Low-Flow Characteristics and Surface Water Availability in East Maui, Hawai‘i

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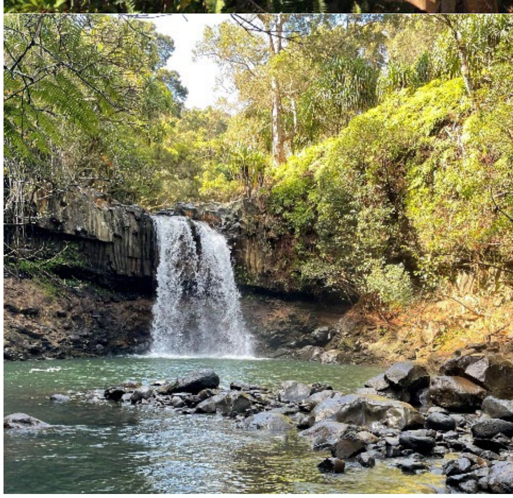

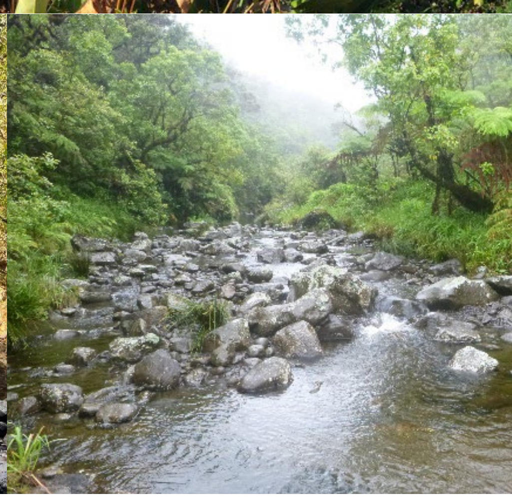

State of Hawaii

Department of Land and Natural Resources

Commission on Water Resource Management

Cover. View of the Koʻolau Forest Reserve on the island of Maui, Hawaiʻi.Photograph by Ayron M. Strauch, Commission on Water Resource Management 2020.

(bottom left inset). View of Hoʻolawanui Stream at an altitude of about 800 feet on the island of Maui,Hawaiʻi. Photograph by Ayron M. Strauch, Commission on Water Resource Management 2020.

(bottom center inset). View of Honomanō Stream at an altitude of about 4,200 feet on the island of Maui,Hawaiʻi. Photograph by Ayron M. Strauch, Commission on Water Resource Management 2017.

(bottom right inset). View of Kaʻaiea Stream at an altitude of about 1,300 feet on the island of Maui,Hawaiʻi. Photograph by Ayron M. Strauch, Commission on Water Resource Management 2021.

Acknowledgments

The author is grateful to the many individuals, landowners, and agencies that provided the support needed to conduct this study. Landowners that graciously allowed access to their properties including Alexander & Baldwin, East Maui Irrigation, Wailele Farm, Megan Loomis-Powers, Laf Young, and Oho‘olawa Gardens. The author is especially thankful to the following individuals for arranging access to streams in the study area: James Bickford, Keith Douglas, Skippy Hau, Jody Kimmel, Wes Crile, Tova Calendar, Lucienne De Naie, Doug Jones, Abel Kailiponi, Richard Perry, Megan Loomis-Powers, Robert Sajdak, Ramana Sawyer, and Laf Young. The following U.S. Geological Survey (USGS) personnel conducted additional discharge measurements in East Maui: Paige Blasberg, Rylen Nakama, and Anela Whisenhunt. Madison May expedited analysis of hydrologic data at continuous-record stream-gaging stations for use in the study. Chui L. Cheng from USGS provided valuable technical support and inspiration throughout the study. Much of this work would not be possible without the support of DLNR Division of Forestry and Wildlife Maui Branch, particularly Kevin Cooney and Lance De Silva. Kathy Yoda was instrumental in making this study happen and deserves more praise than I can put into words for carrying us through the pandemic to accomplish this fieldwork. Thank you to Dean Uyeno and Kaleo Manuel for supporting this work and providing comments on previous drafts. Finally, to Doug Kagawa, who spent much of the pandemic stuck with me in East Maui working on this project.

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Low-Flow Characteristics and Surface Water Availability in East Maui, Hawaiʻi

By Ayron M. Strauch

Abstract

The purpose of this study is to characterize streamflow availability under natural (unregulated) low-flow conditions for streams affected by the water delivery systems in northeast Maui, Hawaiʻi. The study was broken down into four main areas: (1) streamflow characteristics at inactive continuous and partial-record gaging stations maintained by the USGS in East Maui; (2) streamflow characteristics in the Huelo region; (3) the impact of the Upper and Lower Kula water systems on streamflow in the Honomanū, Haipuaena, Puohokamoa, and Waikamoi hydrologic units; and (4) the availability of water from other stream sources between Honopou and Māliko gulches. Fieldwork primarily focused on the 11 hydrologic units in the Huelo region that include, from east to west, Kōlea, Punaluʻu, Kaʻaiea, ʻOʻopuola, Puehu, Nailiilihaele, Kailua, Hanawana, Hoalua, Waipio, and Hoʻolawa. These hydrologic units include the tributary streams of Makanali (ʻOʻopuola hydrologic unit), Oanui (Kailua hydrologic unit), East Hoalua (Hoalua hydrologic unit), as well as Hoolawaliilii, Hoʻolawanui, and West Hoʻolawanui streams (Hoʻolawa hydrologic unit). Mokupapa is a separate watershed in the Hoʻolawa hydrologic unit. Streamflow measurements at partial-record gaging stations were used to develop low-flow duration discharge characteristics. Synoptic measurements at differing elevations conducted as seepage runs were made to provide an understanding of surface water-groundwater interactions. The results of this study can be used to develop quantitative instream-flow standards for the study-area streams.

Low-flow characteristics for natural streamflow conditions were represented by flow-duration discharges that are equaled or exceeded 95 to 50 percent of the time. Partial-record sites were established at 20 locations, with 17 locations upstream from existing surface-water diversions on the Wailoa and New Hāmākua Ditches at approximately 1250 ft[1] and at 3 locations above the Lowrie Ditch at approximately 750 ft. The site on Mokupapa Stream was located above Haiku Ditch intake where it flowed continuously. Low-flow characteristics were determined using historical and current streamflow data from continuous-record stream-gaging stations and miscellaneous sites, as well as additional data collected as part of this study. Low-flow-duration discharges were estimated for the 30-year base period (water years 1984–2013) using record-augmentation techniques. The 95-percent flow-duration discharges (Q_{95}) ranged from 0.05 to 2.8 cubic feet per second (ft^3/s). The 50-percent flow-duration discharges (Q_{50}) ranged from 0.24 to 13 ft^3/s. Upper-bound estimates of low-flow duration discharges at a partial-record site on Mokupapa Stream was estimated based on the highest discharges measured as part of this study during Q_{95} to Q_{50} flow conditions, which was 0.72 ft^3/s, because measured discharges did not correlate with data at any active long-term continuous-record stream-gaging stations and therefore low-flow duration discharges could not be estimated.

This study also estimated streamflow gains and losses using seepage-run discharge measurements in nine of the hydrologic units (Mokupapa and Punaluʻu streams were excluded). Streams gained flow downstream from the uppermost diversions. Measured seepage-gain rates ranged between 0.01 and 15.7 ft^3/s per mile of stream reach. Only one reach, located on Nailiilihaele, had measured seepage loss, due to the prevalence of late phase Hana volcanics, which was quickly recovered below a series of waterfalls downstream. Seepage gains are presumed to originate mainly from groundwater discharge seeping out from incised perched water bodies of the Kula volcanics series. Under natural-flow conditions and flow conditions of the seepage runs, streams flow continuously from the mountains to the ocean, except in reaches where highly permeable Honmanū volcanics are exposed (e.g., Honomanū and ʻOʻopuola hydrologic units) where the stream losses water to groundwater recharge near the coast. Where a stream is diverted into a ditch, a dry reach may occur immediately downstream from the diversion to the point of seepage gain in the stream. However, in most circumstances, groundwater seepage, or leakage past or underneath the diversion, contribute to a wetted path immediately downstream.

It is worth noting that streamflow values estimated by Gingerich (2005) was based upon low-flow duration statistics from streamflow records between 1942 and 2001, with the assumption that such a record reduced estimated error in streamflow without consideration in any large shift in climate patterns. However, data indicates that the 1984-2013 period was substantially drier than the 1942-2001 period and therefore previous streamflow values are not applicable in today's climate conditions.

[1]all elevations will be listed in feet above sea level

Introduction

Surface water is a critical component of social-ecological systems across Pacific Islands, supporting important economic, ecological, and cultural uses. Traditional customs and cultural practices are dependent on flowing water, as are freshwater, estuarine, and nearshore ecosystems. Communities depend on streams for drinking water supply, agricultural irrigation, and hydropower. In the tropics, streams support unique species assemblages of endemic freshwater fauna. In Hawaiʻi, fauna such as ʻoʻopu (freshwater fish), ʻōpae kalaʻole (freshwater mountain shrimp), and hīhīwai (freshwater snail) exhibit amphidromous life history characteristics, with adults spawning in freshwater habitat and larvae drifting to saltwater environments before migrating back to freshwater.

As the sugar industry grew in Hawaiʻi, large, engineered diversion and irrigation systems were built to remove water from wet, windward environments and transport it across drainage basins to dry, leeward environments, resulting in reductions in streamflow downstream of diversions (Figure 1). Many diversion structures have been constructed to capture most of the flow in streams during low-flow conditions, leaving some reaches downstream of the diversion dry. Consequently, the diversion of surface water during low-flow conditions greatly influences water availability for instream uses.

A lack of water to meet instream and non-instream uses has continued to be a major issue across Hawaiʻi. Conflicts have led to long and costly litigation over rights to water. In 1987, the State of Hawaiʻi passed Hawaiʻi Revised Statute 174C and associated Hawaiʻi Administrative Rules, commonly known as the State Water Code, which created the Commission on Water Resource Management (CWRM) to address the ongoing struggle to balance water resource management. CWRM staff support management decisions made by a seven member decision-making Commission. Following a petition to amend instream flow standards for 27 streams filed in 2001, interim instream-flow standards (interim IFS) for certain streams in East Maui were first established in 2006 by Commission action for Honopou, Hanehoi, Piʻinaʻau, Palauhulu, Waiokamilo, and Wailuanui.

Additional instream flow standards were recommended in 2010, and although official action was delayed following a request for a contested case hearing, the recommended standards were implemented in 2010 by East Maui Irrigation (EMI). Following the conclusion of the contested cast hearing, CWRM issued a final Decision & Order in June of 2018, establishing interim IFS on 24 streams in East Maui (Appendix A).

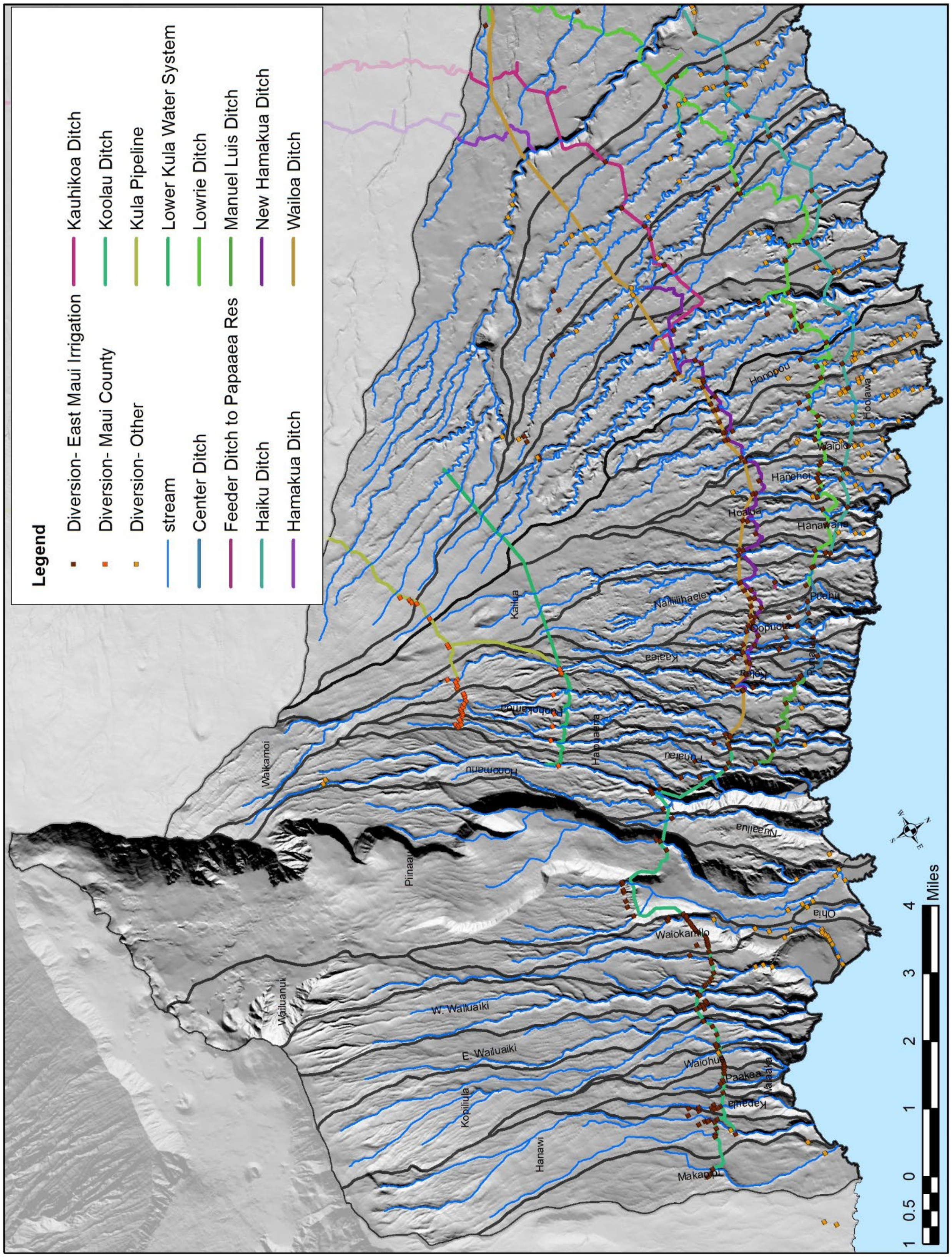
Following a series of lawsuits filed against the State of Hawaiʻi Department of Land and Natural Resources Board of Land and Natural Resources regarding to the leasing of surface water from streams originating on state-owned portions of the East Maui region, as well as the public's general interest in securing sufficient water to meet the current and foreseeable future potable and non-potable needs in Maui County, the need for additional data was evident. In September 2021, the Sierra Club of Hawaiʻi filed a petition to amend the interim IFS for 11 streams and tributaries in the Huelo region.

Description of Study Area

Maui is the second youngest island and the second largest of the main Hawaiian Islands. The island consists of two main volcanoes, Mauna Kahalawai (peak at Puʻu Kukui of 5,787 ft) to the west and Haleakalā (peak at 10,023 ft) to the east, with a low-lying isthmus between. The EMI system consists of approximately 63 miles of ditches, excluding abandoned ditches and stream conveyances, that starts in the Nāhiku region and brings water to central Maui (Cheng, 2020). Sections of the system were built starting in the 1870s, with subsequent modifications, expansions, and abandonments into the early 1920s (Figure 1). The system was originally built to deliver water to support sugarcane cultivation, processing, and plantation communities. Today, the system delivers water primarily for diversified agriculture and municipal drinking water supply.

Two additional water delivery systems, the Upper and Lower Kula systems, were built at higher elevations to deliver water from East Maui for diversified agriculture and drinking water to the upcountry regions of Makawao and Kula. The purpose of this study is to characterize streamflow conditions in hydrologic units utilized by these water systems to understand the availability of water for instream and non-instream uses. Fieldwork focused on streams with limited or no hydrologic data, or without data in the current climate period. Analysis of existing data, largely gathered in the 1920s and 1930s, provides additional context for regulated flow conditions in streams affected by diversion systems at multiple elevations. For the purposes of this study, the study region described as East Maui consists of the hydrologic units from Māliko gulch to Makapipi, on the northeast slopes of Haleakalā. The largest watersheds are Piʻinaʻau (20.5 mi^2), Māliko (14.6 mi^2), Kakipi (8.9 mi^2), Wailuanui (6.6 mi^2), Hanawi (5.7 mi^2), Honomanū (5.4 mi^2), and Makapipi (5.3 mi^2). The watersheds with greatest maximum elevations are Piʻinaʻau (10,007 ft), Wailuanui (8,858 ft), West Wailuaiki (8,839 ft), East Wailuaiki (8,497 ft), Kopiliula (8,323 ft), Honomanū (8,314 ft), and Hanawi (8,074 ft).

Figure 1. Streams, stream diversions registered to East Maui Irrigation, stream diversions not registered to East Maui Irrigation, and irrigation systems in East Maui, Hawai‘i.



Climate and Rainfall

Haleakalā and Pu‘u Kukui are the driving forces affecting the distribution of rainfall on Maui, with rainfall affected by the orographic effect and the rainshadow effect. Mean annual rainfall in East Maui is depicted in Figure 2. Orographic refers to influences of mountains and mountain ranges on airflow but is also used to describe effects on other meteorological quantities such as temperature, humidity, or precipitation distribution.

Orographic precipitation occurs when the prevailing northeasterly trade winds push warm air up the windward side of the mountains into higher elevations where cooler temperatures persist (Giambelluca and Nullet, 1991). The steep gradient around the island forces moisture-laden air to rapidly rise in elevation (over 3,000 feet) in a short distance, resulting in a rapid release of rainfall. As moist air cools, water condenses, and the air mass releases precipitation. As a result, frequent and heavy rainfall is observed on the windward mountain slopes. The elevation of distribution of rainfall is limited by the temperature inversion in the troposphere. The temperature inversion zone, the range of elevations where temperature increases with elevation, typically extends from 6,560 feet to 7,874 feet. This region is identified by a layer of moist air below and dry air above (Giambelluca and Nullet, 1992).

A majority of the mountains in Hawai‘i peak in the fog drip zone, where cloud-water is intercepted by vegetation. In such cases, air passes over the mountains, warming and drying, while descending on the leeward mountain slopes. The fog drip zone on the windward side of islands extends from the cloud base level at about 2,000 feet to the lower limit of the most frequent temperature inversion base height at 6,560 feet (Giambelluca and Nullet, 1992). This zone occurs below the elevation where cloud height is restricted by the temperature inversion (Sholl et al., 2002). Fog drip is a result of cloud-water droplets impacting vegetation (Scholl et al., 2002) and can contribute significantly to groundwater recharge. Above the inversion zone, the air is dry and the sky is frequently clear (absence of clouds) with high solar radiation, creating an arid atmosphere with little rainfall (Figure 2). Across relatively homogenous geology, the frequency and distribution of rainfall is the primary driver of surface runoff and streamflow (Strauch et al., 2015).

Hydrogeology

East Maui was built up by successive lava flows of relatively fluid lava occurring in rapid succession, ranging from 10 to 75 feet thick (Izuka et al., 2018). These lava flows are grouped together as Honomanū volcanics. They are predominantly pahoehoe flows (lava characterized by a smooth or ropy surface with variable interior, including lava tubes and other voids). The Honomanū basalts are extremely permeable and yield water freely (Stearns and MacDonald, 1947). This series is composed of thin, vesicular, gas filled layers of relatively low specific gravity, and broken by many closely spaced cracks. Drainage patterns are not well developed in this series because of its rapid succession and high porosity and no soil surfaces were formed. The large dome that would become Haleakalā was later buried by flows of a thicker, more massive and less permeable series, with interbedded layers of ash between successive eruption events. This geology is grouped together as the Kula volcanics, which are mainly aa flows (lava characterized by jagged, sharp surfaces with massive, relatively dense interior) poured out at progressively longer intervals so that numerous valleys were cut between the younger lava flows (Figure 3). The older flows are massive, aggregating 2,000 feet thick on the summit and thin toward the isthmus where they are only about 50 feet thick.

Kula lava flows are separated by soil surfaces, often of great depth, and ash beds ranging in thickness from one to two feet. Present day soil surfaces are as much as 50 feet thick, resulting from the decomposition of lava and ash. The exception to this in East Maui is the region covered by the late-phase Hana volcanics, where clinker lava is too young to have weathered much. This is apparent in parts of the Makapipi, Pi‘ina‘au, Nailiilihaele, Kailua, Hanehoi, and Ho‘olawa watersheds (Figure 3).

In the eastern end of Haleakalā near Nāhiku, there is a thickly saturated high-level ground water body (Gingerich, 1999a). Perched water is water that is confined by an impermeable or slowly permeable layer, thus accumulating in a perched water table above the general regional water table. Perched water bodies are generally near-surface and supply springs along gulch walls or directly into streams. Small geologic formations (weathered cinders, spatter, and pumice) originally built along fissures by fire fountains (sprays of gases carrying magma from vents, spewing up to several hundred feet high, producing “spatter”) at the source of the lava flows, also form a few perched spring water systems (Gingerich, 1999b).

In many locations, stream channel incision has eroded gulches that intercept groundwater in highly saturated mountain sides. Exposed ash and soil beds with intervening lava and cemented clinker formations support perched water. Some gulches are eroded to a depth of at least 250 ft and act as drainages to the infiltrated water whose downward movement is impeded by these geologic formations. There continues to be large amounts of deep seepage when infiltrating rainfall seeps through broken ash or lava. Although relatively impermeable, ash and soil beds may have been baked and broken by subsequent lava

Figure 2. Mean annual precipitation in East Maui with the idealized zone of fog drip depicted, East Maui, Hawai‘i**.** (Source: Giambelluca et al., 2013)

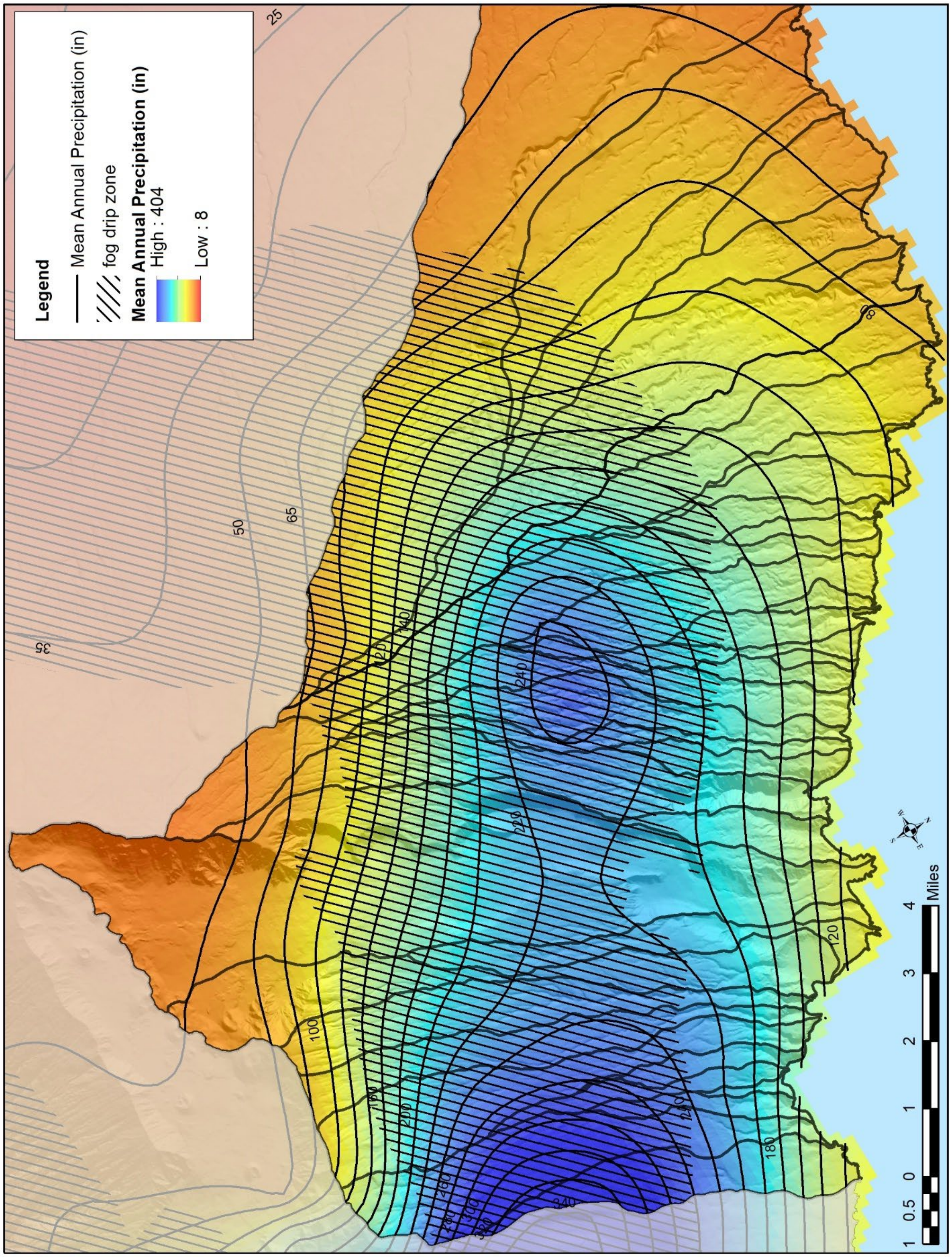
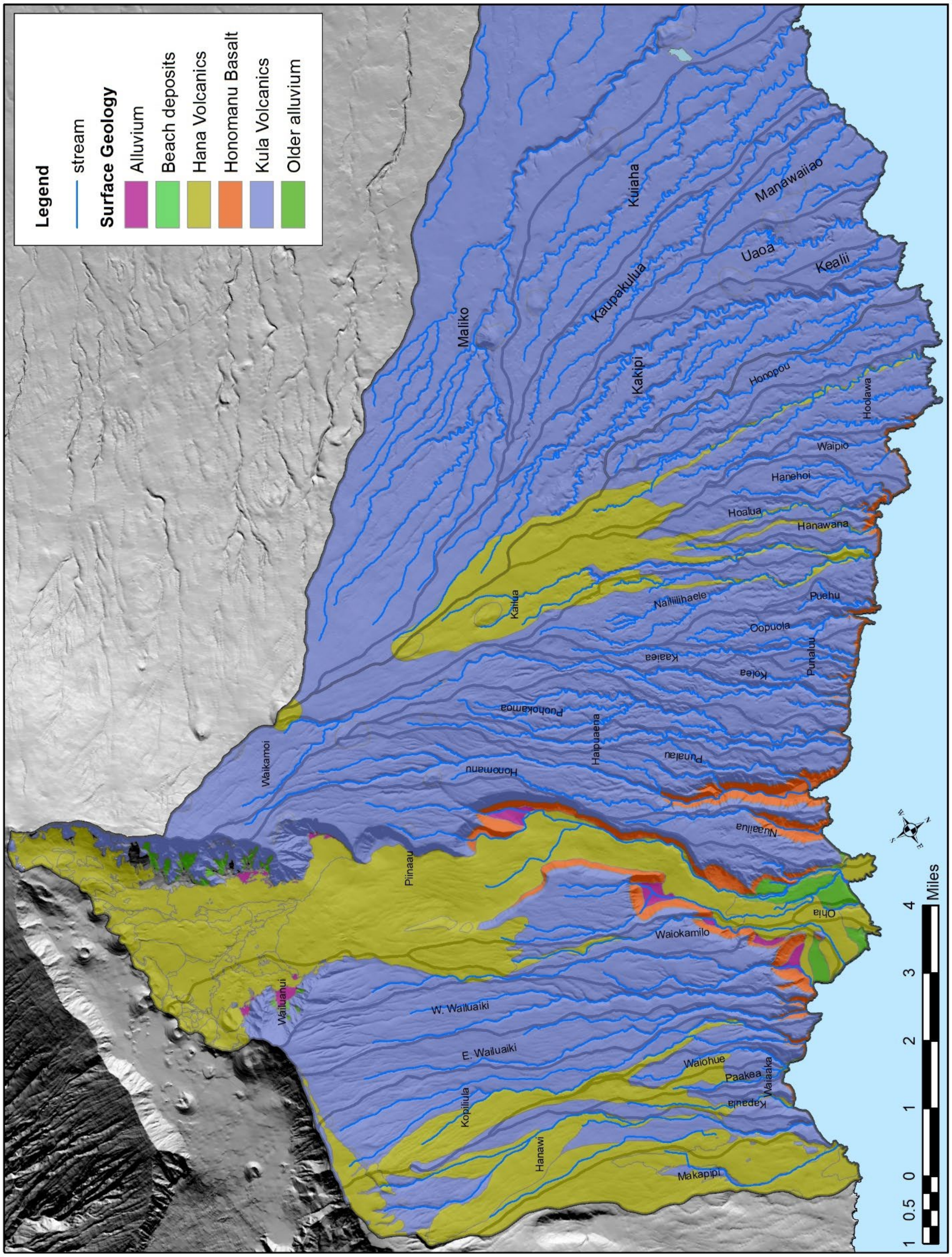


Figure 3. Generalized surface geology for surface water hydrologic units, East Maui, Hawai'i. (Source: Sherrod et al., 2007)



flows, broken by earthquakes, eroded by streams and then reburied beneath later phase Kula Volcanics, penetrated by tree roots, tree molds, or lava pits, or may have been naturally thin, increasing the permeability of the layer and increasing the basal groundwater recharge. In short, low-gradient stream reaches without waterfalls, siltation and the accumulation of alluvium or gravel deposits in the stream channel may affect the surface flow of the stream. However, streams in East Maui that are principally found eroding Kula volcanics are gaining streamflow.

The mantel of dense soils, ashes, cemented clinkers and lavas overlaying pahoehoe series prevent seepage loss, except where erosion has exposed the underlying Honomanū basalt, mostly near the stream mouth. Streams found principally on the older Honomanū volcanics (e.g., such as those found to the west of Māliko Gulch), lose streamflow to basal recharge as a result of the high permeability of this geology. Rainfall and watershed characteristics such as geology, topography, maximum elevation, and area contribute to the rate of groundwater recharge, as evident in Figure 4.

Previous Hydrogeological Studies in East Maui

In the 1930s and 1940s, the U.S. Geological Survey (USGS) conducted extensive hydrogeological fieldwork across Hawaiʻi, which resulted in the publication of a series of U.S. Geological Survey Bulletins on Hydrogeology for the Hawaiian Islands. In their report, Stearns and MacDonald (1947) provided detailed descriptions of fieldwork and data analysis, including work conducted by other hydrologists, such as John Hoffman, a consultant for East Maui Irrigation (EMI). Some datasets and figures are reproduced in Stearns and MacDonald (1947). Additional relevant data from EMI are also analyzed in this report.

Gingerich studied the occurrence of groundwater and contributions to stream flow in the Haʻikū region (1999a) and across the Huelo, Keanae, Wailua, and Nāhiku regions (1999b). Following up on this work, Gingerich (2005) conducted fieldwork to support topographic models that estimated low-flow characteristics at discontinued USGS gaging stations and ungagged locations from Kōlea to Makapipi streams. This work was funded by the Commission on Water Resource Management to support the development of quantifiable interim instream flow standards (IFS). Gingerich (2005) concluded that, for the period from 1942-2001, there was no statistical trend in median streamflow, and therefore, the entire period of record was used to develop flow statistics for index stations and the relevant overlapping records at discontinued stations in East Maui. However, it is generally accepted that there has been a distinct shift in rainfall regimes starting in 1978 (Frazier and Giambelluca, 2017) and that these historical estimates need to be updated. At inactive USGS gaging sites and historic partial-record stations, Cheng (2016) updated low-flow duration statistics using the 1984-2013 base period. Updated rainfall and groundwater recharge data are now available from Giambelluca et al. (2013) and Johnson et al. (2018) for the island of Maui.

I. Natural Streamflow at Inactive USGS Gaging Stations

As previously mentioned, streamflow characteristics have been extensively studied in East Maui using continuous-record gaging stations, seepage runs, and watershed characteristics (Gingerch, 2005; Cheng, 2016). This work was dependent on the extensive historic network of stream and ditch gaging stations that existed in East Maui (Figure 5). Fieldwork also focused on the gains and losses within the EMI water delivery systems (Cheng, 2012).

In phase I of a statewide study of low-flow duration streamflow characteristics, Cheng (2016) developed low-flow duration statistics for natural flow conditions at previously gaged continuous and partial-record gaging stations across the State of Hawaiʻi for the 1984-2013 climate period. This included the analysis of dozens of discontinued stations throughout the study region. The relevant datasets for active continuous monitoring stations (Table 1) and discontinued continuous and partial-record monitoring stations (Table 2), are reproduced in this report.

The development of low-flow duration discharge statistics utilized multiple methods. Continuous record data for discontinued stations that measured natural flow in the study region were analyzed relative to active continuous monitoring stations for the base period from 1984 to 2013 using record augmentation. Continuous record data for short-term monitoring stations were available for one location in the study region from 2018 to 2021 and from one location from 2021 to 2022 (Table 1). Record augmentation at partial-record sites were analyzed with an index station using the MOVE.1 technique.

II. Estimates of Streamflow in the Huelo Region

We conducted fieldwork in the Huelo region to quantify low-flow characteristics in streams with either no continuous record or a continuous record that had been discontinued prior to the current climate period.

Figure 4. Estimated groundwater recharge for surface water hydrologic units, East Maui, Hawai'i. (Source: Johnson et al., 2017)

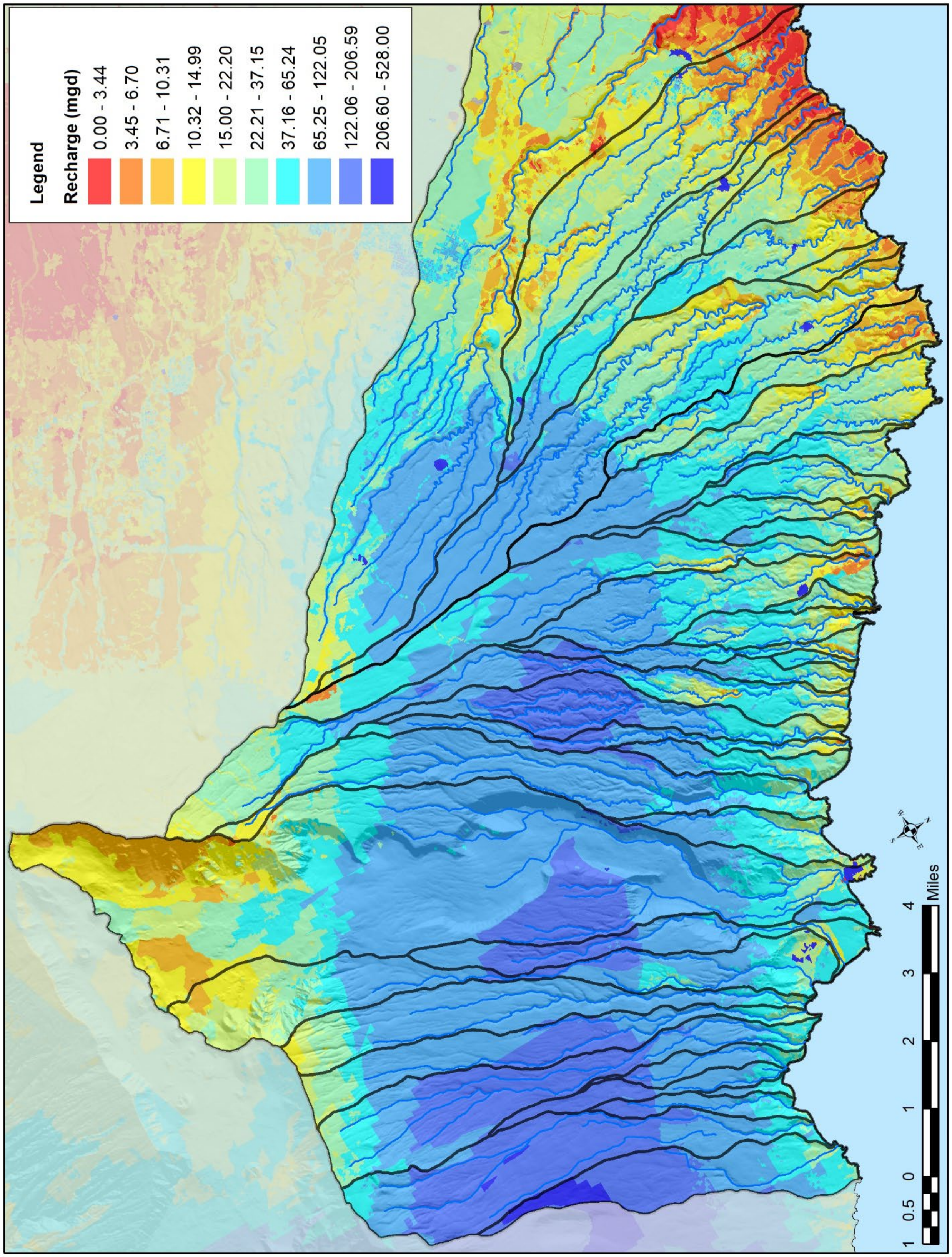


Table 1. Low-flow duration discharges at active long-term continuous-record natural-flow stream gaging stations and short-term continuous-record natural-flow stream gaging stations in East Mauʻl, Hawaii, Hawaiʻi.
[ID, identifier; USGS, U.S. Geological Survey; elev, elevation; ft, feet]

USGS station ID	USGS station name	elev (ft)	Drainage area (mi^2)	Period of record	Number of complete water years	Record used in computation	Discharge, in ft^3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded: Total flow 50	55	60	65	70	75	80	85	90	95	Base flow 50	70
Long-Term Continuous-Record Gaging Stations																		
16508000	Hanawi Stream near Nahiku	1,318	3.29	1914-16, 1919–P	99	1914-2005	7.0	6.2	5.6	5.0	4.4	4.0	3.6	3.2	2.8	2.3	4.5	3.5
					70	1944-2013	6.2	5.5	5.0	4.4	4.0	3.7	3.3	2.9	2.6	2.2		
					30	1984-2013	6.2	5.4	4.8	4.3	3.9	3.6	3.2	2.9	2.6	2.2		
16518000	West Wailuaiki Stream near Keanae	1,550	2.1	1914–17, 1921–31, 1953–P	103	1914-2005	10	8.9	7.9	7.0	6.2	5.4	4.6	4.0	3.3	2.5	5.8	4.2
					70	1944-2013	9.0	8.0	7.1	6.3	5.6	4.9	4.2	3.6	3.0	2.3		
					30	1984-2013	8.9	7.8	6.9	6.0	5.2	4.5	3.9	3.4	2.8	2.2		
16587000	Honopou Stream near Huelo	1,208	0.59	1913–14, 1916-17, 1920–P	104	1912-2005	2.4	2.1	1.9	1.6	1.4	1.2	1.1	0.87	0.72	0.54	1.5	1.0
					70	1944-2013	2.1	1.9	1.6	1.4	1.2	1.1	0.90	0.74	0.63	0.47		
					30	1984-2013	2.0	1.8	1.6	1.3	1.2	1.0	0.86	0.72	0.60	0.47		
16522800	Waikamoi Str abv Kula PL intake nr Olinda	4,487	2.50	1953-68, 2009–P	15	1953-68	0.12	0.11	0.08	0.08	0.06	0.06	0.05	0.04	0.03	0.02		
						1984–2013	0.12	0.09	0.07	0.06	0.05	0.04	0.03	0.03	0.02	0.01		
Short-Term Continuous-Record Gaging Stations																		
16522950	Piʻinaʻau Str 470 ft US Koolau Ditch	1,350	14.8	2018-21	3	2018-21	0.42	0.35	0.29	0.23	0.19	0.15	0.12	0.09	0.06	0.04		
16570000	Nailiilihaele near Huelo	1,250	3.69	1911-12, 1914-75, 2021-P	55	1915-75	17	15	13	12	11	9.4	8.2	7.0	5.8	4.5	9.4	7.0
						1984-2013	14	13	12	9.8	8.6	8.0	7.0	5.6	4.6	3.6		
						2021-P	7.7	6.1	5.0	4.3	3.6	3.3	2.9	2.7	2.4	2.2		

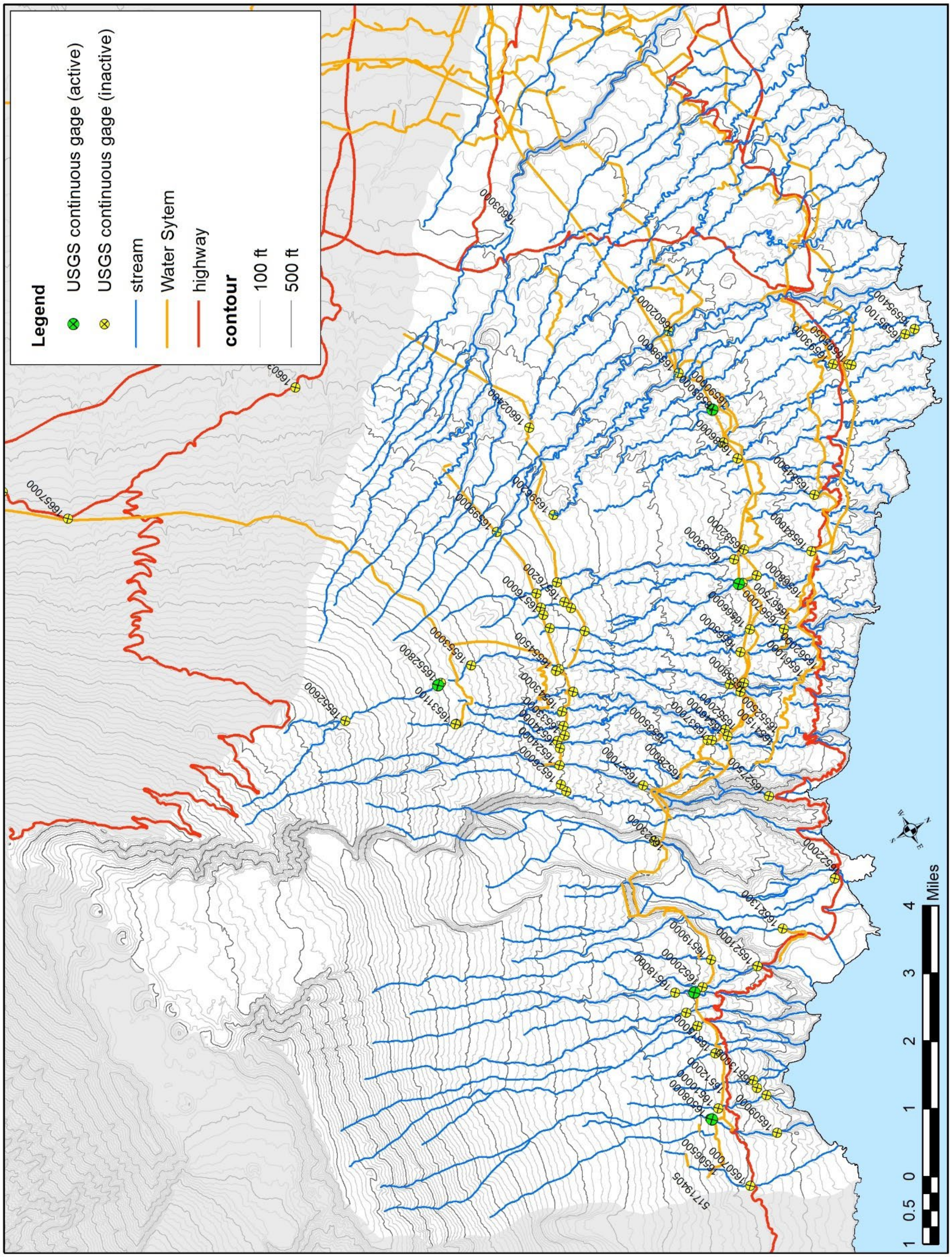
Table 2. Low-flow duration discharges at inactive continuous-record natural-flow gaging stations for historic (period of record) and current climate conditions in East Maui, Hawai‘i. (Source: USGS, 2021; Cheng, 2016)

USGS ID	USGS station name	elev (ft)	drainage area (mi^2)	Period of Record	Number of complete water years	Length of record	Discharge, in ft^3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded									
							Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
16510000	Kapaula Gulch near Nahiku	1,346	0.69	1921-62	40	1921-1962	5.2	4.5	4.0	3.6	3.1	2.8	2.4	2.0	1.7	1.4
						1984-2013	4.3	3.6	3.1	2.7	2.3	2.3	1.7	1.5	1.3	0.98
16515000	Waiohue Gulch near Nahiku	1,316	0.32	1922-63	40	1923-1962	6.5	6.0	5.6	5.3	4.9	4.5	4.2	3.9	3.6	3.1
						1984-2013	5.2	4.7	4.4	4.2	3.9	3.7	3.4	3.2	2.9	2.5
16516000	Kopiliula Stream near Keanae	1,292	4.31	1914-17, 1922-58	36	1915-1957	9.0	7.7	7.0	6.2	5.5	4.9	4.3	3.8	3.2	2.6
						1984-2013	6.6	5.5	5.0	4.2	3.8	3.4	3.0	2.7	2.4	2.1
16517000	East Wailuaiki Stream near Keanae	1,329		1914-17, 1922-58	37	1916-1957	10	9.0	8.0	7.1	6.5	5.7	5.1	4.5	3.8	3.1
						1984-2013	7.7	6.9	5.9	5.3	4.6	4.2	3.6	3.2	2.8	2.1
16519000	West Wailuanui Stream near Keanae	1,268		1914-17, 1922-2005		1944-2013	5.1	4.5	3.9	3.4	2.9	2.6	2.2	1.9	1.5	1.2
						1984-2013	3.8	3.3	3.0	2.5	2.2	1.9	1.6	1.4	1.1	0.75
16520000	East Wailuanui Stream near Keanae	1,287	0.51	1914-17, 1922-58	38	1915-1957	3.7	3.2	2.9	2.6	2.3	2.0	1.8	1.5	1.3	1.0
						1984-2013	3.1	2.7	2.4	2.0	1.7	1.5	1.3	1.1	0.91	0.65
16524000	Honomanu at Haiku-Uka Boundary	2,900	2.54	1920-27, 1932-35, 1962-69	14	1920-1964	2.0	1.7	1.6	1.2	1.1	0.93	0.77	0.62	0.46	0.31
						1984-2013	1.6	1.3	1.1	0.92	0.76	0.62	0.50	0.42	0.32	0.23
16527000	Honomanu Stream near Keanae	1,733	3.17	1914-1964	49	1915-1963	6.2	5.3	4.6	4.0	3.6	3.1	2.6	2.2	1.7	1.1
						1984-2013	4.9	4.3	3.8	3.1	2.6	2.2	1.8	1.4	1.1	0.73
16531100	Haipuaena Str at Kula Diversion	4,320	0.27	1946-68	21	1946-1968	0.47	0.41	0.34	0.29	0.23	0.19	0.15	0.11	0.08	0.05
						1984-2013	0.43	--	--	--	--	0.12	--	0.06	--	--
16542000	East Branch Puohokumoa	2,800	0.14	1921-27, 1931-33	7	1921-1933	0.77	0.77	0.62	0.62	0.62	0.46	0.46	0.46	0.31	0.31
						1984-2013	0.41	0.32	0.29	0.27	0.25	0.24	0.22	0.21	0.19	0.16
16557000	Alo Stream near Huelo	1,248	0.47	1911-58	46	1912-1958	3.1	2.6	2.3	2.0	1.7	1.5	1.3	1.1	0.93	0.74
						1984-2013	2.5	2.1	1.7	1.5	1.3	1.2	0.96	0.82	0.69	0.53
16565000	Ka‘aiea Gulch near Huelo	1,310	0.58	1922-61	39	1923-1961	2.4	2.1	1.9	1.6	1.3	1.1	0.94	0.82	0.69	0.52
						1984-2013	2.9	2.5	2.2	1.9	1.7	1.5	1.3	1.1	0.93	0.77

Table 2. [continued]. [LF-PR, flow-flow partial-record station (number of measurements)] (Source: USGS, 2021; Cheng, 2016)

USGS ID	USGS station name	elev (ft)	drainage area (mi²)	Period of Record	Number of complete water years	Length of record	Discharge, in ft³/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded									
							Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
16566000	‘O‘opuola Stream near Huelo	1,205	0.2	1931-57	27	1931-1957	1.1	0.99	0.85	0.74	0.62	0.56	0.46	0.39	0.32	0.28
						1984-2013	0.95	0.79	0.69	0.54	0.50	0.42	0.36	0.33	0.26	0.18
16569700	W Br Nailiilihaele Stream nr	2,860	0.04	LF-PR (19)	n/a											
	Kailiili			1965-1969		1984-2013	0.73	0.52	0.39	0.29	0.23	0.19	0.14	0.11	0.08	0.06
16570000	Nailiilihaele Stream near Huelo	1,205	3.49	1915-17, 1921-23,	55	1915-1974	17	15	13	12	11	9.4	8.2	7.0	5.8	4.5
				1926-74		1984-2013	14	13	12	9.8	8.6	8.0	7.0	5.6	4.6	3.6
16576200	E Br Kailua Stream nr Kailiili	2,880	0.35	LF-PR (35)	n/a											
				1963-1969		1984-2013	0.67	0.55	0.47	0.41	0.36	0.32	0.27	0.24	0.20	0.16
16577000	Kailua Stream near Huelo	1,253	2.41	1913-1958	40	1915-1957	9.3	8.0	7.1	6.2	5.4	4.6	3.9	3.4	2.6	1.7
						1984-2013	7.8	6.8	5.9	4.9	4.2	3.8	3.2	2.5	2.0	1.4
16585000	Ho‘olawanui Stream nr Huelo	1,219	1.34	1911-1971	60	1911-1972	5.6	4.9	4.3	3.8	3.3	2.9	2.5	2.1	1.7	1.2
						1984-2013	4.4	3.9	3.5	2.9	2.6	2.2	1.9	1.6	1.4	1.0
16586000	Hoolawaliilii Stream nr Huelo	1,245	0.62	1912-1957	45	1912-1958	4.4	4.0	3.7	3.4	3.2	3.0	2.8	2.5	2.2	1.8
						1984-2013	3.6	3.4	3.1	2.8	2.7	2.4	2.2	1.9	1.7	1.4
16596200	Halehaku Gulch near Kailiili	2,610	0.12	1965-1971	6	1965-1971	0.51	0.42	0.37	0.32	0.26	0.23	0.20	0.14	0.12	0.08
						1984-2013	0.87	0.69	0.56	0.44	0.34	0.27	0.21	0.17	0.12	0.08

Figure 5. USGS active and discontinued stream gages in East Maui, Hawai'i.



Streams targeted for data collection spanned a wide range of sizes, stream networks, hydrogeological characteristics (Table 3). The largest streams in the Huelo Region (e.g., Honopou, Hoʻolawanui, Hoolawaliilii, Kailua, Nailiilihaele) each had continuous record gaging stations with long periods of record. However, the original water delivery systems built by Henry Baldwin (e.g., Old Hāmākua Ditch) and Claus Spreckels (e.g., Spreckels, Old Haiku Ditch) captured streamflow from many streams in the Huelo region that never had any hydrological monitoring data. Thus, it was necessary to develop low-flow duration discharge statistics for these streams.

Methods

Analysis of Low Flows at Different Types of Measurement Sites

For this study, 19 partial-record and 1 short-term continuous monitoring station was established in the Huelo region. Record augmentation at partial-record sites were analyzed with an index station using the MOVE.1 technique. All flow measurements were made using a Sontek FlowTracker 2 acoustic-doppler velocity meter. For quality control and quality assurance, measurements were made during stable flow conditions monitored using temporary gages.

Short-Term Stations

A short-term continuous-record stream-gaging station has less than 10 complete water years of natural-flow record. The procedures for estimating low-flow duration discharges at short-term stations are documented in Cheng (2016, p. 13–14) and summarized as follows:

1. Extract daily mean discharges during stable streamflow recessions from the short-term station. A streamflow recession is the period when flows return to low-flow conditions following a period of direct runoff. Stable recession daily mean discharges are selected from streamflow recessions that continue for 4 or more consecutive days.

2. Extract stable recession daily mean discharges from the index stations using criteria in step 1, and select the stable recession daily mean discharges that are less than the base-period Q_{40} discharge (rather than the Q_{50} discharge). This allows for the statistical relation to be defined for the full range of low-flow statistics to be estimated, particularly for cases in which stable recession daily mean discharges at Q_{50} conditions are not available at the index station but stable recession daily mean discharges at higher flow conditions are available.

3. Determine pairs of concurrent stable recession daily means between the short-term and index stations. Concurrent stable recession daily mean discharges from the short-term and index stations must be from at least 10 independent recessions.

4. Using the data determined in the previous step, apply steps 2 and 3 of the initial procedures used prior to the application of record-augmentation techniques as described in the “Record Augmentation” section.

5. Develop a model, using the appropriate record-augmentation technique (MOVE.1 or graphical) determined in step 4, between concurrent stable recession daily means at the short-term and index stations.

6. Using the model developed in step 5, compute flow-duration discharges at the short-term station from corresponding flow-duration discharges at the index station for the base period.

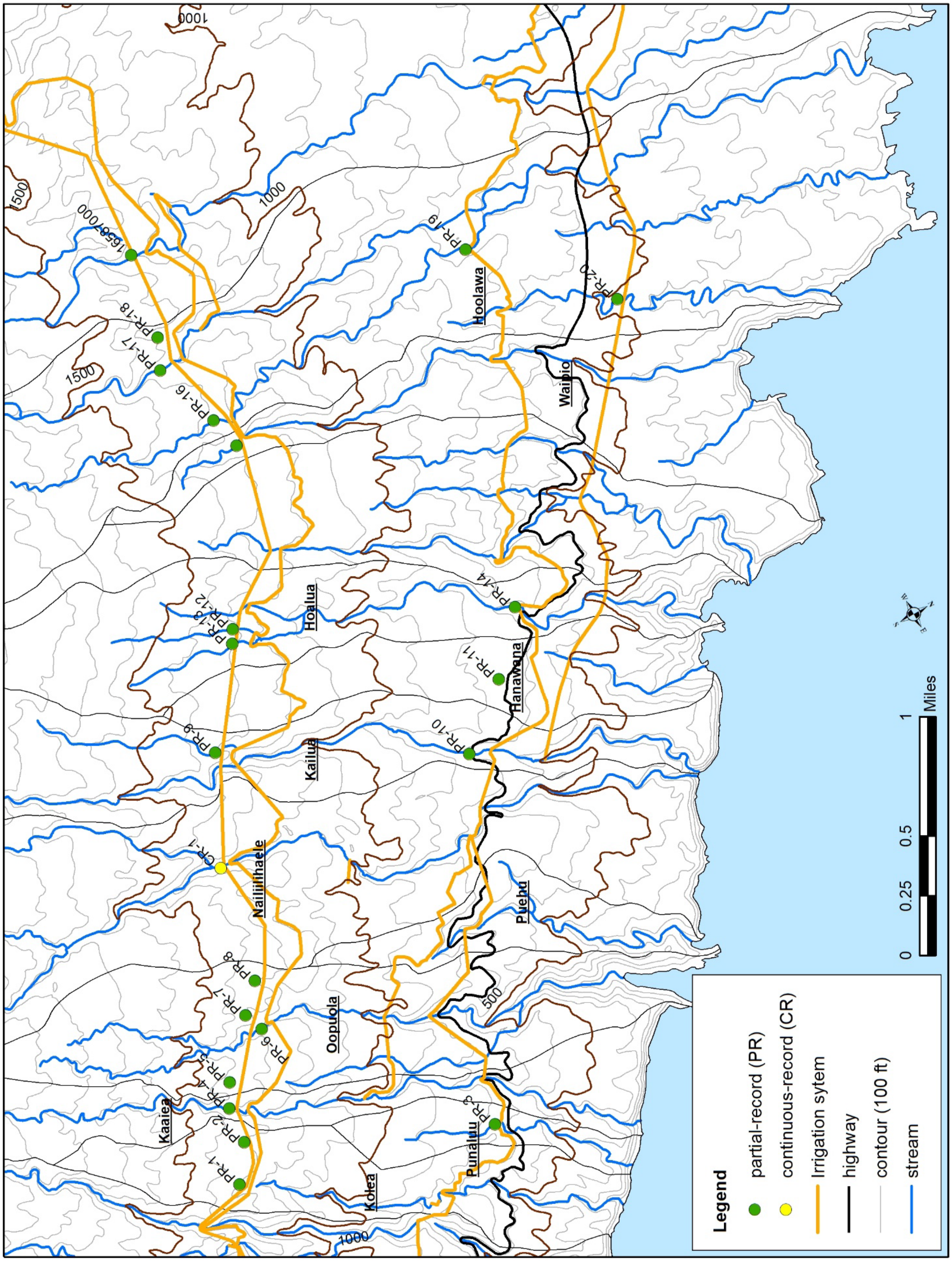
Partial-Record Sites

Partial-record sites were established in the Huelo region to develop low-flow duration characteristics for streams without any hydrological data as well as to update statistics for streams with stations that were discontinued 50-70 years ago (Figure 5). A partial-record site commonly has 10 or more systematic (consistent) streamflow measurements at a location in the stream. The procedures for estimating low-flow duration discharges at partial-record sites are documented in Cheng (2016, p. 14–15) and are summarized as follows:

1. Determine daily mean discharges at the index stations that are concurrent with the streamflow measurements at the partial-record site, and select the daily mean discharges at the index stations that are less than the Q_{40} discharge. This allows for the statistical relation to be defined for the full range of low-flow statistics to be estimated, particularly for cases in which daily mean discharges at Q_{50} conditions are not available at the index station but daily mean discharges at higher flow conditions are available.

2. Using the data determined in step 1, apply steps 2 and 3 of the initial procedures used prior to the application of record-augmentation techniques as described in the “Record Augmentation” section. Develop a model, using the appropriate record-augmentation technique (MOVE.1 or graphical) determined in step 2, between streamflow measurements at the partial-record site and concurrent daily mean discharges at the index station.

Figure 6. Location of Partial-Record (PR) gaging stations and continuous-record (CR) gaging stations in the Huelo region.



3. Using the model developed in step 2, compute flow-duration discharges at the partial-record site from corresponding flow-duration discharges at the index station for the base period.

Seepage-Run Discharge-Measurement Sites

The spatial distribution of streamflow gains and losses along stream reaches in the Huelo region was characterized by seepage-run measurements. A seepage run consists of several streamflow measurements collected on the same day at specific sites along a stream under stable flow conditions to determine the magnitude of streamflow gains and losses, and to identify flowing and dry stream reaches. Stream reaches can either gain water (groundwater discharge into stream) or lose water (stream discharge into a groundwater body), depending on the altitude of the water table relative to the streambed. Seepage-run measurements combined with low-flow duration discharge estimates can provide water-availability information for downstream reaches and help determine whether the stream flows continuously from the mountains to the ocean.

Flow-Duration Statistics

Natural low-flow characteristics of the study-area streams are described using flow-duration discharges. Flow-duration curves display the complete range of flows in a stream and have been extensively used for hydrologic planning and design (Vogel and Fennessey, 1995). A flow-duration curve is a cumulative-frequency distribution that shows the percentage of time that specified discharges at a location in a stream are equaled or exceeded during a specified period; the curve shows the relationship between magnitude and frequency of streamflow.

Daily mean discharges are typically used to construct the flow-duration curves because they allow for more detailed examination of the duration characteristics of a stream (Smakhtin, 2001) compared to flow-duration curves constructed from weekly, monthly, or annual streamflow data. A flow-duration curve is constructed by first ranking the daily mean discharges for a given period of record in descending order, then computing the exceedance probability of each discharge, and finally plotting the discharges against their exceedance probabilities (Ries and Friesz, 2000). The exceedance probabilities are computed with the Weibull formula (Loaiciga, 1989):

$$P_k = \frac{k}{n+1}, k = 1,2,3,\ldots,n \qquad (1)$$

where:
P_k is the exceedance probability of a daily mean discharge with rank k;
k is the rank of a daily mean discharge; and
n is the total number of daily mean discharges for the given period of record.

The 50-percent flow-duration discharge, commonly referred to as median (Q_{50}) discharge, is one of the most representative and frequently computed flow-duration statistics. The Q_{50} discharge is the flow that has been equaled or exceeded 50 percent of the time during a specified period. Flow-duration discharges that describe low-flow conditions are generally considered to be those equal to or less than the Q_{50} discharge, and they are represented by the lower end of the flow-duration curve. The natural low-flow characteristics of this study are represented by flow-duration discharges between the Q_{95} and Q_{50} discharges in 5-percent increments—Q_{95}, Q_{90}, Q_{85}, Q_{80}, Q_{75}, Q_{70}, Q_{65}, Q_{60}, Q_{55}, and Q_{50}.

Record Augmentation

Record augmentation is used to determine selected low-flow duration discharges for short-term and partial-record stations for a base period that is representative of long-term hydrologic conditions in the study area. It is an index-station approach in which streamflow information from a continuously gaged basin is applied to a basin with limited streamflow data (Eng et al., 2011). This method involves correlating concurrent streamflow data between the measurement site of interest (short-term stations and partial-record sites) and a nearby long-term station (index station) to develop a statistical relationship. About 10 concurrent streamflow data points are generally needed to apply record augmentation (USGS Office of Surface Water, Technical Memorandum no. 86.02, December 16, 1985). The model built from the correlation between the data points is used to compute flow-duration discharges at the measurement site of interest from corresponding flow-duration discharges at the index station for the base period. The base period is a common period during which all index stations used in the analysis are in operation with complete water years of streamflow data for computing various flow-duration discharges.

The MOVE.1 record-augmentation technique described by Hirsch (1982) was previously used in Hawaiʻi by Fontaine (2003), Cheng (2014), and Cheng (2020) for record-augmentation. The technique was also used in this study and assumes that the relation between concurrent records at the index stations and measurement site of interest is the same during the selected base period (Ries, 1993). Selecting the appropriate record-augmentation technique for estimating streamflow characteristics depends on the relation between data points at the measurement site of interest and the concurrent data points at the index station. The initial procedures used prior to the application of record-augmentation techniques are as follows:

1. Compute the 95-, 90-, 85-, 80-, 75-, 70-, 65-, 60-, 55-, and 50-percent flow-duration discharges for the base period at selected index stations (table 2).

2. Plot the base-10 logarithms of data points at the measurement sites (short-term stations and partial-record sites) and concurrent data points at each selected index station to determine which index station provides the best statistical relation by comparing the correlation coefficients. Index stations with correlation coefficients greater than 0.80 are examined.

3. Assess for curvature in the plots developed in step 2. When little or no curvature is detected in a relation on a logarithmic plot, the MOVE.1 technique is used to estimate flow-duration discharges. When curvature is evident in the relation, the graphical-correlation technique is used.

MOVE.1 Technique

The statistical relation developed with the MOVE.1 technique is based on the line of organic correlation regression method. The general procedure for the MOVE.1 technique begins with the transformation of concurrent data points at the index station and measurement site to base-10 logarithms, and then computation of the means and standard deviations of the transformed values. The low-flow duration discharges for the base period at the index station are also computed and transformed to base-10 logarithms. Estimates of low-flow duration discharges at the measurement site are determined using the MOVE.1 formula (eq. 2) and then converted to the original (nontransformed) units of measurement in ft^3/s.

$$Y_i = m_y + \frac{s_y}{s_x}(X_i - m_x) \qquad (2)$$

where:
Y_i is the base-10 logarithm of the estimated low-flow duration discharge at the partial-record site;
X_i is the base-10 logarithm of the computed low-flow duration discharge at the index station;
m_y is the mean of the base-10 logarithms of the discharge measurements at the partial-record site;
m_x is the mean of the base-10 logarithms of the concurrent daily mean discharges at the index station;
s_y is the standard deviation of the base-10 logarithms of the discharge measurements at the partial-record site; and
s_x is the standard deviation of the base-10 logarithms of the concurrent daily mean discharges at the index station.

The MOVE.1 results are evaluated by analyzing several regression statistics. Those statistics include the coefficient of regression (R^2), the root mean square error (RMSE), and a modified Nash-Sutcliff coefficient of efficiency (NSE). The coefficient of regression is the square of the correlation coefficient (Vogel and Stedinger, 1985; Helsel and Hirsch, 2002) and measures the strength of the linear relation between concurrent discharges at the index station and measurement site. The RMSE (or standard deviation) is the square root of the variance, and it aggregates the differences (or residuals) between individual estimated and measured discharges at the measurement sites into a single predictive measure. The modified NSE evaluates the accuracy to which the statistical relation predicts low-flow duration discharges at the measurement sites from the low-flow duration discharges at the index station, with values ranging from negative infinity to 1. An NSE of zero indicates that the mean of discharges at the measurement site is as accurate for predicting flow-duration discharges as the regression model. A negative NSE occurs when the mean of discharges at the measurement site is a better predictor than the regression model. For this study, acceptable values of coefficients of regression (R^2) and modified NSE are those equal to or greater than 0.75 and 0.70, respectively.

Index Stations and Selection of Base Period

An index station is a continuous-record stream-gaging station that measures natural flow and has a sufficient length of record for estimating streamflow characteristics representative of long-term conditions. It can be located along the same stream as the site of interest or in a nearby stream basin that is hydrologically similar to that of the site of interest. Searcy (1959) defines hydrologic similarity between two drainage basins as having the same probability of rainfall, not necessarily the occurrence of concurrent rainfall. Proximity is a common criterion for selecting index stations, although remote index stations as far away as 50 miles have been used to estimate streamflow characteristics (Searcy, 1959). In a study of that characterized low-flow availability for streams in west Maui, Cheng (2014) found that data at one partial-record site correlated with an index station on another island.

Four active long-term continuous-record stream-gaging stations on Mau‘i were considered potential index stations (table 2). Station 16508000 on Hanawi, station 16518000 on West Wailuaiki, and station 16587000 on Honopou Stream are the only active long-term stations that occur at elevations similar to those of the partial-record measurement sites, while 16552800 on Waikamoi Stream is located on a higher elevation headwater tributary (Figure 5). Many other discontinued stations have existed in the study area (Table 2).

Selection of a base period for adjusting streamflow records is critical to obtaining comparable low-flow estimates among the measurement sites. Flow-duration discharges may vary when computed from different time periods because the distribution of streamflow is not constant with time (Ries, 1993). When flow-duration discharges are estimated from multiple index stations with different time periods or record lengths, the time-sampling errors are generally larger than those computed with similar record periods. Therefore, streamflow records at index stations are commonly limited to a common base period to minimize time-sampling errors and to ensure that differences in flow characteristics are associated with spatial differences in climate and drainage basin characteristics (Searcy, 1959).

The base period should also be of sufficient length that is representative of long-term streamflow conditions. A minimum of 10 years of record generally is used to estimate streamflow characteristics such as the long-term median discharge. If the length of record is deemed inadequate for representing long-term streamflow conditions, record-augmentation techniques are commonly used to adjust the short-term record to a longer period (Ries, 1993). The 30-year period 1984–2013 is selected as the base period for this study because: (1) this period is representative of recent hydrologic conditions, (2) this period is of sufficient length to represent long-term hydrologic conditions, and (3) previous studies (e.g., Cheng, 2014; Cheng, 2016) used this base period, allowing for comparisons among methods.

At the three active long-term stations that monitored natural flow, selected annual statistics—total flow Q_{50} and base flow Q_{50} discharges—computed for each year from daily mean values of total flow (TF) and base flow (BF) were evaluated for trends for the complete 100-year period from 1922-2021. The base-flow component of total flow was estimated from daily mean values of streamflow using a base-flow separation method as described in Strauch et al. (2017). This method was previously used for streams on Hawai‘i Island and similar methods have been used across the state to estimate base flow (Oki, 1997; Gingerich, 1999; Fontaine, 2003; Johnson et al., 2018; Izuka et al., 2018) and provides a reasonable estimate of base flow for perennial streams in Hawai‘i. Trend analyses at the stations were conducted using methods described in Bassiouni and Oki (2013) and Clilverd et al. (2020). Trends were tested using the nonparametric Mann-Kendall test (Hirsch and Slack, 1984) at a significance level (α) of 5 percent. Kendall's tau coefficient, which ranges from -1 to +1, measures the strength of the correlation between flow and time. A tau value of -1 indicates that all flows decrease with increasing time; a tau value of +1 indicates that all flows increase with increasing time. Sen's slope was used to assess the magnitude of the overall change associated with each significant trend at the 5-percent level of significance. Sen's slope is most accurate for evenly spaced data, which was the case for data at the active long-term stations in this study.

Results

Long-term trends at Continuous-Record Stations

Trends at continuous-record gaging stations indicate a general decline in annual flow statistics for the 100-year period from 1922 to 2021. TFQ_{50} (not shown) and BFQ_{50} (Figure 6) for stations 16508000, 16518000 and 16587000, all demonstrated significant ($p < 0.05$) negative trends. For TFQ_{50}, station 16518000 had the strongest trend (tau = -0.26, Z = -3.73, $p < 0.001$), followed by station 16508000 (tau = -0.22, Z = -3.17, $p < 0.01$), and station 16587000 (tau = -0.15, Z = -2.05, $p < 0.05$). Similarly, for BFQ_{50}, station 16518000 had the strongest trend (tau = -0.27, Z = -4.08, $p < 0.001$), followed by station 16508000 (tau = -0.25, Z = -3.64, $p < 0.001$), and station 16587000 (tau = -0.13, Z = -2.00, $p < 0.05$).

Downward trends in streamflow are consistent with earlier assessments (Bassiouni and Oki, 2013; Cliverd et al., 2020) and indicate that decreases in streamflow are following similar decreasing trends in rainfall as described in Frazier and Giambelluca (2017). Long-term downward trends in base flows of streams may indicate a reduction in water availability for off-stream and instream uses. Whether the downward trends in total flow and base flow of streams will continue in the future is unknown owing to uncertainties associated with potential climate change and watershed response to the changes (Mair et al., 2019). Therefore, low-flow duration discharges estimated at measurement sites established as part of this study need to be re-evaluated periodically to ensure that they are representative of flow conditions during which interim instream-flow standards are being established.

Fieldwork in the Huelo Region

Estimates of natural low-flow duration discharges of short-term continuous-record stations, partial-record sites, and results of seepage runs for streams in the Huelo area are discussed in the following sections. Map identifier (Map ID) is used for references to partial-record (PR), short-term continuous record (CR) and seepage-run discharge-measurement sites (alphabetical by hydrologic unit).

Streamflow at Partial-Record Stations

Measured discharges at the partial-record sites in the Huelo region and concurrent daily mean discharges at selected index stations are summarized in tables 4-14. A measured discharge at a partial-record site was not used in record augmentation if (1) the discharge was measured when the hydrograph from the selected index station indicated highly variable flows, (2) the discharge was measured on the same streamflow recession as another measurement, or (3) the discharge has high measurement error.

Table 3. Upstream catchment basin characteristics for partial-record (PR) and continuous record (CR) sites in the study area, East Maui, Hawaiʻi. (Source: Rea and Skinner, 2012)

USGS station ID	Station ID	station name	Elevation (ft)	Catchment Area (mi^2)	Maximum Elevation (ft)	Mean Annual Precipitation (in)	Longest upstream length of channel (mi)
	PR-1	East Kōlea abv Wailoa Ditch	1240	0.07	1870	177	0.92
	PR-2	West Kōlea abv Wailoa Ditch	1270	0.10	1840	175	0.97
	PR-3	Punaluʻu Stream abv Center Ditch	740	0.14	1190	138	1.01
16565000	PR-4	Kaʻaiea abv Wailoa Ditch	1310	0.68	3240	209	3.54
	PR-5	Makanali abv Wailoa Ditch	1220	0.04	1550	169	0.49
16566000	PR-6	ʻOʻopuola abv Wailoa Ditch	1250	0.25	2060	180	1.56
	PR-7	ʻOʻopuola Tributary abv Wailoa Ditch	1200	0.08	1890	174	1.05
	PR-8	West ʻOʻopuola abv Wailoa Ditch	1190	0.09	1730	172	0.88
16570000	CR-1	Nailiilihaele abv Wailoa Ditch	1220	3.69	6760	188	8.02
	PR-9	Oanui abv Wailoa Ditch	1180	0.86	3310	194	3.92
16584000	PR-10	Kailua abv Lowrie Ditch	680	3.58	4980	202	7.49
	PR-11	Hanawana abv Lowrie Ditch	720	0.31	1540	143	1.78
	PR-12	Hoalua abv Wailoa Ditch	1710	0.21	2020	175	1.30
	PR-13	East Hoalua Tributary abv Wailoa Ditch	1700	0.41	3530	186	4.34
	PR-14	Hoalua abv Lowrie Ditch	640	1.10	3530	164	5.99
	PR-15	Waipiʻo abv Wailoa Ditch	1010	0.11	1530	148	0.93
16585000	PR-16	Hoʻolawaliilii abv Wailoa Ditch	1250	0.62	2600	176	2.87
16586000	PR-17	Hoʻolawanui abv Wailoa Ditch	1230	1.34	3510	188	5.14
	PR-18	West Hoʻolawanui abv Wailoa Ditch	1170	0.10	1730	158	0.93
	PR-19	Hoʻolawaliilii abv Lowrie Ditch	600	1.03	2600	153	4.75
	PR-20	Mokupapa abv Haiku Ditch	440	0.24	880	90	1.17

The MOVE.1 technique was used to estimate low-flow duration discharges for a majority of the partial-record sites in the study area, including two streams in the Kōlea hydrologic unit, four streams in the ‘O‘opuola hydrologic unit Streams, two streams in the Kailua hydrologic unit, three streams in the Hoalua hydrologic unit, four streams in the Ho‘olawa hydrologic unit, and one stream each in the Punalu‘u, Hanawana, and Waipi‘o hydrologic units.

The MOVE.1 model at the partial-record sites and concurrent daily mean discharges at the index stations had R^2 values that ranged from 0.76 to 0.99, correlation coefficients (*r*) that ranged from 0.87 to 0.99 (not shown), RMSE values that ranged from 0.02 to 1.54, and NSE that ranged from 0.75 to 0.99 (Table 15). Note that the closer the NSE is to 1, the more accurate the statistical model is.

The index stations used, record-augmentation techniques applied, and selected regression statistics computed for the low-flow duration-discharge estimates at short-term stations and partial-record sites in the study-area streams are summarized in Table 15.

Low-flow duration discharges were estimated with 7-16 measurements at each partial-record site. Low-flow duration discharges for 10 sites were estimated with less than 10 measurements when there was strong agreement between the partial-record site measurements and the selected index station discharge, indicating that hydrological conditions estimated with this technique were accurately depicted. Measured discharges at the partial-record sites used for record augmentation generally captured a wide distribution of flows between the Q_{99} and Q_{40} duration discharges that are of interest in this study. Therefore, the low-flow duration-discharge estimates are considered representative of the entire range of low-flow conditions in these streams. Estimated flow-duration discharges at partial-record sites in these streams are summarized in Table 16.

Low-flow duration discharges for partial-record sites on Oanui and Makanali were estimated using a logarithmic relationship within the linear model (table 4). Measured discharges at the partial-record site on Mokupapa Stream did not correlate with any index stations. On the day with the highest discharge, the corresponding concurrent daily mean discharge at the nearest continuous-record station was greater than the median discharge at that index station. Thus, low-flow duration discharges are likely to be below the highest discharge measured (i.e., below 0.72 ft^3/s) during the study period. Accessible reaches of Pā stream were limited to between the highway and Center Ditch, and only a limited number of measurements were made: 0.077 ft^3/s on 04/12/2021 above Center Ditch; 0.088 ft^3/s on 08/16/2021 above Center Ditch.

Streamflow Gains and Losses in the Huelo Region

As part of this study, a seepage run was conducted on all streams in the Huelo region except Punalu‘u, Pā, and Mokupapa streams, which were too small and inaccessible below Center Ditch or Hā‘iku Ditch (Figure 8-17). Results of seepage runs are provided from upstream to downstream order. Seepage gains and losses along a reach were computed as the difference between the upstream and downstream discharges, accounting for major tributary inflows and diversions of water within the reach (Table 18). To determine whether a stream supports continual flow to the stream mouth under natural-flow conditions, seepage rates (expressed as the streamflow gain or loss in ft^3/s per mile of stream reach [$(ft^3/s)/mi$]) computed using discharges on measured reaches were extrapolated to nearby reaches on the same stream where measurements were not available.

Above the Wailoa Ditch (e.g., ~1250 ft elevation), streams were observed to flow continuously. Previous work by Gingerich (1999b) and Gingerich (2005) quantified seepage gains in reaches above this elevation. As new information relating to seepage gains above this elevation was not critical to current data needs in the Huelo region, additional seepage runs above this elevation were not conducted.

Almost in entirety, streams gained flow from the upstream most measurements to the downstream-most measurements. This is a consequence of the stream gaining from groundwater seepage produced by incised Kula volcanics which have numerous perched water bodies as described in the section on hydrogeology and in previous studies (Gingerich, 1999b). The one exception to this was a small reach of the Nailiilihaele Stream where there was a losing stream reach. This reach is also overlain with Hana volcanics, and its not uncommon for streamflow to be lost in reaches with this geology (Gingerich, 1999b). All the lost flow was gained back as well as additional streamflow gained below a series of waterfalls. Helicopter reconnaissance by DLNR during extreme drought conditions in 2021 confirmed that each stream in the Huleo region continued to flow at the stream mouth, even when stream diversions were active.

Estimates of seepage gains across the Huelo Region

Low flow duration statistics for the gains in seepage between the Wailoa/New Hāmākua Ditch elevation at approximately 1250 ft and the Spreckels/Lowrie Ditch elevation at approximately 750 ft were measured on three streams. The mean drainage area normalized flow duration statistic was then used to predict low-flow duration

Figure 7. Trends in annual median baseflow (ft³/s) for three long-term continuous-record gaging stations in East Maui.

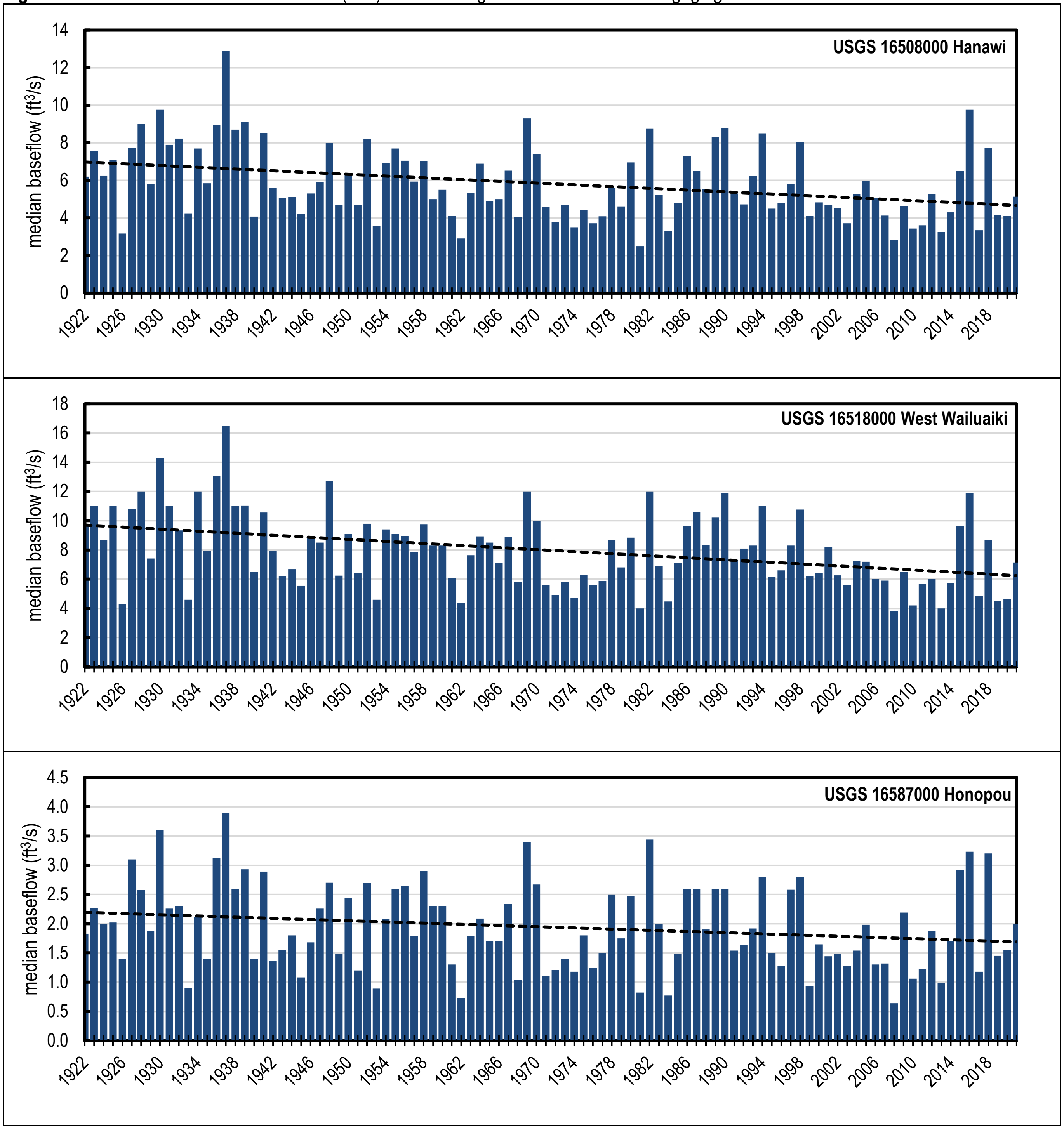


Table 4. Measured discharges at partial-record sites East Kōlea (PR-1) and West Kōlea (PR-2) stream and concurrent daily mean discharges at stream-gaging station 16570000 on Nailiilihaele Stream, East Maui, Hawai‘i.

[--, no value available; all values in cubic feet per second, ft^3/s]

Date	Mean daily flow on Nailiilihaele Stream at USGS 16570000	Measured discharge on East Kōlea at PR-1	Measured discharge on West Kōlea at PR-2
10/31/2007	--	0.47	1.53
7/15/2021	--	0.09	0.15
9/24/2021	8.1	0.14	0.28
10/5/2021	8.96	0.27	0.56
10/21/2021	15	0.34	0.63
11/5/2021	4.43	0.12	0.20
11/16/2021	3.28	0.07	0.11
11/23/2021	3.23	0.05	0.17
12/6/2021	40.4	<u>0.70</u>	<u>1.59</u>
12/10/2021	13.6	0.43	1.11
1/24/2022	3.42	0.10	0.18
2/25/2022	2.69	0.06	0.14

Table 5. Measured discharges at a partial-record site on Punalu‘u Stream (PR-3) and concurrent daily mean discharges at stream- gaging station 16587000 on Honopou Stream, East Maui, Hawai‘i.

[--, no value available; all values in cubic feet per second, ft^3/s; Measured discharge that is <u>underlined</u> is excluded from record augmentation because the hydrograph from the index station indicated highly variable flows during the time the measurement was made]

Date	Mean daily flow on Honopou Stream at USGS 16587000	Measured discharge on Punalu‘u Stream at PR-3
10/16/2007	2.57	0.55
4/12/2021	2.06	0.68
4/29/2021	5.89	1.55
7/7/2021	0.45	0.10
7/12/2021	0.33	0.06
7/19/2021	0.78	0.13
8/16/2021	1.07	<u>0.35</u>
9/20/2021	0.76	0.20
10/12/2021	10.1	2.95
11/1/2021	1.57	0.35
11/9/2021	1.02	0.21

Table 6. Measured discharges at a partial-record sites on the Ka‘aiea Stream (PR-4) and concurrent daily mean discharges at stream-gaging station 16570000 on Nailiilihaele Stream, East Maui, Hawai‘i.

[--, no value available; all values in cubic feet per second, ft^3/s]

Date	Mean daily flow on Nailiilihaele Stream at USGS 16570000	Measured discharge on Ka‘aiea Stream at PR-4
10/31/2007	--	3.80
7/15/2021	--	0.81
10/5/2021	8.96	2.23
11/5/2021	4.43	0.91
11/16/2021	3.28	0.82
11/23/2021	3.23	0.83
12/6/2021	40.4	<u>5.04</u>
1/24/2022	3.42	0.63
2/25/2022	2.69	0.48
3/28/2022	4.91	1.21

Table 7. Measured discharges at partial-record sites on Makanali (PR-5), ʻOʻopuola (PR-6), ʻOʻopuola Tributary (PR-7), West ʻOʻopuola (PR-8) streams and concurrent daily mean discharges at stream-gaging station 16570000 on Nailiʻiihaʻele Stream, East Maui, Hawaiʻi.
[--, no value available; all values in cubic feet per second, ft^3/s; Measured discharge that is underlined is excluded from record augmentation because the hydrograph from the index station indicated highly variable flows during the time the measurement was made]

Date	Mean daily flow on Nailiilihaele Stream at USGS 16570000	Measured discharge on Makanali Stream at PR-5	Measured discharge on ʻOʻopuola Stream at PR-6	Measured discharge on ʻOʻopuola Tributary at PR-7	Measured discharge on West ʻOʻopuola Stream at PR-8
10/24/2007	--		0.29	0.03	0.67
10/31/2007	--	0.47			
5/10/2021	--	0.21	0.62		
7/15/2021	--	0.09	0.35	0.05	
9/24/2021	8.10	0.14	0.78	0.14	0.26
10/5/2021	8.96	0.28	0.78	0.22	0.31
10/21/2021	15.0	0.28	1.03	0.24	0.34
11/5/2021	4.43	0.08	0.35	0.09	0.18
11/16/2021	3.28	0.05	0.24	0.05	0.12
11/23/2021	3.23	0.07	0.39	0.08	0.13
12/6/2021	40.4	0.31	2.26	0.53	1.15
12/10/2021	13.6	0.36	2.0	0.52	0.89
1/24/2022	3.42	0.15			0.14
2/25/2022	2.69	0.05	0.34	0.06	0.11

Table 8. Measured discharges at partial-record site on Kailua (PR-10) and Oanui Stream (PR-9) and concurrent daily mean discharges at stream-gaging station 16570000 on Nailiilihaele Stream and 16587000 on Honopou Stream, East Maui, Hawaiʻi.
[--, no value available; all values in cubic feet per second, ft^3/s; Measured discharge that is underlined is excluded from record augmentation because the hydrograph from the index station indicated highly variable flows during the time the measurement was made]

Date	Mean daily flow on Nailiilihaele Stream at USGS 16570000	Measured discharge on Oanui Stream at PR-9	Date	Mean daily flow on Honopou Stream at USGS 16587000	Measured discharge on Kailua Stream at PR-10
10/25/2007	--	1.51	5/22/1969	3.4	0.61
8/16/2021	9.92	1.55	10/11/2007	3.26	1.12
9/24/2021	8.1	0.82	1/22/2021	4.05	1.68
9/28/2021	28.4	3.35	4/29/2021	5.89	2.39
10/5/2021	8.96	1.05	7/12/2021	0.33	0.02
10/21/2021	15	1.94	8/16/2021	4.6	0.21
10/29/2021	6.71	1.00	11/22/2021	1.05	0.25
11/1/2021	5.26	0.87	11/30/2021	0.62	0.22
11/5/2021	4.43	0.60	12/6/2021	5.07	1.74
11/16/2021	3.28	0.22	1/11/2022	3.45	0.87
11/23/2021	3.23	0.17	1/24/2022	1.17	0.40
11/30/2021	24.9	1.63			
12/6/2021	40.4	5.22			

Table 9. Measured discharges at partial-record site on Hoalua (PR-12; PR-14) and East Hoalua Tributary (PR-13) and concurrent daily mean discharges at stream-gaging station 16570000 on Nailiilihaele Stream and at 16587000 on Honopou Stream, East Maui, Hawaiʻi.
[--, no value available; all values in cubic feet per second, ft^3/s; Measured discharge that is underlined is excluded from record augmentation because the hydrograph from the index station indicated highly variable flows during the time the measurement was made]

Date	Mean daily flow on Nailiilihaele Stream at USGS 16570000	Measured discharge on Hoalua Stream at PR-12	Measured discharge on East Hoalua Tributary at PR-13	Mean daily flow on Honopou Stream at USGS 16587000	Measured discharge on Hoalua Stream at PR-14
10/11/2007	--			3.26	2.21
12/14/2020	--			1.42	1.23
1/22/2021	--			5.16	6.03
4/9/2021	--	2.38	1.73		
7/12/2021	--	0.29	0.35		
7/19/2021	--			1.16	0.79
8/16/2021	9.92	1.01	0.86		
9/20/2021	5.69	0.64	0.83		
9/24/2021	8.1	0.69	0.51		
9/28/2021	28.4	2.25	2.09		
10/5/2021	8.96	0.79	0.63		
11/5/2021	4.43	0.69	0.49		
11/23/2021	3.23	0.45	0.27	0.76	0.40
11/29/2021				1.15	0.48
12/10/2021	13.6	1.5	1.27		
1/24/2022	3.42	0.7	0.40	1.17	0.86
2/25/2022	2.69	0.46	0.30	0.62	0.45

Table 10. Measured discharges at a partial-record site on the Hanawana Stream (PR-11) and concurrent daily mean discharges at stream-gaging station 16587000 on Honopou Stream, East Maui, Hawaiʻi.
[all values in cubic feet per second, ft^3/s]

Date	Mean daily flow on Honopou Stream at USGS 16587000	Measured discharge on Hanawana Stream at PR-11
10/4/2007	3.75	1.39
12/14/2020	1.42	0.46
1/22/2021	5.16	1.48
2/26/2021	5.45	1.28
4/9/2021	8.96	1.54
4/29/2021	5.89	0.90
5/10/2021	1.56	0.36
7/7/2021	0.45	0.08
7/12/2021	0.33	0.06
7/15/2021	0.35	0.05
7/19/2021	0.78	0.16
9/20/2021	0.76	0.14
11/1/2021	1.57	0.35
11/19/2021	0.64	0.14
11/29/2021	1.15	0.28
2/25/2022	0.62	0.12

Table 11. Measured discharges at a partial-record site on the Waipiʻo Stream (PR-15) and concurrent daily mean discharges at stream- gaging station 16508000 on Hanawi Stream, East Maui, Hawaiʻi.
[all values in cubic feet per second, ft^3/s]

Date	Mean daily flow on Hanawi Stream at USGS 16508000	Measured discharge on Waipiʻo Stream at PR-15
11/2/2007	13.8	0.44
8/10/2011	6.26	0.03
9/20/2021	2.93	0.12
9/24/2021	3.38	0.20
10/28/2021	6.14	0.67
11/5/2021	4.54	0.30
11/16/2021	3.13	0.07
11/22/2021	2.84	0.19
11/30/2021	5.31	0.58
12/10/2021	6.29	0.63
1/11/2022	6.33	0.86
1/24/2022	3.85	0.19
2/25/2022	2.38	0.08

Table 12. Measured discharges at partial-record sites on Hoolawaliilii (PR-16; PR-19), Hoʻolawanui (PR-17), West Hoʻolawanui (PR-18) and concurrent daily mean discharges at stream-gaging station 16587000 on Honopou Stream, East Maui, Hawaiʻi.
[all values in cubic feet per second, ft^3/s]

Date	Mean daily flow on Honopou Stream at USGS 16587000	Measured discharge on Hoolawaliilii Stream at PR-16	Measured discharge on Hoʻolawanui Stream at PR-17	Measured discharge on West Hoʻolawanui Stream at PR-18	Measured discharge on Hoolawaliilii Stream at PR-19
2/5/1998	0.87	1.89	0.39		0.82
10/10/2007	3.57		0.83		2.39
11/5/2007	2.0			0.34	
11/8/2007	1.64	3.9			
10/29/2020	0.20				0.32
2/26/2021	5.45				1.69
4/29/2021	5.89				2.07
9/20/2021	0.76	2.04	1.58	0.13	0.54
10/28/2021	2.07	3.37	3.32	0.31	
11/5/2021	1.27	2.27	2.03	0.14	
11/16/2021	0.78	1.84	1.33	0.11	
11/29/2021	1.32				0.75
1/11/2022	3.45[a]	4.22	5.04	0.15	2.34
1/24/2022	1.28	2.11	1.84	0.21	
2/25/2022	0.71	1.46	0.85	0.43	
3/28/2022	0.48				0.41

[a]mean discharge for the 24 hrs prior to measurement

Table 13. Measured discharges at partial-record site on Mokupapa Stream (PR-20), East Maui, Hawaiʻi.
[all values in cubic feet per second, ft^3/s]

Date	Measured discharge on Mokupapa Stream at PR-20
10/4/2007	0.450
1/22/2021	0.072
4/9/2021	0.064
7/19/2021	0.017
8/16/2021	0.088
1/11/2022	0.720

Table 14. Measured discharges at continuous-record site on Nailiilihaele Stream (CR-1) taken at noon from USGS 16570000 and concurrent mean daily discharges at stream-gaging station 16518000 on West Wailuaiki Stream, East Maui, Hawaiʻi.
[all values in cubic feet per second, ft^3/s]

Date	Mean daily flow on West Wailuaiki Stream at USGS 16518000	Measured discharge on Nailiilihaele Stream at CR-1
8/14/2021	7.97	13.4
8/20/2021	3.97	6.62
9/10/2021	3.69	4.05
9/24/2021	6.25	6.93
9/29/2022	7.08	12.9
10/21/2021	8.86	15.1
10/28/2021	5.65	7.31
11/13/2021	2.48	3.18
11/27/2021	2.07	2.72
12/9/2021	7.86	8.42
1/26/2022	2.8	3.16
2/12/2022	1.81	2.28
3/12/2022	1.43	2.19

Table 15. Summary of record augmentation methods regression equations, and selected regression statistics for partial-record sites in the study area streams, East Maui, Hawai'i.
[ID, identifier; USGS station number if a USGS station was historically operated at the given location; abv, above; R^2, coefficient of regression; NSE, Nash-Sutcliff coefficient of efficiency; RMSE, root mean square error]

USGS ID	Station ID	station name	USGS Index Station	regression equation	Number of measurements used (n)	R^2	NSE	RMSE
	PR-1	East Kōlea abv Wailoa Ditch	16570000	$Y_i = -0.81 + 1.028 * (x_i - 0.84)$	10	0.90	0.78	0.09
	PR-2	West Kōlea abv Wailoa Ditch	16570000	$Y_i = -0.48 + 1.052 * (x_i - 0.84)$	10	0.86	0.77	0.23
	PR-3	Punalu'u Stream abv Center Ditch	16587000	$Y_i = -0.47 + 1.129 * (x_i - 0.16)$	10	0.99	0.99	0.07
16565000	PR-4	Ka'aiea abv Wailoa Ditch	16570000	$Y_i = -0.04 + 1.226 * (x_i - 0.61)$	7	0.97	0.96	0.11
	PR-5	Makanali abv Wailoa Ditch	16570000	$Y_i = 0.7304 * LN(x_i) - 0.666$	8	0.76	0.75	0.04
16566000	PR-6	'O'opuola abv Wailoa Ditch	16570000	$Y_i = -0.31 + 0.846 * (x_i - 0.73)$	7	0.96	0.85	0.11
	PR-7	'O'opuola Tributary abv Wailoa Ditch	16570000	$Y_i = -0.97 + 0.912 * (x_i - 0.73)$	7	0.90	0.89	0.02
	PR-8	West 'O'opuola abv Wailoa Ditch	16570000	$Y_i = -0.74 + 0.724 * (x_i - 0.71)$	8	0.98	0.91	0.03
16570000	CR-1	Nailiilihaele abv Wailoa Ditch	16518000	$Y_i = 0.74 + 1.103 * (x_i - 0.61)$	13	0.88	0.87	1.54
	PR-9	Oanui abv Wailoa Ditch	16570000	$Y_i = 1.1294 * LN(x_i) + 0.137$	10	0.97	0.96	0.17
16584000	PR-10	Kailua abv Lowrie Ditch	16587000	$Y_i = -0.74 + 0.724 * (x_i - 0.71)$	9	0.92	0.86	0.27
	PR-11	Hanawana abv Lowrie Ditch	16587000	$Y_i = -0.52 + 1.10 * (x_i - 0.15)$	16	0.82	0.76	0.27
	PR-12	Hoalua abv Wailoa Ditch	16570000	$Y_i = -0.09 + 0.683 * (x_i - 0.83)$	9	0.93	0.93	0.14
	PR-13	East Hoalua Tributary abv Wailoa Ditch	16570000	$Y_i = -0.20 + 0.869 * (x_i - 0.83)$	9	0.93	0.93	0.14
	PR-14	Hoalua abv Lowrie Ditch	16587000	$Y_i = -0.002 + 1.298 * (x_i - 0.16)$	8	0.96	0.95	0.39
	PR-15	Waipi'o abv Wailoa Ditch	16508000	$Y_i = -0.59 + 2.464 * (x_i - 0.06)$	11	0.94	0.94	0.06
16585000	PR-16	Hoolawaliilii abv Wailoa Ditch	16587000	$Y_i = 0.38 + 0.670 * (x_i - 0.10)$	9	0.89	0.89	0.32
16586000	PR-17	Ho'olawanui abv Wailoa Ditch	16587000	$Y_i = 0.29 + 0.997 * (x_i - 0.11)$	7	0.99	0.99	0.14
	PR-18	West Ho'olawanui abv Wailoa Ditch	16587000	$Y_i = -0.77 + 0.949 * (x_i - 0.10)$	8	0.95	0.95	0.02
	PR-19	Hoolawaliilii abv Lowrie Ditch	16587000	$Y_i = 0.01 + 0.660 * (x_i - 0.21)$	11	0.84	0.83	0.37
	PR-20	Mokupapa abv Haiku Ditch			6		no correlation	

Table 16. Estimated natural low-flow duration discharges at partial-record (PR) and short-term continuous record (CR) sites and seepage gains at selection stream locations in the Huelo region, East Maui, Hawai‘i.
[ID, identifier; USGS station number if a USGS station was historically operated at the given location; abv, above]

			Discharge, in ft^3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded									
USGS ID	**Station ID**	**station name**	Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
	PR-1	East Kōlea abv Wailoa Ditch	0.30	0.26	0.23	0.19	0.16	0.14	0.12	0.10	0.08	0.06
	PR-2	West Kōlea abv Wailoa Ditch	0.65	0.56	0.48	0.41	0.35	0.29	0.25	0.21	0.17	0.13
	PR-3	Punalu‘u abv Center Ditch	0.48	0.43	0.37	0.30	0.27	0.22	0.19	0.15	0.12	0.09
16565000	PR-4	Ka‘aiea abv Wailoa Ditch	3.8	3.2	2.7	2.2	1.8	1.5	1.2	1.0	0.79	0.57
	PR-5	Makanali abv Wailoa Ditch	0.28	0.26	0.23	0.20	0.18	0.15	0.13	0.11	0.08	0.05
16566000	PR-6	‘O‘opuola abv Wailoa Ditch	1.0	0.92	0.82	0.72	0.63	0.55	0.48	0.42	0.35	0.28
	PR-7	‘O‘opuola Tributary abv Wailoa Ditch	0.24	0.21	0.19	0.16	0.14	0.12	0.11	0.09	0.08	0.06
	PR-8	West ‘O‘opuola abv Wailoa Ditch	0.36	0.32	0.29	0.26	0.23	0.21	0.19	0.17	0.14	0.12
16570000	CR-1	Nailiilihaele abv Wailoa Ditch	13	11	9.9	8.5	7.3	6.2	5.3	4.5	3.7	2.8
	PR-9	Oanui abv Wailoa Ditch	1.7	1.5	1.3	1.1	0.89	0.72	0.58	0.46	0.32	0.18
16577000	*PR-10	Kailua abv Lowrie Ditch	0.55	0.48	0.42	0.33	0.30	0.24	0.20	0.16	0.13	0.10
	PR-11	Hanawana abv Lowrie Ditch	0.44	0.39	0.34	0.27	0.25	0.21	0.17	0.14	0.12	0.09
	PR-12	Hoalua abv Wailoa Ditch	1.3	1.1	1.0	0.94	0.85	0.76	0.68	0.61	0.53	0.44
	PR-13	East Hoalua Tributary abv Wailoa Ditch	1.1	0.98	0.87	0.76	0.67	0.58	0.51	0.44	0.37	0.29
	*PR-14	Hoalua abv Lowrie Ditch	1.5	1.3	1.2	0.88	0.79	0.63	0.51	0.41	0.32	0.23
	PR-15	Waipi‘o abv Wailoa Ditch	0.73	0.52	0.39	0.30	0.23	0.19	0.14	0.11	0.09	0.06
16585000	PR-16	Hoolawaliilii abv Wailoa Ditch	3.3	3.1	2.8	2.5	2.3	2.1	1.9	1.7	1.5	1.2
16586000	PR-17	Ho‘olawanui abv Wailoa Ditch	3.0	2.7	2.4	2.0	1.8	1.5	1.3	1.1	0.91	0.71
	PR-18	West Ho‘olawanui abv Wailoa Ditch	0.26	0.23	0.21	0.17	0.16	0.13	0.12	0.10	0.08	0.07
	*PR-19	Hoolawaliilii abv Lowrie Ditch	1.2	1.1	1.0	0.88	0.83	0.74	0.67	0.60	0.53	0.45
	PR-20	Mokupapa abv Haiku Ditch	<0.72	<0.72	<0.72	<0.72	<0.72	<0.72	<0.72	<0.72	<0.72	<0.72

*represents seepage gains below Wailoa/New Hāmākua Ditches

Table 17. Estimated natural low-flow duration discharges at partial-record (PR) sites combined with the upstream PR sites for Huelo region streams above the Center or Lowrie Ditches (e.g., 750 ft elevation), East Maui, Hawaiʻi.

		Discharge, in ft^3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded									
Notes	**station name**	Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
PR-1 + PR-2 + Seepage Run	Kōlea at Center Ditch	0.97	0.84	0.73	0.62	0.53	0.45	0.39	0.33	0.27	0.21
PR-4 + Seepage Run	Kaʻaiea at Center Ditch	4.1	3.5	3.0	2.5	2.1	1.8	1.5	1.3	1.1	0.91
PR-6 + PR-7 + PR-8 + Seepage Run	ʻOʻopuola at Center Ditch	1.8	1.7	1.5	1.4	1.2	1.1	1.0	0.92	0.81	0.70
CR-1 + Seepage Run	Nailiilihaele abv Spreckels Ditch	16	14	12	11	9.7	8.6	7.7	6.9	6.1	5.2
PR-9 + PR-10 + USGS 16557000	Kailua at Lowrie Ditch	10	9.0	7.9	6.5	5.6	5.0	4.2	3.3	2.6	1.8
PR-12 + PR-13 + PR-14	Hoalua at Lowrie Ditch	4.0	3.7	3.4	2.8	2.5	2.3	2.0	1.6	1.4	1.1
PR-15 + Seepage Run	Waipiʻo at Lowrie Ditch	0.74	0.53	0.4	0.31	0.24	0.2	0.15	0.12	0.1	0.07
PR-16 + PR-19	Hoolawaliilii at Lowrie Ditch	4.4	4.1	3.8	3.3	3.2	2.8	2.5	2.2	2.0	1.7
PR-17 + PR-18 + Seepage Run	Hoʻolawanui at Lowrie Ditch	3.9	3.5	3.1	2.6	2.4	2.0	1.7	1.5	1.3	1.0

Table 18. Seepage run discharge measurements and net streamflow gains/loss in the study area streams, East Maui, Hawaiʻi.

Seepage Site ID	Station Name	Elevation (ft)	Date	Time	Discharge (ft^3/s)	stream reach length (mi)	Streamflow gain or loss (ft^3/s)	Streamflow gain or loss rate ($ft^3/s/mi$)
				Kōlea Stream				
July 15, 2021								
A-1	East Kōlea abv Wailoa Ditch	1240	07/15/21	12:45	0.05			
A-2	East Kōlea blw New Hāmākua Ditch	1220	07/15/21	12:30	0.00			
A-5	West Kōlea abv Wailoa Ditch	1250	07/15/21	12:45	0.15			
A-6	West Kōlea blw Wailoa Ditch	1220	07/15/21	12:30	0.00			
A-3	Kōlea Stream abv Center Ditch	750	07/15/21	9:15	0.014	1.05	0.014	0.013
A-7	Kōlea Tributary abv Center Ditch	750	07/15/21	9:15	0.0035			
A-4	Kōlea Stream at Hana Hwy	600	07/15/21	10:30	0.29	0.26	0.273	1.05
				Kaʻaiea Stream				
March 28, 2022								
B-1	Kaʻaiea Stream abv Wailoa Ditch	1340	03/28/22	13:45	1.21			
B-2	Kaʻaiea Stream blw Wailoa Ditch	1220	03/28/22	13:40	0.04			
B-3	Kaʻaiea Stream abv Spreckels Ditch	925	03/28/22	10:40	0.25	0.69	0.21	0.30
B-4	Kaʻaiea Stream blw Spreckels Ditch	910	03/28/22	10:50	0.095			
B-5	Kaʻaiea Stream abv Center Ditch	700	03/28/22	9:10	0.22	0.59	0.13	0.21
				ʻOʻopuola Stream				
May 10, 2021								
C-1	Makanali Stream abv Wailoa Ditch	1220	05/10/21	11:40	0.213			
C-2	Makanali Stream blw New Hāmākua Ditch	1200	05/10/21	11:30	0.093			
C-3	Makanali Stream abv Spreckels Ditch	930	05/10/21	14:40	0.333	0.56	0.24	0.43
C-17	Makanali Stream blw Spreckels Ditch	910	05/10/21	14:40	0.00			
C-4	Makanali Stream abv Center Ditch	700	05/10/21	16:00	0.063	0.46	0.063	0.14
C-5	Makanali Tributary abv New Hāmākua Ditch	1150	05/10/21	11:00	0.00			
C-6	Makanali Tributary abv Spreckels Ditch	905	05/10/21	14:00	0.065	0.35	0.065	0.19

Table 18. [continued].

Seepage Site ID	Station Name	Elevation (ft)	Date	Time	Discharge (ft^3/s)	stream reach length (mi)	Streamflow gain or loss (ft^3/s)	Streamflow gain or loss rate (ft^3/s/mi)
‘O‘opuola Stream—continued								
C-7	‘O‘opuola Stream abv Wailoa Ditch	1250	05/10/21	10:30	0.623			
C-8	‘O‘opuola Stream blw New Hāmākua Ditch	1200	05/10/21	11:00	0.00			
C-13	‘O‘opuola Tributary abv Wailoa Ditch	1230	05/10/21	10:30	0.217			
C-14	‘O‘opuola Tributary blw New Hāmākua Ditch	1220	05/10/21	10:10	0.012			
C-15	West ‘O‘opuola Stream abv Wailoa Ditch	1180	05/10/21	9:15	0.314			
C-16	West ‘O‘opuola Stream blw New Hāmākua Ditch	1160	05/10/21	9:30	0.00			
C-9	‘O‘opuola Stream abv Spreckels Ditch	890	05/10/21	13:20	0.244	0.64	0.232	0.36
C-10	‘O‘opuola Stream blw Spreckels Ditch	870	05/10/21	13:30	0.040			
C-11	‘O‘opuola Stream abv Center Ditch	710	05/10/21	16:10	0.043	0.22	0.003	0.01
Nailiilihaele Stream								
October 23, 2020								
D-2	Nailiilihaele blw New Hāmākua Ditch	1190	10/23/20	16:30	0.00			
D-5	Nailiilihaele abv Sprecekles Ditch Inflow	670	10/23/20	13:10	0.49	1.15	0.49	0.43
December 18, 2020								
D-6	Nailiilihaele at Mouth	200	12/18/20	14:30	4.57			
May 12, 2022								
D-1	Nailiilihaele at USGS 1657000	1225	05/12/22	12:30	16.3			
D-2	Nailiilihaele blw New Hāmākua Ditch	1190	05/12/22	12:45	14.9[a]			
D-3	Nailiiliihaele at road crossing	1160	05/12/22	13:55	17.1	0.14	2.2	15.7
D-4	Nailiilihaele abv Feeder Ditch	1030	05/12/22	14:45	16.2	0.44	-0.9	-2.05
D-5	Nailiilihaele abv Sprecekles Ditch Inflow	670	05/12/22	16:04	19.3	0.57	3.1	5.44

[a]an uknown amount of water was diverted at Wailoa Ditch and an unknown amount of water was returned from New Hāmākua Ditch so no seepage change was calculated

Table 18. [continued].

Seepage Site ID	Station Name	Elevation (ft)	Date	Time	Discharge (ft^3/s)	stream reach length (mi)	Streamflow gain or loss (ft^3/s)	Streamflow gain or loss rate ($ft^3/s/mi$)
				Kailua Stream				
August 16, 2021								
E-1a	Oanui abv Wailoa Ditch	1300	08/16/21	14:20	1.55			
E-1b	Oanui blw Wailoa Ditch	1280	08/16/21	14:10	0.01			
E-2	Oanui abv New Hāmākua Ditch	1240	08/16/21	14:15	0.41			
E-3	Oanui blw New Hāmākua Ditch	1200	08/16/21	14:10	0.00			
E-4	Kailua Stream blw Wailoa Ditch	1260	08/16/21	15:00	0.01			
E-5	Kailua Stream abv Lowrie Ditch	1230	08/16/21	16:00	0.21	1.36	0.20	0.15
December 18, 2020								
E-6	Kailua Stream blw Haiku Ditch		12/18/21	9:30	0.01			
E-7	Kailua Stream at mouth	180	12/18/21	12:30	0.48	0.22	0.47	2.14
				Hanawana Stream				
February 26, 2021								
F-1	Hanawana Stream abv Lowrie Ditch	760	02/26/21		1.28			
F-2	Hanawana Stream blw Lowrie Ditch	730	02/26/21		0.51			
F-3	Hanawana Stream at 400ft	400	02/26/21		0.88	0.38	0.24	0.97
F-4	Hanawana Stream at 300ft	300	02/26/21		1.24	0.31	0.36	1.16
				Hoalua Stream				
November 26, 2021								
G-1	Hoalua Stream abv Wailoa Ditch	1250	11/23/21	13:40	0.45			
G-2	Hoalua Tributary abv Wailoa Ditch	1200	11/23/21	14:30	0.27			
G-3	Hoalua Stream blw New Hāmākua Ditch	1100	11/23/21		0.00			
G-4	Hoalua Stream abv Lowrie Ditch	640	11/23/21		0.40	1.55	0.40	0.26
November 29. 2021								
G-4	Hoalua Stream abv Lowrie Ditch	640	11/29/21		0.48			
G-5	Lowrie Ditch bf Hoalua Stream	640	11/29/21		0.16			
G-6	Hoalua Stream abv Haiku Ditch	500	11/29/21		1.04	0.33	0.40	1.21

Table 18. [continued].

Seepage Site ID	Station Name	Elevation (ft)	Date	Time	Discharge (ft^3/s)	stream reach length (mi)	Streamflow gain or loss (ft^3/s)	Streamflow gain or loss rate ($ft^3/s/mi$)
				Waipi‘o Stream				
November 16, 2021								
H-1	Waipi‘o Stream abv New Hāmākua Ditch	1100	11/16/21	14:46	0.07			
H-2	Waipi‘o Stream blw New Hāmākua Ditch	1080	11/16/21	15:00	0.00			
H-3	Waipi‘o Stream abv Lowrie Ditch	670	11/16/21	17:15	0.01	0.78	0.01	0.01
November 19, 2021								
H-4	Waipi‘o Stream blw Lowrie Ditch	660	11/19/21	09:00	0.00			
H-6	Waipi‘o Stream abv Haiku Ditch	430	11/19/21	09:45	0.10	0.77	0.35	0.13
January 11, 2022								
H-1	Waipi‘o Stream abv New Hāmākua Ditch	1100	01/11/22	13:00	0.86			
H-2	Waipi‘o Stream blw New Hāmākua Ditch	1080	01/11/22	13:30	0.00			
H-4	Waipi‘o Stream blw Lowrie Ditch	660	01/11/22	16:00	0.00			
H-5	Waipi‘o Stream at Hana Hwy	550	01/11/22	17:02	0.13	0.42	0.13	0.31
				Ho‘olawa Stream				
September 20, 2021								
J-1	Hoolawaliilii abv Wailoa Ditch	1250	09/20/2021	11:20	2.04			
J-1	Hoolawaliilii blw Wailoa Ditch	1230	09/20/2021	11:20	0.00			
J-3	Hoolawaliilii abv Lowrie Ditch	700	09/20/2021	13:03	0.54	1.88	0.54	0.29
J-11	Ho‘olawanui abv Wailoa Ditch	1230	09/20/2021	10:35	1.58			
J-12	Ho‘olawanui blw New Hāmākua Ditch	1170	09/20/2021	10:00	0.00			
J-13	Ho‘olawanui abv confl w/West Ho‘olawanui	1120	09/20/2021	10:15	0.013			
J-16	West Ho‘olawanui abv Wailoa Ditch	1220	09/20/2021	09:26	0.134			
J-17	West Ho‘olawanui blw New Hāmākua Ditch	1210	09/20/2021	10:00	0.00			
J-14	Ho‘olawanui blw confl w/West Ho‘olawanui	1100	09/20/2021	10:15	0.043	0.22	0.43	0.20
J-13	Ho‘olawanui abv Lowrie Ditch	710	09/20/2021	13:40	0.40	1.28	0.35	0.28

Figure 8. Seepage run results for Kōlea Stream in East Maui, Hawaiʻi.

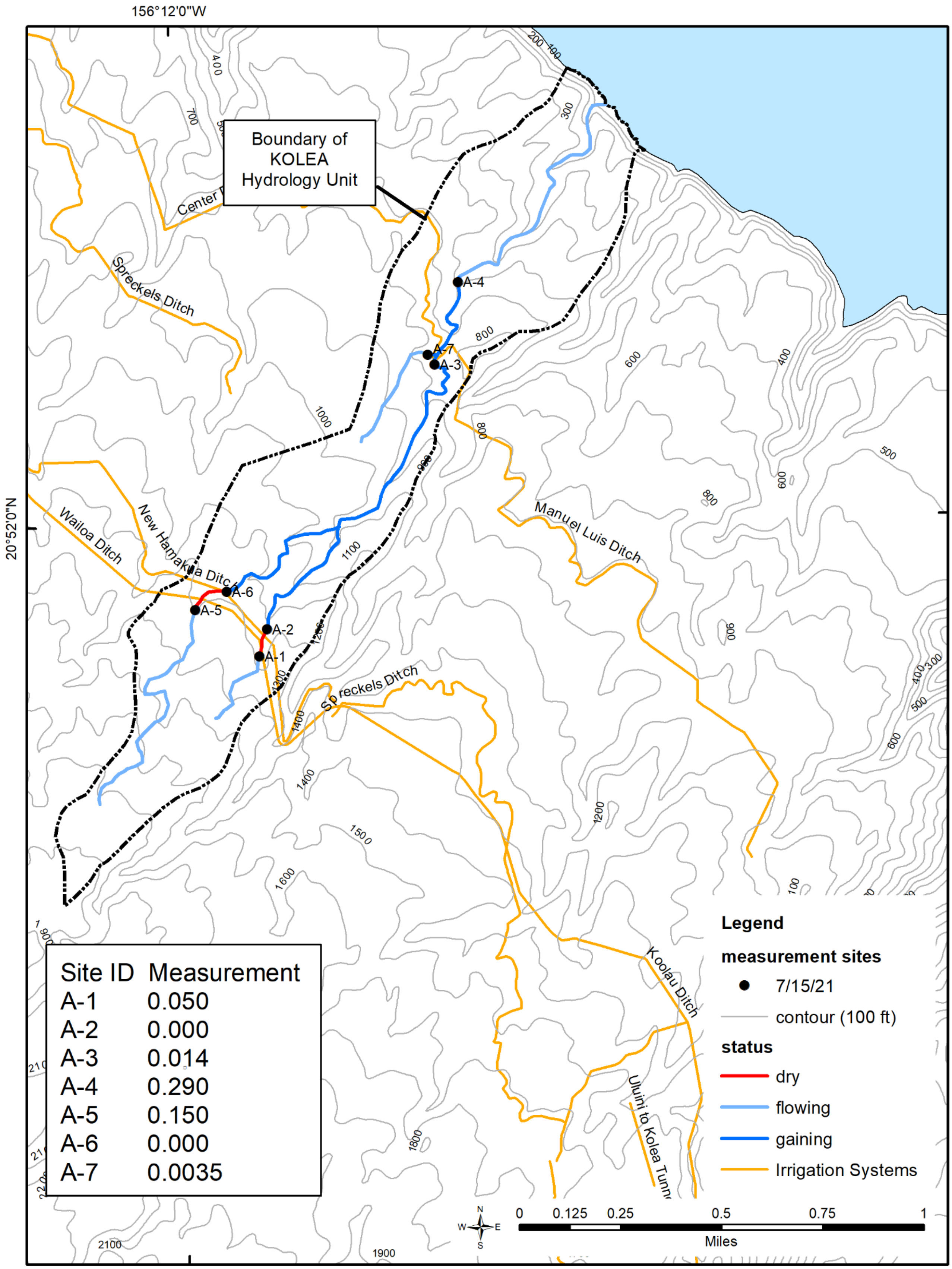


Figure 9. Seepage run results for Ka‘aiea Stream on 03/28/2022 in East Maui, Hawai‘i.

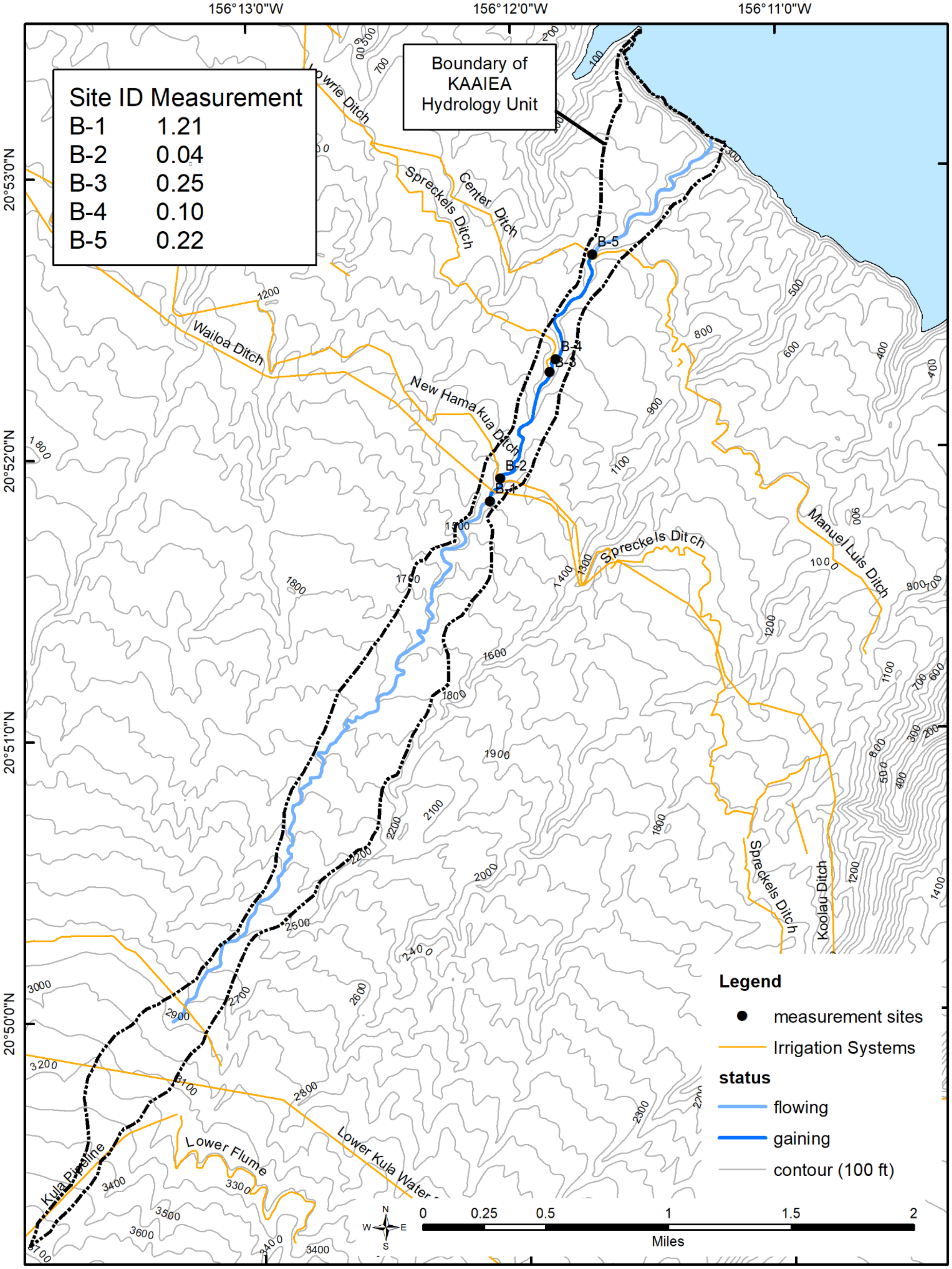


Figure 10. Seepage run results for ‘O‘opuola Stream in East Maui, Hawai‘i.

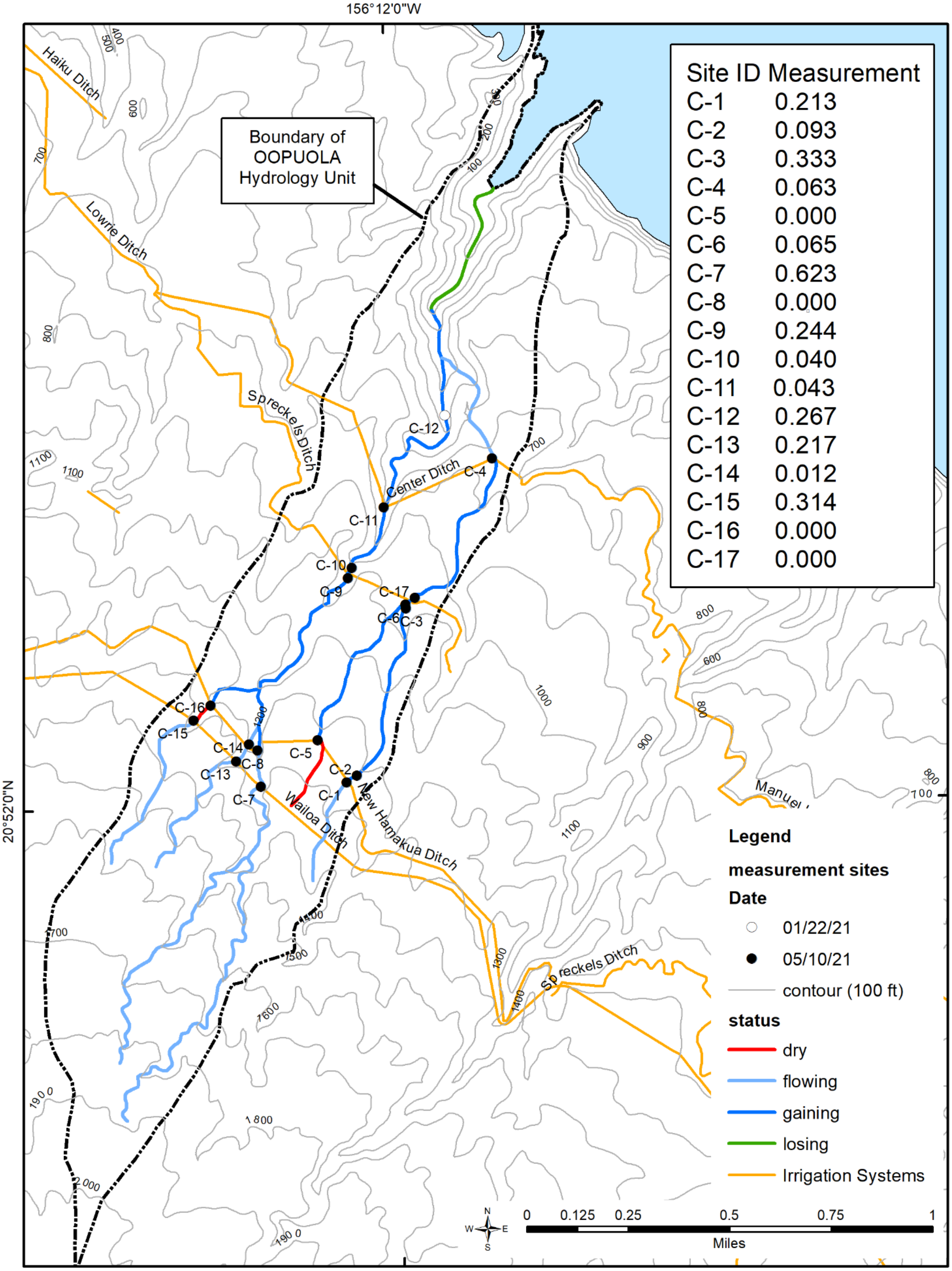


Figure 11. Seepage run results for Nailiilihaele Stream in East Maui, Hawai'i

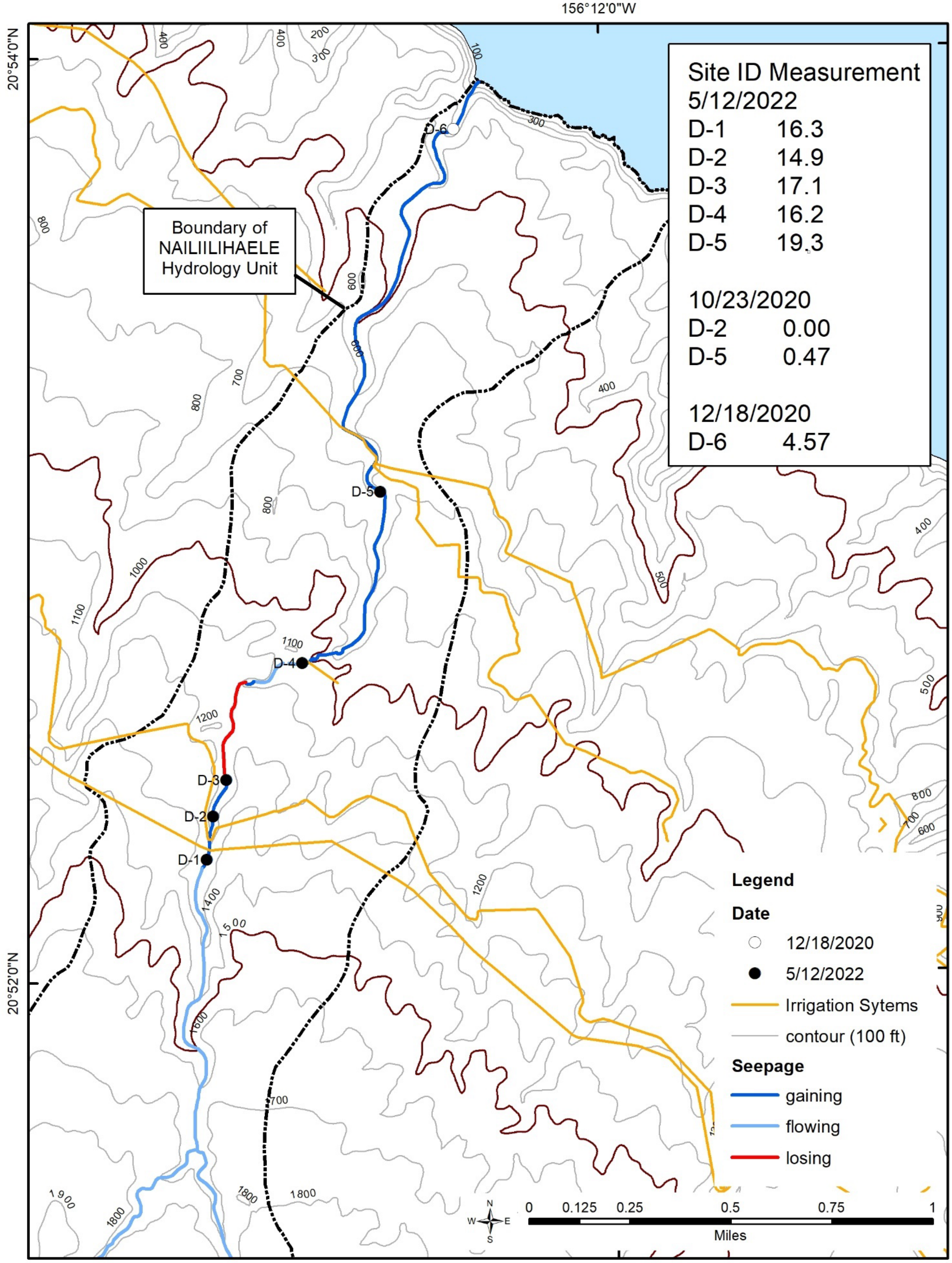


Figure 12. Seepage run results for Kailua Stream in East Maui, Hawaiʻi

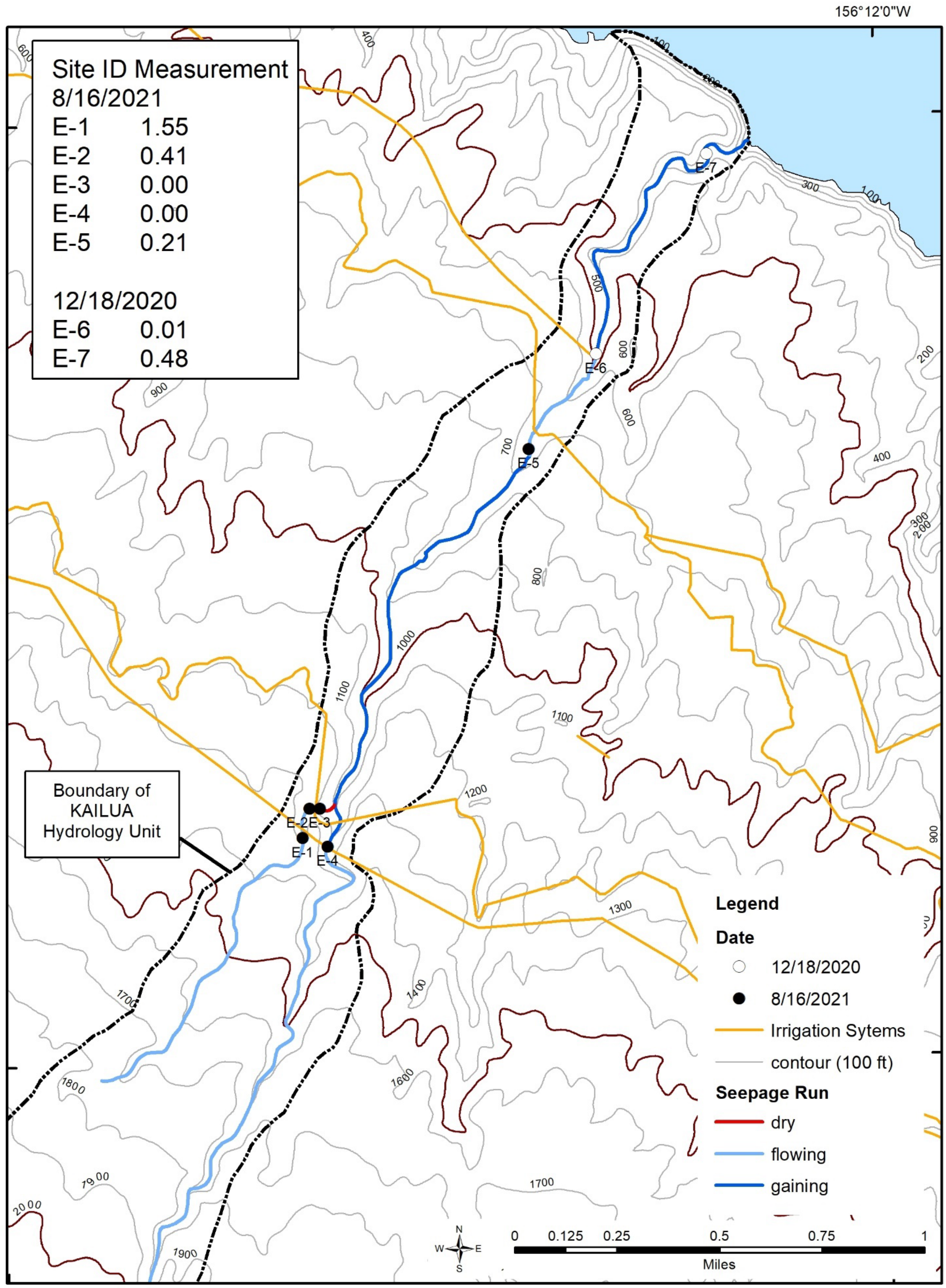


Figure 13. Seepage run results for Hanawana Stream in East Maui, Hawaiʻi.

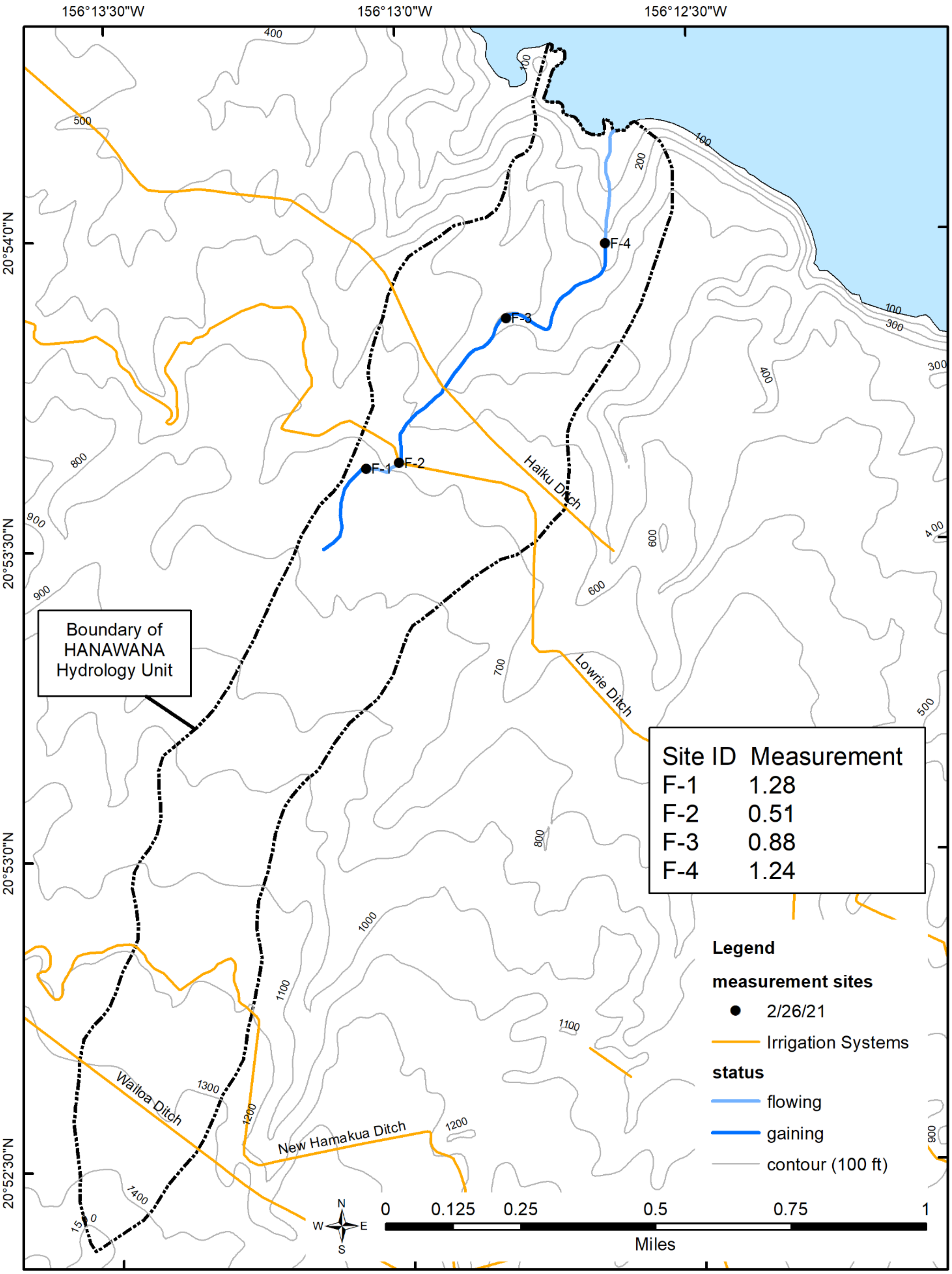


Figure 14. Seepage run results for Hoalua Stream in East Maui, Hawaiʻi.

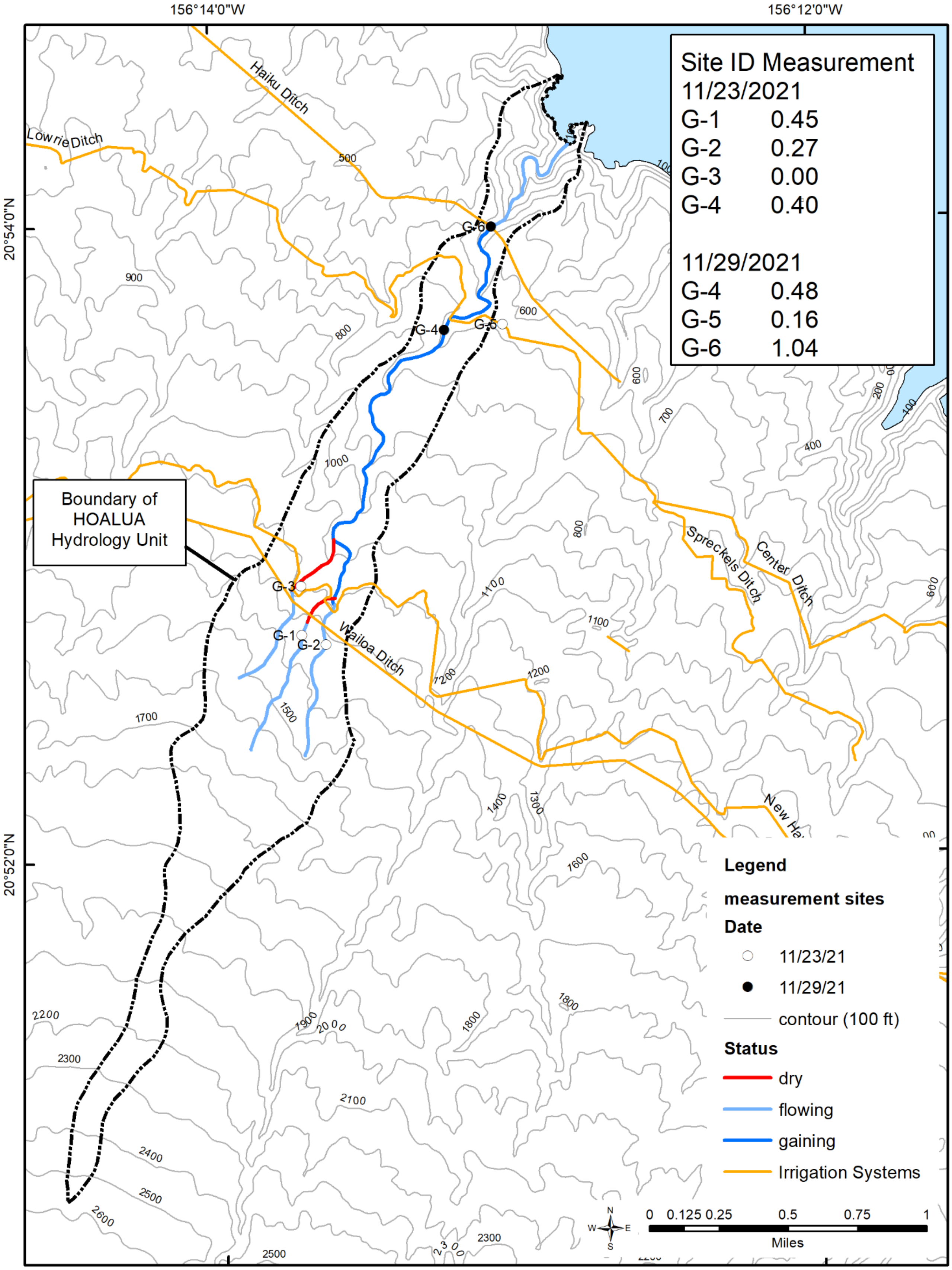


Figure 15. Seepage run results for Waipi'o Stream in East Maui, Hawai'i.

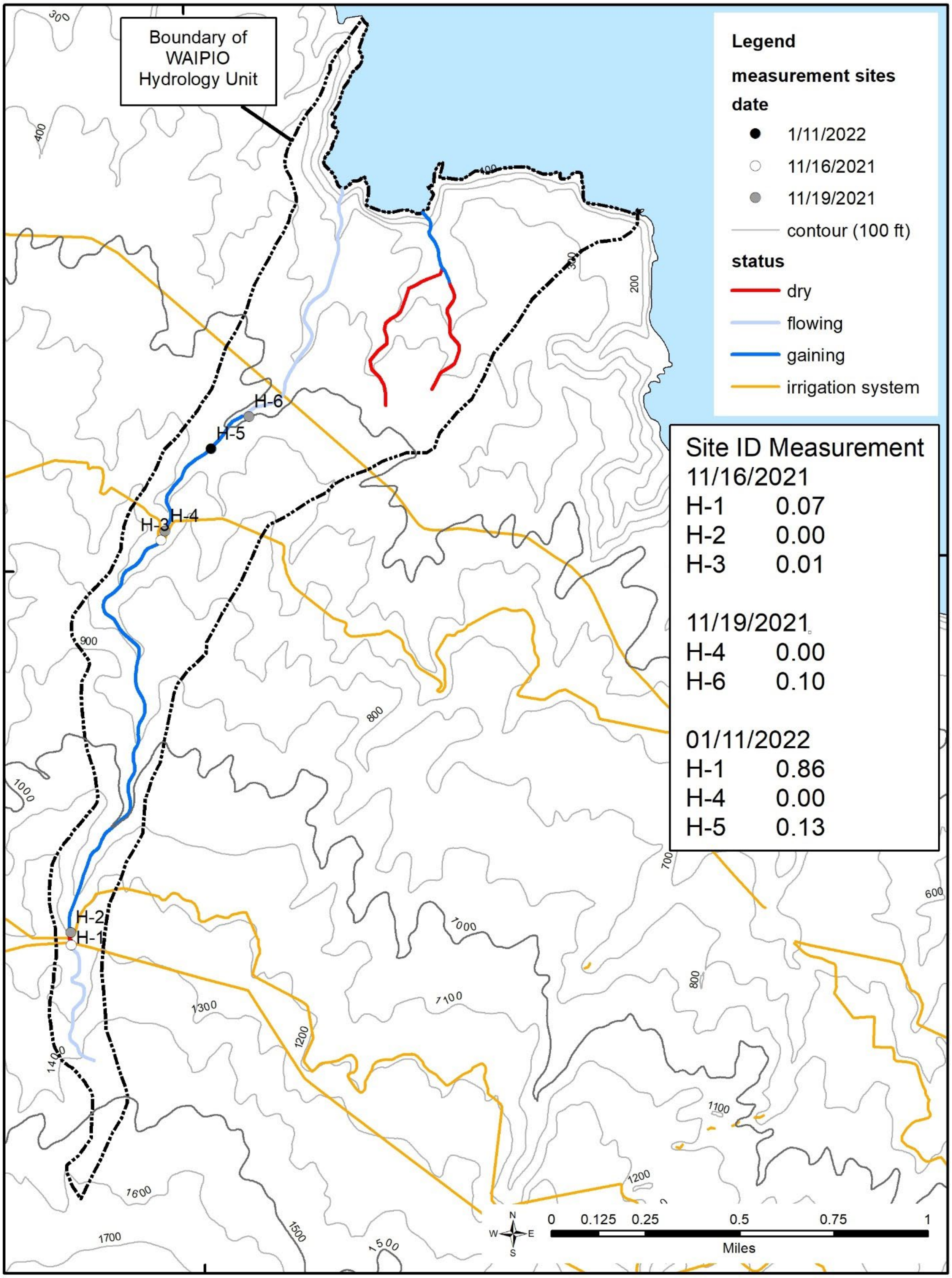


Figure 16. Seepage run results from 2020 and 2021 on Ho'olawa Stream in East Maui, Hawai'i.

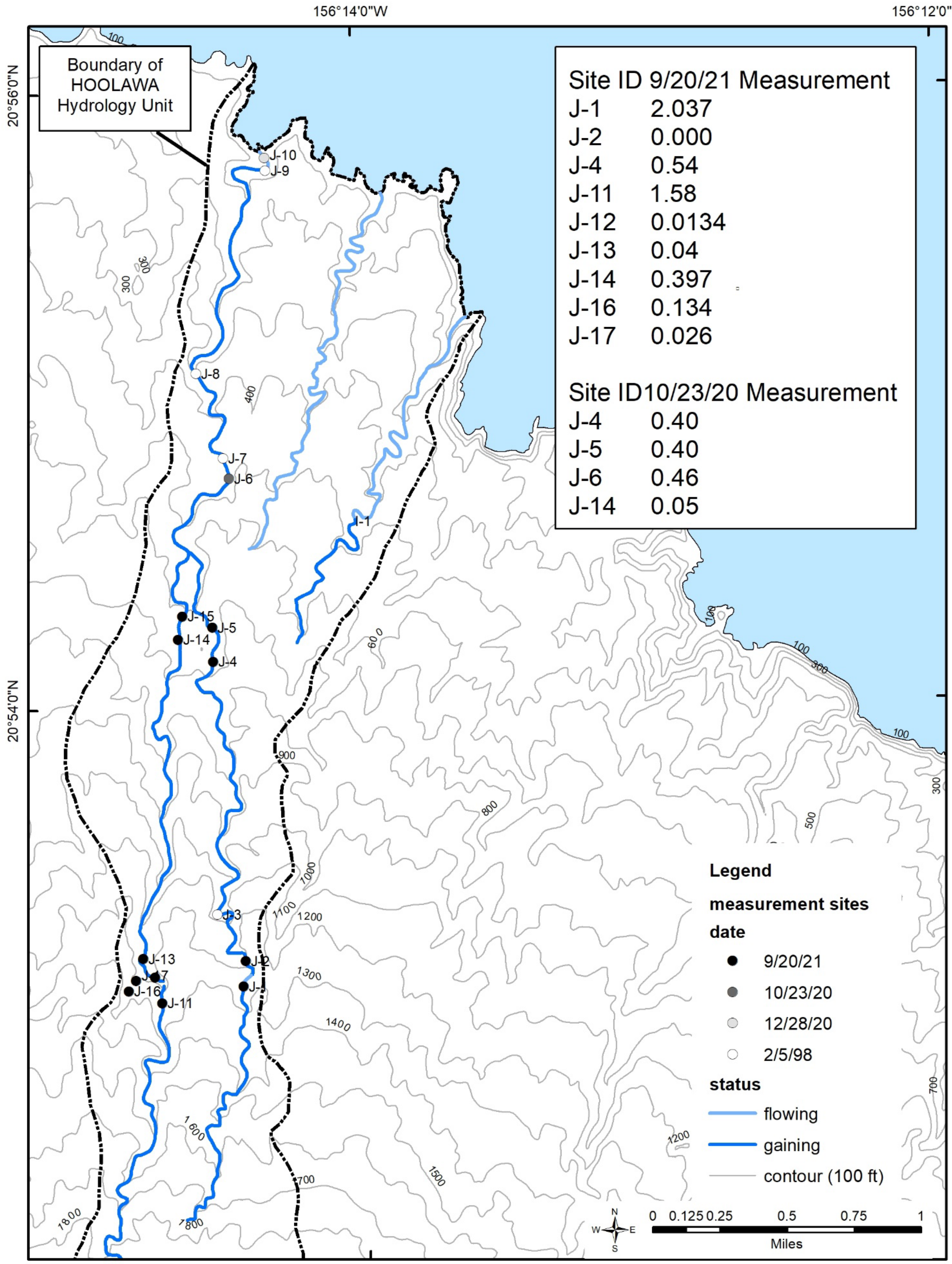
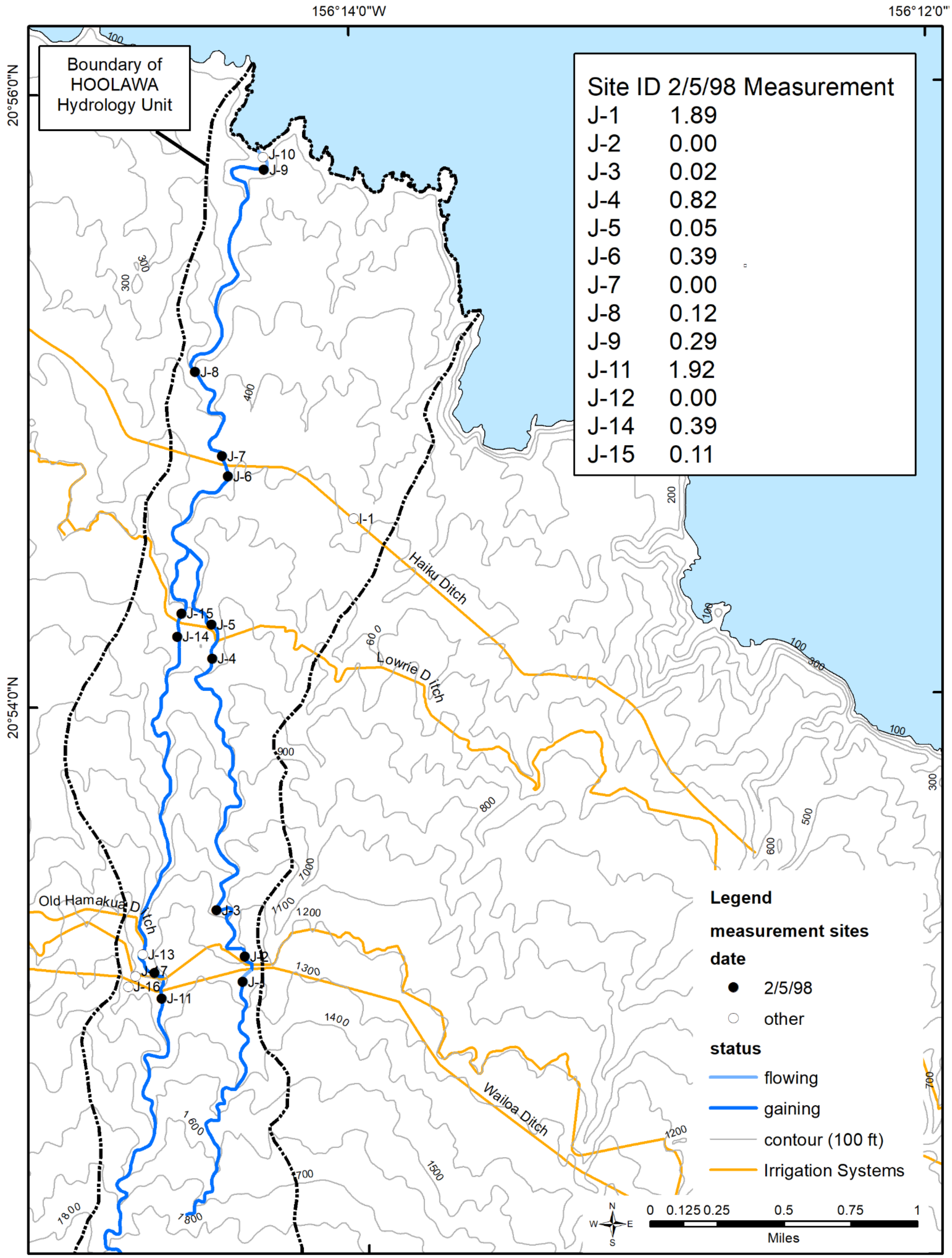


Figure 17. Seepage run results from 1998 on Ho'olawa Stream in East Maui, Hawai'i. (Source: Gingerich, 1999)



statistics at similar elevations at other locations in the Huelo region. Values were then verified with streamflow measurements during seepage runs.

III. Estimates of Streamflow at Upper and Lower Kula Systems

There are two water systems that divert surface flows from East Maui streams that exclusively serve the County of Maui Department of Water Supply: the Upper Kula System and the Lower Kula System (Figure 18). The Upper Kula System consists of four major stream diversions and dozens of minor stream diversions between the Haipuaʻena and Māliko gulches and transports diverted flow through four large reservoirs to the Olinda Water Treatment facility. The Lower Kula System consists of seven major diversions between the Honomanū and Waikamoi gulches and transports diverted flow to the Piʻiholo Reservoir and Water Treatment facility.

Upper Kula System

The Upper Kula system first started as a pipeline built in the 1890s to bring water from headwater perennial streams at approximately the 4,500 ft elevation to the Kula region of Upcountry Maui to support domestic and newly established diversified agricultural activities, including dairy farming, vegetable crops, and other diversified agriculture. The initial system was built in 1912 to divert water from small perennial streams between Waikamoi and Māliko gulches through the construction of cut stone and concrete masonry dams. These dams exist on tributaries of Nailiilihaele, Kailua, Opana, and Māliko streams. Iron pipelines 8-12 inches in diameter connect the dams to a main transmission pipeline, which is now a 36-inch galvanized pipeline. A dam was constructed across Waikamoi gulch at 4,500 ft in elevation to store water as an instream reservoir.

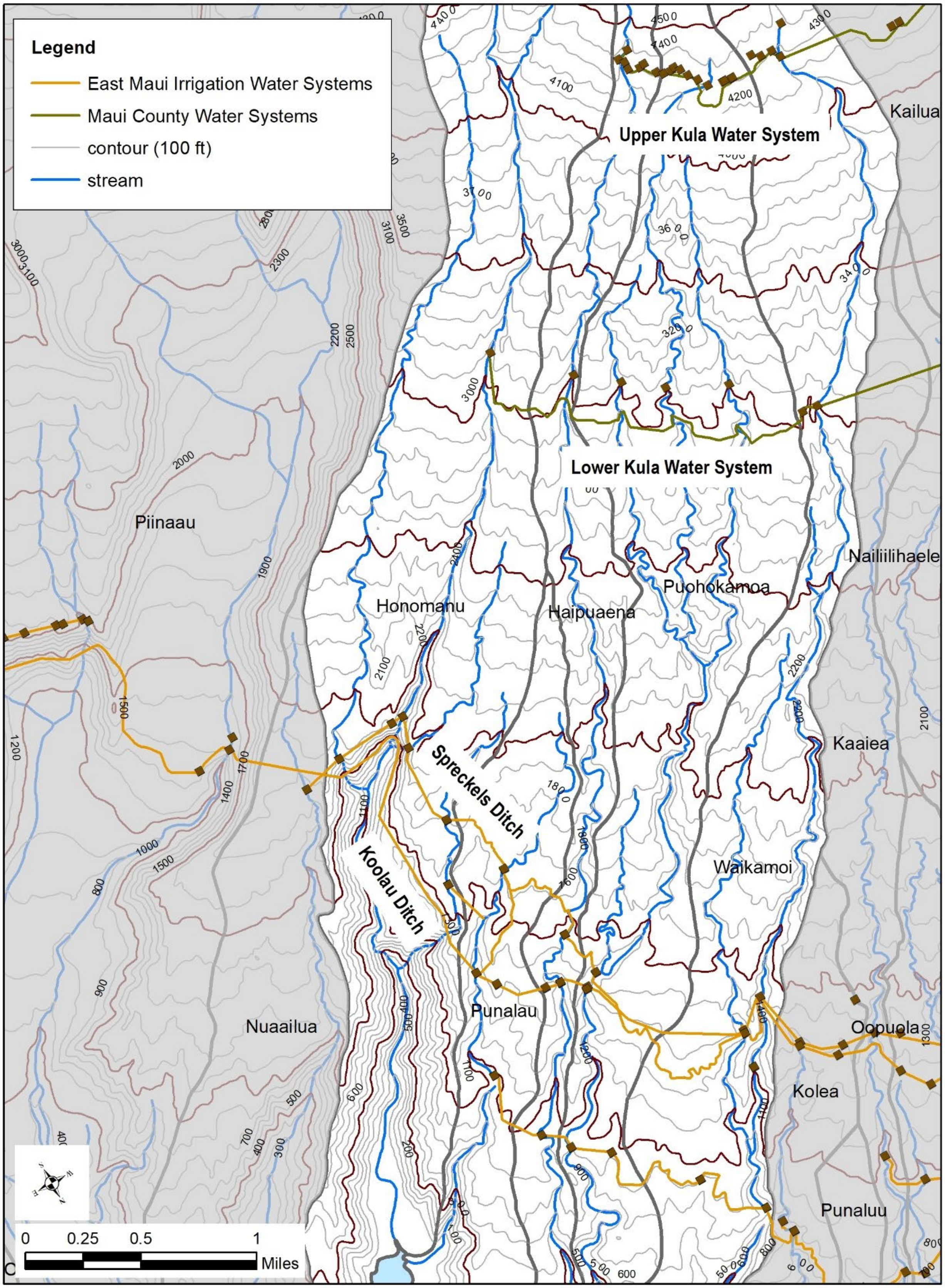
By the 1930s, the system was expanded eastward to Puohokamoa, Haipuaena, and Honomanū gulches using a redwood cedar flume, diverting many small springs along the way (Takasaki and Yamanaga, 1970). The flume was replaced in sections in the 1960s, although the terminus then became Haipuaena. In the 2010s, it was completely replaced using a prefabricated, aluminum design. While there are dozens of small diversions, the three main sources of water are Waikamoi Stream, the Middle Branch of Puohokamoa Stream, and Haipuaʻena Stream.

Prior to the extension of the Upper Kula System to Haipuaena, additional streamflow measurements were made in the Haipuaena watershed by EMI staff in the 1930s on Haleakala Ranch at Ukulele Camp, or at approximately 5,200 ft in elevation (Table 19) and at Piʻinaʻau (Appendix B).

Table 19. Miscellaneous EMI streamflow measurements from Haipuaʻena watershed at approximately 5,200 ft elevation and flow duration (FD) estimate based on concurrent mean daily flow (MDF) for Honopou Stream at USGS 16587000 for the historic (1920-1929) period.
[Br = branch]

location	Date	measured flow (ft^3/s)	MDF at USGS 16587000 (ft^3/s)	FD (%)
East Br.	9/20/29	0.01	0.93	Q_{85}
Haipuaena	10/10/29	0.43	4.8	Q_{20}
West Br.	9/27/29	0.05	1.1	Q_{80}
Haipuaena	10/10/29	0.25	4.8	Q_{20}
	10/11/29	0.05	2.3	Q_{45}
Haipuaena	10/04/29	0.08	0.93	Q_{85}
Stream	10/18/29	0.04	1.1	Q_{80}
	10/26/29	0.03	1.1	Q_{80}
	11/03/29	0.05	0.93	Q_{85}
	11/08/29	0.01	0.93	Q_{85}

Figure 18. Diversions and water delivery systems associated with the Upper and Lower Kula Water Systems, East Maui.



From 1946-1968, USGS station 16531100 continuously monitored flow on Haipuaena Stream, with one station in the flume and one below the flume to quantify total streamflow. From 1953 to 1968, USGS 16552800 on Waikamoi Stream above the Kula Pipeline intake was active. This station was reactivated in 2009. Cheng (2016) adjusted low-flow duration discharge characteristics from these stations to the common base period from 1984-2013. In addition to these stations as well as a partial-record station on Pi‘ina‘au Stream (Appendix B), and USGS 16596200 on Halehāku Stream, a linear regression model using basin characteristics (n = 4) was developed to estimate low-flow duration discharge values for the Middle Branch of Puohokamoa. Model results strongly predicted observed values for Q_{50} ($R^2 = 0.996$, NSE = 0.996) and Q_{95} ($R^2 = 0.998$, NSE = 0.998). These data are provided in Table 20. Total flow diverted from the three main sources (e.g., Haipuaena, Middle Branch Puohokamoa, Waikamoi) has a Q_{50} of approximately 0.86 cfs and a Q_{90} of approximately 0.11 cfs.

Table 20. Estimated low-flow duration statistics for USGS 16531100 on Haipuaena Stream at Kula Diversion and for USGS 16552800 on Waikamoi Stream above Kula Pipeline for the period of record (1946-1968) for the current climate period (1984-2013) from Cheng (2016) and at Middle Branch Puohokamoa at 4310 ft based on watershed modeling.
[all values in cubic feet per second, ft^3/s]

	USGS 16531100 Haipuaena Stream		USGS 16552800 Waikamoi Stream		Middle Branch Puohokamoa
	1946-1968	1984-2013	1953-1968	1984-2013	1984-2013
Q_{50}	0.47	0.43	0.15	0.12	0.31
Q_{55}	0.41		0.12	0.09	0.24
Q_{60}	0.34		0.09	0.07	0.19
Q_{65}	0.29		0.08	0.06	0.15
Q_{70}	0.23		0.06	0.05	0.11
Q_{75}	0.19	0.12	0.06	0.04	0.09
Q_{80}	0.15		0.05	0.03	0.07
Q_{85}	0.11	0.06	0.05	0.03	0.06
Q_{90}	0.08		0.03	0.02	0.04
Q_{95}	0.05	0.04	0.03	0.01	0.03

Lower Kula System

The Lower Kula system was constructed in the 1930s in response to the expansion of sugarcane which resulted in population growth and increased demand for locally sourced foods. The system originally incorporated a series of stream diversions and flumes at approximately the 3,200 ft elevation, above the Hā‘iku-Uka boundary, designed to transport water from two branches of Puohokamoa, two branches of Waikamoi, and numerous springs to a pumphouse where it was pumped up to the Upper Kula Pipeline.

By the 1960s, population growth in Upcountry Maui demanded additional domestic water and in 1972, a new pipeline was installed with new stream diversions from Waikamoi to Honomanū. Each diversion was constructed in a similar manner, with a capacity of approximately 7.7 ft^3/s (Figure 19). Pipeline capacity limits the cumulative flow diverted by each successive stream intake.

From 1918 to 1932, continuous streamflow monitoring on these streams provided natural flow conditions at the 3,000 ft elevation. By the time the Upper Kula System was eventually extended to Haipuaena in 1932, these monitoring stations were discontinued, and their records did not measure the effects of the small amounts of water diverted at the higher elevations (see Table 20). Despite the diversion of water at the 4,500 ft elevation by the Upper Kula System, these estimates are still considered representative of natural flow. These data were then adjusted to current climate conditions (Figure 20).

The availability of water at the 1,500 ft elevation above Spreckels Ditch in Honomanu, Haipuaena, Puohokamoa, and Waikamoi is dependent on the quantity of flow diverted at the Lower Kula Pipeline and the groundwater gains in flow between this water system and the Spreckels Ditch. Hoffman (1938) conducted a series of seepage runs in each of the main channels that cross the Haiku-Uka boundary and contribute to surface flow at the Lower Kula System as well as the Spreckels/Ko‘olau/Wailoa Ditch. Each of the stream channels in these gulches demonstrate a large amount of seepage gain downstream. Flow duration estimates of seepage gain for the current climate period are provided in Table 22.

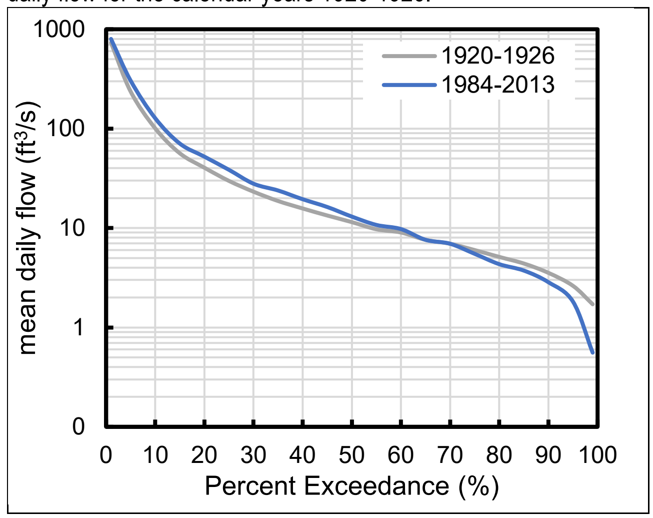
Based on a maximum capacity of 9.29 ft^3/s between LP-7 and LP-5, 10.07 ft^3/s between LP-5 and LP-2, and 10.97 ft^3/s between LP-2 and the Piiholo Reservoir the water diverted at any single stream via the Lower Kula System can be modeled for the calendar years 1920 to 1926, with flow duration statistics adjusted to the 1984-2013 period. Thus, the flow that continues downstream can be estimated as provided in Table 22. The total regulated flow available at Honomanū (at S-4), Haipuaena (at S-8), Puohokamoa (at S-9), Alo (W-1), and Waikamoi (at W-2) below the Lower Kula Pipeline is provided in Table 21 based on diverted flow duration statistics and seepage gains.

Figure 19. Lower Kula Pipeline intake (LP-1) on Honomanū Stream (top) and intake (LP-7) on Waikamoi Stream (bottom).

Table 21. Estimated total low-flow duration statistics for natural and regulated flow conditions below the Lower-Kula Pipeline at the Spreckels Ditch or Koʻolau Ditch.
[all values in cubic feet per second, ft^3/s]

	Total Natural flow	Total Regulated Flow
Q_{50}	35	25
Q_{55}	28	18
Q_{60}	24	14
Q_{65}	21	13
Q_{70}	19	12
Q_{75}	15	8.9
Q_{80}	11	6.3
Q_{85}	9.2	5.4
Q_{90}	7.0	4.1
Q_{95}	4.1	2.3

Figure 20. Flow-duration curve for the total flow in Waikamoi, Puohokamoa, Haipuaena, and Honomanū at approximately the 3,000 ft elevation for the 1920-1926 period and estimated for the 1984-2013 period. Data derived from complete records of mean daily flow for the calendar years 1920-1926.



IV. Estimates of Diverted Flow from Other Regions

Low-flow statistics may be estimated for the sum of diversions on streams without any monitoring data by using mean daily flow at continuous-record ditch-flow gaging stations and subtracting out mean daily flow from streams with continuous-record gaging stations. This was done for the Koʻolau Ditch at Nāhiku (USGS 16512000), Koʻolau Ditch near Keanae (USGS 16243000), Spreckels Ditch near Huelo (USGS 16538000), and Wailoa Ditch at Honopou (USGS 16588000).

Koʻolau Ditch in Nāhiku

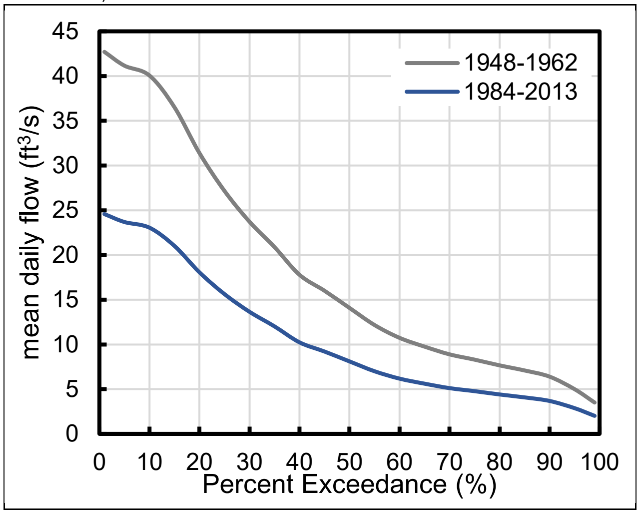
From July 1, 1948 to December 31, 1962, USGS stations 16506000 on the Makapipi Ditch into Koʻolau Ditch from Makapipi Tunnel, 16508000 on Hanawi Stream above Koʻolau Ditch, and Kapalua Stream above Koʻolau Ditch were all active simultaneously with station 16512000 Koʻolau Ditch at Nāhiku. During this period, there were five "major" registered diversions and 11 "minor" registered diversions not accounted for by the USGS stations in the Makapipi, Hanawi, or Kapalua hydrologic units. These diversions ranged in size from a 2-inch driscoe pipe to a 10-inch PVC pipe from springs, streams, and tunnels. The maximum divertible amount from Hanawi and Kapalua is 18.56 ft^3/s and 9.28 ft^3/s, respectively. An approximate flow duration curve for the cumulative flow diverted by these ungagged intakes to Koʻolau Ditch at USGS station 16512000 can be produced for the period of record (Figure 21).

Table 22. Estimated natural-flow duration discharge statistics at continuous record USGS sites on streams in the Hāʻiku-Uka area of East Maui, estimated flow diverted at the Lower Kula System (approximately 3,000 ft), estimated natural flow duration gains below the Hāʻiku-Uka boundary, estimated natural flow duration discharge statistics at the Spreckels/Wailoa Ditches (approximately 1,300 ft), and regulated flow available at the Spreckels/Wailoa Ditches for the current climate period (water years 1984-2013).
[ID, identifier; abv, above; USGS stations identified with an 8-digit number, stream diversions identified with system abbreviation and diversion number; H-U, Hāʻiku-Uka; LP, Lower Pipeline; S, Spreckels Ditch, W, Wailoa Ditch]

		Discharge, in ft^3/s, for selected percentages of time (from 5 to 95 percent) the indicated discharge was equaled or exceeded																		
Location ID	**station name**	Q_{5}	Q_{10}	Q_{15}	Q_{20}	Q_{25}	Q_{30}	Q_{35}	Q_{40}	Q_{45}	Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
16524000	Honomanū at H-U	98	34	16	12	8.4	5.8	4.7	3.8	3.0	2.5	2.0	1.7	1.2	1.1	0.85	0.65	0.53	0.37	0.22
LP-1	Diverted at Lower Pipeline	9.3	9.3	9.3	9.3	8.4	5.8	4.7	3.8	3.0	2.5	2.0	1.7	1.2	1.1	0.85	0.65	0.53	0.37	0.22
	Gains in flow blw H-U	55	28	20	13	8.7	6.8	6.5	5.0	4.1	3.8	2.9	2.6	2.4	2.1	1.6	1.2	1.0	0.74	0.47
16527000	Honomanū abv Spreckels	146	61	37	24	17	13	11	8.8	7.3	6.3	4.8	4.3	3.8	3.3	2.5	2.0	1.6	1.2	0.70
S-4	Regulated flow available	137	51	28	15	8.7	6.8	6.5	5.0	4.1	3.8	2.9	2.6	2.4	2.1	1.6	1.2	1.0	0.74	0.47
16532000	Haipuaena at H-U	31	18	12	8.0	5.6	4.1	3.3	2.7	2.3	1.7	1.5	1.3	1.1	0.93	0.71	0.65	0.53	0.37	0.22
LP-2	Diverted at Lower Pipeline	0.0	0.0	0.0	0.0	1.1	3.4	3.2	2.9	2.2	1.9	1.6	1.2	1.1	0.93	0.71	0.65	0.53	0.50	0.22
	Gains in flow blw H-U	52	24	14	11	9	7.1	6.3	5.6	5.0	4.8	4.0	3.3	2.9	2.8	2.3	1.7	1.6	1.0	0.62
16536000	Haipuaena abv Spreckels	82	42	26	18	14	11	9.5	8.5	7.3	6.7	5.6	4.5	4.0	3.7	3.0	2.4	2.1	1.5	0.83
S-8	Regulated flow available	82	42	26	18	13	8.0	6.3	5.6	5.0	4.8	4.0	3.3	2.9	2.8	2.3	1.7	1.6	1.0	0.62
16542000	E Br Puohokamoa at H-U	8.3	4.5	2.9	2.2	1.8	1.4	1.4	1.2	1.1	0.96	0.69	0.67	0.54	0.46	0.46	0.26	0.26	0.12	0.10
LP-3	Diverted at Lower Pipeline	0.78	0.78	0.78	0.78	0.78	0.78	1.4	1.2	1.1	0.96	0.69	0.67	0.54	0.46	0.46	0.26	0.26	0.12	0.10
16543000	M Br Puohokamoa at H-U	26	11	6.9	5.0	3.7	3.0	2.8	2.4	1.9	1.8	1.3	1.2	1.0	0.93	0.77	0.52	0.39	0.37	0.22
LP-4	Diverted at Lower Pipeline	0.0	0.0	0.0	0.0	0.0	0.0	0.67	2.3	1.9	1.8	1.3	1.2	1.0	0.93	0.77	0.52	0.39	0.37	0.22
16544000	W Br Puohokamoa at H-U	31	14	8.7	6.8	5.4	4.1	3.6	3.0	2.4	2.4	1.7	1.5	1.4	1.3	0.93	0.79	0.65	0.50	0.32
LP-5	Diverted at Lower Pipeline	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	2.4	2.4	1.7	1.5	1.4	1.3	0.93	0.79	0.65	0.50	0.32
	Gains in flow blw H-U	87	56	39	26	20	16	14	13	10	8.7	7.1	6.0	5.7	5.3	3.7	2.5	2.3	1.7	1.0
16545000	Puohokamoa abv Spreckels	152	85	57	40	31	24	22	17	14	13	11	9.4	8.6	7.9	5.9	4.1	3.6	2.7	1.6
S-9	Regulated flow available	150	83	56	38	29	22	19	15.0	10.3	8.7	7.1	6.0	5.7	5.3	3.7	2.5	2.3	1.7	0.96
16554000	East Waikamoi at H-U	23	12	7.7	5.5	4.1	3.2	2.7	2.2	1.9	1.6	1.3	1.1	0.93	0.93	0.71	0.52	0.52	0.37	0.32
LP-6	Diverted at Lower Pipeline	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.3	1.1	0.93	0.93	0.71	0.52	0.52	0.37	0.32
16554000	Waikamoi at H-U	77	31	16	12	7.8	5.9	4.4	3.6	2.9	2.7	2.3	1.8	1.7	1.4	1.1	0.93	0.79	0.62	0.43
LP-7	Diverted at Lower Pipeline	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	1.8	1.7	1.4	1.1	0.93	0.79	0.62	0.43
	Gains in flow blw H-U	34	26	21	14	9.4	7.7	7.0	5.1	4.6	3.8	3.3	2.5	2.1	1.7	1.3	0.91	0.55	0.41	0.22
16555000	Waikamoi abv Wailoa[b]	132	68	46	32	22	17	14	11	9.7	8.0	6.8	5.4	4.8	4.0	3.1	2.4	1.9	1.5	0.97
W-2	Regulated flow available	132	68	46	32	22	17	14	11	9.7	6.6	3.3	2.5	2.1	1.7	1.3	0.91	0.55	0.41	0.22

[a]record includes data from USGS 16556000 Waikamoi Stream prior to construction of Koʻolau Ditch to Waikamoi (02/02/1922)

Figure 21. Flow-duration curve at USGS 16512000 Koʻolau Ditch for the 1948-1962 period and estimated for the 1984-2013 period minus the concurrent mean daily flow at USGS 16506000, USGS 16508000, and USGS 16510000.



The data can be adjusted for shifts in the flow duration curve based on the continuous record at USGS 16508000 on Hanawi. Based on these data, divertible flow into the Koʻolau Ditch from the ungagged major and minor diversions upstream of USGS 16512000 (i.e., from the Nāhiku license area for the 1984-2013 period) has a Q_{50} of 8.1 ft^3/s, a Q_{70} of 5.1 ft^3/s, a Q_{90} of 3.68 ft^3/s, and a Q_{95} of 2.88 ft^3/s, representing a decline of between 25.6% and 63.6% from the 1948-1962 period.

Koʻolau Ditch in Keanae

Gingerich (2005), used basin characteristics to model TFQ_{50}, TFQ_{95}, BFQ_{50}, and BFQ_{95} for the base period from 1942 to 2001. Values were adjusted to the 1984-2013 climate period based on the percent change in the flow duration curve using 16518000 on West Wailuaiki as an index station. Additional low-flow duration discharge estimates were determined based on a regression formula using ordinary least-squares regression for the values provided by Gingerich (2005) and the equivalent flow-duration values at USGS 16518000 (Table 23). Due to a lack of data, Gingerich (2005) did not make any estimates of streamflow at Piʻinaʻau Stream above Koʻolau Ditch. However, a continuous-record low-flow gaging station was installed at this location (USGS 16522950) as part of Phase II of the Statewide Low-Flow study in 2018. Measurements made at this location correlated well with USGS 16518000 and results are also provided in Table 23. Following the 2018 Commission Decision & Order, which fully restored flow to Waiokomilo and Palauhulu, most of these flows are now returned to the stream of origin and the diversions have been abandoned.

Table 23. Estimated natural low-flow duration discharge statistics at ungagged locations above the Koʻolau Ditch using partial-record gaging (at USGS 16522950 on Piʻinaʻau Stream), or basin characteristics based on values determined by Gingerich (2005) and corrected for the current climate period (water years 1984-2013) using USGS 16518000 on West Wailuaiki (all streams except Hanehoi, which used USGS 16587000 on Honopou).

		Discharge, in ft^3/s, for selected percentages of time (from 5 to 50 percent) the indicated discharge was equaled or exceeded									
Stream	**Equation to translate data from 1942-2001 to 1983-2013 periods of record**	Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
Paʻakea	$Y = -0.0121*X^2 + 0.2984 * X + 0.198$	1.5	1.4	1.3	1.2	1.0	0.90	0.78	0.68	0.54	0.40
Puaʻakaʻa	$Y = 0.0076*X^2 + 0.0078 * X + 0.3571$	0.97	0.83	0.73	0.64	0.57	0.52	0.48	0.45	0.42	0.40
Waiokomilo	$Y = 0.0048*X^2 + 0.7064 * X - 0.4929$	6.1	5.3	4.6	3.9	3.3	2.8	2.3	2.0	1.5	1.1
Kano	$Y = 0.0095*X^2 + 0.3496 * X + 0.0714$	3.9	3.4	2.9	2.5	2.1	1.8	1.6	1.4	1.1	0.88
Hauʻoliwahine	$Y = 0.5802 * X^{0.4249}$	1.5	1.4	1.3	1.2	1.2	1.1	1.0	1.0	0.90	0.81
Piʻinaʻau	$Y = -1.6285 + 1.2865 * X$	0.38	0.32	0.28	0.23	0.19	0.16	0.13	0.11	0.09	0.06
Nuaailua	$Y = 0.0059*X^2 - 0.0245*X + 0.2143$	0.46	0.38	0.33	0.28	0.25	0.22	0.21	0.20	0.19	0.19
Honomanū: Banana Falls	$Y = 0.0059*X^2 - 0.0245*X + 0.2143$	2.3	2.0	1.8	1.6	1.4	1.4	1.3	1.3	1.2	1.2
Honomanū: Center Falls	$Y = 0.0019*X^2 + 0.1006*X + 0.1025$	1.1	1.0	0.89	0.77	0.68	0.59	0.52	0.47	0.40	0.33
Honomanū: High Falls	$Y = 0.0018*X^2 + 0.1159*X + 0.1835$	1.4	1.2	1.1	0.94	0.83	0.74	0.66	0.60	0.52	0.45
Punalau	$Y = 1.2215 * X^{0.728}$	6.0	5.4	5.0	4.5	4.1	3.7	3.3	3.0	2.6	2.2
Hanehoi	$Y = 0.3374 + 0.8458 * X$	2.0	1.9	1.7	1.4	1.4	1.2	1.1	0.95	0.84	0.73

Streamflow in the three tributaries to Honomanū were also not estimated by Gingerich (2005). Using the same basin characteristics model, TFQ_{50}, TFQ_{95}, and BFQ_{50} (i.e., TFQ_{75}) for the base period from 1942 to 2001 were estimated for each location and regression equations were then used to develop the low-flow duration statistics for the 1984-2013 climate period as identified in Table 23.

East Maui Irrigation System Gains and Losses

To quantify the gains and losses of water diverted from East Maui streams, EMI contracted with USGS to conduct seepage runs on all available sections of the irrigation system deemed feasible (Cheng 2012). Using this data the USGS quantified the total gains and losses in each ditch. Ditch lengths and characteristics are reproduced in Table 24.

Table 24. Approximate length (mi) and characteristics of East Maui Irrigation water delivery system.
[lined, both bottom and sides lined with concrete; partial, at least one surface lined; unlined, earthen material on bottom and walls]

			Open Ditch		
System	**Length**	**Tunnel**	**lined**	**partial**	**unlined**
Ko‘olau	10.20	7.70	2.47	0.02	0.00
Wailoa	9.56	9.49	0.07	0.00	0.00
Spreckels	3.58	2.00	0.01	1.28	0.29
New Hāmākua	8.05	5.61	0.13	0.86	1.44
Kauhikoa	4.96	4.78	0.16	0.02	0.00
Spreckels-Pāpa‘a‘ea	1.04	0.42	0.01	0.03	0.57
Manuel Luis	1.79	0.97	0.00	0.06	0.76
Center	2.20	1.51	0.11	0.04	0.54
Lowrie	12.41	4.61	0.21	0.13	7.46
Hā‘iku	9.68	9.30	0.38	0.00	0.00

Of the approximately 63 miles of EMI system surveyed, only 17 miles in length are open ditch, with 11 miles unlined. The majority of open, unlined ditch occurs in the Lowrie and Spreckels-Pāpa‘a‘ea. Open ditches tended to have small seepage losses while tunnel sections had seepage gains. Seepage run measurements on the Ko‘olau, Wailoa, New Hāmākua, and Kauhikoa Ditches had seepage gains except for a small section of Ko‘olau Ditch in Nāhiku where overflow of ditch resulted in seepage loss.

The majority of water diverted, especially during low-flow periods, occurs at the Ko‘olau and Wailoa Ditches, which are almost entirely tunnel: 75.5%, 99.3%, respectively. Further, Spreckels (55.9%) and New Hāmākua (69.7%) Ditches are mostly in tunnel. Large seepage losses occur in the Manuel Luis, Center, and Lowrie Ditches, which have larger sections of unlined ditch, although they act as secondary ditches to transport water during higher flow events when the capacities of the higher elevation ditches are exceeded. The Hā‘iku Ditch is almost entirely in tunnel (96.1%), and is primarily used to capture seepage gains below the Wailoa and New Hāmākua Ditches.

Honopou to Māliko

West of Honopou Stream, streamflow is diverted into the Wailoa Ditch at Piiloi and Halehaku streams, into the New Hāmākua Ditch at Piiloi, West Piiloi, Kaula, Makaa, and Halehaku streams, and into the Kauhikoa Ditch from Makaa, Halehaku, Opana, Opaepilau, West Kaupakulua East Kuiaha, West Kuiaha, and Lilikoi streams. Very little streamflow data are available from these locations. Low-flow duration streamflow statistics estimated by the USGS in this region are only available on Halehaku Stream at USGS 16596200 at 2,610 feet in elevation. This stream was gaged continuously from 1965-1971. Concurrent continuous records allow for the estimate of low-flow statistics for the 1984-2013 climate period at this station (Table 2).

From July 1, 1932, to June 30, 1938, John Hoffman, consultant with EMI, compiled daily flow data at each ditch as they crossed the Honopou Gulch ditch gaging stations and the Māliko Gulch ditch gaging stations, including the inflow to and outflow from reservoirs in the Lowrie and Haiku Ditches. The resulting datasets were adjusted for concurrent time periods (e.g., water flows faster between stations in the lined, mostly tunnel Wailoa Ditch compared to the New/Old Hāmākua and Kauhikoa) depending on the ditch and rate of flow. Estimates of flow to two county pipelines from the Wailoa Ditch were also made. Days where streamflow exceeded intake capacity were determined and days where ditch capacity was exceeded were excluded.

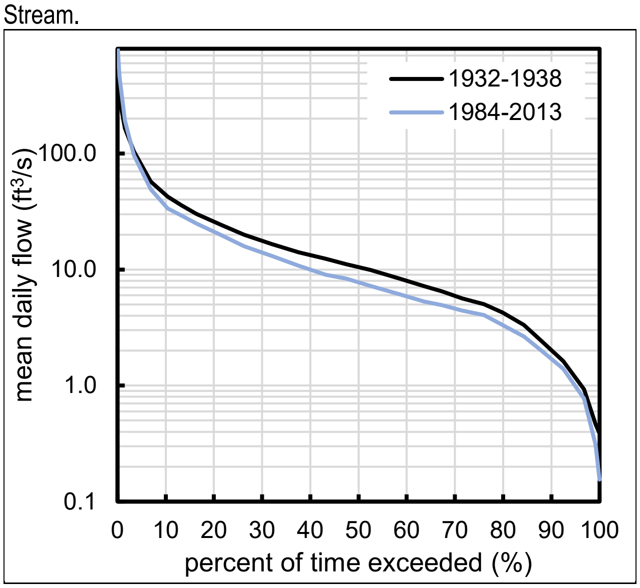
The daily pickup for each ditch was then compiled for the period of record and a flow duration curve was calculated for the 1932-1938 period of record (Table 25). At Q_{99}, the Wailoa Ditch gained about 0.5 ft^3/s. At flows less than Q_{96}, the New Hāmākua/Kauhikoa and Lowrie/Haiku Ditches had small (approximately 0.3 to 1.0 ft^3/s) losses, as a result of both ditches being unlined.

Values were then adjusted by comparing the concurrent flow duration curve for USGS 16587000 on Honopou Stream to the water year 1984-2013 period of record. The percent change for each resulting percentile was applied to the ditch flow duration curve and plotted in Figure 23. The resulting flow duration curve for the 1984-2013 period has a Q_{50} of 6.4 ft^3/s, a Q_{70} of 4.7 ft^3/s, and a Q_{90} of 1.4 ft^3/s (Table 25).

Table 25. Low-flow duration statistics for total water sourced from the from streams between Honopou and Māliko Gulch from 1932 to 1938 at Wailoa, New Hāmākua/Kauhikoa, Lowrie, and Haiku Ditches and estimated from 1984 to 2013 based on concurrent mean daily flow in Honopou Stream at USGS 16587000.
[values in ft³/s, cubic feet per second]

	1932-1938	1984-2013
Q_{50}	10.5	6.4
Q_{55}	9.3	5.4
Q_{60}	8.0	4.7
Q_{65}	6.7	4.0
Q_{70}	6.0	4.0
Q_{75}	5.2	3.6
Q_{80}	4.2	2.8
Q_{85}	2.3	1.5
Q_{90}	2.0	1.4
Q_{95}	1.2	0.95

Figure 22. Ditch flow gains between Honopou and Māliko Gulch flow duration exceedance curve for the 1932-1938 period of record and estimated for the 1984-2013 period based on concurrent daily streamflow at USGS 16587000 on Honopou Stream.



Opana Sources

Prior to 2009, Maui Land & Pineapple (MLP) cultivated pineapple in the Hailiimalie region of central Maui. The irrigation needs for pineapple were met with water sourced from Nāhiku: one well (no. 6-4806-048) and one pump from Hanawi Stream; and water sourced from the Opana tributary of Kakipi Gulch and Awalau Stream. These sources were transmitted to MLP via the East Maui Irrigation System (Koʻolau/Wailoa/Kauhikoa Ditches).

Total monthly water from Opana Stream was reported as the combined flow through two metered pipelines (a 12-inch and a 2.5-inch) and from Awalau Stream through one metered pipeline (4-inch) from 1988 to 1999. Flow-duration statistics from Opana and Awalau are provided in Table 26.

Total Available Water

Quantifying the total amount of water available in the EMI system under current climate conditions is of importance for determining the consequences of existing water withdrawals for instream and non-instream uses, including the delivery of surface water for municipal water supply, the agricultural needs of future Department of Hawaiian Home Lands developments in Central Maui, and agricultural water needs of diversified agriculture in Central Maui.

Table 26. Mean daily flow (MDF) and low-flow duration statistics for water sourced from the Opana and Awalau streams from 1988 to 1999 based on monthly reported values.
[values in ft³/s, cubic feet per second]

	Opana Stream	Awalau Stream
MDF	0.51	0.12
Q_{50}	0.40	0.11
Q_{60}	0.31	0.09
Q_{70}	0.20	0.07
Q_{80}	0.10	0.05
Q_{90}	0.01	0.00
Q_{95}	0.01	0.00

The Koʻolau/Spreckels/Wailoa Ditch is the highest elevation EMI ditch and is the most important for capturing and transporting streamflow. The majority of the 2018 CWRM Decision & Order established interim IFS below the Koʻolau Ditch in streams of the Nāhiku and Keanae regions, with two streams fully restored in Huelo: Hanehoi and Honopou.

While streamflow records across East Maui have demonstrated consistent declines in both total flow and base flow for 100 years (Figure 7), over the last 30 years, there has been a steady decline in surface flows, as demonstrated by the magnitude of the Q_{50}, Q_{75}, and Q_{90} flow at USGS 16587000 on Honopou Stream (Figure 23a). There is a strong similarity between declines in streamflow in East Maui and declines in ditch flow (Figure 23b).

Table 27. Summary of all low-flow duration discharge under current (1984-2013) climate conditions for natural or regulated streams at the Koʻolau/Spreckels/Wailoa Ditches and total water available following the implementation of the 2018 CWRM Decision & Order.

			Discharge, in ft³/s, for selected percentages of time (from 5 to 50 percent) the indicated discharge was equaled or exceeded									
Stream	**scenario**	**notes**	**Q_{50}**	**Q_{55}**	**Q_{60}**	**Q_{65}**	**Q_{70}**	**Q_{75}**	**Q_{80}**	**Q_{85}**	**Q_{90}**	**Q_{95}**
Makapipi	1984-2013 flow	Natural flow										
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hanawi	1984-2013 flow	Natural flow	6.2	5.4	4.8	4.3	3.9	3.6	3.2	2.9	2.6	2.2
	2018 interim IFS	Available after implementation	5.3	4.5	3.9	3.4	3.0	2.7	2.3	2.0	1.7	1.3
Kapaula	1984-2013 flow	Natural flow	4.3	3.6	3.1	2.7	2.3	2.3	1.7	1.5	1.3	0.98
	2018 interim IFS	Available after implementation	3.7	3.0	2.5	2.1	1.7	1.7	1.1	0.94	0.74	0.42
Paakea	1984-2013 flow	Natural flow	1.5	1.4	1.3	1.2	1.0	0.90	0.78	0.68	0.54	0.40
	2018 interim IFS	Available after implementation	1.5	1.4	1.3	1.2	1.0	0.90	0.78	0.68	0.54	0.40
Waiohue	1984-2013 flow	Natural flow	5.2	4.7	4.4	4.2	3.9	3.7	3.4	3.2	2.9	2.5
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Puaʻakaʻa	1984-2013 flow	Natural flow	0.97	0.83	0.73	0.64	0.57	0.52	0.48	0.45	0.42	0.40
	2018 interim IFS	Available after implementation	0.77	0.63	0.53	0.44	0.37	0.32	0.28	0.25	0.22	0.20
Kopiliula	1984-2013 flow	Natural flow	6.6	5.5	5.0	4.2	3.8	3.4	3.0	2.7	2.4	2.1
	2018 interim IFS	Available after implementation	3.4	2.3	1.8	1.0	0.60	0.20	0.0	0.0	0.0	0.0
East Wailuaiki	1984-2013 flow	Natural flow	7.7	6.9	5.9	5.3	4.6	4.2	3.6	3.2	2.8	2.1
	2018 interim IFS	Available after implementation	4.0	3.2	2.2	1.6	0.90	0.50	0.0	0.0	0.0	0.0
West Wailuaiki	1984-2013 flow	Natural flow	8.9	7.8	6.9	6.0	5.2	4.5	3.9	3.4	2.8	2.2
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Wailuanui	1984-2013 flow	Natural flow	3.1	2.7	2.4	2.0	1.7	1.5	1.3	1.1	0.91	0.65
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West Wailuanui	1984-2013 flow	Natural flow	3.8	3.3	3.0	2.5	2.2	1.9	1.6	1.4	1.1	0.75
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waiokomilo	1984-2013 flow	Natural flow	6.1	5.3	4.6	3.9	3.3	2.8	2.3	2.0	1.5	1.1
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kano	1984-2013 flow	Natural flow	3.9	3.4	2.9	2.5	2.1	1.8	1.6	1.4	1.1	0.88
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hauʻoliwahine	1984-2013 flow	Natural flow	1.5	1.4	1.3	1.2	1.2	1.1	1.0	1.0	0.90	0.81
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 27. [continued]

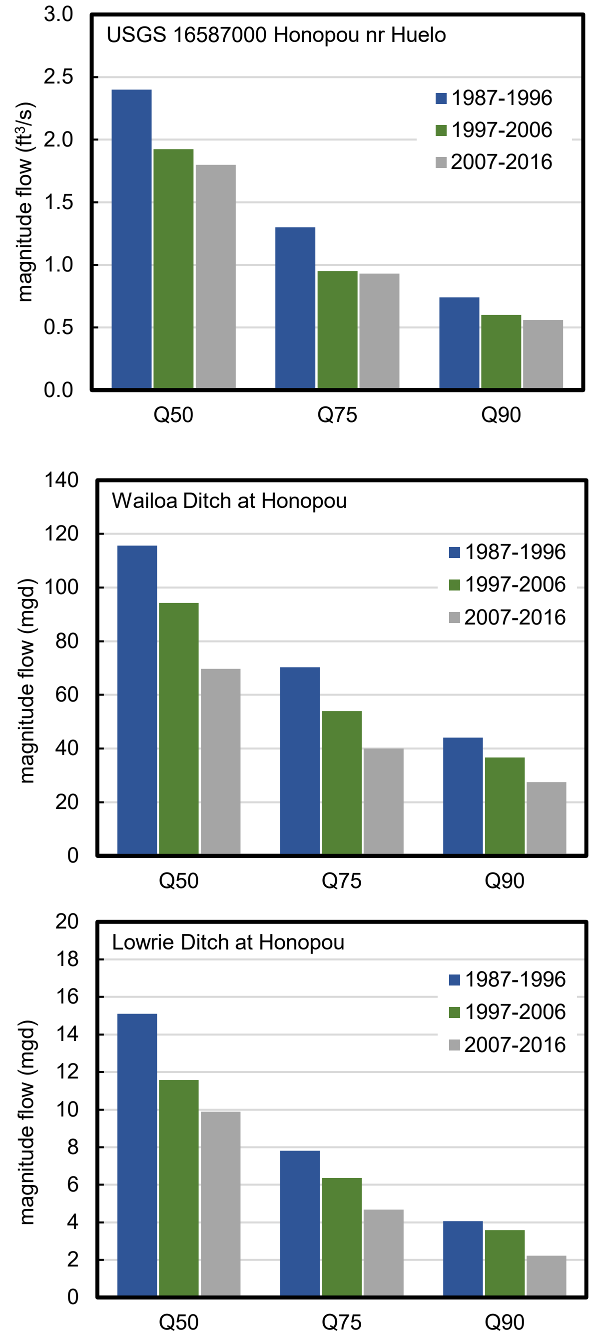
Stream	scenario	notes	Discharge, in ft^3/s, for selected percentages of time (from 5 to 50 percent) the indicated discharge was equaled or exceeded									
			Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
Pi‘ina‘au	1984-2013 flow	Natural flow	0.38	0.32	0.28	0.23	0.19	0.16	0.13	0.11	0.09	0.06
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nuaailua	1984-2013 flow	Natural flow	0.46	0.38	0.33	0.28	0.25	0.22	0.21	0.20	0.19	0.19
	2018 interim IFS	Available after implementation	0.46	0.38	0.33	0.28	0.25	0.22	0.21	0.20	0.19	0.19
Honomanū: Banana Intake	1984-2013 flow	Natural flow	2.3	2.0	1.8	1.6	1.4	1.4	1.3	1.3	1.2	1.2
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Honomanū: Center Intake	1984-2013 flow	Natural flow	1.1	1.0	0.89	0.77	0.68	0.59	0.52	0.47	0.40	0.33
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Honomanū	1984-2013 flow	regulated flow	3.8	2.9	2.6	2.4	2.1	1.6	1.2	1	0.74	0.47
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Honomanū: High Falls Intake	1984-2013 flow	Natural flow	1.4	1.2	1.1	0.94	0.83	0.74	0.66	0.60	0.52	0.45
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kōlea/Punalau	1984-2013 flow	Natural flow	6.0	5.4	5.0	4.5	4.1	3.7	3.3	3.0	2.6	2.2
	2018 interim IFS	Available after implementation	3.8	3.2	2.8	2.3	1.9	1.5	1.1	0.8	0.4	0.0
Haipuaena	1984-2013 flow	regulated flow	4.8	4	3.3	2.9	2.8	2.3	1.7	1.6	1	0.62
	2018 interim IFS	Available after implementation	4.8	4	3.3	2.9	2.8	2.3	1.7	1.6	1	0.62
Puohokamoa	1984-2013 flow	regulated flow	8.7	7.1	6	5.7	5.3	3.7	2.5	2.3	1.7	0.96
	2018 interim IFS	Available after implementation	8.7	7.1	6	5.7	5.3	3.7	2.5	2.3	1.7	0.96
Alo	1984-2013 flow	Natural flow	2.5	2.1	1.7	1.5	1.3	1.2	0.96	0.82	0.69	0.53
Waikamoi	1984-2013 flow	regulated flow	6.6	3.3	2.5	2.1	1.7	1.3	0.91	0.55	0.41	0.22
	2018 interim IFS	Available after implementation	5.3	1.6	0.40	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Kōlea	1984-2013 flow	Natural flow	0.30	0.26	0.23	0.19	0.16	0.14	0.12	0.10	0.08	0.06
West Kōlea	1984-2013 flow	Natural flow	0.65	0.56	0.48	0.41	0.35	0.29	0.25	0.21	0.17	0.13
Ka‘aiea	1984-2013 flow	Natural flow	3.8	3.2	2.7	2.2	1.8	1.5	1.2	1.0	0.79	0.57
Makanali	1984-2013 flow	Natural flow	0.28	0.26	0.23	0.20	0.18	0.15	0.13	0.11	0.08	0.05
‘O‘opuola	1984-2013 flow	Natural flow	1.0	0.92	0.82	0.72	0.63	0.55	0.48	0.42	0.35	0.28
‘O‘opuola Tributary	1984-2013 flow	Natural flow	0.24	0.21	0.19	0.16	0.14	0.12	0.11	0.09	0.08	0.06
West ‘O‘opuola	1984-2013 flow	Natural flow	0.36	0.32	0.29	0.26	0.23	0.21	0.19	0.17	0.14	0.12

Table 27. [continued]

Stream	scenario	notes	Discharge, in ft³/s, for selected percentages of time (from 5 to 50 percent) the indicated discharge was equaled or exceeded Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
Nailiilihaele	1984-2013 flow	Natural flow	13	11	9.9	8.5	7.3	6.2	5.3	4.5	3.7	2.8
Kailua	1984-2013 flow	Natural flow	7.8	6.8	5.9	4.9	4.2	3.8	3.2	2.5	2.0	1.4
Oanui	1984-2013 flow	Natural flow	1.7	1.5	1.3	1.1	0.89	0.72	0.58	0.46	0.32	0.18
East Hoalua	1984-2013 flow	Natural flow	1.1	0.98	0.87	0.76	0.67	0.58	0.51	0.44	0.37	0.29
Hoalua	1984-2013 flow	Natural flow	1.3	1.1	1.0	0.94	0.85	0.76	0.68	0.61	0.53	0.44
Hanehoi	1984-2013 flow	Natural flow	2.0	1.9	1.7	1.4	1.4	1.2	1.1	0.95	0.84	0.73
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Waipi‘o	1984-2013 flow	Natural flow	0.73	0.52	0.39	0.30	0.23	0.19	0.14	0.11	0.09	0.06
Hoolawaliilii	1984-2013 flow	Natural flow	3.3	3.1	2.8	2.5	2.3	2.1	1.9	1.7	1.5	1.2
Ho‘olawanui	1984-2013 flow	Natural flow	3.0	2.7	2.4	2.0	1.8	1.5	1.3	1.1	0.91	0.71
West Ho‘olawanui	1984-2013 flow	Natural flow	0.26	0.23	0.21	0.17	0.16	0.13	0.12	0.10	0.08	0.07
Honopou	1984-2013 flow	Natural flow	2.0	1.8	1.6	1.3	1.2	1.0	0.86	0.72	0.60	0.47
	2018 interim IFS	Available after implementation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maui County Systems												
Upper Kula System*	1984-2013 flow	Natural flow	0.86	0.64	0.52	0.42	0.32	0.25	0.19	0.15	0.11	0.07
Lower Kula System	1984-2013 flow	Regulated flow	13.7	10.8	9.3	7.9	7.1	5.5	4.3	3.7	2.7	1.8
Ko‘olau/Spreckels/Wailoa Ditch												
Total flow	1984-2013 flow	Natural flow	150	127	112	98	87	76	65	57	48	37
Total flow	1984-2013 flow	Available after implementation	94	76	65	55	48	41	33	29	23	17
Groundwater gains downstream to Manuel Luis/Center/Lowrie Ditch												
Total flow	1984-2013 flow	regulated flow	9.5	8.5	7.7	6.2	5.7	4.8	4.2	3.5	3.0	2.4
		Available after implementation	7.1	6.3	5.7	4.6	4.2	3.5	3.0	2.6	2.2	1.7
Total flow	1984-2013 flow	Honopou to Māliko	6.4	5.4	4.7	4.0	4.0	3.6	2.8	1.5	1.4	0.95
EMI System below 2,000 ft												
Total flow	1984-2013 flow	Available before implementation	168	143	126	110	98	85	73	63	53	41
Total flow	1984-2013 flow	Available after implementation	107	88	75	64	56	48	39	33	27	20

*only includes contributions from the three main stream intakes on Haipuaena, Middle Branch Puohokamoa, and Waikam

Figure 23. Median (Q_{50}), baseflow (Q_{75}) and low (Q_{90}) flow duration statistics for three 10-year periods (July 1-June 30) for USGS 16587000 on Honopou Stream and flow-duration statistics for Wailoa and Lowrie Ditches for these same periods.
[note: differing units between graphs]



The low-flow duration discharge statistics for total groundwater gains in streamflow for the 1984-2013 period between the Ko‘olau/Wailoa Ditch elevation and the Manual Luis/Center/Lowrie Ditch elevation are provided in Table 27, with estimates for individual streams provided in Appendix C. Shifts in the magnitude of low-flow duration statistics in the Lowrie Ditch indicate a steady decline in groundwater gains below the Wailoa Ditch. This trend is affecting the availability of water for instream and non-instream uses. For example, the Q_{50} flow in the 2007-2016 period was 25% less than Q_{50} in the 1987-1996 period, while the Q_{75} flow declined by 28% during these same periods.

The total water available in the 1984-2013 climate at the Ko‘olau/Spreckels/Wailoa Ditch elevation from Nahiku to Māliko gulch, estimated from record augmentation, modeling, and seepage gains prior to the 2018 Decision & Order, had a Q_{50} of approximately 168 ft^3/s (109 mgd), a Q_{75} of approximately 85 ft3/s (55 mgd), and a Q_{90} of approximately 53 ft^3/s (34 mgd). Following the implementation of the 2018 Decision & Order, the total water available had a Q_{50} of approximately 107 ft^3/s (69 mgd), a Q_{75} of approximately 48 ft^3/s (31 mgd), and a Q_{90} of approximately 27 ft^3/s (17 mgd).

By comparison, measured flow in Wailoa Ditch at Honopou Gulch (i.e., without the contribution of streamflow between Honopou to Māliko Gulch) from 1987-2016, had a Q_{50} of approximately 93 ft^3/s (60 mgd), a Q_{75} of approximately 55 ft^3/s (36 mgd), and a Q_{90} of approximately 36 ft^3/s (23 mgd). Measured flow in Lowrie Ditch at Honopou Gulch (i.e., without the contribution of streamflow between Honopou to Māliko Gulch) from 1987-2016, had a Q_{50} of approximately 12 ft^3/s (8 mgd), a Q_{75} of approximately 6 ft3/s (4 mgd), and a Q_{90} of approximately 3 ft^3/s (2 mgd).

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Appendix A. Existing interim instream flow standards for streams in East Maui following the 2018 Decision and Order issued by the Commission on Water Resource Management.

stream	2018 D&O Restoration Type	2018 D&O Interim IFS quantity (cfs)
Honopou	full	--
Hanehoi	full	--
Waikamoi	habitat	3.8
Waihinepee	none	0.90
Puhokamoa	connectivity	0.71
Haipuaena	connectivity	0.88
Punalau	habitat	1.87
Honomanū	habitat	4.2
Nua‘ailua	connectivity	2.2
Pi‘ina‘au	full	--
Waiokamilo	full	--
Wailuanui	full	--
West Wailuaiki	full	--
East Wailuaiki	habitat	3.7
Kopiliula	habitat	3.2
Puaakaa	connectivity	0.2
Waiohue	full	--
Pa‘akea	connectivity	0.18
Waiaaka	none	0.77
Kapaula	connectivity	0.56
Hānawī	connectivity	0.92
Makapipi	full	--

Appendix B. Streamflow measurements made by EMI staff on Pi‘ina‘au Stream at approximately 5900 ft and concurrent mean daily flow at USGS 16587000 on Honopou Stream, East Maui.

Date	Measurement (cfs)	USGS 16587000
08/06/1929	0.51	2.2
08/07/1929	0.28	1.7
08/09/1929	0.58	1.6
09/07/1929	0.08	1.1
09/15/1929	0.009	1.1
09/20/1929	0.009	0.93
09/28/1929	0.011	1.4
09/29/1929	0.046	1.4
10/04/1929	0.278	0.93
10/10/1929	0.526	4.8
10/11/1929	0.309	2.3
10/18/1929	0.053	1.1
10/26/1929	0.031	1.1
11/03/1929	0.062	0.93
11/08/1929	0.009	0.93
11/16/1929	0.008	0.93
11/21/1929	0.186	3.1
11/30/1929	0.541	9.6
12/14/1929	0.029	14
12/17/1929	1.098	14
02/22/1930	2.51	34
06/04/1930	0.124	5.7

Appendix C. Estimated low-flow duration statistics for seepage gains between the upper East Maui Irrigation Koʻolau/Wailoa Ditches (at 1250 ft) and the Manuel Luis Ditch (at 900 ft), Center Ditch (at 800 ft), or Lowrie Ditch (at 750 ft), including streams not diverted by the upper ditch.

	Discharge, in ft^3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded									
station name	Q_{50}	Q_{55}	Q_{60}	Q_{65}	Q_{70}	Q_{75}	Q_{80}	Q_{85}	Q_{90}	Q_{95}
Punalau at Manuel Luis Ditch	0.99	0.88	0.80	0.65	0.60	0.51	0.44	0.38	0.32	0.26
Haipuaena at Manuel Luis Ditch	0.39	0.35	0.31	0.26	0.24	0.20	0.17	0.15	0.13	0.10
Puohokamoa at Manuel Luis Ditch	0.30	0.27	0.24	0.20	0.18	0.15	0.13	0.11	0.10	0.08
Waikmaoi at Center Ditch	0.61	0.54	0.49	0.40	0.37	0.31	0.27	0.23	0.20	0.16
Kōlea at Center Ditch	0.55	0.49	0.44	0.36	0.33	0.28	0.24	0.21	0.18	0.14
Punaluʻu at Center Ditch	0.48	0.43	0.37	0.3	0.27	0.22	0.19	0.15	0.12	0.09
Kaʻaiea at Center Ditch	0.27	0.24	0.22	0.18	0.16	0.14	0.12	0.10	0.09	0.07
Makanali at Center Ditch	0.36	0.32	0.29	0.24	0.22	0.19	0.16	0.14	0.12	0.10
ʻOʻopuola at Center Ditch	0.09	0.08	0.08	0.06	0.06	0.05	0.04	0.04	0.03	0.02
Nailiilihaele abv Spreckels Ditch	0.53	0.48	0.43	0.35	0.32	0.27	0.24	0.20	0.17	0.14
Kailua at Lowrie Ditch	0.55	0.48	0.42	0.33	0.3	0.24	0.2	0.16	0.13	0.1
Hanawana at Lowrie Ditch	0.44	0.39	0.34	0.27	0.25	0.21	0.17	0.14	0.12	0.09
Hoalua at Lowrie Ditch	1.5	1.3	1.2	0.88	0.79	0.63	0.51	0.41	0.32	0.23
Waipiʻo at Lowrie Ditch	0.27	0.24	0.22	0.18	0.16	0.14	0.12	0.10	0.09	0.07
Hoolawaliilii at Lowrie Ditch	1.2	1.1	1.0	0.88	0.83	0.74	0.67	0.6	0.53	0.45
Hoʻolawanui at Lowrie Ditch	0.81	0.73	0.66	0.53	0.49	0.42	0.36	0.31	0.26	0.21
Honopou at Lowrie Ditch	0.18	0.18	0.17	0.15	0.16	0.13	0.11	0.11	0.10	0.07

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