensive area that is flooded along and around the highway during the 10% AEP event. Additional information on flood-prone areas are summarized in Section 6.1.

Various additional scenarios were evaluated to provide more information into possible causes or solutions to reduce flood risk. However, their effects at reducing the flood hazard were limited.

- Increased channel vegetation resulted in a tributary to Waimānalo Stream overtopping the banks, causing additional shallow flooding along Humuniki Street. Other small areas in the community experienced additional flooding, but the extent was very limited and depths were less than one foot (< 1 ft).
- Small culverts that were at risk of being obstructed with vegetation, sediment, or debris were partially obstructed under another scenario. Flood depths in the channels immediately upstream of these culverts increased. However, additional flooding to the community was limited to shallow (< 1 ft) flooding along Ahiki St and Mekia St.
- A small channel was cut into the terrain to represent dredging at the Waimanalo and Puha (Inoaole) Streams, but the effects from this were also limited. Kalanianaʻole Hwy is still frequently overtopped.
- Clearing shoreline culvert outlets along Kalanianaʻole Hwy in eastern Waimānalo did not significantly reduce flooding to properties on the mountainside of the highway.
- Even under *high* sea level conditions (7.77 ft MSL), the impact to the extent and depths of riverine flooding was minimal. Generally, the impact was limited to the shoreline and the lower reach segment of Waimānalo Stream, where the water surface elevation in the channel increased about 0.2 ft for the 1% AEP flood event. There was no rise in elevation upstream of Kalanianaʻole Highway or in any of the other streams.

The flood hazard was not significantly affected by any of the above scenarios. To effectively reduce flood risk in the community, the effort must be more intentional and thought out than simply restoring existing infrastructure to optimal conditions (i.e. excavated and without vegetation). Site-specific measures should be developed and evaluated under a separate feasibility study.

# 1 Introduction

The Waimānalo community experiences frequent flash flooding events that cause substantial damages, most recently in April 2018 and March 2021. On the evening of 13 April 2018, intense rainfall moved across east Oʻahu with rates greater than 4 inches per hour (NWS, 2018). At Waimānalo Stream, the water level rose 3 feet in about 30 minutes and 5 feet in an hour. Rushing water topped the banks of multiple streams and tributaries. Floodwaters sent cars and debris rushing towards homes along Mekia Street. Several roads were also reportedly impassable, including Kalanianaʻole Highway and Waikupanaha Street. However, this was not an isolated event as significant rains impacted Waimānalo again in March 2021, damaging a charter school, agricultural lands, and educational use lands. This study will serve as a critical first step towards building additional resilience against flood risk in the Waimānalo community.

## 1.1 Study Purpose

The purpose of this study is to evaluate flood risk in the Waimanalo community from rainfall and riverine sources. This study provides community flood hazard maps, where the floodplain for the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) annual exceedance probability (AEP) flood events have been delineated.

## 1.2 Authority

This study was completed and funded through the Flood Plain Management Services (FPMS) Program, authorized by Section 206 of the Flood Control Act of 1960, as amended (33 U.S. Code § 709a). A formal request for assistance was provided by U.S. Congressman Kaialiʻi Kahele on behalf of the Waimānalo community in a letter dated 12 August 2021. The official nonfederal partner for this study is the State of Hawaiʻi, Office of Planning and Sustainable Development.

# 2 Watershed Description

This section provides a broad overview of hydrologic conditions in the study area and corresponding watersheds. It reflects the preliminary investigations and data collection phase of the study. A detailed narrative on the watershed is included in Appendix B, Hydrology, Section 1.

## 2.1 Location

This study focuses on evaluating flood hazards in Waimānalo, a census-designated place in the City & County of Honolulu, in the District of Koʻolaupoko on the island of Oʻahu, Hawaii. Waimānalo is a small town with a population of approximately 6057 (U.S. Census Bureau, 2020). It is home to several beach parks, plant nurseries, Bellows Air Force Base, the Waimānalo Polo Field, and several thousand acres of Hawaiian homelands.

Waimānalo includes areas in the Waimānalo, Kahawai, and Kaiona watersheds (Figure 2-1). The Waimānalo watershed has a drainage area of approximately 6.28 square miles ($mi^2$); the Kahawai watershed has a drainage area of approximately 2.76 $mi^2$; and the Kaiona watershed has a drainage area of approximately 1.63 $mi^2$. These watersheds extend northeast from the steep slopes of the Koʻolau Range to Waimānalo Bay, located on the eastern shore of Oʻahu. The total study area is about 10 $mi^2$, which includes additional coastal drainage areas that do not contribute significant flow to the primary river systems.

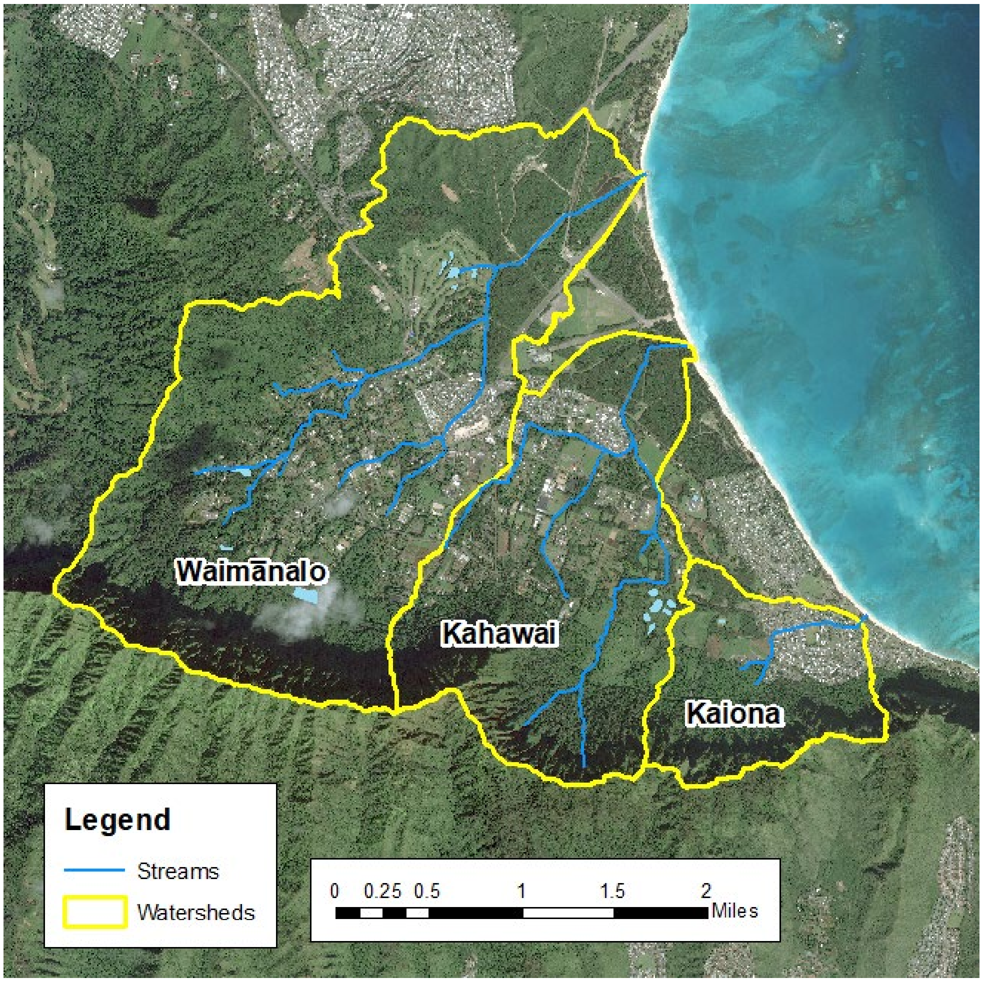


**Figure 2-1: Watershed Map, Waimānalo, Hawai‘i**

## 2.2 Land Use

All lands, including submerged lands, in the State of Hawai‘i are classified into four land use districts: urban, rural, agricultural, and conservation. Along the slopes of the Ko‘olau Range, the upper limits of the Waimānalo, Kahawai, and Kaiona watersheds are classified within the Conservation District. Conservation lands are comprised primarily of lands in existing forest and water reserve zones.

The middle watershed areas are primarily within the Agricultural District. Waimānalo has extensive acreage devoted to diversified agricultural pursuits. The State of Hawai‘i manages an agricultural park in Waimānalo to encourage the continuation or initiation of agricultural activities in a designated area. The Waimānalo Agricultural Park is comprised of 126 acres subdivided into 14 lots (Agricultural Resource Management Division, 2022).

The lower watershed is primarily classified within the Urban District, which generally includes lands characterized by “city-like” concentrations of people, structures, and services. This area includes several residential communities, several beaches and beach parks, and Bellows Air Force Base (AFB). The residential communities are generally small and low-density. More than 200 acres of residential parcels are designated as Hawaiian Home Lands (areas held in trust for Native Hawaiians by the State of Hawai‘i) (Department of Hawaiian Home Lands, 2011). The main beaches along the coastal study limits include Kaiona Beach, Waimānalo Beach, Sherwood Beach, and Bellows Field Beach. Bellows AFB is a former airfield that now serves as a military training area and recreation area, including Bellows Field Beach Park.

## 2.3 Climate

Hawai‘i has a subtropical climate with temperatures that are mild and fairly uniform throughout the year. The climate of the Hawaiian Islands is characterized by a two-season year; a 5-month dry season (summer) and a 7-month wet season (winter). The average monthly precipitation ranges from 2.2 inches in the wettest month (December) to 0.5 inches in the driest month (July) (AM Online Projects, 2019).

Although the northeasterly trade winds produce most of the annual rainfall over the Hawaiian Islands, it is during the absence of these winds that the flood producing rainfall occurs. In particular, southerly winds bring moist warm air that creates "Kona" storms which produce the damaging floods in Hawaiʻi. These storms usually occur during the winter months.

## 2.4 Dams and Reservoirs

### 2.4.1 Waimānalo 60 MG Reservoir

There is one regulated, high-hazard dam in the study area. The Waimanalo 60 MG Reservoir was constructed in 1993. It is owned and operated by the State of Hawaiʻi, Department of Agriculture for the purpose of irrigation. The reservoir has a maximum storage of 182 ac-ft (59.3 MG). The earthen dam is 65 feet high. It is located on the upper end of Mahailua Street, discharging into a tributary of Kahawai Stream in the Waimānalo watershed (Figure 2-2, Photo 2-1).

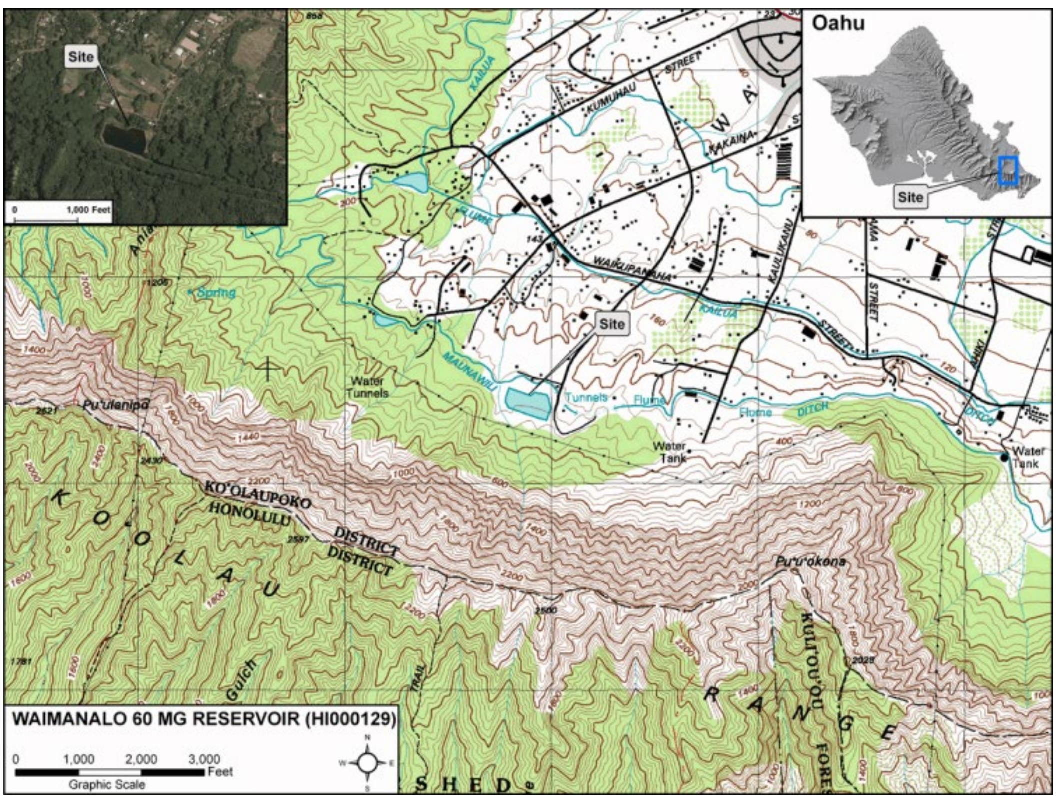


**Figure 2-2: Location Map of Waimānalo 60 MG Reservoir**

Source: State of Hawaii, Department of Land and Natural Resources, Waimānalo 60 MG Reservoir

**Photo 2-1: Aerial Photo of Waimānalo 60 MG Reservoir**

### 2.4.2 Maunawili Reservoir

The Maunawili Reservoir was built in the 1930s for irrigation but is currently inactive. The Maunawili Reservoir and Kailua Reservoir reportedly had a combined storage volume of 5 million gallons (DPW, 1975).

### 2.4.3 Kailua Reservoir

The Kailua Reservoir was reportedly built in the 1930s for irrigation. The State of Hawaiʻi shut down the reservoir in 1993. In April 2006, the reservoir and dam overflowed in a heavy downpour. There were no damages or injuries, although more than 30 homes were evacuated (KHNL/KGMB, 2006). Following the incident, the State breached the dam that same week so that it was no longer able to hold water (Daranciang, 2006).

### 2.4.4 Waimānalo Irrigation System

The Waimānalo Irrigation System (WIS) is owned and operated by the State of Hawaiʻi. It is fully funded by the Hawaii Department of Agriculture. The WIS provides water to the agricultural community in Waimānalo and has a service area of 1,174 acres (EKNA Services, Inc., 2019).

Water from the Maunawili watershed (northwest of the Waimānalo watershed) is screened and picked up in a 16-inch pipe at the east portal of the Aniani Nui Ridge Tunnel. The pipeline carries the water 1.8 miles under gravity pressure to the Waimānalo farming community and the Waimānalo 60 MG Reservoir. Below the reservoir, the delivery system is a closed, pressurized pipe system, 10.9 miles long, ranging from 24 inches to 6 inches in diameter. At certain critical locations along the upper mainline, there are booster pumps to provide sufficient sprinkler pressure to users with land above the gravity pressure contours (Soil Conservation Service, 1981). As the source of water for the irrigation system originates outside of the study area and is contained within a closed system, it was considered to have a minimal impact on the hydrology within the study area and not represented in the hydrologic model.

Before the closed irrigation system was constructed in the early 1980s, the agricultural community relied on other, smaller reservoirs and a collection system comprised of 32 wooden flume-trestle structures and 15 miles of open ditch in generally poor condition (Soil Conservation Service, 1981). These features have since been left abandoned. They may be represented in the terrain but are not otherwise accounted for in the model.


Source: State of Hawaii, Department of Agriculture: *Agricultural Water Use and Development Plan* (December 2003)

**Figure 2-3: Waimānalo Irrigation System, Site Map 1**

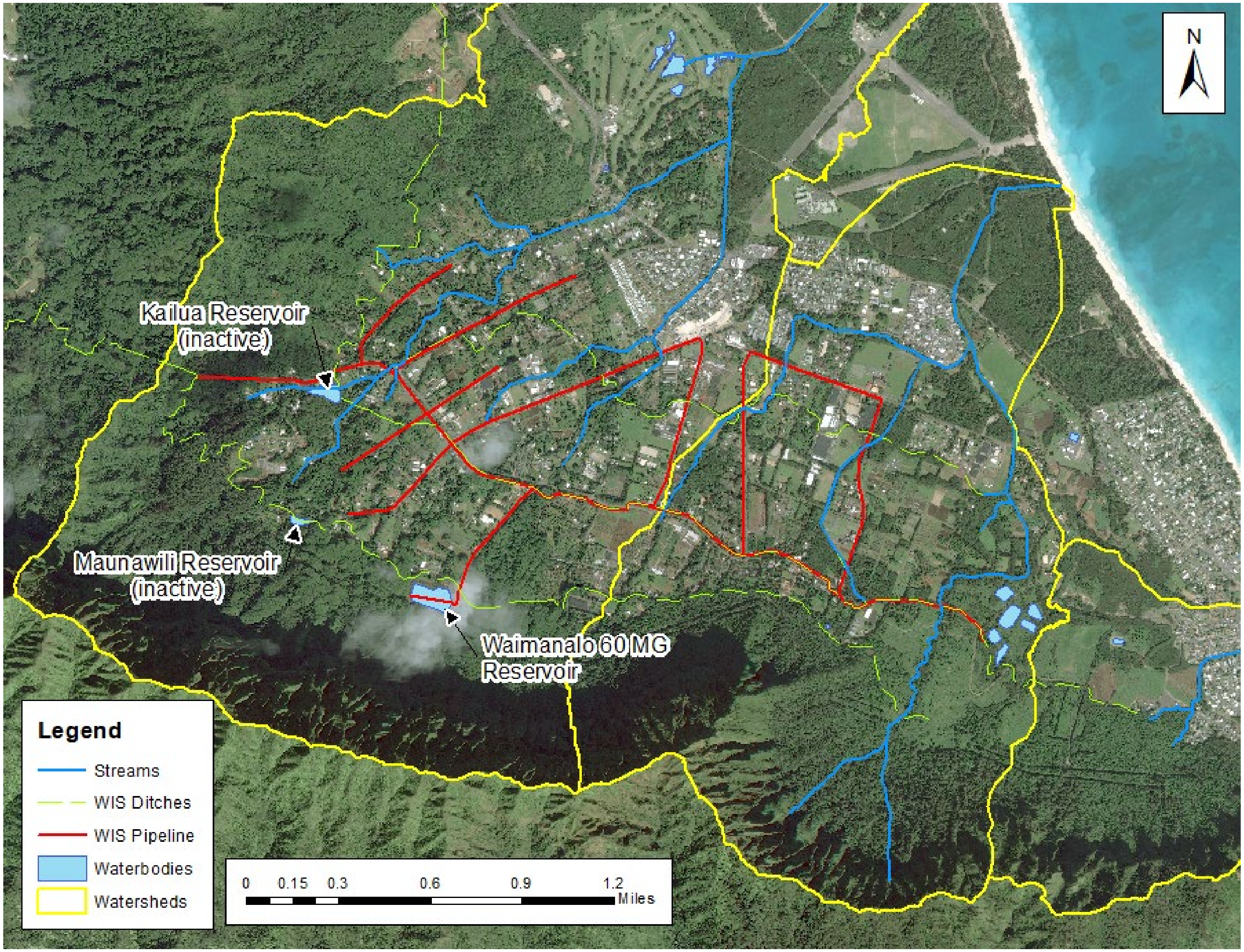


**Figure 2-4: Waimānalo Irrigation Map, Site Map 2**

## 2.5 Rivers and Streams

Waimānalo Stream is the primary river in the Waimānalo watershed (Figure 2-5). It is created by multiple tributaries, originating in the steep slopes of the Ko‘olau Range. The Kahawai Stream (which is in the Waimānalo watershed, not the Kahawai watershed) is the main tributary to the Waimānalo Stream. The tributaries to Kahawai Stream are referred to as “Stream A” and “Stream B,” to be consistent with current terms used in the corresponding flood insurance study for this area (FEMA, 2014)[1].

Puha Stream is the primary river in the Kahawai watershed, although it is sometimes referred to as Inoaole Stream for its proximity to Inoaole Street (Figure 2-5). The tributaries for Puha (Inoaole) Stream are referenced in this study as “Stream C” and “Stream D,” which is also consistent with the corresponding flood insurance study for this area (FEMA, 2014).

There are two unnamed streams in the study area that were also included in this flood hazard analysis for the Waimānalo community (Figure 2-6). The first stream (Unnamed Stream #1) is in the Kaiona watershed. It passes by Waimanalo Country Farms, Blanche Pope Elementary School, and Waimānalo Beach Park before discharging into Waimānalo Bay. The second unnamed stream is in a small, unnamed watershed southeast of the Kaiona watershed. Flow from this stream (Unnamed Stream #2) is collected by an unlined, vegetated swale near the corner of Bell Street and Hoomaha Street. There is an 18-inch conduit at the downstream end of the swale that carries a limited amount of flow through the storm water system to Unnamed Stream #1[2].

Typical photos of these streams are provided as Photo 2-2 through Photo 2-5.

[1] FEMA also refers to the Kahawai Stream as “Waimanalo Stream A,” but in this study, “Stream A” only references the northwestern fork / tributary of the Kahawai Stream.
[2] The outlet for this system is Unnamed Stream #1, just downstream of the Huli Street Bridge.

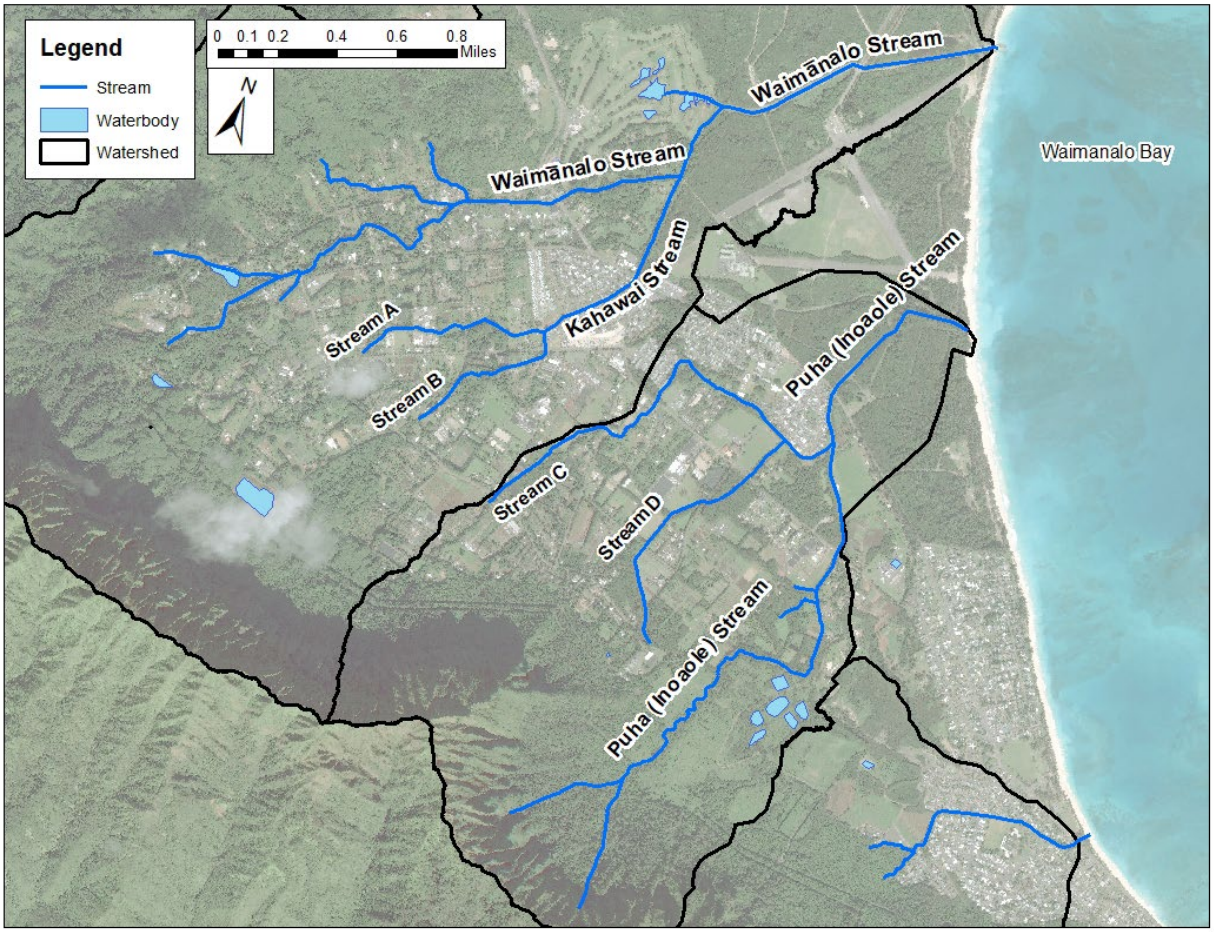


**Figure 2-5: Streams in the Waimānalo and Kahawai Watersheds**

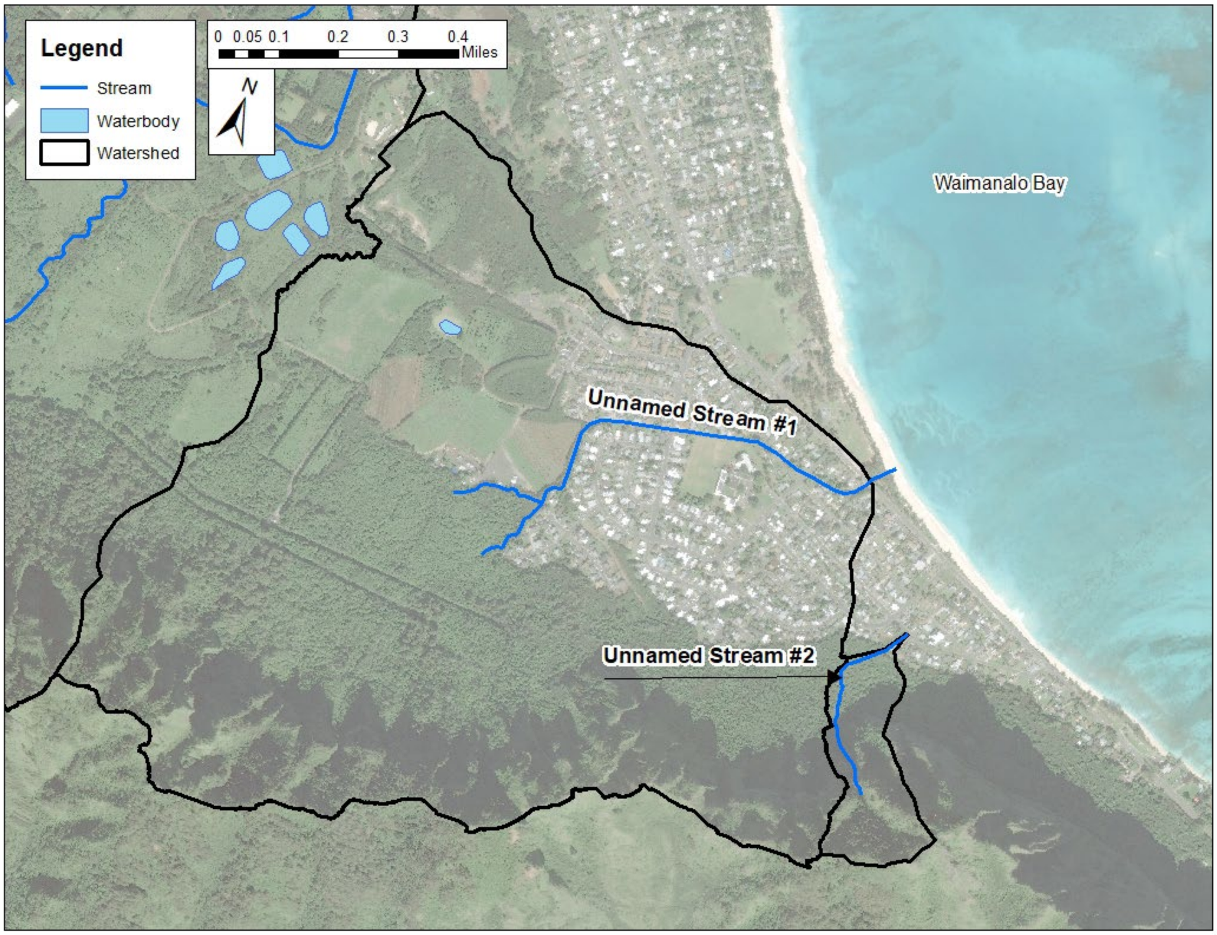


**Figure 2-6: Unnamed Streams in the Kaiona Watershed and Study Area**

**Photo 2-2: Upper Waimanalo Stream, Waimanalo Watershed**

21.345926, -157.734517

**Photo 2-3: Kahawai Stream, Waimanalo Watershed**

21.348047, -157.723116

**Photo 2-4: Puha (Inoaole Stream), Kahawai Watershed**

21.338841, -157.708338

**Photo 2-5: Unnamed Stream #1, Kaiona Watershed**

21.329527, -157.694726

# 3 Geographic Information Systems Data

## 3.1 Datum and Projection

The datum and projection for this study is as follows:

Horizontal projection: State Plane Zone 3 (US Survey Feet)

Horizontal datum: NAD83 (PA11)

Vertical Datum for Land Applications: Local Tidal Datum – MSL

Tidal Epoch: 1983 – 2001

Geoid: 2012B

## 3.2 Elevation

The following sources of elevation data were used in this study:

**Table 3-1: Elevation Data Type and Sources**

| Survey year | Agency | Data type | Areal Extent |
|---|---|---|---|
| 2013 | USACE | Topobathy LiDAR | about 1.0 mi inland from coast |
| 2013 | NOAA/USGS | Topographic LiDAR | middle watershed and coastal areas |
| 2003 | City and County of Honolulu | 5-foot contours | O‘ahu |

Light Detection and Ranging (LiDAR) data were collected by USACE and the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) in 2013. In 2013, the National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS) collected additional topographic LiDAR data, which extends a bit further from the coastal areas and into the middle of the study area. Areas within the study area that were not covered by LIDAR (such as the upper watershed) were supplemented using 5-foot interval contours generated by the City and County of Honolulu, Department of Planning and Permitting, Honolulu Land Information System (HoLIS) Division in 2016.

## 3.3 Imagery

High resolution imagery used for background mapping of the study area is from DigitalGlobe, the National Geospatial-Intelligence Agency and the USGS. World Imagery, provided by Esri, was used for larger scale background mapping, such as when it was necessary to show the entire island of O‘ahu.

## 3.4 Land Cover and Land Use

A circa 2011 high resolution (1 to 5 meter) land cover raster for the study area was developed by NOAA and downloaded from the Multi-Resolution Land Characteristics Consortium (MRLC)'s National Land Cover Database (NLCD). This raster was used to understand the different types of land usage in the study area and compute the directly connected impervious areas for the rainfall-runoff model (Appendix B). This raster was also used to define the Manning's roughness coefficient in the hydraulic model (Appendix C).

## 3.5 Soil Data

A water permeability shapefile provided by the Hawai‘i Soil Data Atlas was used to determine initial loss parameters for the hydrologic model, as described in Appendix B, Hydrology (University of Hawai'i, 2014).

# 4 Data Collection

This section describes available climate and stream data within the study area. Additional information is provided in Appendix B, Section 3.

## 4.1 Climate

Climate data (e.g. rainfall) was available at three National Weather Service (NWS) rain gages within or near the study area (NCEI). These gages are listed in Table 4-1, identified in Figure 4-1, and each provide instantaneous data in either 5- or 15-minute intervals. Historical, instantaneous data were used to calibrate the hydrologic model. There was also one USGS climate station with daily rainfall records in the study area. Although this station is listed in Table 4-1 for inclusivity of all climate stations in the study area, its record was not used in this study.

Point precipitation data for annual exceedance rainfall was obtained from the NWS NOAA Atlas 14 Precipitation-Frequency Data Server (PFDS). This source presents rainfall frequencies from recurrence intervals of 1 to 500 years (100% to 0.2% AEP) at various locations across the study area (NWS, 2017).

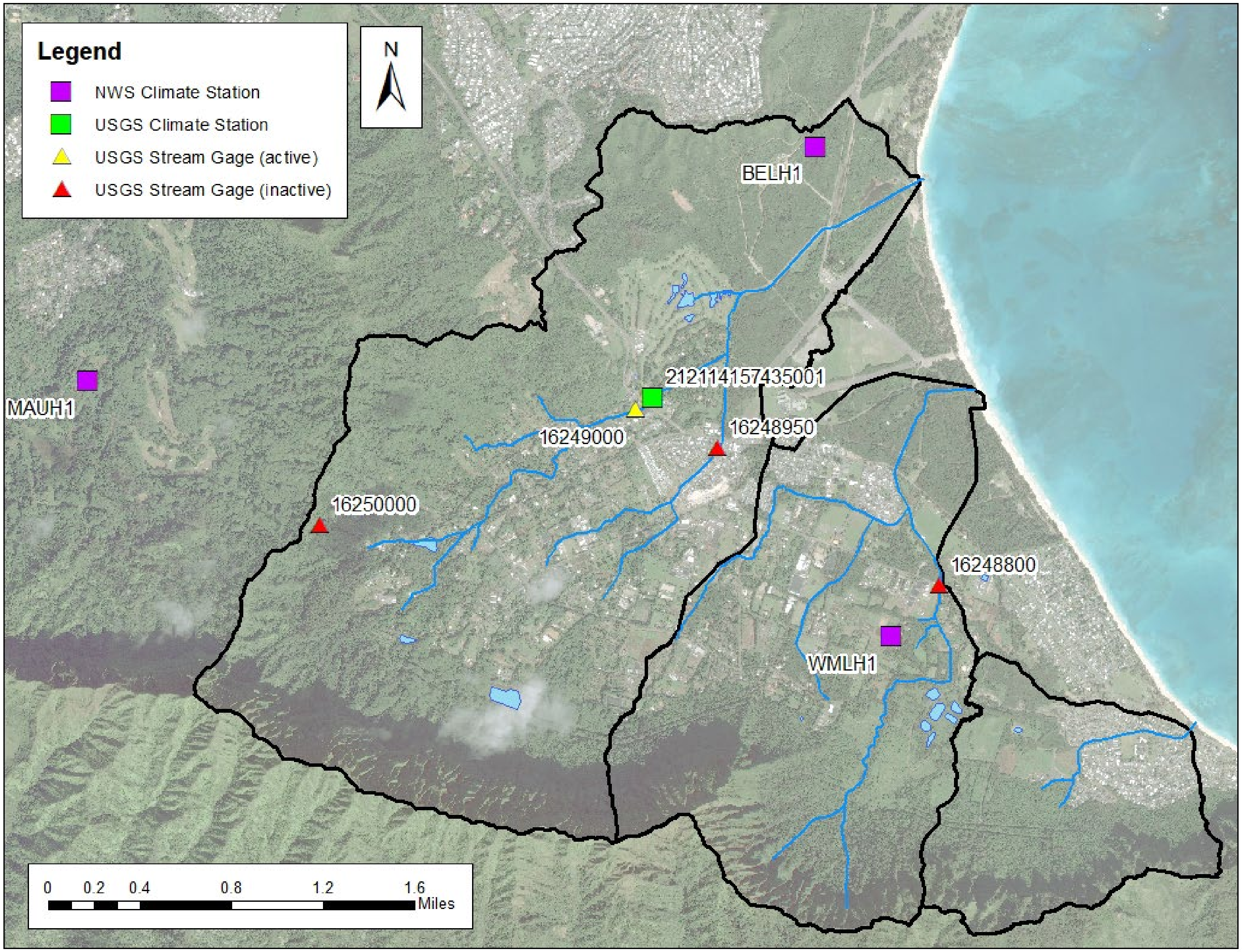


**Figure 4-1: Climate and Stream Gaging Stations in the Study Area**

**Table 4-1: Climate Station Inventory**

| Agency | Site Number / Network:ID | Site Name | Period of Record | Datum of gage (ft above LMSL[1]) | Latitude | Longitude |
|---|---|---|---|---|---|---|
| NWS | BELH1 | Waimanalo – Bellows AFB | 2012 – 2022 | 21.37 | 21.36670 | -157.71670 |
| NWS | MAUH1 | Maunawili Near Waimanalo | 2012 – 2022 | 413 | 21.35111 | -157.76667 |
| NWS | WMLH1 | Waimanalo Nonokio | 2012 – 2022 | 65 | 21.33556 | -157.71167 |
| USGS | 212114157435001 | Waimanalo Rain Gage, Oahu, HI | 1992 – 2005 | 18.89 | 21.35073 | -157.7278 |
| [1]: local mean sea level | | | | | | |

## 4.2 Stream

There are three USGS stream gages within the study area that have annual peak flow data, as presented in Table 4-2: 16248800 *Inoaole Stream at Waimanalo, Oahu, HI*; 16248950 *Kahawai Stream at Waimanalo, Oahu, HI*; and 16249000 *Waimanalo Stream at Waimanalo, Oahu, HI*. The locations of these stream gages are also identified in Figure 4-1. There is also a historical stream gage located on the upper slopes of the study area: 16250000 *Maunawili Ditch nr Waimanalo, Oahu, HI* that provides instantaneous data along Maunawili Ditch from 1993 to 2002. However, this gage likely supported the former irrigation system, and its record was not used in this study.

Figure 4-2 shows the annual peak flow record at the stream flow gaging station with the longest period of record: USGS 16249000. The historic maximum flow recorded at this gage was 4,560 $ft^3/s$ on March 6, 1963. Annual peak flows generally appear to be lower following the construction of the Waimanalo 60 MG Reservoir (Section 2.4.1) in 1993, which may be due to Kailua Reservoir (located upstream of USGS 16249000) being shut down around the same time (water was not intentionally being stored upstream anymore).

**Table 4-2: Stream Station Inventory**

| Agency | Site Number | Site Name | Period of Record | Drainage Area (mi²) | Latitude | Longitude |
|---|---|---|---|---|---|---|
| USGS | 16248950 | Kahawai Stream | Peak Flow: 1999 – 2020 | 1.13 | 21.34758 | -157.7234 |
| USGS | 16248800 | Inoaole Stream | Peak Flow: 1958 – 1996 | 1.28 | 21.33879 | -157.7084 |
| USGS | 16249000 | Waimanalo Stream | Peak Flow: 1963 – 2022 Instantaneous: 2015 - 2022 | 2.13 | 21.34997 | -157.7289 |
| USGS | 16250000 | Maunawili Ditch nr Waimanalo, Oahu, HI | Instantaneous: 1993 – 2002 | N/A | 21.34268 | -157.7503 |

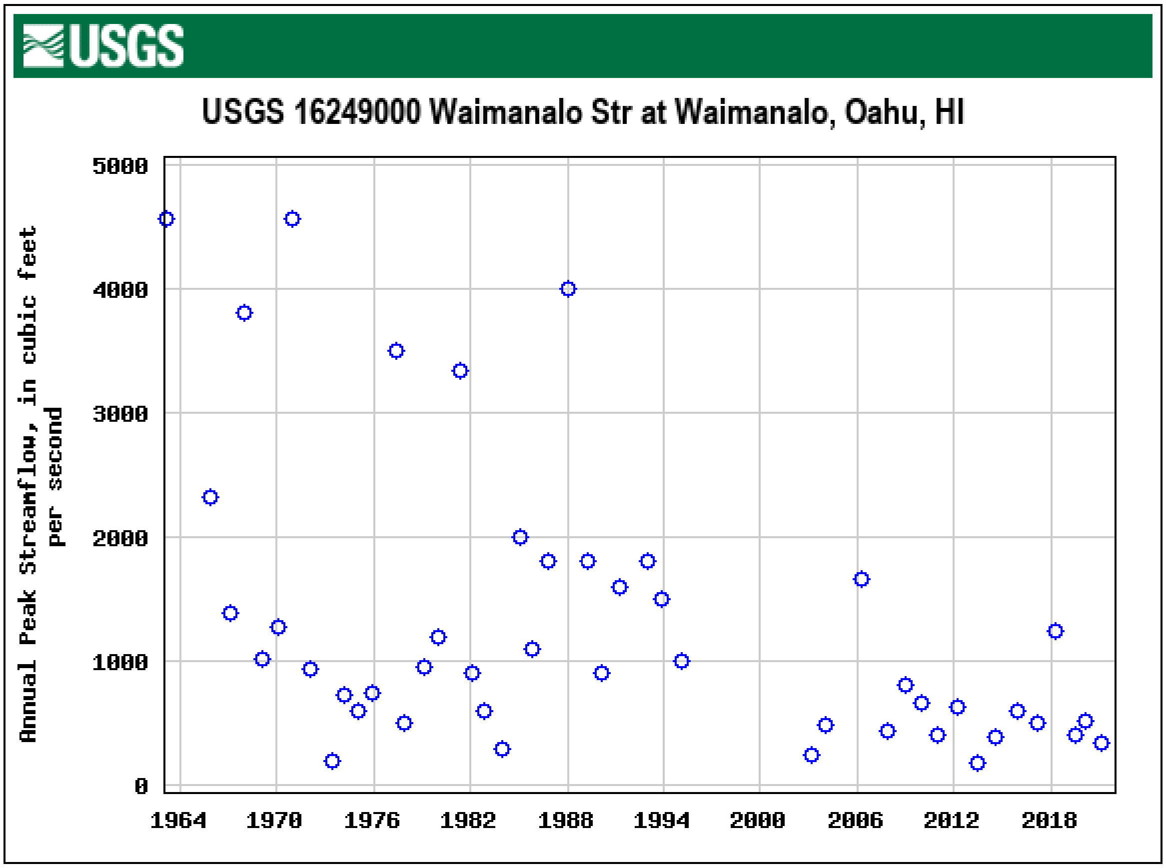


**Figure 4-2: Peak stream flow at USGS 16249000**

## 4.3 Flood History

Since the construction of the Waimanalo 60 MG Reservoir in 1993, there have been two notable floods in the study area: 31 March 2006 and 13 April 2018. On 31 March 2006, heavy rains resulted in Kailua Reservoir overtopping (Section 2.4.3) and spilled wastewater at the Waimanalo Treatment Plant. Reportedly heavy rains over the past several weeks left the ground very saturated (City and County of Honolulu, 2006). Between 10:30 a.m. and 1:00 p.m. HST on 31 March 2006 to 1 April 2006, rain fell at the rate up to three inches an hour in Waimānalo on the southeast coast (Wikinews, 2006). The peak streamflow recorded at USGS 16249000 during this event was 1,670 cubic feet per second ($ft^3/s$).

On the evening of 13 April 2018, intense rainfall moved across east O‘ahu with rates greater than 4 inches per hour (NWS, 2018). Although the affected area was localized, the intensity of the rainfall produced tremendous amounts of runoff which produced substantial damage to communities from Maunawili to Waimānalo. From the NWS report on the event, “Drainage basins responded rapidly to the burst of rain over east Oahu. At Waimānalo Stream on the windward side of the Koolau Range, the water level rose 3 feet in about 30 minutes and 5 feet in an hour” (NWS, 2018). The stage and flow hydrographs for this event at USGS 16249000 are included as Figure 4-3 and Figure 4-4, respectively. The peak streamflow recorded at USGS 16249000 during this event was 1,240 cubic feet per second ($ft^3/s$). Post-flood photos included in the NWS provided were also included in this report. Photo 4-1 shows Kahawai Stream channel at Bellows Air Force Station (21°20'49.87"N, 157°42'39.46"W). Vegetation debris along the banks shows that water got high enough to spill over the road. Photo 4-2 is the tributary of Kahawai Stream at Hihimanu Street (21°20'19.85"N, 21°20'19.85"N). Temporary rails were reinstalled after the event. The channel is quite small at this location and easily overflowed. Photo 4-3 shows Waikupanaha Street, where considerable runoff occurred during the event based on the large amount of debris deposited in the area. The road has already been cleared of debris in the photo.

As reported by Hawaii News Now, “rushing water topped the banks of a canal that runs along Mekia Street, and floodwaters sent cars and debris rushing toward homes" (Lund, 2018). Roads were also reportedly impassable in parts of Waimānalo (HNN Staff, 2018). According to residents who live on Mekia Street, they alerted city officials multiple times to address the debris that was stacking up inside the river running through their neighborhood prior to the flood event. During the event, a massive tree fell over and completely obstructed one of the culverts (Photo 4-4). Waters rose to the street level and sent a wall of mud and debris into the neighborhood (Lincoln, 2018).

A strong Kona low[3] produced heavy rainfall on December 5–6, 2021 that had major impacts throughout the State of Hawaii, including significant flooding and loss of power in urban parts of Honolulu. Its impact to the study area, however, was somewhat limited compared to other parts of Oʻahu. This determination was based on the unremarkable stream flow record and lack of articles on the event impacting the Waimānalo community.

[3] Hawaii is dominated by the trade winds that blow in from the northeast. However, the counter-clockwise flow around a Kona low located west of Hawaii results in southwesterly winds over the islands, which is typically the leeward or "kona" side. Kona storms are common between October and April.

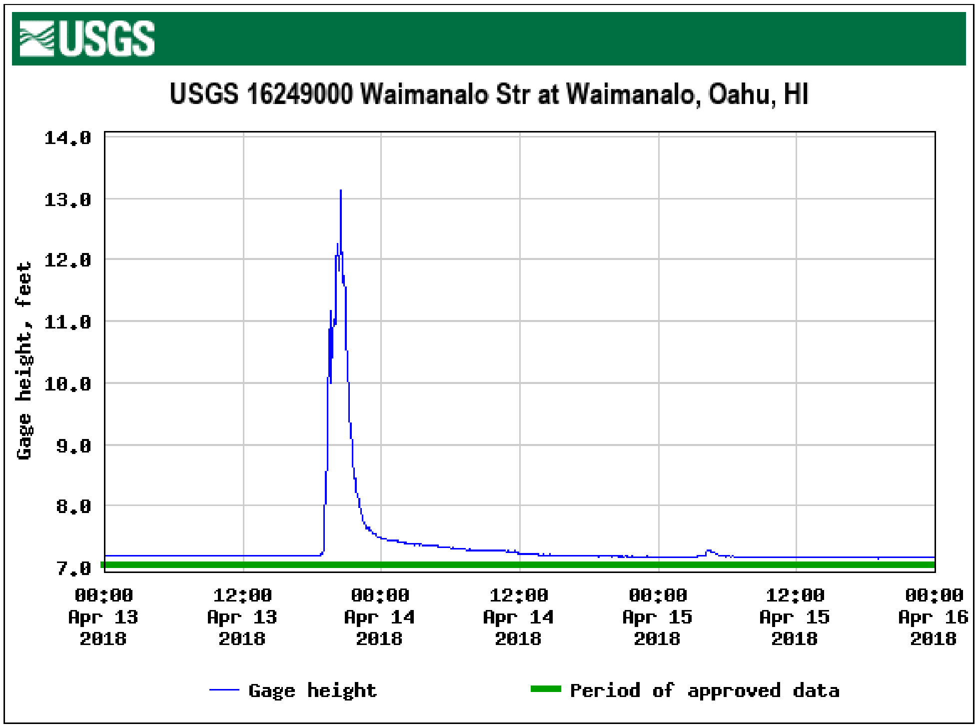


**Figure 4-3: Stage Hydrograph at USGS 16249000, Waimanalo Stream during the April 13 – 15, 2018 Flood Event**

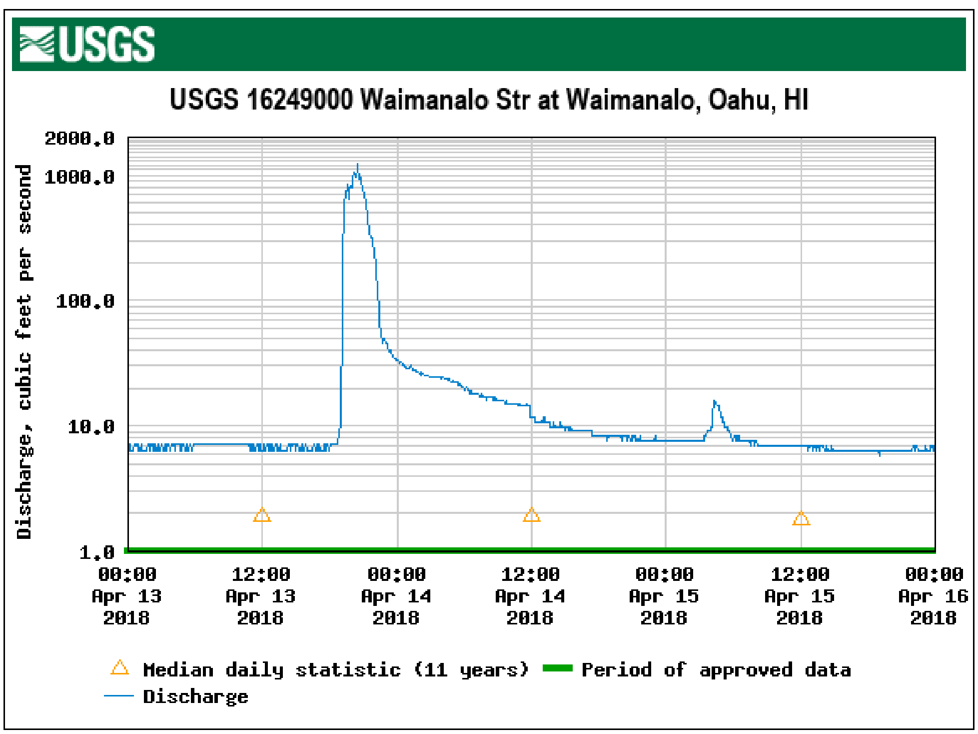


**Figure 4-4: Flow Hydrograph at USGS 16249000, Waimānalo Stream during the April 13 – 15, 2018 Flood Event**

Source: *April 13 – 15, 2018 Flash Flooding on Kauai and Oahu*, NWS Report

**Photo 4-1: Kahawai Stream channel at Bellows Air Force Station**

Source: *April 13 – 15, 2018 Flash Flooding on Kauai and Oahu*, NWS Report

**Photo 4-2: Tributary of Kahawai Stream at Hihimanu St**

Source: *April 13 – 15, 2018 Flash Flooding on Kauai and Oahu*, NWS Report

**Photo 4-3: Cleared Debris on Waikupanaha Street**

Source: *Mileka Lincoln, 2018*

**Photo 4-4: Culvert Obstructed by Debris during April 2018 Flood Event**

# 5 Flood Frequency Analysis

A flood frequency analysis was performed to determine the magnitude of the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) annual exceedance probability (AEP) flood discharges for the Waimānalo community. Methods for estimating the peak flow for these five profiles include the following:

1. Stream gage analysis
2. Regional regression equations
3. Rainfall-runoff model

Detailed information on the application of each method of analysis and a comparison of results is included in Appendix B, Hydrology.

## 5.1 Final Flow Frequency Estimates

The resulting flow frequency estimates computed by the rainfall-runoff method were determined to be the final “adopted” peak flow values to carry forward in this study. This method of analysis was selected to be the best representation of the site and flow conditions, as site-specific characteristics were used to develop the rainfall-runoff model, which was then calibrated to real and recent historical storm events. Final peak flow estimates are presented in Tables 5-1 through 5-4. Figure 5-1 is provided as a location reference.

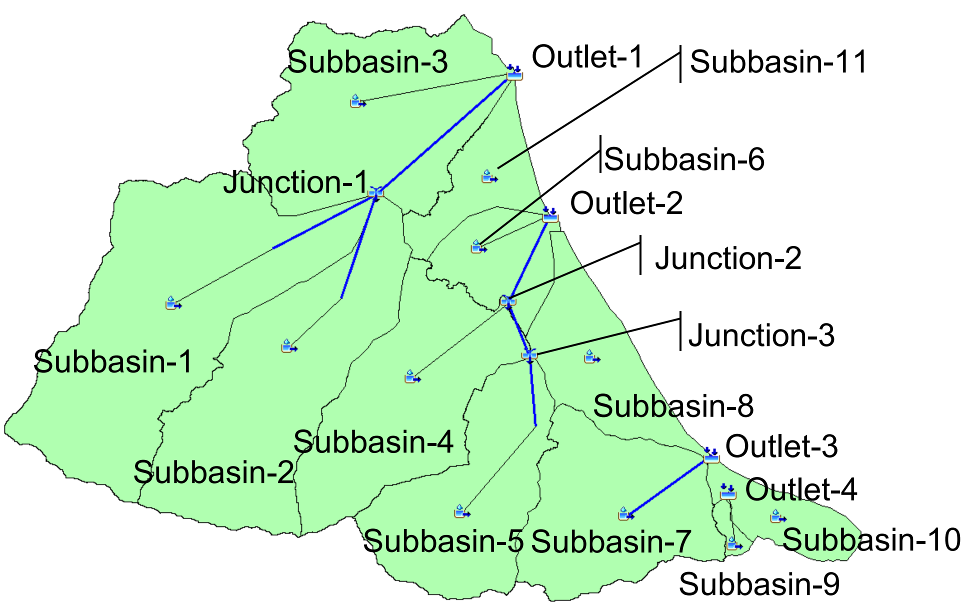


**Figure 5-1: HMS Basin Layout for Reference**

**Table 5-1: Peak flow estimates for the Waimānalo Watershed**

| HEC-HMS Element | | | | | | |
|---|---|---|---|---|---|---|
| | | Subbasin-1 | Subbasin-2 | Junction-1 | Subbasin-3 | Outlet-1 |
| **Peak Flow ($ft^3/s$)[1]** | | | | | | |
| **Annual Exceedance Probability (AEP)** | **1/2** | 843 | 809 | 1,630 | 300 | 1,530 |
| | **1/5** | 1,450 | 1,320 | 2,740 | 499 | 2,620 |
| | **1/10** | 2,514 | 2,210 | 4,680 | 885 | 4,640 |
| | **1/25** | 2,510 | 2,210 | 4,680 | 885 | 4,640 |
| | **1/50** | 3,020 | 2,620 | 5,590 | 1,060 | 5,630 |
| | **1/100** | 3,550 | 3,040 | 6,540 | 1,240 | 6,660 |
| | **1/200** | 4,110 | 3,490 | 7,540 | 1,430 | 7,740 |
| | **1/500** | 4,880 | 4,100 | 8,920 | 1,700 | 9,240 |

[1]: rounded to three significant figures

**Table 5-2: Peak flow estimates for the Kahawai Watershed**

| HEC-HMS Element | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Subbasin-4 | Subbasin-5 | Junction-3 | Junction-2 | Subbasin-6 | Outlet-2 |
| Peak Flow ($ft^3/s$)[1] | | | | | | | |
| Annual Exceedance Probability (AEP) | **1/2** | 553 | 246 | 245 | 765 | 399 | 1,030 |
| | **1/5** | 897 | 402 | 402 | 1,268 | 682 | 1,750 |
| | **1/10** | 1,500 | 676 | 675 | 2,150 | 1,180 | 3,070 |
| | **1/25** | 1,500 | 676 | 675 | 2,150 | 1,180 | 3,070 |
| | **1/50** | 1,790 | 801 | 801 | 2,560 | 1,400 | 3,680 |
| | **1/100** | 2,080 | 931 | 931 | 2,980 | 1,650 | 4,320 |
| | **1/200** | 2,380 | 1,070 | 1,070 | 3,420 | 1,900 | 4,990 |
| | **1/500** | 2,810 | 1,260 | 1,250 | 4,040 | 2,270 | 5,930 |

[1]: rounded to three significant figures

**Table 5-3: Peak flow estimates for the Kaiona Watershed**

| HEC-HMS Element | | | |
|---|---|---|---|
| | | Subbasin-7 | Outlet-3 |
| Peak Flow ($ft^3/s$)[1] | | | |
| Annual Exceedance Probability (AEP) | **1/2** | 963 | 552 |
| | **1/5** | 1,510 | 897 |
| | **1/10** | 1,900 | 1,180 |
| | **1/25** | 2,430 | 1,560 |
| | **1/50** | 2,840 | 1,890 |
| | **1/100** | 3,270 | 2,240 |
| | **1/200** | 3,710 | 2,610 |
| | **1/500** | 4,330 | 3,150 |

[1]: rounded to three significant figures

**Table 5-4: Peak flow estimates for the Unnamed Watershed**

| HEC-HMS Element | | | |
|---|---|---|---|
| | | Subbasin-9 | Outlet-4 |
| Peak Flow ($ft^3/s$)[1] | | | |
| Annual Exceedance Probability (AEP) | **1/2** | 96.3 | 96.3 |
| | **1/5** | 128 | 128 |
| | **1/10** | 153 | 153 |
| | **1/25** | 188 | 188 |
| | **1/50** | 216 | 216 |
| | **1/100** | 244 | 244 |
| | **1/200** | 275 | 275 |
| | **1/500** | 318 | 318 |

[1]: rounded to three significant figures

# 6 Development of the Hydraulic Model

A two-dimensional (2D), unsteady flow hydraulic model was developed for this study using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software (version 6.2, HEC, 2022). This model was used to simulate flow in streams and across the floodplain within the limits of the study area. The following list provides an overview of the steps completed to create this model. Additional information is provided in the sections that follow.

1. **Establish a horizontal coordinate projection to use in the model.** The horizontal coordinate projection was set to NAD83 (PA11), State Plane Zone 3 (US Survey Feet).
2. **Develop a terrain model in RAS Mapper.** A terrain model was created in RAS Mapper based on 2013 LiDAR data 2003 IfSAR data, as described in Section 0.
3. **Build a land classification data set to establish Manning's n values (roughness coefficient) within the 2D Flow Areas.** A circa 2011 high resolution (1 to 5 meter) land cover raster was used to represent various land covers in the study area. Each cover type was assigned a unique roughness coefficient.
4. **Add any additional mapping layers needed (i.e. aerial imagery, road networks).** High resolution imagery used for background mapping of the study area is from DigitalGlobe, the National Geospatial-Intelligence Agency and the USGS. World Imagery, provided by Esri, was used for larger scale background mapping, such as when it was necessary to show the entire island of O‘ahu. Other GIS data (i.e. road networks) was provided by the City and County of Honolulu, Department of Planning and Permitting through the Hawaii Statewide GIS Program's Geospatial Data Portal [https://geoportal.hawaii.gov/].
5. **Outline the 2D Flow Area.** The 2D Flow Area defines the boundary for which 2D computations will occur. Four 2D Flow Areas were drawn to represent the study area, extending from Waikupanaha Street to the shoreline. The primary 2D Flow Area represents the main river systems in the Waimānalo, Kahawai, and Kaiona watersheds. Three additional 2D Flow Areas were added that are somewhat independent drainage areas along the coast (they do not contribute significant flow to the main river systems).

6. **Layout any break lines within the 2D flow area to force the mesh to align the computation cell faces along the break lines.** Break lines were added to represent significant barriers to flow (i.e. levees, roads, high ground). They were also added along the channel invert and banks of main river systems.
7. **Create the 2D computational mesh for each 2D flow area.** The primary 2D Flow Area "Perimeter 1" has a base cell size of 40, refined as needed along rivers, road embankments, high ground barriers, and hydraulic structures (i.e. bridges and culverts). The three 2D Flow Areas representing independent coastal drainage areas have a base cell size of 30, which was also refined, as needed.
8. **Add internal hydraulic structures or bridges inside the 2D Flow Area(s) using the SA/2D Area Hydraulic Connection feature**. An SA/2D Area Hydraulic Connection feature was created to represent each major bridge, culvert, or crossing in the study area. Bridge and culvert data (i.e. field measurements and photos) are summarized in Appendix D**.**
9. **Draw any external boundary condition lines along the perimeter of the 2D Flow Areas.** Several external boundary condition lines were drawn along the upper boundary of the study area, representing flow coming from the steep slopes of the Koolau Range. Along the coast, external boundary conditions were drawn to represent the ocean stage and attenuation of flow entering it.
10. **Enter all the necessary boundary and initial condition data for the 2D Flow Areas in the Unsteady Flow data editor.** Data for the internal "Precipitation" and external "Flow Hydrograph" boundary conditions were computed outputs from the rainfall-runoff model described in Appendix B, Hydrology. The "Precipitation" boundary condition was used to directly apply rainfall excesses to the three coastal 2D Flow Areas. An external "Stage Hydrograph" boundary condition was used to represent the ocean at the downstream end of the study area for all 2D Flow Areas.
11. **Run the Unsteady Flow simulation and review the results in RAS Mapper.** Results are summarized in Section 7, Conclusion.

## 6.1 Results

Flood hazard maps are included in Appendix A. General flood risk to the community is described in the following sections.

### 6.1.1 Upper Waimānalo Stream:

There is moderate risk of flooding to the residential and commercial properties near Waimānalo Stream, upstream of Kalaniana‘ole Highway (Figure 6-1), where properties are inundated 1 – 3 feet during the 1% AEP flood event. Flooding along Flamingo Street is also expected to occur during smaller frequency events, such as the 10% AEP flood (statistically, once every ten years).

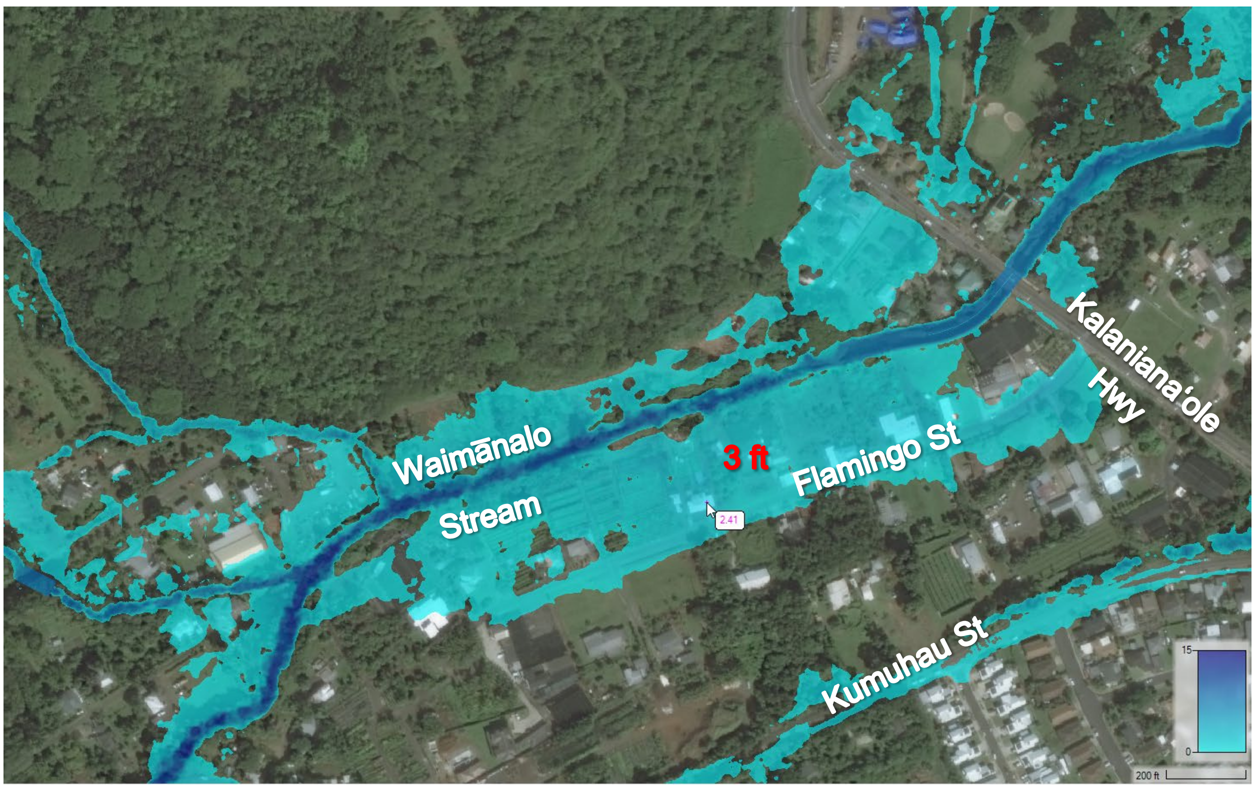


**Figure 6-1: Flood Hazard Map for the 1% AEP Flood, Waimānalo Stream near Kalaniana‘ole Highway.**

### 6.1.2 Tributaries to Kahawai Stream (Stream A and Stream B)

Some commercial properties along Stream A (north of Kakaina Street) are at risk of flooding at depths of approximately 1 – 5 ft (Figure 6-2). At the junction between Stream A and Stream B, there is also overtopping into the floodplain (Camp Kibble).

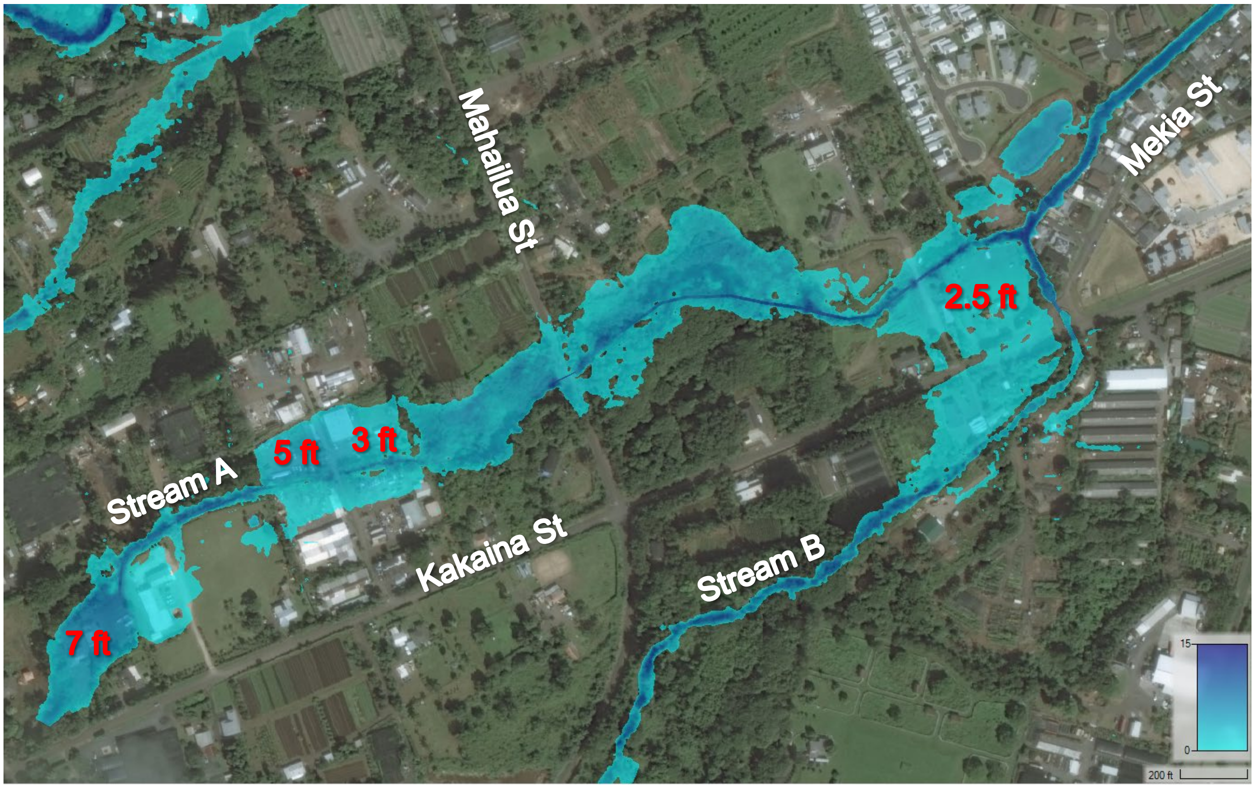


**Figure 6-2: Flood Hazard Map for the 1% AEP Flood, Tributaries to Kahawai Stream (Stream A and Stream B), Waimānalo Watershed**

### 6.1.3 **Kahawai Stream**

Overtopping from Stream C results in additional flow entering the Kahawai Stream just downstream (north) of the Kalanianaʻole Hwy. Residential and commercial properties along Mokulama St are likely to experience shallow flooding of 1 – 3 ft. Properties along Kalanianaʻole Hwy that are close to a stream or tributary also experience shallow flooding of 1 – 3 ft.


**Figure 6-3: Flood Hazard Map for the 1% AEP Flood, Kahawai, Waimānalo Watershed**

### 6.1.4 Lower Waimānalo Stream

Flooding is more extensive along the lower reach of Waimānalo Stream, with frequent overtopping of the stream even during lower frequency events (i.e. the 10% AEP flood). The impact, however, is limited to flooding of the Olomana Golf Links grounds (depths ranging from 1 – 10 ft) and overtopping of a bridge on Bellows AFB (with approximately 3 feet of overtopping predicted). The coastal bridge (Tinker Rd) is not overtopped during the 1% AEP event simulation.

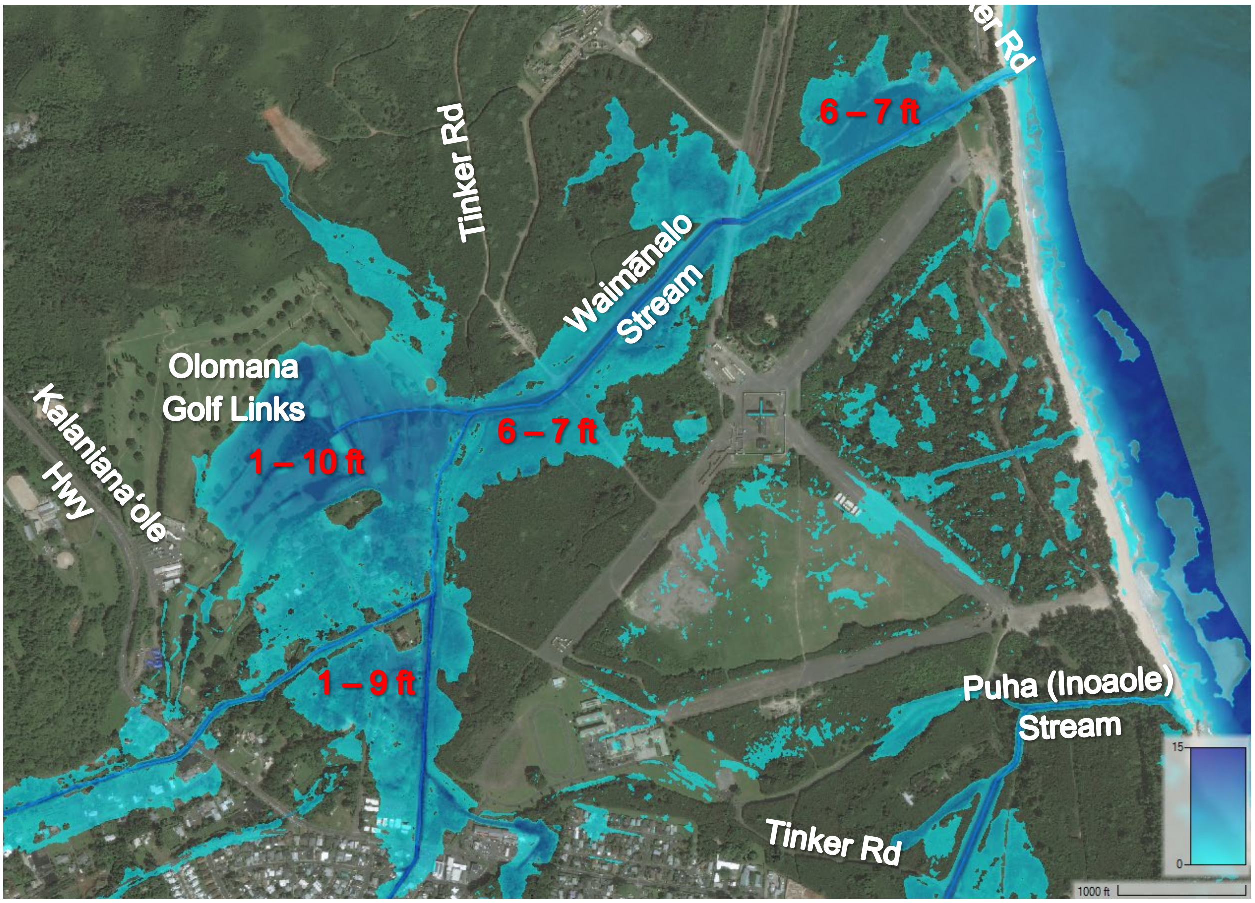


**Figure 6-4: Flood Hazard Map for the 1% AEP Flood, Lower Waimānalo Stream**

### 6.1.5 **Tributaries to Puha (Inoaole) Stream (Stream C and Stream D)**

Overflow from Stream C travels north towards Hihimanu St and Kakaina St, inundating properties along Mokulama St with 1 – 2 ft of flooding during the 1% AEP flood. Properties north of Hihimanu Street and west of the Waimānalo District Park are also at risk of flooding, primarily along the roads and low spots at predicted depths of 1 – 2 ft during the 1% AEP flood. Stream D overtops the banks near Ahiki St, flowing north towards Hihimanu St and eventually joining Stream C.


**Figure 6-5: Flood Hazard Map for the 1% AEP Flood, Tributaries to Puha (Inoaole) Stream, Kahawai Watershed**

### 6.1.6 **Puha (Inoaole) Stream**

Overflow from Puha (Inoaole) Stream results in widespread flooding along the right bank. Kalanianaʻole Hwy is overtopped by approximately 1 – 2 feet from the bridge near Inoaole Street to Aloiloi Street. Properties along Kalanianaʻole Hwy are inundated by approximately 2 – 4 feet.


**Figure 6-6: Flood Hazard Map for the 1% AEP Flood, Puha (Inoaole) Stream, Kahawai Watershed**

### 6.1.7 **Coastal Properties near Sherwood Beach**

There was no defined channel system affecting this subdivision between Kalanainaʻole Hwy and Waimanalo Bay, so areas at risk of flooding were identified by simulating direct rainfall on the area. Overall, there is a low risk of flooding due to rainfall. However, there may be a few properties at risk of localized flooding (approx. 1 – 2 ft depths) if their property is in a low spot and not otherwise designed to facilitate flow away from their property. Properties along Kalanianaʻole Hwy appear to also have an increased risk of flooding.

Existing stormwater systems are not reflected in this model, so actual flooding due to rainfall may be less. However, these systems are typically designed to accommodate flows up to the 10% AEP event (statistically, once every ten years) and unlikely to accommodate larger events, such as the 1% AEP event (statistically, once every one hundred years). This study does not include evaluation of flood risk due to wave action. Potential impacts from sea level change were evaluated separately and described in Section 6.2.6.


**Figure 6-7: Flood Hazard Map for the 1% AEP Flood, Subdivision between Kalaniana'ole Hwy and Waimanalo Bay**

### 6.1.8 **Unnamed Stream #1, Kaiona Watershed**

Flows from the Koʻolau Range (upper watershed) overwhelm the concrete-lined ditch resulting in shallow street flooding along mountain-side properties, specifically those on the southern bend of Nakini Street. The Nakini St Bridge and a pedestrian bridge near Blanche Pope Elementary School are overtopped by approximately 3 feet of water during the 1% AEP flood event. The surrounding area is also inundated by approximately 3 feet of water for 1 – 2 hours.

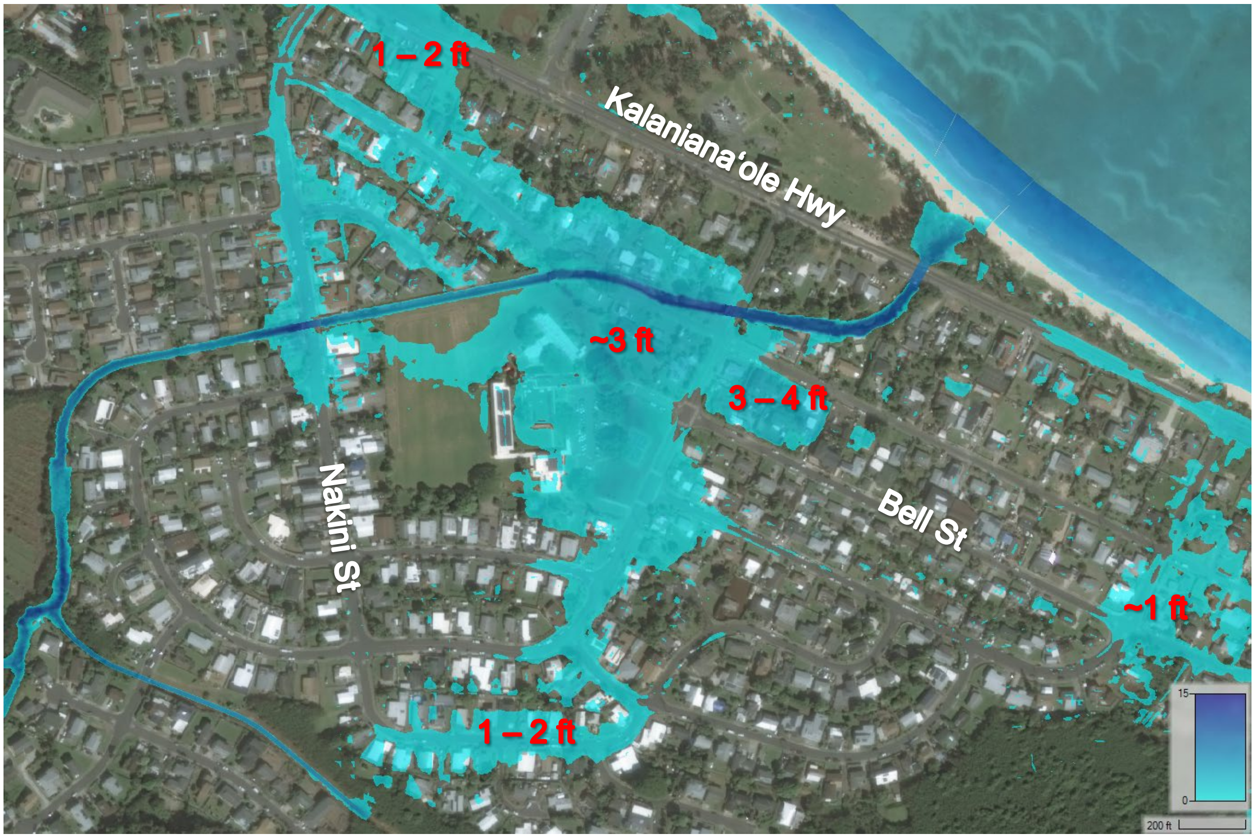


**Figure 6-8: Flood Hazard Map for the 1% AEP Flood, Unnamed Stream #1, Kaiona Watershed**

### 6.1.9 **Residential Properties in Eastern Waimānalo**

Some residential properties between the Koʻolau Range and Kalanianaʻole Hwy may experience as much as 5 feet of flooding as a result of ponding / rainfall accumulation. In this scenario, the 24-inch culvert that runs under Bell St and Kalanianaʻole Hwy was not included (representing its obstruction near the outlet due to sand or debris). An additional simulation was run where the culvert was cleared and is described in Section 6.2.3.


**Figure 6-9: Flood Hazard Map for the 1% AEP Flood, Eastern Waimanalo Residential Area**

## 6.2 Additional Scenarios

The hydraulic model representing existing site conditions was adjusted to represent theoretical scenarios that had the potential to increase or decrease the community flood hazard. The following scenarios were modeled:

1. Increasing vegetation in the streams and channels;
2. Bridge and culvert obstructions by debris and vegetation;
3. Clearing sand bars at the outlet; and
4. Sea level change

### 6.2.1 **Increased Channel Vegetation**

Manning's roughness coefficient, *n*, is an empirically derived coefficient that is dependent on several variables, such as vegetation, obstructions, and meandering when applied to open channels. In this scenario, Manning's n was increased only in the channel and by 50% to represent increased vegetation in the channels. The resulting flood impacts (shown as a red bottom layer in Figure 6-10), however, were not much different than the original, existing conditions scenario (shown as a blue top layer in Figure 6-10) under the 1% AEP flood. Additional flooding was noted along Humuniki Street. Other small areas in the community experienced additional flooding, but the extent was very limited and depths were less than one foot (< 1 ft).

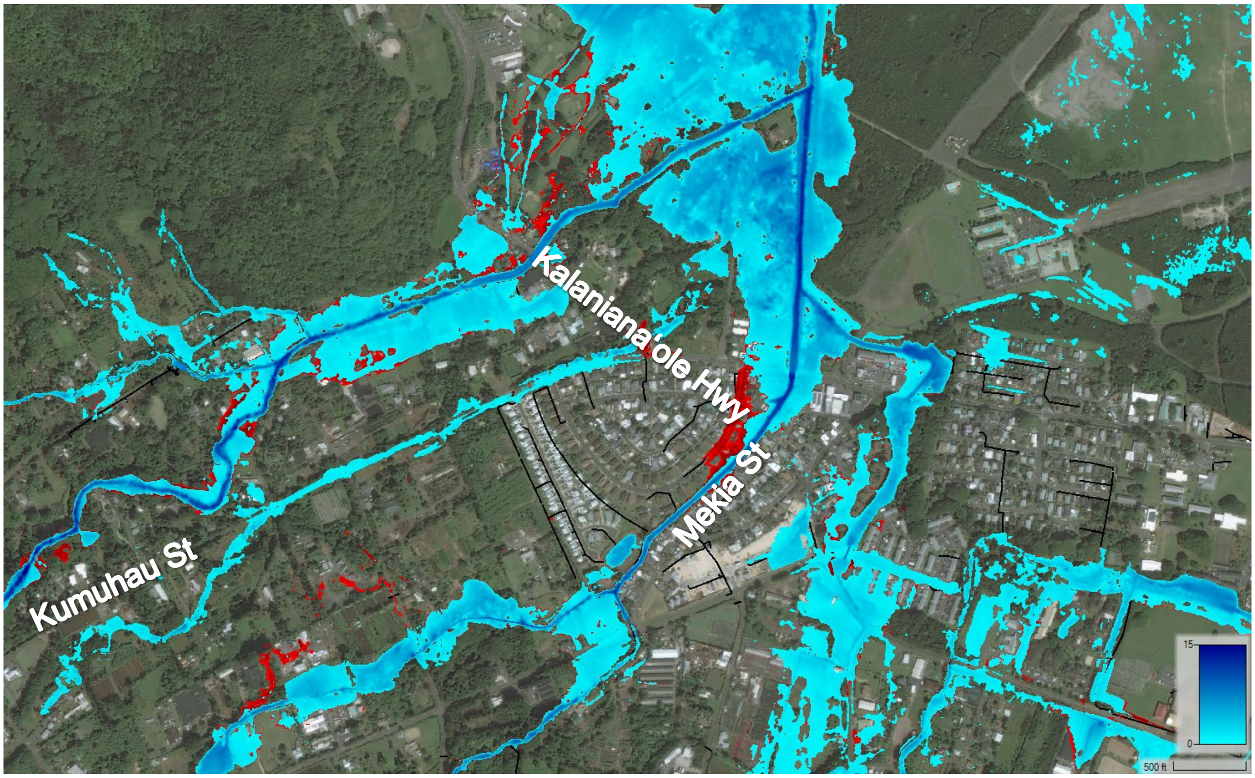


**Figure 6-10: Resulting difference in the 1% AEP floodplain boundary from the original, existing conditions model (blue) and increasing channel vegetation (red)**

### 6.2.2 Bridge and Culvert Obstructions by Debris

For this scenario, the following culverts were obstructed with debris or sediment:

- 9 Mahaiulua St Culvert 1
- 10 Mekia St Culvert 1
- 11 Kakaina St Culvert 1
- 12 Hihimanu St Culvert 1
- 15 Makakalo St Culvert 1
- 16 Ahiki St Culvert 2
- 25 Mahiku Pl Culvert 1
- 38 Mokulama St Culvert 1
- 39 Bell St Culvert 1

The vertical clearance was reduced to 25% of its original height (75% obstruction). Bridges or large culverts that were likely to pass most vegetation, debris, and sediment, or those associated with lined channels where there was a low probability of an obstruction were not selected. Flood depths in the channels immediately upstream of these culverts increased. However, additional flooding to the community was limited to shallow (< 1 ft) flooding along Ahiki St (Figure 6-11) and Mekia St (Figure 6-12).

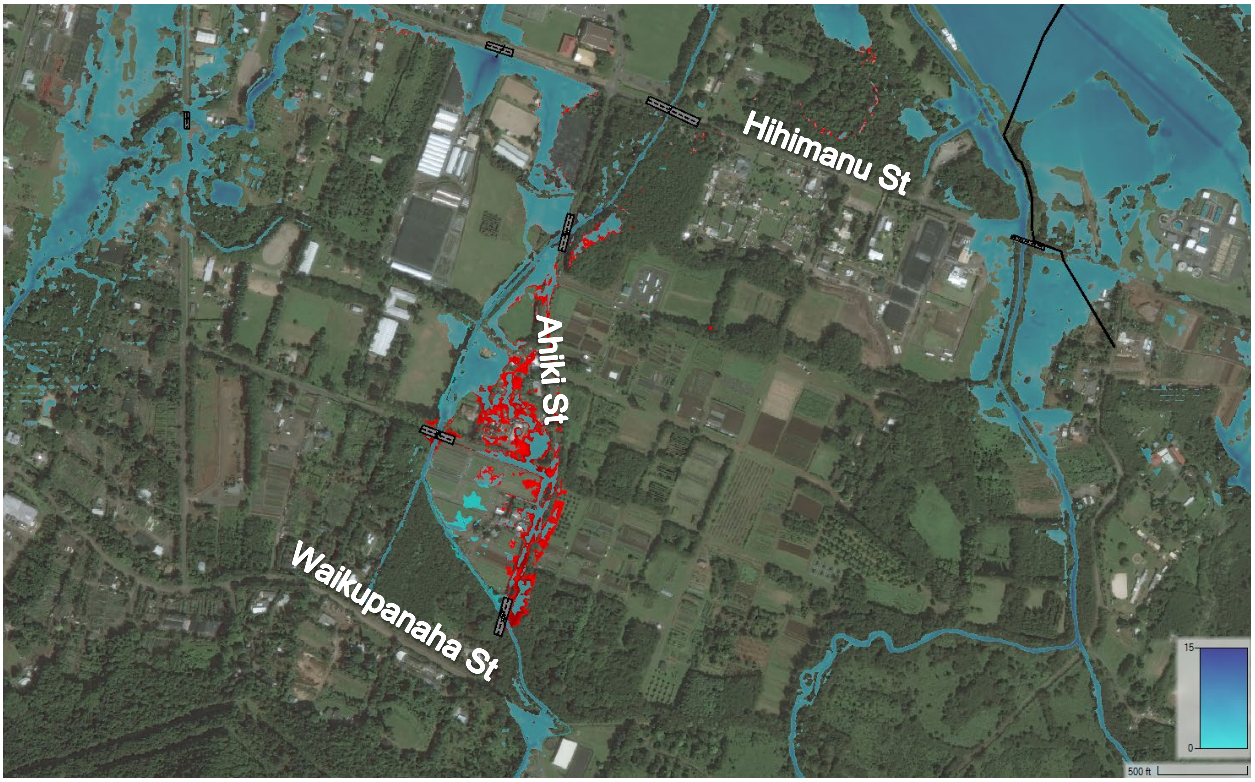


**Figure 6-11: Increased flooding due to culvert obstructions near Ahiki St**


**Figure 6-12: Increased flooding due to culvert obstructions near Mekia St**

### 6.2.3 **Waimānalo Stream Outlet Cleared**

Approximately 2,360 ft of the channel was lowered and cut to represent dredged conditions along the lower reach of Waimānalo Stream. As seen in Figure 6-13, the effects were negligible.

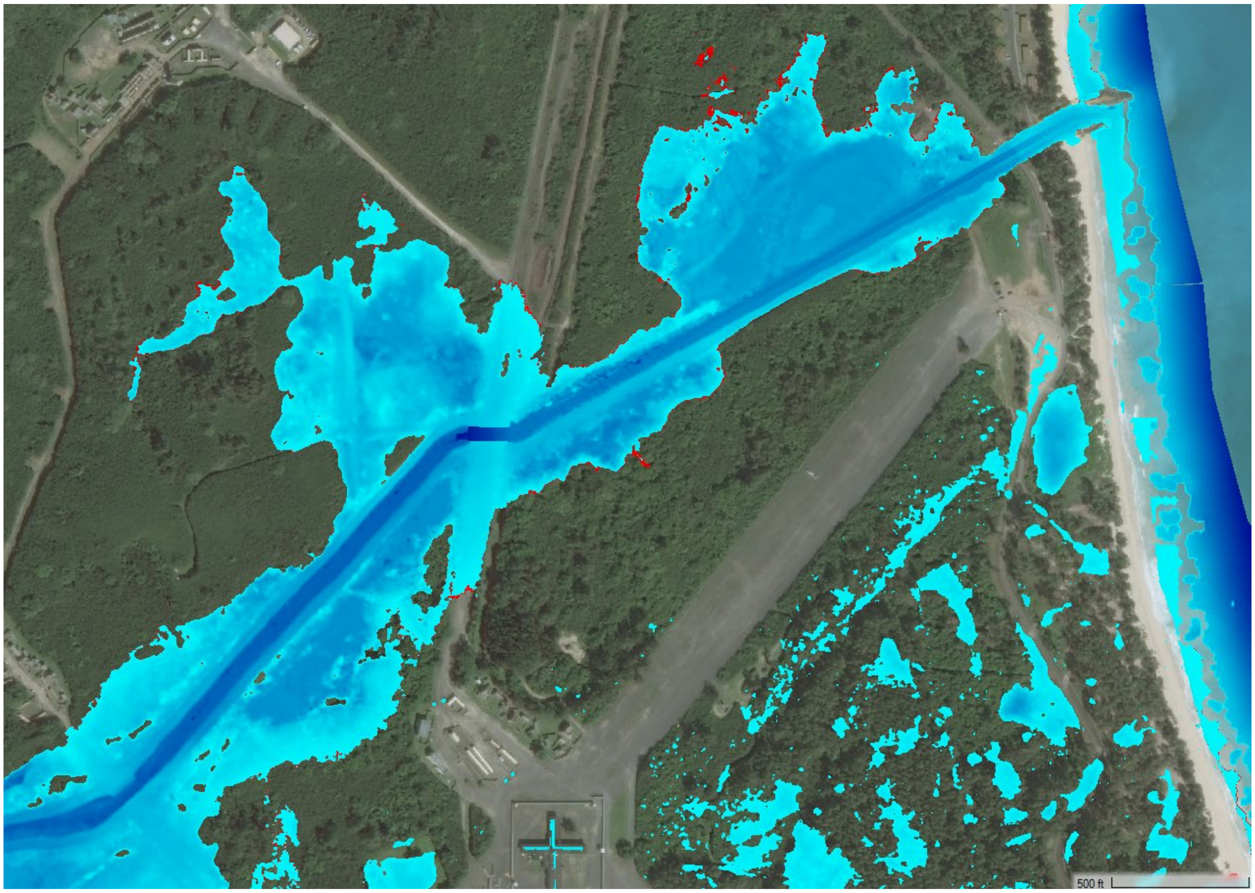


**Figure 6-13: Resulting difference in the 1% AEP floodplain boundary between the original, existing conditions model (red) and dredged scenario (blue) for Waimānalo Stream**

### 6.2.4 **Puha (Inoaole) Stream Lower Channel and Outlet Dredged**

Approximately 1,700 feet of the downstream reach of Puha (Inoaole) Stream was lowered and cut to represent dredged conditions and a continuous channel downslope to Waimānalo Bay. This did not significantly affect the floodplain boundary or depths. Kalaniana‘ole Hwy is still overtopped upstream, as shown in Figure 6-14.

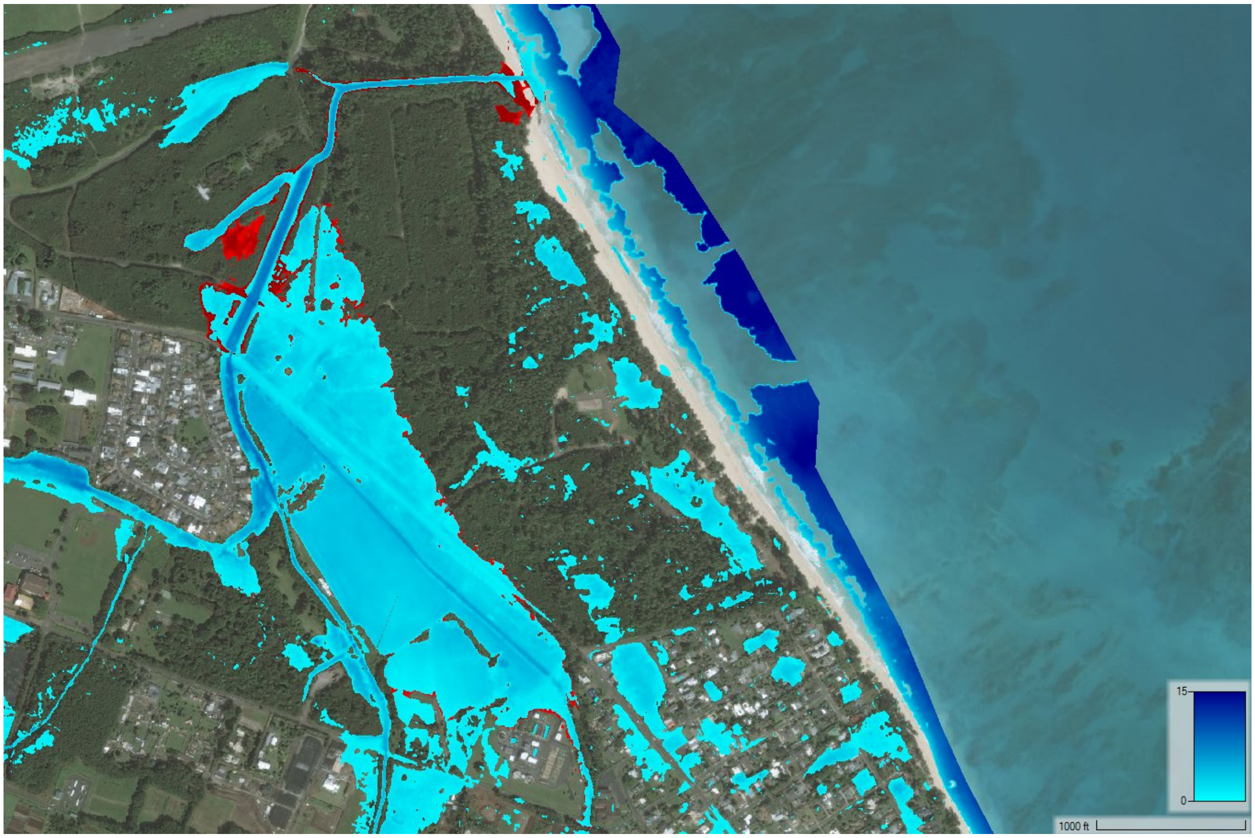


**Figure 6-14: Resulting difference in the 1% AEP floodplain boundary between the original, existing conditions model (red) and dredged scenario (blue) for Puha (Inoaole) Stream**

### 6.2.5 **Cleared Culverts in Eastern Waimānalo**

In eastern Waimānalo, two changes were made to increase the effectiveness of existing structures. First, a culvert was added representing the existing intake and culvert along Bell Street that carries flow under Kalaniana‘ole Hwy and discharges into Waimānalo Bay (Photo 6-2). In the original (existing conditions) model, this culvert was not included because it was observed in the field to be obstructed (ineffective), as shown in Photo 6-3. In this simulation, the culvert was cleared and there were no obstructions to flow.

Although the culvert near the intersection of Bell St and Hoomaha St was included in the original model, the heavily vegetated swale was cleared for this simulation. The effects from these two changes were not significant during the 1% AEP (1/100) flood event. This was expected as most stormwater systems are designed to a higher frequency event, such as the 10% AEP (1/10) flood event. Although the extent of flooding is still about the same, it did reduce the depth by about 0.5 ft. The 10% AEP flood was also run under this scenario, but the effects were similar (not much difference in the floodplain boundary, and lower flood depths of about 0.5 ft).

**Photo 6-1: Heavily vegetated swale leading to culvert / stormwater system near Hoomaha St**

**Photo 6-2: Intake / Culvert Inlet along Bell Street**

**Photo 6-3: Culvert Outlet Buried and Broken**


**Figure 6-15: Resulting difference in the 1% AEP floodplain boundary due to operational (cleared) culverts in Eastern Waimānalo**

### 6.2.6 **Sea Level Change**

In following Engineer Regulation 1100-2-8162, *Incorporating Sea Level Change in Civil Works Programs* (USACE, 2013) and ETL 1100-2-1, *Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation* (USACE, 2014), three scenarios of sea level change were projected: *low*, *intermediate*, and *high.* The gage at Mokuoloe, HI (NOAA ID: 1612480) was used for the analysis (NOAA). This gage was established in 1957 and in its present location since 1989. It is located on the west side of Moku o Lo‘e (Coconut) Island, approximately 3 miles northwest of the Waimanalo Stream outlet. The relative sea level trend for this tidal gauge is 1.69 mm/year (0.0055 ft/yr) with a 95% confidence interval of +/- 0.52 mm/yr based on monthly mean sea level data from 1957 to 2021, which is equivalent to a change of 0.55 feet in 100 years.

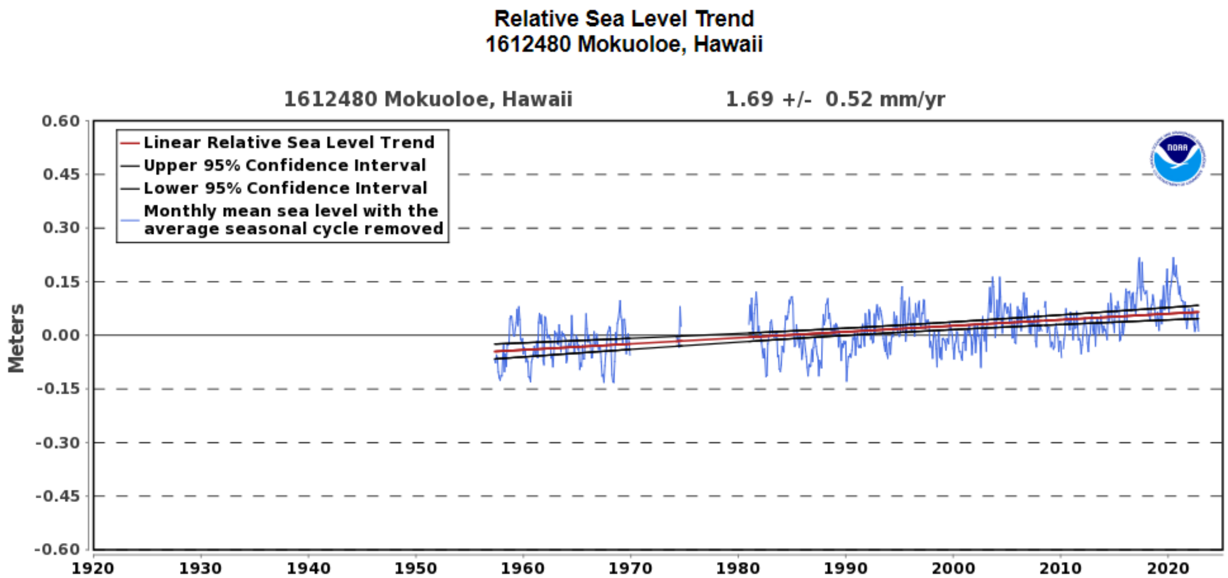


**Figure 6-16: Relative Sea Level Trend for Station 1612480, Mokuoloe, Hawaii**

The gage site was selected in the USACE Sea Level Change Calculator (Version 2022.72). The 2006 NOAA sea level change rate of 0.00430 ft/yr was less than the 2021 rate (0.00554 ft/yr). The more conservative rate (2021) was entered as the SLC rate for estimating relative sea level change projections.

The result of the calculation indicates a relative sea level change of 6.58 feet over the next 100 years for the *high* condition (7.29 feet for the year 2125 minus 0.59 feet for the year 2025 equals 6.70 feet). For the *intermediate* condition, the change was 2.03 feet, and the *low* condition shows an increase of 0.56 feet. These values are relative to Local Mean Sea Level (LMSL) as the calculator states NAVD88 datum is not available at this station. The resulting sea level rise curve is shown in Figure 6-17.

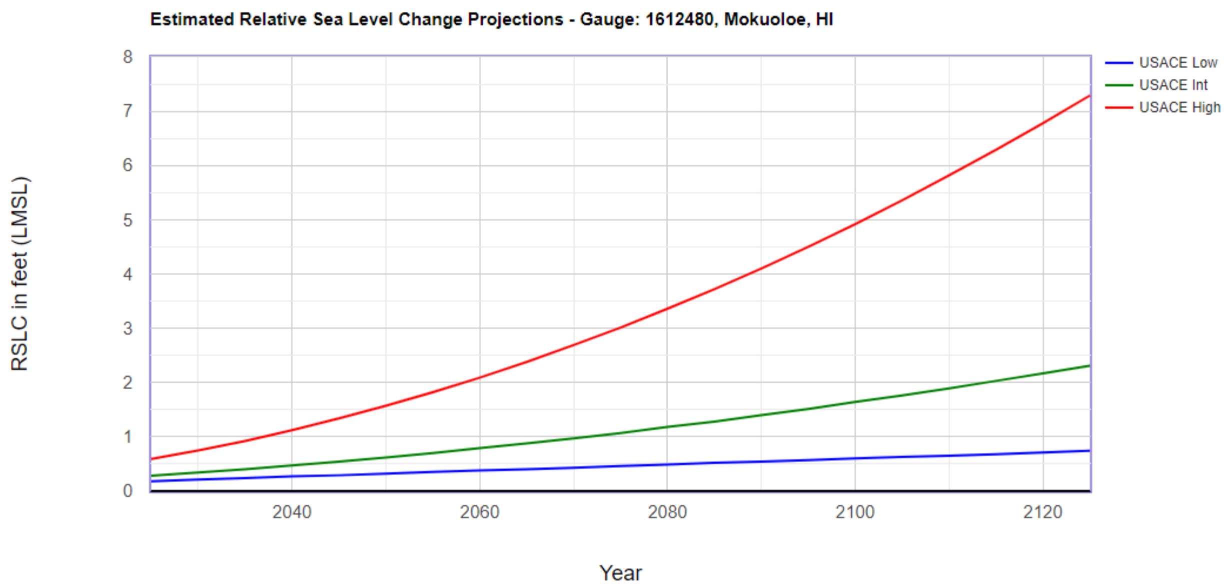


**Figure 6-17: Estimated Relative Sea Level Change Projections – Gauge: 1612480, Mokuoloe, HI**

The downstream boundary in the hydraulic model was adjusted to represent the mean higher high water (MHHW) elevation under the three different sea level change conditions. Even under *high* sea level conditions (7.77 ft MSL), the impact to the extent and depths of flooding was minimal.[4] Generally, the impact was limited to the shoreline and the lower reach segment of Waimānalo Stream, where the water surface elevation in the channel increased about 0.2 ft for the 1% AEP flood event. There was no rise in elevation upstream of Kalanianaʻole Highway or in any of the other streams.

[4] Impacts from wave action or shoreline erosion are not represented in this analysis.

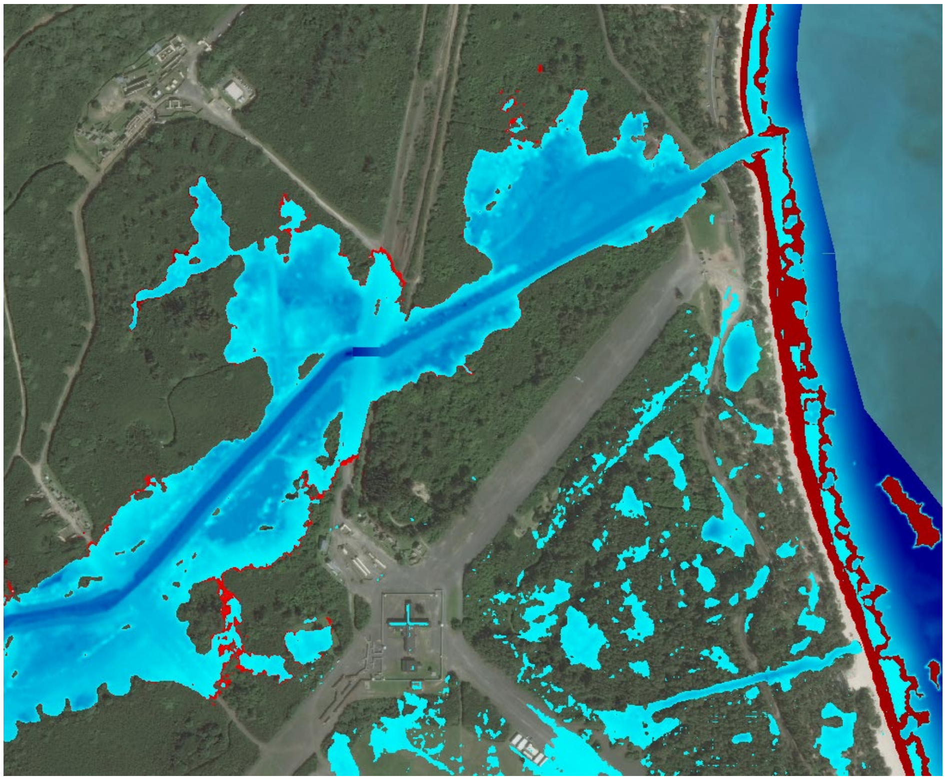

**Figure 6-18: Resulting Impact from *High* Sea Level Change (Red) for the 1% AEP Flood Profile for Waimānalo Stream**

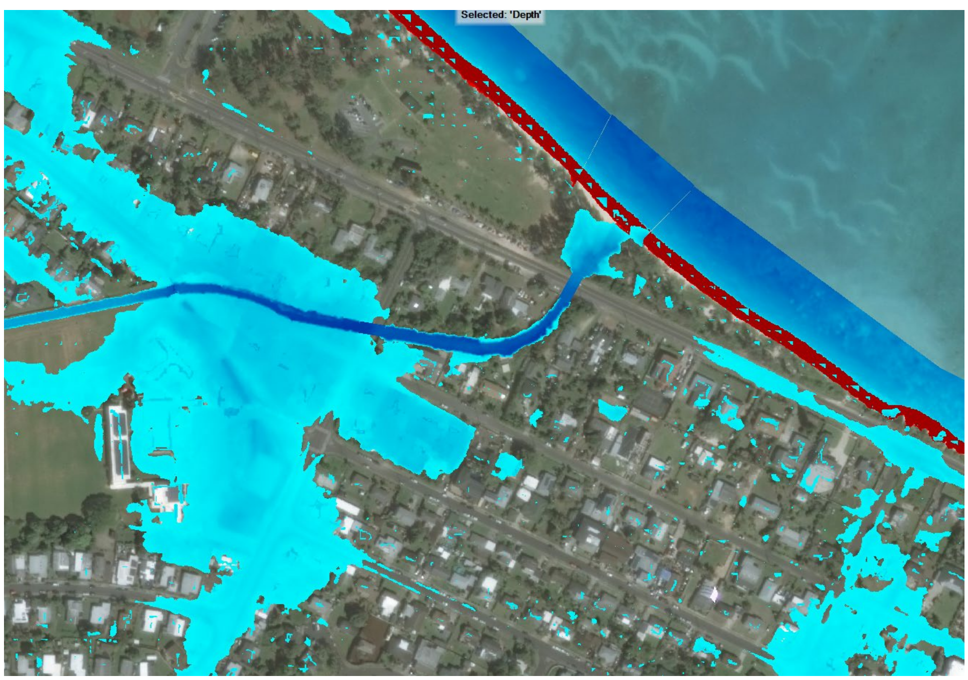


**Figure 6-19: Resulting Impact from *High* Sea Level Change (Red) in 2125 for the 1% AEP Flood Profile for Unnamed Stream #1, Kaiona Watershed**

# 7 Conclusion

The results of this study make available the water surface profiles, flood elevations, and areal extent of the floodplain for the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) AEP flood events (5 profiles). With several streams in the study area, many residential properties and commercial buildings are at risk of being flooded frequently. Kalanianaʻole Hwy near Sherwood Beach becomes flooded and unusable during the highest frequency event evaluated, the 10% AEP flood event (statistically, once every ten years). It likely floods more frequently given the extensive area that is flooded along and around the highway during the 10% AEP event.

Various additional scenarios were evaluated to provide more information into possible causes or solutions to reduce flood risk. However, their effects at reducing the flood hazard were limited.

- Increased channel vegetation resulted in a tributary to Waimānalo Stream overtopping the banks, causing additional shallow flooding along Humuniki Street. Other small areas in the community experienced additional flooding, but the extent was very limited and depths were less than one foot (< 1 ft).
- Small culverts that were at risk of being obstructed with vegetation, sediment, or debris were partially obstructed under another scenario. Flood depths in the channels immediately upstream of these culverts increased. However, additional flooding to the community was limited to shallow (< 1 ft) flooding along Ahiki St and Mekia St.
- A small channel was cut into the terrain to represent dredging at the Waimanalo and Puha (Inoaole) Streams, but the effects from this were also limited. Kalanianaʻole Hwy is still frequently overtopped.
- Clearing shoreline culvert outlets along Kalanianaʻole Hwy in eastern Waimānalo did not significantly reduce flooding to properties on the mountainside of the highway.

- Even under *high* sea level conditions (7.77 ft MSL), the impact to the extent and depths of flooding was minimal.[5] Generally, the impact was limited to the shoreline and the lower reach segment of Waimānalo Stream, where the water surface elevation in the channel increased about 0.2 ft for the 1% AEP flood event. There was no rise in elevation upstream of Kalanianaʻole Highway or in any of the other streams.

The flood hazard was not significantly affected by any of the above scenarios. To effectively reduce flood risk in the community, the effort must be more intentional and thought out than simply restoring existing infrastructure to optimal conditions (i.e. excavated and without vegetation). Site-specific measures should be developed and evaluated under a separate feasibility study.

Other recommended studies related to this work includes:

- An update to this flood hazard study when complete LiDAR coverage becomes available for the entire Waimānalo area (expected later this year in 2023) so the study area and flood hazard analysis can be expanded further upstream.
- A dam break analysis on the Waimanalo 60 MG reservoir to identify the hazard potential downstream should a breach or overtopping failure occur.
- An interior drainage study, to include a topographic survey of all stormwater structures and modeling of the existing stormwater system, to identify flood-prone areas specifically caused by capacity limitations of the stormwater systems (versus riverine flooding).

[5] Impacts from wave action or shoreline erosion are not represented in this analysis.

# 8 References


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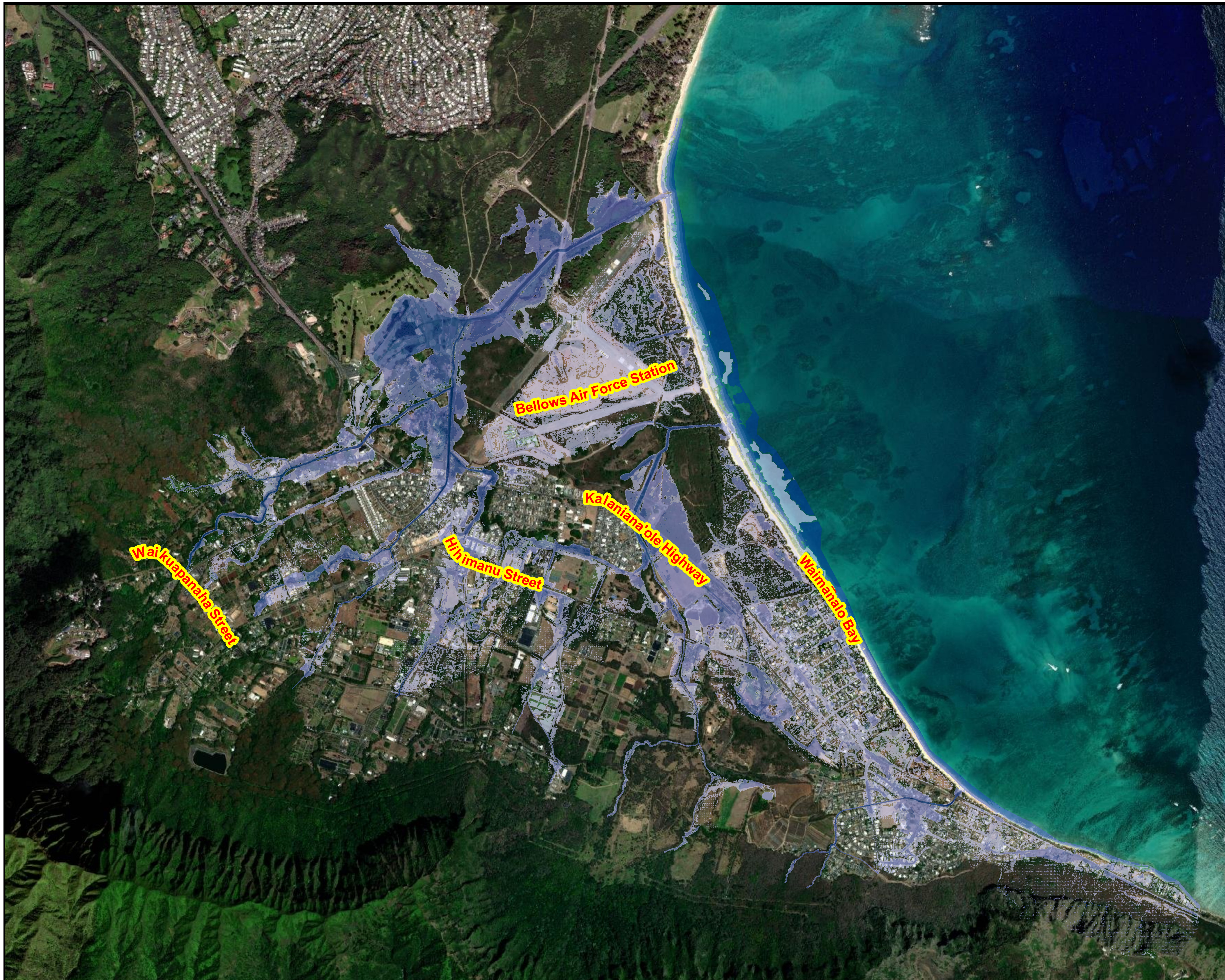
# Appendix A

## Flood Hazard Maps

U.S. Army Corps
of Engineers
Honolulu District


## Legend

**1% AEP (100 yr) Flood Depth**

**<VALUE>**

- < 1 ft
- 1 - 4 ft
- 4 - 7 ft
- 7 - 10 ft
- > 10 ft

N
W E
S

0 1,000 2,000 3,000 4,000 5,000 Feet

0 250 500 1,000 1,500 Meters

Coordinate System:
NAD1983 PA11 StatePlane Hawaii 3 FIPS

# Flood Hazard Map

Waimānalo, Oʻahu, Hawaiʻi

Map 1

Prepared by: USACE, Honolulu District
27 Jan 2023

This map is for reference only. USACE shall not be liable for any errors, omissions, or damages that result from inappropriate use of this document.


U.S. Army Corps
of Engineers
Honolulu District


## Legend

**1% AEP (100 yr) Flood Depth**

**<VALUE>**

- < 1 ft
- 1 - 4 ft
- 4 - 7 ft
- 7 - 10 ft
- > 10 ft

N
W E
S

0 500 1,000 1,500 Feet

0 50 100 200 300 Meters

Coordinate System:
NAD1983 PA11 StatePlane Hawaii 3 FIPS

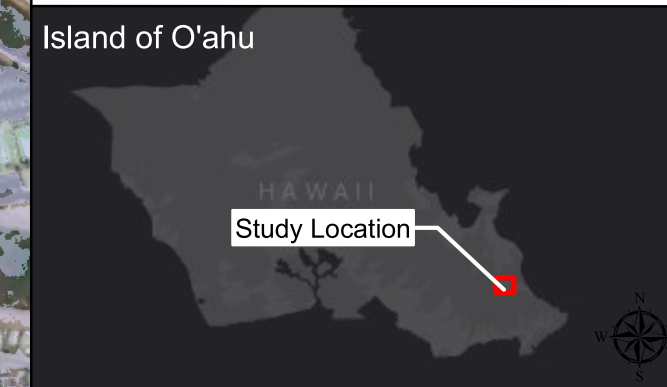
# Flood Hazard Map

Waimānalo, O'ahu, Hawai'i

Map 2

Prepared by: USACE, Honolulu District
27 Jan 2023


U.S. Army Corps
of Engineers
Honolulu District




## Legend

**1% AEP (100 yr) Flood Depth**

**<VALUE>**

- < 1 ft
- 1 - 4 ft
- 4 - 7 ft
- 7 - 10 ft
- > 10 ft

N S E W

0 500 1,000 1,500 Feet

0 50 100 200 300 Meters

Coordinate System:
NAD1983 PA11 StatePlane Hawaii 3 FIPS

# Flood Hazard Map

Waimānalo, O‘ahu, Hawai’i

Map 3

Prepared by: USACE, Honolulu District
27 Jan 2023

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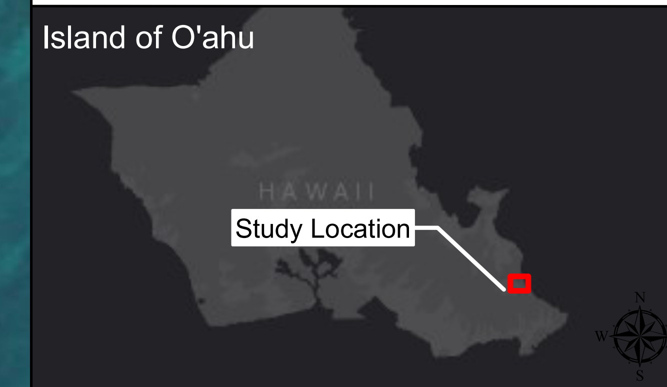
U.S. Army Corps
of Engineers
Honolulu District


## Legend

**1% AEP (100 yr) Flood Depth**

**<VALUE>**

- < 1 ft
- 1 - 4 ft
- 4 - 7 ft
- 7 - 10 ft
- > 10 ft

N W E S

0 500 1,000 1,500 Feet

0 50 100 200 300 400 Meters

Coordinate System:
NAD1983 PA11 StatePlane Hawaii 3 FIPS

# Flood Hazard Map

Waimānalo, O‘ahu, Hawai’i

Map 4

Prepared by: USACE, Honolulu District
27 Jan 2023

This map is for reference only. USACE shall not be liable for any e1rrors, omissions, or damages that result from inappropriate use of this document.


U.S. Army Corps
of Engineers
Honolulu District


## Legend

**1% AEP (100 yr) Flood Depth**

**<VALUE>**

- < 1 ft
- 1 - 4 ft
- 4 - 7 ft
- 7 - 10 ft
- > 10 ft

N S W E

0 500 1,000 1,500 Feet

0 50 100 200 300 400 Meters

Coordinate System:
NAD1983 PA11 StatePlane Hawaii 3 FIPS

# Flood Hazard Map

Waimānalo, O'ahu, Hawai'i

Map 5

Prepared by: USACE, Honolulu District
27 Jan 2023

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# Appendix B

## Hydrology

# PREFACE

This appendix describes the hydrologic analysis of the Waimānalo Community Flood Hazard Study, Oahu, Hawaii. This analysis was performed to determine the magnitude of the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) annual exceedance probability (AEP) flood discharges for the Waimānalo community.

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# LIST OF ACRONYMS & ABBREVIATIONS

| | |
|---|---|
| AEP | annual exceedance probability |
| DA | drainage area |
| F | Fahrenheit |
| FEMA | Federal Emergency Management Agency |
| FIS | Flood Insurance Study |
| ft | feet |
| GIS | geographic information system |
| HEC | Hydrologic Engineering Center |
| HMS | Hydrologic Modeling Software |
| HoLIS | Honolulu Land Information System |
| IfSAR | Interferometric Synthetic Aperture Radar |
| JALBTCX | Joint Airborne Lidar Bathymetry Technical Center of Expertise |
| LiDAR | Light Detection and Ranging |
| LMSL | local mean sea level |
| mi | mile |
| MG | million gallons |
| MRLC | Multi-Resolution Land Characteristics Consortium |
| MSL | mean sea level |
| NAD83 | North American Datum of 1983 |
| NLCD | National Land Cover Database |
| NOAA | National Oceanic and Atmospheric Administration |
| NSE | Nash-Sutcliffe model efficiency |
| NWS | National Weather Service |
| OCM | Office for Coastal Management |
| PFDS | Precipitation-Frequency Data Server |
| $Q_T$ | Peak discharge for T-year recurrence interval |
| R | storage coefficient |
| SSP | Statistical Software Package |
| $T_C$ | time of concentration |

| | |
|---|---|
| TR-55 | Technical Release 55 |
| US | United States |
| USACE | U.S. Army Corps of Engineers |
| USGS | U.S. Geological Survey |
| WIS | Waimānalo Irrigation System |

# 1 Watershed Description

This section provides a broad overview of hydrologic conditions in the study area and corresponding watersheds. It reflects the preliminary investigations and data collection phase of the study.

## 1.1 Location

This study focuses on evaluating flood hazards in Waimānalo, a census-designated place in the City & County of Honolulu, in the District of Ko‘olaupoko on the island of O‘ahu, Hawaii. Waimānalo is a small town with a population of approximately 6057 (U.S. Census Bureau, 2020). It is home to several beach parks, plant nurseries, Bellows Air Force Base, the Waimānalo Polo Field, and several thousand acres of Hawaiian homelands.

Waimānalo includes areas in the Waimānalo, Kahawai, and Kaiona watersheds. The Waimānalo watershed has a drainage area of approximately 6.28 square miles ($mi^2$); the Kahawai watershed has a drainage area of approximately 2.76 $mi^2$; and the Kaiona watershed has a drainage area of approximately 1.63 $mi^2$. These watersheds extend northeast from the steep slopes of the Ko‘olau Range to Waimānalo Bay, located on the eastern shore of O‘ahu. The total study area is about 10 $mi^2$, which includes additional coastal drainage areas that do not contribute significant flow to the primary river systems.

## 1.2 Topography

Along the upper boundary of the three watersheds, the highest elevation is approximately 2,590 feet above mean sea level (ft MSL). The steep and deeply incised Ko‘olau Range is aligned northwest to southeast, nearly perpendicular to the prevailing northeast trade winds. The Waimānalo watershed is oblong in shape, approximately 20,000 feet long and 9,000 feet wide. It has an average basin slope of 1.2%. The Kahawai watershed is also somewhat oblong in shape, approximately 13,000 feet long and 7,000 feet wide. It has an average basin slope of 1.2%. The Kaiona watershed is square- or rhombus-shaped approximately 6,000 feet long and 6,000 feet wide. It has an average basin slope of 1.8%.

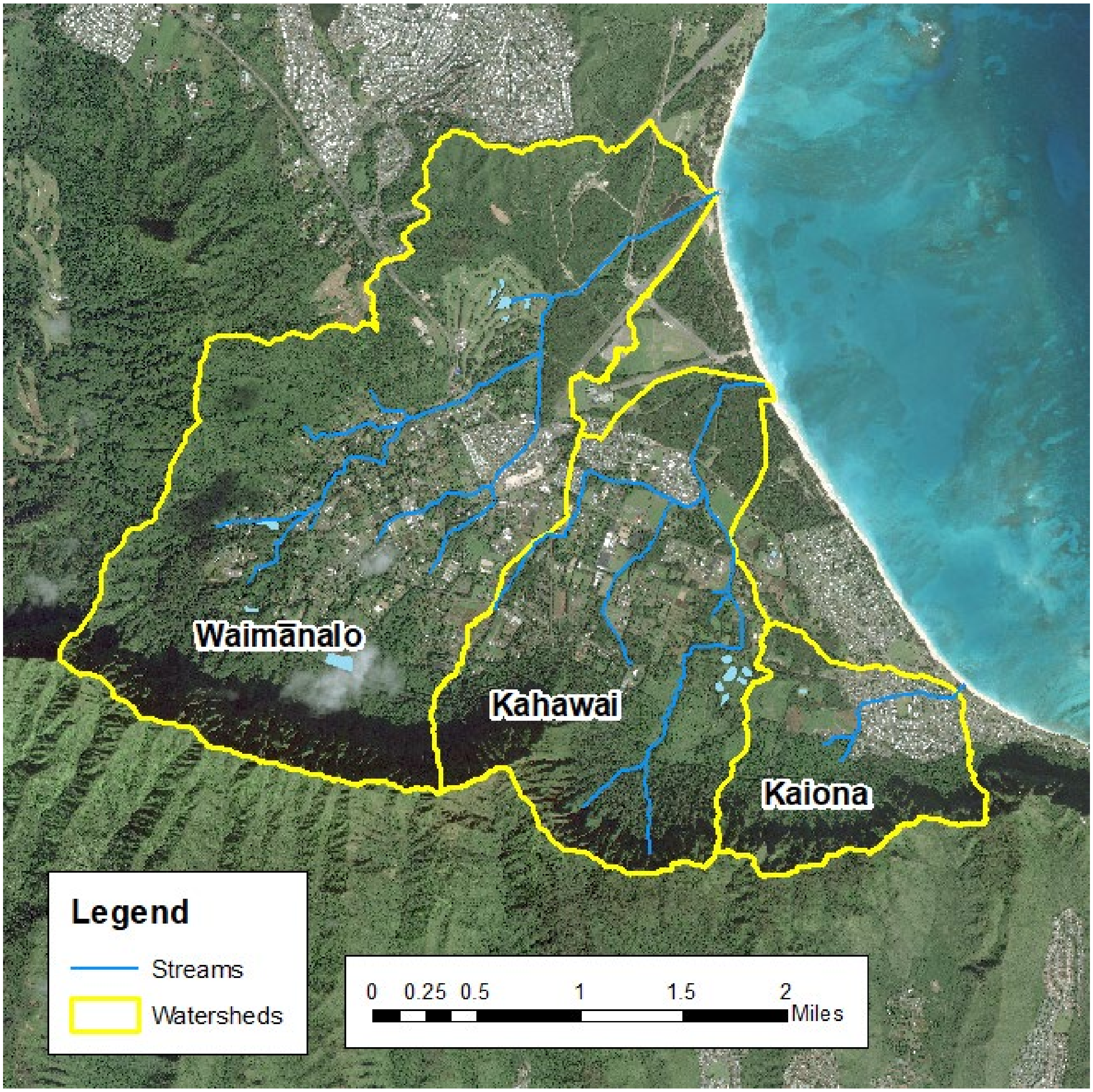



**Figure 1-1: Watershed Map, Waimānalo, Hawai‘i**

## 1.3 Geology and Soils

The eastern part of O‘ahu was formed by the Ko‘olau volcano. The main rocks consist of lava flows, breccia, cinders, tuff, and sedimentary rocks derived from volcanic materials. The coastal plain includes sedimentary rocks of volcanic origin, calcareous reef material, and windblown calcareous beach sand (Takasaki, Hirashima, & Lubke, 1969).

In the upper half of the Waimānalo and Kahawai watersheds, surficial deposits of alluvium overlay the volcanic rocks (Sherrod, Sinton, Watkins, & Brunt, 2007). In the Waimānalo area, the alluvium layer can be more than 700 feet thick (Takasaki, Hirashima, & Lubke, 1969). This alluvium is composed of silt and clay, lesser amounts of sand and gravel, and a few beds of poorly sorted gravel and cobbles. Permeability is low.

Dune deposits are mapped in the lower half of the Waimānalo and Kahawai watersheds (Sherrod, Sinton, Watkins, & Brunt, 2007). Lithified dune sand blown inland from ancient beaches is extensive near the coast in the Waimānalo area. In the Waimānalo area, dunes extend inland for more than 1 mile and are extremely permeable (Takasaki, Hirashima, & Lubke, 1969).

## 1.4 Land Use

All lands, including submerged lands, in the State of Hawai‘i are classified into four land use districts: urban, rural, agricultural, and conservation. Along the slopes of the Ko‘olau Range, the upper limits of the Waimānalo, Kahawai, and Kaiona watersheds are classified within the Conservation District. Conservation lands are comprised primarily of lands in existing forest and water reserve zones.

The middle watershed areas are primarily within the Agricultural District. Waimānalo has extensive acreage devoted to diversified agricultural pursuits. The State of Hawai‘i manages an agricultural park in Waimānalo to encourage the continuation or initiation of agricultural activities in a designated area. The Waimānalo Agricultural Park is comprised of 126 acres subdivided into 14 lots (Agricultural Resource Management Division, 2022).

The lower watershed is primarily classified within the Urban District, which generally includes lands characterized by “city-like” concentrations of people, structures, and services. This area includes several residential communities, several beaches and beach parks, and Bellows Air Force Base (AFB). The residential communities are generally small and low-density. More than 200 acres of residential parcels are designated as Hawaiian Home Lands (areas held in trust for Native Hawaiians by the State of Hawai‘i) (Department of Hawaiian Home Lands, 2011). The main beaches along the coastal study limits include Kaiona Beach, Waimānalo Beach, Sherwood Beach, and Bellows Field Beach. Bellows AFB is a former airfield that now serves as a military training area and recreation area, including Bellows Field Beach Park.

## 1.5 Climate

Hawai‘i has a subtropical climate with temperatures that are mild and fairly uniform throughout the year. The mean annual temperature in Waimānalo, based on data collected from 1999 to 2019, is 75.2° Fahrenheit (F). The warmest month of the year is September, with an average temperature of 78.1 °F; the coldest month of the year is February, with an average temperature of 72.1 ° F (AM Online Projects, 2019).

The climate of the Hawaiian Islands is characterized by a two-season year; a 5-month summer or dry season and a 7-month winter or wet season; mild and uniform temperatures, strikingly marked geographic differences in rainfall, generally humid conditions, and prevailing dominance of trade wind flow from the northeast. During the 5-month summer from May through September, trade winds prevail 80-95 percent of the time. During the 7-month winter from October through April, the prevalence of the trade winds decreases to 50-80 percent.

The study area is located on the windward side of O‘ahu, which is familiar with wet and cloudy conditions. As the Ko‘olau Range is nearly perpendicular to the prevailing trade winds, air is forced to rise, producing orographic clouds and rain on the windward slopes. Trade winds are most prevalent during the summer months (June through August), where they blow more than 90% of the time. In the winter months (January through March), trade winds may occur only 40% to 60% of the time (Pacific Disaster Center, n.d.).

The climate of the Waimānalo and Kahawai watersheds is tropical with cooler and wetter areas at higher elevations in the belt of the northeasterly trade winds. The average monthly precipitation ranges from 2.2 inches in the wettest month (December) to 0.5 inches in the driest month (July) (AM Online Projects, 2019).

Although the northeasterly trade winds produce most of the annual rainfall over the Hawaiian Islands, it is during the absence of these winds that the flood producing rainfall occurs. In particular, southerly winds bring moist warm air that creates “Kona” storms which produce the damaging floods in Hawai‘i. These storms usually occur during the winter months.

## 1.6 Dams and Reservoirs

### 1.6.1 Waimānalo 60 MG Reservoir

There is one regulated dam in the study area. The following information was provided by the State of Hawaii, Department of Land and Natural Resources as published in their Dam Inventory System [https://dams.hawaii.gov/]:

National ID: HI00129

State ID: OA-0129

Name: WAIMANALO 60 MG RESERVOIR

Hazard Rating: High

Owner: State of Hawaii, Department of Agriculture

Location: 21°19’55.84"N, 157°44'16.14"W

Type of Dam: Earthen

Purpose: Irrigation

Completed / Last Modified: 1993

Dam Height: 65.0 ft

Dam Length: 2,118 ft

Drainage Area: 0.008 $mi^2$ / 5.12 acres

Primary Spillway Type: Channel

Maximum Storage: 182.0 acre-ft / 59.3 MG

Additional information for the reservoir, as summarized in the original proposal for its construction (Soil Conservation Service, 1981), is included below. Actual elevations and lengths may vary slightly:

Elevation Crest Inflow (Submerged): 242.0 ft MSL

Elevation Top of Dam: 311.7 ft MSL

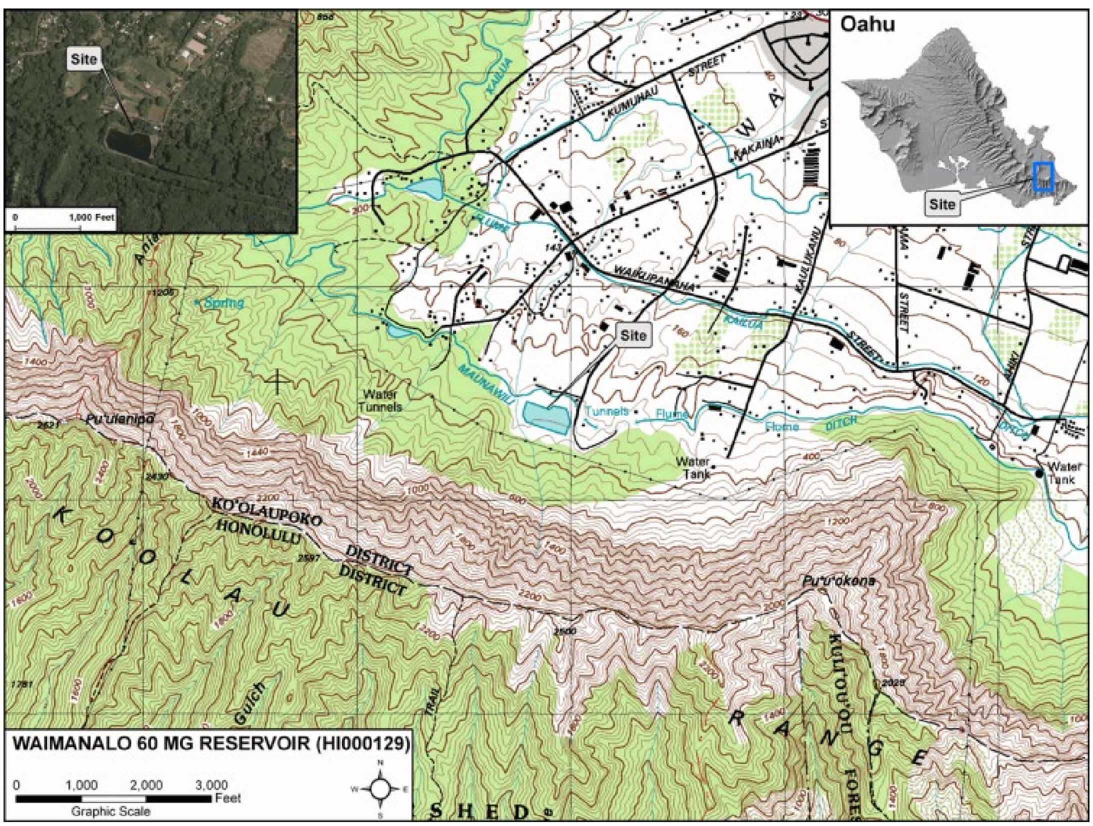
Elevation – Irrigation Storage Pool: 308.7 ft MSL

Elevation Crest of Ungated Spillway: 308.7 ft MSL

Spillway Crest Length: 12.5 ft

Spillway Capacity at Top of Dam Elevation: 200 $ft^3/s$

The Waimānalo 60 MG Reservoir is represented in the terrain as having a water surface elevation at approximately 265 ft MSL, which are typical baseline conditions.




Source: State of Hawaii, Department of Land and Natural Resources, HI00129 – Dam Data Sheet

**Figure 1-2: Location Map of Waimānalo 60 MG Reservoir**

Source: State of Hawaii, Department of Land and Natural Resources, Waimānalo 60 MG Reservoir

**Photo 1-1: Aerial Photo of Waimānalo 60 MG Reservoir**

### 1.6.2 **Maunawili Reservoir**

The Maunawili Reservoir was built in the 1930s for irrigation but is currently inactive. The Maunawili Reservoir and Kailua Reservoir (Section 1.6.3) reportedly had a combined storage volume of 5 million gallons (DPW, 1975).

### 1.6.3 **Kailua Reservoir**

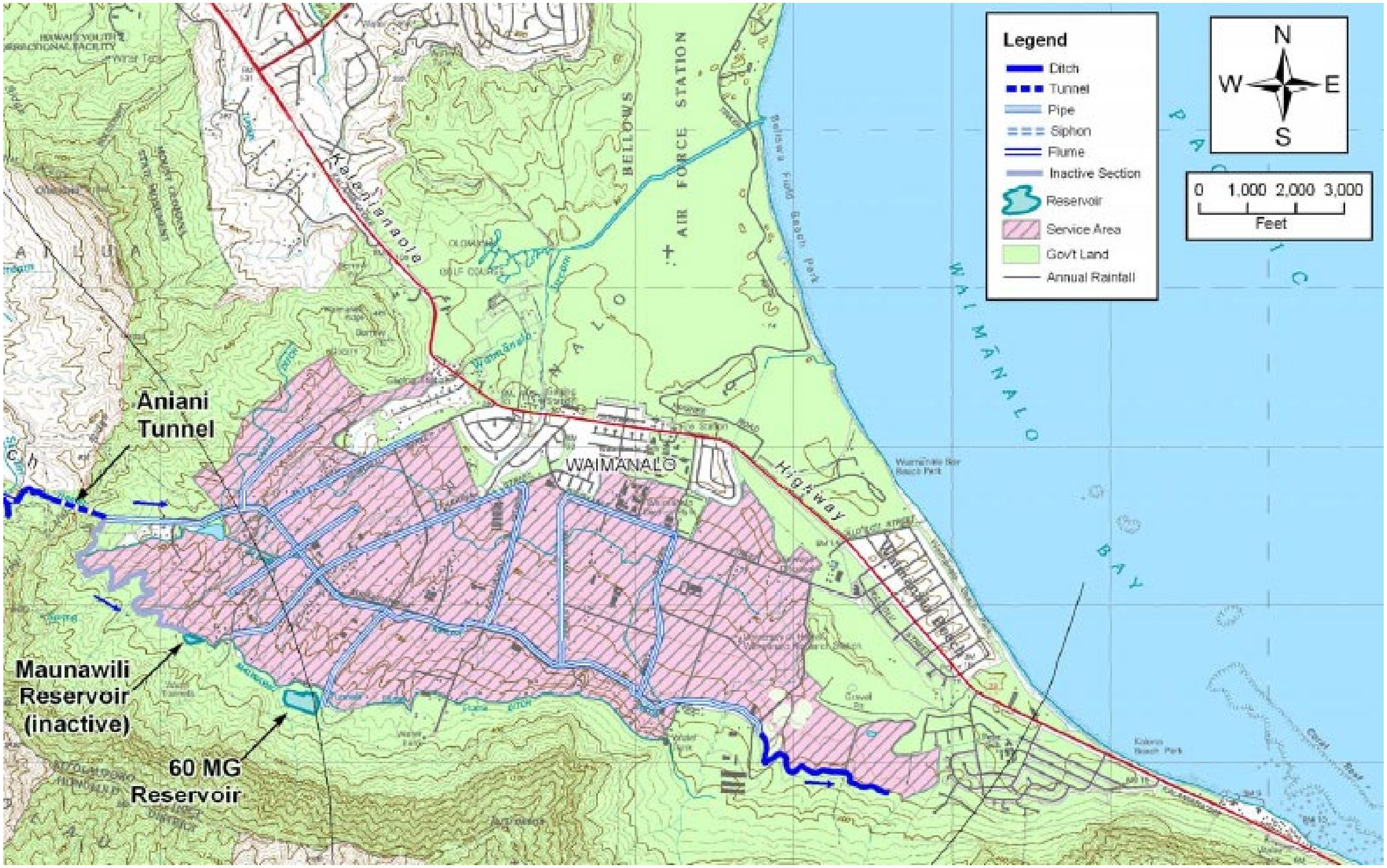
The Kailua Reservoir was reportedly built in the 1930s for irrigation. The State of Hawai‘i shut down the reservoir in 1993. In April 2006, the reservoir and dam overflowed in a heavy downpour. There were no damages or injuries, although more than 30 homes were evacuated (KHNL/KGMB, 2006). Following the incident, the State breached the dam that same week so that it was no longer able to hold water (Daranciang, 2006).

### 1.6.4 **Waimānalo Irrigation System**

The Waimānalo Irrigation System (WIS) is owned and operated by the State of Hawai‘i. It is fully funded by the Hawaii Department of Agriculture. The WIS provides water to the agricultural community in Waimānalo and has a service area of 1,174 acres (EKNA Services, Inc., 2019).

Water from the Maunawili watershed (northwest of the Waimānalo watershed) is screened and picked up in a 16-inch pipe at the east portal of the Aniani Nui Ridge Tunnel. The pipeline carries the water 1.8 miles under gravity pressure to the Waimānalo farming community and the Waimānalo 60 MG Reservoir. Below the reservoir, the delivery system is a closed, pressurized pipe system, 10.9 miles long, ranging from 24 inches to 6 inches in diameter. At certain critical locations along the upper mainline, there are booster pumps to provide sufficient sprinkler pressure to users with land above the gravity pressure contours (Soil Conservation Service, 1981). As the source of water for the irrigation system originates outside of the study area and is contained within a closed system, it was considered to have a minimal impact on the hydrology within the study area and not represented in the hydrologic model.

Before the closed irrigation system was constructed in the early 1980s, the agricultural community relied on other, smaller reservoirs and a collection system comprised of 32 wooden flume-trestle structures and 15 miles of open ditch in generally poor condition (Soil Conservation Service, 1981). These features have since been left abandoned. They may be represented in the terrain but are not otherwise accounted for in the model.




Source: State of Hawaii, Department of Agriculture: *Agricultural Water Use and Development Plan* (December 2003)

**Figure 1-3: Waimānalo Irrigation System, Site Map 1**

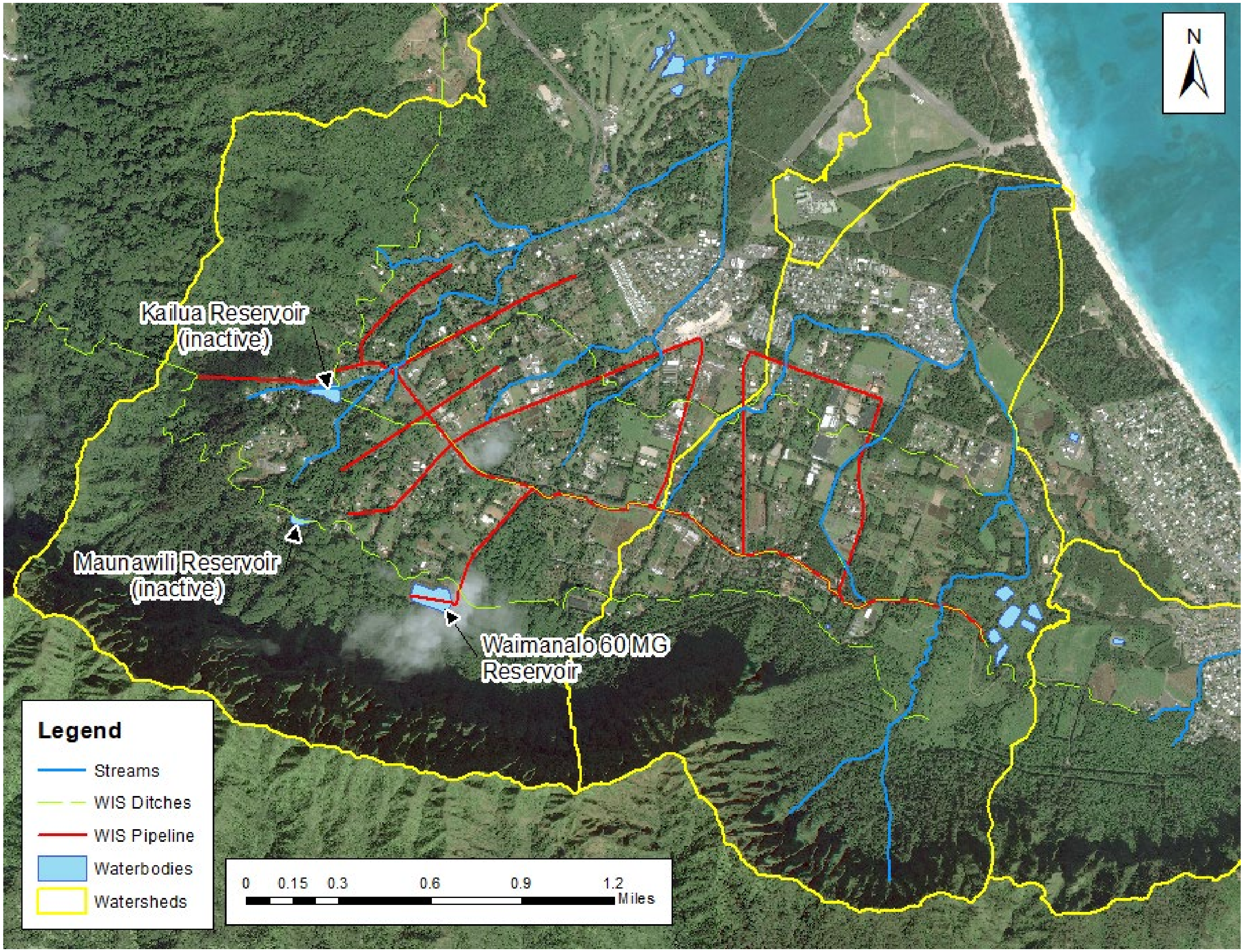



**Figure 1-4: Waimānalo Irrigation Map, Site Map 2**

## 1.7 Rivers and Streams

Waimānalo Stream is the primary river in the Waimānalo watershed (Figure 1-5). It is created by multiple tributaries, originating in the steep slopes of the Ko‘olau Range. The Kahawai Stream (which is in the Waimānalo watershed, not the Kahawai watershed) is the main tributary to the Waimānalo Stream. The tributaries to Kahawai Stream are referred to as “Stream A” and “Stream B,” to be consistent with current terms used in the corresponding flood insurance study for this area (FEMA, 2014)[1].

Puha Stream is the primary river in the Kahawai watershed, although it is sometimes referred to as Inoaole Stream for its proximity to Inoaole Street (Figure 1-5). The tributaries for Puha (Inoaole) Stream are referenced in this study as “Stream C” and “Stream D,” which is also consistent with the corresponding flood insurance study for this area (FEMA, 2014).

There are two unnamed streams in the study area that were also included in this flood hazard analysis for the Waimānalo community (Figure 1-6). The first stream (Unnamed Stream #1) is in the Kaiona watershed. It passes by Waimanalo Country Farms, Blanche Pope Elementary School, and Waimānalo Beach Park before discharging into Waimānalo Bay. The second unnamed stream is in a small, unnamed watershed southeast of the Kaiona watershed. Flow from this stream (Unnamed Stream #2) is collected by an unlined, vegetated swale near the corner of Bell Street and Hoomaha Street. There is an 18-inch conduit at the downstream end of the swale that carries a limited amount of flow through the storm water system to Unnamed Stream #1[2].

Typical photos of these streams are provided as Photo 1-2 through Photo 1-5.

[1] FEMA also refers to the Kahawai Stream as “Waimanalo Stream A,” but in this study, “Stream A” only references the northwestern fork / tributary of the Kahawai Stream.
[2] The outlet for this system is Unnamed Stream #1, just downstream of the Huli Street Bridge.

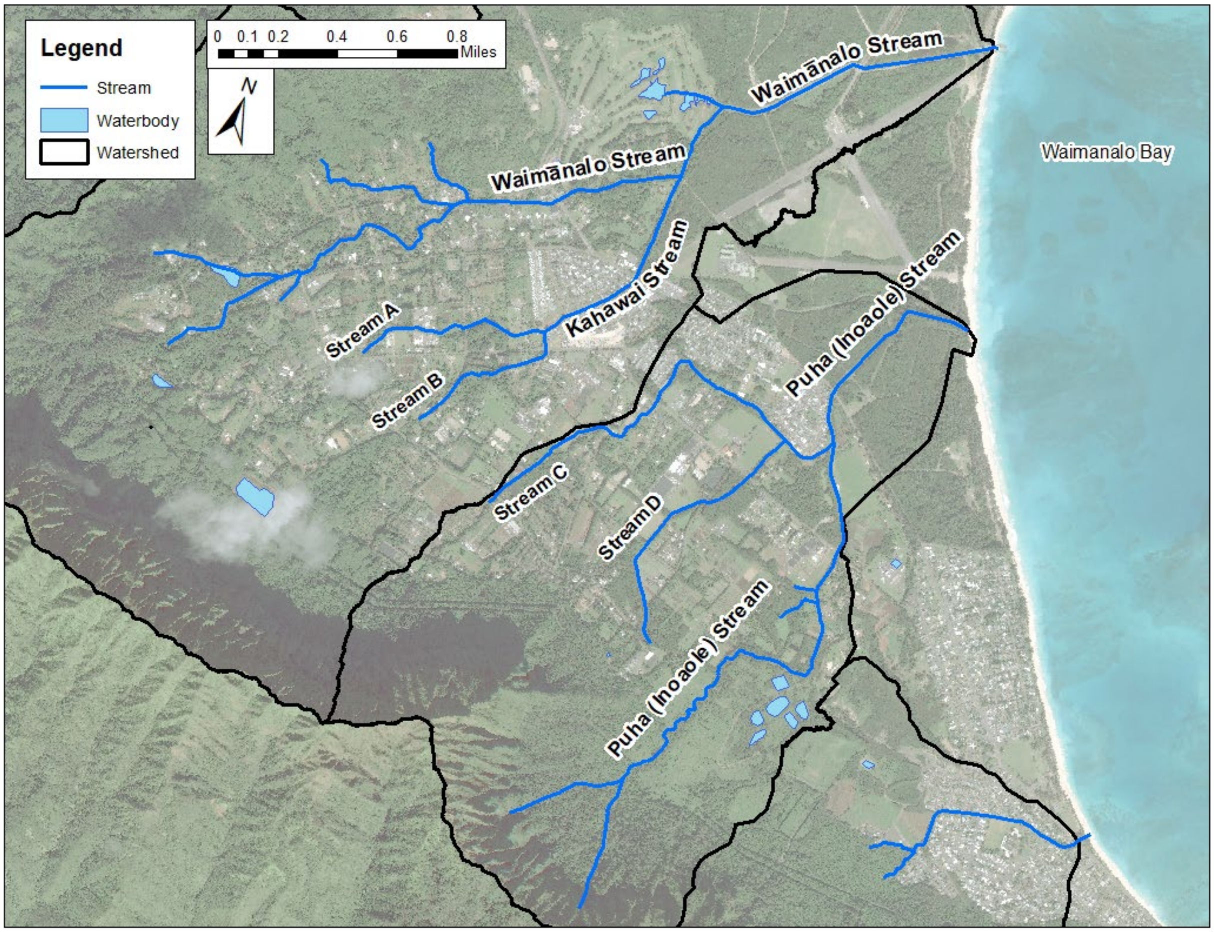



**Figure 1-5: Streams in the Waimānalo and Kahawai Watersheds**

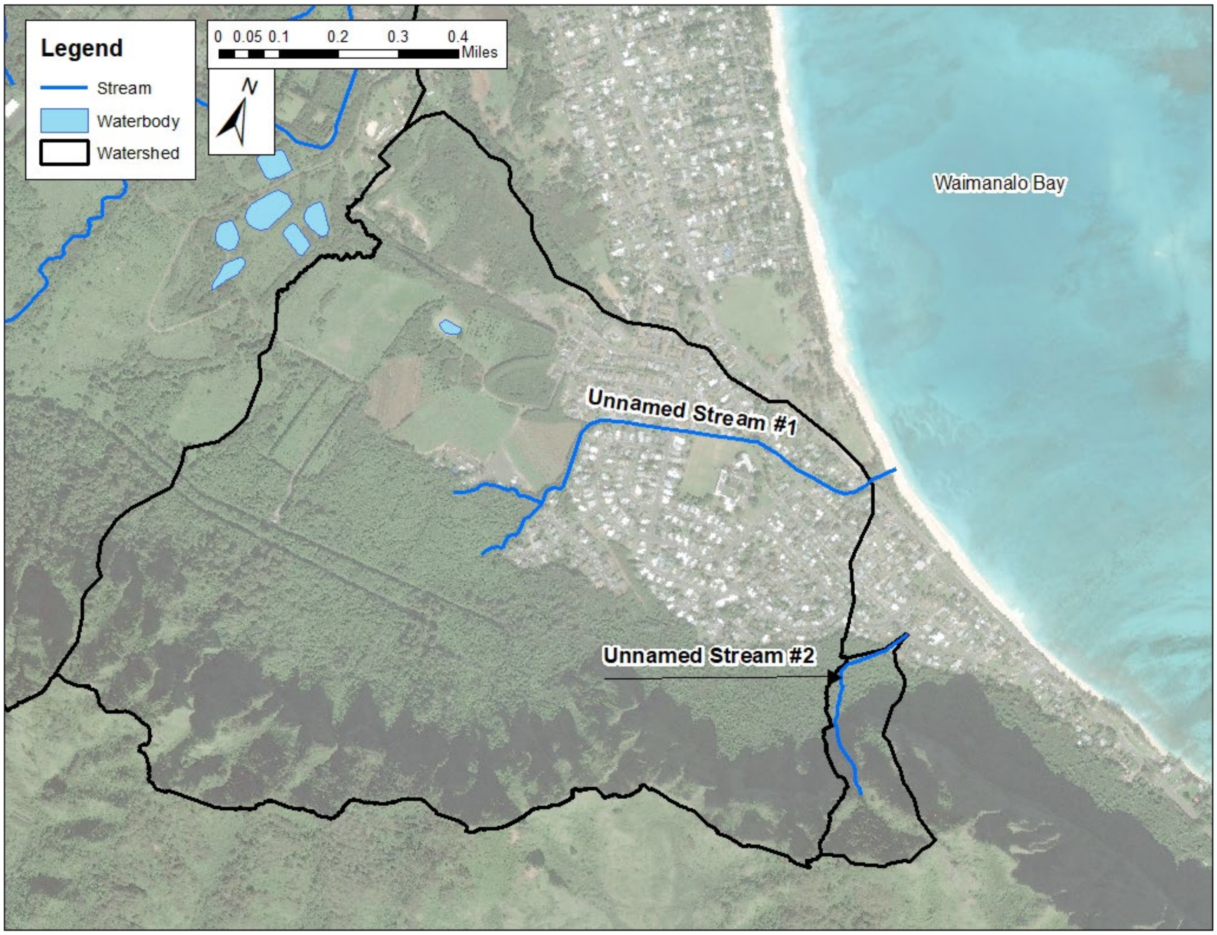



**Figure 1-6: Unnamed Streams in the Kaiona Watershed and Study Area**

**Photo 1-2: Upper Waimanalo Stream, Waimanalo Watershed**

21.345926, -157.734517

**Photo 1-3: Kahawai Stream, Waimanalo Watershed**

21.348047, -157.723116

**Photo 1-4: Puha (Inoaole Stream), Kahawai Watershed**

21.338841, -157.708338

**Photo 1-5: Unnamed Stream #1, Kaiona Watershed**

21.329527, -157.694726

# 2 Geographic Information Systems Data

## 2.1 Datum and Projection

The datum and projection for this study is as follows:

Horizontal projection: State Plane Zone 3 (US Survey Feet)

Horizontal datum: NAD83 (PA11)

Vertical Datum for Land Applications: Local Tidal Datum – MSL

Tidal Epoch: 1983 – 2001

Geoid: 2012B

## 2.2 Elevation

The following sources of elevation data were used in this study:

**Table 2-1: Elevation Data Type and Sources**

| Survey year | Agency | Data type | Areal Extent |
|---|---|---|---|
| 2013 | USACE | Topobathy LiDAR | about 1.0 mi inland from coast |
| 2013 | NOAA/USGS | Topographic LiDAR | middle watershed and coastal areas |
| 2003 | City and County of Honolulu | 5-foot contours | O‘ahu |

Light Detection and Ranging (LiDAR) data were collected by USACE and the Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) in 2013. This data includes hydrograph and topographic data depicting elevations above and below the immediate coastal water [available at coast.noaa.gov/dataviewer]. The vertical height of the Topobathy LiDAR data set was in Local Mean Sea Level (LMSL). The data set has a vertical accuracy of 0.2 m and a horizontal accuracy of 1 m. The selected projection is State Plane Zone 5102 Hawaii 3. Horizontal coordinates reference the North American Datum of 1983 (NAD83) in U.S. Feet. The vertical control datum is based on Hawaii GPS-derived orthometric height (ft). The extent of this data is limited to the coastal areas (approximately 1.0 mi inland).

In 2013, the National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS) collected additional topographic LiDAR data, which extends a bit further from the coastal areas and into the middle of the study area. This data was also available for download from the U.S. Interagency Elevation Inventory [available at coast.noaa.gov/dataviewer]. The vertical height of the Topobathy LiDAR data set was in Local Mean Sea Level (LMSL). The data set has a vertical accuracy of 0.1 m and a horizontal accuracy of 1 m. The selected projection is State Plane Zone 5102 Hawaii 3. Horizontal coordinates reference the North American Datum of 1983 (NAD83) in U.S. Feet. The vertical control datum is based on Hawaii GPS-derived orthometric height (ft).

Areas within the study area that were not covered by LIDAR (such as the upper watershed) were supplemented using 5-foot interval contours generated by the City and County of Honolulu, Department of Planning and Permitting, Honolulu Land Information System (HoLIS) Division in 2016. This was available for download on the Hawaii Statewide GIS Program's Geospatial Data Portal [https://geoportal.hawaii.gov/]. These contours were generated based on Interferometric Synthetic Aperture Radar (IfSAR) data collected by the NOAA's Office for Coastal Management (OCM) in 2005. This original dataset is restricted, however, and not publicly available for use (the contours are not restricted). These three datasets were merged to create a single raster file.

## 2.3 Imagery

High resolution imagery used for background mapping of the study area is from DigitalGlobe, the National Geospatial-Intelligence Agency and the USGS. World Imagery, provided by Esri, was used for larger scale background mapping, such as when it was necessary to show the entire island of Oʻahu.

## 2.4 Land Cover and Land Use

A circa 2011 high resolution (1 to 5 meter) land cover raster for the study area was developed by NOAA and downloaded from the Multi-Resolution Land Characteristics Consortium (MRLC)'s National Land Cover Database (NLCD). This raster was used to understand the different types of land usage in the study area and compute the directly connected impervious areas for the rainfall-runoff model (Section 4.3.3).

## 2.5 Soil Data

A water permeability shapefile provided by the Hawai‘i Soil Data Atlas was used to determine initial loss parameters for the hydrologic model, as described in Section 4.3.3 (University of Hawai'i, 2014).

# 3 Data Collection

This section describes available climate and stream data within the study area.

## 3.1 Climate

Climate data (e.g. rainfall) was available at three National Weather Service (NWS) rain gages within or near the study area (NCEI). These gages are listed in Table 3-1, identified in Figure 3-1, and each provide instantaneous data in either 5- or 15-minute intervals. Historical, instantaneous data were used to calibrate the hydrologic model (Section 4.3.6). There was also one USGS climate station with daily rainfall records in the study area. Although this station is listed in Table 3-1 for inclusivity of all climate stations in the study area, its record was not used in this study.

Point precipitation data for annual exceedance rainfall was obtained from the NWS NOAA Atlas 14 Precipitation-Frequency Data Server (PFDS). This source presents rainfall frequencies from recurrence intervals of 1 to 500 years (100% to 0.2% AEP) at various locations across the study area (NWS, 2017). The location points used to extract PFDS data were the approximate centroid locations for each subbasin (Table 4-9). This data was put into the calibrated hydrologic model to compute the peak flow estimates for various recurrence intervals.

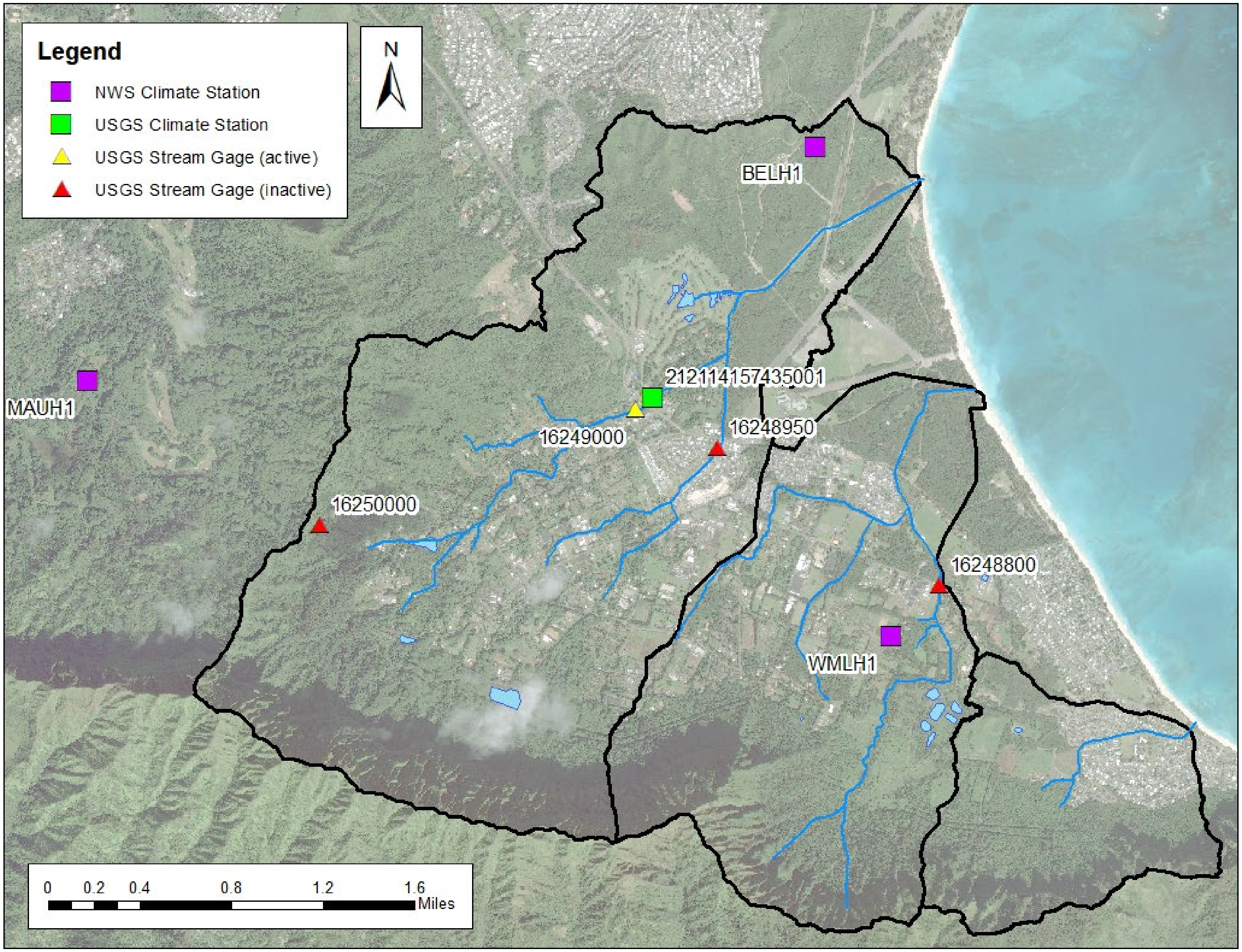



**Figure 3-1: Climate and Stream Gaging Stations in the Study Area**

**Table 3-1: Climate Station Inventory**

| Agency | Site Number / Network:ID | Site Name | Period of Record | Datum of gage (ft above LMSL[1]) | Latitude | Longitude |
|---|---|---|---|---|---|---|
| NWS | BELH1 | Waimanalo – Bellows AFB | 2012 – 2022 | 21.37 | 21.36670 | -157.71670 |
| NWS | MAUH1 | Maunawili Near Waimanalo | 2012 – 2022 | 413 | 21.35111 | -157.76667 |
| NWS | WMLH1 | Waimanalo Nonokio | 2012 – 2022 | 65 | 21.33556 | -157.71167 |
| USGS | 212114157435001 | Waimanalo Rain Gage, Oahu, HI | 1992 – 2005 | 18.89 | 21.35073 | -157.7278 |

[1]: local mean sea level

## 3.2 Stream

There are three USGS stream gages within the study area that have annual peak flow data, as presented in Table 3-2: 16248800 *Inoaole Stream at Waimanalo, Oahu, HI*; 16248950 *Kahawai Stream at Waimanalo, Oahu, HI*; and 16249000 *Waimanalo Stream at Waimanalo, Oahu, HI*. The locations of these stream gages are also identified in Figure 3-1. USGS 16248800 has an older record of 39 annual peak flow events recorded between 1958 and 1996. This record is before significant changes were made to the WIS in 2004. USGS 16248950 is an inactive stream gage, which provides annual peak flow records from 1999 to 2021. USGS 16249000 is perhaps the most useful gage for this study, providing annual peak flow data from 1963 to 2021; and continuous flow (instantaneous) data from 2015 to 2022 in 5-minute intervals. The Iowa Environmental Mesonet also provides gage height data for a station identified as WLSH1, but this seems to correspond with USGS 16249000 records. There is also a historical stream gage located on the upper slopes of the study area: 16250000 *Maunawili Ditch nr Waimanalo, Oahu, HI* that provides instantaneous data along Maunawili Ditch from 1993 to 2002. However, this gage likely supported the former irrigation system, and its record was not used in this study.

Figure 3-2 shows the annual peak flow record at the stream flow gaging station with the longest period of record: USGS 16249000. The historic maximum flow recorded at this gage was 4,560 $ft^3/s$ on March 6, 1963. Annual peak flows generally appear to be lower following the construction of the Waimanalo 60 MG Reservoir (Section 1.6.1) in 1993, which may be due to Kailua Reservoir (located upstream of USGS 16249000) being shut down around the same time (water was not intentionally being stored upstream anymore).

**Table 3-2: Stream Station Inventory**

| Agency | Site Number | Site Name | Period of Record | Drainage Area (mi$^2$) | Latitude | Longitude |
|---|---|---|---|---|---|---|
| USGS | 16248950 | Kahawai Stream | Peak Flow: 1999 – 2020 | 1.13 | 21.34758 | -157.7234 |
| USGS | 16248800 | Inoaole Stream | Peak Flow: 1958 – 1996 | 1.28 | 21.33879 | -157.7084 |
| USGS | 16249000 | Waimanalo Stream | Peak Flow: 1963 – 2022 Instantaneous: 2015 - 2022 | 2.13 | 21.34997 | -157.7289 |
| USGS | 16250000 | Maunawili Ditch nr Waimanalo, Oahu, HI | Instantaneous: 1993 – 2002 | N/A | 21.34268 | -157.7503 |

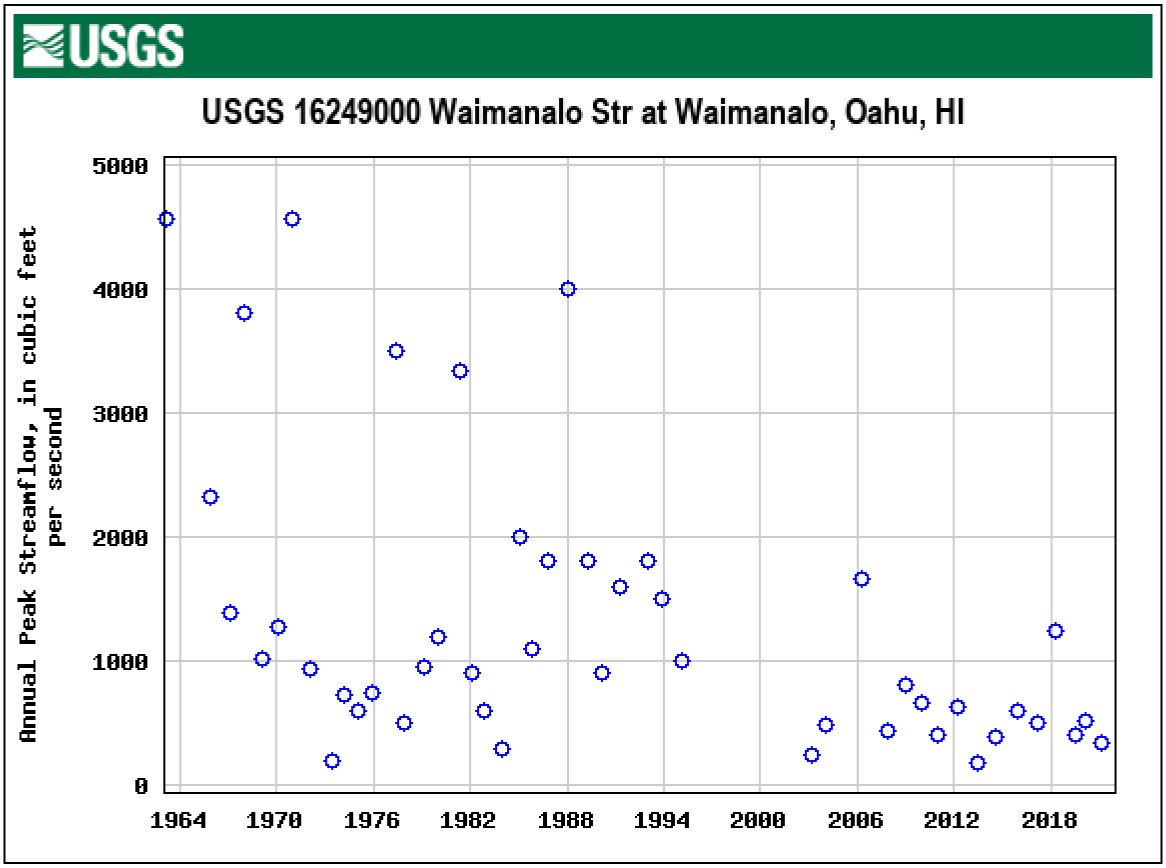



**Figure 3-2: Peak stream flow at USGS 16249000**

## 3.3 Flood History

Since the construction of the Waimanalo 60 MG Reservoir in 1993, there have been two notable floods in the study area: 31 March 2006 and 13 April 2018. On 31 March 2006, heavy rains resulted in Kailua Reservoir overtopping (Section 1.6.3) and spilled wastewater at the Waimanalo Treatment Plant. Reportedly heavy rains over the past several weeks left the ground very saturated (City and County of Honolulu, 2006). Between 10:30 a.m. and 1:00 p.m. HST on 31 March 2006 to 1 April 2006, rain fell at the rate up to three inches an hour in Waimānalo on the southeast coast (Wikinews, 2006). The peak streamflow recorded at USGS 16249000 during this event was 1,670 cubic feet per second ($ft^3/s$).

On the evening of 13 April 2018, intense rainfall moved across east O‘ahu with rates greater than 4 inches per hour (NWS, 2018). Although the affected area was localized, the intensity of the rainfall produced tremendous amounts of runoff which produced substantial damage to communities from Maunawili to Waimānalo. From the NWS report on the event, “Drainage basins responded rapidly to the burst of rain over east Oahu. At Waimānalo Stream on the windward side of the Koolau Range, the water level rose 3 feet in about 30 minutes and 5 feet in an hour” (NWS, 2018). The stage and flow hydrographs for this event at USGS 16249000 are included as Figure 3-3 and Figure 3-4, respectively. The peak streamflow recorded at USGS 16249000 during this event was 1,240 cubic feet per second ($ft^3/s$). Post-flood photos included in the NWS provided were also included in this report. Photo 3-1 shows Kahawai Stream channel at Bellows Air Force Station (21°20'49.87"N, 157°42'39.46"W). Vegetation debris along the banks shows that water got high enough to spill over the road. Photo 3-2 is the tributary of Kahawai Stream at Hihimanu Street (21°20'19.85"N, 21°20'19.85"N). Temporary rails were reinstalled after the event. The channel is quite small at this location and easily overflowed. Photo 3-3 shows Waikupanaha Street, where considerable runoff occurred during the event based on the large amount of debris deposited in the area. The road has already been cleared of debris in the photo.

As reported by Hawaii News Now, “rushing water topped the banks of a canal that runs along Mekia Street, and floodwaters sent cars and debris rushing toward homes” (Lund, 2018). Roads were also reportedly impassable in parts of Waimānalo (HNN Staff, 2018). According to residents who live on Mekia Street, they alerted city officials multiple times to address the debris that was stacking up inside the river running through their neighborhood prior to the flood event. During the event, a massive tree fell over and completely obstructed one of the culverts (Photo 3-4). Waters rose to the street level and sent a wall of mud and debris into the neighborhood (Lincoln, 2018).

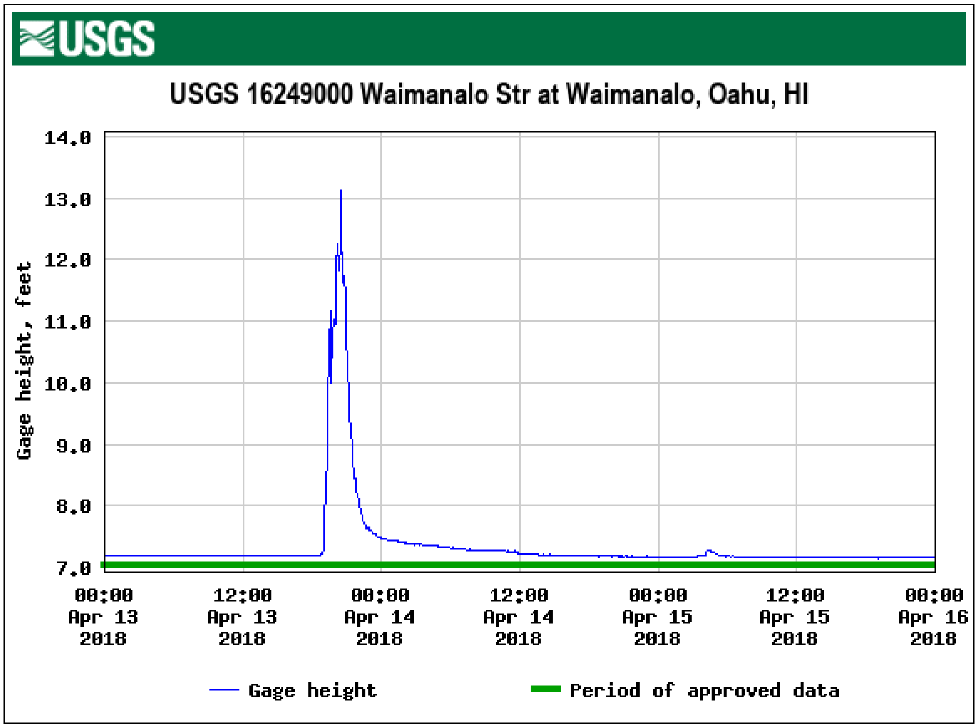



**Figure 3-3: Stage Hydrograph at USGS 16249000, Waimanalo Stream during the April 13 – 15, 2018 Flood Event**

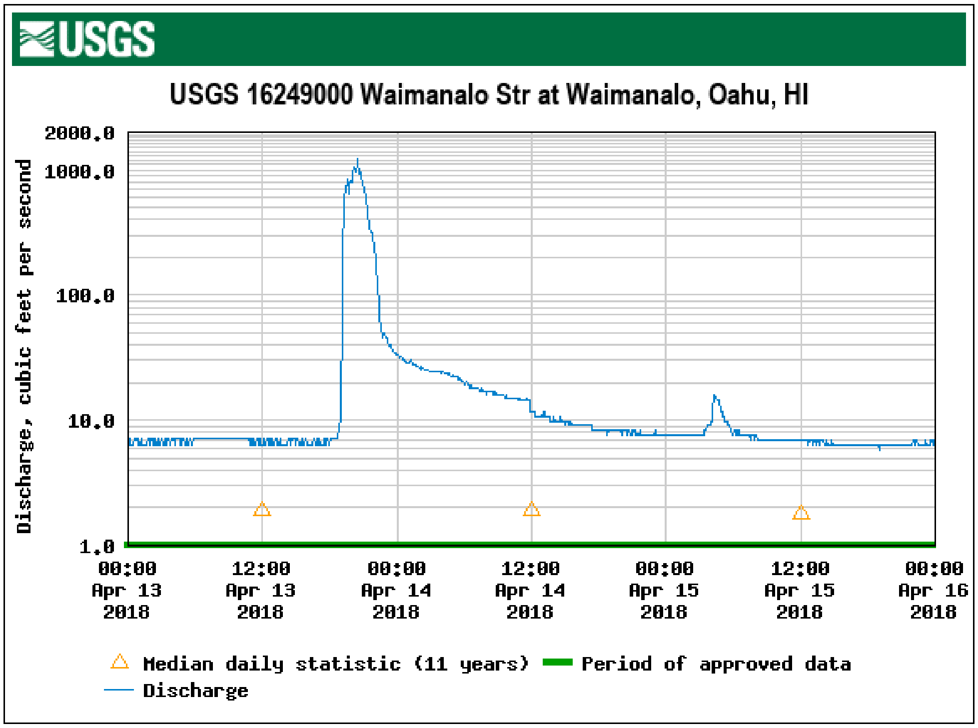



**Figure 3-4: Flow Hydrograph at USGS 16249000, Waimānalo Stream during the April 13 – 15, 2018 Flood Event**

Source: *April 13 – 15, 2018 Flash Flooding on Kauai and Oahu*, NWS Report

**Photo 3-1: Kahawai Stream channel at Bellows Air Force Station**

Source: *April 13 – 15, 2018 Flash Flooding on Kauai and Oahu*, NWS Report

**Photo 3-2: Tributary of Kahawai Stream at Hihimanu St**

Source: *April 13 – 15, 2018 Flash Flooding on Kauai and Oahu*, NWS Report

**Photo 3-3: Cleared Debris on Waikupanaha Street**

Source: *Mileka Lincoln, 2018*

**Photo 3-4: Culvert Obstructed by Debris during April 2018 Flood Event**

A strong Kona low[3] produced heavy rainfall on December 5–6, 2021 that had major impacts throughout the State of Hawaii, including significant flooding and loss of power in urban parts of Honolulu. Its impact to the study area, however, was somewhat limited compared to other parts of Oʻahu. This determination was based on the unremarkable stream flow record and lack of articles on the event impacting the Waimānalo community.

[3] Hawaii is dominated by the trade winds that blow in from the northeast. However, the counter-clockwise flow around a Kona low located west of Hawaii results in southwesterly winds over the islands, which is typically the leeward or "kona" side. Kona storms are common between October and April.

# 4 Flood Frequency Analysis

A flood frequency analysis was performed to determine the magnitude of the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) annual exceedance probability (AEP) flood discharges for the Waimānalo community. Methods for estimating the peak flow for these five profiles include the following:

1. Stream gage analysis
2. Regional regression equations
3. Rainfall-runoff model

Other peak flow estimates previously published (for reference):

1. 2014 Flood Insurance Study

## 4.1 Stream Gage Analysis

Annual peak flow data from three stream gages in or near the study area were analyzed individually using methodology from Bulletin 17C (USGS, 2019) as applied by the Hydrologic Engineering Center’s Statistical Software Package (HEC-SSP) program (version 2.2, HEC, 2019). A Bulletin 17C analysis offers the opportunity to use intervals or thresholds to represent the magnitudes of flood peaks that might be known with less precision, such as historical flood data. There is no known additional historical flood data to add to the record. Thresholds were added to indicate all other floods that may have occurred during data gaps in the record. The weighted skew option was used, which weights the computed station skew with the generalized regional skew. A generalized skew value of -0.05 and mean-square error of 0.302 was used per the national map in Bulletin 17B and verified by USGS in 2010 (Oki, Rosa, & Yeung). Table 4-1 contains the number and names of the stream-gaging stations upon which a Bulletin 17C analysis was performed. Table 4-2, Table 4-3, and Table 4-4 contain the results from completing the analysis.

**Table 4-1: Relevant stream gages**

| Site Number | Site Name | Data Type | Period of record | No. years of usable record | Drainage area ($mi^2$) |
|---|---|---|---|---|---|
| 16248800 | Inoaole Stream at Waimanalo, Oahu, HI | Peak Flow | 1958–1996 | 39 | 1.28 |
| 16248950 | Kahawai Str at Waimanalo, Oahu, HI | Peak Flow | 1999–2020 | 22 | 1.13 |
| 16249000 | Waimanalo Str at Waimanalo, Oahu, HI | Peak Flow<br>Instantaneous | 1963–2021<br>2015–2022 | 53 | 2.13 |

**Table 4-2: Peak flow estimates computed using Bulletin 17C methodology for USGS 16248800, Inoaole Stream, 1958–1996**

| Annual Exceedance Probability (AEP) | Computed Curve Flow in $ft^3/s$ | Variance Log | Confidence Limits | |
|---|---|---|---|---|
| | | | 0.05 | 0.95 |
| 1/500 | 3,610.3 | 0.03003 | 9,229.7 | 2163.5 |
| 1/200 | 2,933.7 | 0.02171 | 6,402.4 | 1883.3 |
| 1/100 | 2,456.7 | 0.01655 | 4,791.8 | 1656.6 |
| 1/50 | 2,010.6 | 0.01236 | 3,528.9 | 1418.0 |
| 1/25 | 1,596.1 | 0.00914 | 2,541.4 | 1,169.3 |
| 1/10 | 1,097.5 | 0.00626 | 1566.0 | 832.8 |
| 1/5 | 757.8 | 0.00504 | 1018.4 | 582.8 |
| 1/2 | 353.7 | 0.00481 | 460.3 | 267.0 |
| Station Skew: -0.603 \| Regional Skew: -0.050 \| Weighted Skew: -0.321<br>Systematic Events: 39 | | | | |

**Table 4-3: Peak flow estimates computed using Bulletin 17C methodology for USGS 16248950, Kahawai Stream, 2008–2020**

| Annual Exceedance Probability (AEP) | Computed Curve Flow in ft³/s | Variance Log | Confidence Limits | |
|---|---|---|---|---|
| | | | 0.05 | 0.95 |
| 1/500 | 948.9 | 0.01691 | 2,291.4 | 668.0 |
| 1/200 | 836.8 | 0.01271 | 1,763.1 | 613.4 |
| 1/100 | 755.1 | 0.01001 | 1,439.0 | 569.9 |
| 1/50 | 675.6 | 0.00772 | 1,167.7 | 523.9 |
| 1/25 | 597.8 | 0.00582 | 939.5 | 475.1 |
| 1/10 | 495.9 | 0.00391 | 694.8 | 404.7 |
| 1/5 | 417.5 | 0.00290 | 542.6 | 345.6 |
| 1/2 | 302.6 | 0.00218 | 367.2 | 251.3 |
| Station Skew: 0.329 \| Regional Skew: -0.050 \| Weighted Skew: 0.114<br>Historic Events: 0 \| Systematic Events: 13 | | | | |

**Table 4-4: Peak flow estimates computed using Bulletin 17C methodology for USGS 16249000, Waimānalo Stream, 1963–2021**

| Annual Exceedance Probability (AEP) | Computed Curve Flow in ft³/s | Variance Log | Confidence Limits | |
|---|---|---|---|---|
| | | | 0.05 | 0.95 |
| 1/500 | 10,533.6 | 0.03020 | 28,119.8 | 6,369.7 |
| 1/200 | 7,885.5 | 0.02126 | 17,624.6 | 5,131.5 |
| 1/100 | 6,232.4 | 0.01575 | 12,244.7 | 4,274.8 |
| 1/50 | 4,837.7 | 0.01128 | 8,401.6 | 3,486.2 |
| 1/25 | 3,667.2 | 0.00783 | 5,683.5 | 2,763.1 |
| 1/10 | 2,411.0 | 0.00470 | 3,288.6 | 1,907.3 |
| 1/5 | 1,643.9 | 0.00333 | 2,092.9 | 1,334.2 |
| 1/2 | 812.3 | 0.00261 | 987.2 | 666.0 |
| Station Skew: 0.123 \| Regional Skew: -0.050 \| Weighted Skew: 0.071<br>Historic Events: 0 \| Systematic Events: 46 | | | | |

**Table 4-5: Peak flow estimates computed using Bulletin 17C methodology for USGS 16249000, Waimanalo Stream, 1963–1991**

| Annual Exceedance Probability (AEP) | Computed Curve Flow in $ft^3/s$ | Variance Log | Confidence Limits | |
|---|---|---|---|---|
| | | | 0.05 | 0.95 |
| 1/500 | 11,281.2 | 0.03352 | 31,568.4 | 6,630.1 |
| 1/200 | 9,133.4 | 0.02441 | 21,739.0 | 5,767.4 |
| 1/100 | 7,652.0 | 0.01871 | 16,167.9 | 5,083.0 |
| 1/50 | 6,289.2 | 0.01401 | 11,829.8 | 4,373.5 |
| 1/25 | 5,039.6 | 0.01032 | 8,474.1 | 3,643.1 |
| 1/10 | 3,551.2 | 0.00692 | 5,230.0 | 2,662.3 |
| 1/5 | 2,537.1 | 0.00542 | 3,464.9 | 1,932.5 |
| 1/2 | 1,304.6 | 0.00491 | 1,706.5 | 986.5 |
| Station Skew: -0.222 \| Regional Skew: -0.050 \| Weighted Skew: -0.152<br>Historic Events: 0 \| Systematic Events: 27 | | | | |

**Table 4-6: Peak flow estimates computed using Bulletin 17C methodology for USGS 16249000, Waimanalo Stream, 2003–2021**

| Annual Exceedance Probability (AEP) | Computed Curve Flow in $ft^3/s$ | Variance Log | Confidence Limits | |
|---|---|---|---|---|
| | | | 0.05 | 0.95 |
| 1/500 | 2,591.3 | 0.02814 | 7,766.1 | 1,637.8 |
| 1/200 | 2,155.0 | 0.02072 | 5,374.8 | 1,441.0 |
| 1/100 | 1,854.3 | 0.01603 | 4,043.9 | 1,290.6 |
| 1/50 | 1,576.4 | 0.01212 | 3,025.1 | 1,138.2 |
| 1/25 | 1,319.1 | 0.00896 | 2,238.3 | 984.3 |
| 1/10 | 1,005.9 | 0.00590 | 1,477.6 | 777.2 |
| 1/5 | 784.2 | 0.00439 | 1,056.0 | 617.1 |
| 1/2 | 493.9 | 0.00348 | 622.5 | 390.1 |
| Station Skew: 0.342 \| Regional Skew: -0.050 \| Weighted Skew: 0.130<br>Historic Events: 0 \| Systematic Events: 16 | | | | |

The differences between Table 4-5 and Table 4-6 highlight the potentially significant hydrologic changes that have occurred in the watershed since improvements to the Waimānalo Irrigation System were made in the early 1980s, the Waimānalo 60 MG Reservoir was constructed in 1993, and Kailua Reservoir was intentionally breached in 2006 (Section 1.6). Performing a Bulletin 17C analysis on the complete record at USGS 16249000 results in a 1% AEP peak flow of approximately 6,230 $ft^3/s$. Performing a Bulletin 17C analysis on the older record (1963 – 1991) results in a larger 1% AEP peak flow of about 7,652 $ft^3/s$. Performing a Bulletin 17C analysis on the recent record (2003 – 2021) results in a much smaller 1% AEP peak flow of about 1,850 $ft^3/s$. There is low confidence in the results that include and rely upon older streamflow records (Table 4-2 and Table 4-4) to represent existing site conditions. Results based on recent streamflow records (Table 4-3 and Table 4-6) should still be taken with caution as past flood events were reportedly impacted by debris[4] (Section 3.3).

## 4.2 Regional Regression Equations

In 2010, the U.S. Geological Survey published *Flood Frequency Estimates for Streams on Kauaʻi, Oʻahu, Molokaʻi, Maui, and Hawaii, State of Hawaii*, which includes regional regression equations for estimating peak flow for the 50%, 20%, 10%, 4%, 2%, 1%, and 0.2% AEP (2-, 5-, 10-, 25-, 50-, 100-, and 500-year) flood events (7 profiles). The Waimānalo watershed is located in the windward region of Oʻahu, *Region 4*. The equations for this region are presented in Table 4-7. Results of using these equations to estimate peak flow at each subbasin are presented in Table 4-8 for the various points of interest identified in Figure 4-1.

[4] Reduced flows, higher stages

**Table 4-7: Regional regression equations for peak flow estimates in Region 4**

| Regression equation | Range of explanatory variables | Standard error of prediction, in percent | $R^2$ | Standard model error, in percent |
|---|---|---|---|---|
| $Q_2$=570.2($DA^{0.770}$) | 0.04 ≤ DA ≤ 5.44 | 63 | 0.77 | 60 |
| $Q_5$=1,086($DA^{0.763}$) | 0.04 ≤ DA ≤ 5.44 | 51 | 0.83 | 48 |
| $Q_{10}$=1,517($DA^{0.754}$) | 0.04 ≤ DA ≤ 5.44 | 47 | 0.85 | 44 |
| $Q_{25}$=2,148($DA^{0.743}$) | 0.04 ≤ DA ≤ 5.44 | 46 | 0.85 | 42 |
| $Q_{50}$=2,679($DA^{0.735}$) | 0.04 ≤ DA ≤ 5.44 | 46 | 0.85 | 43 |
| $Q_{100}$=3,251($DA^{0.726}$) | 0.04 ≤ DA ≤ 5.44 | 48 | 0.84 | 44 |
| $Q_{500}$=4,786($DA^{0.706}$) | 0.04 ≤ DA ≤ 5.44 | 54 | 0.79 | 49 |
| $Q_T$ = peak discharge for T-year recurrence interval<br>DA = drainage area, in square miles<br>a < DA < b = the drainage area may be greater than or equal to a and less than or equal to b | | | | |

**Table 4-8: Regional regression peak flow estimates at key points in the study area**

| Point of Interest | Watershed | Location | Drainage area ($mi^2$) | Peak flow ($ft^3/s$)[1] | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1/2 | 1/5 | 1/10 | 1/25 | 1/50 | 1/100 | 1/500 |
| 1 | Waimānalo | USGS 16249000 | 1.96 | 957 | 1,815 | 2,520 | 3,541 | 4,393 | 5,299 | 7,697 |
| 2 | Waimānalo | USGS 16248950 | 1.40 | 739 | 1,404 | 1,955 | 2,758 | 3,431 | 4,151 | 6,069 |
| 3 | Waimānalo | Waimānalo-Kahawai Stream Junction | 3.63 | 1,539 | 2,904 | 4,010 | 5,598 | 6,910 | 8,289 | 11,892 |
| 4 | Waimānalo | Waimānalo Stream Outlet | 5.05 | 1,984 | 3,736 | 5,144 | 7,155 | 8,808 | 10,534 | 15,014 |
| 5 | Kahawai | USGS 16248800 | 1.00 | 570 | 1,086 | 1,517 | 2,148 | 2,679 | 3,251 | 4,786 |
| 6 | Kahawai | Puha Stream Junction | 2.19 | 1,043 | 1,975 | 2,740 | 3,846 | 4,766 | 5,744 | 8,324 |
| 7 | Kahawai | Puha Stream Outlet | 2.59 | 1,187 | 2,245 | 3,109 | 4,356 | 5,392 | 6,487 | 9,370 |
| 8 | Kaiona | Unnamed Stream #1 Outlet | 1.02 | 579 | 1,103 | 1,540 | 2,180 | 2,718 | 3,298 | 4,853 |
| 9 | Unnamed | Unnamed Stream #2 Outlet | 0.043 | 51 | 98 | 141 | 207 | 265 | 331 | 519 |
| [1]: rounded to three significant figures | | | | | | | | | | |

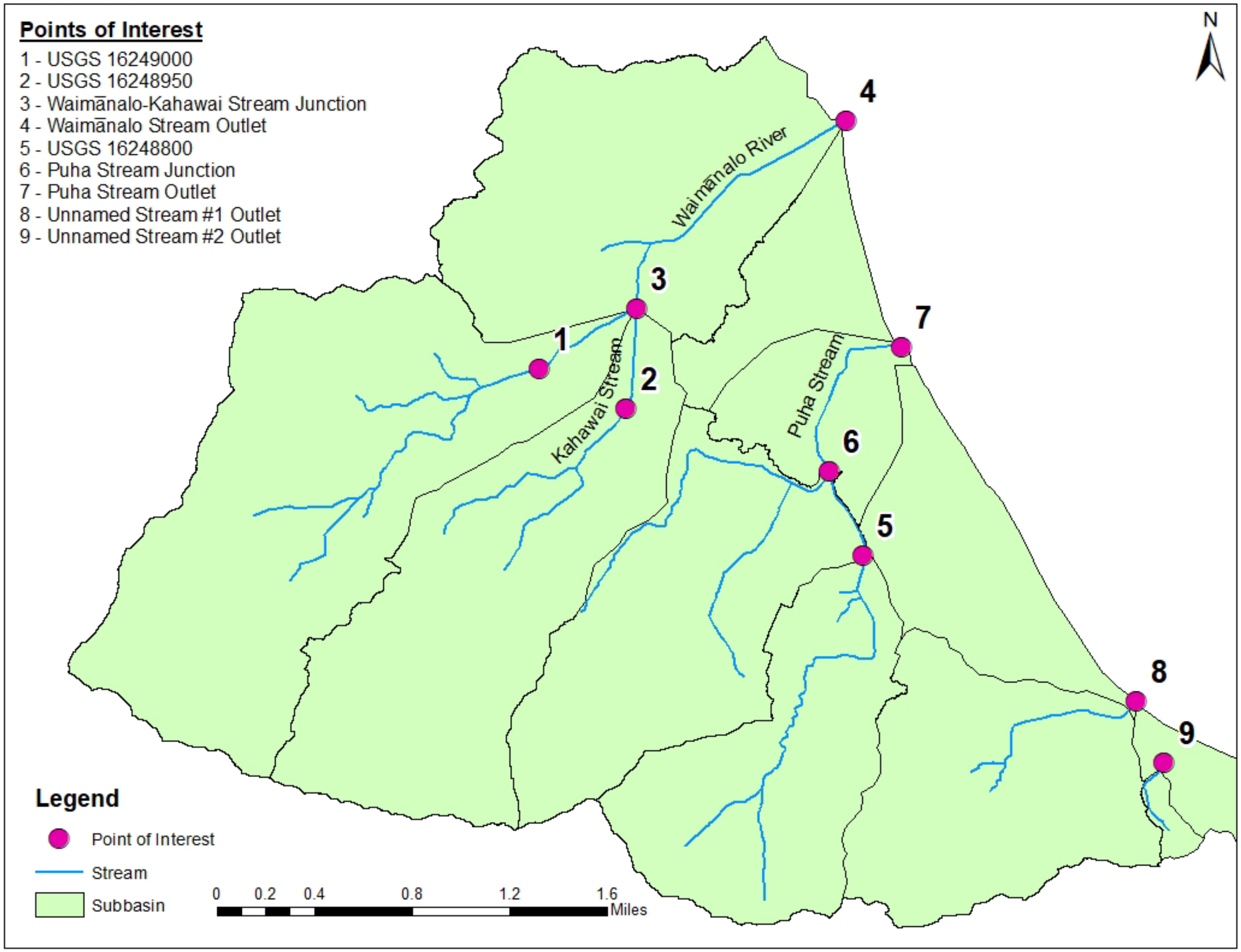



**Figure 4-1: Key Points of Interest in the Study Area**

## 4.3 Rainfall-Runoff Model

The rainfall-runoff model for this study was developed using the Hydrologic Engineering Center’s Hydrologic Modeling System (HEC-HMS, version 4.9, 2022) software. The HMS model was calibrated to two historic storm events using nearby climate and stream gaging stations. The calibrated model was then used to estimate discharge-frequency relationships throughout different points throughout the study area. Initial parameters required for the HMS model were estimated using the methodology presented in Technical Release 55 (TR-55) for the transformation parameters, and hydraulic conductivity for the loss parameters. The calibrated parameters estimated by the rainfall-runoff model are presented in Section 4.3.6, Table 4-21. Final peak flow estimates computed by the calibrated rainfall-runoff model are presented in Section 4.3.8.

### 4.3.1 **Terrain Data**

The coordinate system was set to State Plane Zone 3 (US Survey Feet) with reference to NAD83 (PA11). The terrain data was created from the GIS raster file created by merging the three elevation datasets presented in Section 2.2, Table 2-1.

### 4.3.2 **Basin Characteristics**

The basin and subbasins were initially delineated in HMS, but then manually corrected in GIS. Manual delineation involves carefully following the contours of the watershed and splitting the watershed into portions based on how the water will flow. The final subbasins are listed in Table 4-9 and shown below in Figure 4-1.

Variations of Subbasin 1 and Subbasin 2 were also created for calibration purposes to represent the unique drainage areas specific to USGS 16249000 and USGS 16248950, respectively. These subbasins, which are slightly smaller than their original counterparts, are marked with an apostrophe and referred to as Subbasin 1’ and Subbasin 2’. Subbasin 5 did not need to be modified to be reflective of USGS 16248800.

**Table 4-9: Subbasin Identification and Information**

| Watershed | Subbasin ID | Drainage area ($mi^2$) | Centroid location | |
|---|---|---|---|---|
| | | | Latitude | Longitude |
| Waimānalo | 1 | 2.09 | 21.342437 | -157.74315 |
| Waimānalo | 1’ | 1.96 | 21.341951 | -157.744171 |
| Waimānalo | 2 | 1.54 | 21.335897 | -157.732567 |
| Waimānalo | 2’ | 1.40 | 21.334628 | -157.733643 |
| Waimānalo | 3 | 1.42 | 21.360486 | -157.723183 |
| Kahawai | 4 | 1.19 | 21.334908 | -157.720264 |
| Kahawai | 5 | 1.00 | 21.326264 | -157.714012 |
| Kahawai | 6 | 0.398 | 21.347442 | -157.711097 |
| Kaiona | 7 | 1.02 | 21.32485 | -157.700281 |
| Other | 8 | 0.613 | 21.33844 | -157.701696 |
| Other | 9 | 0.043 | 21.323072 | -157.689 |
| Other | 10 | 0.292 | 21.32423 | -157.683859 |
| Other | 11 | 0.378 | 21.354798 | -157.712919 |

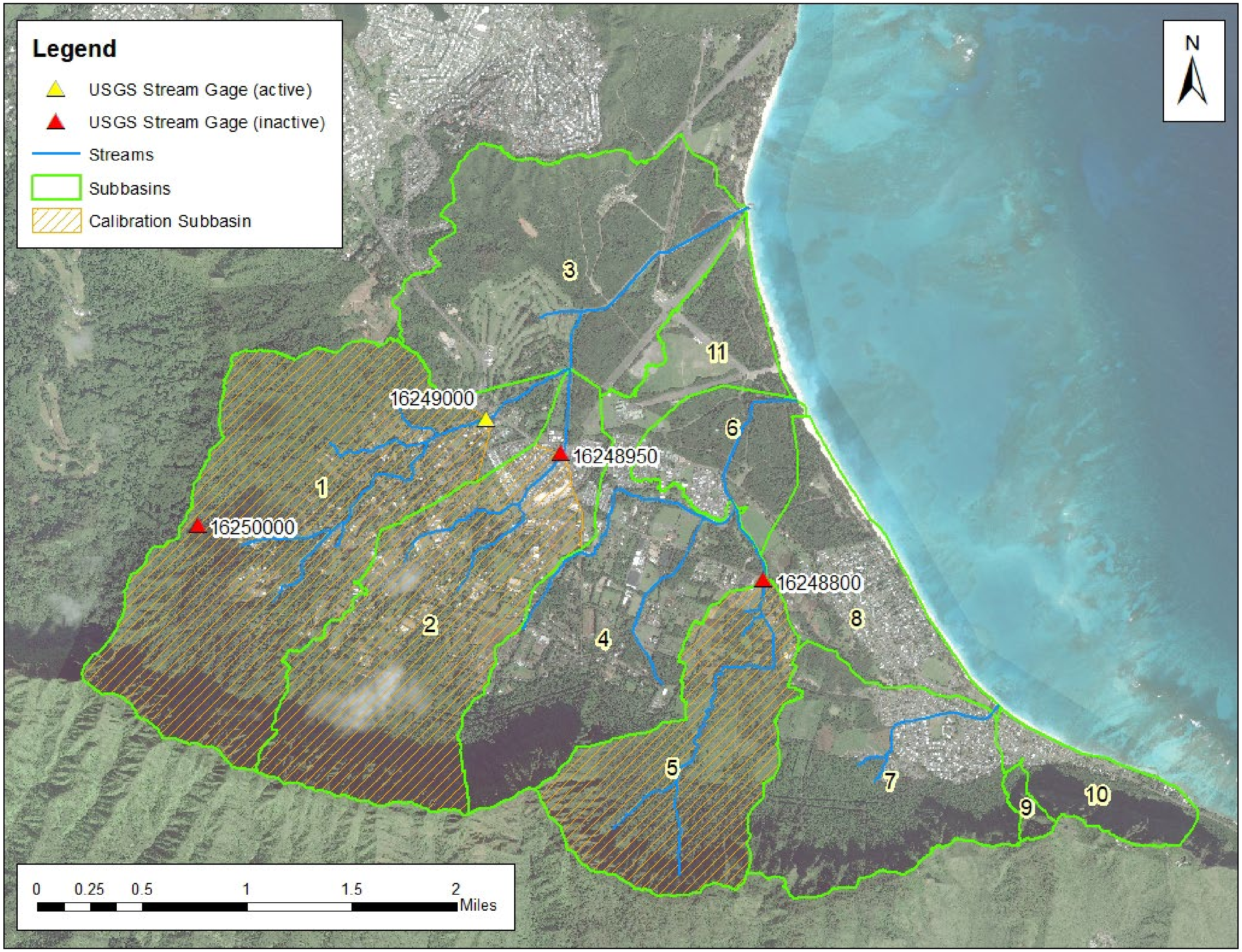

Legend
USGS Stream Gage (active)
USGS Stream Gage (inactive)
Streams
Subbasins
Calibration Subbasin
N
16249000
16248950
16250000
16248800
1
2
3
4
5
6
7
8
9
10
11
0
0.25
0.5
1
1.5
2
Miles

**Figure 4-2: Subbasin Delineation Map**

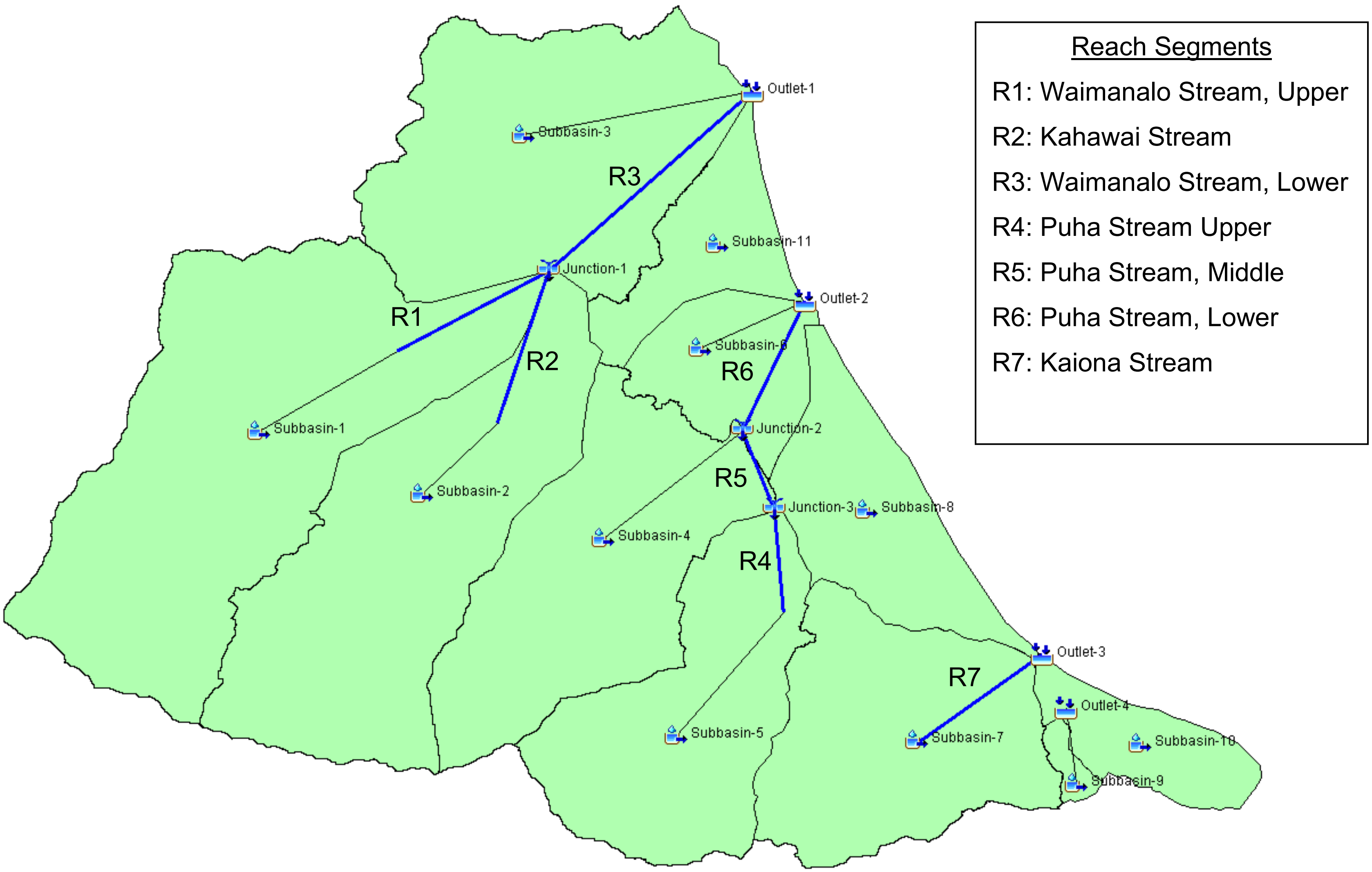



**Figure 4-3: HEC-HMS Basin Model Layout**

#### 4.3.3 **Initial estimation for loss parameters**

The initial and constant loss methods were applied to the model to account for precipitation loss due to infiltration. There are three parameters for this loss method: initial loss, constant loss, and percent impervious area.

The initial loss, the amount of precipitation lost to the soil at the beginning of the rainfall event, depends on the saturation of the soil and varies for each event. 0.1 inches of precipitation was assumed to be the initial loss due to absorption of the soil.

The constant loss rates were determined using soil data from the Hawaiʻi Soil Data Atlas, an interactive and online tool for providing basic information about each soil type (University of Hawai'i, 2014). Each soil type had previously been classified by their saturated hydraulic conductivity (Ksat) as either slow (< 3 micrometers per second; μm/s), moderate (3 to 10 μm/s), fast (10 to 100 μm/s), or very fast (> 100 μm/s); see Figure 4-4. A geospatial shapefile provided by the Hawaiʻi Soil Data Atlas was used to compute a weighted average Ksat[5] for each subbasin, and then converted to the appropriate units – inches per hour (in/hr). This value was used as the initial constant loss values, as presented in Table 4-10.

Finally, the land cover raster (Section 2.4), which identifies specific areas across the study area as impervious, was used to determine the percent impervious area. Results are provided in Table 4-10.

[5] Based on engineering judgment and review of typical rates within each subbasin, the following rates were assigned for each classification: slow = 1.5 μm/s; moderate = 8 μm/s; fast = 23 μm/s; very fast = not applicable; except for Subbasin 8 where fast = 92 μm/s.

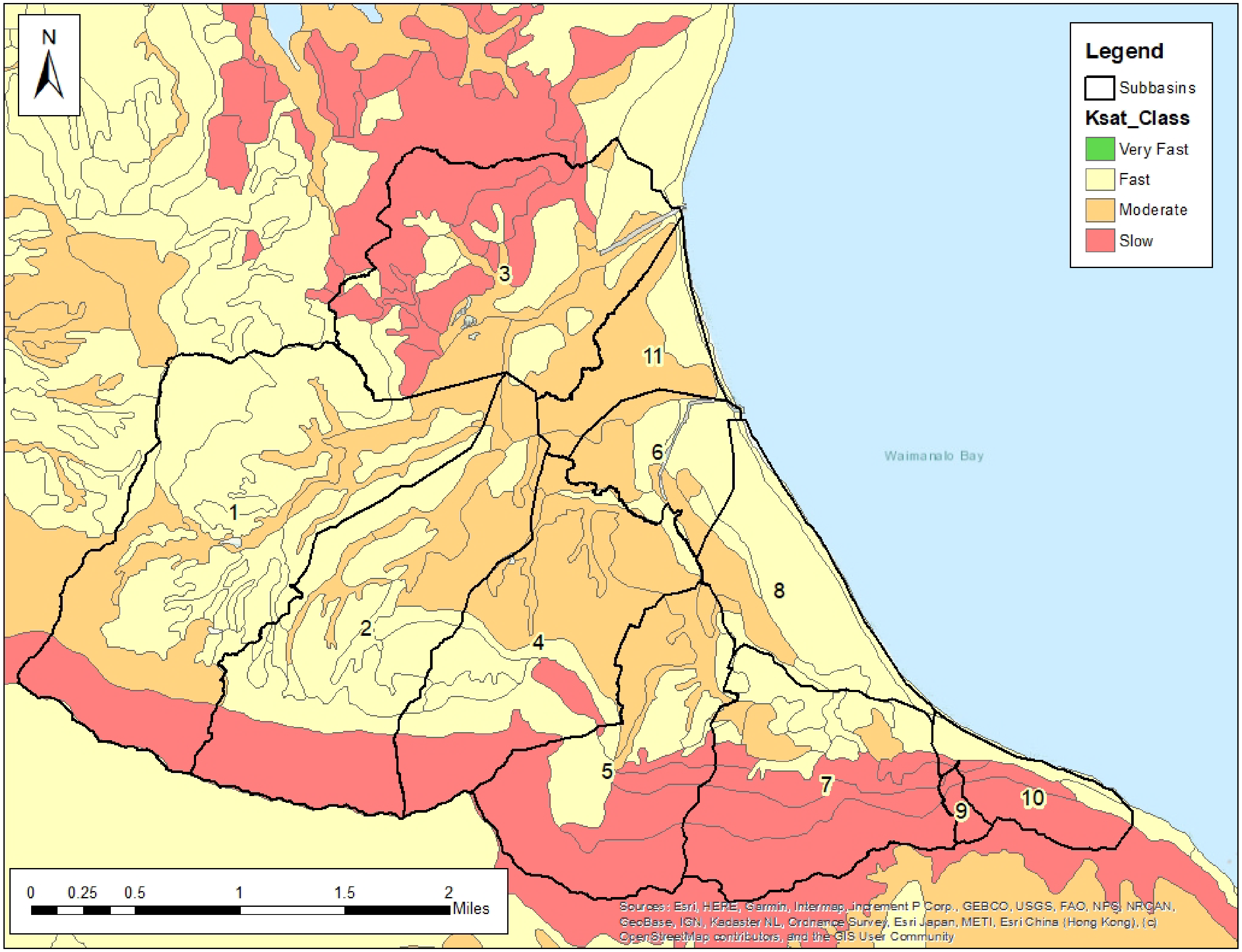



**Figure 4-4: Saturated Hydraulic Conductivity, Ksat, Classification Map**

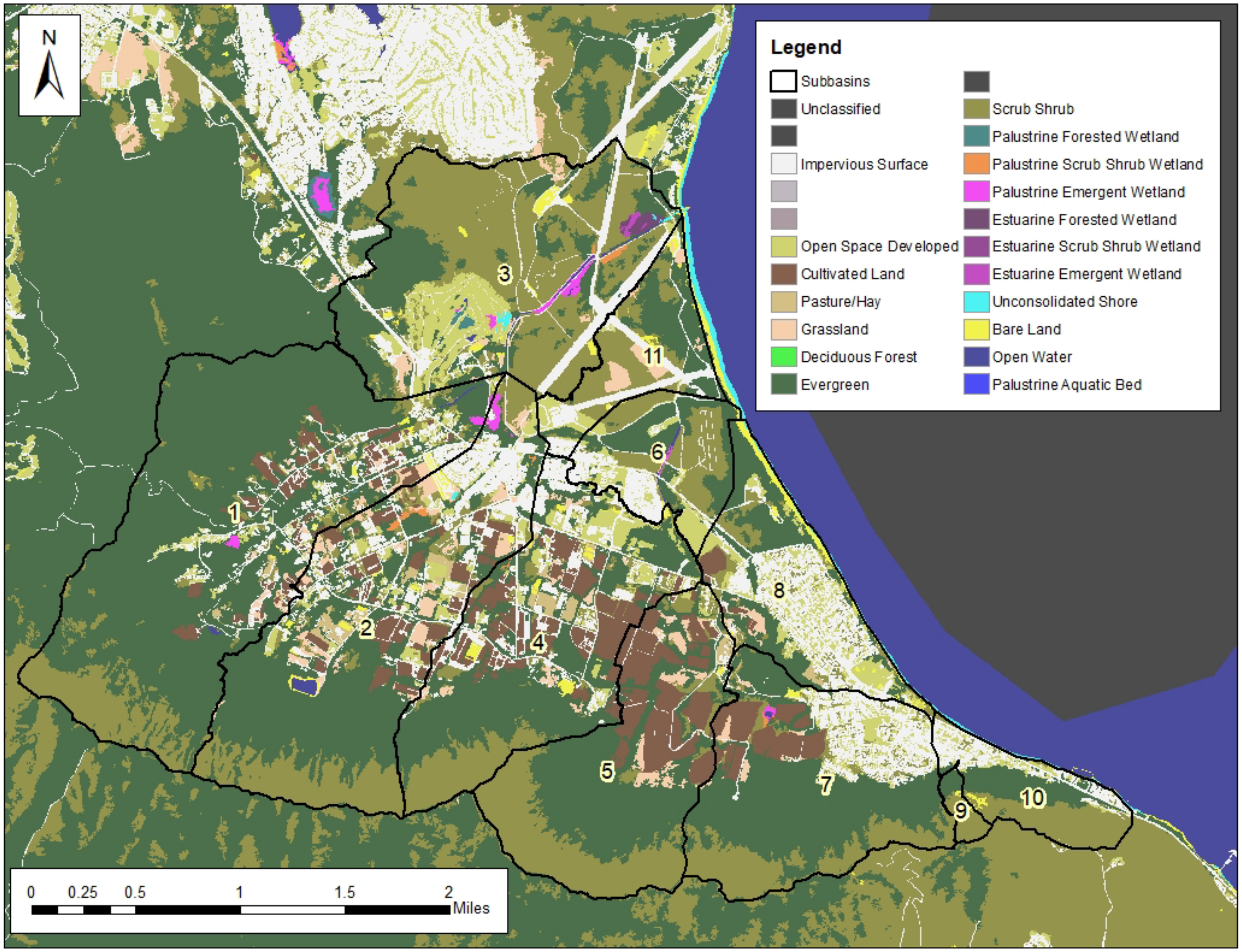



**Figure 4-5: Land Cover Map**

**Table 4-10: Initial Loss and Constant Rate Parameters for each Subbasin**

| Subbasin Name | Drainage area ($mi^2$) | Initial Loss (in) | Constant Loss (in/hr) | Impervious (%) |
|---|---|---|---|---|
| Subbasin 1 | 2.09 | 0.1 | 2.28 | 7.59 |
| Subbasin 1’ | 1.96 | 0.1 | 2.30 | 6.44 |
| Subbasin 2 | 1.54 | 0.1 | 1.99 | 16.7 |
| Subbasin 2’ | 1.40 | 0.1 | 2.03 | 14.7 |
| Subbasin 3 | 1.42 | 0.1 | 1.48 | 10.5 |
| Subbasin 4 | 1.19 | 0.1 | 1.63 | 15.5 |
| Subbasin 5 | 1.00 | 0.1 | 1.21 | 2.01 |
| Subbasin 6 | 0.398 | 0.1 | 2.30 | 20.9 |
| Subbasin 7 | 1.02 | 0.1 | 1.10 | 14.4 |
| Subbasin 8 | 0.613 | 0.1 | 10.98 | 31.5 |
| Subbasin 9 | 0.043 | 0.1 | 0.213 | 0.202 |
| Subbasin 10 | 0.292 | 0.1 | 4.47 | 22.5 |
| Subbasin 11 | 0.378 | 0.1 | 4.42 | 20.3 |

### 4.3.4 **Initial estimation for transform parameters**

The Clark Unit Hydrograph method was used to account for the transformation of excess precipitation into surface runoff for this study. This method requires two parameters: time of concentration ($t_c$) and storage coefficient (R).

The time of concentration parameter, $t_c$ is defined as the time needed for water to flow from the most remote point in a watershed to the watershed outlet. This parameter was calculated using TR-55, which splits the surface flow in each watershed into three different flows. The three different flows are: sheet flow, shallow concentrated flow, and open channel flow. There are travel times associated with each type of flow, and the combination of those three are considered to be the overall time of concentration for each subbasin. The various parameters needed for TR-55 were found using various tools in GIS and are shown below in Table 4-11, Table 4-12, and Table 4-13.

Subbasins 8, 10, and 11 are coastal drainage areas that do not contribute significant flow to any of the primary river systems and do not have a defined channel system. These independent drainage areas are represented in the hydraulic model with rainfall applied directly to these areas and relies upon the hydraulic model to transform surface water appropriately. For this reason, transform parameters were not calculated for Subbasins 8, 10, and 11 as they were not needed.

**Table 4-11: Sheet Flow Characteristics for each Sub-Basin**

| Subbasin Name | Manning's *n* Overland[1] | Sheet Flow Length (ft) | 2-yr, 24-hr Rainfall (in) | Land Slope (ft/ft) | $t_c$, sheet (hrs) |
|---|---|---|---|---|---|
| Subbasin 1 | 0.16 | 294 | 6.62 | 0.87 | 0.063 |
| Subbasin 1’ | 0.16 | 294 | 6.62 | 0.87 | 0.063 |
| Subbasin 2 | 0.16 | 156 | 6.01 | 0.89 | 0.039 |
| Subbasin 2’ | 0.16 | 156 | 6.01 | 0.89 | 0.039 |
| Subbasin 3 | 0.16 | 85 | 5.08 | 0.15 | 0.053 |
| Subbasin 4 | 0.16 | 165 | 5.39 | 0.85 | 0.044 |
| Subbasin 5 | 0.16 | 218 | 4.88 | 1.04 | 0.054 |
| Subbasin 6 | 0.011 | 298 | 4.77 | 0.02 | 0.042 |
| Subbasin 7 | 0.16 | 270 | 4.67 | 0.42 | 0.093 |
| Subbasin 9 | 0.13 | 48.6 | 4.77 | 0.44 | 0.020 |
| [1]: with reference to TR-55, Table 3-1 (NRCS, 1986) | | | | | |

**Table 4-12: Shallow Concentrated Flow Characteristics for each Sub-Basin**

| Subbasin Name | Surface Type | Flow Length (ft) | Watercourse Slope (ft/ft) | Average Velocity (ft/s) | $t_c$, shallow (hrs) |
|---|---|---|---|---|---|
| Subbasin 1 | Unpaved | 10,130 | 0.224 | 7.64 | 0.368 |
| Subbasin 1’ | Unpaved | 10,130 | 0.224 | 7.64 | 0.368 |
| Subbasin 2 | Unpaved | 10,121 | 0.223 | 7.61 | 0.370 |
| Subbasin 2’ | Unpaved | 10,121 | 0.223 | 7.61 | 0.370 |
| Subbasin 3 | Unpaved | 4,706 | 0.067 | 4.19 | 0.312 |
| Subbasin 4 | Unpaved | 10,121 | 0.215 | 7.48 | 0.376 |
| Subbasin 5 | Unpaved | 6,857 | 0.187 | 6.97 | 0.273 |
| Subbasin 6 | Unpaved | 2,750 | 0.010 | 1.61 | 0.475 |
| Subbasin 7 | Unpaved | 3,943 | 0.344 | 9.46 | 0.116 |
| Subbasin 9 | Unpaved | 2590 | 0.498 | 11.38 | 0.063 |

**Table 4-13: Channel Flow Characteristics for each Sub-Basin**

| Subbasin Name | Cross Sectional Flow Area ($ft^2$) | Wetted Perimeter (ft) | Hydraulic Radius (ft) | Channel Slope (ft/ft) | Manning's *n* Channel | Velocity (ft/s) | Flow Length (ft) | $t_c$, channel (hrs) |
|---|---|---|---|---|---|---|---|---|
| Subbasin 1 | 238.2 | 54.2 | 4.39 | 0.009 | 0.036 | 10.4 | 5,821 | 0.155 |
| Subbasin 1’ | 238.2 | 54.2 | 4.39 | 0.011 | 0.036 | 11.5 | 3,267 | 0.079 |
| Subbasin 2 | 493.9 | 72.8 | 6.79 | 0.005 | 0.036 | 10.5 | 3,893 | 0.103 |
| Subbasin 2’ | 493.9 | 72.8 | 6.79 | 0.008 | 0.036 | 13.5 | 1,672 | 0.035 |
| Subbasin 3 | 241.6 | 78.6 | 3.07 | 0.000 | 0.038 | 1.4 | 5,008 | 0.970 |
| Subbasin 4 | 373.8 | 79.5 | 4.70 | 0.005 | 0.043 | 6.8 | 1,494 | 0.061 |
| Subbasin 5 | 109.7 | 34.9 | 3.15 | 0.017 | 0.043 | 9.6 | 2,947 | 0.085 |
| Subbasin 6 | 439.0 | 97.5 | 4.50 | 0.001[6] | 0.038 | 3.4 | 1,763 | 0.145 |
| Subbasin 7 | 454.6 | 59.6 | 7.63 | 0.023 | 0.026 | 33.9 | 4,302 | 0.035 |
| Subbasin 9 | not applicable (no well-defined channel) | | | | | | | |

[6] Actual channel slope based on GIS terrain data was negative due to gradual build-up of sediment near the outlet. However, as these sediments are likely to become washed out during a storm event, the channel was assumed to have a shallow, positive slope 0.001 ft/ft for computation purposes.

The storage coefficient parameter, R, is an index of the temporary storage of precipitation excess in the watershed as it drains to the outlet point. The HEC-HMS User's Manual states that the storage coefficient, R, divided by the sum of R and $t_c$, is reasonably constant over a region. As a starting point, the initial R value was estimated by assuming:

$$\frac{R}{t_c + R} = 0.5$$

When simplified, the formula is shown as: $R = t_c$. Therefore, the time of concentration found through TR-55 was used to set the initial R value.

**Table 4-14: Initial Time of Concentration and Storage Area for each Subbasin**

| Subbasin Name | Drainage area ($mi^2$) | Time of Concentration (hr) | Storage Coefficient (hr) |
|---|---|---|---|
| Subbasin 1 | 2.09 | 0.586 | 0.586 |
| Subbasin 1' | 1.96 | 0.510 | 0.510 |
| Subbasin 2 | 1.54 | 0.512 | 0.512 |
| Subbasin 2' | 1.40 | 0.443 | 0.443 |
| Subbasin 3 | 1.42 | 1.335 | 1.335 |
| Subbasin 4 | 1.19 | 0.481 | 0.481 |
| Subbasin 5 | 1.00 | 0.412 | 0.412 |
| Subbasin 6 | 0.398 | 0.662 | 0.662 |
| Subbasin 7 | 1.02 | 0.244 | 0.244 |
| Subbasin 9 | 0.043 | 0.083 | 0.083 |

### 4.3.5 Reach Routing and Loss Parameterization

Four reaches were added to the HMS model (Figure 4-3), representing the lower reach segments: one for Waimānalo Stream, two for Puha (Inoaole) Stream, and one for the unnamed reach in the Kaiona watershed. The Muskingum-Cunge routing method was selected as the routing reach method because it is based off the physical parameters of each reach (i.e., channel shape, routing reach length, Manning’s n). These parameters are easily obtainable by taking representative cross-sections in HEC-RAS[7] for each reach in the model.

**Table 4-15: HEC-HMS Muskingum-Cunge Channel Routing Parameters**

| Reach Name | Length (ft) | Slope (ft/ft) | Manning’s n | Shape | Bottom Width (ft) | Side Slope (xH:1V) |
|---|---|---|---|---|---|---|
| Waimānalo Stream, Upper | 4,114 | 0.008 | 0.043 | Trapezoidal | 24.4 | 2.2 |
| Kahawai Stream | 3,894 | 0.005 | 0.043 | Trapezoidal | 31.7 | 1.8 |
| Waimānalo Stream, Lower | 6,617 | 0.0005 | 0.038 | Trapezoidal | 54.5 | 3.1 |
| Puha Stream, Upper | 2,308 | 0.0160 | 0.043 | Trapezoidal | 8.5 | 2.3 |
| Puha Stream, Middle | 2,224 | 0.004 | 0.043 | Trapezoidal | 48.1 | 2.4 |
| Puha Stream, Lower | 3,824 | 0.0005 | 0.043 | Trapezoidal | 24.1 | 4.9 |
| Kaiona Stream | 3,769 | 0.016 | 0.023 | Rectangular | 22.4 | 0 |

[7] HEC-RAS refers to HEC’s River Analysis System software, which was used to develop the hydraulic model presented in Appendix C.

### 4.3.6 **Model Calibration**

Since the construction of the Waimānalo 60 MG Reservoir in 1993, there have been two significant floods: 31 March 2006 and 13 April 2018. These events are described in detail in Section 3.3. However, there is no instantaneous rainfall data available from any of the nearby climate stations for the 31 March 2006 event. The model was calibrated to the 13 April 2018 event and a smaller storm event that occurred on 15 March 2020. Instantaneous rainfall data from climate station WMLH1 and instantaneous streamflow data from USGS 16249000 were used to calibrate Subbasin 1’. The simulated hydrographs (blue lines) are compared to the observed hydrographs (black lines) in Figure 4-6 and Figure 4-7.

#### 4.3.6.1 Performance Metrics

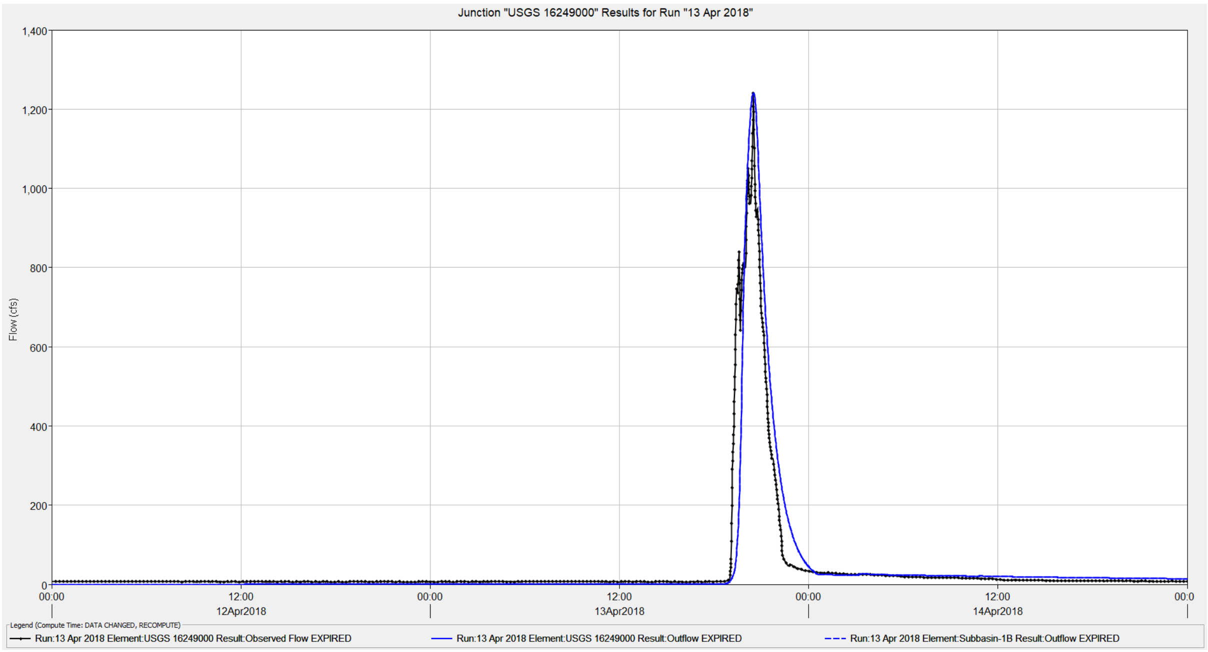
The Nash-Sutcliffe model efficiency (NSE) coefficient is used to assess the predictive power of hydrologic models. This number can range from -∞ to 1. Typically, an NSE between 0.75 to 1.00 is a very good fit, between 0.64 to 0.74 is a good fit, between 0.50 to 0.64 is a satisfactory fit and less than 0.50 is an unsatisfactory fit (Moriasi, et al., 2007). An efficiency of 1 corresponds to a perfect match of the simulated discharge to observed data. The NSE coefficients for each storm event at the stream flow gage are also included in the tables that follow.

Percent Bias (PBIAS) has also been included as a secondary performance metric indicative of calibration. PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The closer the percentage value is to zero (0%), the better the calibration is. Typically, a percent bias of less than 10% is very good, between 10 to 15% is good, and between 15 to 25% is fair (Moriasi, et al., 2007). Positive values indicate under-estimation bias, and negative values indicate over-estimation bias. The allowable bias in this study is +/- 35%.

Percent difference was used to compare the simulated and observed peak discharges at both stream gages. A percent difference of 5% or less was acceptable in this study.

Table 4-16 through Table 4-19 summarize the calibration metrics for each event.

**Figure 4-6: Comparison of the simulated and observed hydrographs near USGS 16249000 for the April 2018 flood**




The baseflow parameters selected during calibration were 0 $ft^3/s$ for the *initial discharge*, 0.5 for the *recession constant*, and 0.02 for the *ratio to peak*.

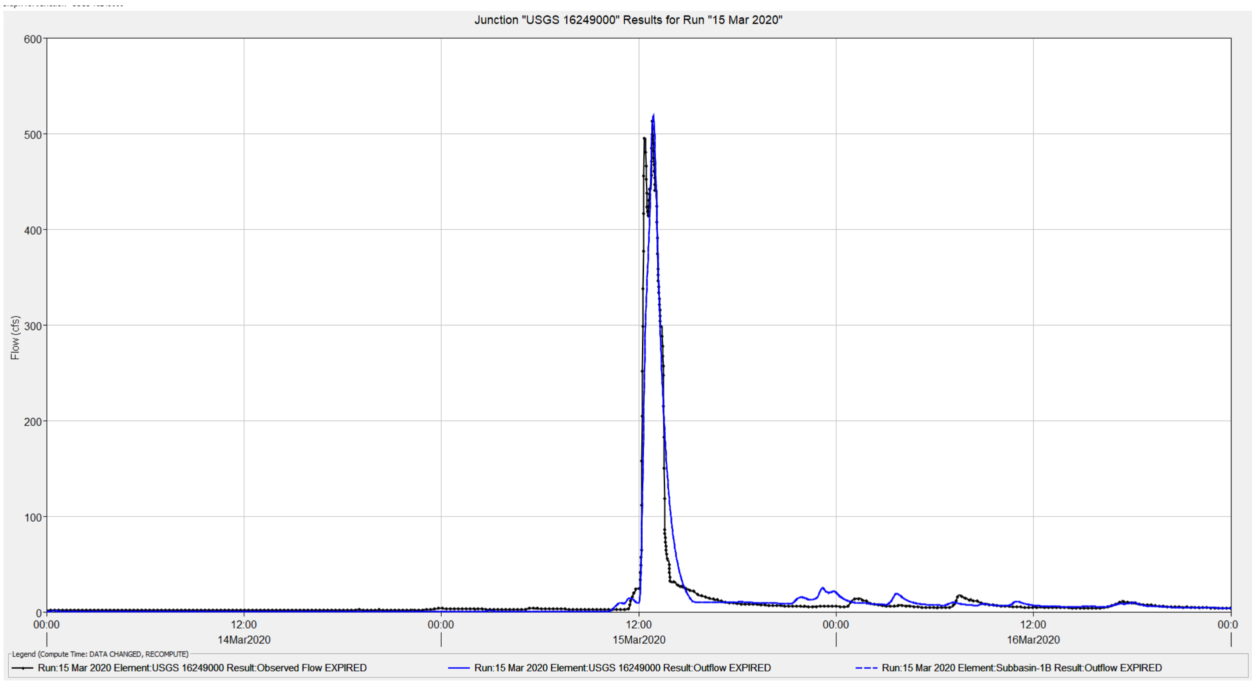
**Table 4-16: Subbasin 1’ optimized parameters for the April 2018 flood**

| Calibration status | Initial loss (in) | Constant loss (in/hr) | Time of concentration, $T_c$ (hrs) | Storage coefficient, R | Nash-Sutcliffe | Percent Bias |
|---|---|---|---|---|---|---|
| Initial | 0.1 | 2.30 | 0.510 | 0.510 | -- | -- |
| April 2018 | 0.1 | 1.92 | 0.300 | 1.00 | 0.845 | -1.30% |
| *% change:* | *0%* | *-16.5%* | *-41.2%* | *96.1%* | | |

**Table 4-17: Simulated peak discharges versus observed data at USGS 16604500 for the April 2018 flood**

| Storm event | Simulated ($ft^3/s$) | Observed ($ft^3/s$) | Percentage difference (%) |
|---|---|---|---|
| 13 April 2018 | 1,240 | 1,240 | 0 |

**Figure 4-7: Comparison of the simulated and observed hydrographs near USGS 16249000 for the March 2020 flood**




The baseflow parameters selected during calibration were 0 ft$^3$/s for the *initial discharge*, 0.5 for the *recession constant*, and 0.02 for the *ratio to peak*.

**Table 4-18: Subbasin 1’ optimized parameters for the March 2020 flood**

| Calibration status | Initial loss (in) | Constant loss (in/hr) | Time of concentration, $T_c$ (hrs) | Storage coefficient, R | Nash-Sutcliffe | Percent Bias |
|---|---|---|---|---|---|---|
| Initial | 0.1 | 2.30 | 0.510 | 0.510 | -- | -- |
| March 2020 | 0.1 | 1.3 | 0.300 | 0.600 | 0.925 | -3.16% |
| *% change:* | *0%* | *-43.5%* | *-41.2%* | *17.6%* | | |

**Table 4-19: Simulated peak discharges versus observed data at USGS 16604500 for the February 2018 flood**

| Storm event | Simulated (ft$^3$/s) | Observed (ft$^3$/s) | Percentage difference (%) |
|---|---|---|---|
| 15 March 2020 | 519 | 513 | 1.16 |

4.3.6.2 Results

Both performance metrics (Nash-Sutcliffe and Percent Bias) indicate Subbasin 1’ is well calibrated to the observed record at USGS 16249000 for both storm events. The resulting percent difference between the observed and simulated hydrographs is less than 5% for both storm events and also indicates that Subbasin 1’ is well calibrated. The final calibrated parameter values for Subbasin 1’ were determined by calculating the mean value between the two storm events for each parameter (Table 4-20, Row 5).

To calibrate the other subbasins in the model, an adjustment factor was established that reflects how each parameter should be adjusted from its initial estimate. The adjustment factor was determined by calculating the percentage change between the initial parameter values for Subbasin 1’ and the final calibrated parameter values for Subbasin 1’ (Table 4-20, Row 6). The final, calibrated parameter estimates for all subbasins are listed in Table 4-21.

**Table 4-20: Calibration Parameters for Subbasin 1’**

| (1) | **Storm event** | **Initial loss (in)** | **Constant loss (in/hr)** | **Time of concentration, $T_c$ (hrs)** | **Storage coefficient, R** |
|---|---|---|---|---|---|
| (2) | Initial | 0.1 | 2.30 | 0.510 | 0.510 |
| (3) | 13 April 2018 | 0.1 | 1.92 | 0.300 | 1.00 |
| (4) | 15 March 2020 | 0.1 | 1.3 | 0.300 | 0.600 |
| *(5)* | *Mean* | *0.1* | *1.61* | *0.300* | *0.800* |
| *(6)* | *% change* | *0%* | *-30%* | *-41.2%* | *56.9%* |

**Table 4-21: Calibrated Parameters for All Subbasins**

| Subbasin | Initial loss (in) | Constant loss (in/hr) | Time of concentration, $T_c$ (hrs) | Storage coefficient, R |
|---|---|---|---|---|
| Subbasin 1 | 0.1 | 1.60 | 0.345 | 0.919 |
| Subbasin 1’ | 0.1 | 1.61 | 0.300 | 0.800 |
| Subbasin 2 | 0.1 | 1.39 | 0.301 | 0.803 |
| Subbasin 2’ | 0.1 | 1.42 | 0.260 | 0.695 |
| Subbasin 3 | 0.1 | 1.04 | 0.785 | 2.095 |
| Subbasin 4 | 0.1 | 1.14 | 0.283 | 0.755 |
| Subbasin 5 | 0.1 | 0.847 | 0.242 | 0.646 |
| Subbasin 6 | 0.1 | 1.61 | 0.389 | 1.039 |
| Subbasin 7 | 0.1 | 0.770 | 0.143 | 0.383 |
| Subbasin 8 | 0.1 | 7.69[8] | -- | -- |
| Subbasin 9 | 0.1 | 0.15 | 0.049 | 0.130 |
| Subbasin 10 | 0.1 | 3.13 | -- | -- |
| Subbasin 11 | 0.1 | 3.09 | -- | -- |

[8] This subbasin is primarily composed of *Jaucas* soils, which consists of very deep, excessively drained, very rapidly permeable soils on vegetated beach areas along the coast (University of Hawai'i, 2014).

#### 4.3.7 **Precipitation Frequency Data**

Point precipitation data was obtained from the National Weather Service’s (NWS) NOAA Atlas 14 Precipitation-Frequency Data Server (PFDS). This source presents the estimated total rainfall from recurrence intervals of 1 to 1000 years (100% to 0.1% annual exceedance probabilities) for various durations (5 minutes to 60 days) within or adjacent to the study area (NOAA, 2017). The location points used to extract PFDS data were the approximate centroid locations for each subbasin (Table 4-9).

#### 4.3.8 **Flow Frequency Estimates**

The final calibrated HEC-HMS model discussed above was used to determine the rainfall-runoff computations of the eight frequency events (50%, 20%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% AEP events). Point precipitation data was obtained from the NWS NOAA Atlas 14 Precipitation-Frequency Data Server (PFDS). This data server has estimated total rainfall for each of the eight frequency events and provides data for specific latitude-longitude coordinates. The coordinates used were the ten different centroids from each subbasin. This point precipitation data was input into the calibrated model to compute peak flow estimates for the eight frequency events (listed above) at each subbasin. The table below shows the resulting peak flow estimates for each of the eight frequency events.

**Table 4-22: Peak flow estimates for the Waimānalo Watershed**

| HEC-HMS Element | | | | | | |
|---|---|---|---|---|---|---|
| | | Subbasin-1 | Subbasin-2 | Junction-1 | Subbasin-3 | Outlet-1 |
| **Peak Flow (ft$^3$/s)[1]** | | | | | | |
| **Annual Exceedance Probability (AEP)** | **1/2** | 843 | 809 | 1,630 | 300 | 1,530 |
| | **1/5** | 1,450 | 1,320 | 2,740 | 499 | 2,620 |
| | **1/10** | 2,514 | 2,210 | 4,680 | 885 | 4,640 |
| | **1/25** | 2,510 | 2,210 | 4,680 | 885 | 4,640 |
| | **1/50** | 3,020 | 2,620 | 5,590 | 1,060 | 5,630 |
| | **1/100** | 3,550 | 3,040 | 6,540 | 1,240 | 6,660 |
| | **1/200** | 4,110 | 3,490 | 7,540 | 1,430 | 7,740 |
| | **1/500** | 4,880 | 4,100 | 8,920 | 1,700 | 9,240 |

[1]: rounded to three significant figures

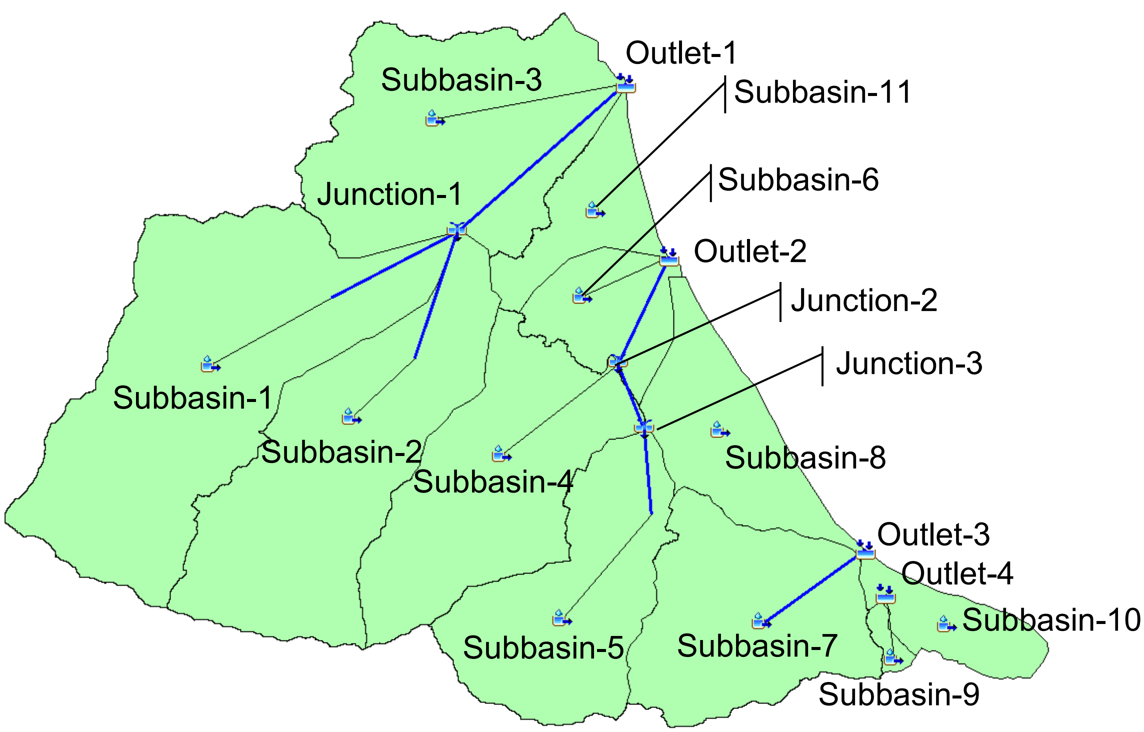



**Figure 4-8: HMS Basin Layout for Reference**

**Table 4-23: Peak flow estimates for the Kahawai Watershed**

| HEC-HMS Element | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Subbasin-4 | Subbasin-5 | Junction-3 | Junction-2 | Subbasin-6 | Outlet-2 |
| Peak Flow ($ft^3/s$)[1] | | | | | | | |
| Annual Exceedance Probability (AEP) | **1/2** | 553 | 246 | 245 | 765 | 399 | 1,030 |
| | **1/5** | 897 | 402 | 402 | 1,268 | 682 | 1,750 |
| | **1/10** | 1,500 | 676 | 675 | 2,150 | 1,180 | 3,070 |
| | **1/25** | 1,500 | 676 | 675 | 2,150 | 1,180 | 3,070 |
| | **1/50** | 1,790 | 801 | 801 | 2,560 | 1,400 | 3,680 |
| | **1/100** | 2,080 | 931 | 931 | 2,980 | 1,650 | 4,320 |
| | **1/200** | 2,380 | 1,070 | 1,070 | 3,420 | 1,900 | 4,990 |
| | **1/500** | 2,810 | 1,260 | 1,250 | 4,040 | 2,270 | 5,930 |

[1]: rounded to three significant figures

**Table 4-24: Peak flow estimates for the Kaiona Watershed**

| HEC-HMS Element | | | |
|---|---|---|---|
| | | Subbasin-7 | Outlet-3 |
| **Peak Flow ($ft^3/s$)[1]** | | | |
| **Annual Exceedance Probability (AEP)** | **1/2** | 963 | 552 |
| | **1/5** | 1,510 | 897 |
| | **1/10** | 1,900 | 1,180 |
| | **1/25** | 2,430 | 1,560 |
| | **1/50** | 2,840 | 1,890 |
| | **1/100** | 3,270 | 2,240 |
| | **1/200** | 3,710 | 2,610 |
| | **1/500** | 4,330 | 3,150 |

[1]: rounded to three significant figures

**Table 4-25: Peak flow estimates for the Unnamed Watershed**

| HEC-HMS Element | | | |
|---|---|---|---|
| | | Subbasin-9 | Outlet-4 |
| Peak Flow ($ft^3/s$)[1] | | | |
| Annual Exceedance Probability (AEP) | **1/2** | 96.3 | 96.3 |
| | **1/5** | 128 | 128 |
| | **1/10** | 153 | 153 |
| | **1/25** | 188 | 188 |
| | **1/50** | 216 | 216 |
| | **1/100** | 244 | 244 |
| | **1/200** | 275 | 275 |
| | **1/500** | 318 | 318 |

[1]: rounded to three significant figures

**Table 4-26: Peak flow estimates at USGS Stream Gage Locations**

| HEC-HMS Element | | | | |
|---|---|---|---|---|
| | | USGS 16249000 | USGS 16248950 | USGS 16248800 |
| Peak Flow ($ft^3/s$)[1] | | | | |
| Annual Exceedance Probability (AEP) | **1/2** | 873 | 797 | 618 |
| | **1/5** | 1,510 | 1,310 | 1,010 |
| | **1/10** | 1,970 | 1,680 | 1,300 |
| | **1/25** | 2,600 | 2,190 | 1,700 |
| | **1/50** | 3,120 | 2,600 | 2,010 |
| | **1/100** | 3,670 | 3,020 | 2,340 |
| | **1/200** | 4,240 | 3,460 | 2,680 |
| | **1/500** | 5,040 | 4,070 | 3,150 |

[1]: rounded to three significant figures

## 4.4 Comparison of Results

All three methods used in this hydrologic analysis are valid methods of estimating peak flow; however, the resulting flow frequency estimates vary significantly. The resulting peak flows computed using the various methods are summarized in Table 4-27, Table 4-28, and Table 4-29 for USGS 16249000, 16248950, and 16248800, respectively. Flow frequency curves are presented as Figure 4-9, Figure 4-10, and Figure 4-11.

**Table 4-27: Comparison of Flow Frequency Estimates at USGS 16249000, Waimānalo Stream, Waimānalo Watershed**

| Method | DA ($mi^2$) | Peak Flow ($ft^3/s$)[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50% AEP | 20% AEP | 10% AEP | 4% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.2% AEP |
| Bulletin 17C Analysis, 1963 – 2021 | 2.13 | 812 | 1,640 | 2,410 | 3,670 | 4,840 | 6,230 | 7,890 | 10,500 |
| Bulletin 17C Analysis, 2003 – 2021 | 2.13 | 494 | 784 | 1,010 | 1,320 | 1,580 | 1,850 | 2,160 | 2,590 |
| Regional Regression Equations | 1.96 | 957 | 1,820 | 2,520 | 3,540 | 4,390 | 5,300 | -- | 7,700 |
| HMS Model | 1.96 | 873 | 1,510 | 1,970 | 2,600 | 3,120 | 3,670 | 4,240 | 5,040 |
| [1]: rounded to three significant figures | | | | | | | | | |

**Table 4-28: Comparison of Flow Frequency Estimates at USGS 16248950, Kahawai Stream, Waimānalo Watershed**

| Method | DA ($mi^2$) | Peak Flow ($ft^3/s$)[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50% AEP | 20% AEP | 10% AEP | 4% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.2% AEP |
| Bulletin 17C Analysis, 2008 – 2020 | 1.13 | 303 | 478 | 496 | 598 | 676 | 755 | 837 | 949 |
| Regional Regression Equations | 1.40 | 739 | 1,400 | 1,960 | 2,760 | 3,430 | 4,150 | -- | 6,070 |
| HMS Model | 1.40 | 797 | 1,310 | 1,680 | 2,190 | 2,600 | 3,020 | 3,460 | 4,070 |
| [1]: rounded to three significant figures | | | | | | | | | |

**Table 4-29: Comparison of Flow Frequency Estimates at USGS 16248800, Puha (Inoaole Stream), Kahawai Watershed**

| Method | DA ($mi^2$) | Peak Flow ($ft^3/s$)[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 50% AEP | 20% AEP | 10% AEP | 4% AEP | 2% AEP | 1% AEP | 0.5% AEP | 0.2% AEP |
| Bulletin 17C Analysis, 1958 – 1996 | 1.20 | 354 | 758 | 1,100 | 1,600 | 2,010 | 2,460 | 2,930 | 3,610 |
| Regional Regression Equations | 1.00 | 570 | 1,090 | 1,520 | 2,150 | 2,680 | 3,250 | -- | 4,790 |
| HMS Model | 1.00 | 618 | 1,010 | 1,300 | 1,700 | 2,010 | 2,340 | 2,680 | 3,150 |
| [1]: rounded to three significant figures | | | | | | | | | |

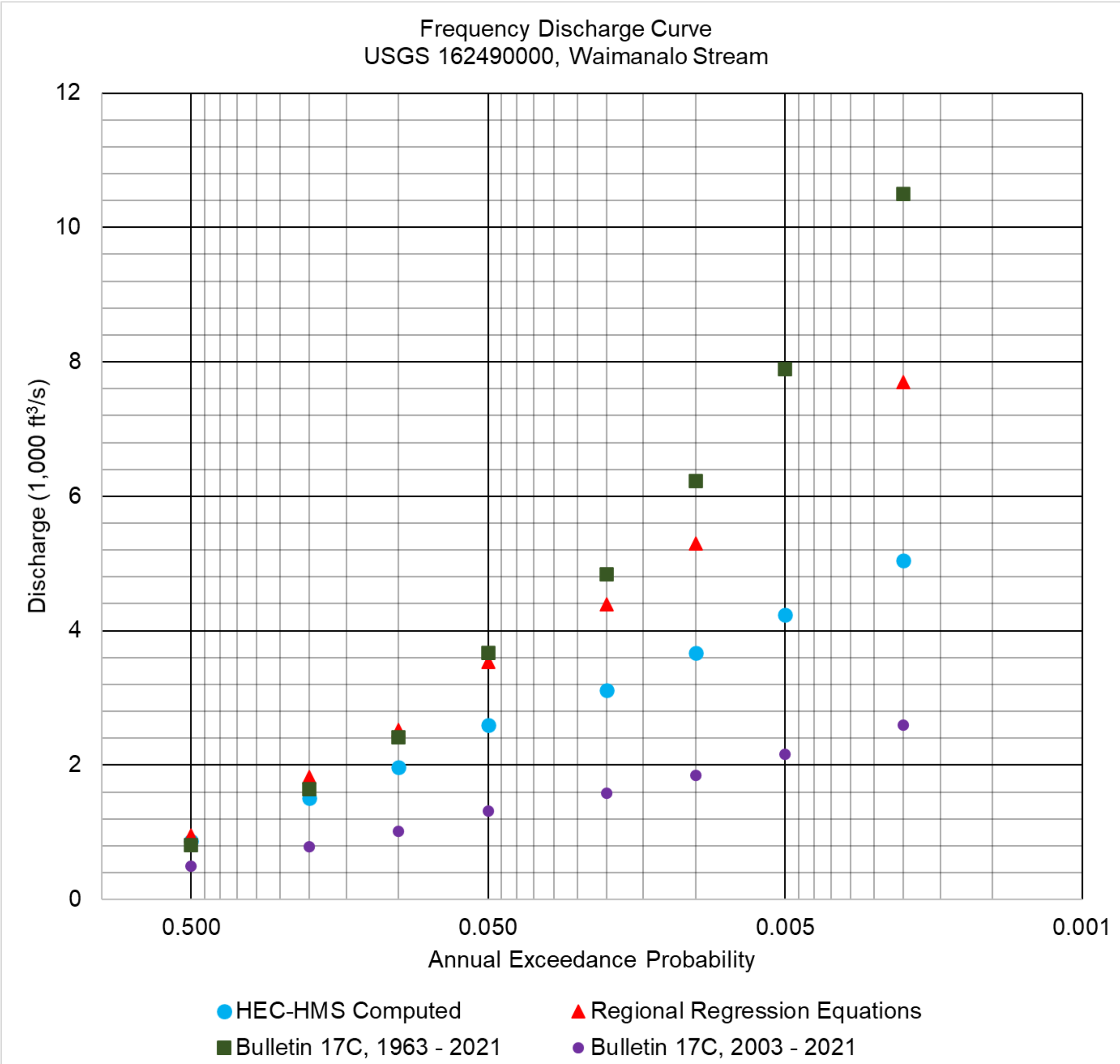



**Figure 4-9: Comparison of Flow Frequency Curves at USGS 162490000, Waimānalo Stream, Waimānalo Watershed**

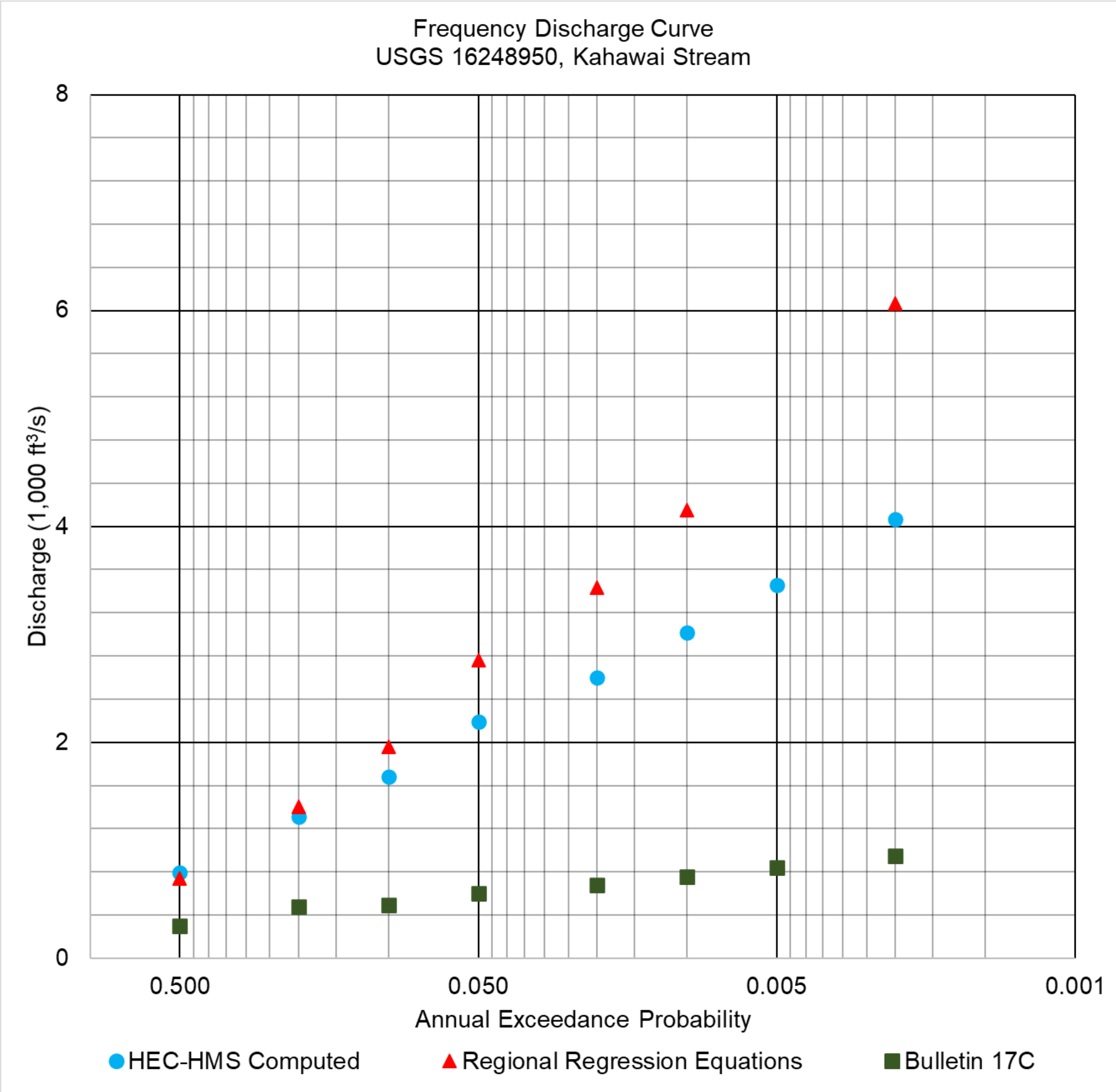



**Figure 4-10: Comparison of Flow Frequency Curves at USGS 16248950, Kahawai Stream, Waimānalo Watershed**

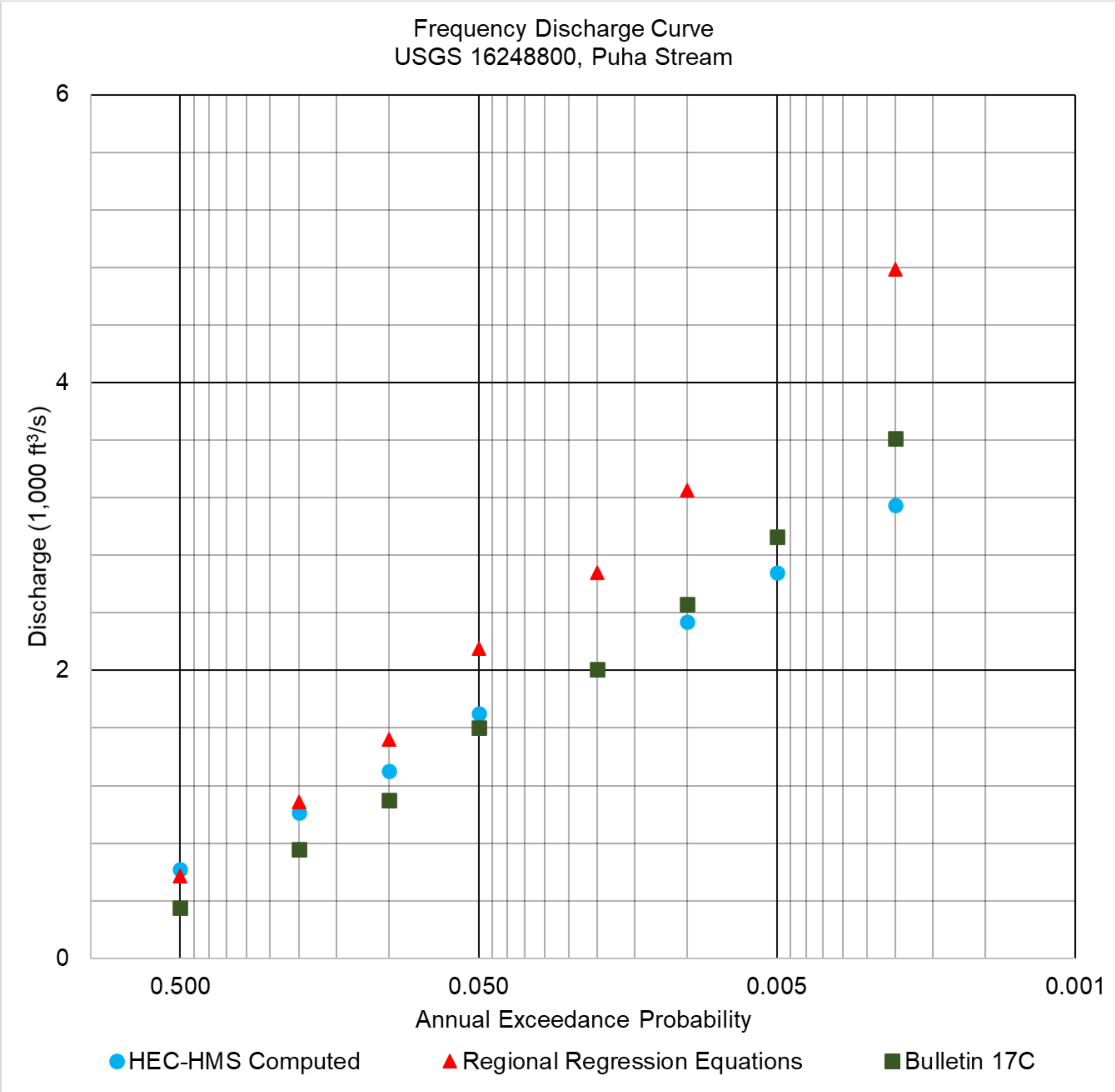



**Figure 4-11: Comparison of Flow Frequency Curves at USGS 16248800, Puha (Inoaole Stream), Kahawai Watershed**

#### 4.4.1 Final Flow Frequency Estimates

The resulting flow frequency estimates computed by the rainfall-runoff method were determined to be the final “adopted” peak flow values to carry forward in this study. This method of analysis was selected to be the best representation of the site and flow conditions, as site-specific characteristics were used to develop the rainfall-runoff model, which was then calibrated to real and recent historical storm events. Final peak flow estimates for this study are those presented earlier in Section 4.3.8

### 4.5 Reference Flows

#### 4.5.1 2014 Flood Insurance Study

Flood Insurance Study (FIS) Number 15003CV001C for the City and County of Honolulu, Hawaii, published on 5 November 2014, is the effective FIS for the study area. The following streams within the study area were identified by FEMA and referenced in this FIS report: Waimānalo Stream, Waimānalo Streams A, B, C, and D, and Inoaole Stream, as identified by Figure 4-12. In this flood hazard study, Stream A is referred to as Kahawai Stream; and Inoaole Stream is referred to as Puha (Inoaole) Stream.

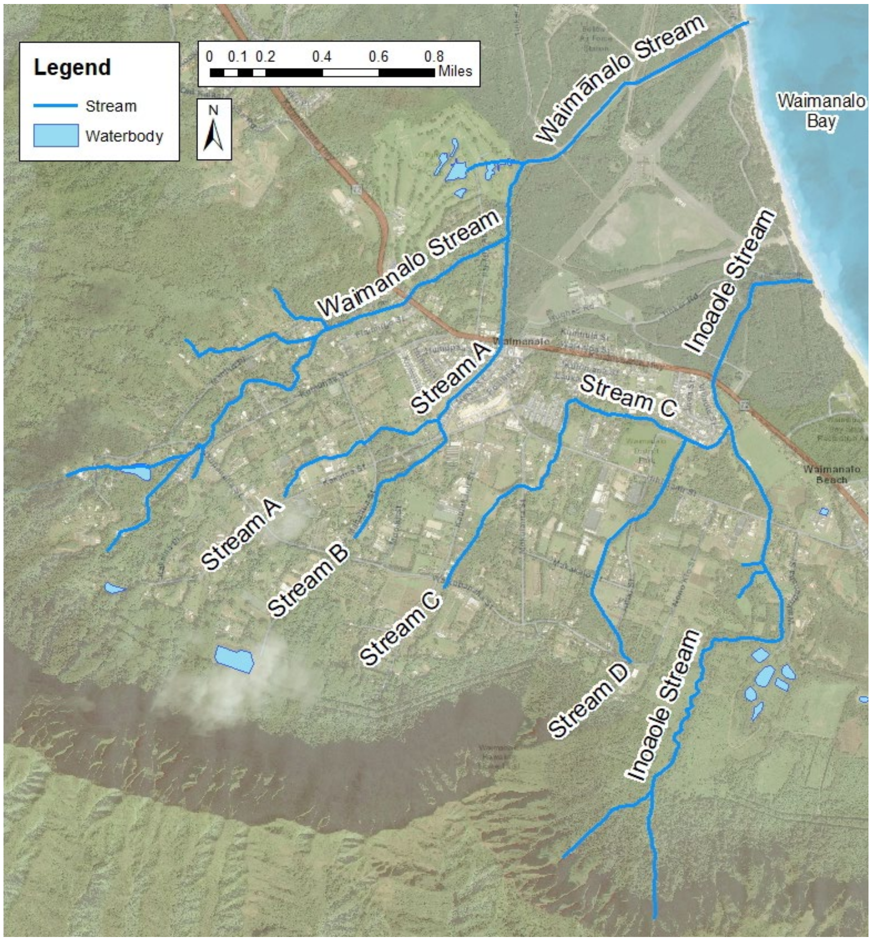



**Figure 4-12: FEMA Stream Names within Waimānalo, HI**

The 2014 FIS only provided an update of peak flow estimates for Waimānalo Stream A, as presented in Table 4-30.

**Table 4-30: Summary of Peak Flow Estimates by Waimānalo Stream A**

| Flooding Source and Location | Drainage Area ($mi^2$) | Peak Flow ($ft^3/s$) | | | | |
|---|---|---|---|---|---|---|
| | | 1/10 | 1/25 | 1/50 | 1/100 | 1/500 |
| Stream A, just upstream of confluence with Stream B | 0.38 | 736 | 1,053 | 1,323 | 1,620 | 2,431 |
| Stream A at confluence with Waimānalo Stream | 1.34 | 1,887 | 2,663 | 3,314 | 4,011 | 5,871 |

This study also mentions that tsunamis are unlikely to affect developments along the seaward portion of the Waimanalo area as "the land along the shoreline rises abruptly to elevations of 10 to 15 feet above sea level. This is higher than the wave height of the tsunami of 1946 (record elevation) which had wave heights of 8.0 feet off the shoreline of Waimānalo Bay" (FEMA, 2014, pp. 24-25).

There is also an ongoing study funded by FEMA to investigate the existence and severity of flood hazards for various streams across the island of Oahu. Inoaole Stream was included in this study. Preliminary results are presented below based on the *Draft Results of Hydrology Study, City and County of Honolulu, HI* dated May 2021. The delineated watersheds for Inoaole Stream are presented as Figure 4-13; preliminary peak flow estimates at various points along Inoaole Stream are presented in Table 4-31.

**Table 4-31: Summary of Peak Flow Estimates for Inoaole Stream**

| Flooding Source and Location | Drainage Area ($mi^2$) | Peak Flow ($ft^3/s$)[1] | | | | |
|---|---|---|---|---|---|---|
| | | 1/10 | 1/25 | 1/50 | 1/100 | 1/500 |
| Inoaole Stream at Pacific Ocean | 2.21 | 2,216 | 2,892 | 3,421 | 3,954 | 5,272 |
| Inoaole Stream at approximately 1,100 feet upstream of Kalanianaole Highway | unknown | 1,971 | 2,546 | 2,990 | 3,434 | 4,534 |
| Inoaole Tributary at confluence with Inoaole Stream | 0.42 | 287 | 391 | 473 | 556 | 762 |

[1]: these numbers are preliminary and may differ from the final published estimates

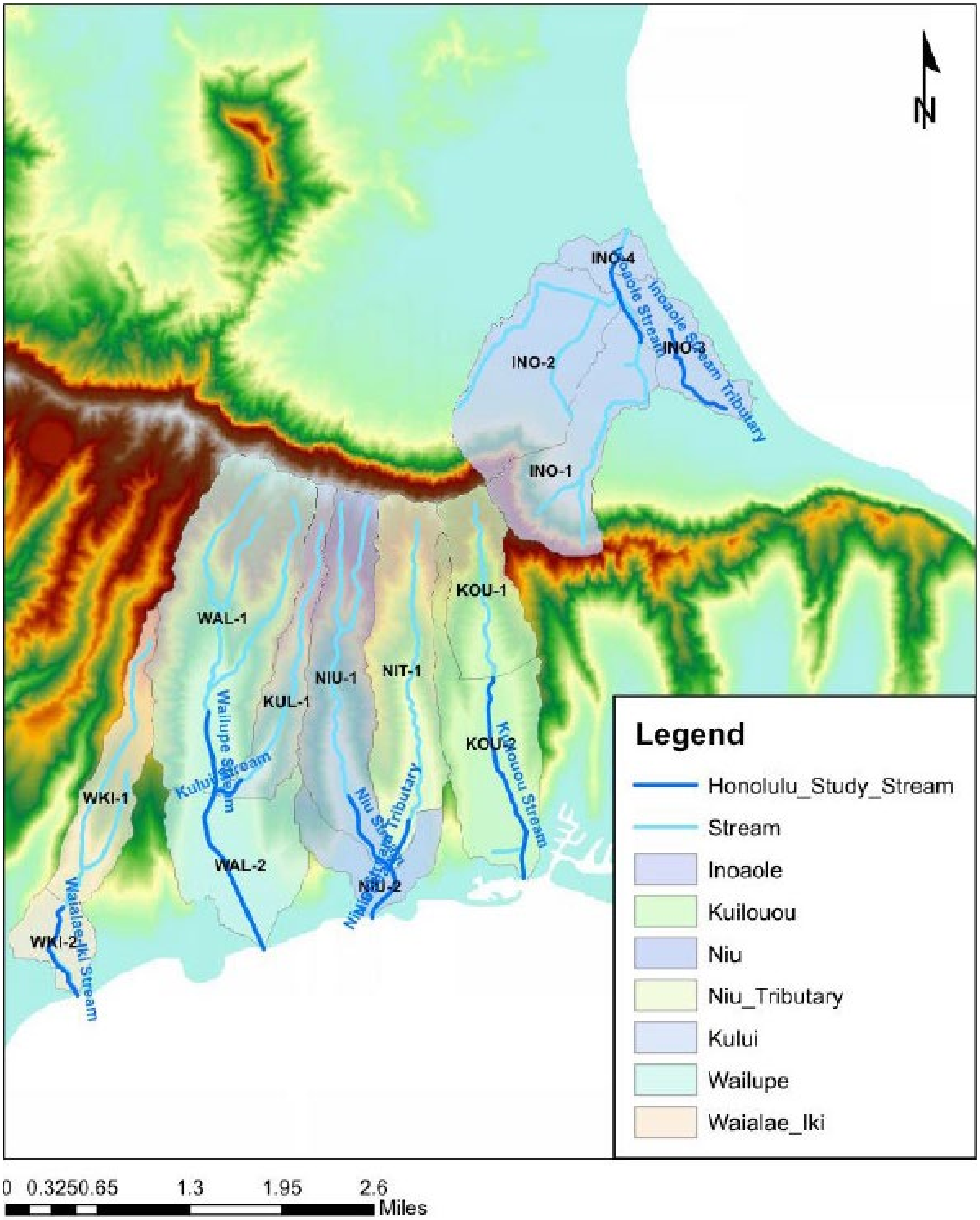



**Figure 4-13: Inoaole Watersheds (and others)**

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# Appendix C

## Hydraulics

# PREFACE

This appendix describes the development of the hydraulic model for the Waimānalo Community Flood Hazard Study, Oahu, Hawaii. This hydraulic model was used to establish the water surface profiles, flood elevations, and floodplain boundary for the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) annual exceedance probability (AEP) flood events in the Waimānalo community.

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# LIST OF ACRONYMS & ABBREVIATIONS

| | |
|---|---|
| 2D | two-dimensional |
| AEP | annual exceedance probability |
| cfs | cubic feet per second |
| DA | drainage area |
| FEMA | Federal Emergency Management Agency |
| ft | feet |
| GIS | geographic information system |
| HEC | Hydrologic Engineering Center |
| IfSAR | Interferometric Synthetic Aperture Radar |
| JALBTCX | Joint Airborne Lidar Bathymetry Technical Center of Expertise |
| LiDAR | Light Detection and Ranging |
| LMSL | local mean sea level |
| mi | mile |
| MHHW | mean higher high water |
| MRLC | Multi-Resolution Land Characteristics Consortium |
| MSL | mean sea level |
| *n* | Manning's roughness coefficient |
| NAD83 | North American Datum of 1983 |
| NLCD | National Land Cover Database |
| NOAA | National Oceanic and Atmospheric Administration |
| RAS | River Analysis System |
| SA | Storage Area |
| US | United States |
| USACE | U.S. Army Corps of Engineers |
| USGS | U.S. Geological Survey |

# 1 Stream Identification

Waimānalo includes areas in the Waimānalo, Kahawai, and Kaiona watersheds. Waimānalo Stream is the primary river in the Waimānalo watershed. It is created by multiple tributaries, originating in the steep slopes of the Ko‘olau Range. The Kahawai Stream (which is in the Waimānalo watershed, not the Kahawai watershed) is the main tributary to the Waimānalo Stream. The tributaries to Kahawai Stream are referred to as “Stream A” and “Stream B,” to be consistent with current terms used in the corresponding flood insurance study for this area (FEMA, 2014)[1]. Typical stream photos are included in Section 2.1.3, Land Classification for Manning’s *n*.

Puha Stream is the primary river in the Kahawai watershed, although it is sometimes referred to as Inoaole Stream for its proximity to Inoaole Street. The tributaries for Puha (Inoaole) Stream are referenced in this study as “Stream C” and “Stream D.” These streams are identified in Figure 1-1.

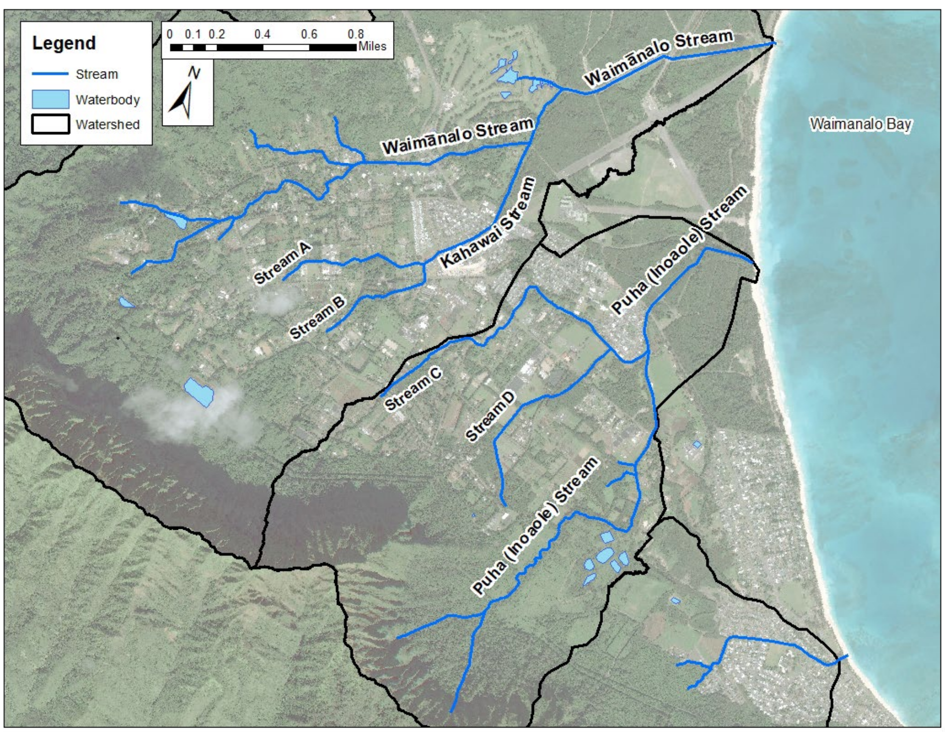


**Figure 1-1: Streams in the Waimānalo and Kahawai Watersheds**

[1] FEMA also refers to the Kahawai Stream as “Waimanalo Stream A,” but in this study, “Stream A” only references the northwestern fork / tributary of the Kahawai Stream.

There are two unnamed streams in the study area that were also included in this flood hazard analysis, as identified in Figure 1-2. The first stream (Unnamed Stream #1) is in the Kaiona watershed. It passes by Waimanalo Country Farms, Blanche Pope Elementary School, and Waimānalo Beach Park before discharging into Waimānalo Bay. The second unnamed stream is in a small, unnamed watershed southeast of the Kaiona watershed. Flow from this stream (Unnamed Stream #2) is collected by an unlined, vegetated swale near the corner of Bell Street and Hoomaha Street. It is possible that there is an 18-inch conduit at the downstream end of the swale that carries a limited amount of flow through the storm water system to Unnamed Stream #1[2], but this could not be confirmed in the field due to heavy vegetation near the outlet.

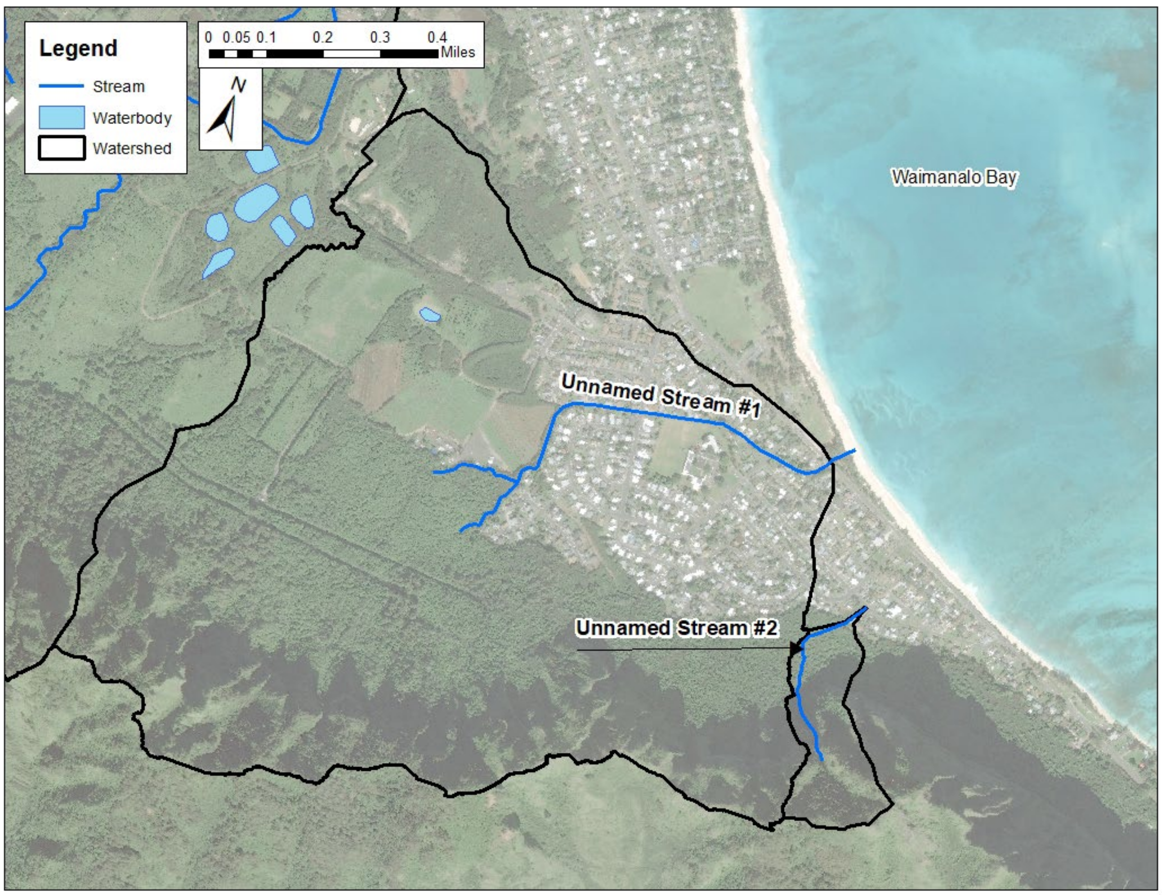


**Figure 1-2: Unnamed Streams in the Kaiona Watershed and Study Area**

[2] The outlet for this system is Unnamed Stream #1, just downstream of the Huli Street Bridge.

# 2 Development of the Hydraulic Model

A two-dimensional (2D), unsteady flow hydraulic model was developed for this study using the Hydrologic Engineering Center’s River Analysis System (HEC-RAS) software (version 6.2, HEC, 2022). This model was used to simulate flow in streams and across the floodplain within the limits of the study area. The following list provides an overview of the steps completed to create this model. Additional information is provided in the sections that follow.

1. **Establish a horizontal coordinate projection to use in the model.** The horizontal coordinate projection was set to NAD83 (PA11), State Plane Zone 3 (US Survey Feet).
2. **Develop a terrain model in RAS Mapper.** A terrain model was created in RAS Mapper based on 2013 LiDAR data 2003 IfSAR data, as described in Section 2.1.1.
3. **Build a land classification data set to establish Manning’s n values (roughness coefficient) within the 2D Flow Areas.** A circa 2011 high resolution (1 to 5 meter) land cover raster was used to represent various land covers in the study area. Each cover type was assigned a unique roughness coefficient, as presented in Section 2.1.3.
4. **Add any additional mapping layers needed (i.e. aerial imagery, road networks).** High resolution imagery used for background mapping of the study area is from DigitalGlobe, the National Geospatial-Intelligence Agency and the USGS. World Imagery, provided by Esri, was used for larger scale background mapping, such as when it was necessary to show the entire island of O‘ahu. Other GIS data (i.e. road networks) was provided by the City and County of Honolulu, Department of Planning and Permitting through the Hawaii Statewide GIS Program’s Geospatial Data Portal [https://geoportal.hawaii.gov/].
5. **Outline the 2D Flow Area.** The 2D Flow Area defines the boundary for which 2D computations will occur. Four 2D Flow Areas were drawn to represent the study area, extending from Waikupanaha Street to the shoreline. The primary 2D Flow Area represents the main river systems in the Waimānalo, Kahawai, and Kaiona watersheds. Three additional 2D Flow Areas were added that are somewhat

independent drainage areas along the coast (they do not contribute significant flow to the main river systems). Additional information on 2D Flow Areas is included in Section 2.1.4.

6. **Layout any break lines within the 2D flow area to force the mesh to align the computation cell faces along the break lines.** Break lines were added to represent significant barriers to flow (i.e. levees, roads, high ground). They were also added along the channel invert and banks of main river systems.
7. **Create the 2D computational mesh for each 2D flow area.** The primary 2D Flow Area “Perimeter 1” has a base cell size of 40, refined as needed along rivers, road embankments, high ground barriers, and hydraulic structures (i.e. bridges and culverts). The three 2D Flow Areas representing independent coastal drainage areas have a base cell size of 30, which was also refined, as needed.
8. **Add internal hydraulic structures or bridges inside the 2D Flow Area(s) using the SA/2D Area Hydraulic Connection feature**. An SA/2D Area Hydraulic Connection feature was created to represent each major bridge, culvert, or crossing in the study area. Additional information on how these features were modeled is described in Section 2.1.6.1. Bridge and culvert data (i.e. field measurements and photos) are summarized in Appendix D**.**
9. **Draw any external boundary condition lines along the perimeter of the 2D Flow Areas.** Several external boundary condition lines were drawn along the upper boundary of the study area, representing flow coming from the steep slopes of the Koolau Range. Along the coast, external boundary conditions were drawn to represent the ocean stage and attenuation of flow entering it.
10. **Enter all the necessary boundary and initial condition data for the 2D Flow Areas in the Unsteady Flow data editor.** Data for the internal “Precipitation” and external “Flow Hydrograph” boundary conditions were computed outputs from the rainfall-runoff model described in Appendix B, Hydrology. The “Precipitation” boundary condition was used to directly apply rainfall excesses to the three coastal 2D Flow Areas. An external “Stage Hydrograph” boundary condition was used to represent the ocean at the downstream end of the study area for all 2D Flow Areas.

11. **Run the Unsteady Flow simulation and review the results in RAS Mapper.** Results are summarized in Section 3, Conclusion.

## 2.1 Geometry Data

RAS Mapper, a geospatial interface in the HEC-RAS software, was used to fully develop the geometric data required for the river hydraulics model. The projection was set to State Plane Zone 3 (US Survey Feet) with reference to the NAD83 (PA11) coordinate system. Elevation data presented in Section 2.1.1 was imported to create the terrain model.

### 2.1.1 Elevation

The following three datasets were merged to create a single terrain, as described previously in Appendix B, Section 2, Geographic Information Systems Data:

**Table 2-1: Elevation Data Type and Sources**

| Survey year | Agency | Data type | Areal Extent |
|---|---|---|---|
| 2013 | USACE | Topobathy LiDAR | about 1.0 mi inland from coast |
| 2013 | NOAA/USGS | Topographic LiDAR | middle watershed and coastal areas |
| 2003 | City and County of Honolulu | 5-foot contours | O‘ahu |

Terrain modifications were applied to remove bridge obstructions, add pilot channels, and add splitter walls, as needed, to create an improved representation of existing site conditions.

### 2.1.2 Imagery

High resolution imagery used for background mapping of the study area is from DigitalGlobe, the National Geospatial-Intelligence Agency and the USGS. World Imagery, provided by Esri, was used for larger scale background mapping, such as when it was necessary to show the entire island of O‘ahu.

### 2.1.3 Land Classification for Manning's *n*

A circa 2011 high resolution (1 to 5 meter) land cover raster for the study area was developed by the National Oceanic and Atmospheric Administration (NOAA) and downloaded from the National Land Cover Database (NLCD). This raster, shown in Figure 2-1, was used to understand the different types of land usage in the study area and compute the directly connected impervious areas for the rainfall-runoff model. This raster was also imported into RAS Mapper to create a spatially varying Land Cover layer for the hydraulic model to reference.

Once a Land Cover layer has been created, the user can then build a table of Land Cover versus Manning's *n* values, which can then be used in defining the roughness values for 2D Flow Areas. Manning's roughness coefficient, *n*, represents the resistance to flow in channels and floodplains. Typical *n* values selected for this study are provided in Table 2-2, which is based on Table 2-1 in the HEC-RAS 2D User's Manual (Hydrologic Engineering Center, 2023). Additionally, the user can define Percent Impervious for each Land Cover Classification type. Percent Impervious is only needed if the user intends to use precipitation and infiltration features within HEC-RAS.

**Table 2-2: Land Cover Data – Manning's n and Percent Impervious**

| NLCD Value | Land Cover Type | Manning's *n* | Percent Impervious |
|---|---|---|---|
| 11 | Open Water | 0.050 | 100 |
| 21 | Developed, Open Space | 0.050 | 10 |
| 24 | Developed, High Intensity | 0.200 | 90 |
| 31 | Barren Land | 0.030 | 0 |
| 42 | Evergreen Forest | 0.160 | 0 |
| 52 | Scrub/Shrub | 0.160 | 0 |
| 71 | Grassland/Herbaceous | 0.050 | 0 |
| 81 | Pasture/Hay | 0.050 | 0 |
| 82 | Cultivated Crops | 0.050 | 0 |
| 90 | Woody Wetlands | 0.150 | 0 |
| 95 | Emergent Herbaceous Wetlands | 0.085 | 0 |

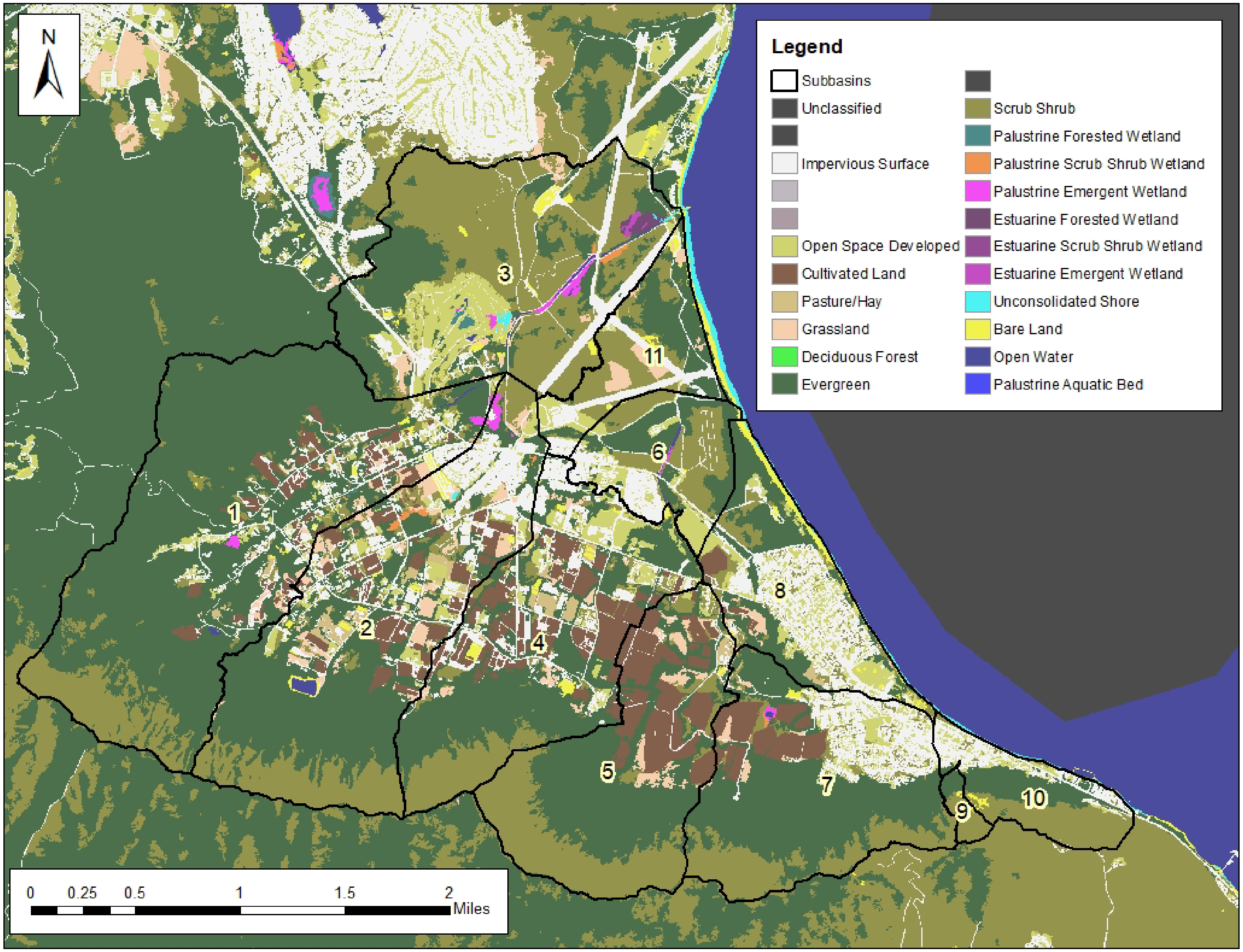


**Figure 2-1: Land Cover Map**

At some locations, it was necessary to override the default values provided by this layer by identifying a specific area and roughness coefficient. For example, a Manning's *n* value of 0.020 was assigned to the footprint of the concrete-lined section of Waimānalo Stream, overriding default values for developed areas (0.050 to 0.200). These values were determined with consideration of irregularity, variation in channel cross section, obstructions, vegetation, and meandering (USGS, 1989).

**Table 2-3: Classification Polygons Overriding the Land Cover Layer**

| Location | Photo | Manning's *n* | Percent Impervious |
|---|---|---|---|
| Upper Waimānalo Stream | Photo 2-1 | 0.055 | 0 |
| Waimānalo Stream near Kalaniana‘ole Highway | Photo 2-2 | 0.025 | 100 |
| Waimānalo Stream above the Kahawai Stream Junction | Photo 2-3 | 0.032 | 0 |
| Stream A, Tributary to Kahawai Stream | Photo 2-4 | 0.045 | 0 |
| Stream B, Tributary to Kahawai Stream | Photo 2-5 | 0.065 | 0 |
| Kahawai Stream, from the top of Mekia Street to Waimānalo Stream near Tinker Road | Photo 2-6 | 0.032 | 0 |
| Lower Waimānalo Stream to the Outlet | Photo 2-7 | 0.022 | 0 |
| Stream C, Tributary to Puha (Inoaole) Stream | Photo 2-8 | 0.038 | 0 |
| Stream D, Tributary to Puha (Inoaole) Stream | Photo 2-9 | 0.037 | 0 |
| Upper Puha (Inoaole) Stream | Photo 2-10 | 0.038 | 0 |
| Lower Puha (Inoaole) Stream to Outlet | Photo 2-11 | 0.027 | 0 |
| West and Central Tributaries to Unnamed Stream #1, Upper Kaiona Watershed | None | 0.047 | 0 |
| East Tributary to Unnamed Stream #1, Upper Kaiona Watershed | None | 0.040 | 0 |
| Unnamed Stream #1 to Outlet, Kaiona Watershed | Photo 2-12 | 0.017 | 100 |
| Unnamed Stream #2 | Photo 2-13 | 0.095 | 0 |

Manning's *n*: 0.055

**Photo 2-1: Upper Waimānalo Stream**

Manning's *n*: 0.025

**Photo 2-2: Waimānalo Stream near Kalanianaʻole Highway**

Manning's *n*: 0.032

**Photo 2-3: Waimānalo Stream near Saddle City Road**

Manning's *n*: 0.045

**Photo 2-4: Stream A, looking downstream from Mahailua Street Culvert**

Manning's *n*: 0.065

**Photo 2-5: Stream B, looking upstream from Kakaina Street**

Manning's *n*: 0.032

**Photo 2-6: Kahawai Stream, looking upstream from Kalaniana'ole Highway**

Manning's *n*: 0.022

**Photo 2-7: Waimānalo Stream near the Outlet**

Manning's *n*: 0.038

**Photo 2-8: Stream C, Looking Downstream from Mokulama St**

Manning's *n*: 0.037

**Photo 2-9: Stream D, Looking Upstream from Hihimanu Street**

Manning's *n*: 0.038

**Photo 2-10: Upper Puha (Inoaole) Street**

Manning's *n*: 0.027

**Photo 2-11: Lower Puha (Inoaole) Street, Looking Downstream from Tinker Road**

Manning's *n*: 0.017

**Photo 2-12: Unnamed Stream #1, Looking Upstream from Huli Street**

Manning's *n*: 0.095

**Photo 2-13: Looking towards Unnamed Stream #2 from Hoomaha Street**

### 2.1.4 **2D Flow Areas**

A 2D Flow Area defines the boundary for which 2D computations will occur. A primary 2D Flow Area, "Perimeter 1," was drawn to represent the main river systems in the Waimānalo, Kahawai, and Kaiona watersheds (Figure 2-2). This 2D Flow Area extends from about Waikupanaha Street to the shoreline, as determined by the availability of the higher resolution (LiDAR) elevation data. Three other 2D Flow Areas were drawn to represent the independent coastal drainage areas: "Subbasin-8," "Subbasin-10," and "Subbasin-11." These 2D Flow Areas are also shown in Figure 2-2.

The default cell spacing for these 2D Flow Areas range from 30 to 40 ft. The default Manning's n value was 0.06.

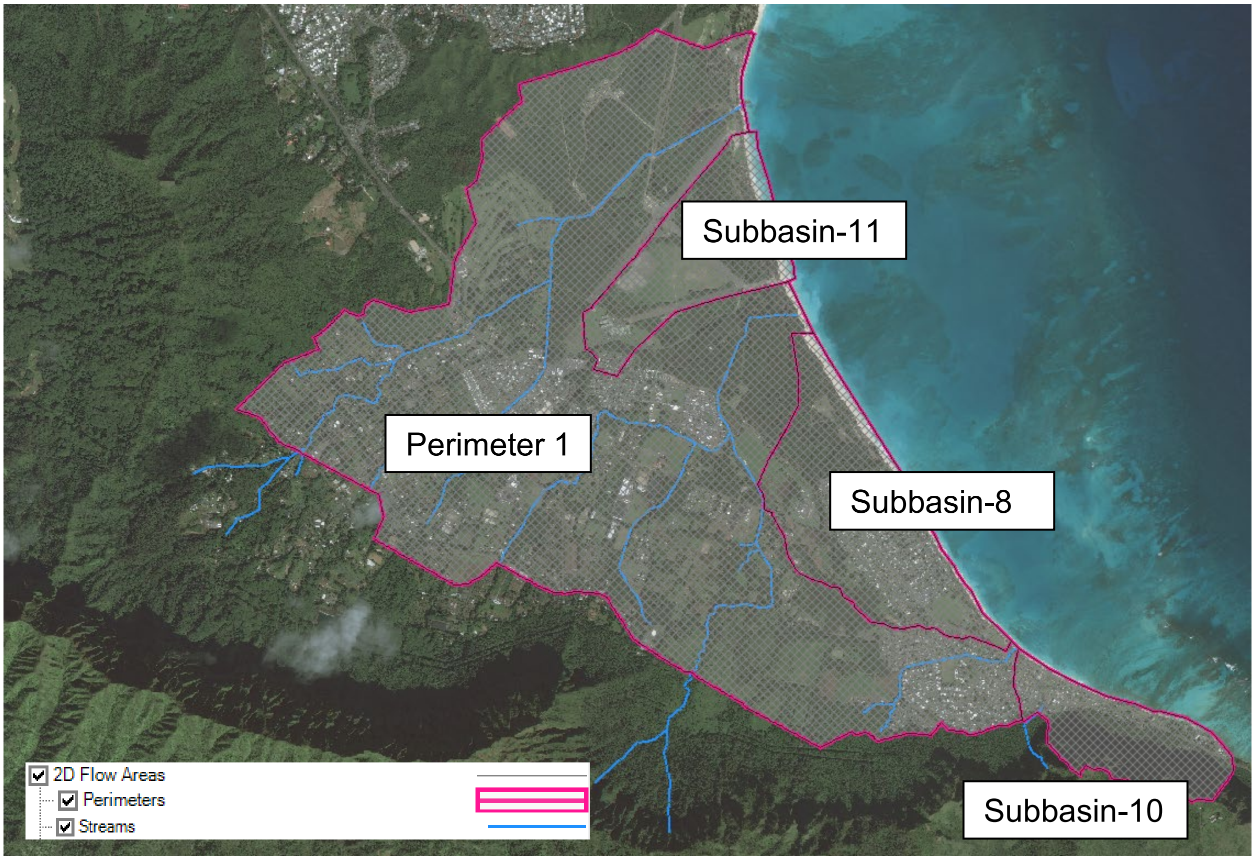


**Figure 2-2: 2D Flow Areas**

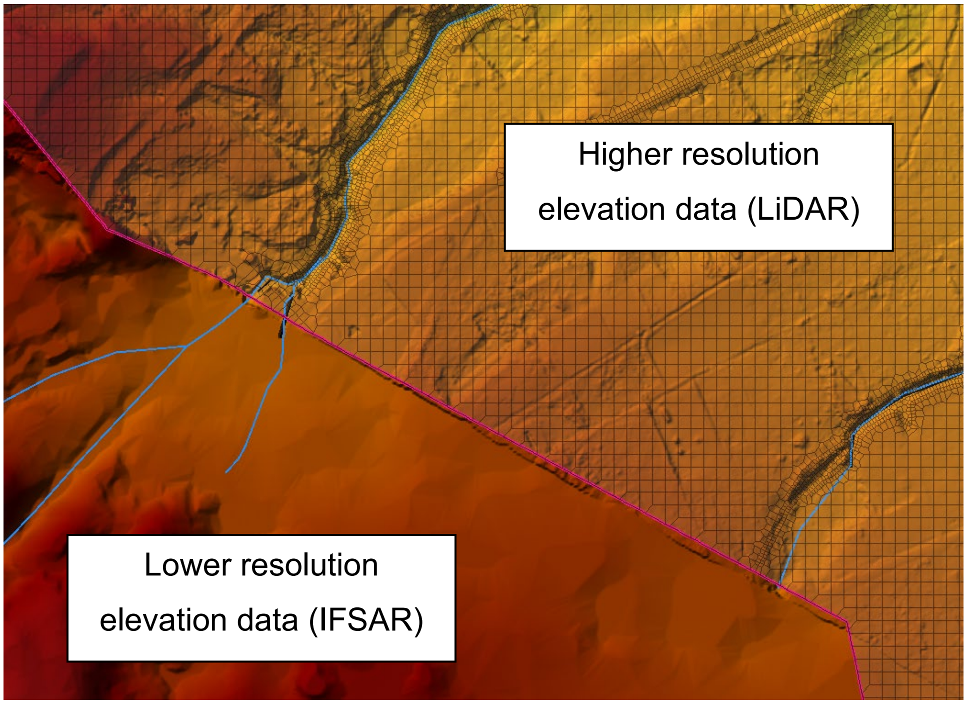


**Figure 2-3: Upper Limits of the Modelled Area**

#### 2.1.5 **Break Lines**

Break lines were sometimes used in 2D Flow Areas to align the computation cell faces along high ground and natural barriers that affect flow and direction (such as river banks). Typically, these break lines would have a Near Spacing of 10 and Far Spacing of 20.

#### 2.1.6 **SA/2D Area Connection**

The SA/2D Area Connection feature was used to recognize and compute weir flow over major roads, over embankment crests and between 2D Flow Areas. For flow over a typical bridge deck, a weir coefficient of 2.6 was used. A weir coefficient of 3.0 was used for flow over elevated roadway approach embankments. A weir coefficient of 0.5 was used for flow between two 2D Flow Areas.

##### 2.1.6.1 Bridges and Culverts

Eleven bridges and seventeen culvert crossings were represented in the model as an SA/2D Area Connection. A summary of the geometric features and typical photos of these crossings is provided as Appendix D, as collected by field surveys, as-built plans, and national bridge inventory data (Baughn, 2019). At locations where bridge data was not available, the terrain raster was modified to remove these obstacles from the raster completely, allowing for channel flows to pass through unimpeded.

## 2.2 Flow Data

Flow frequency hydrographs determined previously in Appendix B, Hydrology were used to represent the amount of water in the system.

#### 2.2.1 **Boundary Conditions**

Boundary conditions are necessary to establish the starting water surface at the upstream and downstream ends of the channel system. A flow hydrograph was used to represent the amount of flow entering at the upstream ends of the hydraulic model. At some locations, it was necessary to further divide the hydrograph developed for each subbasin to represent flow entering from an additional location (typically, a smaller tributary). In this instance, the hydrograph was divided based on the corresponding drainage area for each individual reach segment.

The downstream boundary condition was set to a water surface elevation of 1.07 ft, representing the mean higher high water (MHHW) elevation (in reference to mean sea level) of the ocean. This was determined based on the MHHW elevation at NOAA tidal station at Mokuoloe Harbor, HI – Station ID: 1612480 (NOAA).

## 2.3 Results

Flood hazard maps are included in Appendix A. General flood risk to the community is described in the following sections.

### 2.3.1 Upper Waimānalo Stream:

There is moderate risk of flooding to the residential and commercial properties near Waimānalo Stream, upstream of Kalanianaʻole Highway (Figure 2-4), where properties are inundated 1 – 3 feet during the 1% AEP flood event. Flooding along Flamingo Street is also expected to occur during smaller frequency events, such as the 10% AEP flood (statistically, once every ten years).

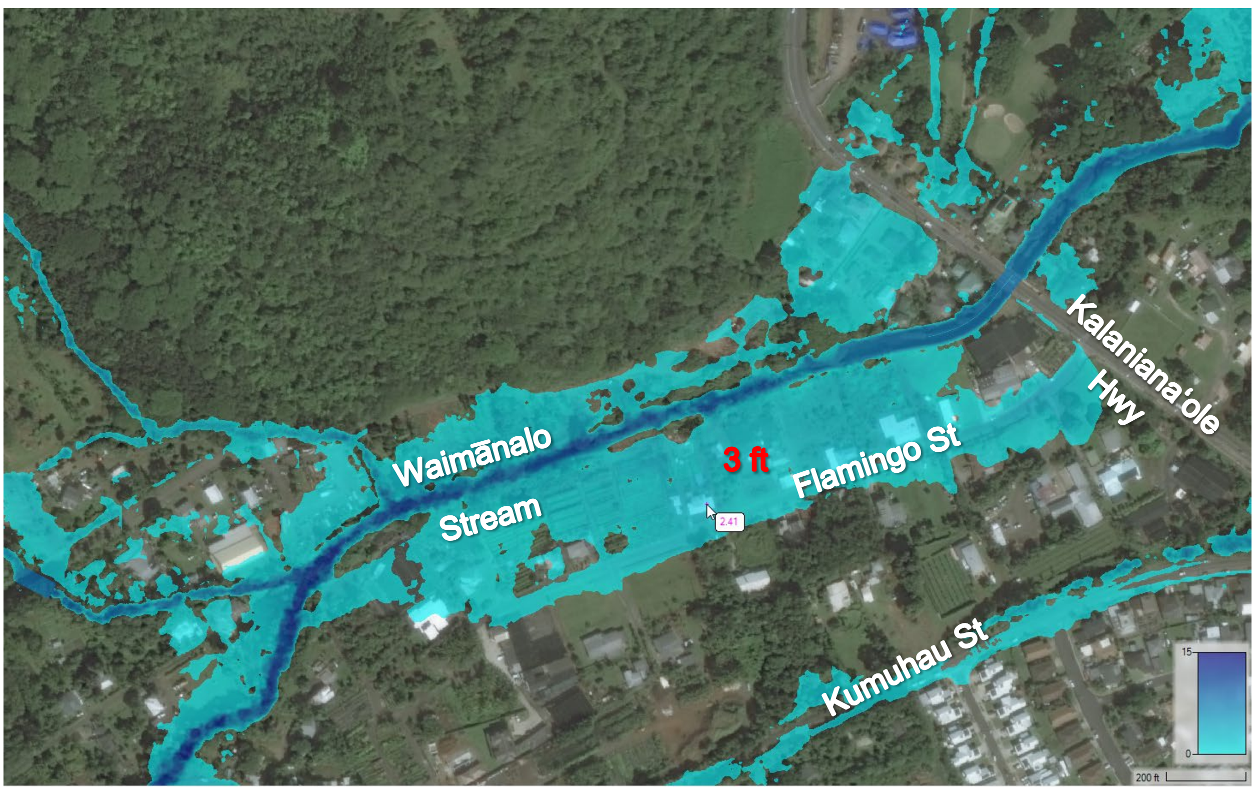


**Figure 2-4: Flood Hazard Map for the 1% AEP Flood, Waimānalo Stream near Kalanianaʻole Highway.**

### 2.3.2 Tributaries to Kahawai Stream (Stream A and Stream B)

Some commercial properties along Stream A (north of Kakaina Street) are at risk of flooding at depths of approximately 1 – 5 ft (Figure 2-5). At the junction between Stream A and Stream B, there is also overtopping into the floodplain (Camp Kibble).

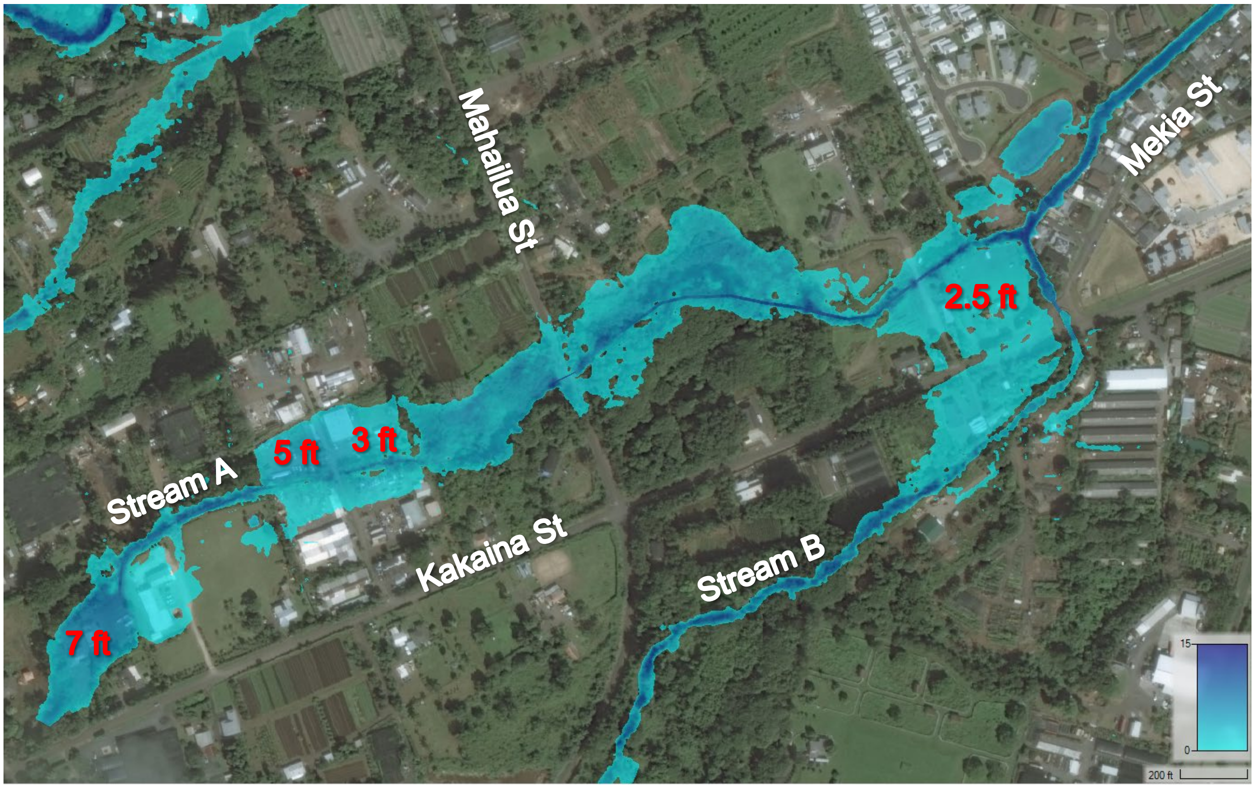


**Figure 2-5: Flood Hazard Map for the 1% AEP Flood, Tributaries to Kahawai Stream (Stream A and Stream B), Waimānalo Watershed**

### 2.3.3 Kahawai Stream

Overtopping from Stream C results in additional flow entering the Kahawai Stream just downstream (north) of the Kalaniana‘ole Hwy. Residential and commercial properties along Mokulama St are likely to experience shallow flooding of 1 – 3 ft. Properties along Kalaniana‘ole Hwy that are close to a stream or tributary also experience shallow flooding of 1 – 3 ft.

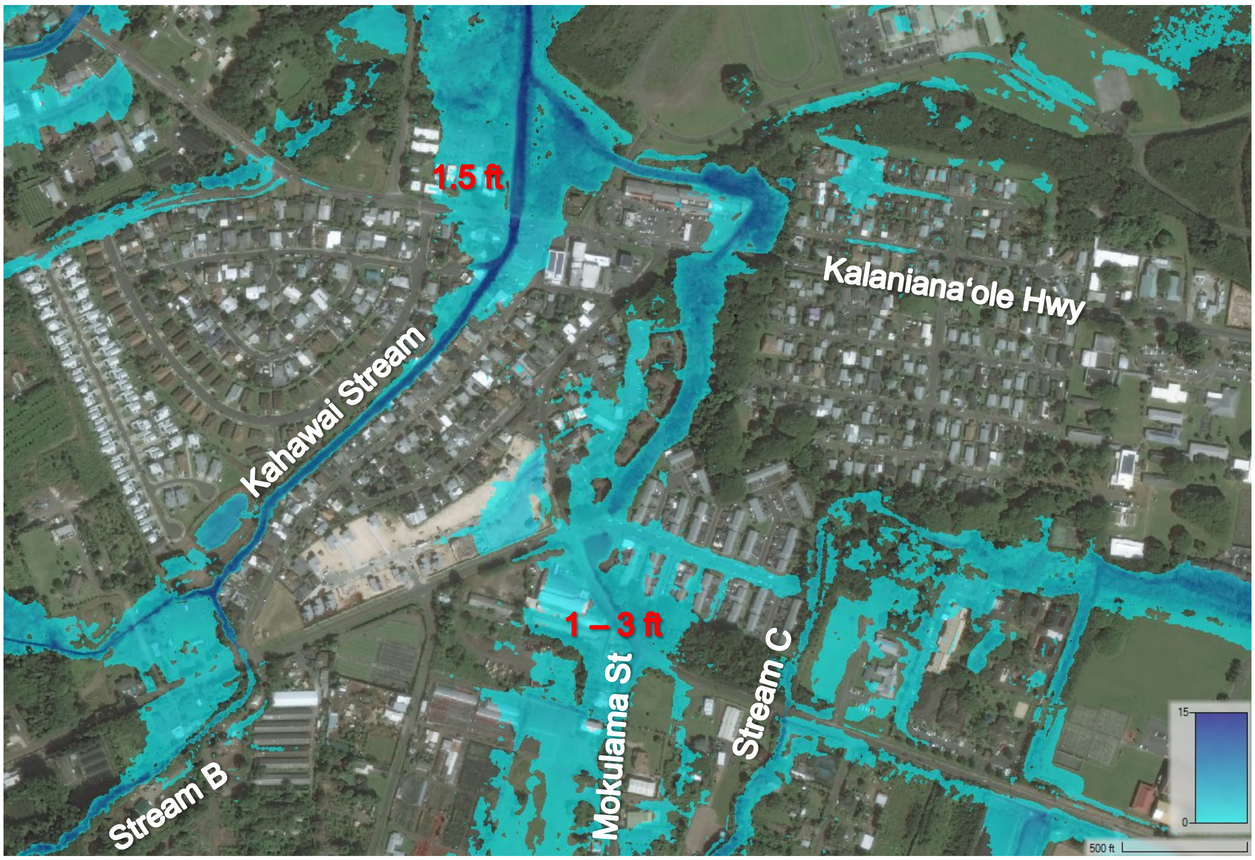


**Figure 2-6: Flood Hazard Map for the 1% AEP Flood, Kahawai, Waimānalo Watershed**

### 2.3.4 **Lower Waimānalo Stream**

Flooding is more extensive along the lower reach of Waimānalo Stream, with frequent overtopping of the stream even during lower frequency events (i.e. the 10% AEP flood). The impact, however, is limited to flooding of the Olomana Golf Links grounds (depths ranging from 1 – 10 ft) and overtopping of a bridge on Bellows AFB (with approximately 3 feet of overtopping predicted). The coastal bridge (Tinker Rd) is not overtopped during the 1% AEP event simulation.

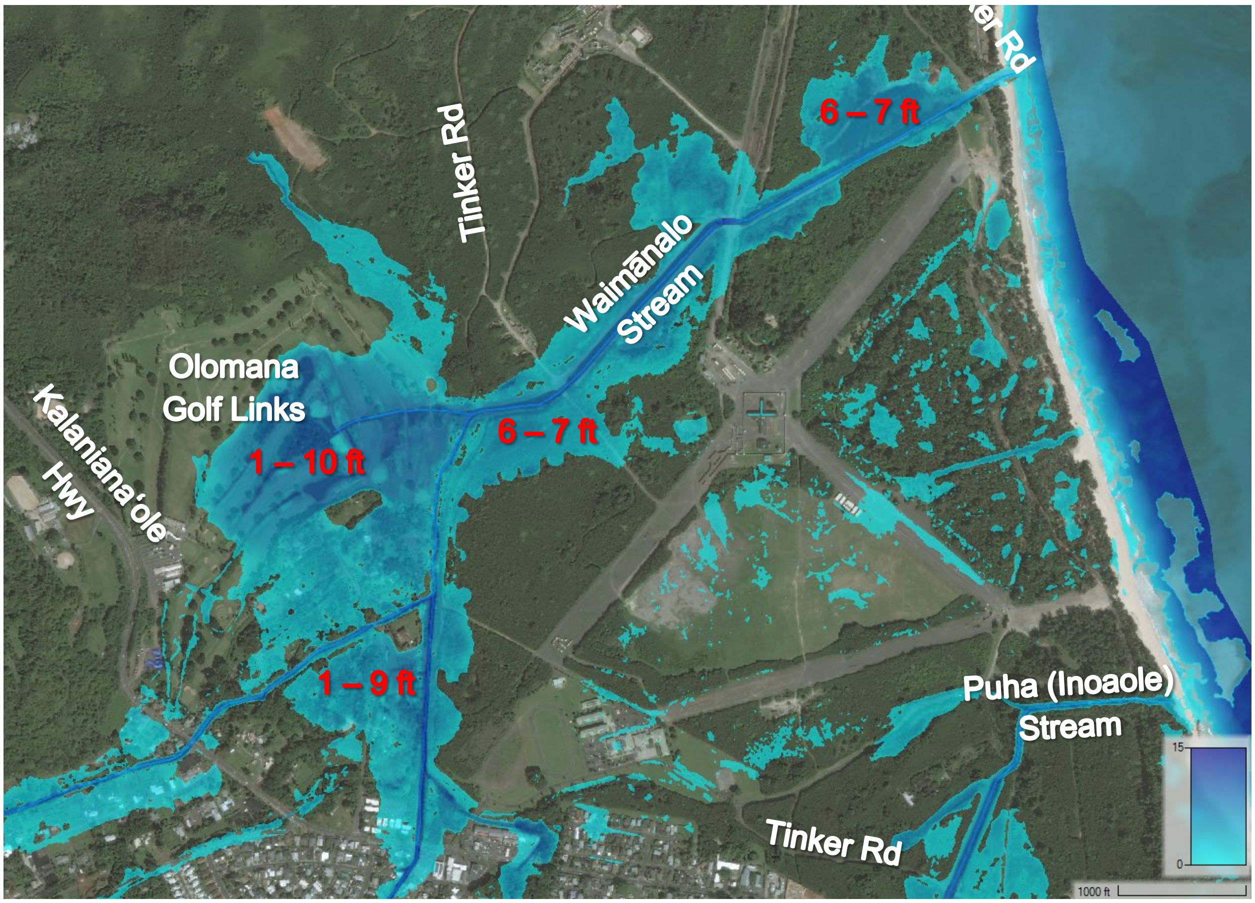


**Figure 2-7: Flood Hazard Map for the 1% AEP Flood, Lower Waimānalo Stream**

### 2.3.5 **Tributaries to Puha (Inoaole) Stream (Stream C and Stream D)**

Overflow from Stream C travels north towards Hihimanu St and Kakaina St, inundating properties along Mokulama St with 1 – 2 ft of flooding during the 1% AEP flood. Properties north of Hihimanu Street and west of the Waimānalo District Park are also at risk of flooding, primarily along the roads and low spots at predicted depths of 1 – 2 ft during the 1% AEP flood. Stream D overtops the banks near Ahiki St, flowing north towards Hihimanu St and eventually joining Stream C.


**Figure 2-8: Flood Hazard Map for the 1% AEP Flood, Tributaries to Puha (Inoaole) Stream, Kahawai Watershed**

### 2.3.6 **Puha (Inoaole) Stream**

Overflow from Puha (Inoaole) Stream results in widespread flooding along the right bank. Kalaniana‘ole Hwy is overtopped by approximately 1 – 2 feet from the bridge near Inoaole Street to Aloiloi Street. Properties along Kalaniana‘ole Hwy are inundated by approximately 2 – 4 feet.


**Figure 2-9: Flood Hazard Map for the 1% AEP Flood, Puha (Inoaole) Stream, Kahawai Watershed**

### 2.3.7 **Coastal Properties near Sherwood Beach**

There was no defined channel system affecting this subdivision between Kalanaina‘ole Hwy and Waimanalo Bay, so areas at risk of flooding were identified by simulating direct rainfall on the area. Overall, there is a low risk of flooding due to rainfall. However, there may be a few properties at risk of localized flooding (approx. 1 – 2 ft depths) if their property is in a low spot and not otherwise designed to facilitate flow away from their property. Properties along Kalaniana‘ole Hwy appear to also have an increased risk of flooding.

Existing stormwater systems are not reflected in this model, so actual flooding due to rainfall may be less. However, these systems are typically designed to accommodate flows up to the 10% AEP event (statistically, once every ten years) and unlikely to accommodate larger events, such as the 1% AEP event (statistically, once every one hundred years). This study does not include evaluation of flood risk due to wave action. Potential impacts from sea level change were evaluated separately and described in Section 2.5.6.


**Figure 2-10: Flood Hazard Map for the 1% AEP Flood, Subdivision between Kalaniana‘ole Hwy and Waimanalo Bay**

### 2.3.8 **Unnamed Stream #1, Kaiona Watershed**

Flows from the Koʻolau Range (upper watershed) overwhelm the concrete-lined ditch resulting in shallow street flooding along mountain-side properties, specifically those on the southern bend of Nakini Street. The Nakini St Bridge and a pedestrian bridge near Blanche Pope Elementary School are overtopped by approximately 3 feet of water during the 1% AEP flood event. The surrounding area is also inundated by approximately 3 feet of water for 1 – 2 hours.

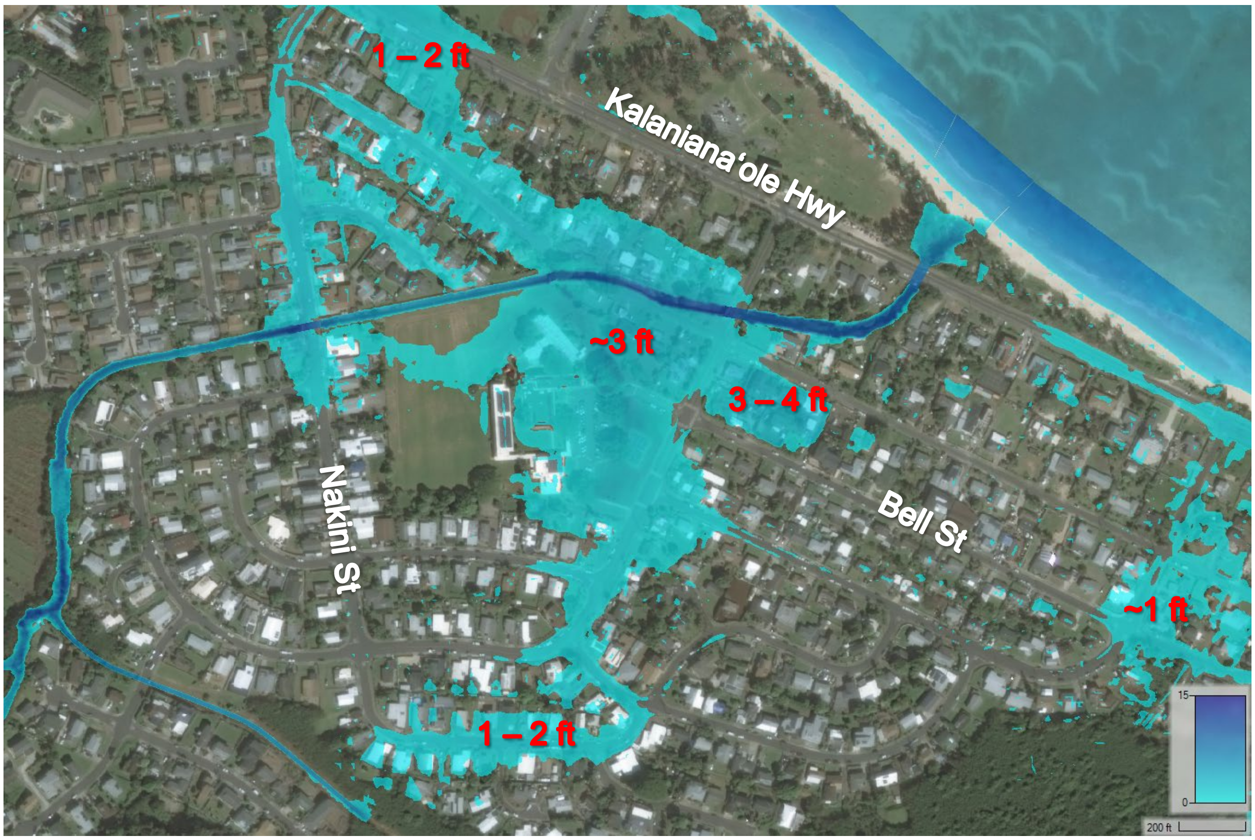


**Figure 2-11: Flood Hazard Map for the 1% AEP Flood, Unnamed Stream #1, Kaiona Watershed**

### 2.3.9 **Residential Properties in Eastern Waimānalo**

Some residential properties between the Koʻolau Range and Kalanianaʻole Hwy may experience as much as 5 feet of flooding as a result of ponding / rainfall accumulation. In this scenario, the 24-inch culvert that runs under Bell St and Kalanianaʻole Hwy was not included (representing its obstruction near the outlet due to sand or debris). An additional simulation was run where the culvert was cleared and is described in Section 2.5.3.


**Figure 2-12: Flood Hazard Map for the 1% AEP Flood, Eastern Waimanalo Residential Area**

## 2.4 Model Sensitivity

Sensitivity tests on the model provide additional information on how sensitive the results are to certain parameters. The following tests were performed on this model:

1. Computing two-dimensional flow routing with Shallow Water equations;
2. Increasing and decreasing the Manning's roughness coefficient, *n* by 20%;

### 2.4.1 **Shallow Water or Diffusion Wave Equations**

Within HEC-RAS, the Diffusion Wave equations are set as the default, however, the user should always test if the Shallow Water equations (SWE) are needed for their specific application. SWE can be useful for modeling super elevation of the water surface on the outside of tight bends and when modeling mixed flow regimes, which is often caused by variation in channel steepness.

As an example, Figure 2-13 shows the difference in the areal extent of flooding when flow routing is computed using Diffusion Wave equations (represented as shades of blue in this figure) and Shallow Wave equations (represented as the lower layer in shades of red). As there are notable differences in the results and SWE is generally considered to produce more accurate results, two-dimensional unsteady flow routing was computed using the SWE equation set in all scenarios simulated under this study.

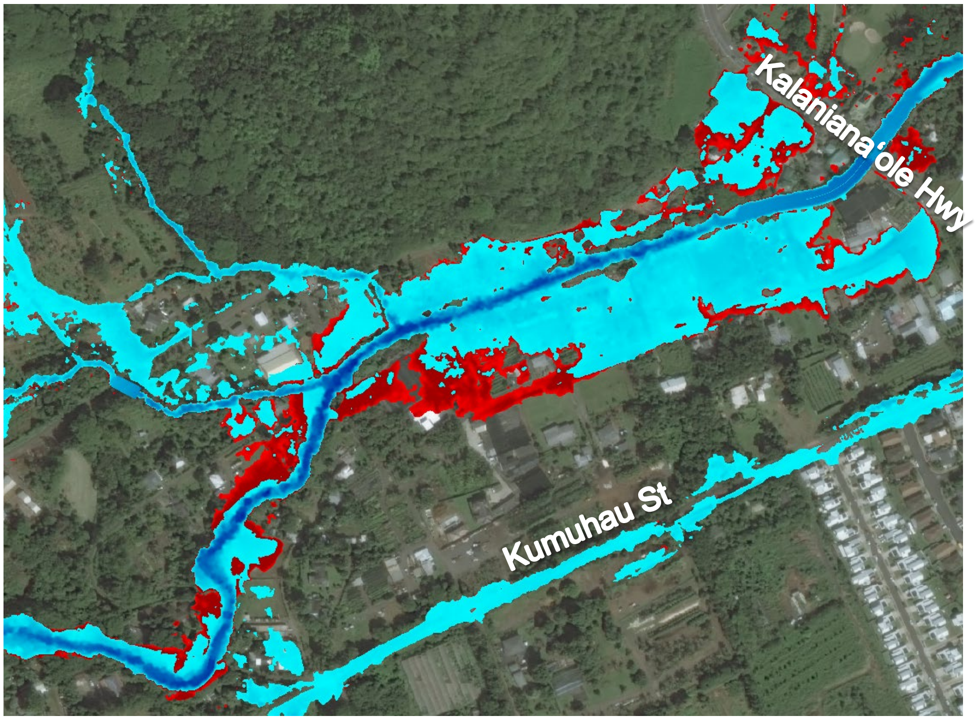


**Figure 2-13: Difference in floodplain boundary for the 1% AEP event when using different flow routing equations**

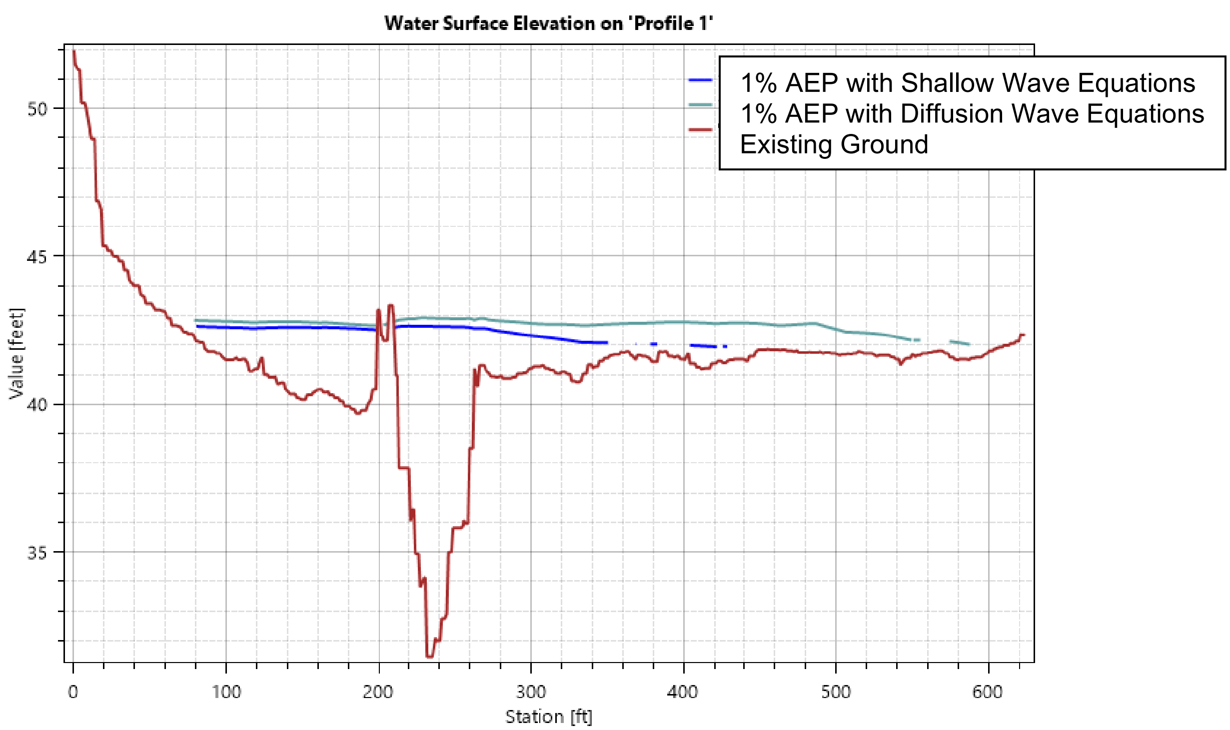


**Figure 2-14: Comparison of Water Surface Elevations along Waimānalo Stream when using Different Flow Routing Equations**

### 2.4.2 **Adjustments to Manning's Roughness Coefficient, n**

A sensitivity analysis was performed on the hydraulic model by varying the values of Manning's *n* to evaluate how water surface elevations were affected by this parameter. Manning's roughness coefficient, *n*, represents the resistance to flow in channels and floodplains. Across the floodplain, this resistance can be caused by rises and depressions in the land surface, structures (e.g., houses and commercial buildings), and vegetation (e.g., shrubs, forests). For this analysis, Manning's *n* was multiplied by 1.2 in one simulation and 0.8 in another for all land cover types. Minor changes in the roughness coefficient (+/- 20%) result in minor changes to the flow profile for the 1% AEP. The original results are shown in Figure 2-15 as shades of blue. The results from increasing Manning's n by 20% is shown as the lower layer in red. The difference is negligible.

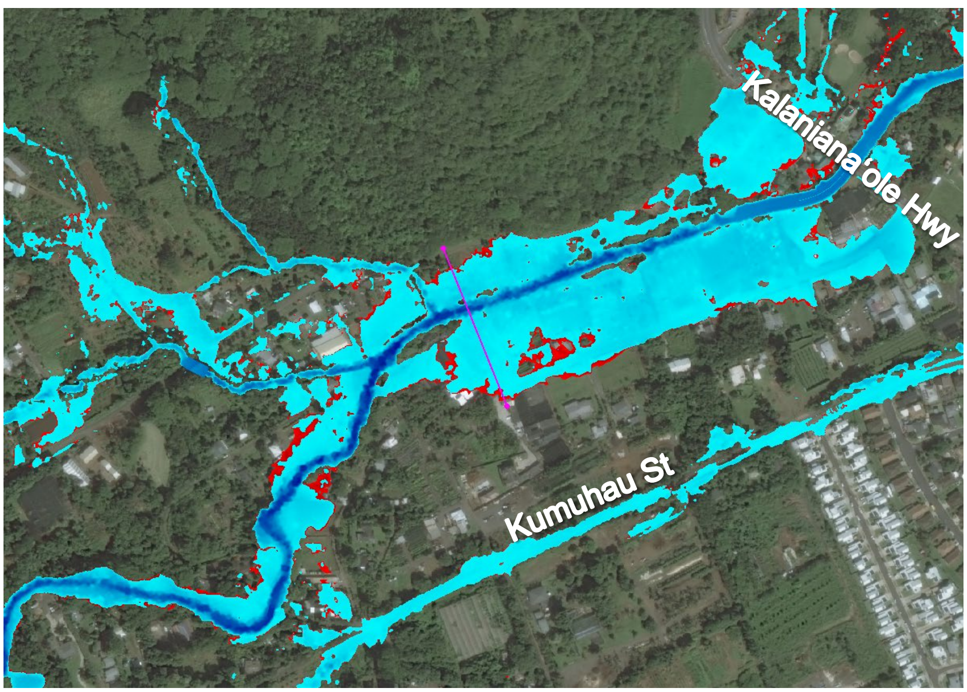


**Figure 2-15: Resulting difference in the 1% AEP floodplain boundary from the original, existing conditions model (blue) and increasing Manning's n (red)**

The results of this analysis against the 1% AEP event show that the uncertainty in the water surface elevation due to the Manning's *n* variation is about ±0.3 feet, with a standard deviation of 0.24 feet (Figure 2-16).

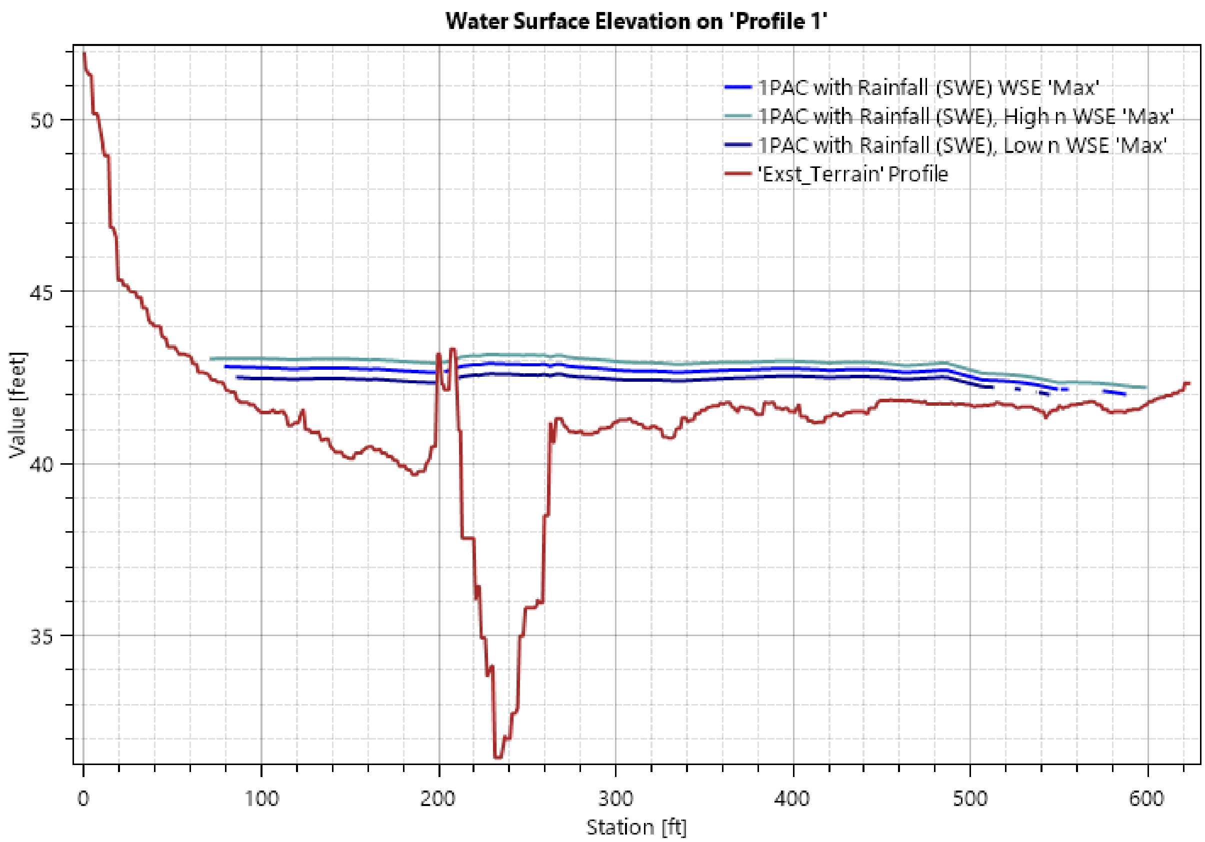


**Figure 2-16: Difference in Water Surface Elevation when Manning's n is changed +/-20%.**

## 2.5 Additional Scenarios

The hydraulic model representing existing site conditions was adjusted to represent theoretical scenarios that had the potential to increase or decrease the community flood hazard. The following scenarios were modeled:

1. Increasing vegetation in the streams and channels;
2. Bridge and culvert obstructions by debris and vegetation;
3. Clearing sand bars at the outlet; and
4. Sea level change

### 2.5.1 **Increased Channel Vegetation**

Manning's roughness coefficient, *n*, is an empirically derived coefficient that is dependent on several variables, such as vegetation, obstructions, and meandering when applied to open channels. In this scenario, Manning's n was increased only in the channel and by 50% to represent increased vegetation in the channels. The resulting flood impacts (shown as a red bottom layer in Figure 2-17), however, were not much different than the original, existing conditions scenario (shown as a blue top layer in Figure 2-17) under the 1% AEP flood. Additional flooding was noted along Humuniki Street. Other small areas in the community experienced additional flooding, but the extent was very limited and depths were less than one foot (< 1 ft).

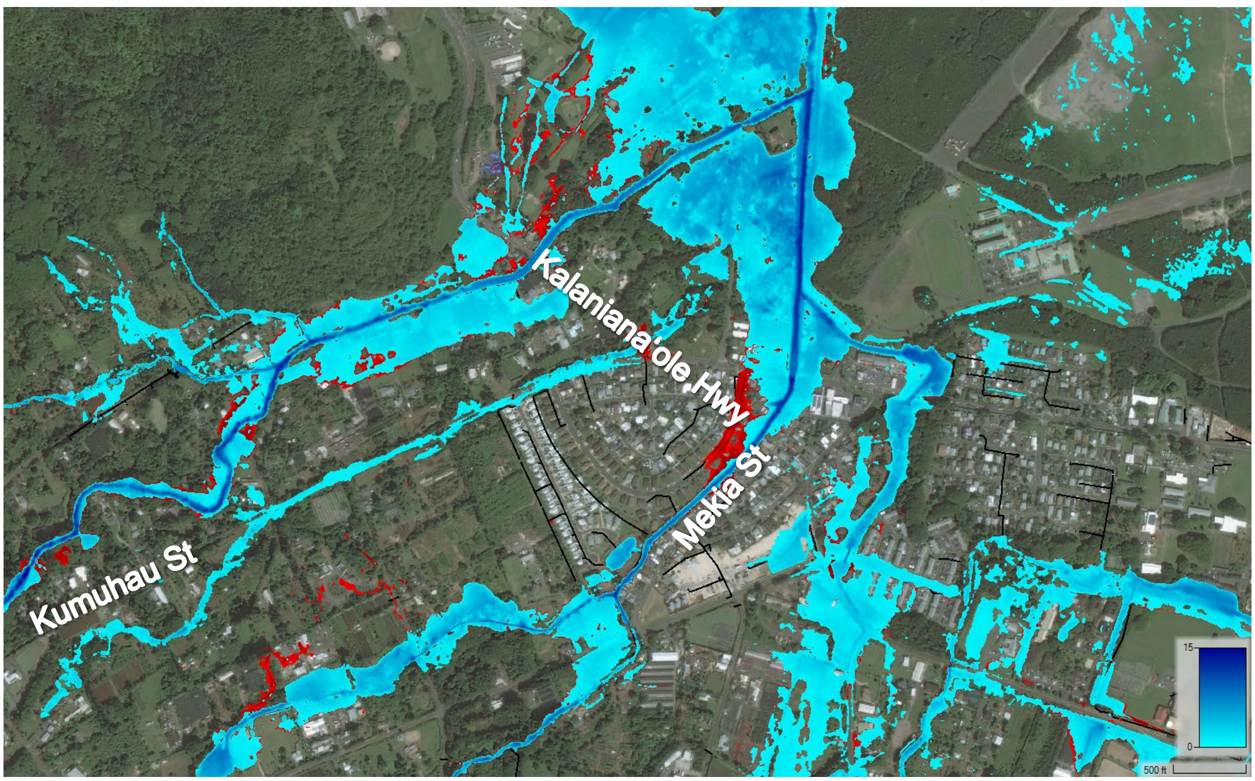


**Figure 2-17: Resulting difference in the 1% AEP floodplain boundary from the original, existing conditions model (blue) and increasing channel vegetation (red)**

### 2.5.2 Bridge and Culvert Obstructions by Debris

For this scenario, the following culverts were obstructed with debris or sediment:

- 9 Mahaiulua St Culvert 1
- 10 Mekia St Culvert 1
- 11 Kakaina St Culvert 1
- 12 Hihimanu St Culvert 1
- 15 Makakalo St Culvert 1
- 16 Ahiki St Culvert 2
- 25 Mahiku Pl Culvert 1
- 38 Mokulama St Culvert 1
- 39 Bell St Culvert 1

The vertical clearance was reduced to 25% of its original height (75% obstruction). Bridges or large culverts that were likely to pass most vegetation, debris, and sediment, or those associated with lined channels where there was a low probability of an obstruction were not selected. Flood depths in the channels immediately upstream of these culverts increased. However, additional flooding to the community was limited to shallow (< 1 ft) flooding along Ahiki St (Figure 2-18) and Mekia St (Figure 2-19).

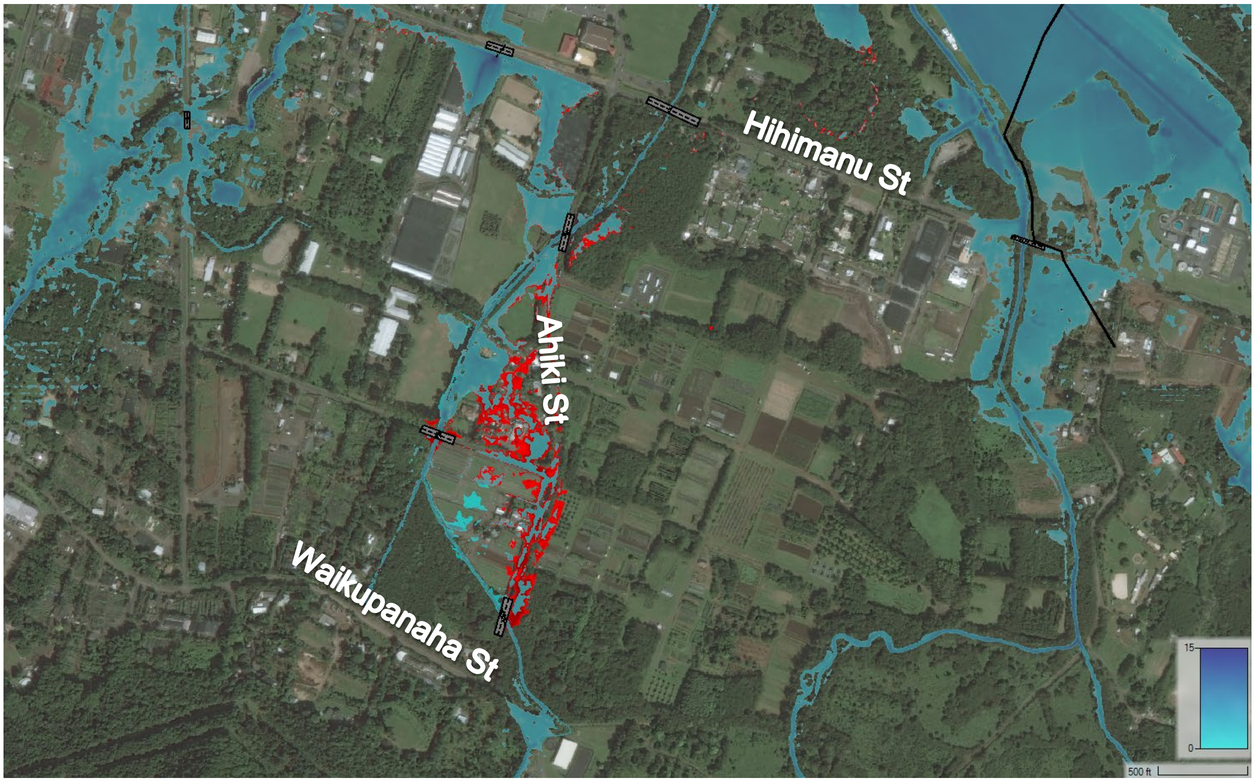


**Figure 2-18: Increased flooding due to culvert obstructions near Ahiki St**


**Figure 2-19: Increased flooding due to culvert obstructions near Mekia St**

### 2.5.3 **Waimānalo Stream Outlet Cleared**

Approximately 2,360 ft of the channel was lowered and cut to represent dredged conditions along the lower reach of Waimānalo Stream. As seen in Figure 2-20, the effects were negligible.

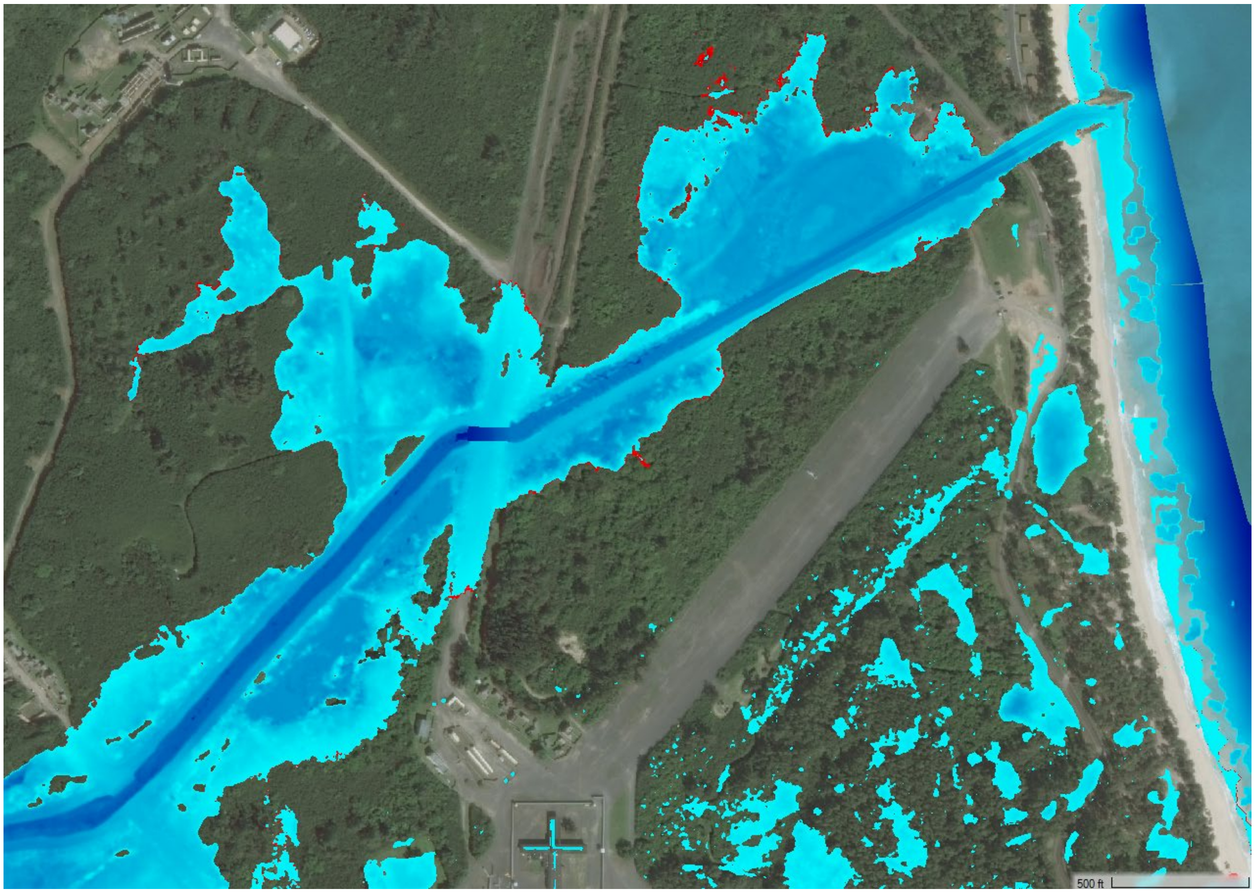


**Figure 2-20: Resulting difference in the 1% AEP floodplain boundary between the original, existing conditions model (red) and dredged scenario (blue) for Waimānalo Stream**

### 2.5.4 **Puha (Inoaole) Stream Lower Channel and Outlet Dredged**

Approximately 1,700 feet of the downstream reach of Puha (Inoaole) Stream was lowered and cut to represent dredged conditions and a continuous channel downslope to Waimānalo Bay. This did not significantly affect the floodplain boundary or depths. Kalanianaʻole Hwy is still overtopped upstream, as shown in Figure 2-21.

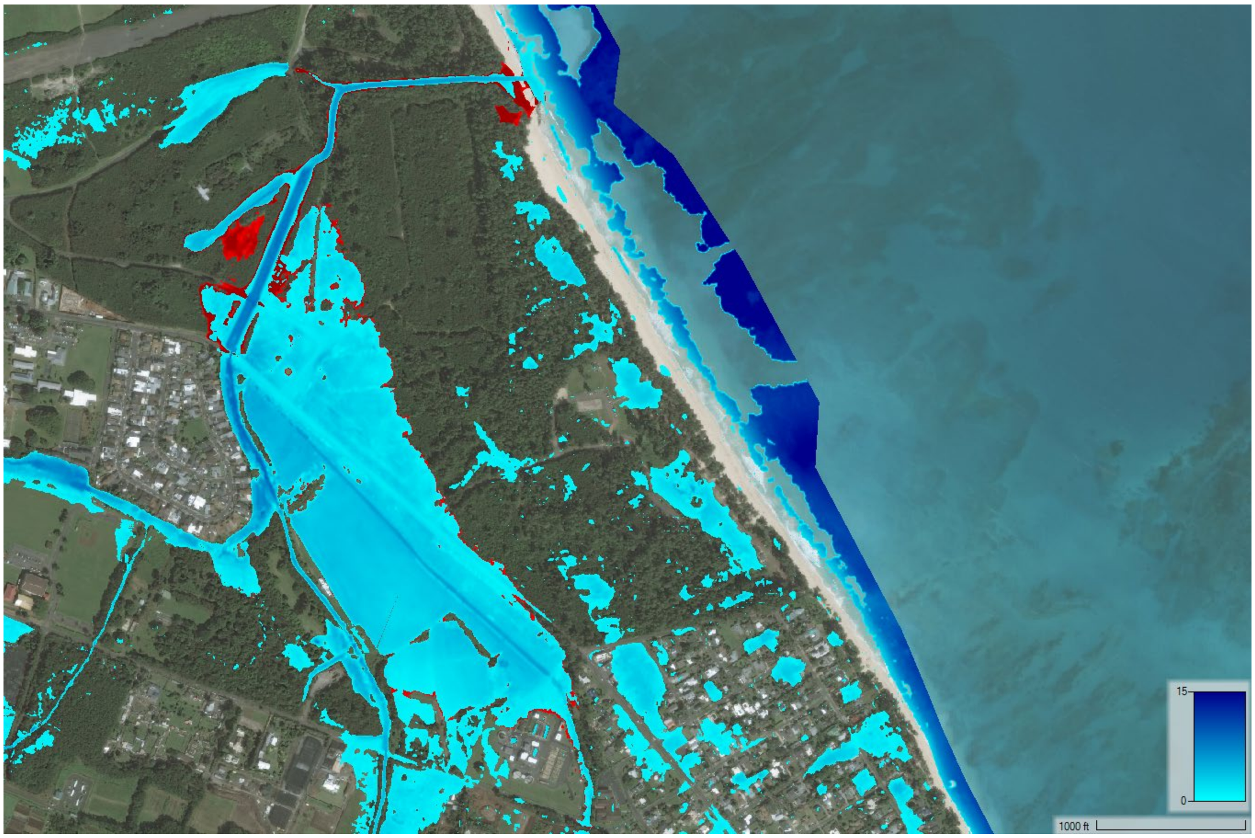


**Figure 2-21: Resulting difference in the 1% AEP floodplain boundary between the original, existing conditions model (red) and dredged scenario (blue) for Puha (Inoaole) Stream**

### 2.5.5 **Cleared Culverts in Eastern Waimānalo**

In eastern Waimānalo, two changes were made to increase the effectiveness of existing structures. First, a culvert was added representing the existing intake and culvert along Bell Street that carries flow under Kalanianaʻole Hwy and discharges into Waimānalo Bay (Photo 2-15). In the original (existing conditions) model, this culvert was not included because it was observed in the field to be obstructed (ineffective), as shown in Photo 2-16. In this simulation, the culvert was cleared and there were no obstructions to flow.

Although the culvert near the intersection of Bell St and Hoomaha St was included in the original model, the heavily vegetated swale was cleared for this simulation. The effects from these two changes were not significant during the 1% AEP (1/100) flood event. This was expected as most stormwater systems are designed to a higher frequency event, such as the 10% AEP (1/10) flood event. Although the extent of flooding is still about the same, it did reduce the depth by about 0.5 ft. The 10% AEP flood was also run under this scenario, but the effects were similar (not much difference in the floodplain boundary, and lower flood depths of about 0.5 ft).

**Photo 2-14: Heavily vegetated swale leading to culvert / stormwater system near Hoomaha St**

**Photo 2-15: Intake / Culvert Inlet along Bell Street**

**Photo 2-16: Culvert Outlet Buried and Broken**


**Figure 2-22: Resulting difference in the 1% AEP floodplain boundary due to operational (cleared) culverts in Eastern Waimānalo**

### 2.5.6 **Sea Level Change**

In following Engineer Regulation 1100-2-8162, *Incorporating Sea Level Change in Civil Works Programs* (USACE, 2013) and ETL 1100-2-1, *Procedures to Evaluate Sea Level Change: Impacts, Responses, and Adaptation* (USACE, 2014), three scenarios of sea level change were projected: *low*, *intermediate*, and *high.* The gage at Mokuoloe, HI (NOAA ID: 1612480) was used for the analysis (NOAA). This gage was established in 1957 and in its present location since 1989. It is located on the west side of Moku o Loʻe (Coconut) Island, approximately 3 miles northwest of the Waimanalo Stream outlet. The relative sea level trend for this tidal gauge is 1.69 mm/year (0.0055 ft/yr) with a 95% confidence interval of +/- 0.52 mm/yr based on monthly mean sea level data from 1957 to 2021, which is equivalent to a change of 0.55 feet in 100 years.

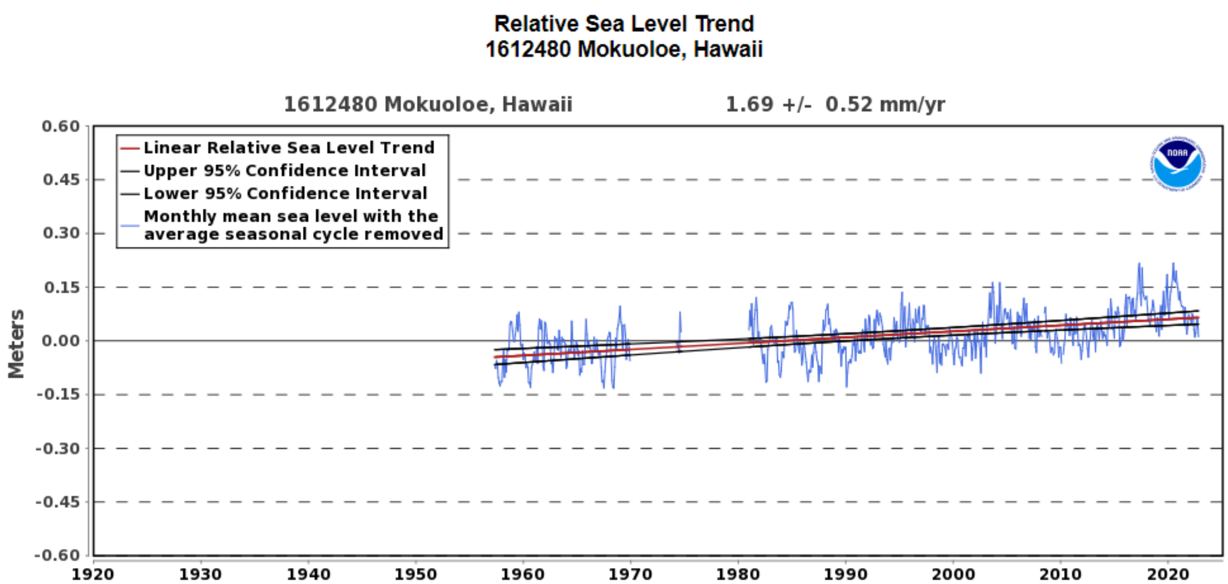


**Figure 2-23: Relative Sea Level Trend for Station 1612480, Mokuoloe, Hawaii**

The gage site was selected in the USACE Sea Level Change Calculator (Version 2022.72). The 2006 NOAA sea level change rate of 0.00430 ft/yr was less than the 2021 rate (0.00554 ft/yr). The more conservative rate (2021) was entered as the SLC rate for estimating relative sea level change projections.

The result of the calculation indicates a relative sea level change of 6.58 feet over the next 100 years for the *high* condition (7.29 feet for the year 2125 minus 0.59 feet for the year 2025 equals 6.70 feet). For the *intermediate* condition, the change was 2.03 feet, and the *low* condition shows an increase of 0.56 feet. These values are relative to Local Mean Sea Level (LMSL) as the calculator states NAVD88 datum is not available at this station. The resulting sea level rise curve is shown in Figure 2-24.

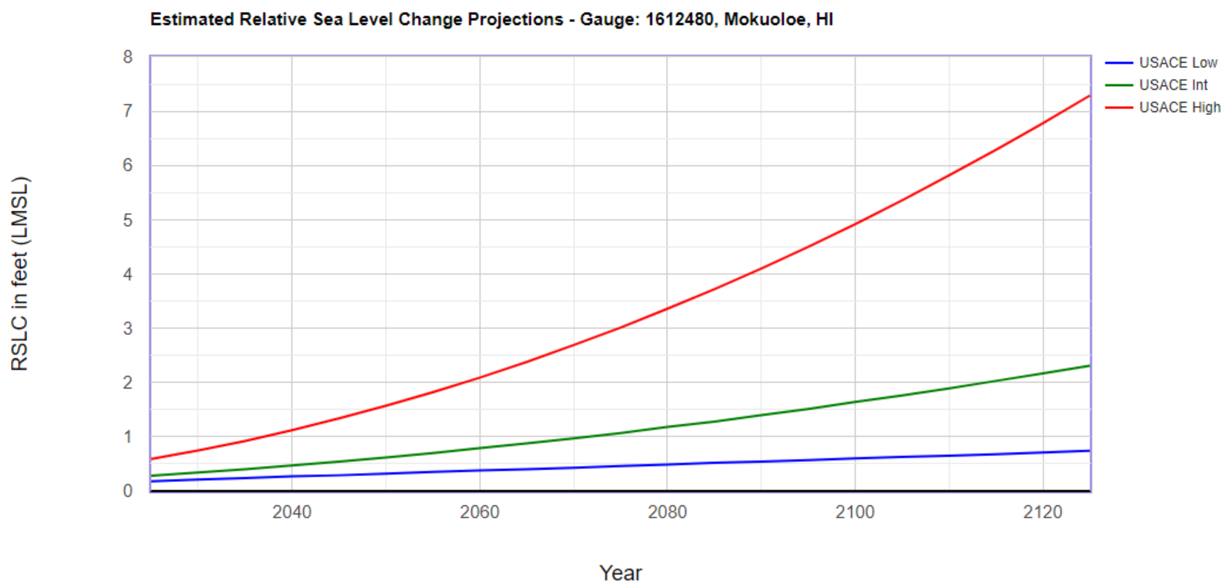


**Figure 2-24: Estimated Relative Sea Level Change Projections – Gauge: 1612480, Mokuoloe, HI**

The calculator also outputs a table showing the progression of sea level rise. This table was derived in 5-year increments and is shown in Table 2-4.

**Table 2-4: Sea Level Rise by Year**

| Year | USACE | | |
|---|---|---|---|
| | ***Low*** | ***Intermediate*** | ***High*** |
| 1992 | 0.00 | 0.00 | 0.00 |
| 1995 | 0.02 | 0.02 | 0.02 |
| 2000 | 0.04 | 0.05 | 0.07 |
| 2005 | 0.07 | 0.09 | 0.13 |
| 2010 | 0.10 | 0.13 | 0.22 |
| 2015 | 0.13 | 0.17 | 0.32 |
| 2020 | 0.16 | 0.22 | 0.45 |
| 2025 | 0.18 | 0.28 | 0.59 |
| 2030 | 0.21 | 0.34 | 0.75 |
| 2035 | 0.24 | 0.40 | 0.92 |
| 2040 | 0.27 | 0.47 | 1.12 |
| 2045 | 0.29 | 0.54 | 1.34 |
| 2050 | 0.32 | 0.62 | 1.57 |
| 2055 | 0.35 | 0.70 | 1.82 |
| 2060 | 0.38 | 0.79 | 2.09 |
| 2065 | 0.40 | 0.88 | 2.38 |
| 2070 | 0.43 | 0.97 | 2.69 |
| 2075 | 0.46 | 1.07 | 3.01 |
| 2080 | 0.49 | 1.18 | 3.36 |
| 2085 | 0.52 | 1.28 | 3.72 |
| 2090 | 0.54 | 1.40 | 4.10 |
| 2095 | 0.57 | 1.51 | 4.50 |
| 2100 | 0.60 | 1.64 | 4.92 |
| 2105 | 0.63 | 1.76 | 5.36 |
| 2110 | 0.65 | 1.89 | 5.82 |
| 2115 | 0.68 | 2.03 | 6.29 |
| 2120 | 0.71 | 2.17 | 6.78 |
| 2125 | 0.74 | 2.31 | 7.29 |

The calculator also provides extreme water levels expected across several datums. These datums and their respective values are shown in the table and figure below:

**Table 2-5: Tidal Datums and Extreme Water Levels, Gauge: 1612480, Mokuoloe, HI**

| Datum / Extreme Water Level (EWL) | Height above LMSL (ft) |
|---|---|
| HAT | 1.86 |
| MHHW | 1.07 |
| MHW | 0.74 |
| MSL | 0.00 |
| MLW | -0.74 |
| MLLW | -1.05 |
| NAVD88 | NaN |
| EWL Type | NOAA GEV |
| 1/100 AEP | 2.56 |
| 1/50 AEP | 2.51 |
| 1/20 AEP | 2.42 |
| 1/10 AEP | 2.34 |
| 1/5 AEP | 2.25 |
| 1/2 AEP | 2.09 |
| Yearly | 1.74 |
| Monthly | NaN |
| From | 1957 |
| To | 2007 |
| Years of Record | 50 |

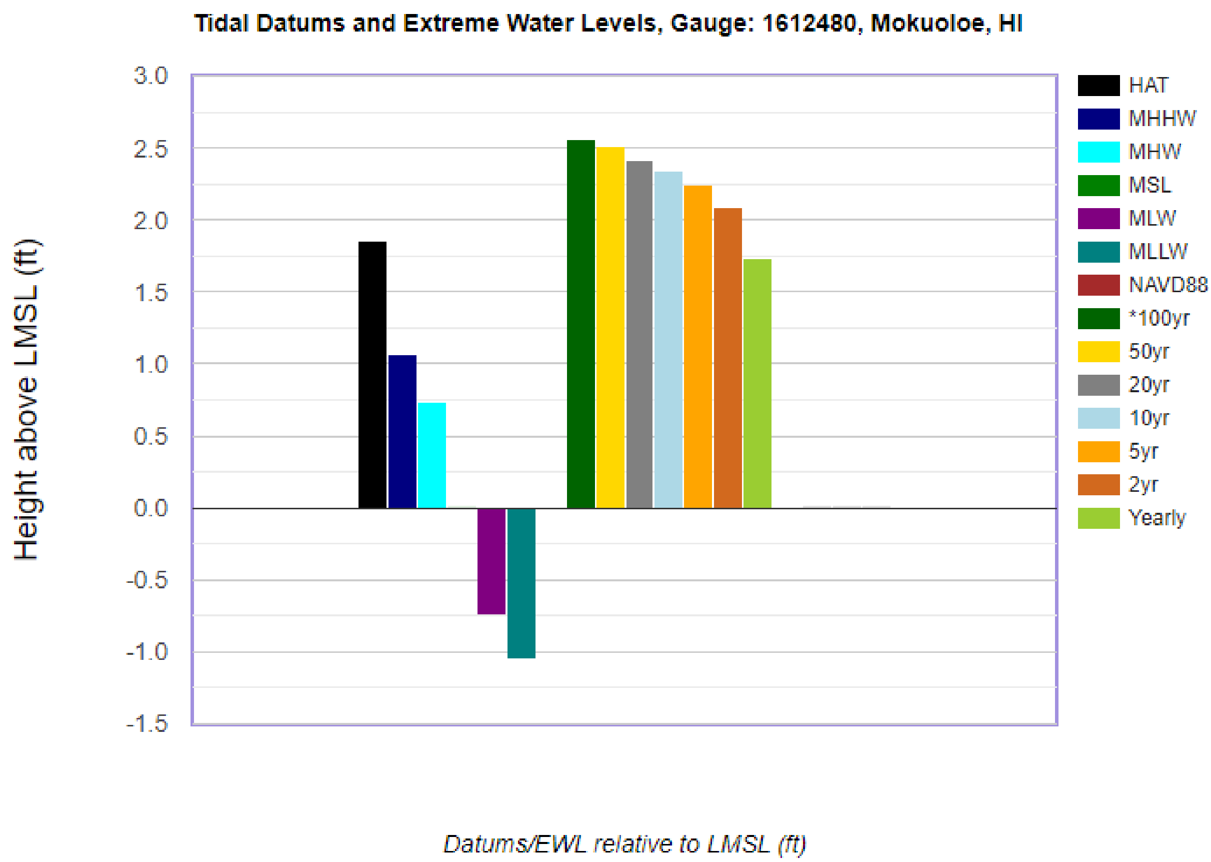


**Figure 2-25: Tidal Datums and Extreme Water Levels, Gauge: 1612480, Mokuoloe, HI**

The highest tide level occurred in December 2019 and was 1.62 ft MHHW (0.55 ft MSL). Under *high* sea level rise conditions, this max tide level would be 8.46 ft MHHW (7.39 ft MSL) in 2125. The relative change in sea level from 2025 to 2125 is 6.70 feet.

The downstream boundary in the hydraulic model was adjusted to represent the mean higher high water (MHHW) elevation under the three different sea level change conditions. Even under *high* sea level conditions (7.77 ft MSL), the impact to the extent and depths of flooding was minimal.[3] Generally, the impact was limited to the shoreline and the lower reach segment of Waimānalo Stream, where the water surface elevation in the channel increased about 0.2 ft for the 1% AEP flood event. There was no rise in elevation upstream of Kalanianaʻole Highway or in any of the other streams.

[3] Impacts from wave action or shoreline erosion are not represented in this analysis.

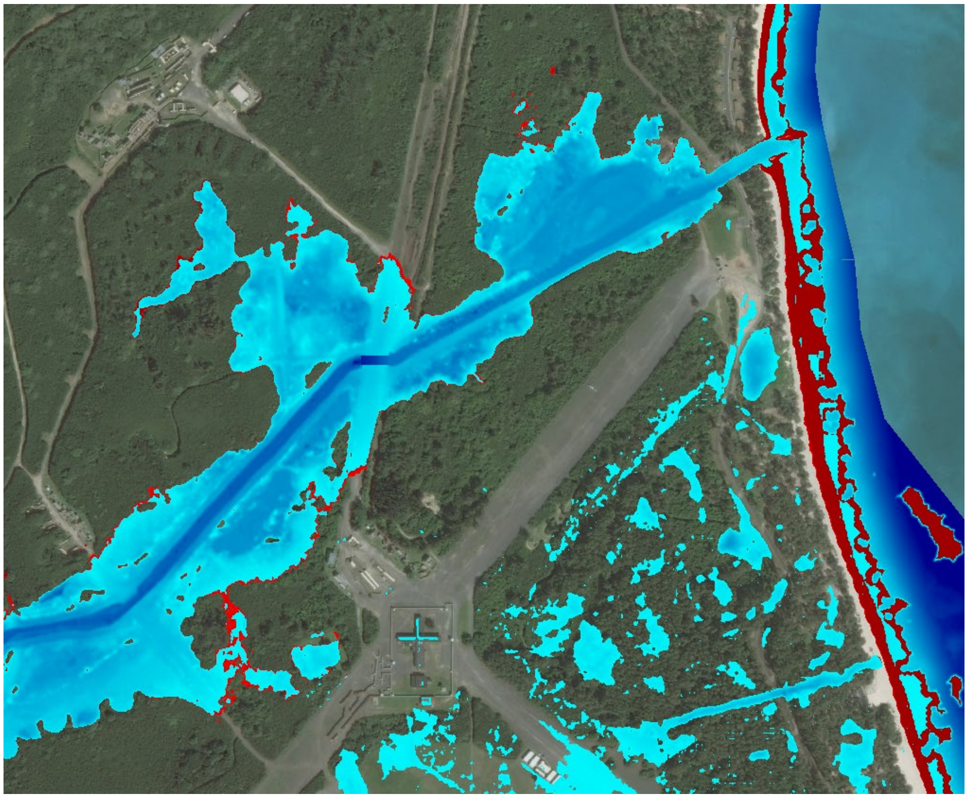

**Figure 2-26: Resulting Impact from *High* Sea Level Change (Red) for the 1% AEP Flood Profile for Waimānalo Stream**

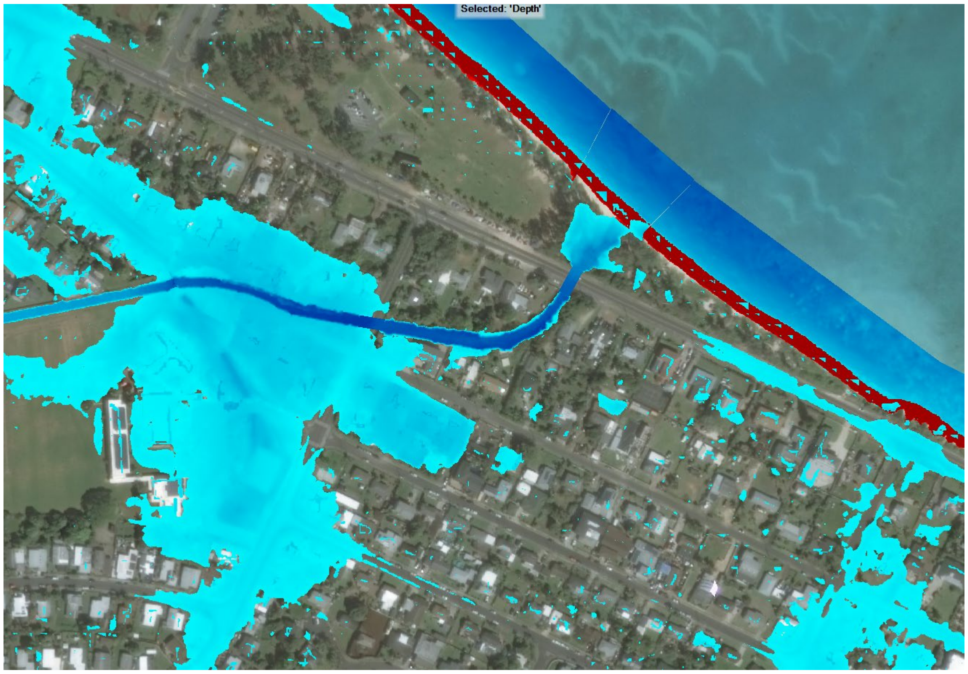


**Figure 2-27: Resulting Impact from *High* Sea Level Change (Red) in 2125 for the 1% AEP Flood Profile for Unnamed Stream #1, Kaiona Watershed**

# 3 Conclusion

The results of this study make available the water surface profiles, flood elevations, and areal extent of the floodplain for the 10%, 4%, 2%, 1%, and 0.2% (1/10, 1/25, 1/50, 1/100, and 1/500) AEP flood events (5 profiles). With several streams in the study area, many residential properties and commercial buildings are at risk of being flooded frequently. Kalanianaʻole Hwy near Sherwood Beach becomes flooded and unusable during the highest frequency event evaluated, the 10% AEP flood event (statistically, once every ten years). It likely floods more frequently given the extensive area that is flooded along and around the highway during the 10% AEP event.

Various additional scenarios were evaluated to provide more information into possible causes or solutions to reduce flood risk. However, their effects at reducing the flood hazard were limited.

- Increased channel vegetation resulted in a tributary to Waimānalo Stream overtopping the banks, causing additional shallow flooding along Humuniki Street. Other small areas in the community experienced additional flooding, but the extent was very limited and depths were less than one foot (< 1 ft).
- Small culverts that were at risk of being obstructed with vegetation, sediment, or debris were partially obstructed under another scenario. Flood depths in the channels immediately upstream of these culverts increased. However, additional flooding to the community was limited to shallow (< 1 ft) flooding along Ahiki St and Mekia St.
- A small channel was cut into the terrain to represent dredging at the Waimanalo and Puha (Inoaole) Streams, but the effects from this were also limited. Kalanianaʻole Hwy is still frequently overtopped.
- Clearing shoreline culvert outlets along Kalanianaʻole Hwy in eastern Waimānalo did not significantly reduce flooding to properties on the mountainside of the highway.
- Even under *high* sea level conditions (7.77 ft MSL), the impact to the extent and depths of flooding was minimal.[4] Generally, the impact was limited to

[4] Impacts from wave action or shoreline erosion are not represented in this analysis.

the shoreline and the lower reach segment of Waimānalo Stream, where the water surface elevation in the channel increased about 0.2 ft for the 1% AEP flood event. There was no rise in elevation upstream of Kalaniana‘ole Highway or in any of the other streams.

# 4 References

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# Appendix D

## Bridges and Culverts

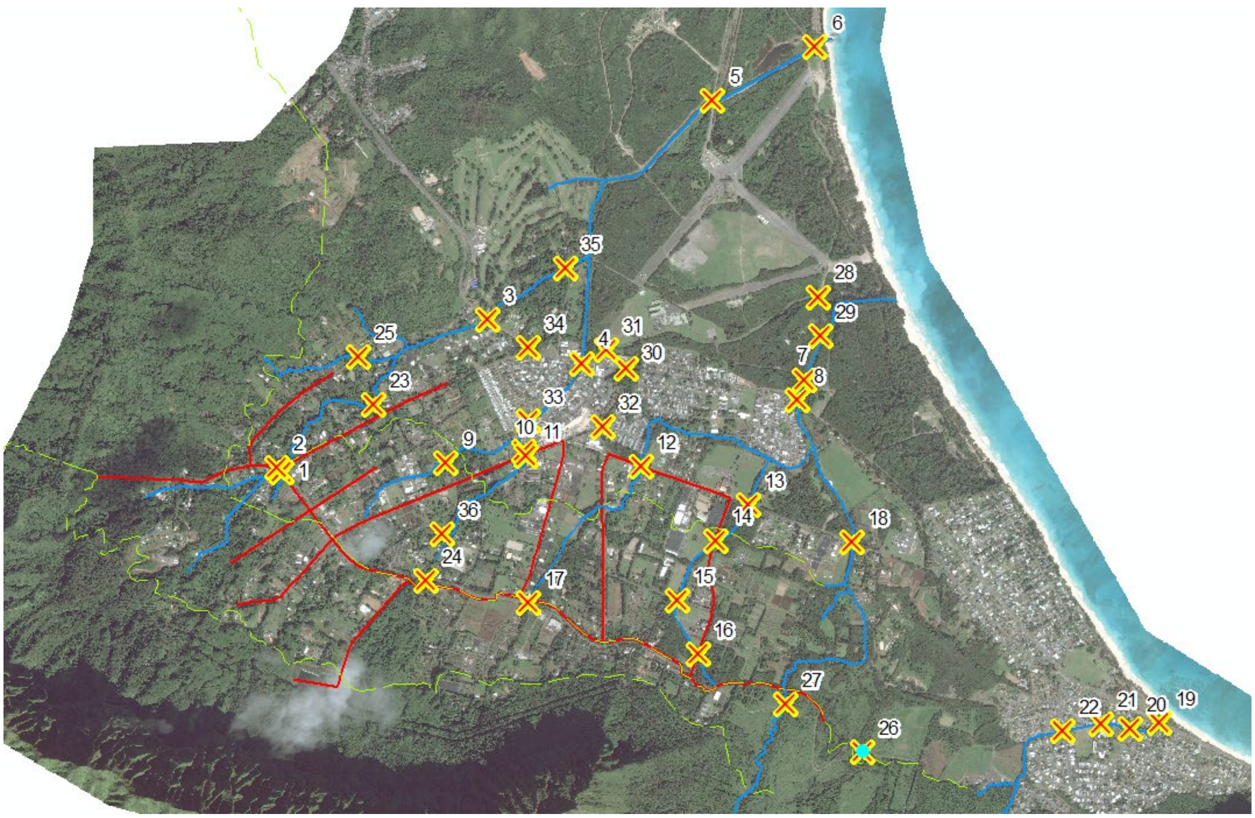
# PREFACE

This appendix provides information on stream crossings (i.e. bridges and culverts) in the study area. Geometric features and typical photos are included, as collected by field surveys, review of as-built plans, and review of National Bridge Inventory data.

# TABLE OF CONTENTS

# Introduction

Initial points of interest where streams potentially intersected with a road were identified prior to the field visit. These crossings are identified in the figure below. Not all crossings were accessible in the field (such as points 26-29). Not all points of interest corresponded with a bridge or culvert (such as point 33, which represents a detention basin). A summary of the field measurements and photos taken in support of this study are provided in this appendix.

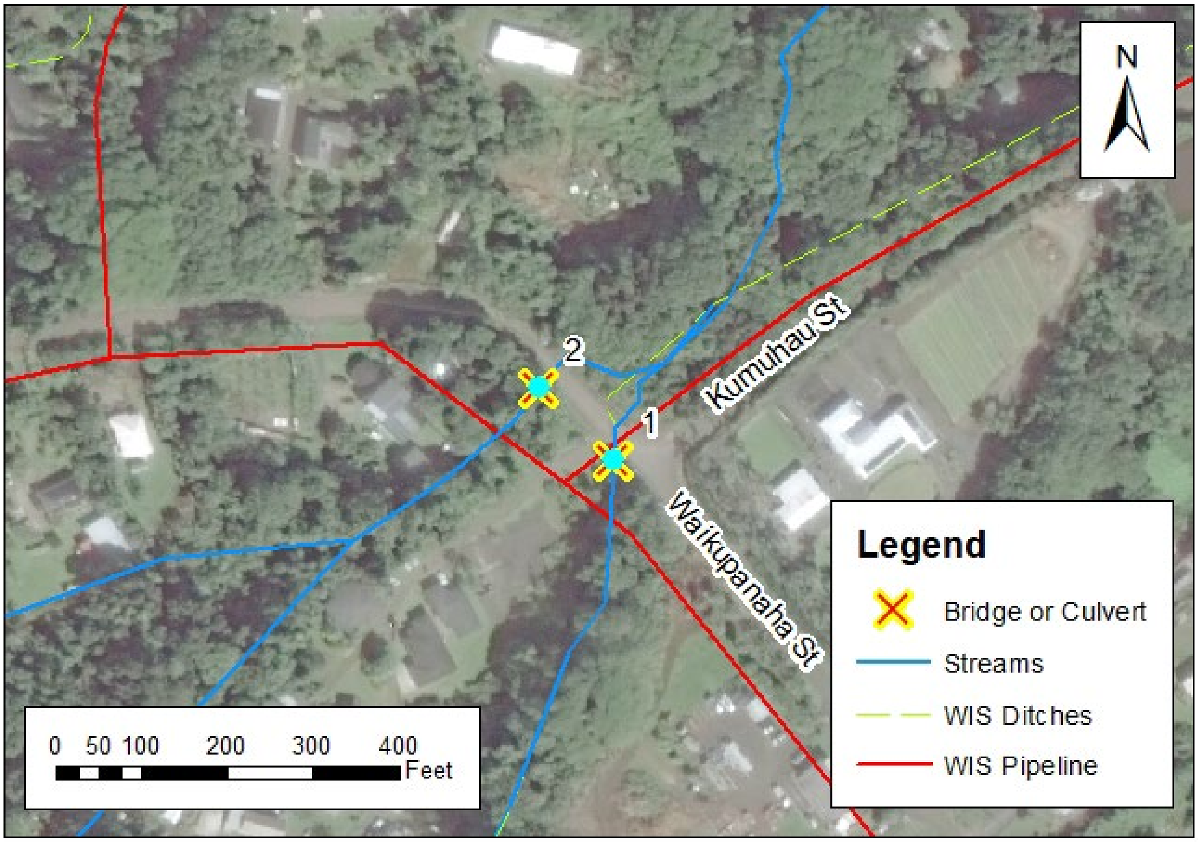



*Above: Initial points of interest (potential crossings)*

# 1 Waikupanaha St Culvert 1

**Stream**: Tributary to Waimānalo Stream, Waimānalo Watershed

**Road**: Waikupanaha Street near Kumuhau Street




**Coordinates**: 157.7396017°W 21.3424931°N

**Field Notes**: Box culvert with approximate (~) vertical span of 13.5 ft, deck thickness of 1.5 ft, and horizontal span of 13 ft 6 in. There is a concrete weir and drop structure located just upstream of the box culvert. Water depths upstream of the weir are very shallow (~ 1 ft).

*Above: Weir and drop structure located upstream of Waikupanha Culvert 1*

*Above: Looking upstream from Waikupanha Culvert 1*

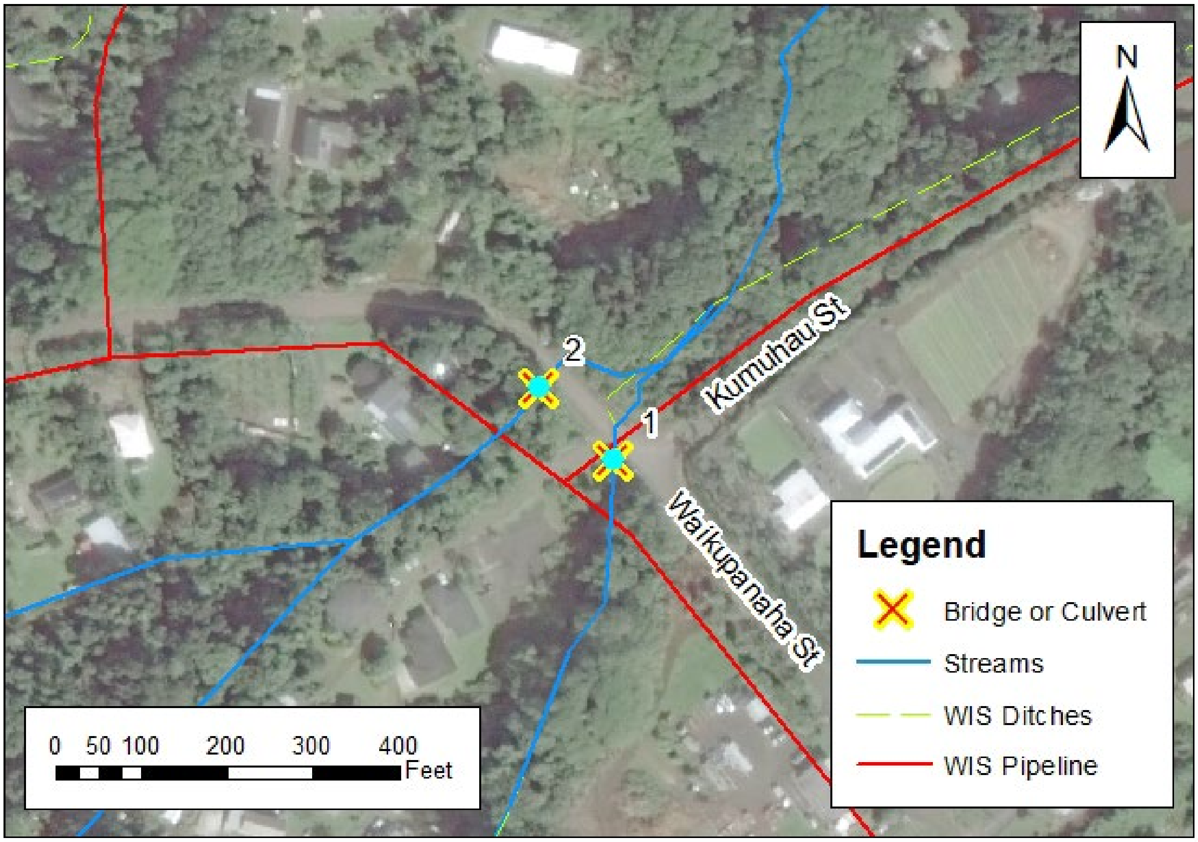
*Above: Looking at the upstream face of Waikupanha Culvert 1*

*Above: Looking downstream from Waikupanha Culvert 1*

# 2 Waikupanaha St Culvert 2

**Stream**: Tributary to Waimānalo Stream, Waimānalo Watershed

**Road**: Waikupanaha Street near Kumuhau Street




**Coordinates**: 157.7398576°W 21.3427230°N

**Field Notes**: Box culvert with approximate vertical span of 11 ft 5 in, deck thickness of 9 ft 7 in, and horizontal span of 30 ft. The channel invert drops approximately 3-4 ft just downstream of the culvert.

**National Bridge Inventory Data**: KUMUHAU ST. over WAIMANALO STREAM[1]

Length of largest span: 29.9 ft

Total length: 29.9 ft

Main span design: Culvert

[1] http://bridgereports.com/1105768

*Above: Looking upstream from Waikupanha Culvert 2*

*Above: Looking at the downstream face of Waikupanha Culvert 2*

*Above: Looking towards the left bank at the area immediately downstream of Waikupanha Culvert 2*

*Above: Looking downstream from Waikupanha Culvert 2*

# 3 Kalaniana‘ole Hwy Bridge 1

**Stream**: Waimānalo Stream, Waimānalo Watershed

**Road**: Kalaniana‘ole Highway


**Coordinates**: 157.7283007°W 21.3503179°N

**Field Notes**: Bridge with splitter wall upstream. Left bank opening is ~23 ft wide; right bank opening is ~24 ft 6 inches wide. Vertical span is ~10 ft. Deck thickness is ~4 ft. Assumed height of splitter wall is the same as the vertical span (~10 ft).

**National Bridge Inventory Data**: KAL HWY over WAIMANALO STRM[2]:

Length of largest span: 30.8 ft

Total length: 33.1 ft

Deck width edge-to-edge: 25.9 ft

Main spans design: Tee beam

[2] http://bridgereports.com/1105223

*Above: Looking upstream from Kalaniana'ole Hwy Bridge 1*

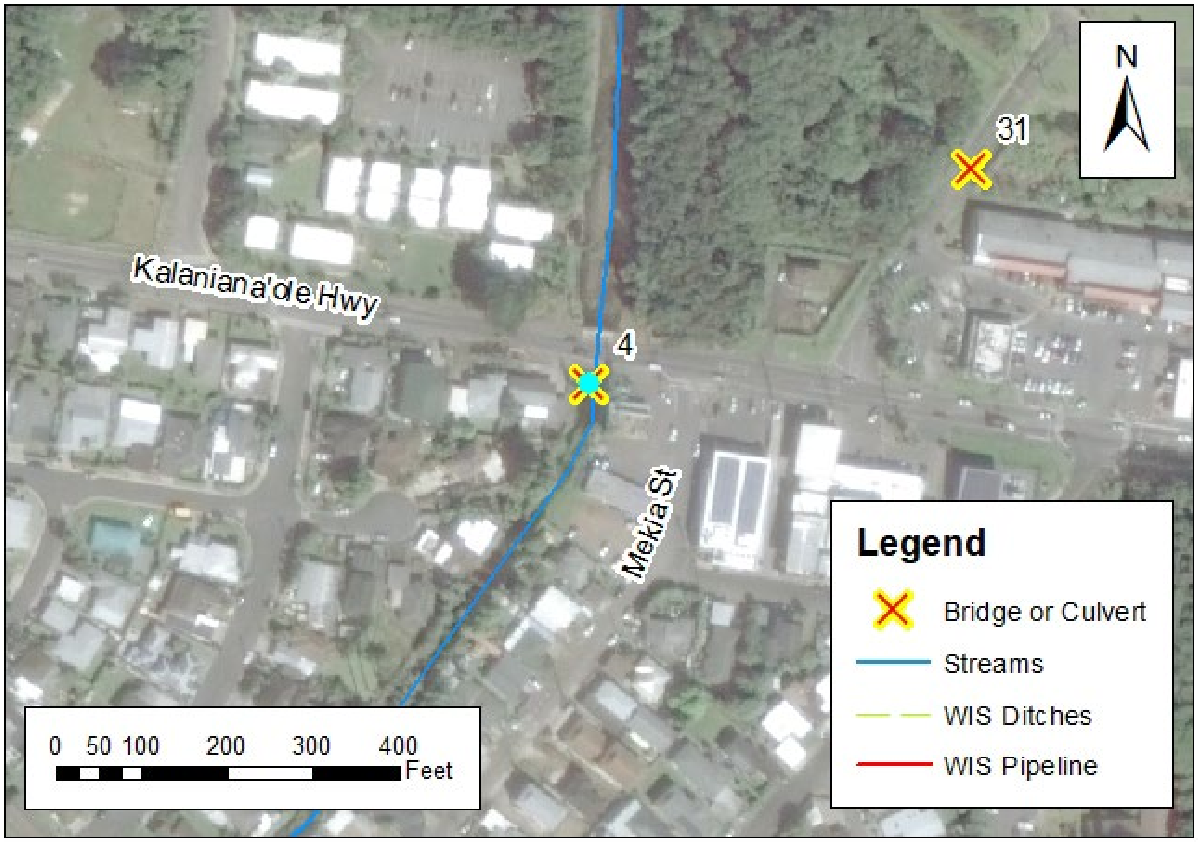
*Above: Looking towards the upstream face of Kalaniana'ole Hwy Bridge 1*

*Above: Looking downstream from Kalaniana'ole Hwy Bridge 1*

# 4 Kalaniana‘ole Hwy Bridge 2

**Stream**: Kahawai Stream (Stream A), Waimānalo Watershed

**Road**: Kalaniana‘ole Highway between Humuniki St and Mekia St




**Coordinates**: 157.7231161°W 21.3480478°N

**Field Notes**: Bridge with approximate (~) vertical span of 7 ft, deck thickness of 5.3 ft, and horizontal span of 40 ft upstream, 33.3 ft downstream.

**National Bridge Inventory Data**: KAL HWY over KAHAWAI STRM(EAST)[3]:

Length of largest span: 24.9 ft

Total length: 53.2 ft

Deck width edge-to-edge: 25.9 ft

Number of main spans: 2

Main spans design: Tee beam

[3] http://bridgereports.com/1105222

*Above: Looking upstream from Kalanianaole Hwy Bridge 2*

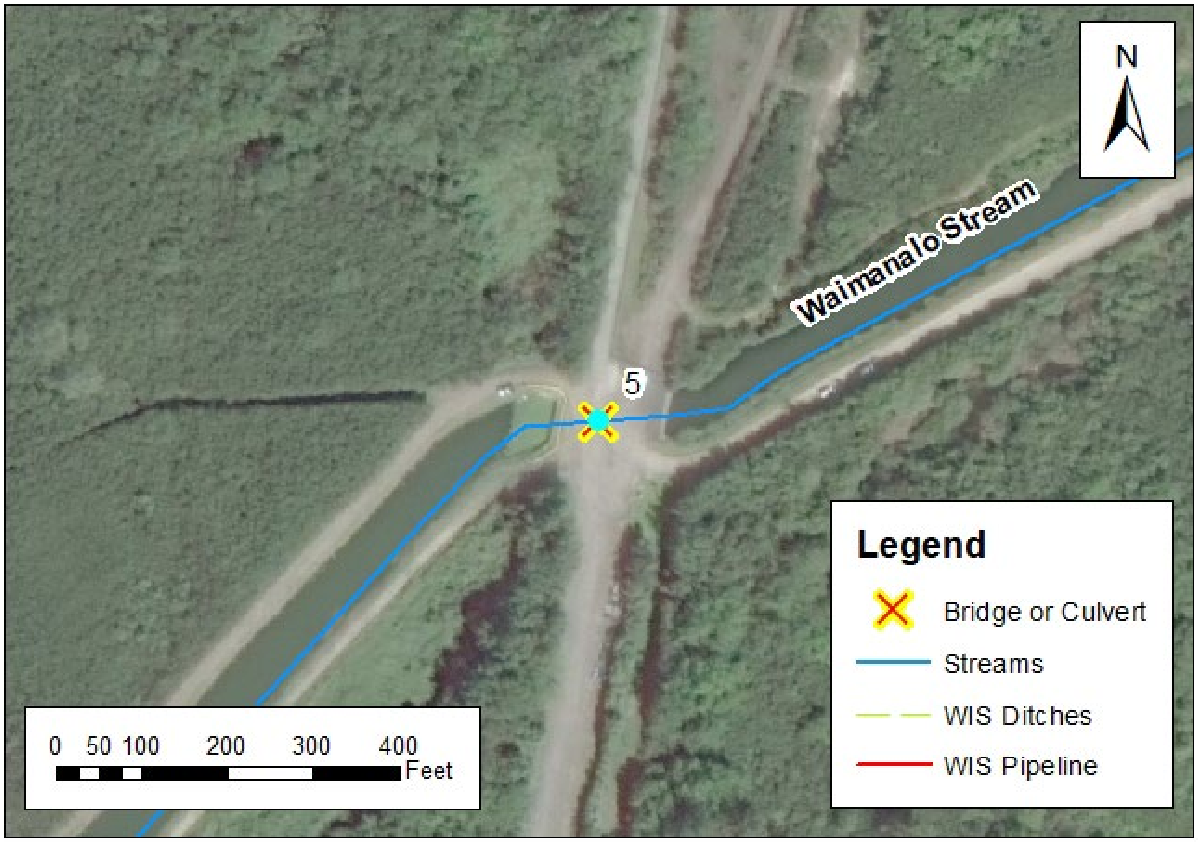
*Above: Looking at the upstream face of Kalanianaole Hwy Bridge 2*

*Above: Looking downstream from Kalanianaole Hwy Bridge 2*

# 5 Bellows Culvert 1

**Stream**: Waimānalo Stream, Waimānalo Watershed

**Road**: Unnamed Road between Tinker Rd and Tinker Rd, Bellows Air Force Station




**Coordinates**: 157.7159411°W 21.3614818°N

**Field Notes**: None

**National Bridge Inventory Data**: BELLOWS ROAD over CANAL[4]

Length of largest span: 11.5 ft

Total length: 50.5 ft

Skew angle: 14°

Number of main spans: 5

Main spans material: Concrete

Main spans design: Culvert

[4] http://bridgereports.com/1647535

*Above: Looking across Bellows Culvert 1*

# 6 Tinker Rd Bridge 1

**Stream**: Waimānalo Stream, Waimānalo Watershed

**Road**: Tinker Rd, Bellows Air Force Station


**Coordinates**: 157.7103198°W 21.3642370°N

**Field Notes**: None

**National Bridge Inventory Data**: TINKER ROAD over WAIMANALO STREAM[5]

Length of largest span: 44.6 ft

Total length: 93.5 ft

Deck width edge-to-edge: 27.2 ft

Number of main spans: 2

Main spans design: Stringer/Multi-beam or girder

[5] http://bridgereports.com/1106096

*Above: Looking upstream from Tinker Rd Bridge 1*

*Above: Looking at the downstream face of Tinker Rd Bridge 1*

*Above: Looking downstream from Tinker Rd Bridge 1*

# 7 Tinker Rd Culvert 1

**Stream**: Puha (Inoaole) Stream, Kahawai Watershed

**Road**: Tinker Rd


**Coordinates**: 157.7109494°W 21.3471910°N

**Field Notes**: 8 box culverts with horizontal opening width of ~10 ft; center two culverts are ~5 ft wide. Vertical span of ~5 ft (including ~1 ft of water). Deck thickness is about 2.5 ft (culvert headwall = 2 ft + road embankment = 6 inches).

*Above: Looking downstream towards Tinker Rd Culvert 1*

*Above: Looking at the upstream face of Tinker Rd Culvert 1*

*Above: Looking downstream from Tinker Rd Culvert 1*

# 8 Kalaniana‘ole Hwy Culvert 1

**Stream**: Puha (Inoaole) Stream, Kahawai Watershed

**Road**: Kalaniana‘ole Highway between Inoaole St and Tinker Rd


**Coordinates**: 157.7113645°W 21.3461535°N

**Field Notes**: Tapered box culvert with horizontal span of 13 ft 9 inches, vertical span / height of opening = 4.5 ft. Deck thickness ~3 ft.

*Above: Looking at the upstream channel from Kalanianaʻole Hwy Culvert 1*

*Above: Looking downstream at Kalanianaʻole Hwy Culvert 1*

*Above: Looking downstream through Kalaniana‘ole Hwy Culvert 1*

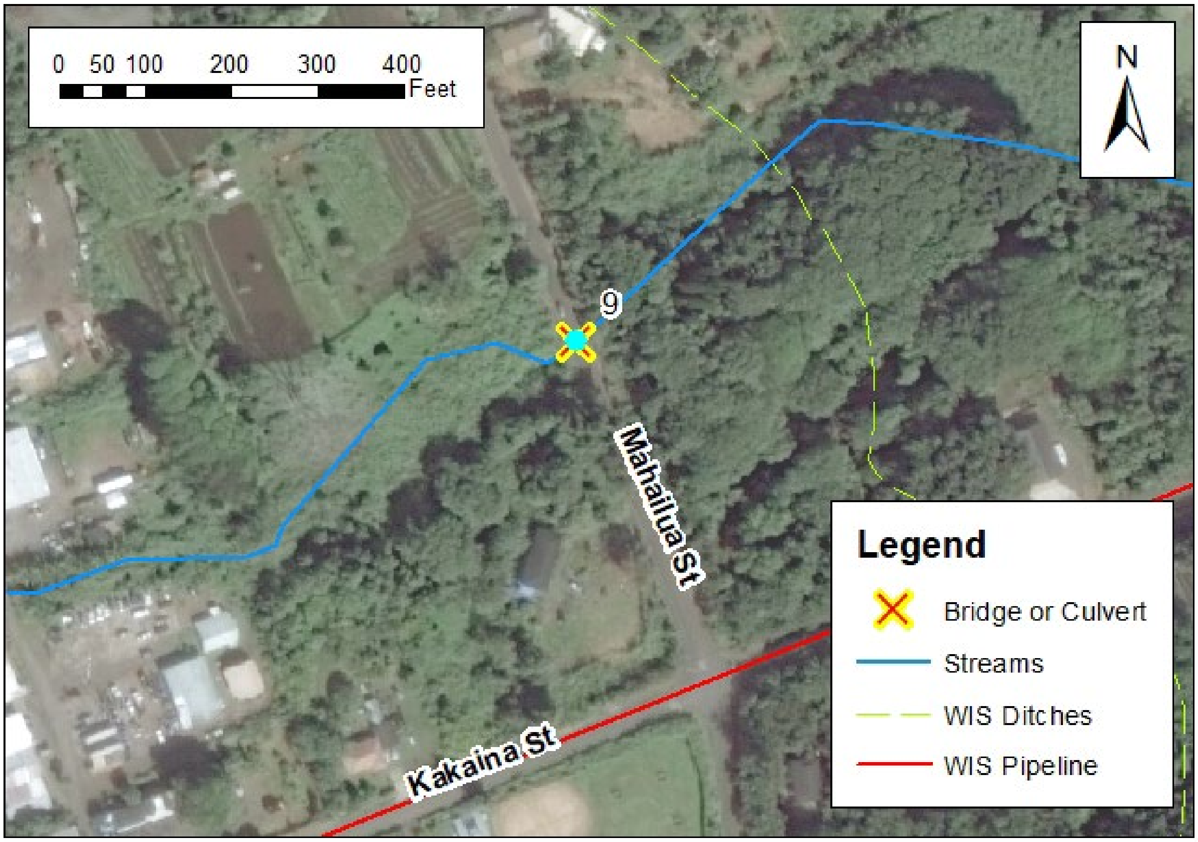
*Above: Looking at the downstream face of Kalaniana‘ole Hwy Culvert 1*

*Above: Looking downstream from Tinker Rd Culvert 1*

# 9 Mahailua St Culvert 1

**Stream**: Kahawai Stream (Stream A), Waimānalo Watershed

**Road**: Mahailua St between Kumuhau St and Kakaina St




**Coordinates**: 157.7305743°W 21.3429713°N

**Field Notes**: 3 ft by 3 ft box culvert. Deck thickness ~ 4 ft. Downstream, there is a ~2 ft drop with 45 degree wingwalls.

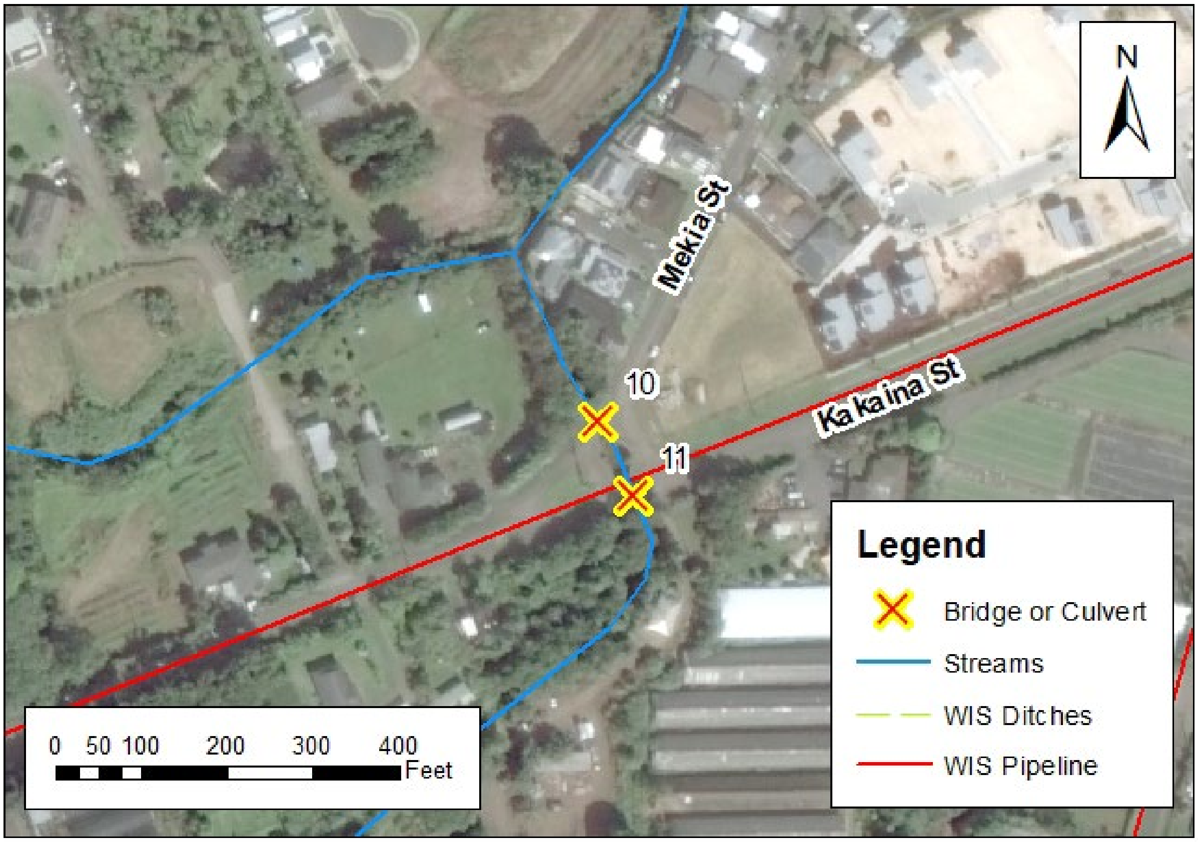
*Above: Looking at the downstream face of Mahailua St Culvert 1*

*Above: Looking downstream from Mahailua St Culvert 1*

# 10 Mekia St Culvert 1

**Stream**: Kahawai Stream (Stream B), Waimānalo Watershed

**Road**: Mekia St near Kakaina St intersection




**Coordinates**: 157.7263407°W 21.3435367°N

**Field Notes**: Arch culvert. 127 inches wide. 100 inches high. Deck thickness = 65 inches.

*Above: Looking at the upstream face of Mekia St Culvert 1*

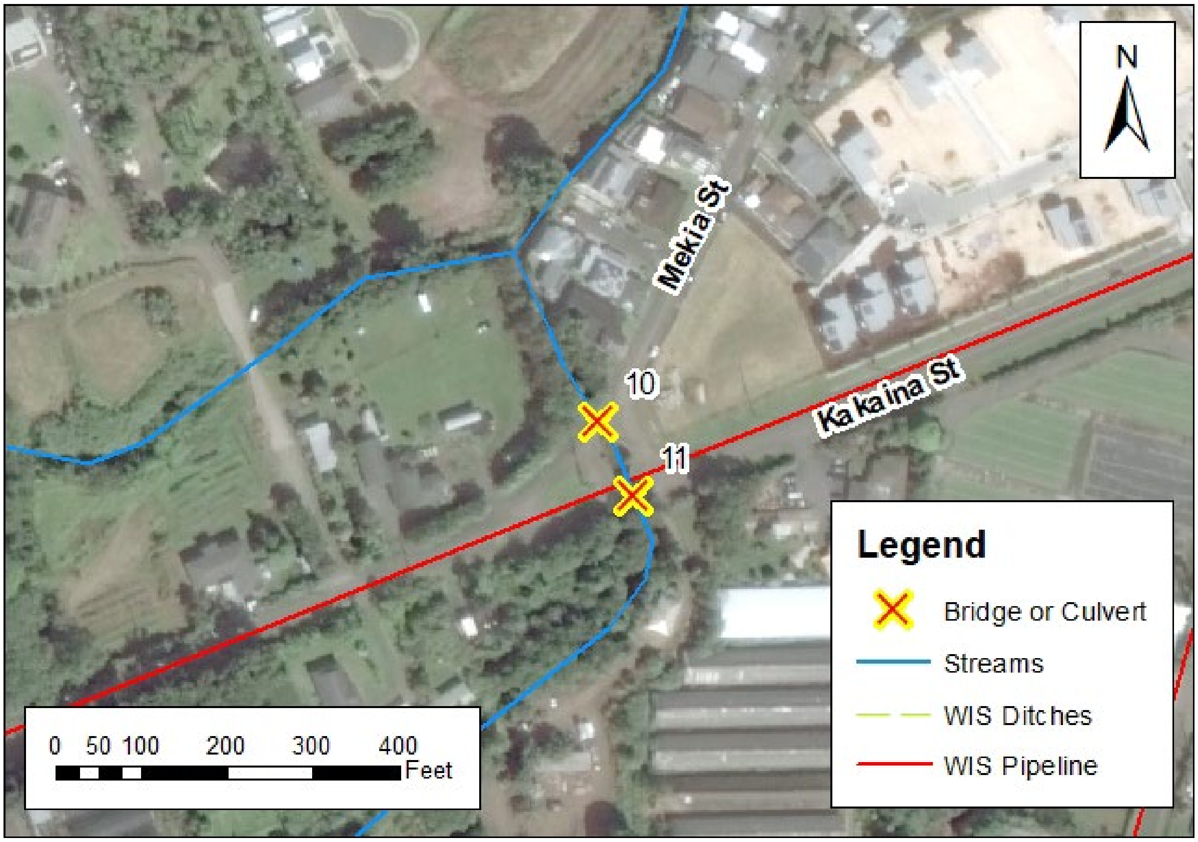
*Above: Looking through the Mekia St Culvert 1*

*Above: Looking at the downstream channel from Mekia St Culvert 1*

# 11 Kakaina St Culvert 1

**Stream**: Kahawai Stream (Stream B), Waimānalo Watershed

**Road**: Kakaina St near Mekia St intersection




**Coordinates**: 157.7262185°W 21.3432957°N

**Field Notes**: Double barrel box culvert. Each culvert is 71 inches by 71 inches. Deck thickness = 53 inches.

*Above: Looking at the upstream channel from Kakaina St Culvert 1*

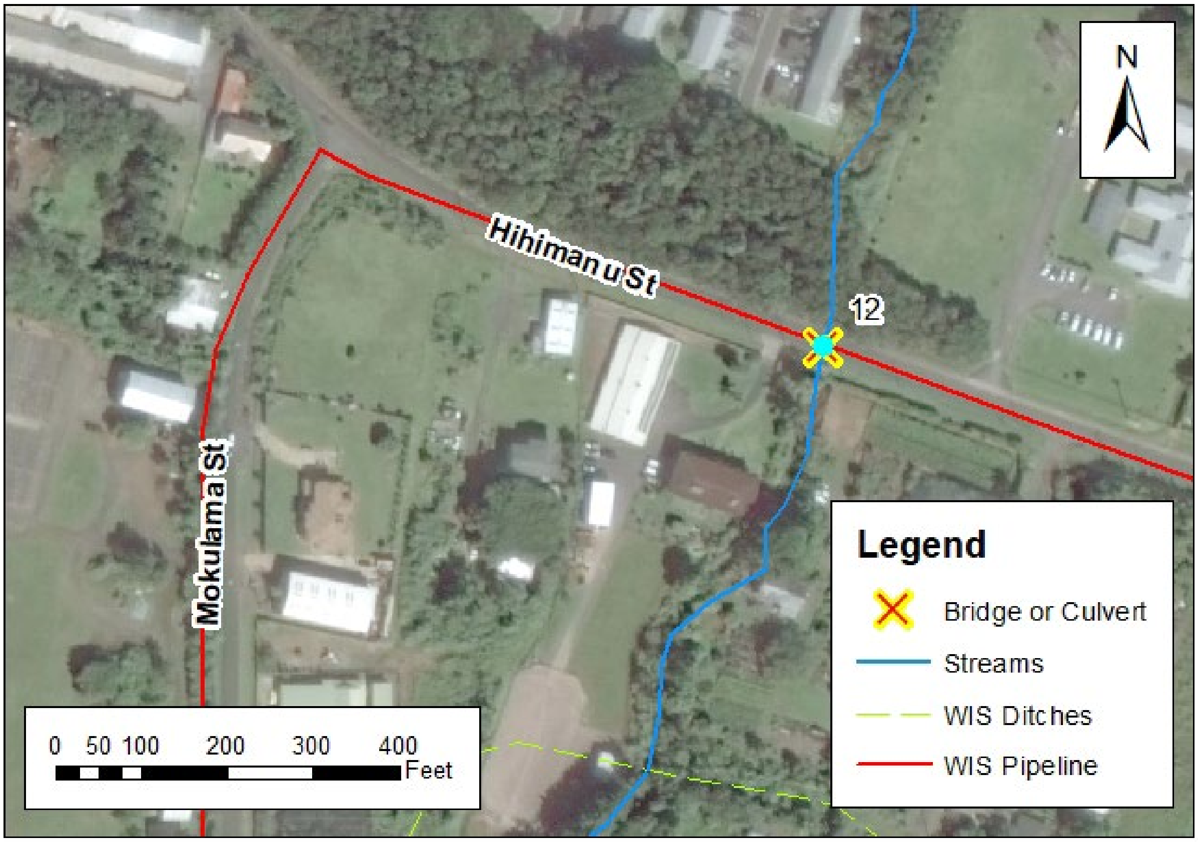
*Above: Looking at the upstream face of Kakaina St Culvert 1*

*Above: Looking at the downstream face of Kakaina St Culvert 1*

# 12 Hihimanu St Culvert 1

**Stream**: Puha (Inoaole) Stream Tributary (Stream C), Kahawai Watershed

**Road**: Hihimanu St between Mokulama St and Ahiki St




**Coordinates**: 157.7199147°W 21.3427519°N

**Field Notes**: Two 24-inch concrete pipes. Pier width ~16 inches.

*Above: Looking at Hihimanu St*

*Above: Looking at the downstream face of Hihimanu St Culvert 1*

*Above: Looking at the downstream channel from Hihimanu St Culvert 1*

# 13 Hihimanu St Culvert 2

**Stream**: Puha (Inoaole) Stream Tributary (Stream D), Kahawai Watershed

**Road**: Hihimanu St near Ahiki St


**Coordinates**: 157.7140325°W 21.3407915°N

**Field Notes**: Two CMPs. CMP width = 48 inches. CMP height = 39 inches. Deck thickness = 22 inches.

*Above: Looking at the upstream channel from Hihimanu St Culvert 2*

*Above: Looking at the upstream face of Hihimanu St Culvert 2*

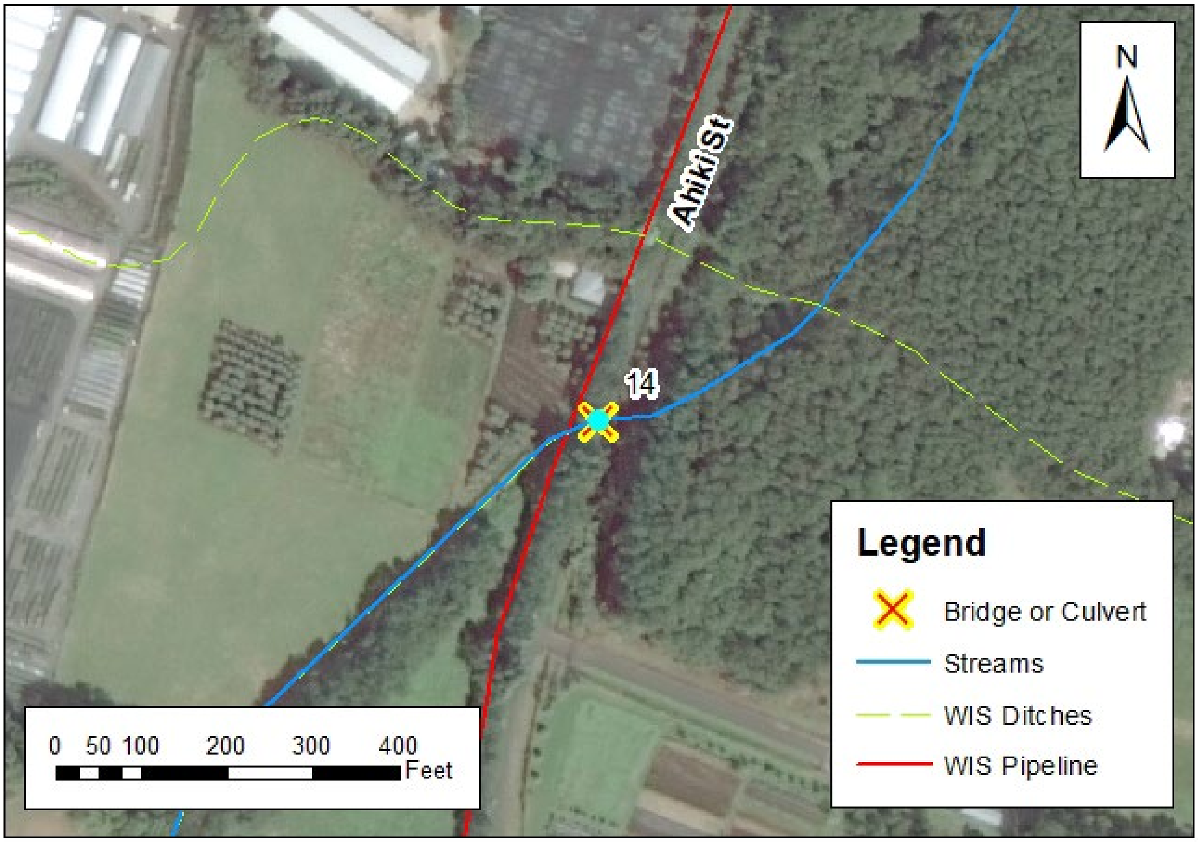
*Above: Looking at Hihimanu St*

*Above: Looking at the downstream channel from Hihimanu St Culvert 2*

# 14 Ahiki St Culvert 1

**Stream**: Puha (Inoaole) Stream Tributary (Stream D), Kahawai Watershed

**Road**: Ahiki St between Hihimanu St and Makakalo St




**Coordinates**: 157.7157917°W 21.3389565°N

**Field Notes**: Three box culverts. Each culvert = 70 inches wide, 22 inches high. Pier width = 7 inches. Deck thickness = 23 inches.

**National Bridge Inventory Data**: AHIKI ST over AHIKI ST/4 CELL RCS #2[6]:

Length of largest span: 5.9 ft

Total length: 24.0 ft

Deck width edge-to-edge: 37.1 ft

Skew angle: 39°

Number of main spans: 4

[6] http://bridgereports.com/1105766

*Above: Looking at the upstream channel from Ahiki St Culvert 1*

*Above: Looking at the upstream face of Ahiki St Culvert 1*

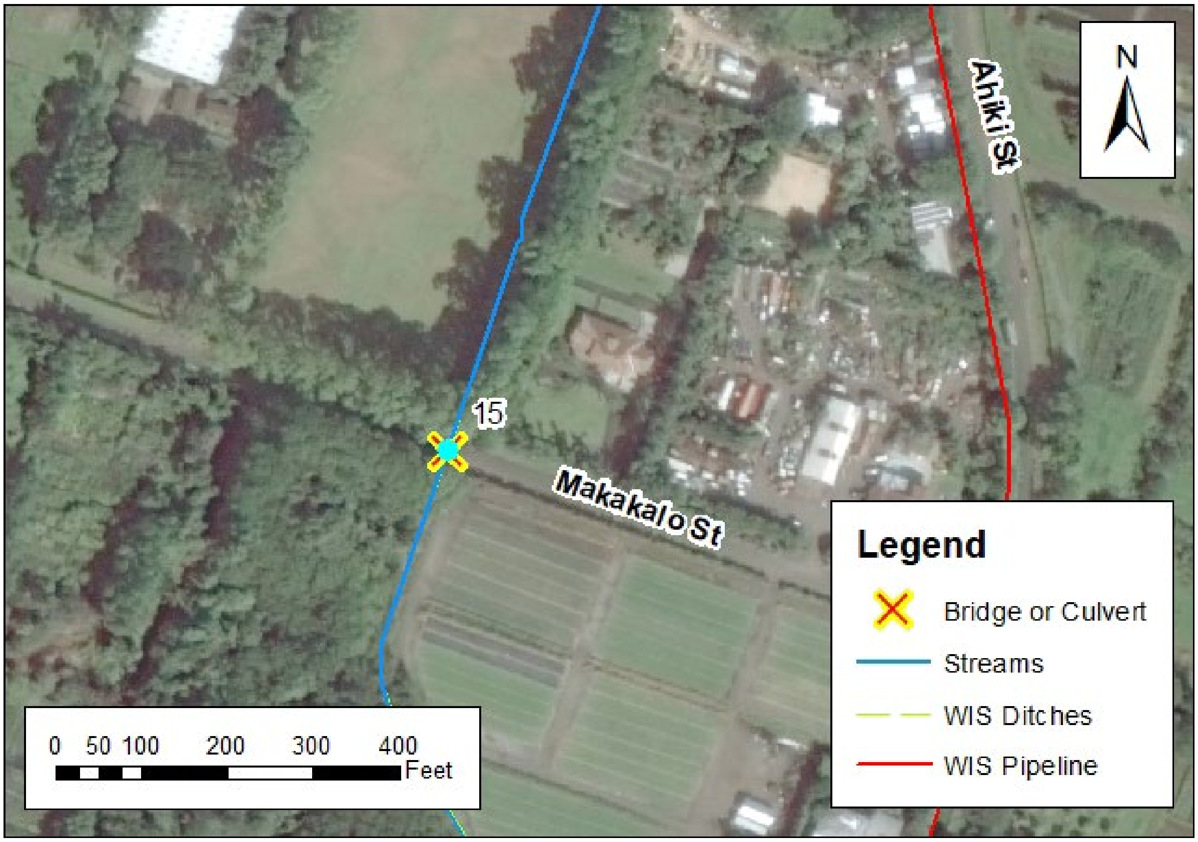
*Above: Looking through Ahiki St Culvert 1*

*Above: Looking at the downstream channel from Ahiki St Culvert 1*

# 15 Makakalo St Culvert 1

**Stream**: Puha (Inoaole) Stream Tributary (Stream D), Kahawai Watershed

**Road**: Makakalo St between Ahiki St and Mokulama St




**Coordinates**: 157.7178958°W 21.3359027°N

**Field Notes**: Four box culverts. Total horizontal width = 26 ft. Each culvert is ~3.1 ft tall, 5.5 ft wide. Upstream pilot channel is ~4.5 ft wide, 1.5 ft deep.

**National Bridge Inventory Data**: MAKAKALO ST. over MAKAKALO ST/4 CELL RCB[7]:

Length of largest span: 5.9 ft

Total length: 24.0 ft

Deck width edge-to-edge: 44.0 ft

Number of main spans: 4

Main spans design: Culvert

[7] http://bridgereports.com/1105754

*Above: Looking at the upstream channel from Makakalo St Culvert 1*

*Above: Looking at the upstream face of the Makakalo St Culvert 1*

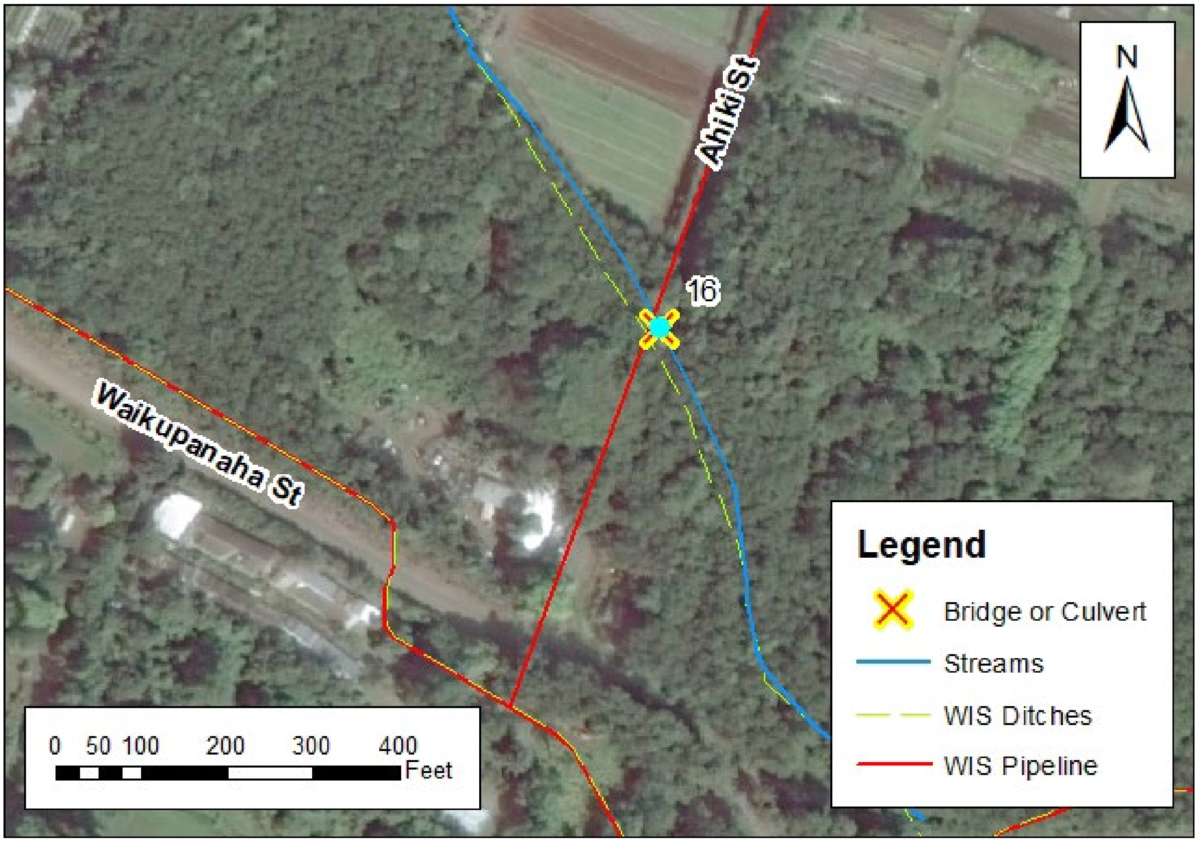

*Above: Looking at the downstream face of Makakalo St Culvert 1*

*Above: Looking at the downstream channel from Makakalo St Culvert 1*

# 16 Ahiki St Culvert 2

**Stream**: Puha (Inoaole) Stream Tributary (Stream D), Kahawai Watershed

**Road**: Ahiki St between Makakalo St and Waikupanaha St




**Coordinates**: 157.7168004°W 21.3331328°N

**Field Notes**: Four box culverts. Each culvert ~87 inches wide, ~40 inches high. Pier width is 8 inches.

**National Bridge Inventory Data**: AHIKI ST over AHIKI ST/DRAINAGE DITCH[8]:

- Length of largest span: 4.9 ft
- Total length: 24.0 ft
- Deck width edge-to-edge: 45.6 ft
- Skew angle: 29°
- Number of main spans: 4

[8] http://bridgereports.com/1105765

*Above: Looking at the upstream channel from Ahiki St Culvert 2*

*Above: Looking through the Ahiki St Culvert 2*

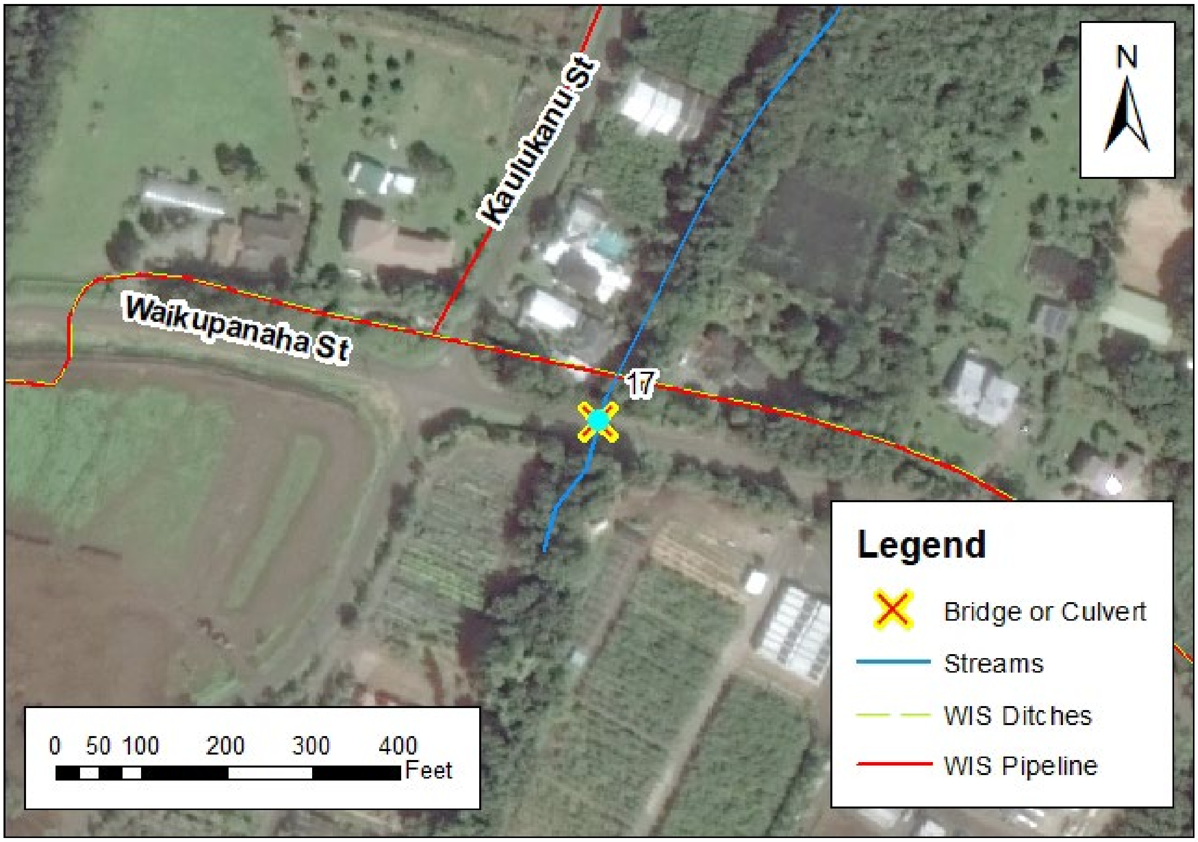
*Above: Looking at the downstream face of Ahiki St Culvert 2*

*Above: Looking at the downstream channel from Ahiki St Culvert 2*

# 17 Waikupanaha St Culvert 3

**Stream**: Puha (Inoaole) Stream Tributary (Stream C), Kahawai Watershed

**Road**: Waikupanaha St between Kaulukanu St and Mokulama St




**Coordinates**: 157.7260802°W 21.3357644°N

**Field Notes**: 9 ft by 9 ft box culvert

*Above: Looking at the upstream channel from Waikupanaha St Culvert 3*

*Above: Looking at the upstream face of Waikupanaha St Culvert 3*

*Above: Looking at Waikupanaha St*

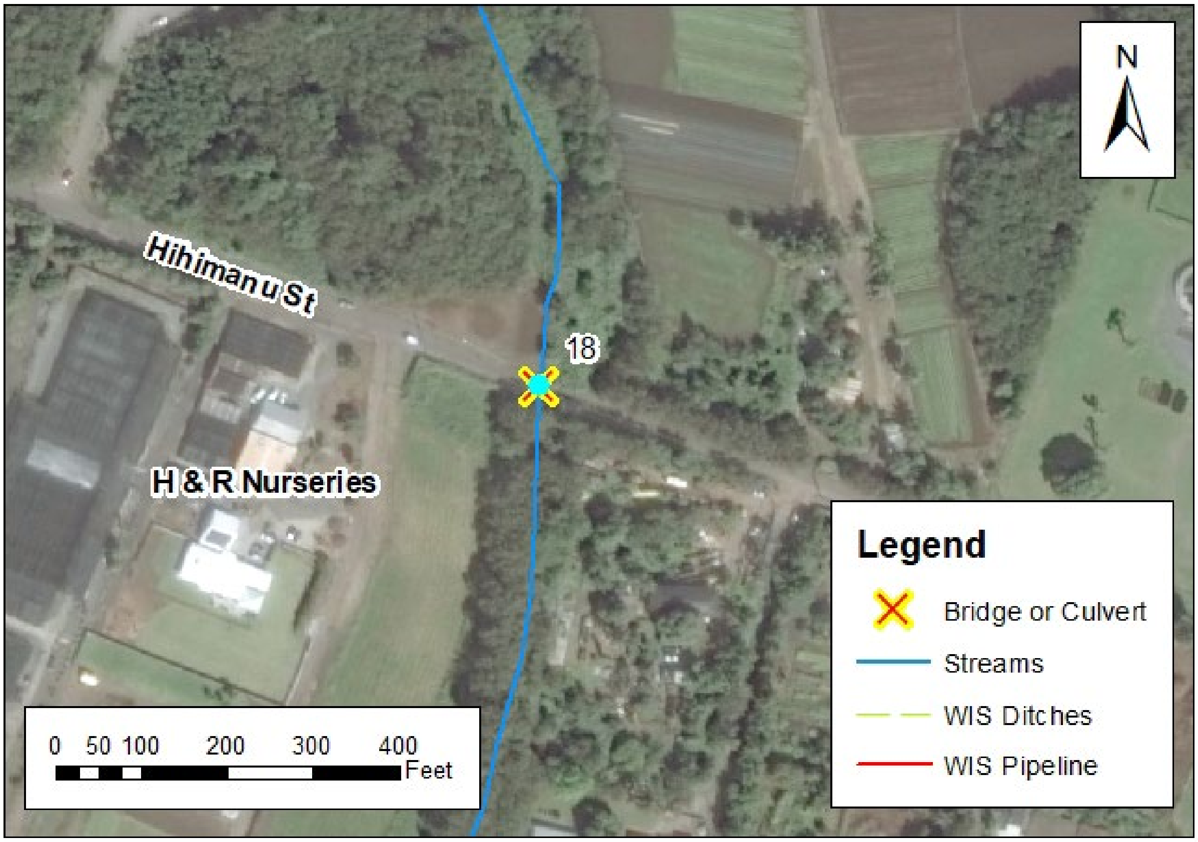
*Above: Looking at the downstream face of Waikupanaha St Culvert 3*

*Above: Looking at the downstream channel from Waikupanaha St*

# 18 Hihimanu St Bridge 1

**Stream**: Puha (Inoaole) Stream, Kahawai Watershed

**Road**: Hihimanu St between Nono Kio St and Waikupanaha St




**Coordinates**: 157.7083380°W 21.3388412°N

**Field Notes**: Bridge with horizontal span of ~155 inches, vertical span of ~30 inches, and deck thickness ~22 inches.

*Above: Looking at the upstream channel from Hihimanu St Bridge 1*

*Above: Looking at the upstream face of Hihimanu St Bridge 1*

*Above: Looking at the Hihimanu St bridge*

*Above: Looking at the downstream face of Hihimanu St Bridge 1*

*Above: Looking at the downstream channel from Hihimanu St Bridge 1*

# 19 Kalaniana‘ole Hwy Bridge 3

**Stream**: Unnamed Stream, Kaiona Watershed

**Road**: Kalaniana‘ole Highway between Huli St and Nalu St


**Coordinates**: 157.6915176°W 21.3295417°N

**Field Notes**:

**National Bridge Inventory Data**: KAL HWY WAIMANALO over 30x10 RCB CULVT[9]:

Length of largest span: 33.1 ft

Total length: 71.9 ft

Deck width edge-to-edge: 72.5 ft

Main spans design: Culvert

[9] http://bridgereports.com/1105216

*Above: Looking at the upstream channel from Kalaniana'ole Hwy Bridge 3*

*Above: Looking at the upstream face of Kalaniana'ole Hwy Bridge 3*

# 20 Huli St Bridge 1

**Stream**: Unnamed Stream, Kaiona Watershed

**Road**: Huli St between Ala Koa St and Kalaniana'ole Hwy


**Coordinates**: 157.6931352°W 21.3292430°N

**Field Notes**: Bridge with horizontal span of ~31 ft 8 inches, vertical span ~8 ft. Upstream deck thickness ~5 ft 10 inches; downstream deck thickness ~5 ft.

**National Bridge Inventory Data**: HULI STREET over WAIMANALO DRAINAGE CNL[10]:

Length of largest span: 29.9 ft

Total length: 33.1 ft

Deck width edge-to-edge: 56.1 ft

Skew angle: 90°

Main spans design: Culvert

---

[10] http://bridgereports.com/1105770

*Above: Looking at the upstream channel from Huli St Bridge 1*

*Above: Looking at the upstream face of Huli St Bridge 1*

*Above: Looking at the downstream channel from Huli St Bridge 1*

# 21 Ala Koa St Bridge 1

**Stream**: Unnamed Stream, Kaiona Watershed

**Road**: Pedestrian Bridge off Ala Koa Street and near Blanche Pope Elementary School


**Coordinates**: 157.6947263°W 21.3295266°N

**Field Notes**: Bridge with horizontal span ~285 inches. Deck thickness ~2 ft.

*Above: Looking at the upstream channel from Ala Koa St Bridge 1*

*Above: Looking at the downstream face of Ala Koa St Bridge 1*

*Above: Looking at the downstream channel from Ala Koa St Bridge 1*

# 22 Nakini St Bridge 1

**Stream**: Unnamed Stream, Kaiona Watershed

**Road**: Nakini St between Kauholokahiki St and Huli St


**Coordinates**: 157.6967987°W 21.3291372°N

**Field Notes**: Bridge with horizontal span ~20 ft, vertical span ~6 ft, 5 inches, deck thickness ~5 ft, 7 inches.

**National Bridge Inventory Data**: NAKINI STREET over MULIWAI OLENA CHANNEL[11]:

Length of largest span: 20.0 ft

Total length: 21.0 ft

Deck width edge-to-edge: 42.0 ft

Main spans design: Slab

[11] http://bridgereports.com/1105767

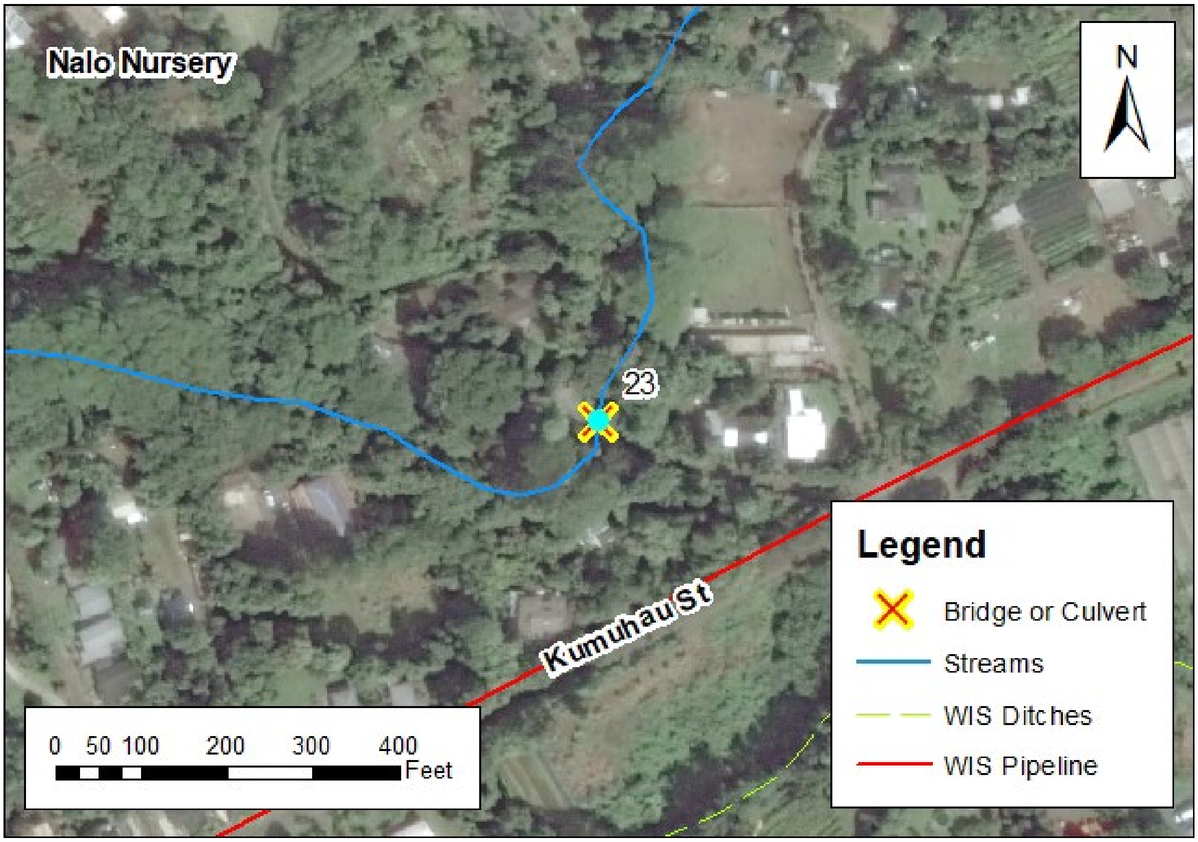
*Above: Looking at the upstream channel from Nakini St Bridge 1*

*Above: Looking at the downstream channel from Nakini St Bridge 1*

# 23 Kumuhau St Bridge 1

**Stream**: Waimānalo Stream, Waimānalo Watershed

**Road**: Private road off Kumuhau St




**Coordinates**: 157.7345168°W 21.3459259°N

**Field Notes**: Bridge with unknown horizontal span. Vertical span ~100 inches, deck width ~190 inches.

**National Bridge Inventory Data**: KUMUHAU ST. over WAIMANALO STREAM[12]

Length of largest span: 29.9 ft

Total length: 30.8 ft

Deck width edge-to-edge: 15.7 ft

Main span design: Stringer/Multi-beam or girder

[12] http://bridgereports.com/1105764

*Above: Looking at the upstream channel from Kumuhau St Bridge 1*

*Above: Looking at the upstream face of Kumuhau St Bridge 1*

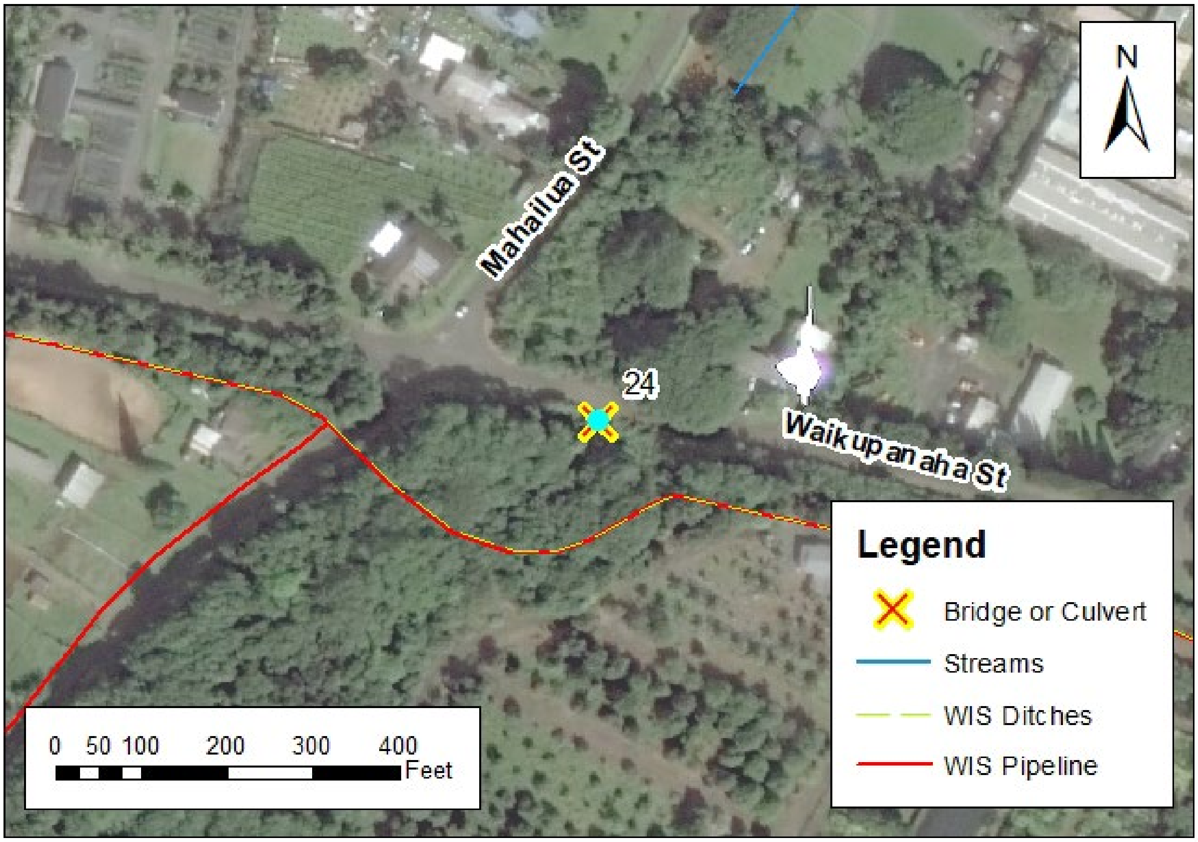

*Above: Looking at the downstream face of Kumuhau St Bridge 1*

*Above: Looking at the downstream channel from Kumuhau St Bridge 1*

# 24 Waikupanaha St Culvert 3

**Stream**: Kahawai Stream Tributary (Stream B), Waimānalo Watershed

**Road**: Waikupanaha St between Mahailua St and Mooiki St




**Coordinates**: 157.7316750°W 21.3369389°N

**Field Notes**: Box culvert with horizontal span ~131 inches, vertical span ~71 inches, ~1 ft debris.

*Above: Looking at the upstream channel from Waikupanaha St Culvert 3*

*Above: Looking at the upstream face of Waikupanaha St Culvert 3*

*Above: Looking through Waikupanaha St Culvert 3*

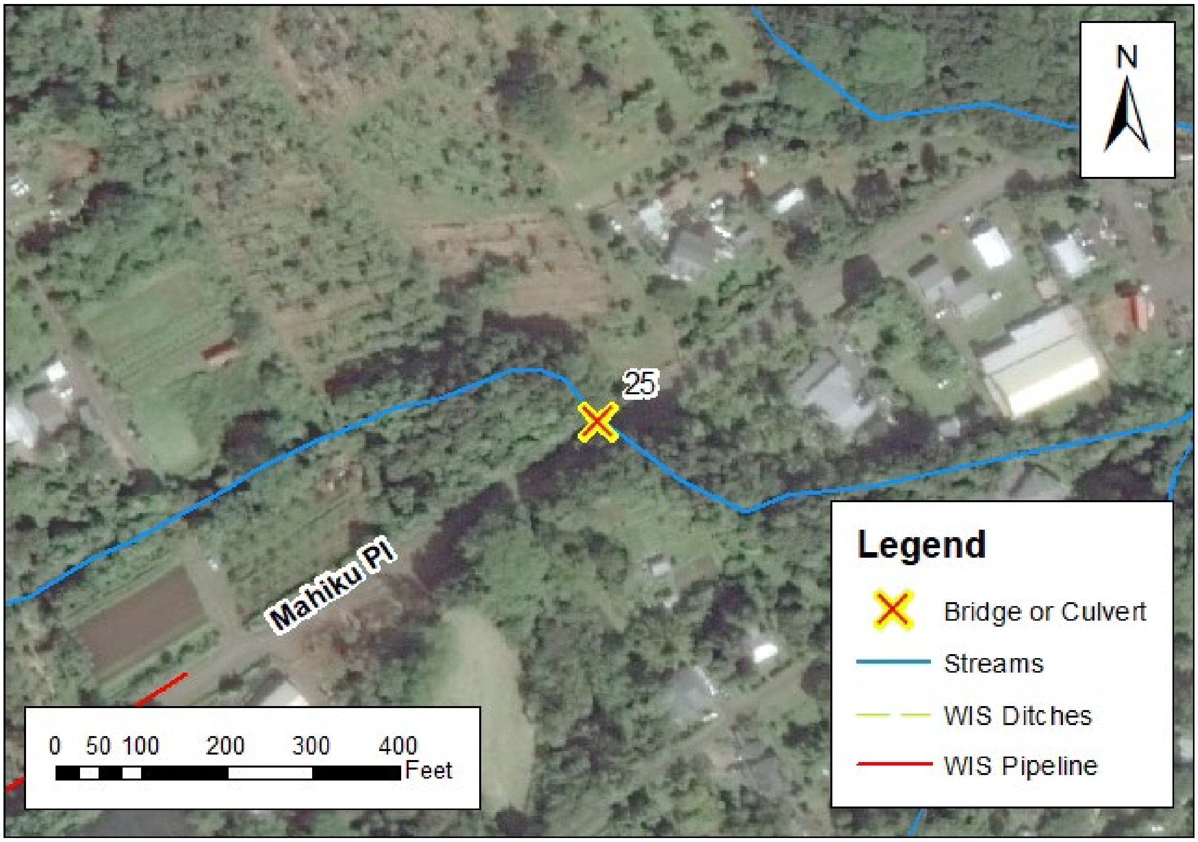
*Above: Looking at the downstream face of Waikupanaha St Culvert 3*

*Above: Looking at the downstream channel from Waikupanaha St Culvert 3*

# 25 Mahiku Pl Culvert 1

**Stream**: Tributary to Waimānalo Stream, Waimānalo Watershed

**Road**: Mahiku Pl




**Coordinates**: 157.7353788°W 21.3483799°N

**Field Notes**: Bridge with two box culverts. Left bank opening ~22 ft. Vertical span of opening is ~6.1 ft. Deck thickness ~7.9 inches. Total horizontal span is ~43 ft.

**National Bridge Inventory Data**: MAHIKU PL over WAIMANALO STRM[13]

Length of largest span: 44.0 ft

Total length: 44.0 ft

Deck width edge-to-edge: 44.6 ft

Main span design: Culvert

[13] http://bridgereports.com/1105752

*Above: Looking upstream from Mahiku Pl Culvert 1*

*Above: Looking at the left bank opening of Mahiku Pl Culvert 1*

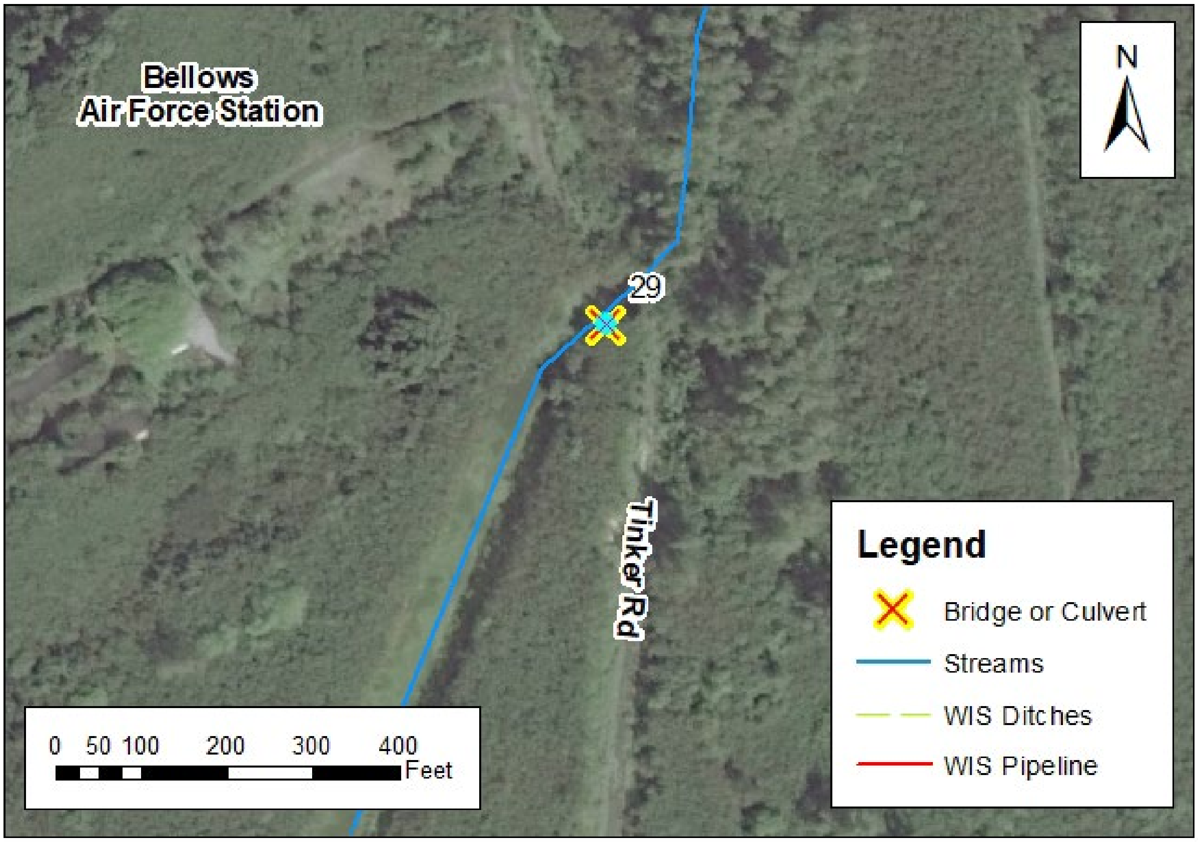
*Above: Looking at the right bank opening of Mahiku Pl Culvert 1*

*Above: Looking at the downstream channel from Mahiku Pl Culvert 1*

# 29 Tinker Rd Bridge 2

**Stream**: Puha (Inoaole) Stream, Kahawai Watershed

**Road**: Tinker Rd, Bellows Air Force Station




**Coordinates**: 157.7206800°W 21.3477536°N

**Field Notes**: Not likely to impact flows (high elevation)

*Above: Looking at downstream towards Tinker Rd Bridge 2*

*Above: Looking at downstream towards Tinker Rd Bridge 2 (zoomed in)*

# 30 Kalaniana‘ole Hwy Culvert 2

**Stream**: Puha (Inoaole) Stream Tributary, Kahawai Watershed

**Road**: Kalaniana‘ole Hwy east of Poalimi St


**Coordinates**: 157.7206800°W 21.3477536°N

**Field Notes**: 4 ft diameter culvert. 3 ft culvert headwall. 6 ft from top of culvert headwall to top of highway wall.

*Above: Looking at the upstream channel from Kalaniana'ole Hwy Culvert 2*

*Above: Looking at the upstream face of Kalaniana'ole Hwy Culvert 2*

# 32 Kakaina St Culvert 2

**Stream**: Puha (Inoaole) Stream Tributary, Kahawai Watershed

**Road**: Kakaina St between Hihimanu St and Haleiki Pl


**Coordinates**: 157.7219579°W 21.3447994°N

**Field Notes**: Box culvert with horizontal span of ~12 ft and vertical span of ~5 ft. Downstream channel ~22 ft wide.

*Above: Looking at the upstream "channel" / detention area from Kakaina St Culvert 2*

*Above: Looking at the upstream face of Kakaina St Culvert 2*


*Above: Looking through Kakaina St Culvert 2*

*Above: Looking downstream from Kakaina St (headwall does not tie into high ground)*

*Above: Looking at the area immediately downstream from Kakaina St Culvert 2*

*Above: Looking at the downstream channel from Kakaina St Culvert 2*

# 34 Kalanianaʻole Hwy Culvert 3

**Stream**: Waimānalo Stream Tributary, Waimānalo Watershed

**Road**: Kalanianaʻole Hwy west of Kumuhau St


**Coordinates**: 157.7260500°W 21.3488422°N

**Field Notes**: ~67-inch diameter culvert[14]. Deck thickness ~ 4.2 ft.

[14] Field measurement. Typical culvert diameters are 60-inches and 72 inches. Possibly interior diameter is ~60 inches.

*Above: Looking at the upstream channel from Kalaniana'ole Hwy Culvert 3*

*Above: Looking at the upstream face of Kalaniana'ole Hwy Culvert 3*

# 35 Saddle City Rd Bridge 1

**Stream**: Waimānalo Stream Tributary, Waimānalo Watershed

**Road**: Saddle City Rd


**Coordinates**: 157.7239448°W 21.3529569°N

**Field Notes**: Bridge with deck thickness = 1 ft; horizontal span = 42 ft; vertical span = 10 ft.

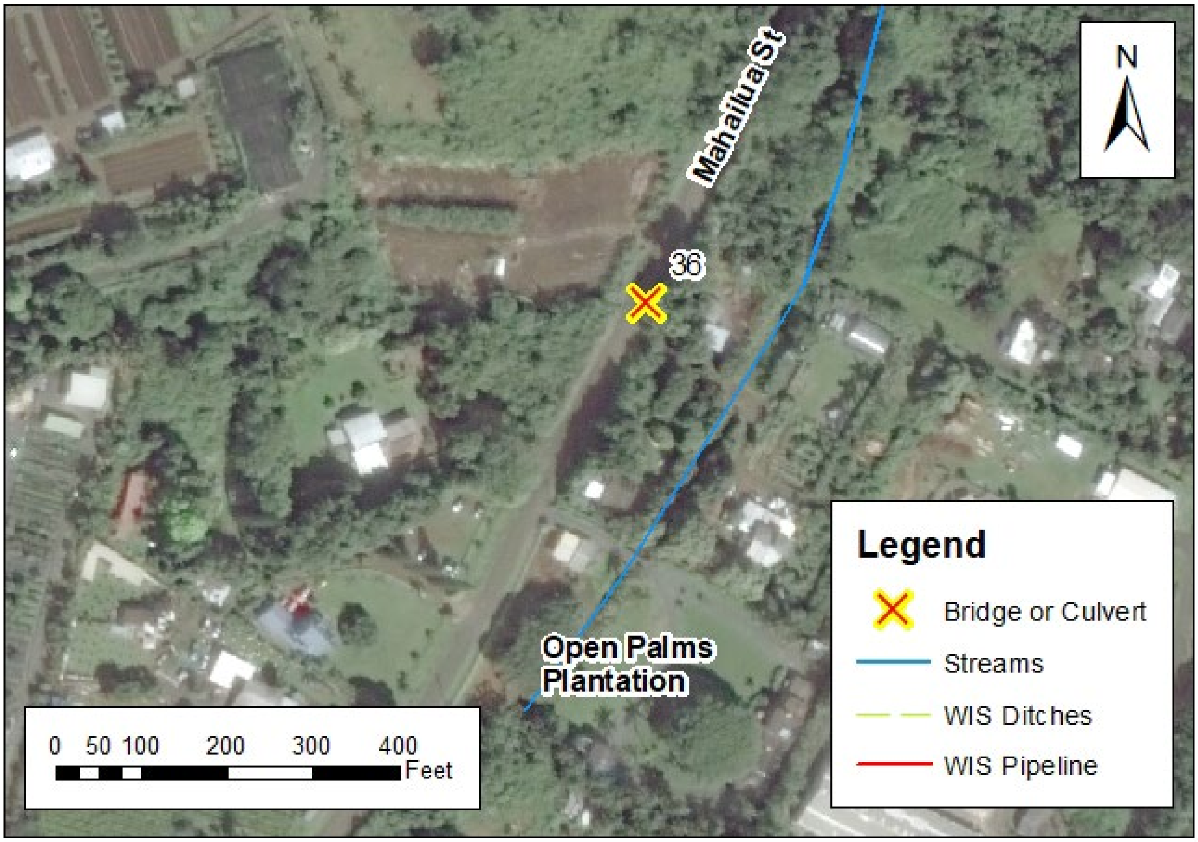
*Above: Looking upstream from Saddle City Rd Bridge 1*

*Above: Looking downstream at Saddle City Rd Bridge 1 from the right bank*

# 36 Mahailua St Culvert 2

**Stream**: Tributary to Kahawai Stream Tributary (Stream B), Waimānalo Watershed

**Road**: Mahailua St between Kakaina St and Waikupanha St




**Coordinates**: 157.7307852°W 21.3393080°N

**Field Notes**: Culvert with horizontal width ~13.5 ft, vertical span ~5 ft, deck thickness ~2 ft.

*Above: Looking at the upstream channel from Mahailua St Culvert 2*

*Above: Looking at Mahailua St*

*Above: Looking at the downstream face of Mahailua St Culvert 2*

# 37 Unnamed Rd Culvert 1

**Stream**: Tributary to Puha (Inoaole) Stream, Kahawai Watershed

**Road**: Unnamed Road between Inoaole Street and Waimānalo District Park


**Coordinates**: 157.7141745°W 21.3436887°N

**Field Notes**: Occupied by homeless.

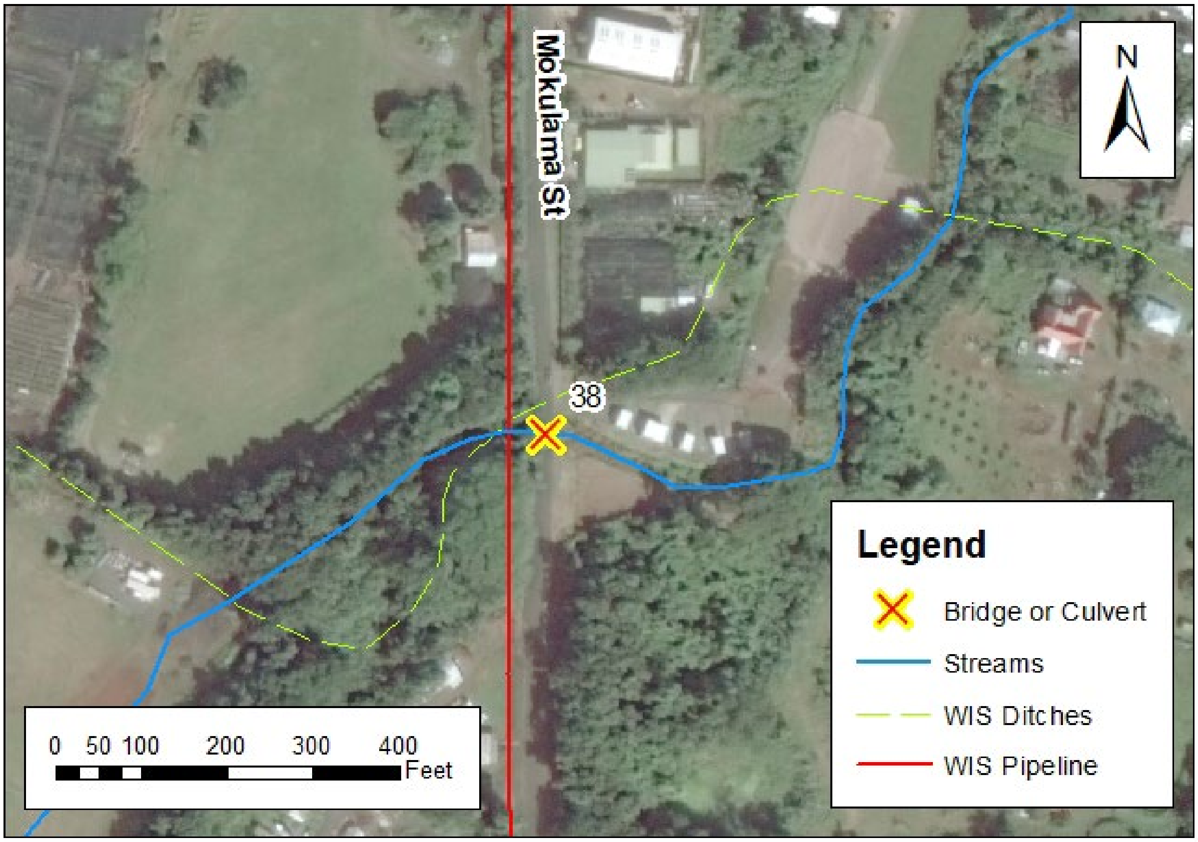

Source: Google Earth (2011)

*Above: Looking North towards Unnamed Rd Culvert 1*

# 38 Mokulama St Culvert 1

**Stream**: Tributary to Puha (Inoaole) Stream (Stream C), Kahawai Watershed

**Road**: Mokulama St




**Coordinates**: 157.7218971°W 21.3406915°N

**Field Notes**: Concrete box culvert opening field measurements: 4 feet high by 11 feet wide upstream; 5 feet high by 9 ft wide downstream. Deck thickness = 3 ft upstream; 3.5 ft downstream.

*Above: Looking at the upstream face of Mokulama St Culvert 1*

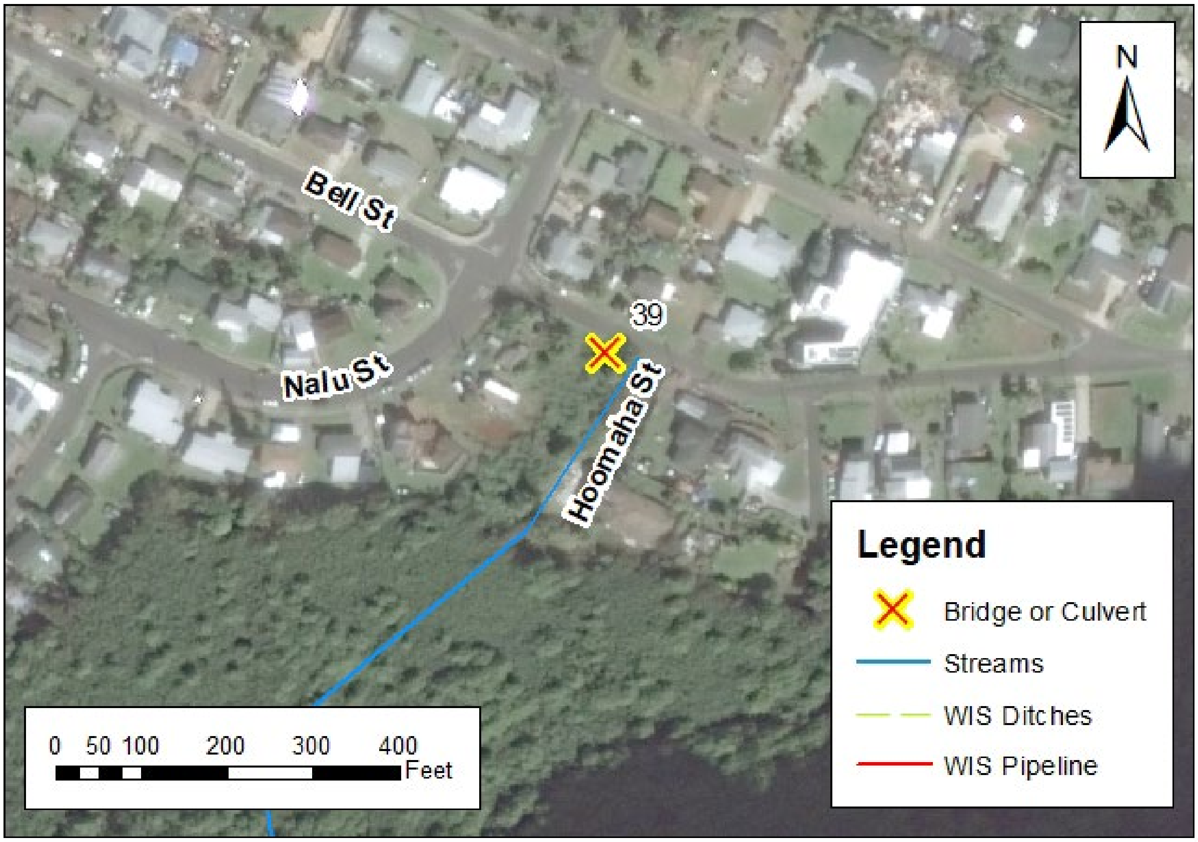
*Above: Looking at the downstream face of Mokulama St Culvert 1*

*Above: Looking at the channel downstream from Mokulama St Culvert 1*

# 39 Bell St Culvert 1

**Stream**: Unnamed Stream, Unnamed Watershed

**Road**: Bell Street near Hoomaha Street




**Coordinates**: 157.6893°W 21.32631°N

**Field Notes**: None

*Above: Looking upstream (South) from Bell Street at the highly vegetated channel*

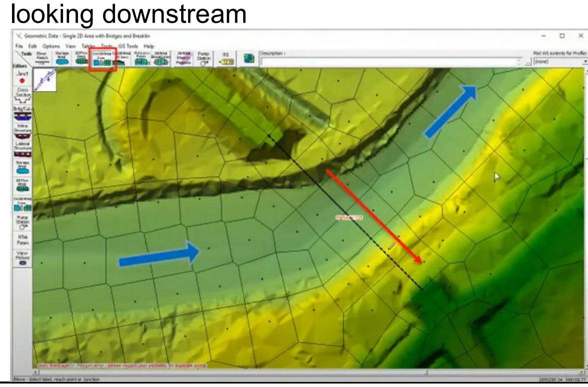
*Above: Looking southwest towards the vegetated channel from Hoomaha St*

# Appendix E

## Review

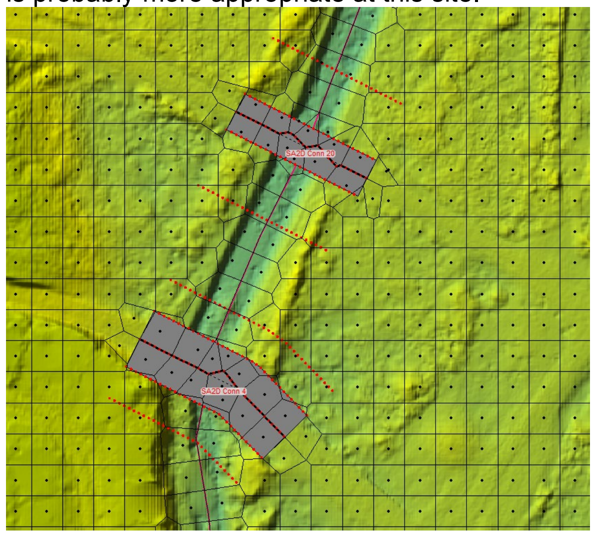
# REVIEW COMMENTS

| | | | | |
|---|---|---|---|---|
| REVIEW COMMENTS | DATE: 3 October 2022 | REVIEW OFFICE: CEPOH | REVIEWER: Jessica Brunty | |
| Study<br>Waimānalo Flood Hazard Study | LOCATION: | JOB/REQ No: | | |
| | | A/E: | | |
| PROJECT PHASE: Hydraulics | | | | |

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | BACKCHECK |
|---|---|---|---|---|---|
| 1 | pg. viii | Acronyms & Abbreviations | This section needs to be updated / include only those acroynms in this appendix | Updated | JB |
| 2 | Section 2.2.2 | Manning's Rougness Coefficient | Photos and description were not updated. Update formatting. | Updated | JB |
| 3 | Section 2.2.3 | Bridges | Include figure showing bridges in the area. Assign each bridge an ID. Rename HEC-RAS Bridge with reference to ID and Road Name (instead of generic "SA2D Conn 8") | Bridges and culverts identified and described in Appendix D | JB |
| 4 | Table 8-7 | HEC-RAS Bridge Information | Only 19 of 34 bridge/culvert crossings represented in the table. Add information for all bridges. Add photos and description for each bridge. | All bridges included and identified in Appendix D | JB |
| 5 | RAS Model | SA/2D Connections | When SA/2D Connections are used to represent bridges, it needs to be drawn from left to right looking downstream  | Corrected | JB |
| 6 | RAS Model | SA/2D Connections | Once the SA/2D Area Conn centerline is drawn, edit the internal cell spacing (if needed) and enforce the internal connection as a breakline (done in Geometry Editor, not RAS Mapper) | Revised | JB |
| 7 | RAS Model | SA/2D Connections | Verify the appropriate structure type is selected (Bridge for Bridges / Culvert for Culverts) | Revised | JB |

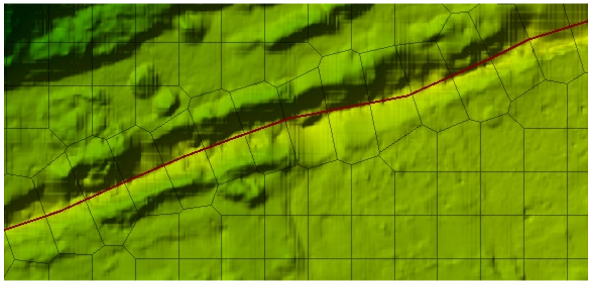
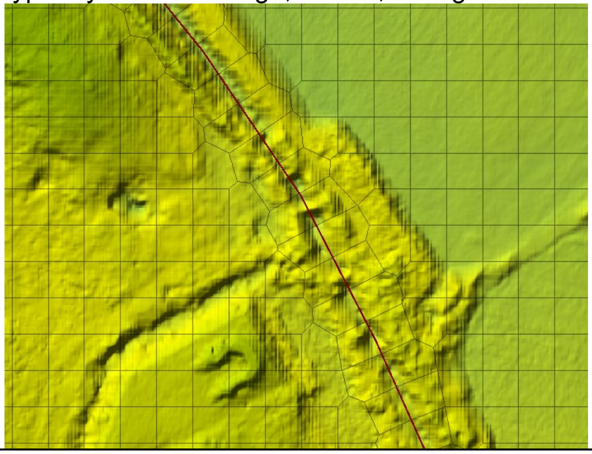
# POD REVIEW COMMENTS

| DATE: | REVIEW AGENCY: | REVIEWER: |
| --- | --- | --- |
| | CEPOD-CW-P | |

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | |
| --- | --- | --- | --- | --- | --- |
| 8 | RAS Model | Bridge Culvert Data | Deck/Roadway distance should be the approximate distance between the US bridge deck and toe of the US embankment. RAS creates US and DS cross-sections for bridge computations based on this distance, represented by the red dotted line (see figure below). 50 ft was used in the model, but ~20-30 ft is probably more appropriate at this site.<br><br>Reference:<br>https://www.youtube.com/watch?v=6qIL3U7gJlo | Revised | JB |

# POD REVIEW COMMENTS

| DATE: | REVIEW AGENCY: CEPOD-CW-P | REVIEWER: |
|---|---|---|

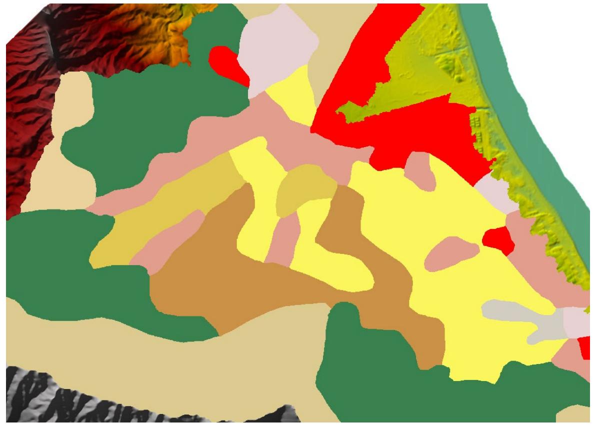
| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | |
|---|---|---|---|---|---|
| 9 | RAS Model | Cell Alignment / Break Lines | A break line was used to align cells along the stream centerline (great!). In some cases, it might also be necessary to add break lines to the banks (where there is high ground or an elevated embankment). If a cell extends from the stream invert (low point) to beyond the top of bank (high ground) and into the lower, landward ground elevation, the system does not recognize the top of bank as a barrier to flow.  Reference: https://www.youtube.com/watch?v=EsG8d248nSg | | |
| 10 | RAS Model | Terrain | The LiDAR terrain shows some obstructions in the channel that should be removed using the channel modification tool in RAS Mapper. This is typically due to a bridge, culvert, or vegetation.  | | |

# POD REVIEW COMMENTS

DATE:

REVIEW AGENCY: CEPOD-CW-P

REVIEWER:

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION |
|---|---|---|---|---|
| 11 | RAS Model | Land Cover | The land cover raster to create the Manning's n layer is too simple. Use the 2011 high resolution land cover raster from the MRLC NLC Database.<br><br>Reference: https://www.mrlc.gov/data/noaa-2011-high-resolution-land-cover-hawaii-0 | |
| 12 | RAS Model | Boundary Condition | Move the DS BC line representing the ocean a little farther out from the shoreline to allow for | |
| 13 | RAS Model | Boundary Condition | For each flow hydrograph, an EG Slope for distributing flow along BC Line is required. Use the measure distance tool in RAS Mapper to get the approximate slope of the stream invert just upstream of the BC line. Enter a positive slope (e.g. 0.421) unique to each BC line. | |
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# REVIEW COMMENTS

| | | | | |
|---|---|---|---|---|
| REVIEW COMMENTS | DATE: 3 November 2022 | REVIEW OFFICE: CENWS | REVIEWER: Tilak Gamage | |
| Study: Waimānalo Flood Hazard Study | LOCATION: | JOB/REQ No: | | |
| | | A/E: | | |
| PROJECT PHASE: Hydraulics | | | | |

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | BACKCHECK |
|---|---|---|---|---|---|
| 1 | RAS Model | Breaklines | As we know, DEM is not perfect and there may be ground features of importance that are not represented in the DEM. Please add breaklines to represent them, if any. | Additional break lines have been added to adjust cell alignment along stream banks, roads, and other high ground elements. | JB |
| 2 | RAS Model | Levees | I have noticed some levees exist. Please add breaklines and correct for elevations, because it is important to have an idea about the level of protection levees provide although study scope does not intend to do levee assessment. | There are no levees in the study area. Small embankments / natural high ground of 1-3 ft is typical. Break lines will be added to these features. | JB |
| 3 | RAS Model | Channels | We have channels with clear sectional data. Because we do not use 1D for those channels, please make sure cell sizes are adjusted according to channels sections. It is hard for me to find where exactly those channels segments are. I see pictures with heavily weeded channel segments which require n value adjustments. | Cell alignment and spacing will be adjusted along the streams. The Manning's n layer will be modified to represent channel roughness coefficients. | JB |
| 4 | RAS Model | Validation of Sensitivity Analysis | Now we have a calibrated model, it should be tested for validation for known event and check against observed data and information. Anything that helps judge model predicts real life scenarios. I suggest we do sensitivity analysis by changing n value +/- by 10% to see if the model behaves correctly. | Yes, a sensitivity test will be conducted after all modeling issue resolved / all comments addressed. | JB |
| 5 | RAS Model | Mud and Debris Flow | The report indicates some flood events brings large amount of mud and debris downstream. Typical FPMS that I know of do not include such analysis. But, this is Hawaii, a different place, and this may be an important thing to check. It is better to run a mud/debris scenario just to check the impact. Ryan Ching has done this type of work for Kuliouou and he may be able to help you set it up. | After the model is complete, a narrative will be written describing the impacts that debris may have on the results and a limited number of tests (i.e. bridge obstructions by vegetation and debris) will be performed. | JB |

# POD REVIEW COMMENTS

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | |
|---|---|---|---|---|---|
| | | | DATE: | REVIEW AGENCY: CEPOD-CW-P | REVIEWER: |
| 6 | Report | Report | Please add few more figures to the report so that the reader find it very useful, such as study area map showing study boundary, stream and important features etc. I would like to see short description of the project at the beginning with study area, critical flood concerns, study scope and expected outcome. Also, add some depth grip maps to the results discussion. I am not sure how the final report looks like. Apparently, H&H reflects in Appendix B and Appendix C. I can expect main part of the report that covers project information, study authority, funding, stakeholders, scope etc. | Concur that more figures should be added. Limited background information added to Section 1 (complete information will be provided in Main Report) | JB |
| 7 | Section 1 | Introduction | It may be better to add a section for study description which basically covers (i) Introduction, scope, existing conditions (ii) Location, available information (iii) Study Approach (iv) Expected results and deliverables etc. If the main report covers these topics, then this information can be condensed to small section with reference to the main body for more details. | Included in main report. | JB |
| 8 | Section 1 | Introduction | This section allows the reviewer to see the project area and features shown in the model. | Included in the main report. | JB |
| 9 | Section 1.4 | Land Cover and Land Use | Suggest to add manning n coefficient map. ArcMap or RAS Mapper can be used to make a map easily | Land cover map figure is provided | JB |
| 10 | Section 2 | Development of the Hydraulic Model | Suggest to add text why 2D was used and why 1D/2D was not considered.<br>Also cell size and number of cells etc | Default cell size is added. There are too many small streams in the study area for 1D/2D. | JB |
| 11 | Section 2.1 | Flow Data | Please add summary of flow data used and refer corresponding section in Appendix B for additional details. | Added | JB |
| 12 | Section 2.1 | Past Significant Flow Events | Add short discussion about past flow events and frequency events considered for the RAS model. Also about calibration and validation events | Flood history added. | JB |
| 13 | Section 2.1.1 | Boundary Conditions | Please explain how hydrograph was split and add a map showing inflow points to the RAS model. Make sure HMS and RAS same reference names for easy use | Described in Section 2.2.1, Boundary Conditions | JB |

# POD REVIEW COMMENTS

| DATE: | REVIEW AGENCY: CEPOD-CW-P | REVIEWER: |
|---|---|---|

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | |
|---|---|---|---|---|---|
| 14 | Section 2.1.1 | Boundary Conditions | Insert table or text where splits are made | It can be viewed in the model, but is not necessary for the report. | JB |
| 15 | Section 2.2 | Geometry Data | Add some details about levees, channel types, conditions and how they are represented in the geometry. It is common to use breaklines to show ground features such as levees, drainage paths that are not clearly visible in the DEM. Expand discussion about how bridges, culverts and drop structures are depicted in the geometry. | Additional geometry data described in Section 2.1. | JB |
| 16 | Table 8-2 | GIS layers created for 2D hydraulic models | Suggest to use breaklines to define channel section with river banks etc. Add manning as appropriate to channel and overbanks. | Breaklines and channel-specific manning's n regions added. | JB |
| 17 | Section 2.2.1 | 2D Flow Area | Add some description why 2D only was used and why particular cell size is best, whether cell refine was done. How channel and ground features were modified with breaklines and cell adjustments etc. | Added | JB |
| 18 | Section 2.2.2 | Manning's Roughness Coefficient, n | Streams and clear conveyance paths require manning coefficients assigned to cells as appropriate. Please make sure this apply for all the streams and canals etc | Added / verified | JB |
| 19 | Table 8-3 | Manning's n values | What is the source of this information? | Reference added (Table 2-1 in the HEC-RAS 2D User's Manual) | JB |
| 20 | Section 2.2.2 | Manning's Roughness Coefficient, n | This might be one of the places where channel banks can be defined with break lines. Having breaklines, specific n values, and perhaps refines cells forced water to flow within these boundaries as channel. (Charleston district used it perfectly in low gradient channel) | Break lines added, as recommended. | JB |
| 21 | Section 2.2.3 | Bridges | Some bridges or crossings were not included because no data available? Not a good approach. We need to collect field data to the best of our ability and add these structures. | Additional bridges added. | JB |
| 22 | Table 8-7 | HEC-RAS Bridge Information | Add names to identify Kalanianaole Bridge etc | In HEC-RAS, a unique bridge ID was added that corresponds with Appendix D. | JB |
| 23 | Table 8-7 | HEC-RAS Bridge Information | This is Market Street bridge? Better to identify with common names and use the name in the description space on the model too. | Market Street Bridge narrative refers to a different study. Removed from report. | JB |

# REVIEW COMMENTS

| | | | | |
|---|---|---|---|---|
| REVIEW COMMENTS | DATE: 01 June 2022 | REVIEW OFFICE: CEPOH | REVIEWER: Jessica Brunty | |
| Study: Waimānalo Flood Hazard Study | LOCATION: | JOB/REQ No: | | |
| | | A/E: | | |
| PROJECT PHASE: Hydrology | | | | |

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | BACKCHECK |
|---|---|---|---|---|---|
| 1 | Figure 1-1 | Watershed Map | Update figure | Figure updated | JB |
| 2 | Section 1 | Watershed Description | Describe the dams and reservoirs in the study area | Section 1.6 Dams and Reservoirs added to the report | JB |
| 3 | Section 1.7 | Rivers and Streams | Identify any stream names and provide typical channel photos | Revised, as recommended. | JB |
| 4 | Table 2-1 | Elevation Data | C&C contours are based on 2003 survey year not 2016 | Survey year revised to 2003 | JB |
| 5 | Section 2.3 | Imagery | Use Digital Globe high resolution imagery | Background imagery updated | JB |
| 6 | Section 2.4 | Land Cover | Instead of using the general land cover raster, use the 2011 high resolution land cover raster from the MRLC National Land Cover database | H&H parameters updated using detailed land cover raster | JB |
| 7 | Section 3 | Data Collection | Add a figure identifying the nearby climate and stream gauging stations. | Figure 3-1 added | JB |
| 8 | Section 3 | Data Collection | Describe the flood history | Section 3.3, Flood History added | JB |
| 9 | Section 4.1 | Stream Gage Analysis | Perform a Bulletin 17C analysis on just the recent record (2003-2020) for USGS 16249000 | See Table 4-5 | JB |
| 10 | Section 4.2 | Regional Regression Equations | Update peak flow estimates for new drainage areas / subbasins | Revised, see Table 4-7 | JB |
| 11 | Section 4.3.3 | Loss Parameters | DCIA seems high. Use detailed land cover raster to estimate impervious % instead of visual approximation | Revised, as recommended, see Table 4-9 | JB |
| 12 | Section 4.3.4 | Transform Parameters | Manning's n is likely to vary between channels | Manning's n updated in Table 4-12 | JB |
| 13 | Section 4.3.6 | Model Calibration | Identify appropriate ranges for calibration metrics (what NSE is acceptable); consider including Percent Bias (PBIAS) also as a calibration metric | Revised, as recommended | JB |
| 14 | Section 4.3.8 | Flow Frequency Estimates | Separate peak flow estimates into different tables for each watersed for the reader to better understand locations | Revised, as recommended | JB |

# REVIEW COMMENTS

| | | | | |
|---|---|---|---|---|
| Study<br>Waimānalo Flood Hazard Study | DATE: | REVIEW OFFICE:<br>CENWS | REVIEWER:<br>Tilak Gamage | |
| | LOCATION: | JOB/REQ No: | | |
| | | A/E: | | |
| PROJECT PHASE: Hydrology | | | | |

| ITEM No | DOC, PG PARA | TITLE | COMMENTS | DISTRICT RESPONSE/ACTION | BACKCHECK |
|---|---|---|---|---|---|
| 1 | 1.6.4 | Waimanalo Irrigation System | Second paragraph text says " Source water originates from outside…" 60 Mil storage is situated in Waimanalo upper watershed. Question is – Does it captures the runoff and reduce downstream flow. I heard earlier, reservoir maintain high water levels and not much capacity to hold runoff. Please clarify. | The amount of inflow from the upper watershed is very limited (it has a small drainage area). | JB |
| 2 | 1.7 | Rivers and Stream | No descriptions about streams in Kaiona sub watershed. The stream in it may be small and not clearly defined, but useful to add bit of information, pictures etc | Added in Section 1. | JB |
| 3 | 3.2 | Stream | Figure 3.2 shows the flow reduction since 1996 but there were couple of storm events occurred since 1996 that did not appear to change the flow to historic levels. Kailua was shut down but Waimanalo was buit, and apparently, downstream flow has reduced since then. May be 60mil storage is important feature in the model | Not so much the addition of the Waimanalo 60 MG, but the fact that the Kailua and Maunawili Reservoirs were no longer storage reservoirs that overtopped frequently (they were very small and easily overtopped). | JB |
| 4 | 3.3 | Flood History | Recent historical flood events never reached to the level of 1960-1990. Is there a way to figure frequency of these two events? | Yes, described in Appendix B. | JB |
| 5 | 4.1 | 17C results tables | Inoaole watershed is smaller than Waimnalo yet produces more flow. Agree to be cautious on data used for further analysis | It does not produce more flow. The gage on Waimanalo is located on a tributary. | JB |
| 6 | 4.3 | Rainfall Runoff Model | HMS model 4.9 or 4.10? | HMS 4.9 | JB |