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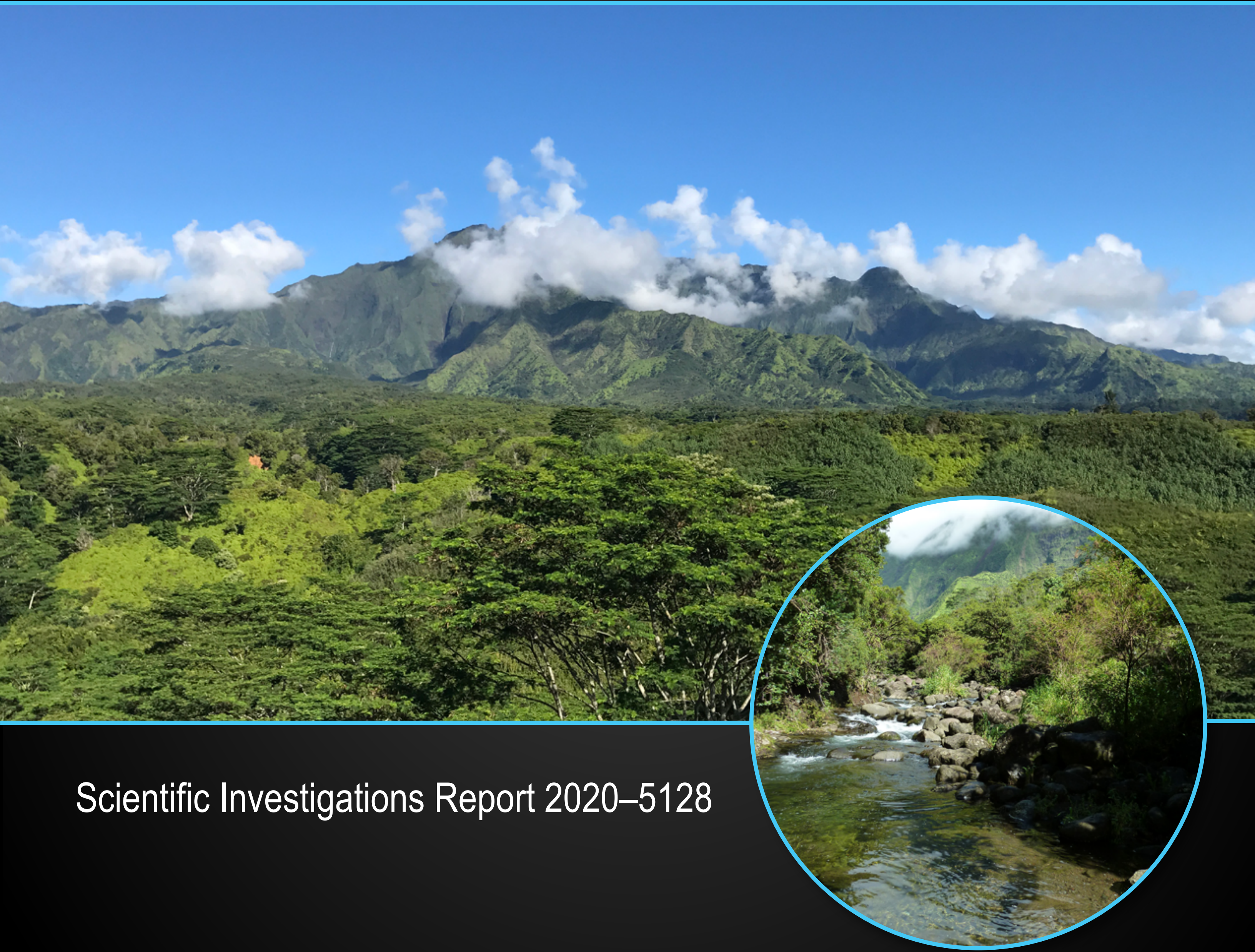
Low-Flow Characteristics of Streams from Wailua to Hanapēpē, Kauaʻi, Hawaiʻi



Scientific Investigations Report 2020–5128

U.S. Department of the Interior
U.S. Geological Survey

Cover. View of Wai‘ale‘ale and the Līhu‘e-Moloa Forest Reserve on the island of Kaua‘i, Hawai‘i. Photograph by Chui Ling Cheng, U.S. Geological Survey, 2017.

(inset). View of North Fork Wailua River at an altitude of about 1,100 feet on the island of Kaua‘i, Hawai‘i. Photograph by Alan Mair, U.S. Geological Survey, 2015.

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DAVID BERNHARDT, Secretary

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
Area		
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
cubic foot per second (ft^3/s)	0.64636	million gallons per day (Mgal/d)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Leakance		
foot per day per foot ([ft/d]/ft)	1	meter per day per meter ([m/d]/m)
inch per year per foot ([in/yr]/ft)	83.33	millimeter per year per meter ([mm/yr]/m)

Seepage rate in cubic feet per second per mile of stream reach [(ft^3/s)/mi] may be converted to cubic meter per second per kilometer of stream reach [(m^3/s)/km] as follows:

$$m^3/s/km = 0.01759 \times [(ft^3/s)/mi]$$

Datum

Vertical coordinate information is referenced relative to local mean sea level.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

ADV	Acoustic Doppler Velocimeter
CWRM	State of Hawai‘i Commission on Water Resource Management
ft^3/s	cubic feet per second
$(ft^3/s)/mi$	cubic feet per second per mile
IVE	Interpolated Variance Estimator
Mgal/d	million gallons per day
MOVE.1	Maintenance of Variance Extension Type 1
MSE	mean square error
RMSE	root mean square error
USGS	U.S. Geological Survey

Low-Flow Characteristics of Streams from Wailua to Hanapēpē, Kaua‘i, Hawai‘i

By Chui Ling Cheng

Abstract

The purpose of this study is to characterize streamflow availability under natural (unregulated) low-flow conditions for streams in southeast Kaua‘i, Hawai‘i. The nine main study-area basins, from north to south, include Wailua River, Hanamā‘ulu, Nāwiliwili, Pū‘ali, Hulē‘ia, Waikomo, Lāwa‘i, and Wahiawa Streams, and Hanapēpē River. The results of this study can be used by water managers to develop technically sound 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 between 95 and 50 percent of the time. Short-term continuous-record stream-gaging stations that monitored low flows on Waiahi and right branch Lāwa‘i Streams were established to serve as potential index stations for partial-record sites in the study area. Continuous-record stream-gaging station on Hanapēpē River monitored natural flow during calendar year 2017 and the streamflow record during that period was used to estimate low-flow characteristics at the station. Partial-record sites were established on 3 main streams and 15 tributary streams, upstream from existing surface-water diversions. 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 for the following streams were estimated for the 59-year base period (water years 1961–2019) using two record-augmentation techniques: right branch ‘Ōpaeka‘a Stream, North Fork Wailua River, north and south fork Waikoko Streams, ‘Ili‘ili‘ula Stream, north and south fork Hanamā‘ulu Streams, Kamo‘oloa Stream, Pāohia Stream, Ku‘ia Stream, Lāwa‘i Stream, Wahiawa Stream, and Hanapēpē River. The 95-percent flow-duration discharges (Q_{95}) ranged from 0.018 to 42 cubic feet per second (ft^3/s). The 50-percent flow-duration discharges (Q_{50}) ranged from 1.1 to 69 ft^3/s. Upper-bound estimates of low-flow duration discharges at partial-record sites on south fork Hanamā‘ulu, Hanamā‘ulu tributary, ‘Ōma‘o, and Pō‘ele‘ele Streams were estimated based on the highest discharges measured as part of this study during Q_{95} to Q_{50} flow conditions, which were 0.44, 0.40, 0.19, and 0.22 ft^3/s, respectively. Measured discharges on Nāwiliwili, Pū‘ali, and left branch Wahiawa Streams do not correlate with data at any active long-term continuous-record stream-gaging stations (10 or more complete water years of natural-flow record) and therefore low-flow duration discharges could not be estimated.

This study also estimated streamflow gains and losses using seepage-run discharge measurements in eight of the nine study basins (Pū‘ali Stream basin was excluded). A majority of the streams gained flow downstream from the uppermost diversions. Measured seepage-gain rates ranged between 0.03 and 24.3 ft^3/s per mile of stream reach. Seepage gains are presumed to originate mainly from groundwater discharge in the Wailua River, Hanamā‘ulu Stream, Nāwiliwili Stream, Hulē‘ia Stream, Lāwa‘i Stream, Wahiawa Stream, and Hanapēpē River basins. Under natural-flow conditions and flow conditions of the seepage runs, a majority of the study-area streams flow continuously from the mountains to the ocean. Where a stream discharges into a reservoir—Hanamā‘ulu and Wahiawa Streams—a dry reach may occur immediately downstream from the reservoir to the point of seepage gain in the stream.

Introduction

Hawai‘i's surface water is a valuable resource that is critical for economic, ecological, and cultural beneficial uses. Traditionally, local communities depended on streams for drinking water, growing crops such as taro, supporting vegetation that provided materials for medicine and shelter, and other cultural practices. Streams can support unique species of endemic freshwater fauna, such as ‘o‘opu (freshwater fish), ‘ōpae (freshwater mountain shrimp), and hīhīwai (freshwater snail). As the sugar industry became established in Hawai‘i, large, engineered diversion and irrigation systems were built to transport water across drainage basins, resulting in reduced streamflow downstream of diversion intakes. As sugarcane cultivation had ceased in many areas of the Hawaiian Islands in the 1990s, some diversion systems were abandoned, whereas others continued to divert water from streams for agricultural, industrial, and municipal uses. Many diversion structures have been constructed to capture a majority of the flow in the streams during low-flow conditions, leaving some reaches downstream from the diversion structures dry. Consequently, the diversion of surface water during low-flow conditions greatly influences water availability for ecosystems, aquatic biota, and other beneficial uses.

Insufficient water supply to meet both offstream and instream uses has been, and continues to be, a major issue in Hawai‘i. Conflicts have led to costly litigation over rights to the water between those currently diverting the water and those desiring sufficient flow in the stream for instream uses. On Kaua‘i, interim instream-flow standards for Waimea River and several of its tributaries, located adjacent to the study area (fig. 1), were amended in April 2017 as a result of a mediation agreement between Pō‘ai Wai Ola (West Kaua‘i Watershed Alliance), Kehaha Agriculture Association, Kaua‘i Island Utility Cooperative, the Hawai‘i State Department of Hawaiian Home Lands, and Agribusiness Development Corporation regarding the diversion of water into the Kōke‘e and Kekaha Irrigation Systems (fig. 1; State of Hawai‘i, 2017b).

The State Water Code mandates that the State of Hawai‘i Commission on Water Resource Management (CWRM) establish a statewide instream-use protection program (State Water Code, Hawai‘i Revised Statutes, chapter 174C, section 71). The principal mechanism that CWRM implements for the purpose of protecting instream uses is establishing instream-flow standards that describe flows necessary to protect the public interest in the stream with consideration of existing and potential offstream water use, including the economic impact of restricting such use (State Water Code, Hawai‘i Revised Statutes, chapter 174C, section 71[1][C]). The instream uses recognized by CWRM include (1) maintenance of fish and wildlife habitat; (2) outdoor recreational activities; (3) maintenance of ecosystems; (4) aesthetic values, such as waterfalls and scenic waterways; (5) maintenance of water quality; (6) the conveyance of irrigation and domestic water supplies; and (7) the protection of traditional and customary Hawaiian rights.

Recognizing the complexity of establishing permanent instream-flow standards for all perennial streams in Hawai‘i, the CWRM originally established interim instream-flow standards at status quo levels in 1988–89. An interim instream-flow standard is originally defined as the amount of water flowing in each stream, considering the natural variability of streamflow, without further amounts of water being diverted offstream through new or expanded diversions existing at the time the administrative rules were adopted in 1988 and 1989 (Hawai‘i Administrative Rules, chapter 169, section 13-169-48). The CWRM first adopted interim instream-flow standards for all streams in southeast Kaua‘i on June 15, 1988 (Hawai‘i Administrative Rules, chapter 169, section 13-169-45). These interim instream-flow standards did not have quantitative flow values and allowed diversions existing at the time of the adoption to continue operating. Additional information could be filed with CWRM to reduce or increase diversion, through a modification of the interim instream-flow standards. Upon reviewing a CWRM decision related to interim instream-flow standards for streams in eastern O‘ahu, the Hawai‘i Supreme Court deemed “status quo” interim instream-flow standards inadequate and required quantitative interim instream-flow standards to be established (State of Hawai‘i, 2000). Within the last two decades, the CWRM has compiled the best available information—hydrology, and instream and offstream uses—on streams of concern to develop quantitative interim instream-flow standards upon receipt of a petition to amend an existing interim instream-flow standard. Quantitative interim instream-flow standards that account for economic, domestic, cultural, ecological, recreational, and aesthetic needs have not yet been established for streams in southeast Kaua‘i, Hawai‘i.

Previous Low-Flow Investigations

Previous low-flow studies of Hawaiian streams have been largely conducted on a basin-scale basis, with a focus on computing a selected range of low-flow duration discharges and examining the effects of surface-water diversions on low flows and habitat availability for native stream fauna. Few studies were conducted to characterize low-flow availability in streams on Kaua‘i. Cheng and Wolff (2012) characterized availability and distribution of low flow in Anahola Stream and assessed flow availability for agricultural use under a variety of potential interim instream-flow standards established for the stream. In an effort to understand the occurrence and movement of groundwater in the Līhu‘e basin, Izuka and Gingerich (1998) conducted base-flow analysis of continuous stream-gaging station records and collected additional discrete streamflow measurements to quantify the magnitude of gains and losses in the measured stream reaches. These streamflow measurements are summarized in this report. Statewide analysis of low flows includes studies by Yamanaga (1972), Fontaine and others (1992), Bassiouni and Oki (2013), Cheng (2016), and Clilverd and others (2019). The application of record-augmentation methods for estimating low-flow characteristics at sites with either short-term records or partial-records of streamflow data is well documented in many of the aforementioned studies.

Purpose and Scope

This report presents the results of a study conducted during 2016–20 (study period) by the U.S. Geological Survey (USGS), in cooperation with CWRM, to provide information that could be used by CWRM to develop technically sound instream-flow standards for streams in southeast Kaua‘i. The objectives of the study were to quantify natural low-flow characteristics upstream of surface-water diversions and characterize the seepage gains and losses on selected reaches of a subset of streams in the study area. For the purposes of this report, low-flow characteristics are represented by flow-duration discharges equal to and less than the median flow. The nine main study-area basins, from north to south, include Wailua River, Hanamā‘ulu, Nāwiliwili, Pū‘ali, Hulē‘ia, Waikomo, Lāwa‘i, and Wahiawa Streams, and Hanapēpē River. The scope of this investigation involved analyzing historical and current (study period) streamflow data at continuous-record stream-gaging stations and miscellaneous sites and the collection of additional data, including (1) streamflow records at continuous-record low-flow stations established on Waiahi and Lāwa‘i Streams; (2) discharge measurements at 18 partial-record sites established upstream from all surface-water diversions; and (3) seepage-run discharge measurements at selected sites in the study-area basins. This report includes descriptions of study-area streams that flow from the mountains to the ocean during low-flow conditions, estimates of selected flow-duration discharges (95 to 50 percent exceedance values) on 13 streams, and estimates of seepage gains and losses on selected reaches of 11 streams.

Description of the Study Area

The study area is situated on the island of Kauaʻi, the fourth largest (553 square miles [mi^2]) and one of the geologically oldest of the eight main Hawaiian Islands (Stearns and Macdonald, 1942). The topography of the island ranges from coastal beaches and the 2,700-foot (ft) sea cliffs of the Nāpali Coast in the northwest to the highest altitude of 5,243 ft above mean sea level at Kawaikini Peak, a mile south of Waiʻaleʻale (fig. 1). The population on the island is more than 72,000, which is 5 percent of the State's 2018 population estimate (State of Hawaiʻi, 2018), with Līhuʻe as the main population center. The study area includes nine stream basins—from Wailua in the north to Hanapēpē in the south—that drain the southeastern part of the island. The streams in the study area consist of the North Fork Wailua River; South Fork Wailua River and its tributaries Waikoko, ʻIliʻiliʻula, and Waiahi Streams; Hanamāʻulu Stream; Nāwiliwili Stream; Pūʻali Stream; Hulēʻia Stream and its tributaries Kamoʻoloa, Pāohia, and Kuʻia Streams; Waikomo Stream and its tributaries ʻŌmaʻo and Pōʻeleʻele Streams; Lāwaʻi Stream; Wahiawa Stream; and Hanapēpē River. Drainage areas delineated by the study-area streams range from 1.5 to 52.5 mi^2, with Pūʻali being the smallest and Wailua the largest. Low-flow characteristics of the study-area streams are mainly affected by (1) climate and rainfall; (2) the physical attributes of the valleys such as topography, land cover, land use, and hydrogeology; and (3) regulation and withdrawal of streamflow.

Climate and Rainfall

The topography of Kauaʻi and the position of the North Pacific subtropical anticyclone relative to the island produce a climate characterized by mild and uniform temperatures, cool and persistent trade winds, and seasonal and geographic variability in rainfall (Blumenstock and Price, 1967; Schroeder, 1993). Rainfall is generated from the rising and cooling of moisture-laden trade winds along the windward slopes of the island. During the dry season (May–September), persistent northeasterly trade winds blow 80–95 percent of the time. During the rainy season (October–April), other migratory weather systems that affect the island reduce trade-wind frequency to 50–80 percent of the time. Heavy and intense rainfall can be caused by low-pressure systems from the northwest and those accompanied with southerly winds (Kona storms), cold fronts associated with mid-latitude cyclones, and tropical cyclones from the eastern Pacific Ocean (Giambelluca and Schroeder, 1998). Dry coastal areas receive most of their annual rainfall amounts from these storms.

Orographic rainfall on the island is characterized by steep spatial gradients with increasing altitude (fig. 2). Mean annual rainfall within the study area ranges from about 400 inches (in.) at Waiʻaleʻale to less than 25 in. in the coastal areas (Giambelluca and others, 2013). Within 1 mi of Waiʻaleʻale, mean annual rainfall can vary spatially by more than 150 in. During the study period, annual rainfall varied from 299 in. in water year 2017 to 530 in. in water year 2018 (fig. 3)—about 24 percent below and 35 percent above the mean annual rainfall for water years 1961–2019, respectively—at rain-gaging station 220427159300201 on Waiʻaleʻale (station 1047.0 in fig. 2). For water years 2016, 2017, and 2019, the month of June was consistently one of the wettest months during the study period. In water year 2018, the month of August had the highest rainfall total of 76 in. out of all months in the water year, which is more than double the mean monthly rainfall total of 32 in. for water years 1961–2019. About 34 in. of rain from the August 2018 rainfall total recorded at the Waiʻaleʻale rain-gaging station was generated from Hurricane Lane. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends. For example, the "2019 water year" is the period from October 1, 2018, to September 30, 2019.

The basin of Wailua River receives the highest maximum rainfall of about 400 in. per year in the study area. Hanapēpē River basin receives a maximum rainfall of about 250 in. per year. The basins of Hulēʻia and Wahiawa Streams receive a maximum rainfall of about 200 in. per year. The basins of Waikomo and Pūʻali Streams receive the lowest maximum rainfall in the study area of less than 120 in. per year.

Bassiouni and Oki (2013) analyzed trends in streamflow and base flow for long-term continuous-record stations in Hawaiʻi. Downward trends in base flow and low-streamflow characteristics occurred during the 1943–2008 period. The detected trends may be related to regionwide changes in climatic and land-cover factors. Statistically significant (5-percent significance level) downward trends in low flows were detected on east branch of North Fork Wailua River during 1943–2008.

Hydrogeology

Hydrogeology, as it relates to the composition and permeability of the aquifer and the position of the water table relative to the streambed, is an important physical characteristic affecting low flows because the natural low flow in a stream is mainly from groundwater sources. Groundwater in the study area occurs in three principal hydrogeologic settings (fig. 4): (1) dike-impounded-groundwater setting, (2) thickly saturated setting, and (3) freshwater-lens setting (Izuka and others, 2018). The following discussion summarizes the three principal hydrogeologic settings and where these settings occur relative to aquifer systems in the study area. Aquifer systems are hydrologic units established by the CWRM to provide a basis for managing groundwater resources and the aquifer systems may not reflect hydrogeologic conditions.

Dike-impounded-groundwater settings occur where low-permeability dikes intrude lava flows and other rocks to form compartments in which groundwater can be impounded to hundreds or thousands of feet above sea level. Water flows from compartments with higher water levels to compartments with lower water levels, and eventually to adjacent groundwater bodies—such as freshwater lenses—or discharges to springs, streams, and submarine seeps. Dike-impounded groundwater maintains perennial flow in streams

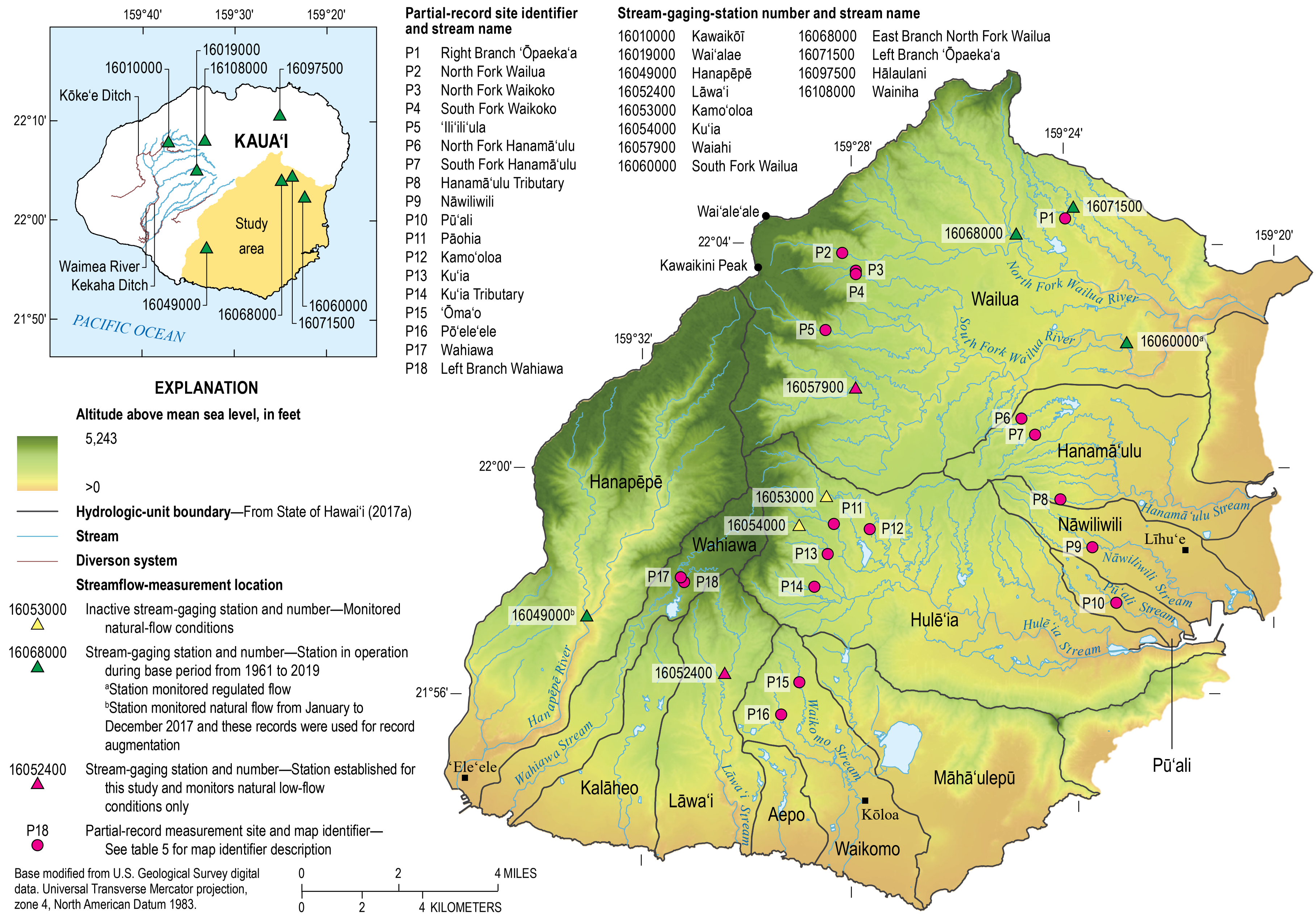


Figure 1. Map showing locations of study area, active and inactive continuous-record stream-gaging stations, and partial-record measurement sites in southeast Kauaʻi, Hawaiʻi.

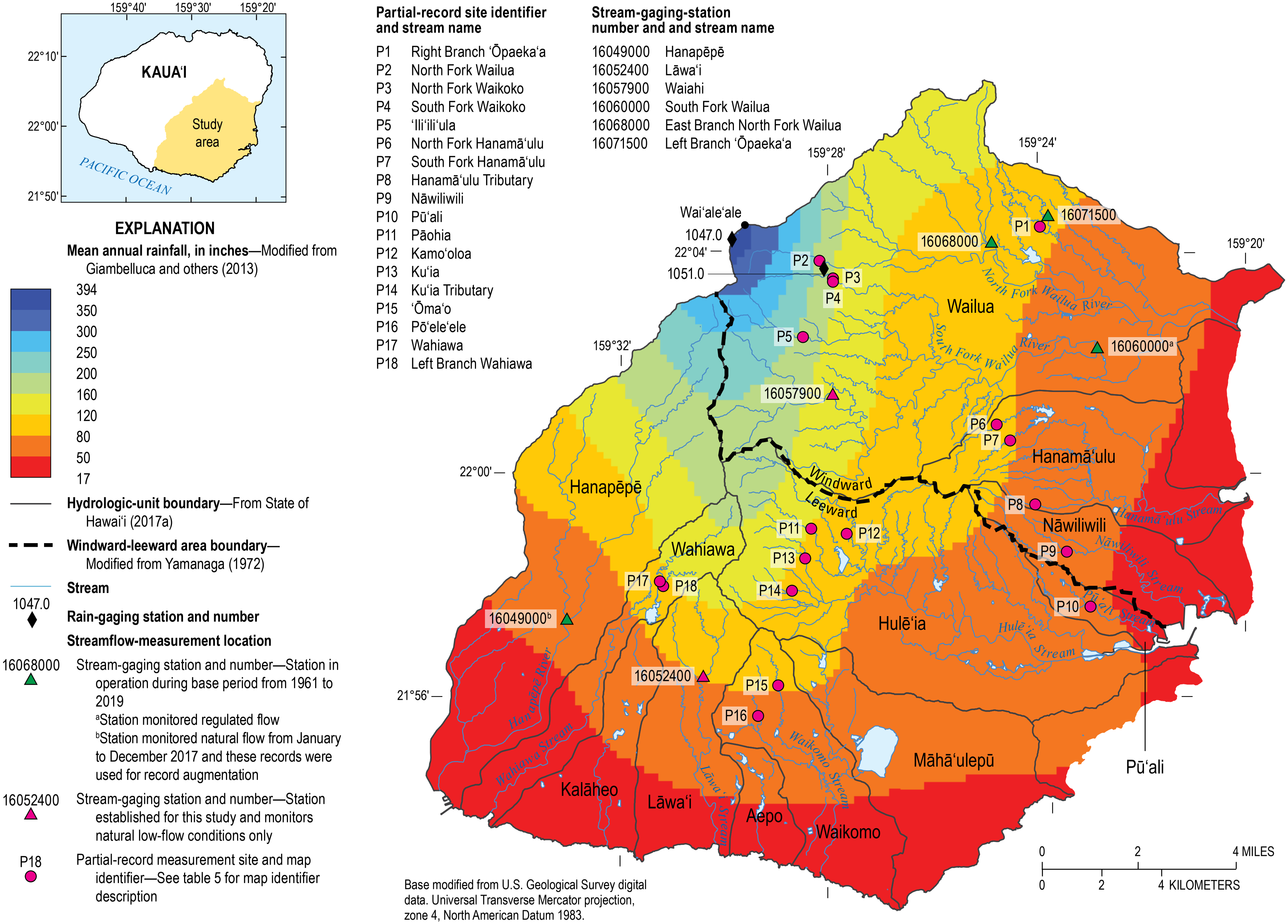


Figure 2. Map of mean annual rainfall in study area, southeast Kauaʻi, Hawaiʻi.

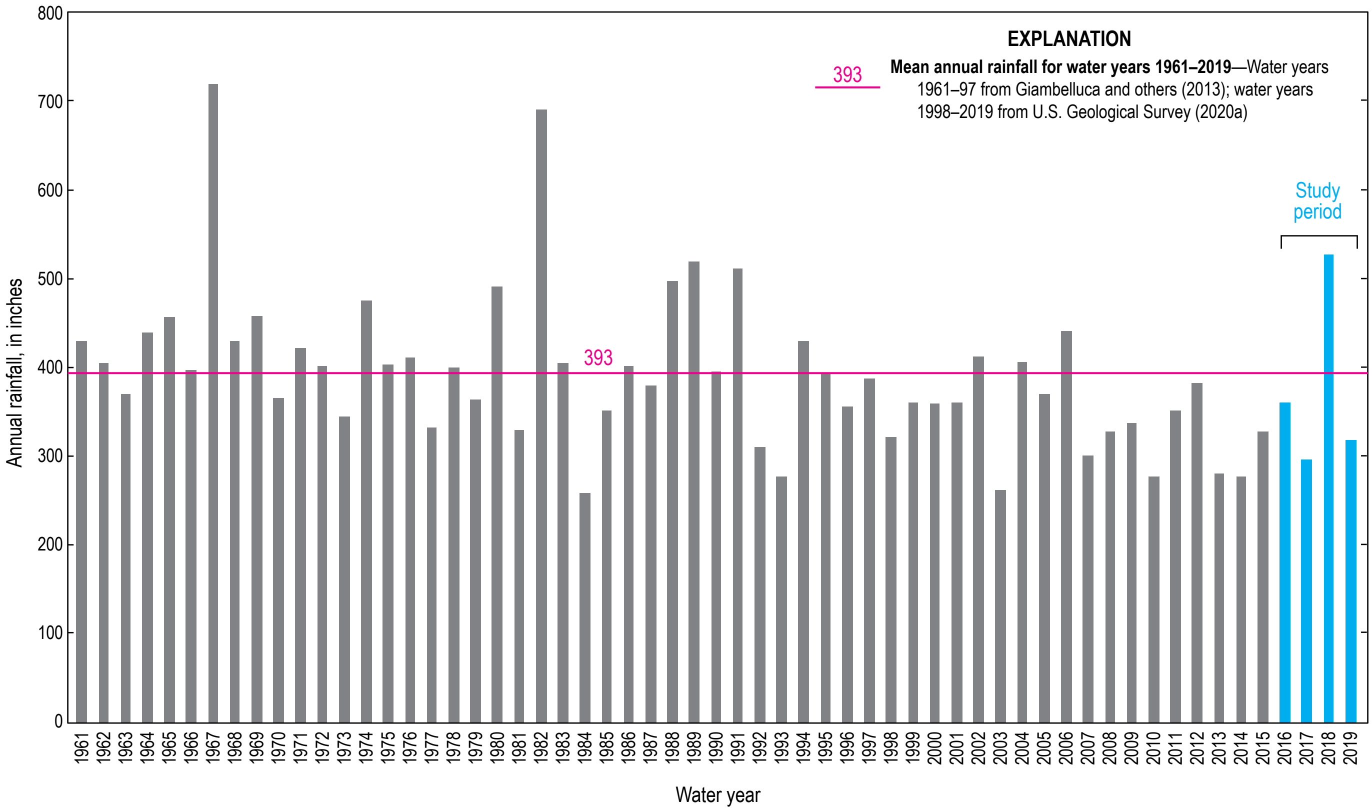


Figure 3. Plot of annual rainfall totals at rain-gaging station 220427159300201 (State key number 1047.0) on Waiʻaleʻale near Līhuʻe, Kauaʻi, Hawaiʻi, for water years 1961–97 (Giambelluca and others, 2013) and water years 1998–2019 (U.S. Geological Survey, 2020a).

in some parts of the Wailua, Hulēʻia, Lāwaʻi, Wahiawa, and Hanapēpē aquifer systems.

Thickly saturated settings occur in low-permeability lava flows situated in an area with wet climate, where groundwater saturates nearly to the land surface and may discharge to the streams rather than as submarine groundwater discharge. This groundwater flow maintains perennial flow in most reaches of North Fork and South Fork Wailua Rivers and Hulēʻia Stream, and the entirety of Hanamāʻulu, Nāwiliwili, and Pūʻali Streams. Stream reaches in dike-impounded-groundwater and thickly saturated settings generally are referred to as “gaining reaches” because groundwater contributes to streamflow.

Freshwater-lens settings are high-permeability aquifers that occur in dike-free lava flows where fresh groundwater forms a lens-shaped body that buoyantly overlies denser saltwater from the ocean. The lens has a low-altitude water table and groundwater flows toward the coast where it naturally discharges to springs, streams, wetlands, and submarine seeps. A freshwater-lens setting is postulated to occur in the southern part of Koloa and Hanapēpē aquifer systems, which underlays most of Waikomo Stream and the lower reaches of Lāwaʻi Stream, Wahiawa Stream, and Hanapēpē River. Stream reaches in the freshwater-lens setting generally are referred to as “losing reaches” because streamflow discharges to the groundwater body. According to Izuka and others (2018), the boundary between dike-impounded-groundwater and freshwater-lens settings in southern Kauaʻi is uncertain owing to insufficient water-level data.

Surface-Water Use

Historically, plains in the low-lying lands in the study area were used mainly for sugarcane cultivation. Established in 1835, Koloa Plantation was the first sugar plantation in Hawaiʻi (Wilcox, 1996). Situated in the Māhāʻulepū area and Waikomo Stream basin (fig. 5), the plantation depended on water from neighboring lands owing to the lack of surface-water and groundwater resources in the area. The diversion, conveyance, and storage systems owned and managed by Koloa Plantation include the 2.3-million gallon Waita Reservoir, the second largest reservoir in Hawaiʻi. Koloa Plantation was acquired by Grove Farm in 1948. Grove Farm originally owned lands and operated diversion systems in the Hulēʻia Stream basin. After ending its sugar business in 1974, Grove Farm leased lands to Līhuʻe Plantation and McBryde Sugar Company for continued sugar production. Līhuʻe Plantation, established in 1849, was the second-oldest sugar plantation in Hawaiʻi. The plantation originally owned lands and operated diversion systems in the Wailua River and Hanamāʻulu Stream basins. The diversion systems span

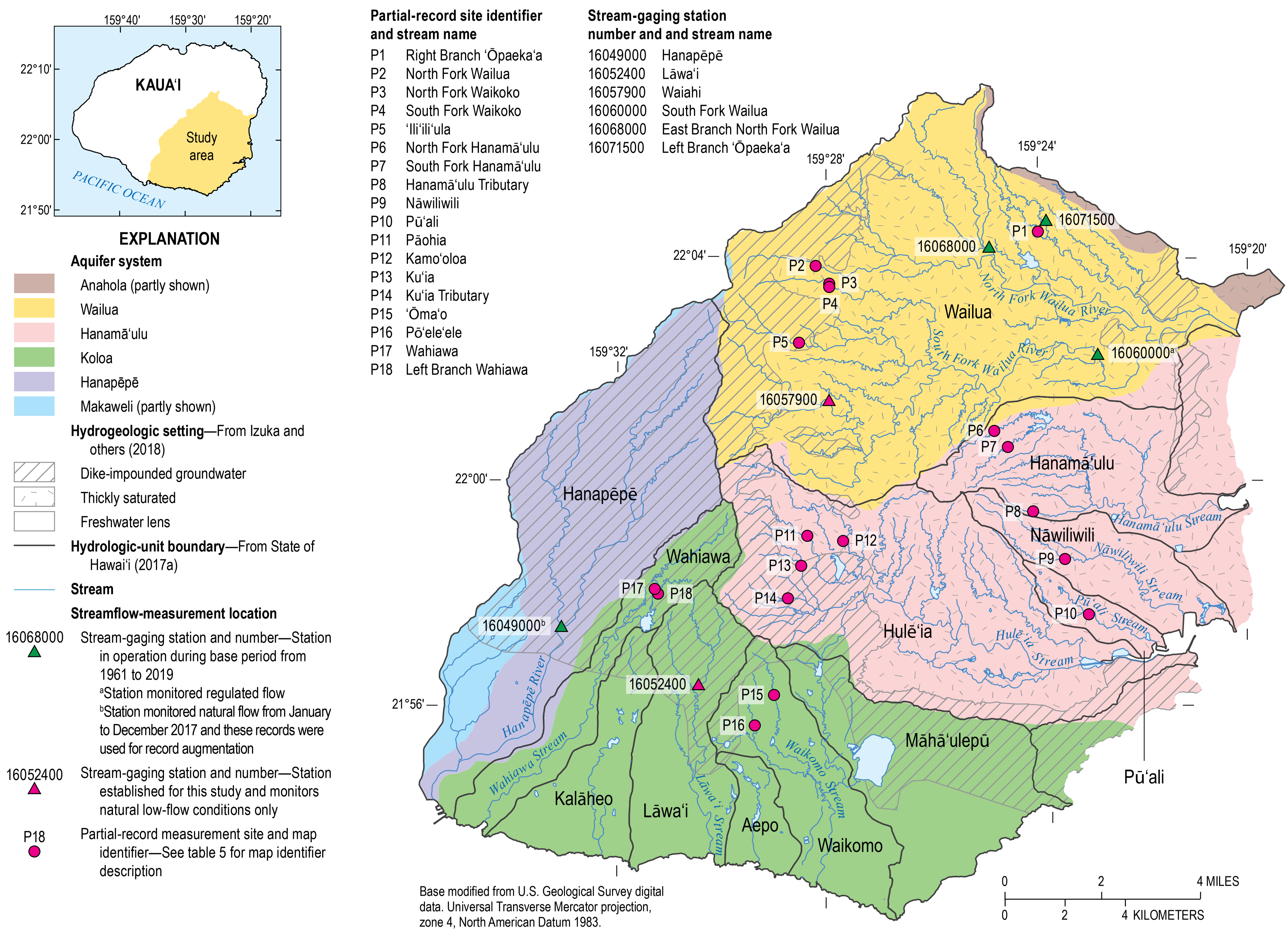


Figure 4. Hydrogeologic settings in the study area, southeast Kaua'i, Hawai'i.

51 mi of ditches with 18 stream intakes and transported an average 100–140 million gallons of water per day. Within the Līhu‘e Plantation lands, the East Kaua‘i Water Company used water from North Fork Wailua River. Līhu‘e Plantation ended sugar production in November 2000 (Sommer, 2000). McBryde Sugar Company originally owned lands and operated diversion systems in the Lāwa‘i Stream, Kalāheo Gulch, Wahiawa Stream, and (lower) Hanapēpē River basins. With limited access to surface-water resources, the company focused on developing groundwater resources and water storage. Groundwater pumps were powered by the company’s two hydropower facilities, one located on the northern slopes of Kaua‘i and the second in Kalāheo Gulch basin. McBryde Sugar Company built Alexander Reservoir (capacity of more than 800 million gallons) to capture water sources at the head of Wahiawa Stream basin (fig. 5). McBryde Sugar Company ended sugar production in 1994.

As a result of sugar plantation closures, water use shifted from irrigation of sugarcane to irrigation of diversified crops and hydropower development. During the study period, many of the surface-water diversions originally operated by the plantations continued to be used (fig. 5). The upper reaches of Wailua River, Hanamā‘ulu Stream, and Hulē‘ia River were diverted by several interconnected ditches that supply irrigation water for seed production, commercial forestry, pasture management, and diversified crops. Water diverted from Waiahi Stream, a tributary of South Fork Wailua River, supported two hydropower facilities in the valley. Nāwiliwili Stream provided irrigation water for taro cultivation and diversified crops within the valley. Lāwa‘i and Wahiawa Streams supplied irrigation water for coffee cultivated near the south shore and landscape irrigation. The upper tributaries of Hanapēpē River provided irrigation water mainly for seed production and pasture management in the western coastal areas (State of Hawai‘i, 2016, p. 50). Hanapēpē River was also diverted in the lower reach to irrigate taro farms in the valley and coffee fields in lower Kalāheo Gulch basin. Information on surface-water diversions is gathered from County of Kaua‘i and State of Hawai‘i reports, accounts from current landowners within the study area, and visual observations during field investigations by USGS personnel. The conditions related to the diversion and uses of surface water in the study area apply to the study period and may not represent future conditions because landownership and the uses of water may change.

Historical Surface-Water Availability

Streamflow data that describe the natural (unregulated) low-flow conditions of the study-area streams are limited. Natural flow is streamflow that is not affected by factors including surface-water diversions, irrigation return flows, or groundwater withdrawals. Two inactive continuous-record stream-gaging stations—station 16053000 on Kamo‘oloa Stream and 16054000 on Ku‘ia Stream (fig. 1)—monitored natural flow from November 1939 to June 1941. The median discharge is the flow that has been equaled or exceeded 50 percent of the time during a specified period. Median discharges for the period of record at the stations are 4.0 cubic feet per second (ft^3/s) on Kamo‘oloa Stream and 1.7 ft^3/s on Kuia Stream (table 1). With less than 2 years of available data, the duration discharges may not be representative of long-term conditions.

Data that describe historical diverted conditions may not apply to the present day; however, they provide information that is useful for understanding the diversion practices that occurred during the study period. In addition, ditch-flow data at surface-water diversion intakes and associated flow-duration discharges can provide some information on streamflow availability because many diversion intakes were constructed to capture a majority of the streamflow during low-flow conditions. Multiple surface-water diversions have existed on the same stream to capture streamflow gained between the diversions.

A number of ditch-flow gaging stations operated at or near surface-water diversions within the study area prior to 2001 (table 1, fig. 5). A majority of ditch-flow gaging stations were located in the Wailua River and Hulē‘ia Stream basins. On North Fork Wailua River, station 16100000 monitored flow diverted from a stream on the island’s northern slopes that was discharged to a tributary of North Fork Wailua River. Station 16061000 monitored flow diverted from the river to ‘Ili‘ili‘ula North Wailua Ditch and downstream station 16062000 monitored flow diverted to Stable Storm Ditch. On South Fork Wailua River, station 16061200 monitored total diverted flow from North Fork Wailua River and Waikoko Stream in the ‘Ili‘ili‘ula North Wailua Ditch. The difference in ditch-flow records at stations 16061000 and 16061200 represents diverted flow from Waikoko Stream assuming no gain or loss of ditch flow between the stations. Station 16057000 monitored flow diverted from Waiahi Stream, a tributary of South Fork Wailua River, to Upper Līhu‘e Ditch. Downstream station 16058000 monitored flow diverted from South Fork Wailua River to Hanamā‘ulu Ditch. In Hulē‘ia Stream basin, station 16056800 monitored flow diverted from two tributaries of South Fork Wailua River and two tributaries of Hulē‘ia Stream to the Waiahi-Ku‘ia Aqueduct. Stations 16053400 and 16053600 monitored flow diverted from two tributaries of Hulē‘ia Stream to upper and lower Ha‘ikū Ditch, respectively. Station 16054200 monitored flow diverted from tributaries of Hulē‘ia Stream to Kōloa Ditch and eventually conveyed to the Māhā‘ulepū area.

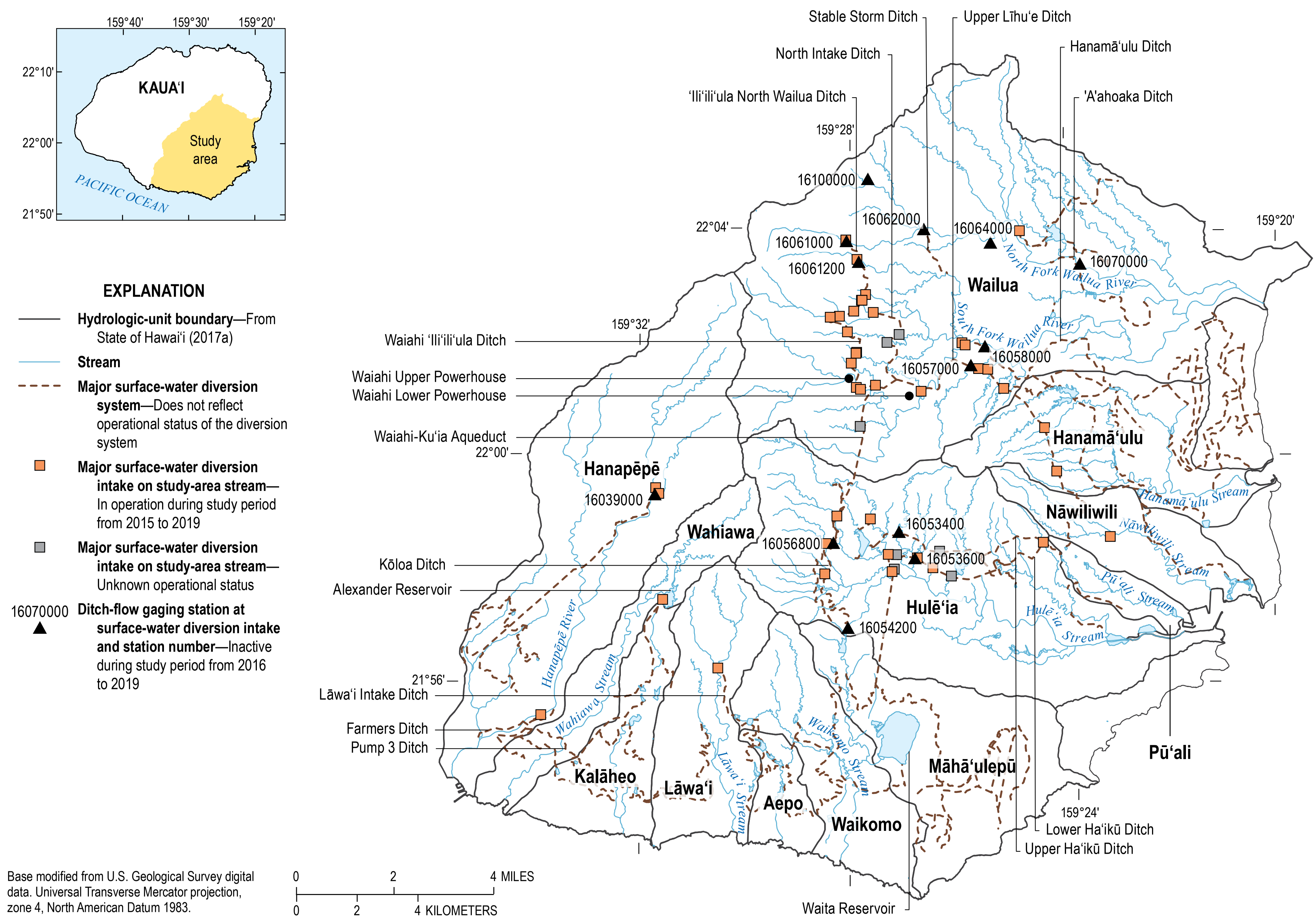


Figure 5. Map showing locations of major surface-water diversion systems and associated intakes, and U.S. Geological Survey ditch-flow gaging stations in the study area, southeast Kaua'i, Hawai'i.

Table 1. Low-flow duration discharges at inactive continuous-record streamflow and ditch-flow gaging stations in the study area, southeast Kaua‘i, Hawai‘i.

[USGS, U.S. Geological Survey; HI, Hawaii; nr, near; N, North; blw, below; Str, Stream; ft^3/s, cubic feet per second. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names. Altitude values interpolated from USGS 1:24,000-scale digital hypsography data. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends]

USGS station number	USGS station name, Kauai, HI	Altitude, in feet	Period of record	Number of complete water years	Complete water years 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									
						50	55	60	65	70	75	80	85	90	95
Historical continuous-record stream-gaging stations															
16053000	Kamooloa Stream nr Koloa	1,050	1939–41	0	Period of record	4.0	3.8	3.5	3.2	3.0	2.8	2.5	2.1	1.9	1.6
16054000	Kuia Stream nr Koloa	1,050	1939–41	0	Period of record	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.4	1.3	1.2
Historical continuous-record ditch-flow gaging stations															
16039000	Hiloa Ditch nr Eleele	700	1911–15	3	1913–15	37	34	33	31	31	28	28	25	23	19
16053400	Upper Haiku Ditch nr Puhi	470	1963–71	6	1965–70	6.7	4.6	3.1	2.3	1.6	0.78	0.32	0.15	0.080	0.030
16053600	Lower Haiku Ditch nr Puhi	400	1963–71	6	1965–70	3.3	2.7	2.4	2.2	1.9	1.7	1.5	1.2	1.1	0.79
16054200	Koloa Ditch nr Koloa	620	1964–71	6	1965–70	15	13	12	11	10	9.0	8.0	6.8	5.2	4.3
16056800	Waiahi-Kuia Aqueduct nr Puhi	730	1964–71	6	1965–70	2.0	1.6	1.1	0.59	0.25	0.090	0	0	0	0
16057000	Lihue Ditch nr Lihue	550	1910–19	4	1910–13	9.6	8.8	8.4	8.1	7.2	5.4	3.8	0	0	0
16058000	Hanamaulu Ditch nr Lihue	420	1910–19	7	1910–14, 1917–18	32	31	29	28	25	19	15	11	8.7	5.6
16061000	North Wailua Ditch nr Lihue	1,100	1932–85	53	1933–85	19	19	18	18	17	17	16	15	14	9.1
16061200	N. Wailua Ditch blw Waikoko Str nr Lihue	1,070	1965–2002	37	1966–2002	22	21	21	20	20	19	18	17	16	9.6
16062000	Stable Storm Ditch nr Lihue	710	1937–2002	65	1938–2002	0.28	0.20	0.14	0.11	0.050	0.020	0	0	0	0
16064000	Kanaha Ditch nr Lihue	540	1912–55	36	1914, 1917–22, 1927–55	2.4	1.5	1.1	0.85	0.67	0.48	0.40	0.32	0.25	0.080
16070000	Aahoaka Ditch nr Kapaa	400	1966–72	5	1967–71	0	0	0	0	0	0	0	0	0	0
16100000	Hanalei Tunnel Outlet nr Lihue	1,210	1932–85	53	1933–85	28	26	25	23	20	17	13	7.0	3.1	0.60

Methods

The following sections provide an overview of data-collection sites established, flow-duration statistics and how they are computed, and the record-augmentation techniques used in this study.

Data-Collection Sites

Three types of streamflow-measurement sites are described in this report: (1) a continuous-record stream-gaging station, which provides a continuous record of discharge at a location in the stream; (2) a partial-record station, which commonly has 10 or more systematic streamflow measurements at a location in the stream; and (3) a miscellaneous site, which typically has less than 10 streamflow measurements that may not have been collected in a systematic manner as with a partial-record station. In this study, a long-term continuous-record stream-gaging station (long-term station) has 10 or more complete water years of natural-flow record, and a short-term continuous-record station (short-term station) has less than 10 complete water years of natural-flow record. A low-flow partial-record site has a series of streamflow measurements that have been made under low-flow conditions. An example of a miscellaneous site is a seepage-run measurement site where only one or two measurements have been made for the purposes of determining seepage gains and loses along a stream reach.

The following sections describe short-term continuous-record stream-gaging stations, partial-record sites, and seepage-run discharge-measurement sites established for this study.

Short-Term Stations

Two short-term continuous-record stream-gaging stations that monitored natural low flow were established to serve as potential index stations (table 2). Station 16057900 was located on Waiahi Stream upstream from the Waiahi upper powerhouse. Station 16052400 was located on right branch Lāwaʻi Stream upstream from the Lāwaʻi Intake Ditch and a diversion intake for a nursery in the area (fig. 1). During the study period, two long-term stations were operated within the northernmost boundary of the study area in the Wailua River basin (fig. 1). The short-term stations were established for this study because of a lack of long-term stations in the southern part of the study area. Information from these short-term stations was needed to estimate streamflow characteristics at partial-record sites in the southern part of the study area where discharges may not correlate well with discharges at existing long-term stations in the northern part of the study area.

Each short-term station recorded instantaneous stage values in 15-minute intervals with no real-time capability. A stage-discharge relation (rating curve) was developed from paired discharge and stage measurements at the short-term stations for the range of flow-duration discharges—between Q_{95} and Q_{50}—that are of interest in this study. Using this relation, discharge at the station is determined from a stage measurement.

The Waiahi short-term station has been in operation since November 2015. The Lāwaʻi short-term station was in operation from February 2016 to March 2017, and May 2017 to March 2018. In March 2017, the station equipment was damaged by a high-flow event and it was repaired in May 2017. Subsequently in March 2018, the station was destroyed by a high-flow event that altered the stream channel near the station. Reinstallation of the station was deemed unfeasible owing to the instability of the stream channel at the time.

Station 16049000 on Hanapēpē River is an active continuous-record stream-gaging station that monitors flow regulated by upstream surface-water diversions on right and left branch Kōʻula Rivers. During calendar year 2017, these upstream diversions were not in operation (Howard Greene, Gay & Robinson, oral commun., 2018). Continuous record during this period that the station monitored natural flow was used in record augmentation to estimate flow-duration discharges at the station. For simplicity, station 16049000 is referred as a short-term station in this report because the station has less than 10 complete water years of natural-flow record.

Partial-Record Sites

Partial-record sites were established on 3 main streams and 15 tributary streams in the study area (fig. 1). To characterize natural low-flow availability of these streams, partial-record sites were established upstream from all surface-water diversions. Discharges measured at the partial-record sites may include discharge from upstream development tunnels because flow from a development tunnel is considered water that would otherwise have naturally discharged into the stream.

For record augmentation, about 10 discharge measurements are generally made at a partial-record site during periods of low flow (Rantz and others, 1982). The discharge measurements should be made under a variety of low-flow conditions and during independent recessions. A streamflow recession is defined as the period when flow returns to low-flow conditions following a period of direct runoff. Hydrographs from nearby active long-term stations were checked to determine when recessions occurred in the study-area streams. For this study, discharge measurements were made at each of the partial-record sites between February 2016 and January 2020, and bracketed the range of flow-duration discharges—between Q_{95} and Q_{50}—as indicated by nearby active continuous-record stream-gaging stations that monitored natural flow. This approach was used to increase the accuracy of the entire range of estimated flow-duration discharges at the partial-record sites. Discharge measurements were made with acoustic Doppler velocimeters (ADV), processed, reviewed, approved, archived, and available in the USGS National Water Information System database at https://waterdata.usgs.gov/hi/nwis/nwis.

Most discharge measurements at the partial-record sites were made during stable-flow conditions, as documented by recording the height of water surface—commonly referred to as gage height or stage—during the time when the discharge

Table 2. Low-flow duration discharges at active long-term continuous-record stream-gaging stations and short-term continuous-record low-flow gaging stations established in the study area, southeast Kaua'i, Hawai'i.

[USGS, U.S. Geological Survey; HI, Hawaii; nr, near; Str, Stream; alt, altitude; ft, feet; EB, East Branch; NF, North Fork; Riv, River; blw, below; RB, Right Branch; US, upstream; P, present (2019); ft^3/s, cubic feet per second; --, not applicable. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names. Altitude values interpolated from USGS 1:24,000-scale digital hypsography data. A water year is a 12-month period that extends from October 1 to September 30 of the following year and is named according to the year during which the period ends]

USGS station number	USGS station name, Kauai, HI	Altitude, in feet	Drainage area, in square miles	Period of record	Number of complete water years	Complete water years used in computation	Length of record, in years	Discharge, in ft3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded: Total flow										Base flow	
								50	55	60	65	70	75	80	85	90	95	50	70
Long-term continuous-record stream-gaging stations																			
16010000	Kawaikoi Stream nr Waimea	3,420	3.8	1909–16, 1919–P	102	1912, 1914, 1920–2019	102	12	11	9.6	8.5	7.4	6.7	5.8	5.0	4.2	3.4	6.7	4.9
						1943–2019	77	12	11	9.3	8.3	7.4	6.5	5.7	4.9	4.2	3.3	6.6	4.9
						1961–2019	59	12	10	9.3	8.2	7.4	6.5	5.8	5.0	4.2	3.3	6.6	4.8
						1984–2013	30	11	9.5	8.4	7.5	6.7	6.0	5.2	4.6	4.0	3.1	6.1	4.5
16019000	Waialae Str at alt 3,820 ft nr Waimea[a]	3,820	2.1	1920–32, 1952–P	76[b]	1921–31, 1953–2019	78	6.4	5.7	5.0	4.5	4.0	3.6	3.3	2.9	2.6	2.2	3.4	2.8
						1953–2019	67	6.4	5.7	5.1	4.5	4.0	3.6	3.3	2.9	2.6	2.2	3.5	2.8
						1961–2019	59	6.4	5.8	5.1	4.5	4.0	3.6	3.3	2.9	2.6	2.2	3.5	2.8
						1984–2013	30	6.0	5.2	4.7	4.2	3.7	3.4	3.0	2.8	2.5	2.2	3.2	2.7
16068000[c]	EB of NF Wailua River nr Lihue	500	6.2	1912–P	104	1913–14, 1916–17, 1920–2019	103	30	28	26	24	23	21	19	18	16	14	22	18
						1943–2019	77	29	27	25	23	22	20	18	17	15	13	21	18
						1961–2019	59	28	26	25	23	21	20	18	16	15	13	21	17
						1984–2013	30	27	25	24	22	21	19	18	16	15	13	20	17
						2017–19	3	31	30	28	26	24	22	20	19	17	15	22	19
16071500[c]	Left Branch Opaekaa Str nr Kapaa	460	0.75	1960–P	59	1961–2019	59	1.5	1.4	1.2	1.1	1.0	0.90	0.80	0.70	0.60	0.50	1.2	0.80
						1984–2013	30	1.3	1.2	1.1	1.0	0.90	0.80	0.70	0.70	0.60	0.50	1.1	0.80
						2017–19	3	1.5	1.4	1.3	1.2	1.1	1.0	1.0	0.90	0.80	0.60	1.2	0.90
16097500	Halaulani Str at alt 400 ft nr Kilauea	390	1.2	1957–P	61	1959–2019	61	7.2	6.8	6.4	6.1	5.7	5.4	5.1	4.8	4.5	4.0	5.8	5.0
						1961–2019	59	7.2	6.8	6.4	6.1	5.7	5.4	5.1	4.8	4.5	4.0	5.8	5.0
						1984–2013	30	6.8	6.4	6.1	5.8	5.5	5.2	4.9	4.6	4.3	3.9	5.6	4.9

Table 2.—Continued

USGS station number	USGS station name, Kauai, HI	Altitude, in feet	Drainage area, in square miles	Period of record	Number of complete water years	Complete water years used in computation	Length of record, in years	Discharge, in ft3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded											
								Total flow										Base flow	
								50	55	60	65	70	75	80	85	90	95	50	70
16108000	Wainiha River nr Hanalei	960	10.4	1952–P	64	1953–55, 1959–2019	64	77	71	67	63	59	56	53	50	47	43	55	49
						1961–2019	59	77	71	67	63	59	56	53	50	47	43	55	49
						1984–2013	30	76	70	66	63	60	56	53	50	47	43	55	49
Short-term continuous-record stream-gaging stations																			
16049000	Hanapepe Riv blw Manuahi Str nr Eleele	222	18.5	1917–20, 1927–P[d]	95	1961–2019[f]	--	69	67	63	56	50	48	46	45	43	42	--	--
16052400	RB Lawai Stream 300 ft US of fork	600	2.2	2016–18	3[e]	1961–2019[f]	--	3.0	2.4	2.2	1.7	1.3	1.2	0.87	0.63	0.53	0.35	--	--
16057900	Waiahi Str US Upper Powerhouse	815	4.1	2015–P	3[e]	Period of record	--	26	24	22	21	19	18	17	16	15	13	--	--
						2017–19	--	25	24	22	21	19	18	17	16	15	14	--	--

[a]Selected flow-duration discharges computed from discharge record at station 16019000 with daily mean discharges estimated for October 13, 2016, June 22, 2019, and June 23, 2019. Daily mean discharge is typically computed from continuous record of unit values collected at 15-minute intervals. Partial record of unit values was used to estimate daily means on the aforementioned days.

[b]Number of complete water years does not include water year 2017 with missing daily mean discharge for October 13, 2016 and water year 2019 with missing daily mean discharge for June 22 and 23, 2019.

[c]Continuous streamgaging station located within the study area.

[d]Station monitored natural flow from January to December 2017 and these records were used in this study for record augmentation.

[e]Number of complete water years for low-flow record.

[f]Selected flow-duration discharges extended with discharge record at 16068000.

measurements were being made. Discharge measurements that were made when the stage was highly variable, that is, when stream stage changed by more than ±0.02 ft, were not used to estimate streamflow characteristics.

Seepage-Run Discharge-Measurement Sites

The spatial distribution of streamflow gains and losses along stream reaches in study-area streams 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 (commonly referred to in Hawai‘i as mauka to makai flows).

Seepage runs were conducted in eight of the nine study basins (Pū‘ali Stream basin was excluded) as part of this study and targeted flow conditions different from those of previous seepage runs. For example, if a previous seepage run was conducted under conditions when an index station was flowing at about a Q_{60} discharge, the seepage run conducted as part of this study would target lower-flow conditions as indicated by the same index station. This was done to characterize seepage gains and losses over a range of flow conditions.

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), especially in the field of water-resource management. 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; hence, the curve shows the relation 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, p. 154) 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, p. 8). The exceedance probabilities are computed with the Weibull formula (Loaiciga, 1989, p. 82):

$$P_k = \frac{k}{n+1},\ k = 1, 2, 3, \ldots,\ n \tag{1}$$

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-streamgage approach in which streamflow information from a continuously gaged basin is applied to a basin with limited streamflow data (Eng and others, 2011). This method involves correlating concurrent streamflow data points 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 relation. 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 Maintenance of Variance Extension Type 1 (MOVE.1) record-augmentation technique described by Hirsch (1982) and the graphical-correlation technique described by Searcy (1959, p. 14) are used to extend streamflow records for this study. Both record-augmentation techniques assume 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, p. 21). 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. Hirsch and Gilroy (1984) and Helsel and Hirsch (2002) showed that the line of organic correlation method was most appropriate for record augmentation of hydrologic data compared with ordinary least squares and least normal squares regression methods. 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.

Granato (2009) developed the Streamflow Record Extension Facilitator program to automate the MOVE.1 technique; this program is used in this study to facilitate record augmentation. The MOVE.1 results are evaluated by analyzing several regression statistics computed by the program. Those statistics include the correlation coefficient (r), residual error for each data point (e_i), the leverage of each data point (h_i), the mean square error (MSE), the root mean square error (RMSE), and a modified Nash-Sutcliff coefficient of efficiency (E). The correlation coefficient (Vogel and Stedinger, 1985; Helsel and Hirsch, 2002) measures the strength of the linear relation between concurrent discharges at the index station and measurement site. The residual error is the uncertainty in the estimated flow-duration discharges at the measurement sites. The leverage of a data point reflects the influence it has on the statistical relation. A high leverage likely indicates an outlier in the discharges at the measurement sites and the statistical relation would be skewed towards this data point. 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 Nash-Sutcliff coefficient of efficiency (Legates and McCabe, 1999), with values ranging from negative infinity to 1, determines 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. A coefficient of efficiency 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 coefficient of efficiency occurs when the mean of discharges at the measurement site is a better predictor than the regression model. For this study, acceptable values of correlation coefficients (r) and modified Nash-Sutcliff coefficients of efficiency (E) are those equal to or greater than 0.80 and 0.50, respectively. The equations used to compute these regression statistics can be found in Granato (2009).

Graphical-Correlation Technique

In the graphical-correlation record-augmentation technique, a curve of relation is plotted through the data points at the measurement site and concurrent data points at the index station. The data points are plotted on an arithmetic scale when drawing the curve of relation to reduce curvature in the extreme low flows and to avoid long downward extrapolations of the data (Ries, 1993, p. 21). The selected low-flow duration discharges at the measurement site are determined by reading the discharges of the measurement site from the best fit curve of relation that correspond to the low-flow duration discharges at the index station.

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 is usually located along the same stream as the site of interest at which flow-duration discharge estimates are needed or in a nearby stream basin that is hydrologically similar to that of the site of interest. Searcy (1959, p. 14) 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, p. 14). In a study by Cheng (2014) that characterized low-flow availability for streams in west Maui, data at one partial-record site correlated with an index station on Moloka‘i about 20 mi away.

Six active long-term continuous-record stream-gaging stations on Kaua‘i that monitored natural flow were considered potential index stations as a result of the limited number of long-term stations in the study area (table 2). Stations 16068000 on east branch of North Fork Wailua River and 16071500 on left branch ‘Ōpaeka‘a Stream are the only long-term stations in the study area, and both stations are located in the North Fork Wailua River basin (fig. 1).

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, p. 18). When flow-duration discharges are estimated from multiple index stations with different time periods and (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, p. 12).

The base period should also be of sufficient length that is representative of long-term streamflow conditions. Fontaine (1995) used data from five long-term stations on the island of O‘ahu, each with more than 60 years of record, and demonstrated that estimates of streamflow characteristics are improved with increased record length (see fig. 2 and table 9 in Fontaine, 1995). 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, p. 18). The 59-year period 1961–2019 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) the greatest number of long-term stations are operated within this 59-year period.

At the six active long-term stations that monitored natural flow, selected annual statistics—Q_{90}, Q_{70}, and Q_{50} discharges and mean flow—computed for each water year from daily mean values of total flow (U.S. Geological Survey, 2020b) and base flow were evaluated for trends in the base period. Trend analyses at the stations were conducted using methods described in Bassiouni and Oki (2013). The base-flow component of total flow was estimated from daily mean values of streamflow using a base-flow separation method described in Wahl and Wahl (1995). This method previously has been used for streams on Moloka‘i, Kaua‘i, Maui, and Oahu to estimate base flow (Oki, 1997; Izuka and Gingerich, 1998; Gingerich, 1999; Fontaine, 2003; Engott and others, 2017; Johnson and others, 2018; Izuka and others, 2018; Oki and others, 2020) and provides a reasonable estimate of base flow for perennial streams in Hawai‘i. The base-flow separation method defines local minimums within consecutive, nonoverlapping N-day periods and requires two parameters: *f*, the turning-point test factor, and N, the number of days in a test window. In this study, the *f* and N values used for the stations were 0.9 and 5 days, respectively, as determined using the method described in Wahl and Wahl (1995). Annual statistics from each station were normalized by dividing each annual statistic by the corresponding statistic calculated over the entire base period. For example, the record of annual mean flows during the base period for a station is normalized by dividing each annual mean flow by the overall mean flow during the base period. Trends were tested using the nonparametric Mann-Kendall test (Hirsch and Slack, 1984) at a significance level 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 generally the case for data at the active long-term stations in this study.

Trends in annual total-flow and base-flow statistics at all the stations were downward except for the trend in Q_{90} discharges at station 16068000 (table 3). At all six stations, trends in mean base flow were statistically significant at the 5-percent level of significance. Statistically significant downward trends of the annual total-flow and base-flow statistics were detected using data from stations 16019000 and 16108000. For station 16068000, the only statistically significant downward trend for the flow characteristics tested is associated with mean base flow. Downward trends in streamflow are consistent with an earlier assessment (Bassiouni and Oki, 2013) that indicated decreases in rainfall. Long-term downward trends in base flows of streams may indicate a reduction in water availability for offstream 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. 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.

Table 3. Results of the Mann-Kendall test for trends in annual flows from 1961 to 2019 at six active long-term stations monitoring natural flow, Kaua'i, Hawai'i.

[**Bold red type** indicates statistically significant negative trend (5-percent level) using the standard Mann-Kendall test; Sen's slope, in cubic feet per second per year; p-value, 2-sided significance level attained by the data; USGS, U.S. Geological Survey; Qxx, discharge in cubic feet per second for selected xx percentages of time (90, 70, 50 percent) the indicated discharge was equaled or exceeded]

Annual statistic	Total streamflow			Base flow		
	Tau	Sen's slope	P-value	Tau	Sen's slope	P-value
USGS station 16010000						
Q_{90}	-0.122	-0.003	0.174	-0.144	-0.004	0.108
Q_{70}	-0.151	-0.004	0.093	-0.158	-0.004	0.079
Q_{50}	**-0.198**	**-0.005**	**0.027**	**-0.183**	**-0.004**	**0.041**
Mean	**-0.181**	**-0.004**	**0.044**	**-0.266**	**-0.005**	**0.003**
USGS station 16019000						
Q_{90}	**-0.208**	**-0.004**	**0.020**	**-0.176**	**-0.003**	**0.050**
Q_{70}	-0.170	-0.004	0.058	-0.164	-0.002	0.068
Q_{50}	**-0.210**	**-0.004**	**0.019**	**-0.226**	**-0.003**	**0.012**
Mean	**-0.219**	**-0.005**	**0.014**	**-0.283**	**-0.004**	**0.002**
USGS station 16068000[a]						
Q_{90}	-0.018	0.000	0.849	0.007	0.000	0.943
Q_{70}	-0.070	-0.001	0.440	-0.009	0.000	0.922
Q_{50}	-0.127	-0.002	0.157	-0.098	-0.002	0.275
Mean	-0.105	-0.003	0.244	**-0.178**	**-0.003**	**0.047**
USGS station 16071500[a]						
Q_{90}	-0.101	-0.004	0.261	-0.061	-0.003	0.496
Q_{70}	**-0.205**	**-0.008**	**0.022**	-0.164	-0.007	0.068
Q_{50}	**-0.224**	**-0.008**	**0.012**	**-0.219**	**-0.007**	**0.014**
Mean	-0.172	-0.006	0.055	**-0.254**	**-0.007**	**0.005**
USGS station 16097500						
Q_{90}	-0.089	-0.001	0.323	-0.106	-0.001	0.236
Q_{70}	-0.118	-0.002	0.189	-0.101	-0.002	0.263
Q_{50}	-0.171	-0.003	0.057	-0.160	-0.002	0.074
Mean	-0.110	-0.002	0.219	**-0.195**	**-0.003**	**0.030**
USGS station 16108000						
Q_{90}	**-0.189**	**-0.002**	**0.035**	-0.145	-0.002	0.106
Q_{70}	**-0.207**	**-0.003**	**0.021**	**-0.197**	**-0.002**	**0.028**
Q_{50}	**-0.210**	**-0.003**	**0.019**	**-0.197**	**-0.002**	**0.028**
Mean	**-0.265**	**-0.004**	**0.003**	**-0.244**	**-0.003**	**0.007**

[a]Continuous stream-gaging station located within the study area.

Analysis of Low Flows at Different Types of Measurement Sites

The data points used to develop the statistical models between the measurement site of interest and the index station for computing low-flow duration discharges differ for different types of measurement sites, which include short-term stations and partial-record sites for this study. These measurement sites are defined in the "Data-Collection Sites" section.

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. The second to last day of each streamflow recession was selected to be used in record augmentation. The second to last day (instead of the last day) of each streamflow recession was used because it

yielded more concurrent data at the index and short-term stations that can be used in record augmentation.

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 the 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

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.

3. 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.

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

Results and Discussion

Estimates of natural low-flow duration discharges of short-term stations and partial-record sites, and results of seepage runs are discussed in the following sections. Data supporting the interpretations and results of this study are available within the report tables and from the USGS National Water Information System (U.S. Geological Survey, 2020a,b). Map identifier (Map ID) is used instead of the USGS station number for references to partial-record and seepage-run discharge-measurement sites. 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 4. Estimated flow-duration discharges at partial-record sites in the study-area streams are summarized in table 5 and figure 6. Flow-duration discharges at short-term stations 16052400 on Lāwa‘i Stream and 16049000 on Hanapēpē River (table 2) were estimated using daily means at the stations and those at the partial-record sites were estimated using discrete discharge measurements collected at the sites.

Natural Low-Flow Duration Discharges

Short-Term Stations

Short-term stations on Waiahi (16057900) and right branch Lāwa‘i Streams (16052400) were established to serve as optional index stations if the discharges at the partial-record sites did not correlate well with discharges at other index stations. Both stations monitored natural low-flow conditions—between Q_{95} and Q_{50}—that are of interest in this study. The Waiahi short-term station had three complete water years of continuous low-flow data (2017–19); water year 2016 was incomplete because the station was installed in November 2015. Low-flow duration discharges computed for water years 2017–19 range from 14 to 25 ft^3/s (table 1). The Lāwa‘i short-term station did not have any complete water years of record because it was damaged twice by high-flow events; therefore, low-flow duration discharges for the period of record were not computed.

At continuous-record stream-gaging stations, an instantaneous discharge record (at 15-min interval) is derived

Table 4. Summary of record-augmentation methods, regression equations, and selected regression statistics for partial-record sites in the study-area streams, southeast Kaua'i, Hawai'i.

[ID, identifier; USGS, U.S. Geological Survey; HI, Hawaii; Riv, River; blw, below; Str, Stream; nr, near; RB, Right Branch; ft, feet; US, upstream; mi, mile; LB, Left Branch; NF, North Fork; N, North; Dt, Ditch; SF, South Fork; trib, tributary; Res, Reservoir; S, South; Rd., Road; DS, downstream; W, West; SW, southwest; Hwy, Highway; EB, East Branch; alt, altitude; MOVE.1, Maintenance of Variance Extension Type 1; X_i, base-10 logarithm of the computed low-flow duration discharge at the index station; Y_i, base-10 logarithm of the estimated low-flow duration discharge at the partial record site; --, not applicable; SREF, Streamflow Record Extension Facilitator program; r, correlation coefficient; RMSE, root mean square error; E, modified Nash-Sutcliff coefficient of efficiency. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID[a]	USGS station number	USGS station name, Kauai, HI	Index station with USGS station number and station name, Kauai, HI	Record-augmentation technique	MOVE.1 regression equation	Regression statistics generated from SREF: r	RMSE	E	Number of measurements (n) used in record augmentation
Short-term continuous-record stream-gaging stations									
16049000	16049000	Hanapepe Riv blw Manuahi Str nr Eleele	16068000 EB of NF Wailua River nr Lihue	Graphical	--	--	--	--	--
16052400	16052400	RB Lawai Stream 300 ft US of fork	16068000 EB of NF Wailua River nr Lihue	MOVE.1	$Y_i = 0.01 + 2.76 (X_i - 1.28)$	0.91	0.131	0.56	10
16057900	16057900	Waiahi Str US Upper Powerhouse	No correlation	--	--	--	--	--	--
Partial-record sites									
P1	220423159235501	RB Opaekaa Stream 0.3 mi US of LB	16071500 Left Branch Opaekaa Str nr Kapaa	Graphical	--	--	--	--	10
P2	220346159280601	NF Wailua River US Blue Hole intake	16019000 Waialae Str at alt 3,820 ft nr Waimea	MOVE.1	$Y_i = 1.35 + 0.42 (X_i - 0.64)$	0.94	0.033	0.62	8
P3 + P4	220326159275401 + 220325159275401	NF Waikoko Str US Iliiliula N Wailua Dt + SF Waikoko Str US Iliiliula N Wailua Dt	16057900 Waiahi Str US Upper Powerhouse	MOVE.1	$Y_i = 0.65 + 1.87 (X_i - 1.28)$	0.89	0.108	0.58	10
P5	220224159282301	Iliiliula Str trib 4 US N Wailua Ditch	16097500 Halaulani Str at alt 400 ft nr Kilauea	MOVE.1	$Y_i = 1.04 + 0.68 (X_i - 0.87)$	0.92	0.040	0.64	11
P6 + P7	220054159244001 + 220037159242901	Hanamaulu Str 1 mi US N Kapaia Res + Hanamaulu Str 0.6 mi US S Kapaia Res	16068000 EB of NF Wailua River nr Lihue	MOVE.1	$Y_i = 0.11 + 0.63 (X_i - 1.31)$	0.88	0.057	0.51	9
P6	220054159244001	Hanamaulu Str 1 mi US N Kapaia Res	16068000 EB of NF Wailua River nr Lihue	Graphical	--	--	--	--	10
P7	220037159242901	Hanamaulu Str 0.6 mi US S Kapaia Res	No correlation	--	--	--	--	--	--
P8	215923159235601	Hanamaulu tributary US of return flow	No correlation	--	--	--	--	--	--
P9	215833159232601	Nawiliwili Stream at Rapoza Rd.	No correlation	--	--	--	--	--	--
P10	215737159230301	Puali Stream 0.6 mi DS Aakukui Rd	No correlation	--	--	--	--	--	--
P11	215853159281801	Paohia Str US Koloa Ditch	16052400 RB Lawai Stream 300ft US of fork	MOVE.1	$Y_i = 0.43 + 0.58 (X_i - 0.01)$	0.89	0.084	0.57	11
P12	215851159273901	Kamooloa Str US Papuaa Res intake	16052400 RB Lawai Stream 300ft US of fork	MOVE.1	$Y_i = 0.82 + 0.45 (X_i - 0.02)$	0.93	0.056	0.60	11

Table 4.—Continued

Map ID[a]	USGS station number	USGS station name, Kauai, HI	Index station with USGS station number and station name, Kauai, HI	Record-augmentation technique	MOVE.1 regression equation	Regression statistics generated from SREF			Number of measurements (n) used in record augmentation
						r	RMSE	*E*	
P13	215822159282601	Kuia Str 0.7 mi W of Papuaa Res	16071500 Left Branch Opaekaa Str nr Kapaa	Graphical	--	--	--	--	10
P14	215751159283901	Kuia Str trib 1 mi SW of Papuaa Res	16052400 RB Lawai Stream 300 ft US of fork	MOVE.1	$Y_i = -0.60 + 2.44 (X_i - 0.02)$	0.90	0.379	0.55	12
P15	215608159285801	Omao Stream at Kaumualii Hwy	No correlation	--	--	--	--	--	--
P16	215538159292301	Poeleele Stream at Kaumualii Hwy	No correlation	--	--	--	--	--	--
P17	215751159311801	Wahiawa Stream US Alexander Res	16097500 Halaulani Str at alt 400 ft nr Kilauea	MOVE.1	$Y_i = 0.50 + 1.55 (X_i - 0.81)$	0.90	0.099	0.59	8
P18	215754159311601	LB Wahiawa Str 400 ft US Alexander Res	No correlation	--	--	--	--	--	--

[a]Refer to figure 1 for station location.

from the rating curve developed for the station and used to compute a record of daily means. An instantaneous discharge is not computed if the corresponding instantaneous stage is outside the range of stage values applicable to the rating curve developed for the station. Low-flow duration discharges for water years 2017–19 at the Waiahi short-term station were computed assuming the daily mean flow for days with incomplete instantaneous discharge record to be higher than the median flow. To determine the validity of this assumption, low-flow duration discharges computed using the assumption were compared to low-flow duration discharges computed by including days during which the daily means were computed from partial instantaneous discharge record. The Waiahi short-term station had 195 days out of 1,095 days (17 percent) with missing instantaneous discharge values for water years 2017–19. For 187 of these days, the daily means were not computed owing to high instantaneous stages falling outside of the range of stage values applicable to the rating curve. Since the daily means for these days computed from partial instantaneous record were higher than the median flow, these daily means would not affect the computed low-flow duration discharges. For the remaining 8 days with missing daily means, the daily means were not computed owing to low instantaneous stages falling outside of the range of stage values applicable to the rating curve. The daily means for these days computed from partial instantaneous record were lower than the median flow and would affect the computation of low-flow duration discharges at the station. Low-flow duration discharges computed by including daily means for days with partial instantaneous discharge record and those computed using the assumption showed differences of 0.2 ft^3/s for the Q_{50} and Q_{60} discharges; 0.1 ft^3/s for the Q_{55}, Q_{70}, and Q_{75} discharges; 0.05 ft^3/s for the Q_{65} and Q_{85} discharges; 0.04 ft^3/s for the Q_{90} discharge; and no difference for the Q_{80} and Q_{95} discharges. Therefore, computing low-flow duration discharges at the Waiahi station using only days with complete instantaneous discharge record is reasonable.

The representativeness of low-flow duration discharges at the Waiahi short-term station of long-term flow conditions was evaluated by comparing low-flow duration discharges computed for the short-term period (water years 2017–19) with those computed for the base period (1961–2019) at the two active long-term stations in the study area—station 16068000 on east branch of North Fork Wailua River and station 16071500 on left branch ‘Ōpaeka‘a Stream. A majority of the differences between low-flow duration discharges computed for water years 2017–19, which correspond to complete water years of data available at the Waiahi short-term station, and those computed for the base period were 2 percent or less at both long-term stations. Data at Waiahi station showed the highest correlation with data at index station 16068000, with a correlation coefficient (*r*) of 0.73. However, this *r* value does not meet acceptable values of *r* for record augmentation set forth in this study (r values ≥0.80); therefore, low-flow duration discharges at the Waiahi short-term station were not extended to the base period. Using the duration discharges at station 16068000 for the period 2017–19 and the base period (table 2), as well as the annual mean

Table 5. Estimated flow-duration discharges at partial-record sites in the study-area streams, southeast Kauaʻi, Hawaiʻi, for base period 1961–2019.

[ID, identifier; USGS, U.S. Geological Survey; HI, Hawaii; RB, Right Branch; mi, mile; US, upstream; LB, Left Branch; NF, North Fork; Str, Stream; N, North; Dt, Ditch; SF, South Fork; trib, tributary; Res, Reservoir; S, South; Rd., Road; DS, downstream; W, West; SW, Southwest; Hwy, Highway; ft, feet; Riv, River; blw, below; nr, near; ft^3/s, cubic feet per second; --, not applicable. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names. Altitude values interpolated from USGS 1:24,000-scale digital hypsography data]

Map ID[a]	USGS station number	USGS station name, Kauai, HI	Drainage area, in square miles	Discharge, in ft^3/s, for selected percentages of time (from 50 to 95 percent) the indicated discharge was equaled or exceeded									
				50	55	60	65	70	75	80	85	90	95
		Wailua River basin											
P1	220423159235501	RB Opaekaa Stream 0.3 mi US of LB	0.4	1.1	1.0	0.98	0.93	0.86	0.80	0.70	0.60	0.52	0.48
P2	220346159280601	NF Wailua River US Blue Hole intake	1.8	26	25	24	23	22	21	20	19	18	17
P3 + P4	220326159275401 + 220325159275401	NF Waikoko Str US Iliiliula N Wailua Dt + SF Waikoko Str US Iliiliula N Wailua Dt	1.1	7.4	6.8	5.8	5.3	4.9	4.0	3.6	3.2	2.8	2.5
P5	220224159282301	Iliiliula Str trib 4 US N Wailua Ditch	1.6	11	10	10	9.7	9.2	8.9	8.6	8.2	7.9	7.3
		Hanamāʻulu Stream basin											
P6 + P7	220054159244001 + 220037159242901	Hanamaulu Str 1 mi US N Kapaia Res + Hanamaulu Str 0.6 mi US S Kapaia Res	1.1	1.6	1.5	1.4	1.4	1.3	1.3	1.2	1.1	1.0	0.96
P6	220054159244001	Hanamaulu Str 1 mi US N Kapaia Res	0.8	1.2	1.2	1.2	1.1	1.1	1.0	1.0	0.83	0.81	0.74
P7	220037159242901	Hanamaulu Str 0.6 mi US S Kapaia Res	0.3	<0.44[b]	<0.44[b]	<0.44[b]	<0.44[b]	<0.44[b]	<0.44[b]	<0.44[b]	<0.44[b]	<0.44[b]	<0.44[b]
P8	215923159235601	Hanamaulu tributary US of return flow	0.2	<0.40[b]	<0.40[b]	<0.40[b]	<0.40[b]	<0.40[b]	<0.40[b]	<0.40[b]	<0.40[b]	<0.40[b]	<0.40[b]
		Nāwiliwili Stream basin											
P9	215833159232601	Nawiliwili Stream at Rapoza Rd.	1.4	--	--	--	--	--	--	--	--	--	--
		Pūʻali Stream basin											
P10	215737159230301	Puali Stream 0.6 mi DS Aakukui Rd	0.8	--	--	--	--	--	--	--	--	--	--
		Hulēʻia Stream basin											
P11	215853159281801	Paohia Str US Koloa Ditch	0.9	5.0	4.4	4.2	3.6	3.1	2.9	2.5	2.0	1.8	1.5
P12	215851159273901	Kamooloa Str US Papuaa Res intake	2.3	11	9.7	9.2	8.3	7.4	7.0	6.1	5.3	4.9	4.1
P13	215822159282601	Kuia Str 0.7 mi W of Papuaa Res	1.0	5.7	5.4	4.7	4.4	4.2	4.0	3.7	3.5	3.4	3.3
P14	215751159283901	Kuia Str trib 1 mi SW of Papuaa Res	0.6	3.2	2.0	1.5	0.84	0.46	0.33	0.16	0.073	0.047	0.018
		Waikomo Stream basin											
P15	215608159285801	Omao Stream at Kaumualii Hwy	0.4	<0.19[b]	<0.19[b]	<0.19[b]	<0.19[b]	<0.19[b]	<0.19[b]	<0.19[b]	<0.19[b]	<0.19[b]	<0.19[b]
P16	215538159292301	Poeleele Stream at Kaumualii Hwy	0.6	<0.22[b]	<0.22[b]	<0.22[b]	<0.22[b]	<0.22[b]	<0.22[b]	<0.22[b]	<0.22[b]	<0.22[b]	<0.22[b]
		Wahiawa Stream basin											
P17	215751159311801	Wahiawa Stream US Alexander Res	1.8	3.7	3.4	3.1	2.9	2.6	2.4	2.2	2.0	1.8	1.5
P18	215754159311601	LB Wahiawa Str 400 ft US Alexander Res	0.3	--	--	--	--	--	--	--	--	--	--

[a]Refer to figure 1 for station location.

[b]Highest discharge measured during the study period.

rainfall at Wai‘ale‘ale rain gage (fig. 3), it was determined that the period 2017–19 was generally wetter than the base period. Therefore, low-flow duration discharges computed for water years 2017–19 at the Waiahi short-term station may also be higher than those for the base period.

Low-flow duration discharges at the Lāwa‘i short-term station were extended to the base period using index station 16068000 on east branch of North Fork Wailua River in the MOVE.1 technique (table 4). Two outliers were removed from the regression relation. Low-flow duration discharges computed for the base period range from 0.35 to 3 ft^3/s (table 2) and these were used to estimate low-flow duration discharges at relevant partial-record sites.

Station 16049000 on Hanapēpē River monitored natural flow during calendar year 2017, when upstream surface-water diversions on right and left branch Kō‘ula Rivers were not in operation (Howard Greene, Gay & Robinson, oral commun., 2018). Flow-duration statistics at the station were estimated using the procedures to estimate low-flow duration discharges at short-term stations. Index station 16068000 on east branch of North Fork Wailua River was used in the graphical-correlation technique to extend the Hanapēpē River calendar year 2017 record to the base period (fig. 7*A*). One outlier was removed from the graphical fit. Low-flow duration discharges computed for the base period range from 42 to 69 ft^3/s (table 2).

Partial-Record Sites

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 North Fork Wailua River, the confluence of north and south Waikoko Streams, ‘Ili‘ili‘ula Stream, the confluence of north and south fork Hanamā‘ulu Streams, Pāohia Stream, Kamo‘oloa Stream, a branch of Ku‘ia Stream, and Wahiawa Stream. Discharges at the confluence of north and south fork Waikoko Streams and at the confluence of north and south fork Hanamā‘ulu Streams were the sum of discharges measured at each stream fork, respectively. Selected natural low-flow duration-discharge estimates at the partial-record sites are listed in table 5. Measured discharges at the partial-record sites and concurrent daily mean discharges at selected index station are summarized in tables 6–13.

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, (3) the discharge has high measurement error and a second measurement (check measurement) may have been made subsequent to the first measurement at a different nearby measurement section in an effort to reduce measurement error, or (4) the concurrent daily mean discharge at the index station is of provisional status at the time this report was prepared. The MOVE.1 relations between measured discharges at the partial-record sites and concurrent daily mean discharges at the index stations have correlation coefficients (r) that range from 0.88 to 0.94 and modified Nash-Sutcliff coefficients of efficiency (E) that range from 0.51 to 0.64. Note that the closer the coefficient of efficiency is to 1, the more accurate the statistical model is. Low-flow duration discharges for three sites—North Fork Wailua River, confluence of north and south fork Hanamā‘ulu Streams, and Wahiawa Stream—were estimated with less than 10 measurements. Measured discharges at the partial-record sites used for record augmentation generally capture a wide distribution of flows between the Q_{95} and Q_{50} duration discharges that are of interest in this study. Therefore, the low-flow duration-discharge estimates are considered to be representative of the entire range of low-flow conditions in these streams.

Low-flow duration discharges for partial-record sites on right branch ‘Ōpaeka‘a Stream, north fork Hanamā‘ulu Stream, and a branch of Ku‘ia Stream were estimated using the graphical-correlation technique (table 4). A curvilinear trend provides the best fit to the plot of measured discharges at the partial-record sites and concurrent daily mean discharges at the selected index station (fig. 7). Low-flow duration discharges were estimated with 10 measurements at each partial-record site and the measured discharges used for record augmentation generally capture a wide distribution of flows between the Q_{95} and Q_{50} duration discharges that are of interest in this study (tables 9, 14, and 15). Therefore, the low-flow duration-discharge estimates are considered to be representative of the entire range of low-flow conditions in these streams.

Measured discharges at partial-record sites on south fork Hanamā‘ulu Stream (table 9), tributary of Hanamā‘ulu Stream (table 9), Nāwiliwili Stream (table 16), Pū‘ali Stream (table 17), left branch Wahiawa Stream (table 13), ‘Ōma‘o Stream (table 18), and Pō‘ele‘ele Stream (table 18) do not correlate with data at any index stations. On the day with the highest discharge at each of these partial-record sites, the corresponding concurrent daily mean discharge at each index station was greater than the median discharge at that index station. Thus, low-flow duration discharges at south fork Hanamā‘ulu Stream, tributary of Hanamā‘ulu Stream, ‘Ōma‘o Stream, and Pō‘ele‘ele Stream are likely below the highest discharges measured during the study period of 0.44, 0.40, 0.19, and 0.22 ft^3/s, respectively. Data collected at the Nāwiliwili Stream partial-record site may have been affected by random diverted-flow releases from the upper Līhu‘e Ditch (fig. 5). Accessible reaches of Pū‘ali Stream were limited owing to streambank vegetation and streambed material, and the only discharge-measurement section available based on reconnaissance survey was downstream from a pond in a golf course. Twelve discharge measurements were collected during the study period; however, the discharges do not correlate with data at any index stations because the measured discharges may have been affected by draining of the pond. Discharge measurements collected at left branch Wahiawa Stream do not correlate with data at any index stations nor do they correlate with data at the partial-record site located on main channel of Wahiawa Stream.

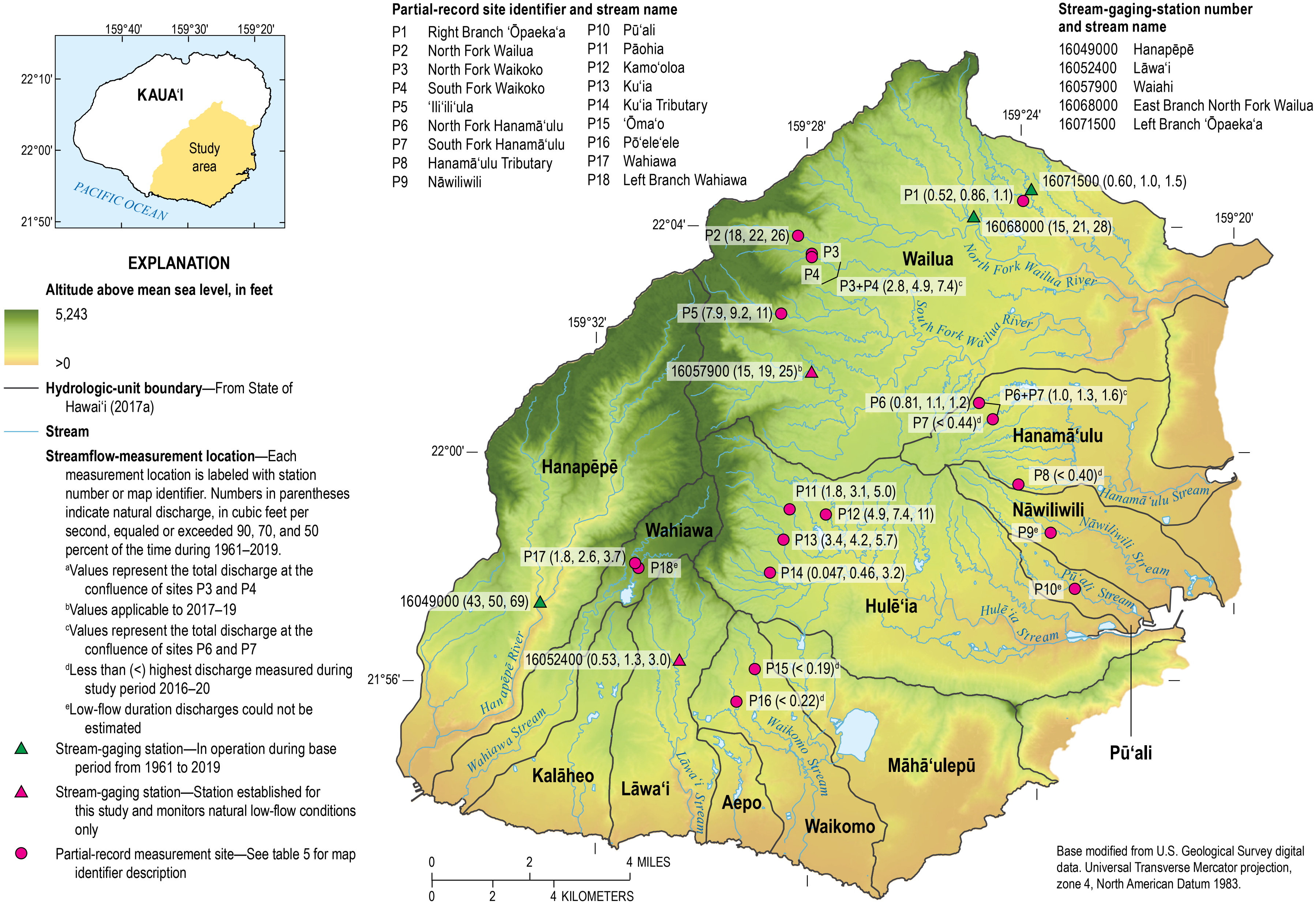


Figure 6. Map showing discharge, in cubic feet per second, that is equaled or exceeded 90, 70, and 50 percent of the time during 1961–2019 at active stream-gaging stations and partial-record sites in the study area, southeast Kauaʻi, Hawaiʻi.

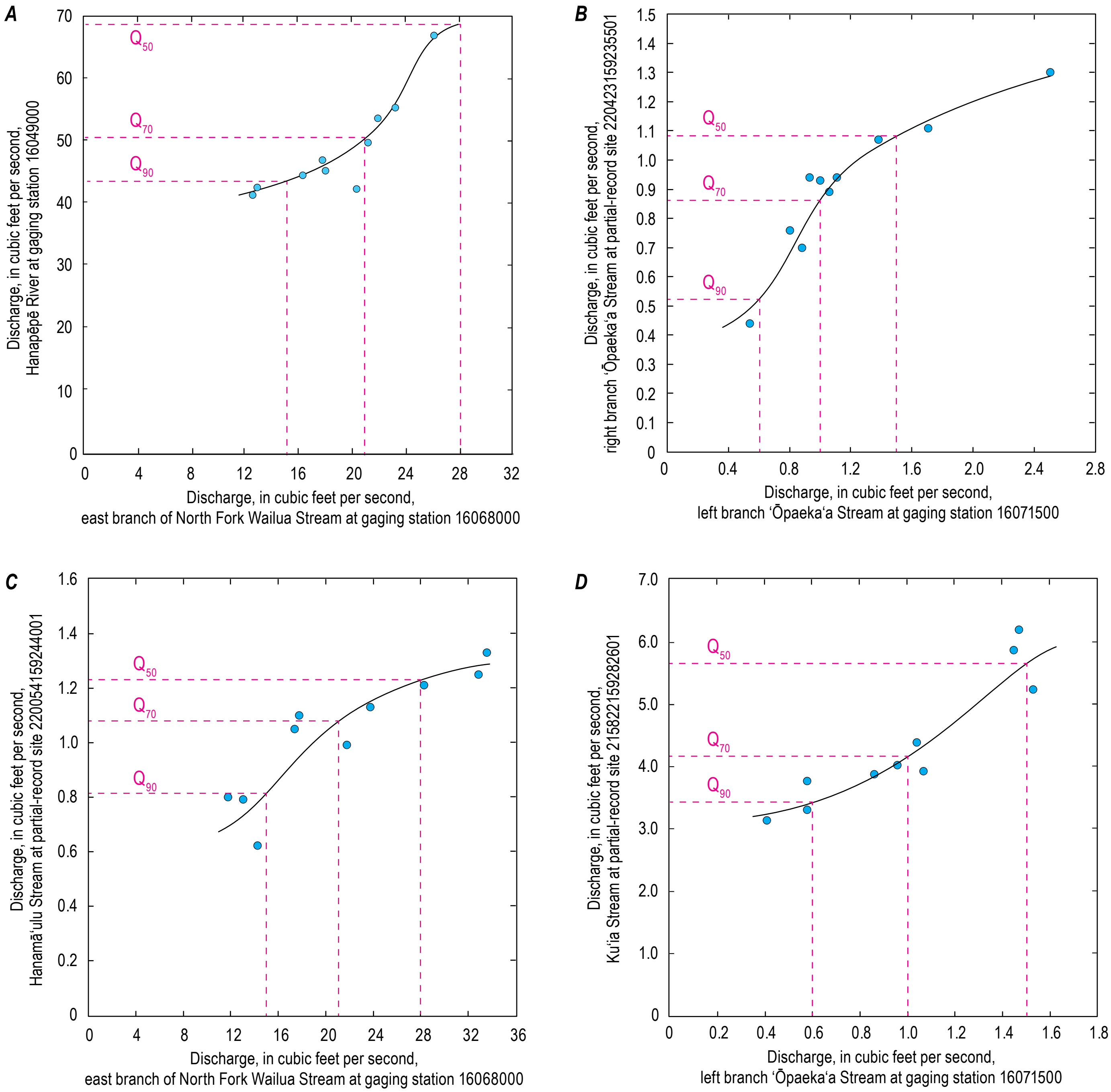


Figure 7. Plots showing the graphical relation between measured discharges at short-term continuous-record and partial-record sites and concurrent daily mean discharges at index stations, southeast Kauaʻi, Hawaiʻi. *A*, Concurrent daily mean discharges at stream-gaging station 16049000 on Hanapēpē River and concurrent daily mean discharges at stream-gaging station 16068000 on east branch of North Fork Wailua River. *B*, Partial-record site 220423159235501 on right branch ʻŌpaekaʻa Stream and concurrent daily mean discharges at stream-gaging station 16071500 on left branch ʻŌpaekaʻa Stream. *C*, Partial-record site 220054159244001 on north fork Hanamāʻulu Stream and concurrent daily mean discharges at stream-gaging station 16068000 on east branch of North Fork Wailua River. *D*, Partial-record site 215822159282601 on Kuʻia Stream and concurrent daily mean discharges at stream-gaging station 16071500 on left branch ʻŌpaekaʻa Stream.

Table 6. Measured discharges at partial-record site 220346159280601 on North Fork Wailua River and concurrent daily mean discharges at stream-gaging station 16019000 on Waiʻalae Stream, southeast Kauaʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ID, identifier. 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	Daily mean discharge in ft^3/s on Waiʻalae Stream	Measured discharge in ft^3/s on North Fork Wailua River (Map ID P2 in fig. 1, tables 4–5)
02/22/2016	8.20	<u>20.2</u>
04/25/2016	9.34	34.0
06/08/2016	6.36	23.6
09/27/2016	3.85	22.3
01/19/2017	2.90	18.7
02/22/2017	5.52	<u>11.3</u>
05/04/2017	3.01	19.7
08/03/2017	2.20	18.1
11/20/2017	7.21	<u>17.4</u>
02/12/2018	4.56	21.2
02/22/2019	7.01	26.4

Table 7. Measured discharges at partial-record sites 220326159275401 on north fork Waikoko Stream and 220325159275401 on south fork Waikoko Stream and concurrent daily mean discharges at stream-gaging station 16057900 on Waiahi Stream, southeast Kauaʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ID, identifier]

Date	Daily mean discharge in ft^3/s on Waiahi Stream	Measured discharge in ft^3/s on north fork Waikoko Stream (Map ID P3 in fig. 1, tables 4–5)	Measured discharge in ft^3/s on south fork Waikoko Stream (Map ID P4 in fig. 1, tables 4–5)	Measured discharge in ft^3/s on north and south fork Waikoko Streams combined
02/22/2016	11.8	2.45	0.42	2.87
04/25/2016	30.0	7.98	2.38	10.4
06/08/2016	20.7	4.06	1.40	5.46
09/27/2016	23.7	4.47	1.28	5.75
01/19/2017	15.2	1.82	0.57	2.39
05/04/2017	19.4	2.02	1.30	3.32
08/03/2017	17.8	2.75	0.81	3.56
09/28/2017	14.9	1.92	0.57	2.49
02/12/2018	22.1	4.92	1.58	6.50
02/22/2019	20.9	5.15	1.87	7.02

Table 8. Measured discharges at partial-record site 220224159282301 on ʻIliʻiliʻula Stream and concurrent daily mean discharges at stream-gaging station 16097500 on Hālaulani Stream, southeast Kauaʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ID, identifier. 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	Daily mean discharge in ft^3/s on Hālaulani Stream	Measured discharge in ft^3/s on ʻIliʻiliʻula Stream (Map ID P5 in fig. 1, tables 4–5)
03/11/1983	5.30	9.80
02/24/2016	6.37	9.01
05/16/2016	6.18	9.16
06/07/2016	11.1	13.2
04/14/2017	8.25	<u>21.0</u>
01/17/2018	4.09	7.50
03/07/2018	9.51	12.8
05/01/2018	10.4	13.8
05/09/2018	9.56	12.4
08/08/2018	9.06	13.8
05/13/2019	6.09	9.27
12/09/2019	7.41	13.0

Table 9. Measured discharges at partial-record sites 220054159244001 on north fork Hanamā‘ulu Stream, 220037159242901 on south fork Hanamā‘ulu Stream, and 215923159235601 on tributary of Hanamā‘ulu Stream, and concurrent daily mean discharges at stream-gaging station 16068000 on east branch of North Fork Wailua River, southeast Kaua‘i, Hawai‘i.

[ft^3/s, cubic feet per second; ID, identifier; --, no data. 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 mseasurement was made]

Date	Daily mean discharge in ft^3/s on east branch of North Fork Wailua River	Measured discharge in ft^3/s on north fork Hanamā‘ulu Stream (Map ID P6 in fig. 1, tables 4–5)	Measured discharge in ft^3/s on south fork Hanamā‘ulu Stream (Map ID P7 in fig. 1, tables 4–5)	Measured discharge in ft^3/s on north and south fork Hanamā‘ulu Streams combined	Measured discharge in ft^3/s on tributary of Hanamā‘ulu Stream (Map ID P8 in fig. 1, tables 4–5)
02/25/2016	11.8	0.80	0.25	1.05	--
04/27/2016	33.6	1.33	0.41	1.74	0.40
05/16/2016	17.8	1.10	0.44	1.54[a]	--
05/20/2016	30.4	--	--	--	0.06
06/06/2016	29.1	--	--	--	0.06
06/07/2016	34.3	<u>0.91</u>	--	--	--
06/13/2016	26.5	--	0.29	--	--
11/07/2016	17.4	1.05	0.23	1.28	0.05
12/16/2016	28.3	1.21	0.20	1.41	0.05
01/05/2017	43.1	<u>1.43</u>	<u>0.10</u>	<u>1.53</u>	0.07
07/20/2017	19.9	<u>1.32</u>	--	--	--
09/22/2017	14.3	0.62	0.18	0.80	0.17
10/19/2017	32.9	1.25	0.34	1.59	--
10/30/2017	21.8	0.99	0.40	1.39	--
12/08/2017	29.2	--	0.35	--	--
12/12/2017	23.8	1.13	0.39	1.52	--
01/17/2018	13.1	0.79	0.24	1.03	--

[a]Measured discharge is excluded from record augmentation because it is an outlier.

Table 10. Measured discharges at partial-record site 215853159281801 on Pāohia Stream and concurrent daily mean discharges at stream-gaging station 16052400 Lāwa‘i Stream, southeast Kaua‘i, Hawai‘i.

[ft^3/s, cubic feet per second; ID, identifier; --, no data. 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	Daily mean discharge in ft^3/s on Lāwa‘i Stream	Measured discharge in ft^3/s on Pāohia Stream (Map ID P11 in fig. 1, tables 4–5)
06/10/2016	1.39	2.97
11/18/2016	0.79	1.70
04/06/2017	--	<u>1.75</u>
06/01/2017	1.11	3.22
08/10/2017	0.25	1.71
09/07/2017	0.47	1.56
12/07/2017	1.60	2.90
12/21/2017	0.59	1.88
05/02/2018	2.99[a]	5.33
08/07/2018	1.44[a]	3.95
08/21/2018	1.43[a]	3.46
11/20/2018	1.61[a]	3.28

[a]Measured discharge. Continuous streamgaging station 160524000 on Lāwa‘i Stream was damaged in March 2018.

Table 11. Measured discharges at partial-record site 215851159273901 on Kamo‘oloa Stream and concurrent daily mean discharges at stream-gaging station 16052400 Lāwa‘i Stream, southeast Kaua‘i, Hawai‘i.

[ft^3/s, cubic feet per second; ID, identifier; --, no data. 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	Daily mean discharge in ft^3/s on Lāwa‘i Stream	Measured discharge in ft^3/s on Kamo‘oloa Stream (Map ID P12 in fig. 1, tables 4–5)
11/29/2016	3.18	11.1
12/16/2016	1.33	6.96
03/16/2017	--	<u>7.82</u>
06/01/2017	1.11	7.28
08/10/2017	0.25	4.20
09/07/2017	0.47	4.30
10/30/2017	1.07	7.15
11/21/2017	1.46	8.24
12/12/2017	1.18	6.17
12/21/2017	0.59	4.44
12/22/2017	0.59	4.34[b]
02/08/2018	--	<u>15.5</u>
03/12/2018	2.19	7.99
08/21/2018	1.43[a]	9.20

[a]Measured discharge. Continuous streamgaging station 160524000 on Lāwa‘i Stream was damaged in March 2018.

[b]Measured discharge is excluded from record augmentation because it is on the same recession as the discharge measured on 12/21/2017.

Table 12. Measured discharges at partial-record site 215751159283901 on Ku‘ia Stream and concurrent daily mean discharges at stream-gaging station 16052400 Lāwa‘i Stream, southeast Kaua‘i, Hawai‘i.

[ft^3/s, cubic feet per second; ID, identifier; --, no data. 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	Daily mean discharge in ft^3/s on Lāwa‘i Stream	Measured discharge in ft^3/s on Ku‘ia Stream (Map ID P14 in fig. 1, tables 4–5)
05/18/2016	0.63	0.18
06/10/2016	1.39	0.50
11/18/2016	0.79	0.21
12/29/2016	3.16	2.24
03/16/2017	--	0.96
04/06/2017	--	0.23
06/01/2017	1.11	0.49
08/10/2017	0.25	0.008
09/07/2017	0.47	0.006
11/21/2017	1.46	0.44[b]
12/21/2017	0.59	0.21
05/02/2018	2.99[a]	1.12
08/07/2018	1.44[a]	0.82
08/21/2018	1.43[a]	0.54
11/20/2018	1.61[a]	0.62

[a]Measured discharge. Continuous streamgaging station 160524000 on Lāwa‘i Stream was damaged in March 2018.

[b]Measured discharge is excluded from record augmentation because of high measurement error.

Table 14. Measured discharges at partial-record site 220423159235501 on right branch ‘Ōpaeka‘a Stream and concurrent daily mean discharges at stream-gaging station 16071500 on left branch ‘Ōpaeka‘a Stream, southeast Kaua‘i, Hawai‘i.

[ft^3/s, cubic feet per second; ID, identifier. Measured discharge that is underlined is excluded from record augmentation due to insuffcent data at the index station that could be used ascertain stable-flow conditions]

Date	Daily mean discharge in ft^3/s on left branch ‘Ōpaeka‘a Stream	Measured discharge in ft^3/s on right branch ‘Ōpaeka‘a Stream (Map ID P1 in fig. 1, tables 4–5)
06/13/2016	1.06	0.89
10/27/2016	0.93	0.94
12/09/2016	1.10	1.24
02/02/2017	0.80	0.76
08/24/2017	0.54	0.44
10/19/2017	1.00	0.93
12/08/2017	1.38	1.07
12/22/2017	1.11	0.94
01/18/2018	0.88	0.70
08/13/2018	2.50	1.30
08/22/2018	1.69	1.11

Table 13. Measured discharges at partial-record sites 215751159311801 on Wahiawa Stream and 215754159311601 on left branch Wahiawa Stream, and concurrent daily mean discharges at stream-gaging station 16097500 on Hālaulani Stream, southeast Kaua‘i, Hawai‘i.

[ft^3/s, cubic feet per second; ID, identifier; --, no data. 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	Daily mean discharge in ft^3/s on Hālaulani Stream	Measured discharge in ft^3/s on Wahiawa Stream (Map ID P17 in fig. 1, tables 4–5)	Measured discharge in ft^3/s on left branch Wahiawa Stream (Map ID P18 in fig. 1, tables 4–5)
03/14/2017	5.77	2.28	3.07
06/06/2017	8.49	4.46	0.23
02/08/2018	11.4	6.92	0.69
06/20/2018	7.54	3.42	0.31
08/21/2019	4.55	2.37	0.11
10/23/2019	6.62	4.85	0.34
11/07/2019	5.04	1.91	0.20
11/12/2019	4.97	1.85	0.11
12/02/2019	16.2	9.07	0.54
01/22/2020	--[a]	3.76[b]	0.64

[a]Approved data not available as of 6/23/2020.

[b]Measured discharge is excluded from record augmentation because concurrent daily mean discharge on Hālaulani Stream is of provisional status.

Table 15. Measured discharges at partial-record site 215822159282601 on Kuʻia Stream and concurrent daily mean discharges at stream-gaging station 16071500 on left branch ʻŌpaekaʻa Stream, southeast Kauaʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ID, identifier]

Date	Daily mean discharge in ft^3/s on left branch ʻŌpaekaʻa Stream	Measured discharge in ft^3/s on Kuʻia Stream (Map ID P13 in fig. 1, tables 4–5)
06/10/2016	1.04	4.38
11/18/2016	0.58	3.76
12/29/2016	1.47	6.20
03/16/2017	1.53	5.23
04/06/2017	1.07	3.92
06/01/2017	0.86	3.87
08/10/2017	0.58	3.30
09/07/2017	0.41	3.13
10/30/2017	0.96	4.02
12/07/2017	1.45	5.87

Table 16. Measured discharges at partial-record site 215833159232601 on Nāwiliwili Stream, southeast Kauaʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ID, identifier]

Date	Measured discharge in ft^3/s on Nāwiliwili Stream (Map ID P9 in fig. 1, tables 4–5)
10/09/1996	0.51
10/05/2017	0.50
10/11/2017	1.77
10/19/2017	0.68
11/21/2017	0.93
12/07/2017	0.62
01/17/2018	0.51
03/07/2018	0.74
08/07/2018	1.62
08/13/2018	1.82
05/13/2019	3.64
06/07/2019	2.57
09/12/2019	1.54

Table 17. Measured discharges at partial-record site 215737159230301 on Pūʻali Stream, southeast Kauaʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ID, identifier]

Date	Measured discharge in ft^3/s on Pūʻali Stream (Map ID P10 in fig. 1, tables 4–5)
02/26/2016	1.88
04/29/2016	3.05
05/17/2016	1.82
06/09/2016	2.01
09/28/2016	0.82
10/27/2016	1.00
11/16/2016	1.33
03/16/2017	2.24
04/26/2017	1.85
06/06/2017	6.39
10/11/2017	2.18
11/21/2017	2.65

Table 18. Measured discharges at partial-record sites 215608159285801 on ʻŌmaʻo Stream and 215538159292301 on Pōʻeleʻele Stream, southeast Kauaʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ID, identifier; --, no data]

Date	Measured discharge in ft^3/s on ʻŌmaʻo Stream (Map ID P15 in fig. 1, tables 4–5)	Measured discharge in ft^3/s on Pōʻeleʻele Stream (Map ID P16 in fig. 1, tables 4–5)
09/15/1939	0.39	--
09/15/1939	0.23	--
09/18/1939	0.38	--
09/18/1939	0.25	--
12/04/1939	0.49	--
12/04/1939	0.30	--
12/08/1939	0.51	--
12/08/1939	0.30	--
01/17/1940	0.31	--
01/17/1940	0.51	--
01/26/1940	0.28	--
01/26/1940	0.46	--
02/26/1940	0.35	--
02/26/1940	0.22	--
03/15/1940	0.37	--
03/15/1940	0.23	--
02/23/2016	0.11	0.04
04/26/2016	0.08	0.19
05/17/2016	0.13	0.08
06/09/2016	0.18	0.06
09/28/2016	0.19	0.22
11/16/2016	0.19	0.22
01/18/2018	0.00	0.06

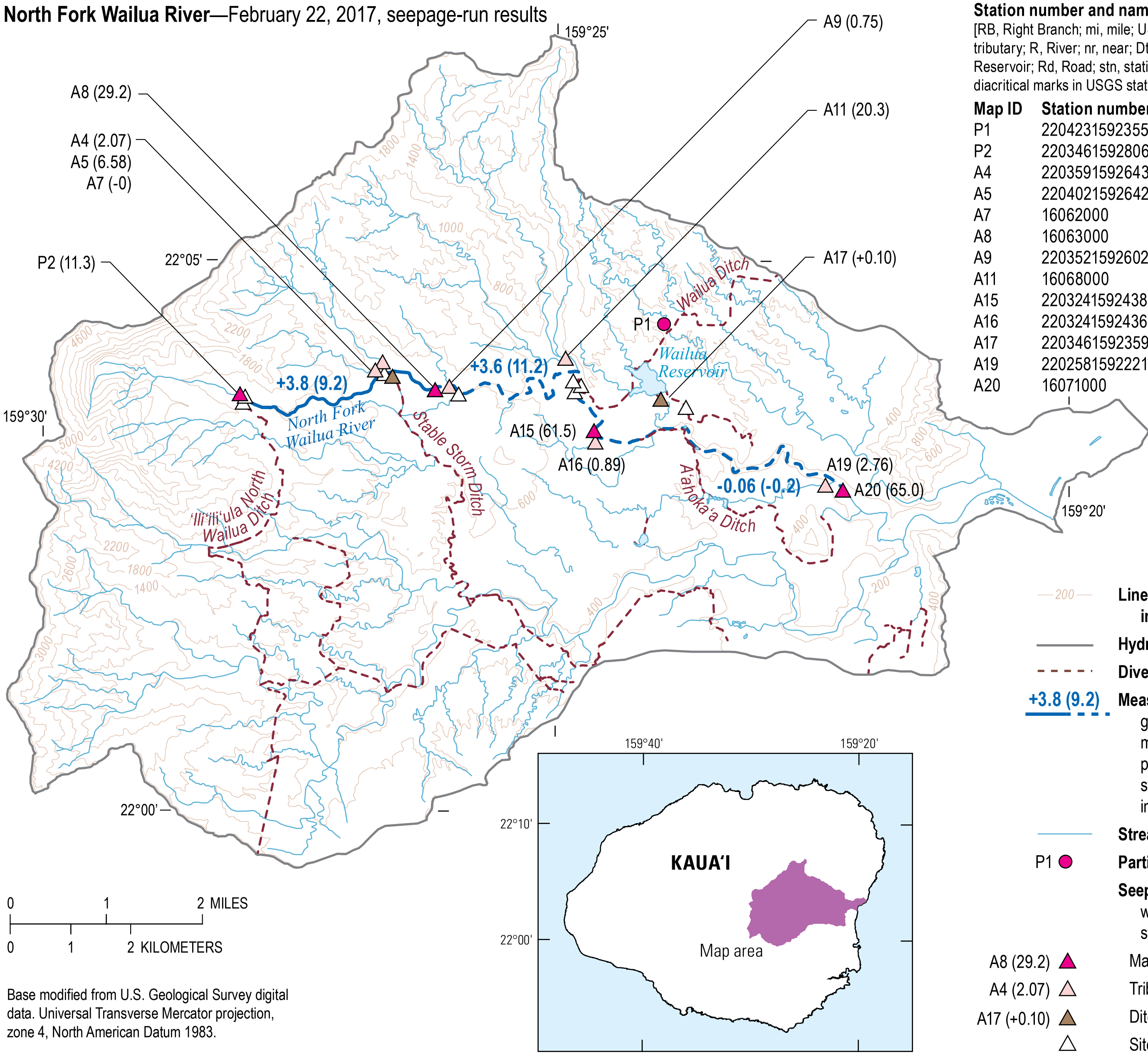
Streamflow Gains and Losses

As part of this study, a seepage run was conducted on all study-area streams except Hanamāʻulu Stream because discharge measurements from three previous seepage runs are available, and Pūʻali Stream because many reaches of the stream were inaccessible. Results of available seepage runs on study-area streams are discussed in 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. To determine whether a stream supports mauka to makai flow 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.

North Fork of Wailua River

Discharge measurements from two seepage runs are available to characterize seepage gains and losses on selected reaches of North Fork Wailua River. The February 22, 2017, seepage run (fig. 8) was conducted under conditions when index station 16068000 on east branch North Fork Wailua River

North Fork Wailua River—February 22, 2017, seepage-run results



Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Station number and name associated with map identifier (ID)
[RB, Right Branch; mi, mile; US, upstream; LB, Left Branch; NF, North Fork; L, left; trib, tributary; R, River; nr, near; Dt, Ditch; alt, altitude; ft, feet; EB, East Branch; Res, Reservoir; Rd, Road; stn, station. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
P1	220423159235501	RB Opaekaa Stream 0.3 mi US of LB
P2	220346159280601	NF Wailua River US Blue Hole intake
A4	220359159264301	Upper L trib of NF Wailua River
A5	220402159264201	L trib NF Wailua R nr Stable Storm Dt
A7	16062000	Stable Storm Ditch nr Lihue
A8	16063000	NF Wailua River nr alt 650 ft
A9	220352159260201	NF Wailua tributary nr station 16063000
A11	16068000	EB of NF Wailua River nr Lihue
A15	220324159243801	NF Wailua R .5 mi US Aahoaka Ditch
A16	220324159243601	NF Wailua trib .45 mi US Aahoaka Ditch
A17	220346159235901	Spillway A Wailua Res at Kuamoo Rd
A19	220258159222101	NF Wailua tributary US of stn 16071000
A20	16071000	NF Wailua River nr Kapaa

EXPLANATION

200 — **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+3.8 (9.2) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

P1 **Partial-record site**—Labeled with map ID

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s. Site with map ID starting with "P" is also a partial-record site

A8 (29.2) Main stream channel

A4 (2.07) Tributary to main stream

A17 (+0.10) Ditch— (-) diversion of flow or (+) return flow

Site from another seepage run

Figure 8. Map of measurement sites and results for the February 2017 seepage run on North Fork Wailua River, Kaua'i, Hawai'i.

was flowing at about a Q_{75} discharge (daily mean of 19.8 ft^3/s, table 2), and the discharge measured at the partial-record site (P2, map identifier in the figure corresponds to the location of the first major stream in discussion) was flowing below a Q_{95} discharge (daily mean of 11.3 ft^3/s, table 5). The September 21, 1982, seepage run (fig. 9) was conducted under conditions when index station 16068000 was flowing above the median-flow discharge (daily mean of 37.0 ft^3/s, table 2), and discharge measured at partial-record site P2, which was 24.3 ft^3/s computed as the sum of discharges measured at sites A2 and A3, was flowing at a Q_{60} discharge (table 5). No dry reaches in the main stream channel were observed during the seepage runs.

The 2017 seepage run (fig. 8) consists of 12 measurement sites located between altitudes of about 30 and 1,110 ft, with flows in the main stream channel ranging from 11.3 to 65.0 ft^3/s. The seepage run was conducted under natural-flow conditions; Stable Storm Ditch was abandoned and all flow diverted by the ʻIliʻiliʻula North Wailua Ditch intake was returned to the river immediately downstream of the intake beginning the day prior to the seepage run at 15:00 hours and continuing through the seepage run. The Wailua Ditch intake was not active during the seepage run; however, a small amount of flow from the reservoir was returned to the river by way of spillway A at Kuamoʻo Road (A17). The river generally gained flow in the reach downstream from ʻIliʻiliʻula North Wailua Ditch intake (P2) to site A15. This gain is presumed to originate mainly from groundwater discharge from a thickly saturated hydrogeologic setting. In the reach between site A15 and about 2 mi upstream from the river mouth (A20), the measured loss of 0.2 ft^3/s does not include flow from a tributary near the Aʻahoakaʻa Ditch intake; thus, the actual seepage loss is greater than computed.

The 1982 seepage run (fig. 9) consists of 17 measurement sites located between altitudes of about 30 and 1,110 ft, with flows in the main stream channel ranging from 23.5 to 82.1 ft^3/s. Flows were measured within the same stream reach as the 2017 seepage run. The 1982 seepage run was conducted following a long period of high rainfall, which contributed to higher base flows in the river. Diversions affecting streamflow during the seepage run include the ʻIliʻiliʻula North Wailua Ditch intake and the streamflow-diversion intake to Wailua Reservoir. Discharge measurements indicate generally a gaining reach between ʻIliʻiliʻula North Wailua Ditch intake (A2) and about 2 miles upstream from the river mouth (A20) with the most substantial gains in the lower reach between sites A15 and A20.

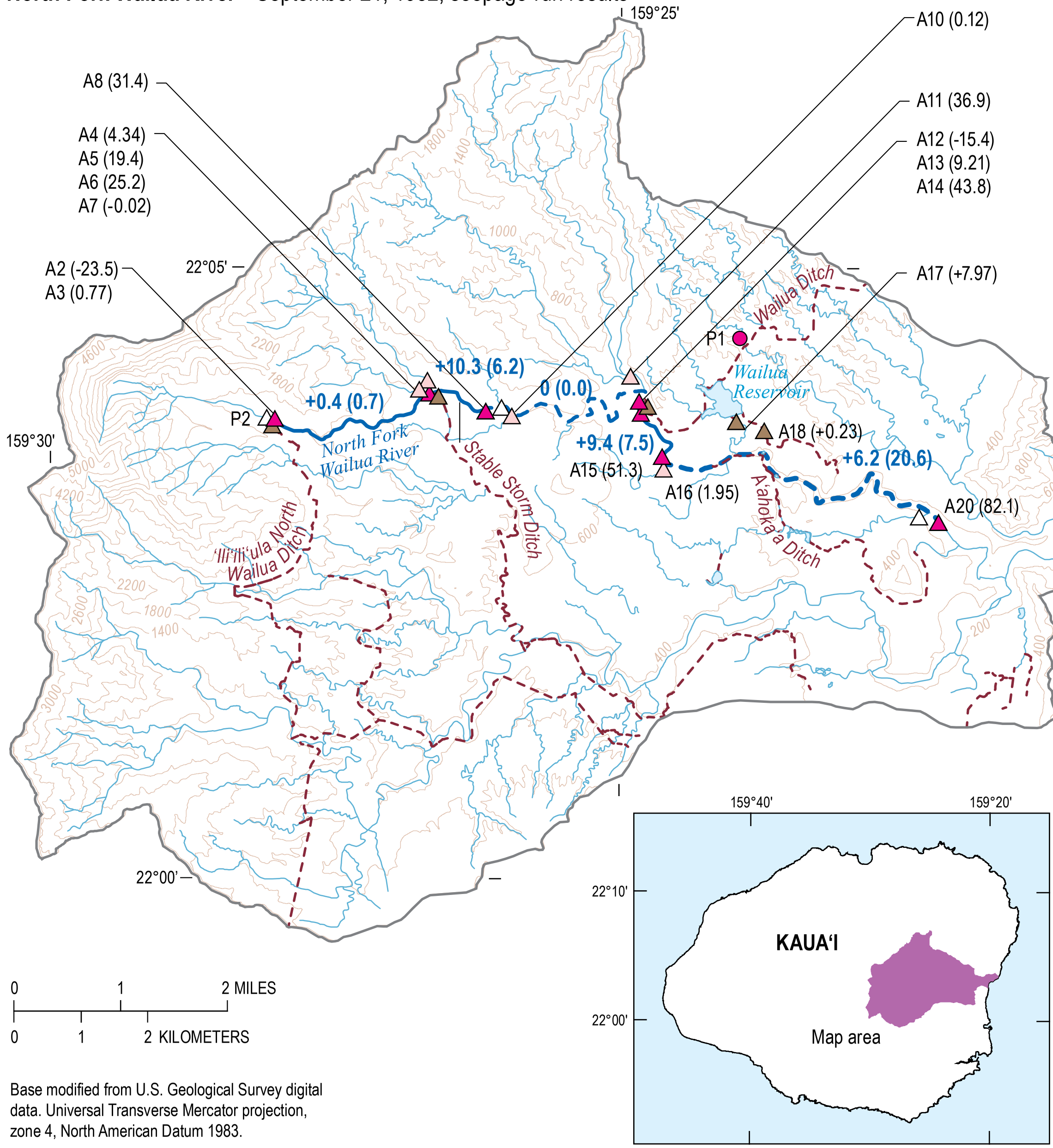
Under flow conditions of the seepage run, North Fork Wailua River flows continuously from the ʻIliʻiliʻula North Wailua Ditch level to site A20 under natural-flow conditions. Under diverted-flow conditions when ʻIliʻiliʻula North Wailua Ditch intake diverts all the low flow in the stream, the stream may run dry in the reach between the intake and the river's confluence with the first major tributary (A4). Most of North Fork Wailua River is within the thickly saturated hydrogeologic setting (fig. 4), where the groundwater level is above stream altitude and groundwater typically discharges into the stream. Extrapolation of seepage rates on North Fork Wailua River to the downstream unmeasured reach to determine flow continuity from site A20 to the confluence with South Fork Wailua River is not appropriate because the seepage rates include unmeasured inflows from tributaries.

South Fork of Wailua River

South Fork Wailua River begins at the confluence of major tributaries ʻIliʻiliʻula and Waiahi Streams. Tributary Waikoko Stream joins with Stable Storm Ditch and discharges to ʻIliʻiliʻula Stream. Discharge measurements from four seepage runs are available to characterize seepage gains and losses on selected reaches of the major tributaries and South Fork Wailua River. As part of this study, seepage runs were conducted for Waikoko Stream on September 28, 2017, ʻIliʻiliʻula Stream on December 9, 2019, and Waiahi Stream and South Fork Wailua River on January 21, 2020 (fig. 10, map areas B and C). The seepage runs were conducted during conditions when long-term station 16068000 was steadily flowing below a Q_{95} discharge (daily mean of 12.1 ft^3/s, table 2) for the 2017 Waikoko Stream seepage run, and above a median discharge for the 2019 ʻIliʻiliʻula Stream (daily mean of 40.4 ft^3/s, table 2), 2020 Waiahi Stream and South Fork Wailua River seepage runs (daily mean of 41.1 ft^3/s, table 2). The March 11, 1983, seepage run (fig. 11, map areas B and C) was conducted during conditions when long-term station 16068000 was flowing at about a Q_{95} discharge (daily mean of 13.0 ft^3/s, table 2).

The 2017, 2019, and 2020 seepage runs (fig. 10, map areas B and C) were conducted under diverted-flow conditions; intakes at ʻIliʻiliʻula North Wailua Ditch, South Intake Ditch, Waiahi-Kuia Aqueduct, transmission ditch between ʻIliʻiliʻula and Waiahi Streams, and Hanamāʻulu Ditch were in operation during the seepage runs. Stable Storm Ditch conveyed water from North Fork Wailua River to Waikoko Stream, which discharges into ʻIliʻiliʻula Stream upstream from its confluence with Waiahi Stream. Intakes at the North Intake Ditch and upper Līhuʻe Ditch on ʻIliʻiliʻula Stream were inactive during the seepage runs. Not all flow contributions from major tributaries to the river were considered in the calculation of seepage gains and losses owing to inaccessibility of the stream sites. The 2017 seepage run on Waikoko Stream (fig. 10, map area B) consists of five measurement sites located between altitudes of about 640 and 1,110 ft, with flows in the main stream channel ranging from 0.35 to 1.64 ft^3/s. Discharge measurements collected during the seepage run show a net gain in the 2.2-mi reach between the ʻIliʻiliʻula North Wailua Ditch dam (B3) to upstream from its confluence with Stable Storm Ditch (B4). The 2019 seepage run on ʻIliʻiliʻula Stream (fig. 10, map area B) consists of 12 measurement sites located between altitudes of about 440 and 1,110 ft, with flows in the main stream channel ranging from 0.21 to 13.0 ft^3/s. Results of the seepage run show a net gain in the 1.2-mi reach from the Waiahi ʻIliʻiliʻula Ditch dam (C2) to the North Intake Ditch dam (C9). The net gain in the 3-mi reach between the North Intake Ditch dam (C9) and the confluence of ʻIliʻiliʻula and Waiahi Streams (C12) includes unmeasured inflow from tributaries. The 2020 seepage run on Waiahi Stream (fig. 10, map area C) consists of 13 measurement sites located between altitudes of about 440 and 820 ft, with flows in the main stream channel ranging from 13.1 to 74.2 ft^3/s. The

North Fork Wailua River—September 21, 1982, seepage-run results



Station number and name associated with map identifier (ID)

[RB, Right Branch; mi, mile; US, upstream; LB, Left Branch; NF, North Fork; nr, near; R, River; DS, downstream; N, North; Dt, Ditch; L, Left; trib, tributary; alt, altitude; ft, feet; EB, East Branch; fr, from; Res, Reservoir; W, West; Rd, Road. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
P1	220423159235501	RB Opaekaa Stream 0.3 mi US of LB
P2	220346159280601	NF Wailua River US Blue Hole intake
A2	16061000	North Wailua Ditch nr Lihue
A3	220346159280201	NF Wailua R DS Iliiliula N Wailua Dt
A4	220359159264301	Upper L trib of NF Wailua River
A5	220402159264201	L trib NF Wailua R nr Stable Storm Dt
A6	220358159263901	NF Wailua River US Stable Storm Dt
A7	16062000	Stable Storm Ditch nr Lihue
A8	16063000	NF Wailua River nr alt 650 ft
A10	220348159255701	NF Wailua trib .9 mi DS Stable Storm Dt
A11	16068000	EB of NF Wailua River nr Lihue
A12	220356159244701	Diversion fr NF Wailua R to Wailua Res
A13	220356159244801	NF Wailua split W of Wailua Res intake
A14	220354159244801	NF Wailua R DS Wailua Res intake
A15	220324159243801	NF Wailua R .5 mi US Aahoaka Ditch
A16	220324159243601	NF Wailua trib .45 mi US Aahoaka Ditch
A17	220346159235901	Spillway A Wailua Res at Kuamoo Rd
A18	220342159234401	Spillway B Wailua Res .2mi DS Kuamoo Rd
A20	16071000	NF Wailua River nr Kapaa

EXPLANATION

200 **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+0.4 (0.7) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

P1 **Partial-record site**—Labeled with map ID

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s. Site with map ID starting with "P" is also a partial-record site

A2 (23.5) Main stream channel

A4 (4.34) Tributary to main stream

A7 (-0.02) Ditch—(-) diversion of flow or (+) return flow

Site from another seepage run

Figure 9. Map of measurement sites and results for the September 1982 seepage run on North Fork Wailua River, Kaua'i, Hawai'i.

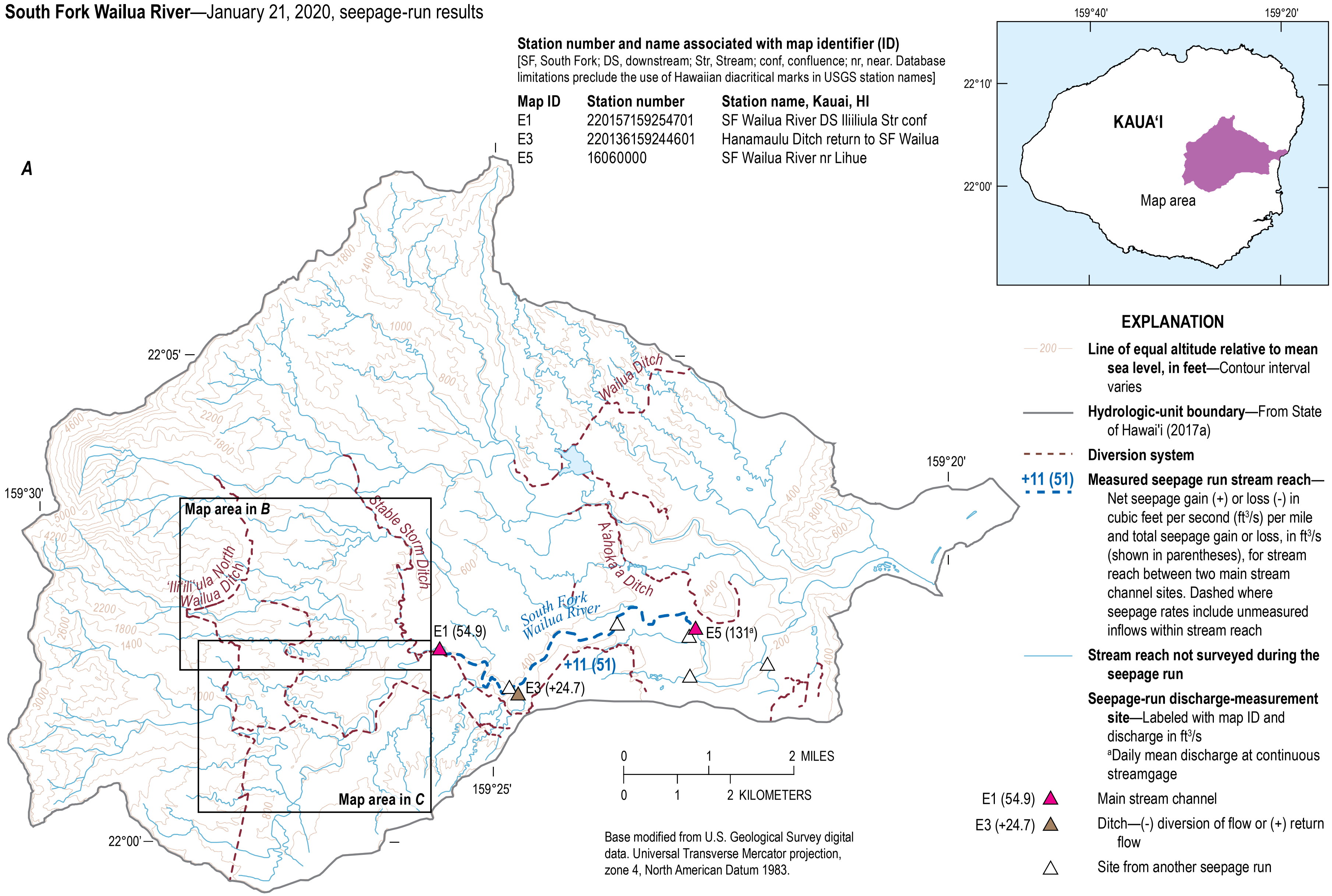
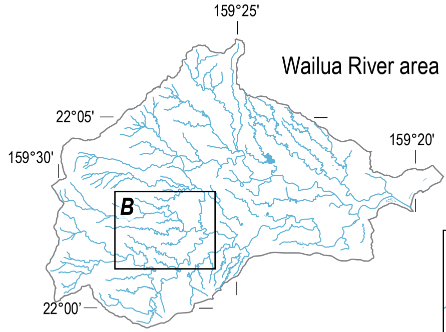


Figure 10. Map of measurement sites and results for the September 2017, December 2019, and January 2020 seepage runs on South Fork Wailua River, Kaua‘i, Hawai‘i.

Waikoko and ʻIliʻiliʻula Streams—September 28, 2017, and December 9, 2019, seepage-run results



Station number and name associated with map identifier (ID)

[NF, North Fork; Str, Stream; US, upstream; N, North; Dt, Ditch; SF, South Fork; blw, below; mi, mile; trib, tributary; L, Left; LB, Left Branch; DS, downstream; conf, confluence; div, diversion. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
P3	220326159275401	NF Waikoko Str US Iliiliula N Wailua Dt
P4	220325159275401	SF Waikoko Str US Iliiliula N Wailua Dt
B3	220325159275201	Waikoko Str blw diversion dam
B4	220309159262101	Waikoko Str .3mi US Stable Storm
B5	220308159262201	Trib to Waikoko .3mi US Stable Storm
P5	220224159282301	Iliiliula Str trib 4 US N Wailua Ditch
C2	220221159282201	Iliiliula Str DS Waiahi Iliiliula Ditch
C3	220221159282101	L trib Iliiliula DS Waiahi Iliiliula Dt
C4	220220159281901	Waiahi Iliiliula Dt spillway, Iliiliula
C5	220224159281001	LB trib Iliiliula DS N Wailua Dt
C6	220207159280101	Waiaka Str DS Waiahi Iliiliula Ditch
C7	220228159273601	Trib to Iliiliula US N Intake Ditch
C8	220229159273201	North Intake Ditch on Iliiliula Stream
C9	220229159273101	Iliiliula Stream DS N Intake Ditch
C10	220205159255801	Waikoko Str at Iliiliula Str conf
C11	220156159255201	Iliiliula Stream div to Waiahi Stream
C12	220157159255101	Iliiliula Str DS div to Waiahi Str

EXPLANATION

200 **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

Diversion system

+1.4 (1.74) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft^3/s) per mile and total seepage gain or loss, in ft^3/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft^3/s. Site with map ID starting with “P” is a partial-record site

C2 (0.21) Main stream channel

C3 (0.20) Tributary to main stream

C4 (+0.10) Ditch—(-) diversion of flow or (+) return flow

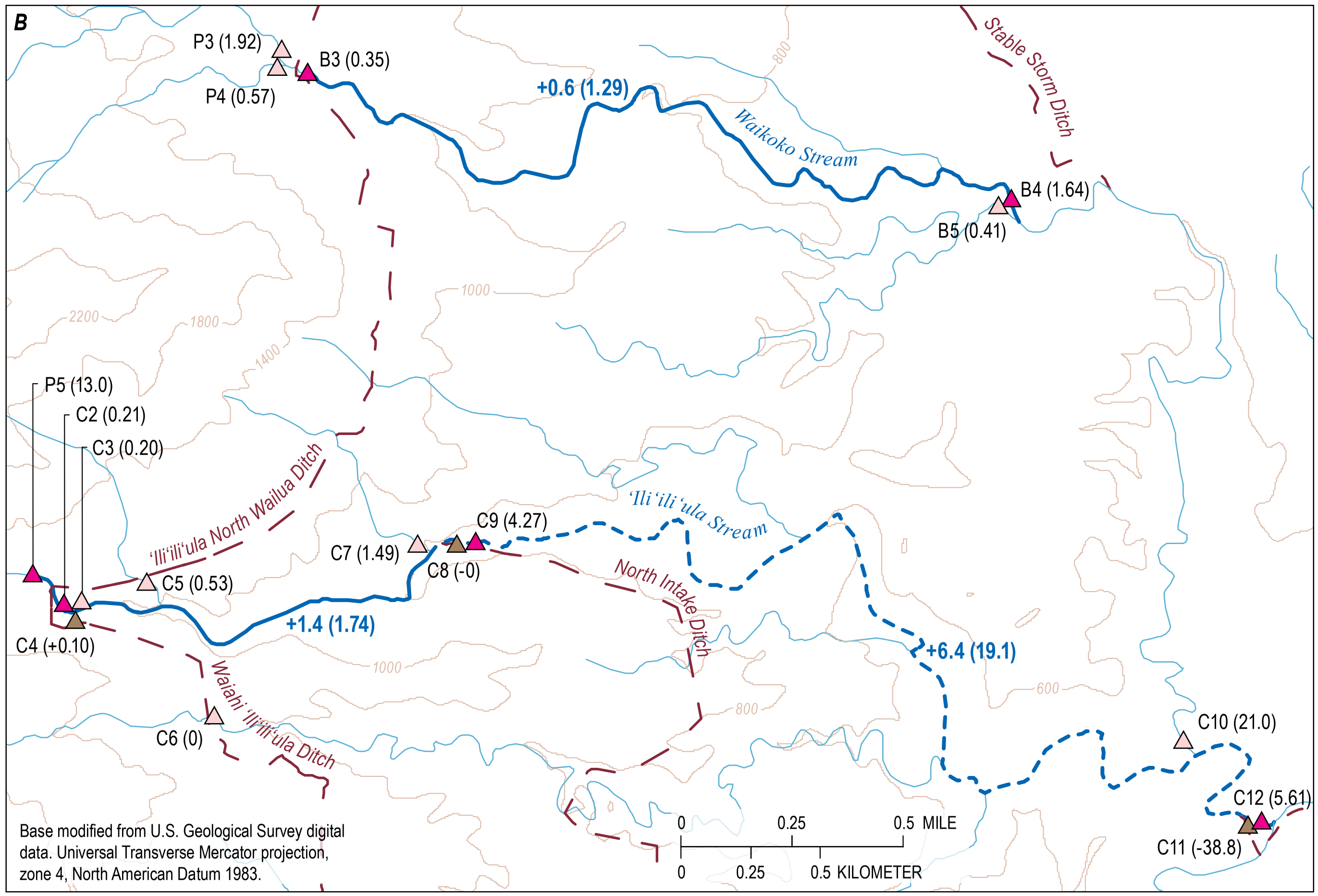
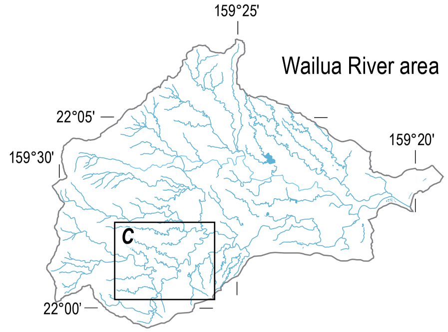


Figure 10.—Continued

Waiahi Stream—January 21, 2020, seepage-run results



Station number and name associated with map identifier (ID)

[Str, Stream; US, upstream; PH, Powerhouse; DS, downstream; L, Left; trib, tributary; Dt, Ditch; nr, near. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
D3	16057900	Waiahi Str US Upper Powerhouse
D4	220122159275301	Waiahi Upper PH throwaway
D6	220108159275201	Waiahi Upper Powerhouse tailrace
D7	220110159275201	South Intake Ditch on Waiahi Str
D8	220108159275202	Waiahi Str DS South Intake Ditch
D9	220107159274801	Waiahi-Kuia Aqueduct Intake on Waiahi Str
D10	220114159274901	Inflow DS Upper PH
D12	220113159273001	L trib Waiahi DS South Intake Ditch
D14	220103159264001	Waiahi Lower PH throwaway
D15	220103159264101	Waiahi Str DS Lower PH throwaway
D16	220106159263801	Waiahi Str US Upper Lihue Dt dam
D18	220108159263901	L trib Waiahi Str nr lower powerhouse
D20	220151159255101	Waiahi Str US Hanamaulu Ditch

EXPLANATION

200 — **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

Diversion system

+3.5 (7.4) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s

[a]Streamgaging station with flow-duration estimates in table 2

D3 (25.2) Main stream channel

D12 (0.71) Tributary to main stream

D6 (+15.9) Ditch—(-) diversion of flow or (+) return flow

Site from another seepage run

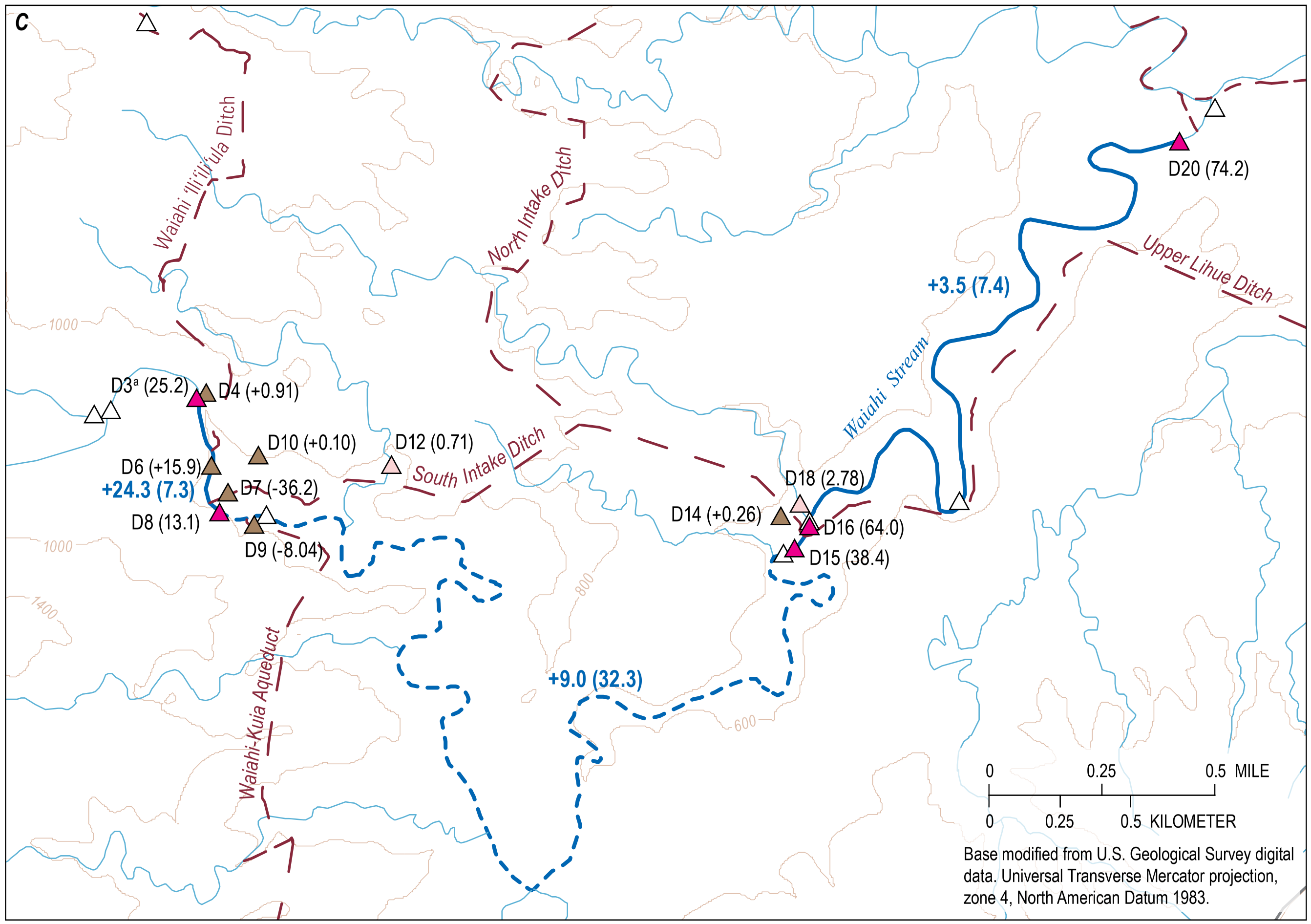


Figure 10.—Continued

South Fork Wailua River—March 11, 1983, seepage-run results

Station number and name associated with map identifier (ID)
[SF, South Fork; DS, downstream; Str, Stream; conf, confluence; nr, near; mi, mile; S, South; R, Right; trib, tributary; US, upstream; Rd, Road. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
E1	220157159254701	SF Wailua River DS Iliiliula Str conf
E2	16058500	SF Wailua River nr Rock Quarry nr Lihue
E4	220219159233901	SF Wailua .3 mi S of Hanamaulu airstrip
E5	16060000	SF Wailua River nr Lihue
E6	220210159224701	R trib SF Wailua River US Wailua Falls
E7	220143159225701	R trib SF Wailua River at Maalo Rd
E8	220151159215901	R trib SF Wailua River US Fern Grotto

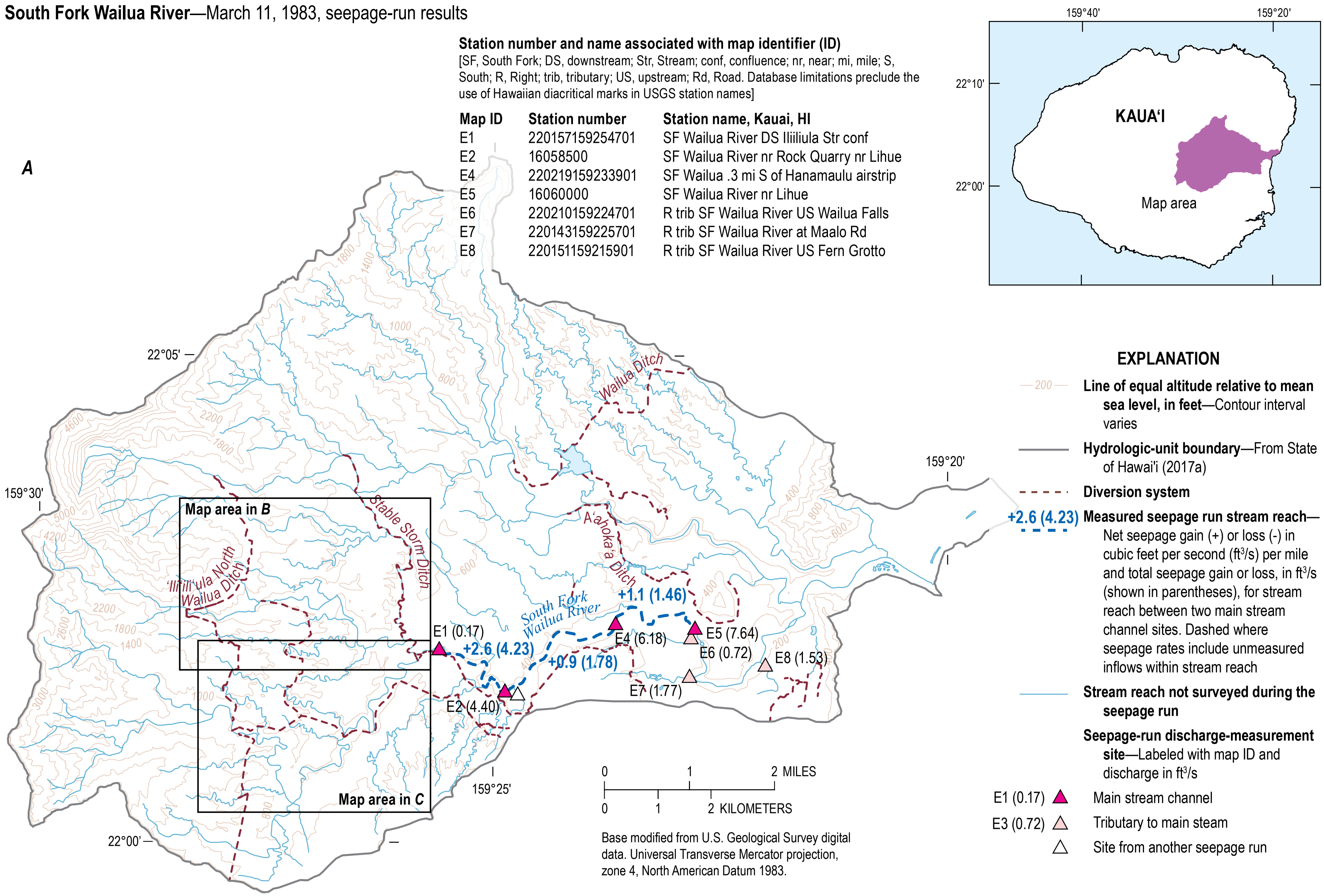
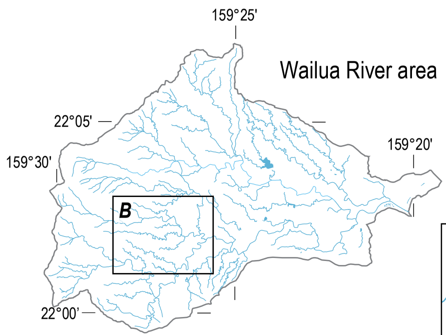


Figure 11. Map of measurement sites and results for the March 1983 seepage runs on South Fork Wailua River, Kaua'i, Hawai'i.

‘Ili‘ili‘ula Stream—March 11, 1983, seepage-run results



Station number and name associated with map identifier (ID)

[NF, North Fork; Str, Stream; US, upstream; N, North; Dt, Ditch; SF, South Fork; trib, tributary; DS, downstream; L, Left; conf, confluence; div, diversion. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
P3	220326159275401	NF Waikoko Str US Iliiliula N Wailua Dt
P4	220325159275401	SF Waikoko Str US Iliiliula N Wailua Dt
P5	220224159282301	Iliiliula Str trib 4 US N Wailua Ditch
C2	220221159282201	Iliiliula Str DS Waiahi Iliiliula Ditch
C3	220221159282101	L trib Iliiliula DS Waiahi Iliiliula Dt
C4	220220159281901	Waiahi Iliiliula Dt spillway, Iliiliula
B6	220320159261801	Stable Storm Dt .27 mi US Waikoko Str
B7	220311159261001	Waikoko Str nr Stable Storm Ditch
C11	220156159255201	Iliiliula Stream div to Waiahi Stream
C12	220157159255101	Iliiliula Str DS div to Waiahi Str

EXPLANATION

200 **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

Diversion system

+1.5 (6.4) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

P3 **Partial-record site**—Labeled with map ID

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s. Site with map ID starting with "P" is a partial-record site

C2 (0.42) Main stream channel

C3 (0.20) Tributary to main stream

C4 (+0.10) Ditch—(-) diversion of flow or (+) return flow

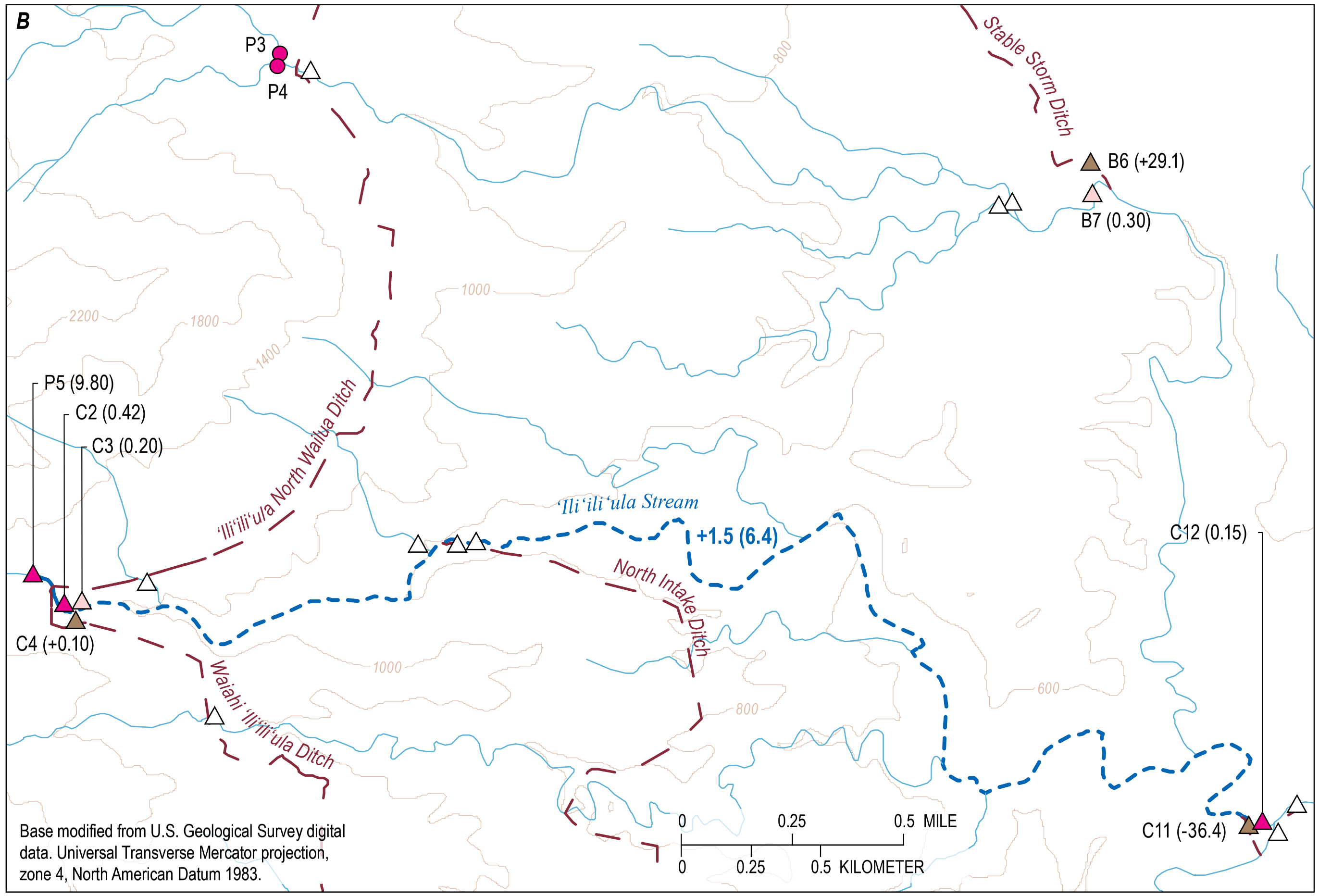
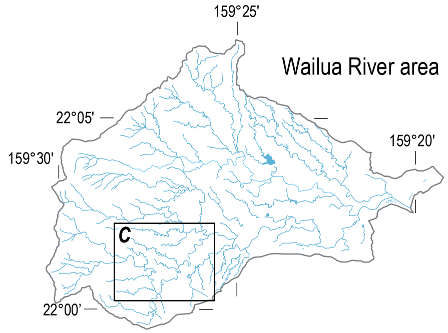


Figure 11.—Continued

Waiahi Stream—March 11, 1983, seepage-run results



Station number and name associated with map identifier (ID)

[div, diversion; Str, Stream; nr, near; DS, downstream; conf, confluence; w, with; US, upstream; PH, powerhouse; Dt, Ditch; L, Left; trib, tributary; mi, mile; fr, from; SF, South Fork; R, River. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
C11	220156159255201	Iliiliula Stream div to Waiahi Stream
D1	220119159280601	Iole Str nr upper powerhouse
D2	220120159280501	Waiahi Str DS conf w Iole Str
D3	16057900	Waiahi Str US Upper Powerhouse
D5	220205159280101	Waiahi Iliiliula Ditch DS Waiaka Str
D7	220110159275201	South Intake Ditch on Waiahi Str
D9	220107159274801	Waiahi-Kuia Aqueduct Intake on Waiahi Str
D11	220107159274701	Waiahi Str DS Waiahi Kuia Aqueduct
D13	220101159264301	Waiahi Str nr lower powerhouse
D14	220103159264001	Waiahi Lower PH throwaway
D17	220107159263801	Waiahi Str DS Upper Lihue Dt dam
D18	220108159263901	L trib Waiahi Str nr lower powerhouse
D19	220109159261901	Upper Lihue Dt .37 mi DS fr intake
D20	220151159255101	Waiahi Str US Hanamaulu Ditch
D21	220156159254701	Hanamaulu Ditch nr SF Wailua R intake

EXPLANATION

200 — **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

- - - **Diversion system**

+9.3 (2.8) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s

[a]Streamgaging station 16057900 with flow-duration discharge estimates in table 2

[b]Discharge computed by subtracting discharge at C11 from discharge at D21

D3 (16.5) ▲ Main stream channel

D12 (5.96) △ Tributary to main stream

D6 (-42.6) ▲ Ditch—(-) diversion of flow or (+) return flow

△ Site from another seepage run

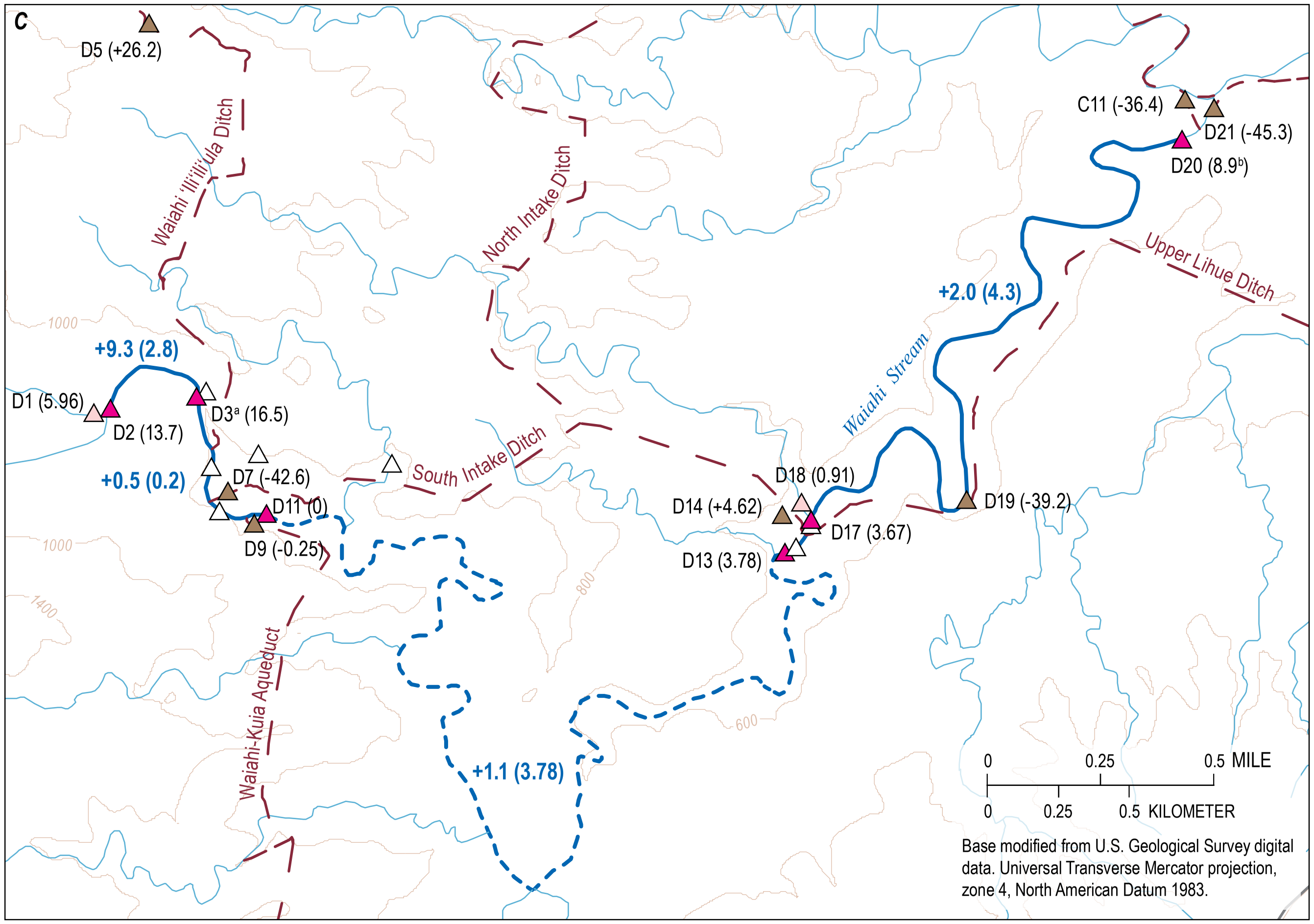


Figure 11.—Continued

2020 seepage run on South Fork Wailua River (fig. 10) consists of three measurement sites located between altitudes of about 240 and 430 ft, with flows in the main stream channel ranging from 54.9 to 131 ft^3/s. The 2020 seepage-run measurements indicate a net gain in the 0.3-mi reach of Waiahi Stream between continuous-record low-flow station 16057900 near the upper powerhouse (D3) and South Intake Ditch dam (D8) and in the 2.1-mi reach between upper Līhu‘e Ditch dam (D16) and Hanamā‘ulu Ditch intake (D20). The net gains in the 3.6-mi reach of Waiahi Stream between South Intake Ditch dam (D8) and upper Līhu‘e Ditch dam (D16), and in the measured reach on South Fork Wailua River from the confluence of ‘Ili‘ili‘ula and Waiahi Streams (E1) to continuous station 16060000 (E5) include unmeasured inflows from tributaries. Seepage gains are presumed to originate mainly from groundwater discharge from the thickly saturated hydrogeologic setting.

The 1983 seepage run on South Fork Wailua River and its tributaries (fig. 11, map areas B and C) consists of 30 measurement sites, located between altitudes of about 230 and 1,110 ft, with flows in the stream channel ranging from 0.15 ft^3/s on ‘Ili‘ili‘ula Stream to 16.5 ft^3/s on Waiahi Stream. Results of the 1983 seepage run are comparable to those of the 2019 and 2020 seepage runs, with lower magnitudes of seepage gains in the selected reaches. Flow at Waikoko Stream upstream from its confluence with ‘Ili‘ili‘ula Stream (fig. 11, map area B) is the sum of discharges measured at the confluence of Waikoko Stream and Stable Storm Ditch (B6 and B7) and assumes no seepage gains and (or) losses in the downstream reach. Flow at Waiahi Stream upstream from Hanamā‘ulu Ditch intake (D20; fig. 11, map area C) was estimated from discharges measured at the transmission ditch (C11) and Hanamā‘ulu Ditch (D21).

Seepage-run measurements indicate that under the flow conditions of the seepage runs, South Fork Wailua River flows continuously from the ‘Ili‘ili‘ula North Wailua Ditch level to continuous-record stream-gaging station 16060000 (E5) under natural-flow conditions. During the base period (1961–2019), the stream did not run dry at station 16060000, with the lowest discharge at 7.6 ft^3/s. Extrapolation of seepage rates on South Fork Wailua River to the downstream unmeasured reach to determine flow continuity to the ocean is not appropriate because the seepage rates include unmeasured inflows from a number of tributaries.

Hanamā‘ulu Stream

Previous seepage runs on Hanamā‘ulu Stream were conducted on October 9, 1996 (fig. 12), September 13, 1973, and September 20, 1973 (fig. 13). The September 13, 1973, seepage run did not consider flow contribution from the tributary at site F8; thus, a subsequent seepage run was conducted a week later that included flow from the tributary. The 1996 seepage run was conducted under conditions when index station 16068000 was flowing at about a Q_{65} discharge (daily mean of 23.0 ft^3/s, table 2). The first 1973 seepage run was conducted under conditions when index station 16068000 was flowing at about a Q_{92} discharge (daily mean of 14.0 ft^3/s, table 2), and the second 1973 seepage run was conducted when index station 16068000 was flowing at about a Q_{62} discharge (daily mean of 24.0 ft^3/s, table 2).

The 1996 seepage run (fig. 12) consists of four measurement sites located between altitudes of about 110 and 360 ft, with flows in the main stream channel ranging from 10.9 to 23.7 ft^3/s. The 1973 seepage run (fig. 13) consists of six measurement sites, located between altitudes of about 90 and 200 ft, with flows in the main stream channel ranging from 5.73 to 19.6 ft^3/s. The 1996 seepage-run measurements indicate a generally gaining reach from sites F3 to F7 and the 1973 seepage-run measurements indicate a generally gaining reach from sites F4 to F9. Flow contributions from major tributaries to the measured reach were considered in the calculation of seepage gains and losses. The measured gains were most likely from groundwater discharge from the thickly saturated hydrogeologic setting. Both seepage runs were conducted under diverted-flow conditions. The headwaters of Hanamā‘ulu Stream flow into Kapaia Reservoir, which regulates downstream flow in the main stream channel. Several tributaries, which may be affected by return flows from the upper and lower Līhu‘e Ditches, flow into the 3.3-mi stream reach downstream from the reservoir. Seepage-run discharge measurements are not available within this reach because many areas may have been inaccessible owing to surrounding vegetation of the stream channel.

Results of these previous seepage runs indicate seepage-gain rates in the measured reaches. Extrapolation of seepage rates to the downstream unmeasured reach for determining flow continuity from mauka to makai would assume that the downstream unmeasured stream reach is also gaining. With this assumption, and under flow conditions of the seepage runs, including flow regulation by Kapaia Reservoir, Hanamā‘ulu Stream flows continuously from site F3 to the ocean.

Nāwiliwili Stream

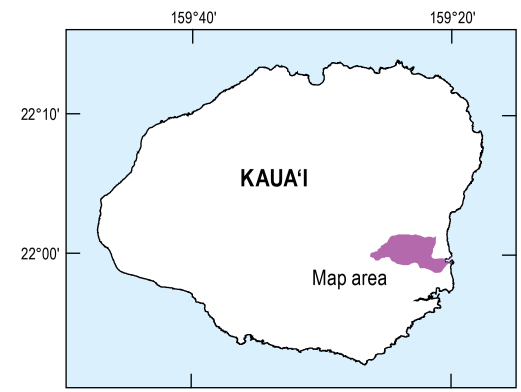
Discharge measurements from two seepage runs are available to characterize seepage gains and losses in selected reaches of Nāwiliwili Stream. The September 12, 2019, seepage run (fig. 14) was conducted during conditions when nearby long-term station 16068000 was flowing at about a Q_{80} discharge (daily mean of 18.6 ft^3/s, table 2). The October 9, 1996, seepage run (fig. 15) was conducted during conditions when nearby station 16068000 was flowing at about a Q_{65} discharge (daily mean of 23.0 ft^3/s, table 2).

The 2019 seepage run (fig. 14) consists of eight measurement sites located between altitudes of about 90 and 230 ft, with flows in the main stream channel ranging from 1.54 to 5.86 ft^3/s. The seepage run was conducted under natural-flow conditions; all the flow diverted at a stream-diversion intake near an altitude of about 195 ft (G2) was returned to the stream at sites G6 and G7. Discharge measurements indicate a net gain in the 0.5-mi reach between the uppermost site (P9) and downstream from the diversion intake at site G3, and a net loss in the 1.8-mi reach downstream from the intake (G3) to about 1.7 mi upstream from the stream mouth (G9). Flow contribution from a tributary just upstream of site G8 was not

Hanamāʻulu Stream—October 9, 1996, seepage-run results

Station number and name associated with map identifier (ID)
[R, Right; trib, tributary; mi, mile; DS, downstream; Dt, Ditch; Lo, Lower; Str, Stream; US, upstream; ft, feet; Hwy, Highway; N, North; Res, Reservoir; S, South. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
F1	220024159234101	R trib 1 Hanamaulu.9mi DS Upper Lihue Dt
F2	220008159230401	R trib 2 Hanamaulu .7mi DS Lo Lihue Dt
F3	215932159225201	Hanamaulu Str .23mi US Kapaia Ditch
F7	215930159215901	Hanamaulu Str 600ft US Kuhio Hwy
P6	220054159244001	Hanamaulu Str 1 mi US N Kapaia Res
P7	220037159242901	Hanamaulu Str 0.6 mi US S Kapaia Res
P8	215923159235601	Hanamaulu tributary US of return flow



EXPLANATION

200 **Line of equal altitude relative to mean sea level**—Contour interval 100 feet

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+6.4 (12.8) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites

Stream reach not surveyed during the seepage run

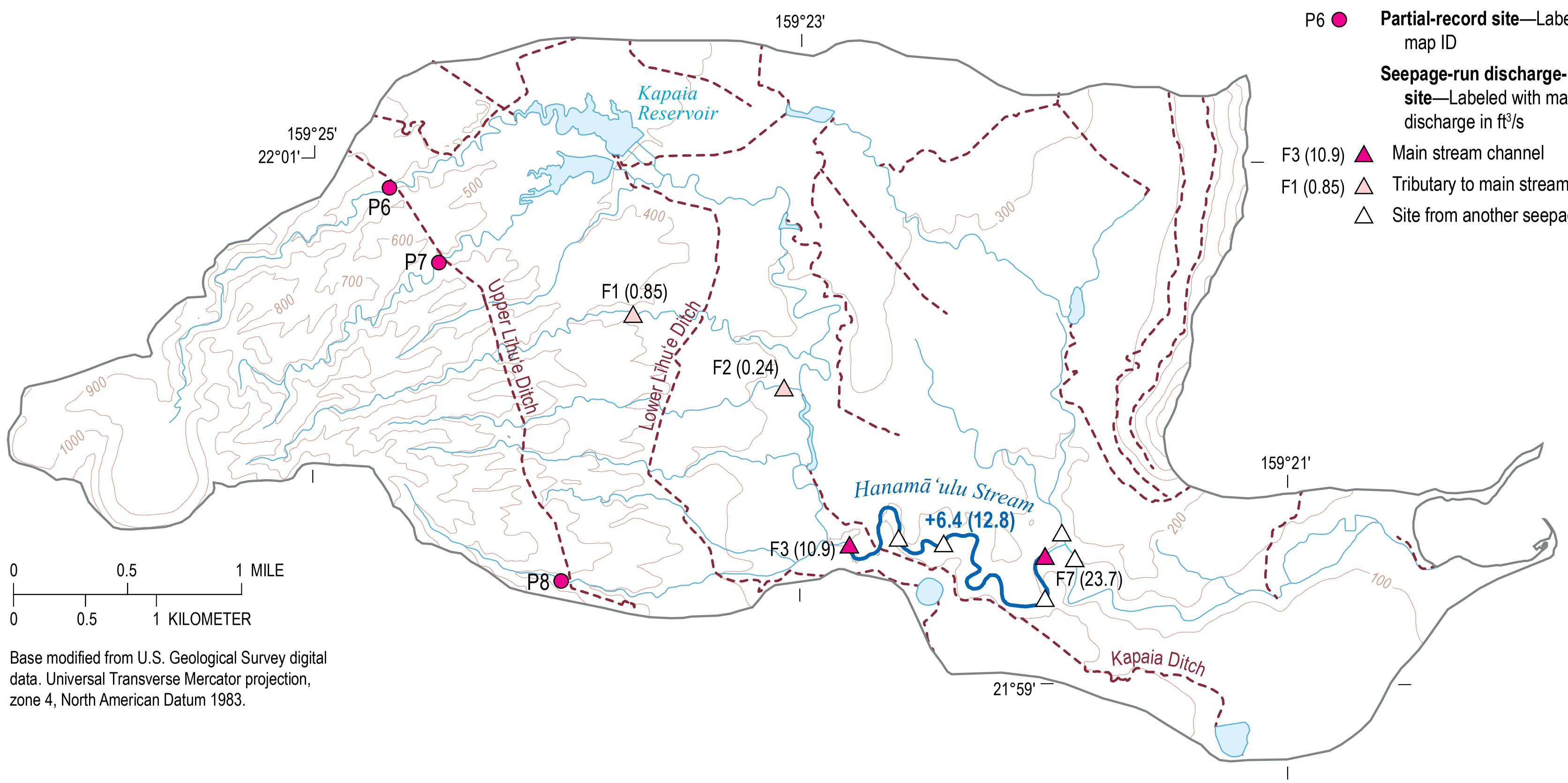
P6 **Partial-record site**—Labeled with map ID

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s

F3 (10.9) Main stream channel

F1 (0.85) Tributary to main stream

Site from another seepage run



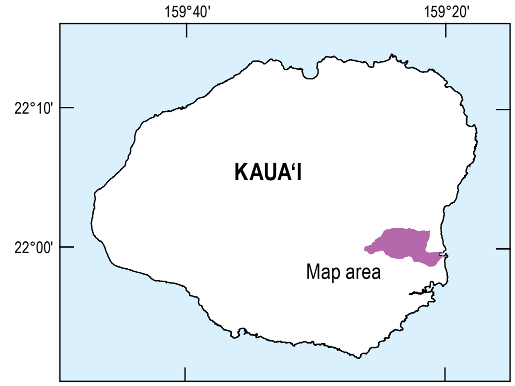
Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 12. Map of measurement sites and results for the October 1996 seepage run on Hanamāʻulu Stream, Kauaʻi, Hawaiʻi.

Hanamā‘ulu Stream—September 13 and 20, 1973, seepage-run results

Station number and name associated with map identifier (ID)
[Str, Stream; mi, mile; blw, below; DS, downstream; nr, near; ft, feet; US, upstream; Hwy, Highway; trib, tributary; Pk, Park; N, North; Res, Reservoir; S, South. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
F4	215932159223501	Hanamaulu Str .14mi blw Kapaia Ditch
F5	215932159222401	Hanamaulu Str .4mi DS Kapaia Ditch
F6	215918159220001	Hanamaulu Str nr Wilcox Hospital
F7	215930159215901	Hanamaulu Str 600ft US Kuhio Hwy
F8	215933159215501	Left trib US Hanamaulu nr Lau Kona Pk
F9	215929159215201	Hanamaulu Str nr Lau Kona Park
P6	220054159244001	Hanamaulu Str 1 mi US N Kapaia Res
P7	220037159242901	Hanamaulu Str 0.6 mi US S Kapaia Res
P8	215923159235601	Hanamaulu tributary US of return flow



EXPLANATION

200 — **Line of equal altitude relative to mean sea level**—Contour interval 100 feet

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

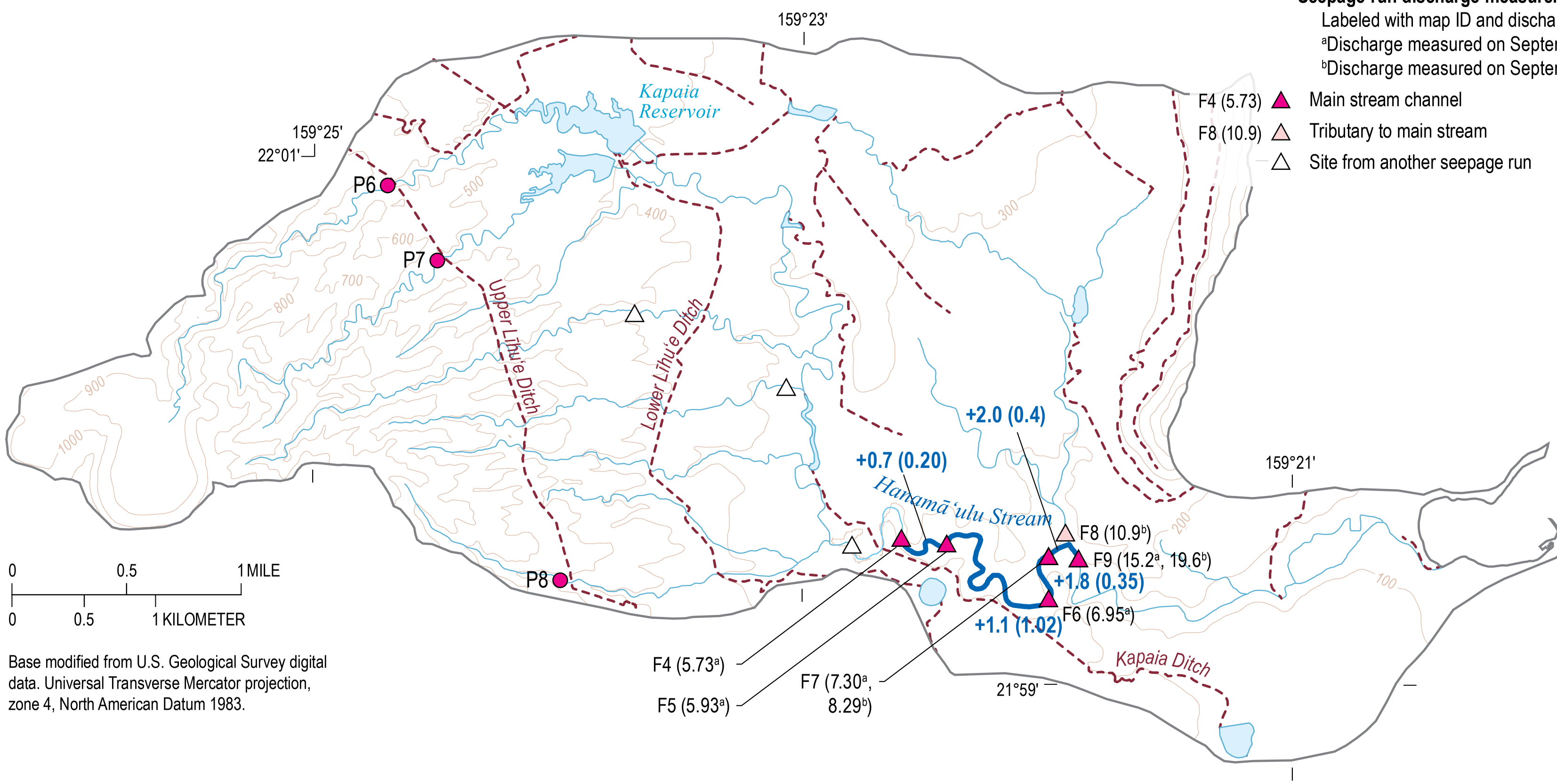
+2.0 (0.4) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites

Stream reach not surveyed during the seepage run

P6 **Partial-record site**—Labeled with map ID

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s
[a]Discharge measured on September 13, 1973
[b]Discharge measured on September 20, 1973

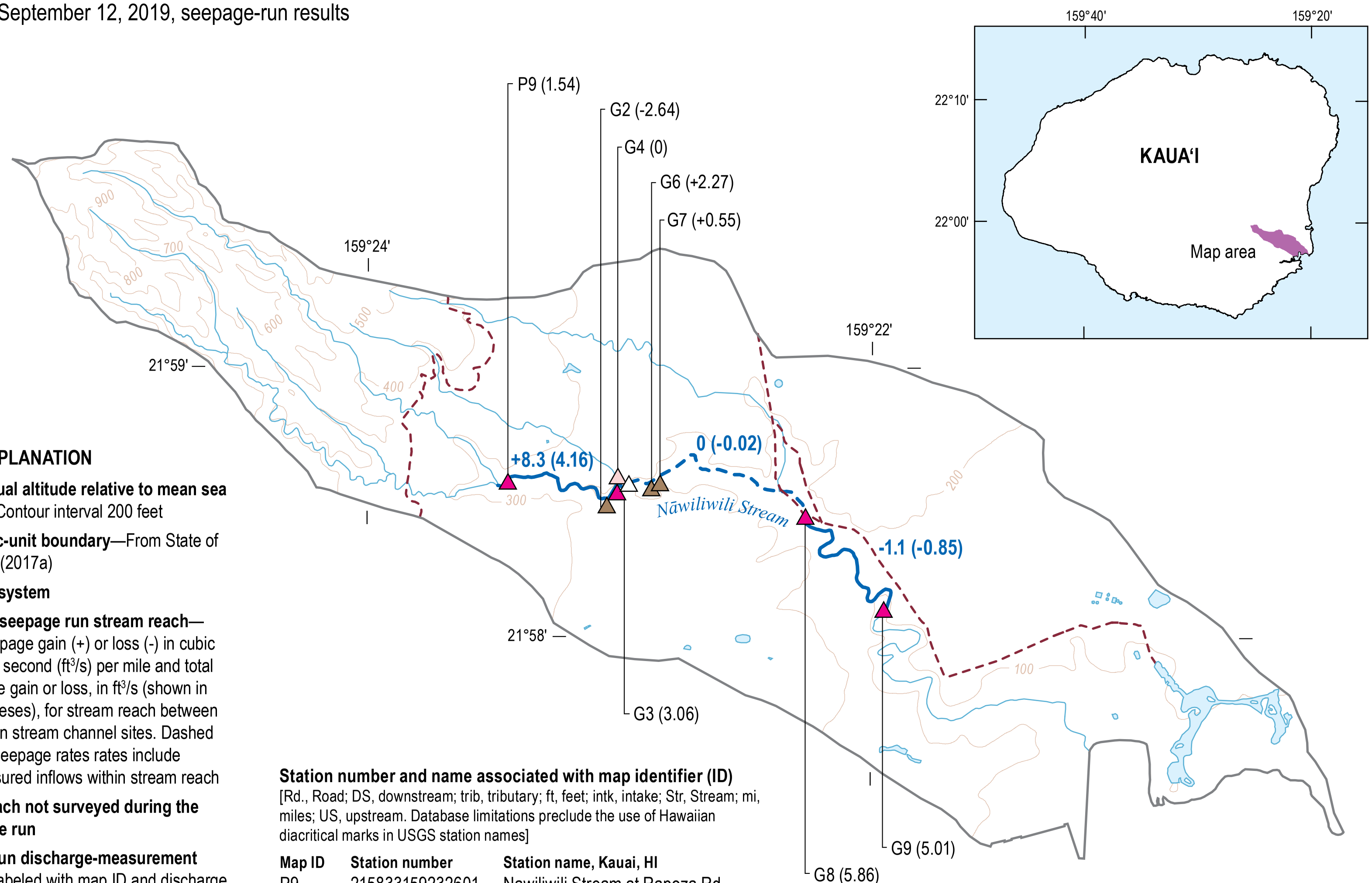
F4 (5.73) Main stream channel
F8 (10.9) Tributary to main stream
Site from another seepage run



Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 13. Map of measurement sites and results for the September 1973 seepage runs on Hanamā‘ulu Stream, Kaua‘i, Hawai‘i.

Nāwiliwili Stream—September 12, 2019, seepage-run results



EXPLANATION

200 — **Line of equal altitude relative to mean sea level**—Contour interval 200 feet

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+8.3 (4.16) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s. Site with map ID starting with "P" is a partial-record site

G8 (5.86) Main stream channel

G4 (0) Tributary to main stream

G2 (-2.64) Ditch—(-) diversion of flow or (+) return flow

Site from another seepage run

Station number and name associated with map identifier (ID)

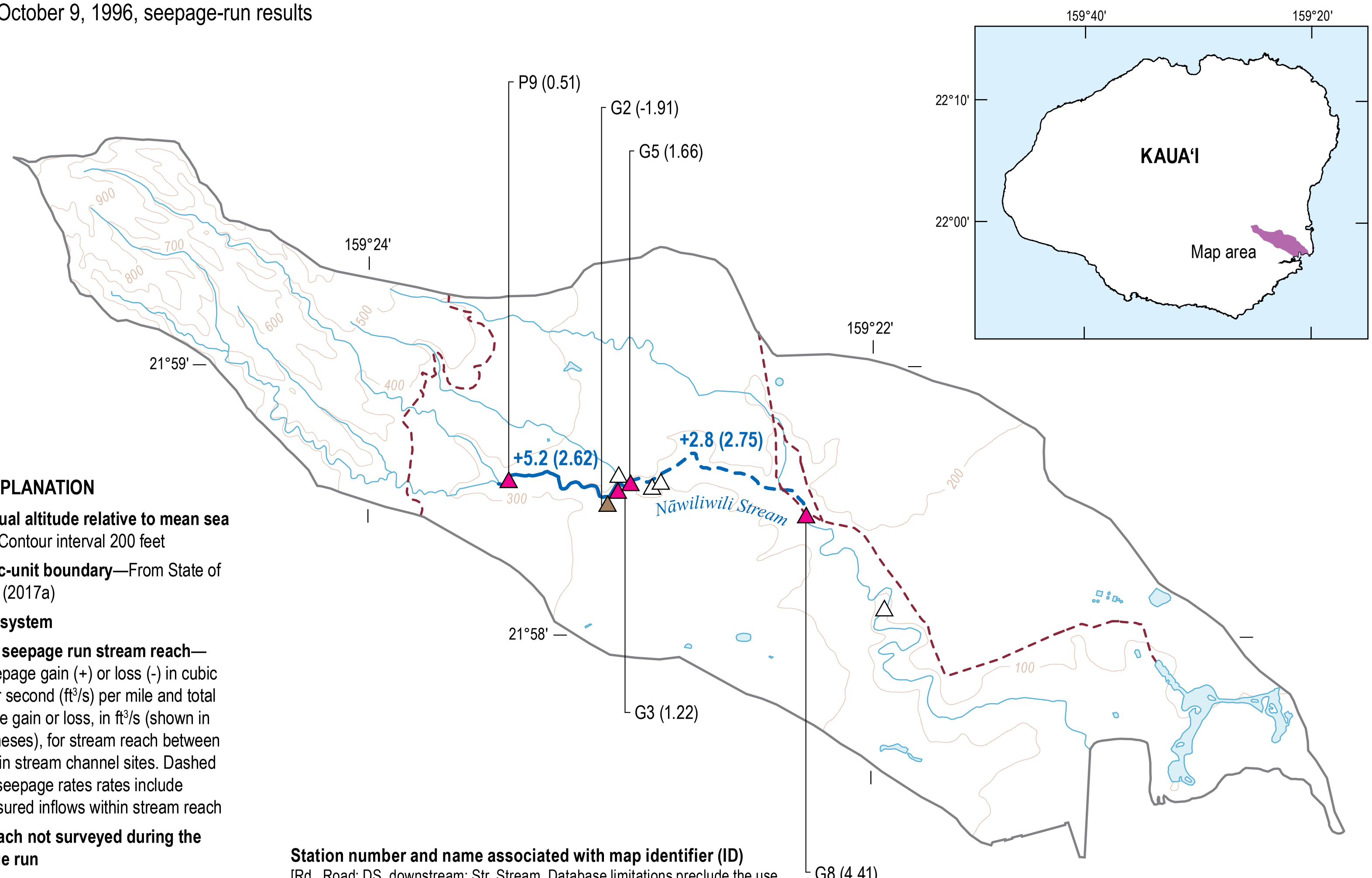
[Rd., Road; DS, downstream; trib, tributary; ft, feet; intk, intake; Str, Stream; mi, miles; US, upstream. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
P9	215833159232601	Nawiliwili Stream at Rapoza Rd.
G2	215831159230201	Taro intake at Nawiliwili Stream
G3	215832159230201	Nawiliwili Stream DS taro intake
G4	215833159230001	Nawiliwili trib 270 ft DS taro intk
G6	215833159225201	Taro ditch return to Nawiliwili Str
G7	215834159225001	Taro side ditch return Nawiliwili Str
G8	16055500	Nawiliwili Str at Heleko Road at Lihue
G9	215807159215801	Nawiliwili Str 1.7 mi US mouth

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 14. Map of measurement sites and results for the September 2019 seepage run on Nāwiliwili Stream, Kaua'i, Hawai'i.

Nāwiliwili Stream—October 9, 1996, seepage-run results



EXPLANATION

—200— **Line of equal altitude relative to mean sea level**—Contour interval 200 feet

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+5.2 (2.62) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s. Site with map ID starting with "P" is a partial-record site

G8 (4.41) Main stream channel

G2 (-1.91) Ditch—(-) diversion of flow or (+) return flow

Site from another seepage run

Station number and name associated with map identifier (ID)
[Rd., Road; DS, downstream; Str, Stream. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
P9	215833159232601	Nawiliwili Stream at Rapoza Rd.
G2	215831159230201	Taro intake at Nawiliwili Stream
G3	215832159230201	Nawiliwili Stream DS taro intake
G5	215834159230001	Nawiliwili Str DS of confluence
G8	16055500	Nawiliwili Str at Heleko Road at Lihue

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 15. Map of measurement sites and results for the October 1996 seepage run on Nāwiliwili Stream, Kaua‘i, Hawai‘i.

considered in the calculation of seepage loss; therefore, the indicated seepage loss may be underestimated. The measured gain in the upper reach was most likely from groundwater discharge from the thickly saturated hydrogeologic setting. Downstream from site G9, the stream was either inaccessible or unmeasurable owing to the surrounding vegetation of the stream channel. Flow was observed in the stream about 0.9 mi upstream from the stream mouth during the seepage run.

The 1996 seepage run (fig. 15) consists of five measurement sites located between altitudes of about 140 and 230 ft, with flows in the main stream channel ranging from 0.51 to 4.41 ft^3/s. The seepage run was conducted under diverted conditions and the magnitude of measured gains in the upper stream reach between sites P9 and G5 is substantially lower than that from the 2019 seepage run. Seepage gains were measured in the lower stream reach between sites G5 and G8 during the 1996 seepage run, although potential unmeasured tributary flow may have contributed to the apparent gain in this reach. No substantial net gain or loss was measured in the same stream reach during the 2019 seepage run.

To determine flow continuity from mauka to makai on Nāwiliwili Stream, the seepage rate of –1.1 $(ft^3/s)/mi$ in the stream reach between sites G8 and G9 for the 2019 seepage run was extrapolated to the 1.9-mi stream reach downstream from the measured reach for the seepage run, with a computed seepage loss of 2.09 ft^3/s within this reach. This loss would be less than the flow of 5.01 ft^3/s measured at site G9; therefore, with this assumption and under flow conditions of the seepage-run measurements, Nāwiliwili Stream flows continuously from an altitude of about 230 ft (P9) to the ocean under natural-flow conditions.

Hulēʻia Stream

Discharge measurements from two seepage runs are available to characterize seepage gains and losses in selected reaches on Hulēʻia Stream. The November 14, 2019, seepage run (fig. 16) was conducted during conditions when long-term station 16068000 was flowing at about a Q_{65} discharge (daily mean of 22.5 ft^3/s, table 2). The October 8, 1996, seepage run (fig. 17) was conducted during conditions when station 16068000 was flowing at about a Q_{62} discharge (daily mean of 24.0 ft^3/s, table 2). Both seepage runs were conducted under diverted-flow conditions; flows in the upper tributaries were diverted by several interconnected ditches. No dry reaches in the main stream channel were observed during the seepage runs.

The 2019 seepage run (fig. 16) consists of six measurement sites located between altitudes of about 240 and 480 ft, with flows in the main stream channel ranging from 17.3 to 24.6 ft^3/s. The 1996 seepage run (fig. 17) consists of nine measurement sites located between altitudes of about 30 and 550 ft, with flows in the main stream channel ranging from 1.33 to 10.6 ft^3/s. Results of both seepage runs indicate a generally gaining stream in the measured reaches. Discharge measurements collected during the 2019 seepage run indicate a gain of 6.3 ft^3/s in the 2.7-mi measured reach between sites H6 and H9; however, three minor tributaries—collectively 0.65 mi^2 or less than 2 percent of the Hulēʻia drainage area—were not measured during the seepage run. Discharge measurements collected during the 1996 seepage run indicate a generally gaining stream between sites H2 and H12, although potential unmeasured tributary flows may have contributed to the apparent gain in some reaches. Measured gains were most likely from groundwater discharge from the thickly saturated hydrogeologic setting.

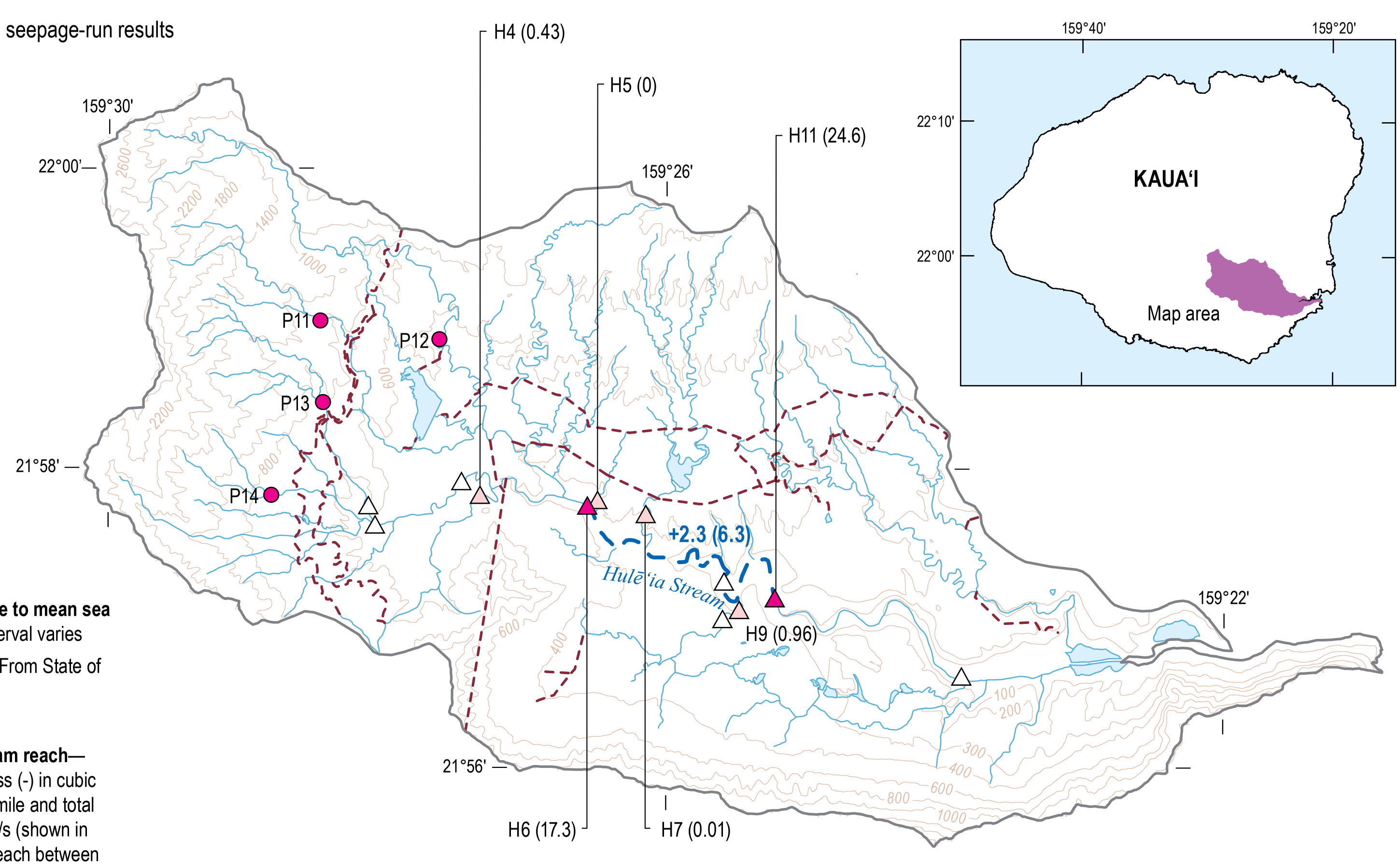
Extrapolation of seepage rates to the downstream unmeasured reach for determining flow continuity from mauka to makai would assume that the downstream unmeasured stream reach is also gaining. With this assumption, and under the flow conditions of the seepage runs, Hulēʻia Stream flows continuously from site H2 to the ocean under natural-flow conditions.

Waikomo Stream

A seepage run was conducted on January 22, 2020, on Waikomo Stream as part of this study (fig. 18) with no available discharge measurements from previous seepage runs. The seepage run was conducted during conditions when long-term station 16068000 was flowing at above the median discharge (daily mean of 37.4 ft^3/s, table 2). The seepage run consists of five measurement sites located between altitudes of about 40 and 210 ft, with flows in the main stream channel ranging from 15.5 to 18.8 ft^3/s. During the seepage run, flow in the upper tributaries was diverted by several ditches and flow from Waita Reservoir (fig. 5) was discharged to Waikomo stream downstream from site I1. A golf course located near site I3 diverted streamflow (measured at site I4) to maintain water level in a pond within the golf course. According to a representative of the golf course, all of the diverted flow was returned to the stream about 800 ft downstream from the diversion intake. Unfortunately, the return flow could not be quantified owing to lack of a usable discharge-measurement section; the return flow was discharged vertically upward through a pipe partly covered with boulders in the stream to mimic a small waterfall on the left streambank. Discharge measurements indicate a net loss in the 1-mi reach upstream from the golf course diversion. The measured loss most likely discharged to the underlying freshwater-lens hydrogeologic setting.

To determine flow continuity from mauka to makai on Waikomo Stream, the seepage rate of –0.1 $(ft^3/s)/mi$ in the stream reach between sites I3 and I5 was extrapolated to the 0.2-mi stream reach downstream from the measured seepage-run reach, with a computed seepage loss of 0.02 ft^3/s within this reach. The lower unmeasured reach of Waikomo Stream is within the same hydrogeologic setting as the measured reach—a freshwater-lens setting (fig. 4) where the groundwater level is below stream altitude and the stream typically discharges to the groundwater body—which suggests that the lower unmeasured reach is most likely a losing reach. With this assumption, and under the flow conditions of the seepage run, which includes a substantial amount of flow contribution from Waita Reservoir, Waikomo Stream flows continuously from site I2 to the ocean. A seepage run conducted under lower flow conditions is needed to determine whether

Hulē‘ia Stream—November 14, 2019, seepage-run results



EXPLANATION

- Line of equal altitude relative to mean sea level, in feet—Contour interval varies (200)
- **Hydrologic-unit boundary**—From State of Hawai'i (2017a)
- **Diversion system**
- +2.3 (6.3) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach
- **Stream reach not surveyed during the seepage run**
- P11 **Partial-record site**—Labeled with map ID
- **Seepage-run discharge-measurement site**—Labeled with map ID and discharge in ft³/s
  - H6 (17.3) Main stream channel
  - H5 (0) Tributary to main stream
  - Site from another seepage run

Station number and name associated with map identifier (ID)

[Str, Stream; Rd, Road; trib, Tributary; nr, near; mi, mile; US, upstream; confl, confluence; ft, feet; Res, Reservoir; W, west; SW, southwest. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

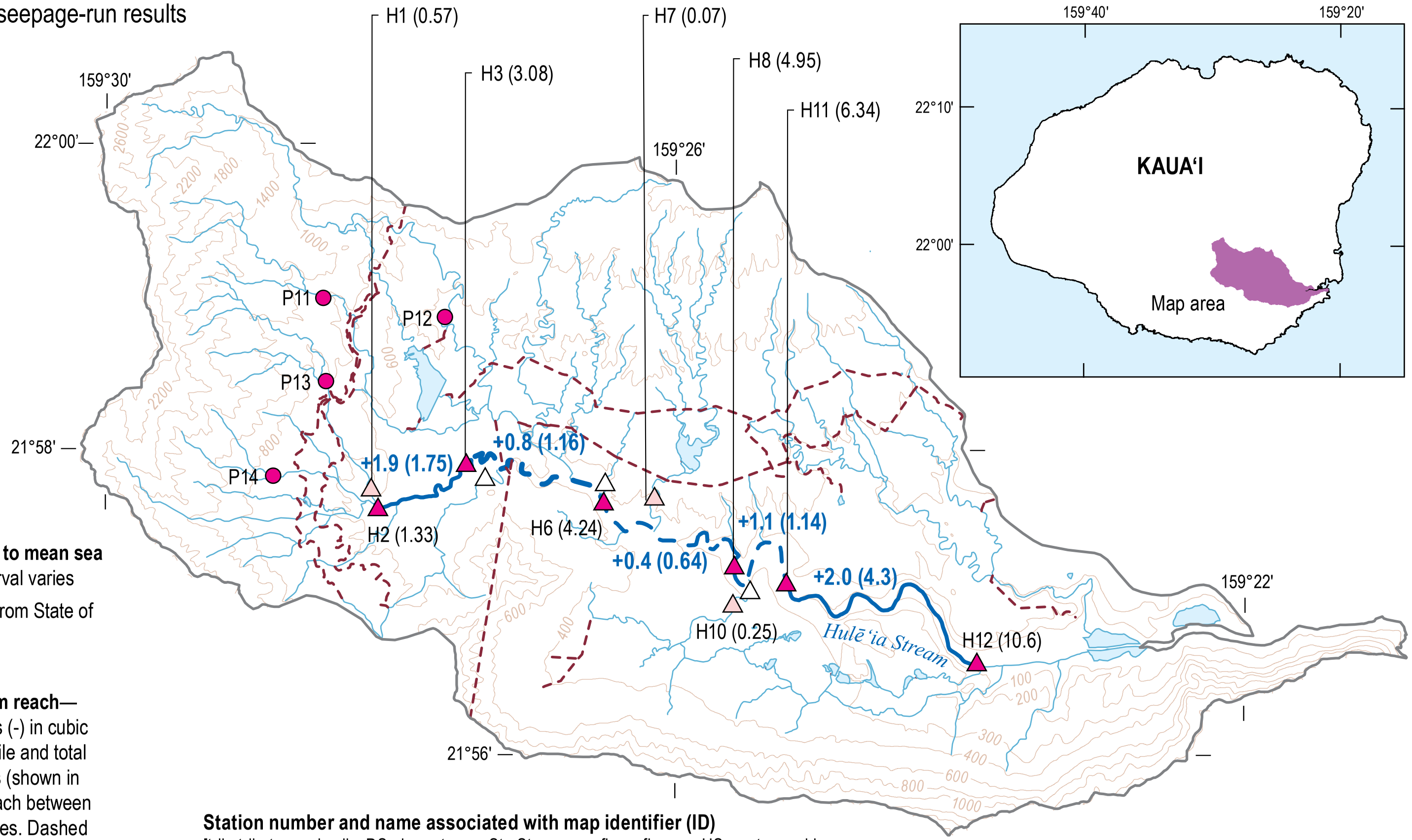
Map ID	Station number	Station name, Kauai, HI
H4	215749159271901	Weoweopilau Str at Kahili Rd
H5	215744159262901	Trib to Huleia Str nr Halfway Bridge
H6	215742159263101	Huleia Stream near Halfway Bridge
H7	215742159260701	Halenanahu Str .4mi US Huleia confl
H9	215704159252801	Puakukui Str 620ft US Huleia Str
H11	16055000	Huleia Str nr Lihue
P11	215853159281801	Paohia Str US Koloa Ditch
P12	215851159273901	Kamooloa Str US Papuaa Res intake
P13	215822159282601	Kuia Str 0.7 mi W of Papuaa Res
P14	215751159283901	Kuia Str trib 1 mi SW of Papuaa Res

0 1 2 MILES
0 1 2 KILOMETERS

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 16. Map of measurement sites and results for the November 2019 seepage run on Hulē‘ia Stream, Kaua‘i, Hawai‘i.

Hulēʻia Stream—October 8, 1996, seepage-run results



EXPLANATION

- 200 — **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies
- **Hydrologic-unit boundary**—From State of Hawaiʻi (2017a)
- **Diversion system**
- +1.9 (1.75) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach
- **Stream reach not surveyed during the seepage run**
- P11 **Partial-record site**—Labeled with map ID
- **Seepage-run discharge-measurement site**—Labeled with map ID and discharge in ft³/s
  - H2 (1.33) Main stream channel
  - H1 (0.57) Tributary to main stream
  - Site from another seepage run

Station number and name associated with map identifier (ID)

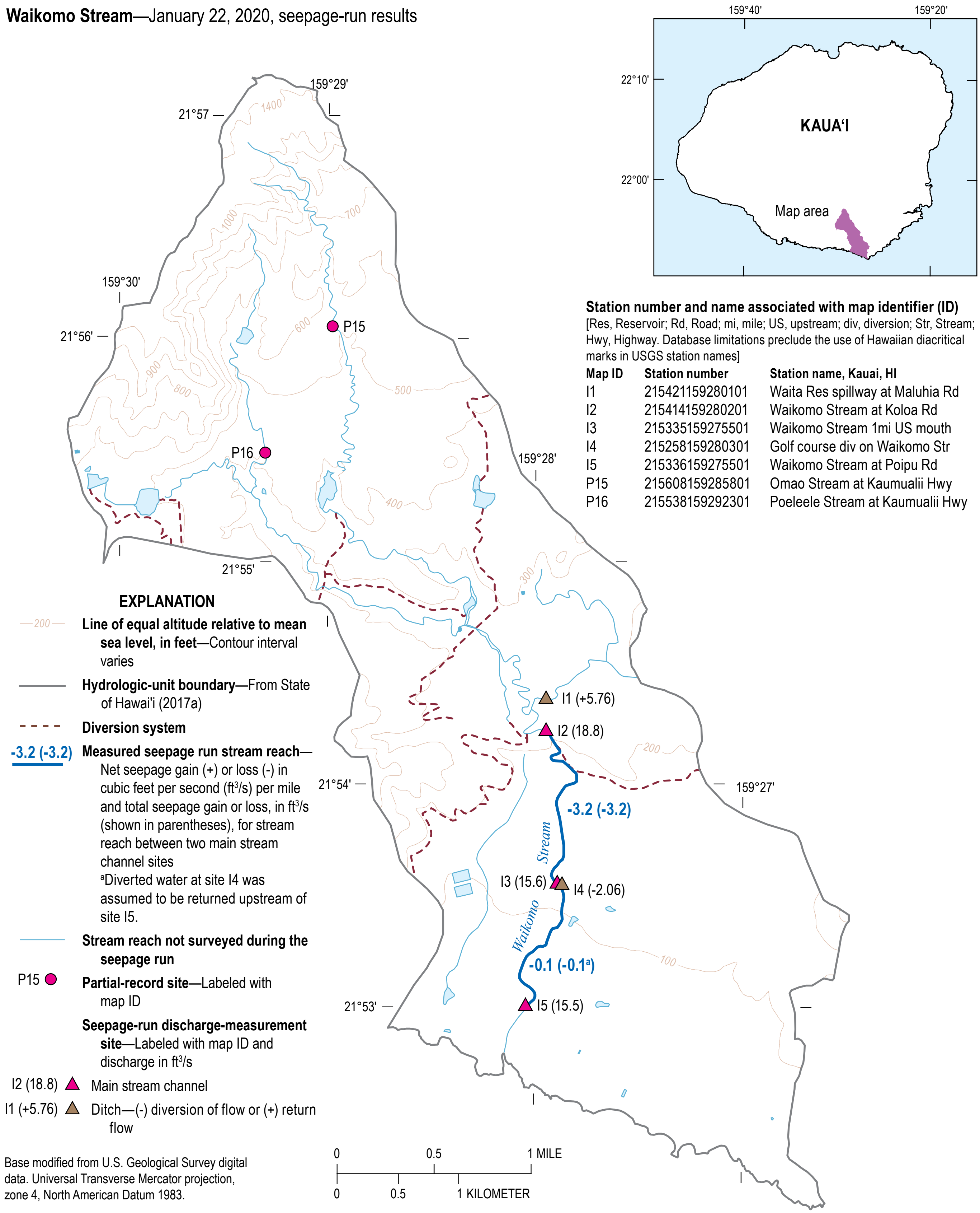
[trib, tributary; mi, mile; DS, downstream; Str, Stream; confl, confluence; US, upstream; blw, below; conf, confluence; w, with; nr, near; Res, Reservoir; W, west; SW, southwest. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
H1	215740159281301	Left trib Huleia .35mi DS Koloa Ditch
H2	215738159280501	Huleia Str below confl with Kuia Str
H3	215753159272601	Huleia Stream at Kahili Road
H6	215742159263101	Huleia Stream near Halfway Bridge
H7	215742159260701	Halenanahu Str .4mi US Huleia confl
H8	215718159253301	Huleia Stream blw Aakukui Road
H10	215702159253401	Puakukui Str .25mi US conf w Huleia Str
H11	16055000	Huleia Str nr Lihue
H12	215635159235101	Huleia Stream at Haiku Road
P11	215853159281801	Paohia Str US Koloa Ditch
P12	215851159273901	Kamooloa Str US Papuaa Res intake
P13	215822159282601	Kuia Str 0.7 mi W of Papuaa Res
P14	215751159283901	Kuia Str trib 1 mi SW of Papuaa Res

0 1 2 MILES
0 1 2 KILOMETERS

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 17. Map of measurement sites and results for the October 1996 seepage run on Hulēʻia Stream, Kauaʻi, Hawaiʻi.



Station number and name associated with map identifier (ID)

[Res, Reservoir; Rd, Road; mi, mile; US, upstream; div, diversion; Str, Stream; Hwy, Highway. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
I1	215421159280101	Waita Res spillway at Maluhia Rd
I2	215414159280201	Waikomo Stream at Koloa Rd
I3	215335159275501	Waikomo Stream 1mi US mouth
I4	215258159280301	Golf course div on Waikomo Str
I5	215336159275501	Waikomo Stream at Poipu Rd
P15	215608159285801	Omao Stream at Kaumualii Hwy
P16	215538159292301	Poeleele Stream at Kaumualii Hwy

Figure 18. Map of measurement sites and results for the January 2020 seepage run on Waikomo Stream, Kaua‘i, Hawai‘i

Waikomo Stream flows continuously when flow contributions from Waita Reservoir are reduced.

Lāwa‘i Stream

Discharge measurements from two seepage runs are available to characterize seepage gains and losses in selected reaches of Lāwa‘i Stream. The September 19, 2019, seepage run (fig. 19) was conducted during conditions when discharge measured at short-term station 16052400 (J1) was flowing at 0.52 ft^3/s, which is about a Q_{90} discharge (station 16052400 in table 2). Discharges measured at sites J4 and J14 during the seepage runs indicate that results from 2019 are representative of lower flow conditions than those from the October 7, 1996, seepage run (fig. 20). Both seepage runs were conducted under diverted-flow conditions; flow in Lāwa‘i Stream was diverted by the Lāwa‘i Intake Ditch near an altitude of about 590 ft.

The 2019 seepage run consists of 12 measurement sites located between altitudes of about 40 to 600 ft, with flows in the main stream channel ranging from 0.08 to 0.52 ft^3/s. Results from the seepage run indicate a generally gaining stream in the 3.7-mi reach downstream from Lāwa‘i Intake Ditch (J3). Flow contribution from major tributaries to the stream was considered in the calculation of seepage gains and losses for the 2019 seepage run. The 1996 seepage run consists of four measurement sites located between altitudes of about 40 to 590 ft, with flows in the main stream channel ranging from 0.67 to 1.15 ft^3/s. Flow contribution from spring input at site J12 was not considered during the 1996 seepage run; thus, the actual seepage gain is less than computed.

To determine flow continuity from mauka to makai on Lāwa‘i Stream, the seepage rate of 0.03 $(ft^3/s)/mi$ in the stream reach between sites J13 and J14 for the 2019 seepage run was extrapolated to the 0.9-mi stream reach downstream from the measured reach for the seepage run as both reaches are in a similar hydrogeologic setting. Seepage-run discharge measurements indicate that under flow conditions of the seepage-run discharge measurements, Lāwa‘i Stream flows continuously from site J1 (station 16052400) to the ocean under natural-flow conditions.

Wahiawa Stream

Two seepage runs were conducted on Wahiawa Stream as part of this study (fig. 21) with no available discharge measurements from previous seepage runs. The November 12, 2019, seepage run was conducted during conditions when discharge measured at the partial-record site (P17) was flowing at 1.85 ft^3/s, which is about a Q_{90} discharge (table 5). The seepage run consists of seven measurement sites located between altitudes of about 220 and 1,720 ft, with flows in the main stream channel ranging from 0.06 to 2.39 ft^3/s. During the seepage run, streamflow was unstable while collecting measurements at sites K6 and K7; thus, repeat discharge measurements were collected at these sites on January 24, 2020, to determine gains and losses in the lower 1.3-mi reach. The headwaters of Wahiawa Stream discharge into Alexander Reservoir and discharge at site K4 represented leakage from the reservoir into the stream. The 2020 seepage run was conducted during conditions when flow was released from the reservoir into the stream upstream from site K6. Stage measurements recorded during the time the two discharge measurements were collected indicate stable-flow conditions.

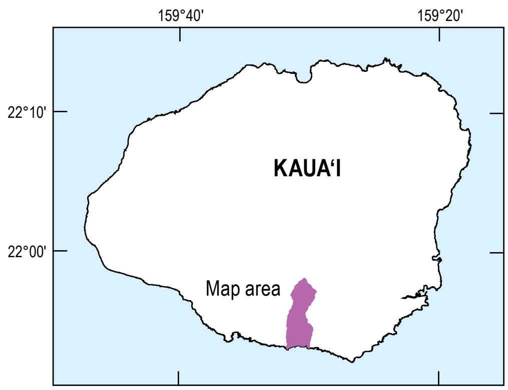
Results from the 2019 and 2020 seepage runs indicate net gains in the 0.3-mi reach upstream from the reservoir and the 5.1-mi reach downstream from the reservoir. The reach downstream of site K6 to the coast is in a uniform hydrogeological setting (Izuka and others, 2018), and the seepage rate between sites K6 and K7 was used to characterize the seepage rate downstream of site K7 to the coast. Seepage-run discharge measurements indicate that under the flow conditions of the seepage run, including flow regulation by Alexander Reservoir, Wahiawa Stream flows continuously from site K4 to the ocean.

Hanapēpē River

Discharge measurements from two seepage runs are available to characterize seepage gains and losses on selected reaches of Hanapēpē River. The September 21, 2017, seepage run (fig. 22) was conducted under conditions when discharge measured at site L4 was 48.0 ft^3/s, which is about a Q_{75} discharge (station 16049000 in table 2). The October 10, 1996, seepage run (fig. 23) was conducted under conditions when discharge measured at site L4 was 17.7 ft^3/s, which is below a Q_{95} discharge (station 16049000 in table 2). Both seepage runs were conducted under diverted-flow conditions; flow in the upper tributaries was diverted by the Kō‘ula Ditch stream-diversion intakes during the 1996 seepage run and flow in the lower reaches was diverted by the Farmers Ditch stream-diversion intake during both seepage runs.

The 2017 seepage run (fig. 22) consists of eight measurement sites located between altitudes of about 10 to 550 ft, with flows in the main stream channel ranging from 20.8 to 48.0 ft^3/s. Measured discharges from the seepage run indicate a generally gaining stream in the upper 3.3-mi reach between the confluence of left and right branch Kō‘ula Rivers (L1 and L2) and continuous station 16049000 (L4), with several tributaries possibly contributing to some of the measured gain within this reach. This upper stream reach is situated within a dike-impounded-groundwater setting where the stream generally gains flow from groundwater discharge. The lower 3.5-mi reach between continuous station 16049000 (L4) and about 1.7 mi upstream from the stream mouth (L11) generally lost flow. Measured losses in the lower reach are within the measurement-error bounds (see Limitations of Approach section). The 1996 seepage run (fig. 23) consists of seven measurement sites located between altitudes of about 20 to 220 ft, with flows in the main stream channel ranging from 1.39 to 19.9 ft^3/s. Measured discharges from the seepage run indicate a net gain in the lower 2.3-mi reach between continuous station 16049000 (L4) and L5 and in the 1-mi reach between sites L8 and L12, and a net loss in the 0.5-mi reach between sites L5 and L8, which may be attributed to an unmeasured diversion within this reach.

Lāwa‘i Stream—September 19, 2019, seepage-run results



Station number and name associated with map identifier (ID)
[RB, Right Branch; ft, feet; US, upstream; trib, tributary; Str, Stream; DS, downstream; mi, mile; Hwy, Highway; Rd, Road; NTBG, National Tropical Botanical Garden; nr, near. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
J1	16052400	RB Lawai Stream 300ft US of fork
J2	215614159303101	Lawai trib US Lawai Ditch
J3	215610159302901	Lawai Ditch intake on Lawai Str
J4	215609159302901	Lawai Str DS Lawai Ditch intake
J5	215544159302901	Lawai Str .2mi US Kaumualii Hwy
J8	215508159301701	Lawai Str .7 mi DS Kaumualii Hwy
J9	215436159303101	Lawai Str .1 mi US spring input trib
J10	215436159303201	Lawai trib .8 mi DS Waha Rd
J11	215434159303401	Lawai Str US spring input
J12	215433159303701	Trib with spring input to Lawai Str
J13	215431159303601	Lawai Str near NTBG
J14	16052500	Lawai Str nr Koloa

EXPLANATION

200 **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+0.06 (0.04) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites

Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s
[a]Streamgaging station 16052400 with flow-duration discharge estimates in table 2

J1 (0.52) Main stream channel

J2 (0.14) Tributary to main stream

J3 (-0.67) Ditch—(-) diversion of flow or (+) return flow

Site from another seepage run

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

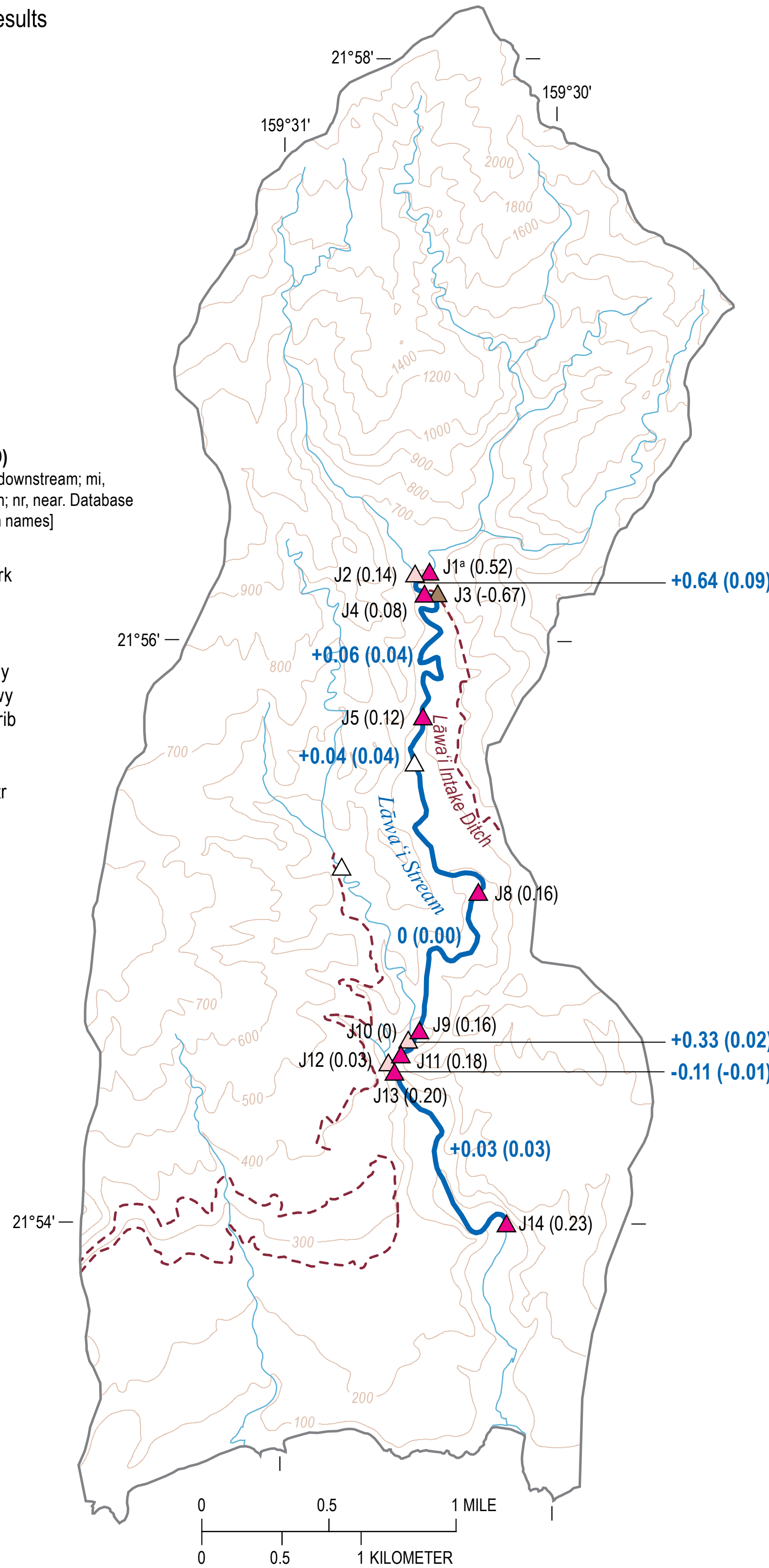
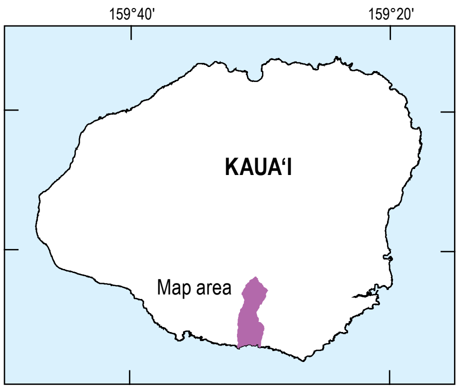


Figure 19. Map of measurement sites and results for the September 2019 seepage run on Lāwa‘i Stream, Kaua‘i, Hawai‘i.

Lāwaʻi Stream—October 7, 1996, seepage-run results



Station number and name associated with map identifier (ID)
[RB, Right Branch; ft, feet; US, upstream; Str, Stream; DS, downstream; Hwy, Highway, trib, tributary; Rd, Road; nr, near. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
J1	16052400	RB Lawai Stream 300ft US of fork
J4	215609159302901	Lawai Str DS Lawai Ditch intake
J6	215535159303101	Lawai Str at Kaumualii Hwy
J7	215514159304901	Lawai trib on Lauoho Rd
J14	16052500	Lawai Str nr Koloa

EXPLANATION

200 **Line of equal altitude relative to mean sea level, in feet**—Contour interval varies

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+0.1 (0.26) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft^3/s) per mile and total seepage gain or loss, in ft^3/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

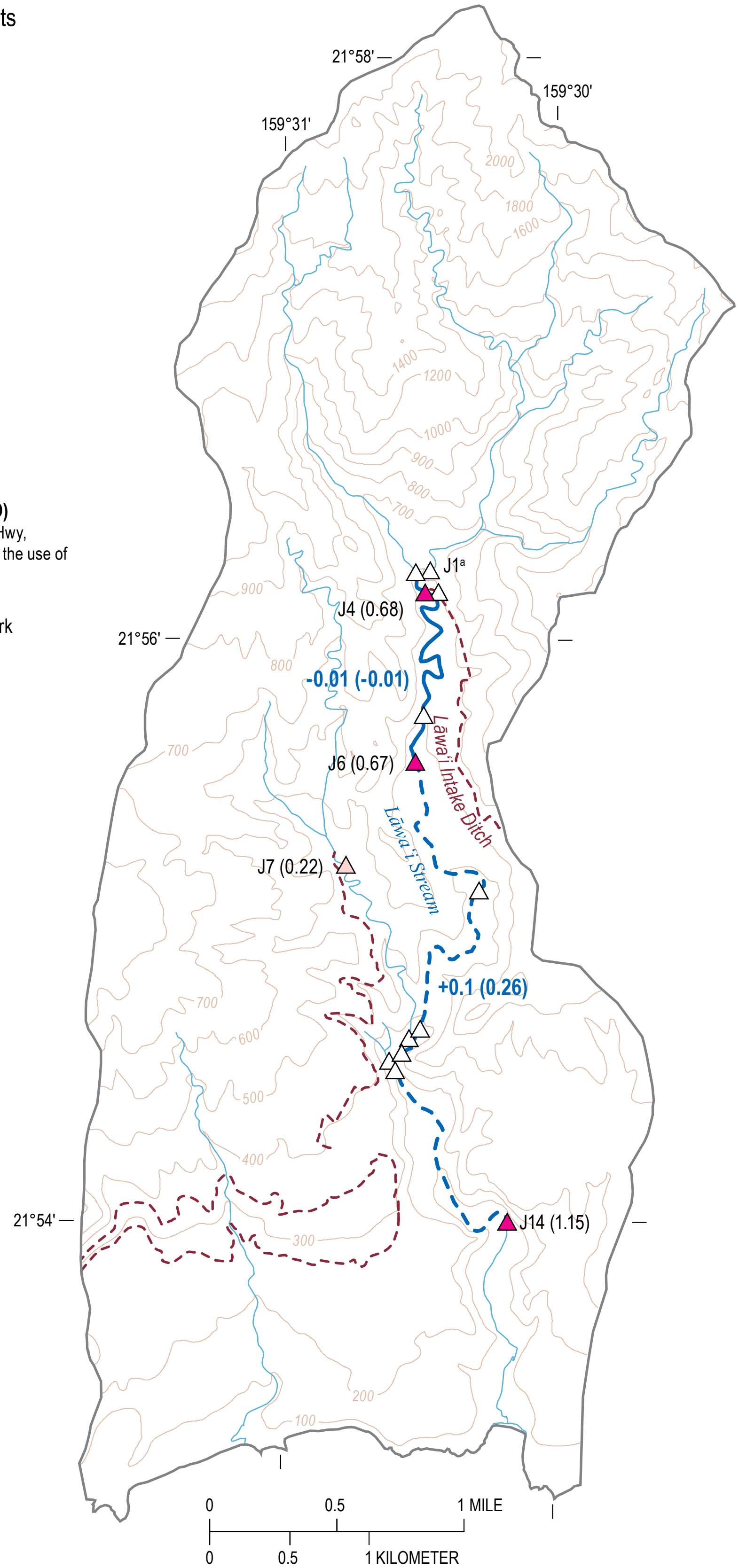
Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft^3/s
[a]Streamgaging station 16052400 with flow-duration discharge estimates in table 2

J4 (0.68) Main stream channel

J7 (0.22) Tributary to main stream

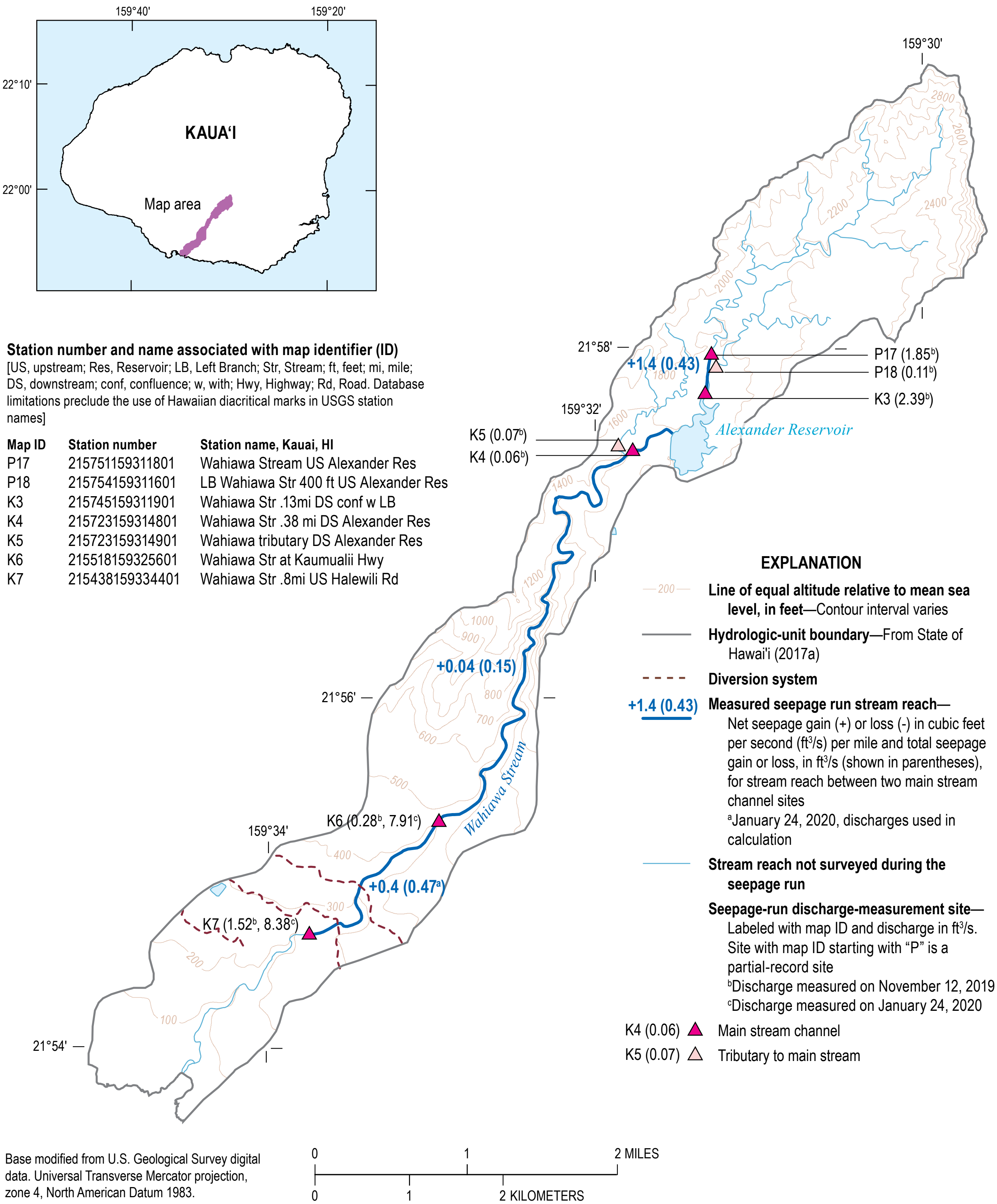
Site from another seepage run



Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 20. Map of measurement sites and results for the October 1996 seepage run on Lāwaʻi Stream, Kauaʻi, Hawaiʻi.

Wahiawa Stream—November 12, 2019, and January 24, 2020, seepage-run results

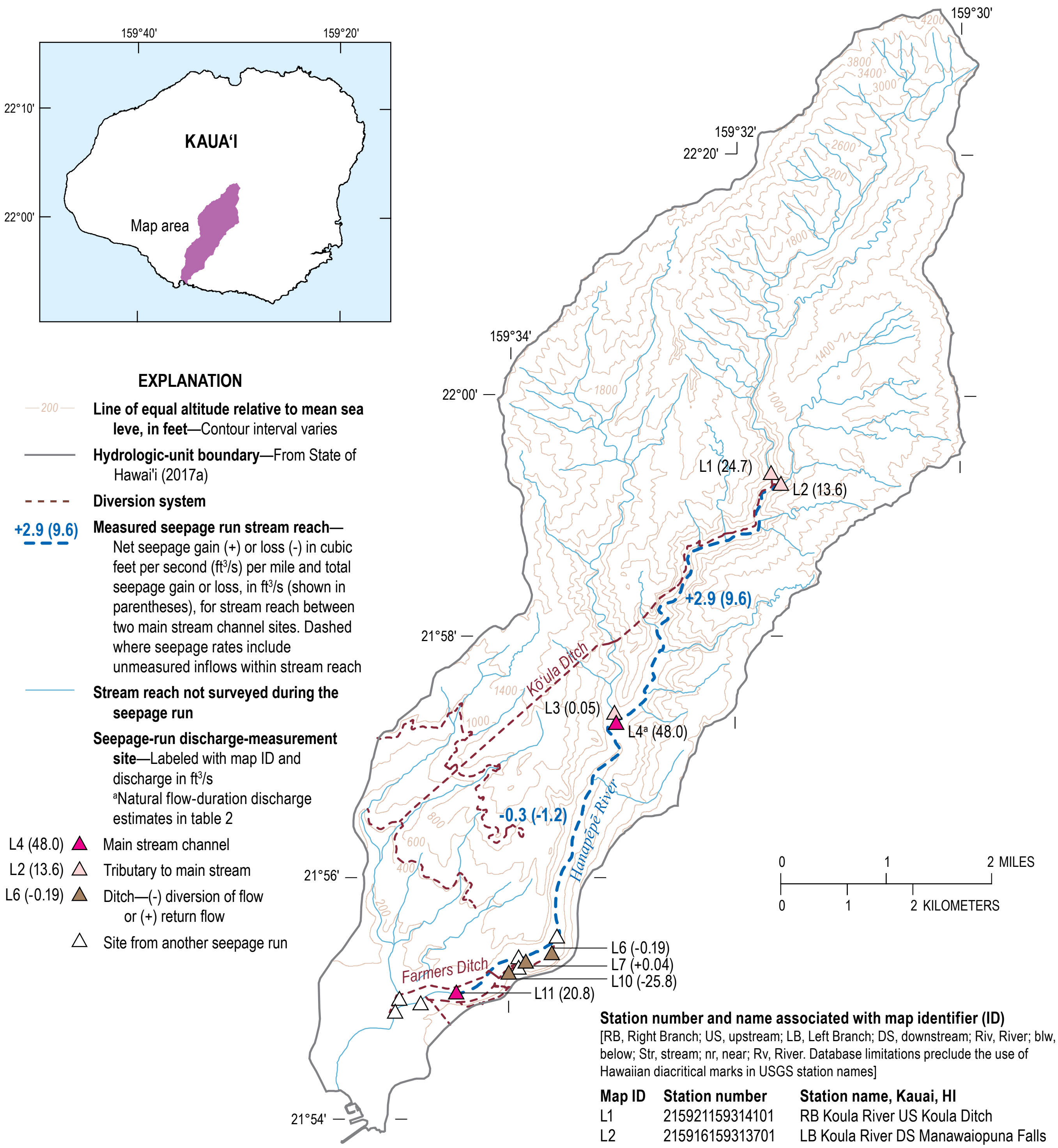


Station number and name associated with map identifier (ID)
[US, upstream; Res, Reservoir; LB, Left Branch; Str, Stream; ft, feet; mi, mile; DS, downstream; conf, confluence; w, with; Hwy, Highway; Rd, Road. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
P17	215751159311801	Wahiawa Stream US Alexander Res
P18	215754159311601	LB Wahiawa Str 400 ft US Alexander Res
K3	215745159311901	Wahiawa Str .13mi DS conf w LB
K4	215723159314801	Wahiawa Str .38 mi DS Alexander Res
K5	215723159314901	Wahiawa tributary DS Alexander Res
K6	215518159325601	Wahiawa Str at Kaumualii Hwy
K7	215438159334401	Wahiawa Str .8mi US Halewili Rd

Figure 21. Map of measurement sites and results for the November 2019 and January 2020 seepage run on Wahiawa Stream, Kaua‘i, Hawai‘i.

Hanapēpē River—September 21, 2017, seepage-run results



Station number and name associated with map identifier (ID)

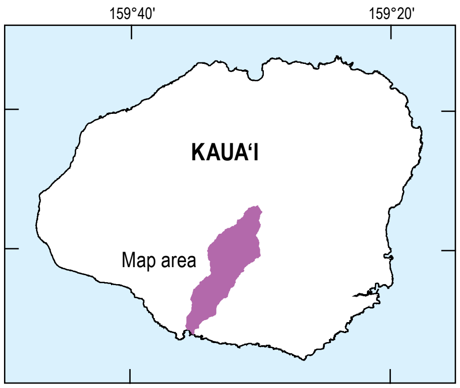
[RB, Right Branch; US, upstream; LB, Left Branch; DS, downstream; Riv, River; blw, below; Str, stream; nr, near; Rv, River. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

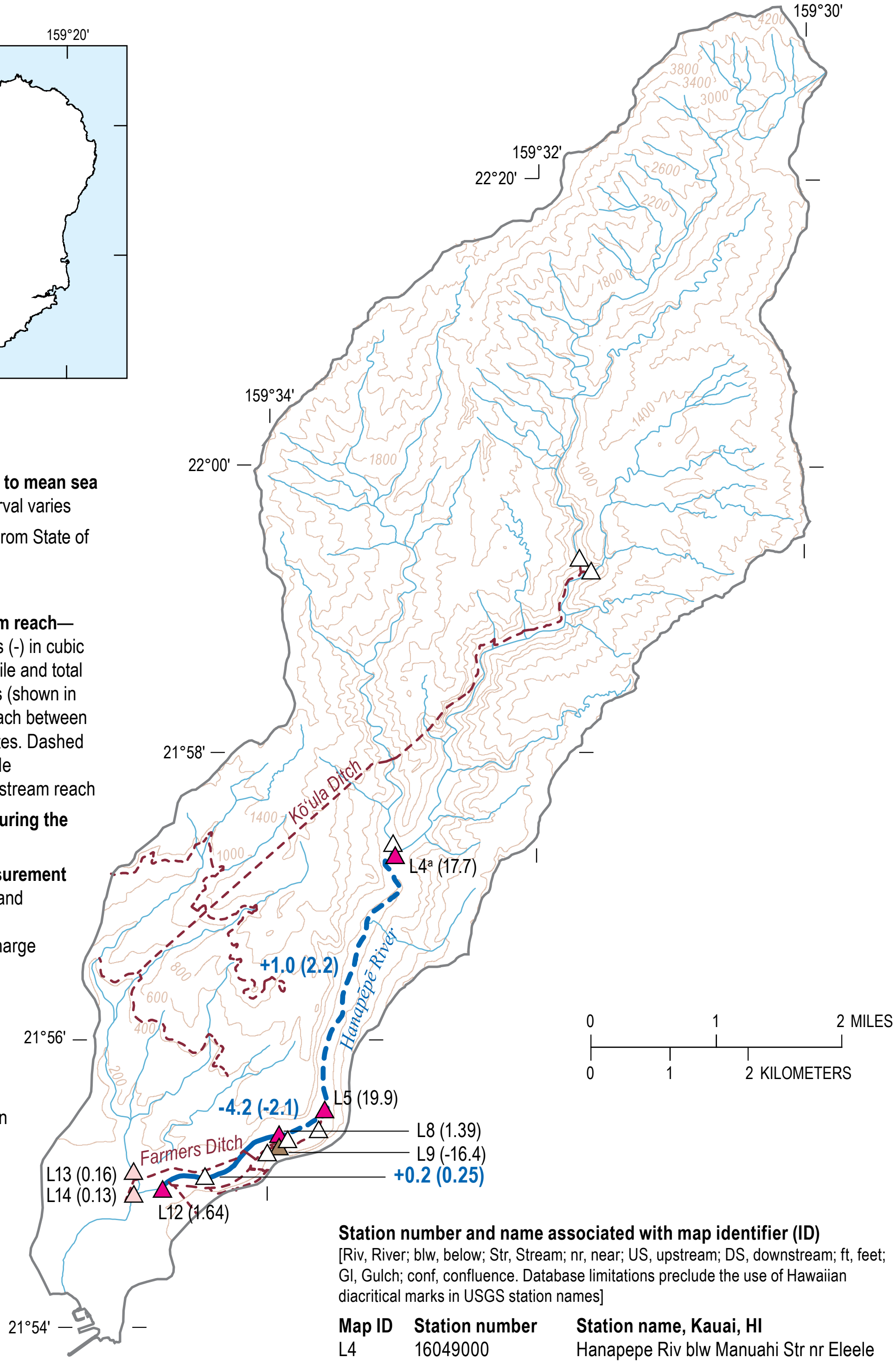
Map ID	Station number	Station name, Kauai, HI
L1	215921159314101	RB Koula River US Koula Ditch
L2	215916159313701	LB Koula River DS Manawaiopuna Falls
L3	16048000	Manuahi Str at Koula nr Eleele
L4	16049000	Hanapepe Riv blw Manuahi Str nr Eleele
L6	215523159333701	Palama intake from Hanapepe River
L7	215519159335101	Palama Ditch return 1 to Hanapepe Rv
L10	215515159335901	Ditch before split to Farmers and Pump 3
L11	215501159342801	Hanapepe River nr Kapa Reservoir

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 22. Map of measurement sites and results for the September 2017 seepage run on Hanapēpē River, Kaua'i, Hawai'i.

Hanapēpē River—October 10, 1996, seepage-run results





EXPLANATION

Line of equal altitude relative to mean sea level, in feet—Contour interval varies

Hydrologic-unit boundary—From State of Hawai'i (2017a)

Diversion system

+1.0 (2.2) **Measured seepage run stream reach**—Net seepage gain (+) or loss (-) in cubic feet per second (ft³/s) per mile and total seepage gain or loss, in ft³/s (shown in parentheses), for stream reach between two main stream channel sites. Dashed where seepage rates include unmeasured inflows within stream reach

Stream reach not surveyed during the seepage run

Seepage-run discharge-measurement site—Labeled with map ID and discharge in ft³/s
[a]Natural flow-duration discharge estimates in table 2

L4 (17.7) Main stream channel
L13 (0.16) Tributary to main stream
L9 (-16.4) Ditch, (-) diversion of flow or (+) return flow
Site from another seepage run

Station number and name associated with map identifier (ID)
[Riv, River; blw, below; Str, Stream; nr, near; US, upstream; DS, downstream; ft, feet; Gl, Gulch; conf, confluence. Database limitations preclude the use of Hawaiian diacritical marks in USGS station names]

Map ID	Station number	Station name, Kauai, HI
L4	16049000	Hanapepe Riv blw Manuahi Str nr Eleele
L5	215532159333201	Hanapepe Riv US Palama intake
L8	215519159335501	Hanapepe Riv DS Farmers Ditch intake
L9	215518159335501	Farmers Ditch from Hanapepe Riv
L12	215459159344601	Hanapepe Riv 250 ft DS Pump 1 Ditch
L13	215502159345801	Kapahili Gl at Farmers Ditch
L14	215456159350001	Kapahili Gl US Hanapepe Riv conf

Base modified from U.S. Geological Survey digital data. Universal Transverse Mercator projection, zone 4, North American Datum 1983.

Figure 23. Map of measurement sites and results for the October 1996 seepage run on Hanapēpē River, Kaua‘i, Hawai‘i.

To determine flow continuity from mauka to makai on Hanapēpē River, the seepage rate of 0.2 (ft^3/s)/mi in the stream reach between sites L8 and L12 for the 1996 seepage run was extrapolated to the 1.3-mi stream reach downstream from the measured reach for the seepage run, with a computed gain of 0.26 ft^3/s within this reach. The 1996 seepage rate between sites L8 and L12 was used to determine flow continuity because it considered all inflows and outflows within the measured reach. The reach downstream of site L12 to the coast is in a uniform hydrogeological setting (Izuka and others, 2018), and the seepage rate between sites L8 and L12 was used to characterize the seepage rate downstream of site L12 to the coast. Seepage-run discharge measurements indicate that under the flow conditions of the seepage run, Hanapēpē River flows continuously from the Kōʻula Ditch level to the ocean under natural-flow conditions. Under diverted-flow conditions, when the Kōʻula Ditch intakes divert all low flows in the river, the river may run dry downstream from the intakes. The length of this potentially dry reach is assumed to be relatively short because available records (water years 1918–20, 1928–2019) at continuous station 16049000 (L4) indicate the river was not dry during the time the gage was in operation and the lowest flow recorded was 5.3 ft^3/s.

Limitations of Approach

Low-flow duration discharges at partial-record sites in the study area were estimated with MOVE.1 and graphical record-augmentation techniques. For this study, the accuracy of the estimates was largely dependent on (1) the strength of the correlation between concurrent discharges at the index stations and partial-record sites; (2) the number of discharge measurements at the partial-record sites that were available for use in record augmentation and the range of flow conditions represented by the measurements; (3) the accuracy of the individual discharge measurements; and (4) the appropriateness of the models used to represent low-flow discharges.

Based on the regression diagnostics, the MOVE.1 regression models provide accurate low-flow duration-discharge estimates. For this study, acceptable values of correlation coefficients (r) and modified Nash-Sutcliff coefficients of efficiency (E) are those greater than or equal to 0.80 and 0.50, respectively. Coefficients of efficiency (E) that indicate the predictive ability of the models range from 0.51 to 0.64 and the correlation coefficients (r) range from 0.88 to 0.94. For right branch ʻŌpaekaʻa Stream, north fork Hanamāʻulu Stream, a branch of Kuʻia Stream, and Hanapēpē River, the graphical fits were plotted through as many of the data points as possible to accurately represent the correlation between concurrent discharges at the index station and partial-record sites. The arithmetic plots generally exhibit minimal spread around the graphical fits without outliers.

The MOVE.1 regression models used to estimate low-flow duration discharges are generally developed based on 10 or more concurrent data points at the index stations and partial-record sites. Models that are developed based on eight or nine concurrent data points—sites P2, P6+P7, and P17 (table 4)—yielded satisfactory low-flow duration-discharge estimates with r values greater than or equal to 0.89 and E values greater than or equal to 0.55. The graphical models were developed based on 10 or more concurrent data points at the index stations and partial-record sites. Most of the discharge measurements used for record augmentation at the partial-record sites generally are between Q_{95} to Q_{40} flow conditions as indicated at the associated index stations. Discharge measurements at Q_{40} flow conditions allow for the statistical relations to be defined for the full range of low-flow statistics to be estimated. Therefore, the flow-duration estimates are considered to be representative of the low-flow conditions at the partial-record sites.

Factors that could contribute to discharge-measurement errors include, but are not limited to, the condition of the measuring instrument and instrument error, characteristics of the measurement cross section, spacing and number of observation verticals in a cross section, changing stage during the measurement, flow depth and velocity, and environment (Rantz and others, 1982, p. 179–180). One of four ratings—excellent, good, fair, or poor—is assigned to the measurement to account for some of the aforementioned factors that could potentially affect the accuracy of the measurement, and thus provide some measure of quality for the discharge measurement. For discharges measured with an ADV, the rating is based on the Interpolated Variance Estimator (IVE) computed by the measuring equipment. The IVE is an estimator of uncertainty based on a statistical analysis of depth and velocity data collected during the discharge measurement (Cohn and others, 2013). Discharge measurements with an IVE value of 2 percent or less are generally rated excellent, between 2 and 5 percent are rated good, between 5 and 8 percent are rated fair, and 8 percent or more are rated poor. Errors that result from changing flow conditions are not considered by the IVE. Out of more than 120 discharge measurements used in record augmentation for this study, more than half of the measurements were rated good, about a quarter were rated fair, about 16 percent were rated excellent, and the remaining were rated poor. Ten of the measurements were made during changing stage conditions of less than ±0.02 ft; six of these measurements were rated good, two rated excellent, one rated fair, and one rated poor.

Low-flow duration discharges at index stations and partial-record sites are applicable to the base period over which they have been computed. For this study, 59 years of streamflow data (water years 1961–2019) were available at the index stations. Whether low-flow duration discharges at the index stations provide estimates of streamflow characteristics at the partial-record sites that are representative of future long-term flow conditions is less certain. Low-flow duration discharges computed from the base-period record are generally lower than those computed from the longer-term record (table 2). At the six active long-term continuous-record stream-gaging stations that monitored natural flow, trends in annual total-flow and base-flow statistics—Q_{90}, Q_{70}, and Q_{50} discharges and mean flow—generally were downward. Trends in mean base flow were statistically significant at the 5-percent level of significance for all stations. Whether the downward trends in total flow and base flow of streams continue in the future is unknown, owing to uncertainties associated with potential climate change and watershed response to the changes. Extrapolation of low-flow duration discharges to future conditions assumes that the hydrologic conditions that occurred during the base period will continue in the future.

Seepage gains and losses along selected study-area stream reaches were computed as the difference between the upstream and downstream discharges, excluding major tributary inflows and diversions of water within the reach when measured. Considering the potential errors in discharge measurements and that some tributary inflows could not be measured owing to inaccessibility, the estimated seepage gains and losses may not accurately reflect the true gains and losses within a reach. Measured tributary inflows and diversions of water introduce additional errors in the seepage estimates, and this is especially apparent in the Waiahi and ‘Ili‘ili‘ula Streams seepage runs. Direct measurement of diverted flow and (or) inflow is preferred when estimating seepage gains and losses along a reach. However, that may not always be possible owing to lack of a representative discharge-measurement section. Where a direct measurement of diverted flow and (or) inflow could not be made because of a lack of usable measurement section, discharges were measured upstream and downstream of the diverted flow and (or) inflow and the difference is the flow of interest. Errors associated with each additional measurement made during a seepage run to quantify inflows and outflows collectively decrease the accuracy of the seepage estimates.

Suggestions for Future Work

Measured discharges at many partial-record sites correlated with discharges at the Lāwa‘i short-term station (16052400) established for this study. Reactivating the continuous station on this stream for the long term would increase the level of confidence of the estimated low-flow duration discharges at relevant partial-record sites. Continued operation of the Waiahi station (16057900) for the long term would increase the accuracy of low-flow duration discharges computed for the station and those at relevant partial-record sites. Accuracy of low-flow duration discharge estimates at the partial-record sites could also benefit from additional measurements, especially for North Fork Wailua River and Hanamā‘ulu and Wahiawa Streams. Discharge measurements are needed at a different measurement section on Nāwiliwili Stream that is not affected by random ditch-flow releases for estimating natural low-flow characteristics. Accessible reaches of Pū‘ali Stream were limited during the study period owing to streambank vegetation and streambed material. If a usable measurement section on Pū‘ali Stream becomes accessible in the future, additional discharge measurements would improve the estimates of natural low-flow characteristics at the measurement site. Additional natural-flow data at the Hanapēpē River continuous-record stream-gaging station that span multiple water years would increase accuracy and confidence in the estimated low-flow duration discharges at the station.

Seepage runs that were made under diverted-flow conditions could be improved by temporarily ceasing diversions and conducting the seepage runs during natural-flow conditions. However, a temporary halt in the operation of surface-water diversions on a stream for the duration of a seepage run is logistically challenging to the diverters and poses hardship on the surface-water users; therefore, this approach is oftentimes impractical. A seepage run conducted under diverted-flow conditions requires discharge measurements made to quantify diverted flow, which increases uncertainty in computed seepage estimates. A seepage run conducted under natural-flow conditions minimizes that uncertainty by eliminating the need to quantify diverted flows, thereby producing more accurate seepage estimates. Changes in diversion practices may occur as the State continues to implement interim instream-flow standards and temporarily stopping diversion of water for the purpose of conducting a seepage run may become more feasible in the future. Additional discharge measurements in the lower reaches during seepage runs conducted under natural-flow conditions could also help to improve the understanding of flow continuity to the coast.

Summary and Conclusions

The State of Hawai‘i Commission on Water Resource Management establishes instream-flow standards to describe flows necessary to protect the public interest in the stream with consideration of current and future water uses. Surface-water resources in an area must be quantified to effectively manage water resources for competing uses. The purpose of this study was to characterize natural (unregulated) streamflow availability under low-flow conditions for selected streams in southeast Kaua‘i, Hawai‘i, which include North Fork Wailua and South Fork Wailua Rivers; Hanamā‘ulu, Nāwiliwili, Pū‘ali, Hulē‘ia, Waikomo, Lāwa‘i, and Wahiawa Streams; and Hanapēpē River. The results of this study can be used by water managers to develop technically sound instream-flow standards for the study-area streams.

Low-flow characteristics under natural streamflow conditions of the study-area streams were determined by analyzing historical and current streamflow data from continuous-record stream-gaging stations and miscellaneous sites, and additional data collected at partial-record sites. Two short-term continuous-record stream-gaging stations that monitored low flows on Waiahi and right branch Lāwa‘i Streams were established to serve as additional index station options for partial-record sites in the study area. A continuous-record stream-gaging station on Hanapēpē River monitored natural flow during calendar year 2017 and the streamflow record during that period was used to estimate low-flow characteristics at the station. Eighteen partial-record sites—3 on main streams and 15 on tributary streams—were established, mainly upstream from all existing surface-water diversions, where discharge measurements were made between February 2016 and January 2020. Along with the two short-term stations established for this study, all six active continuous-record stations that monitored natural flow on Kaua‘i—Kawaikōī Stream, Wai‘alae Stream, east branch of North Fork Wailua River, left branch ‘Ōpaeka‘a Stream, Hālaulani Stream, and Wainiha Stream—were considered as potential index stations for estimating Q_{95} (95-percent) to Q_{50} (median or 50-percent) flow-duration discharges using the MOVE.1 and graphical-correlation record-augmentation techniques.

At the Waiahi short-term continuous-record stream-gaging station, the estimated natural Q_{95} to Q_{50} discharges range from 14 to 25 ft^3/s. At the Lāwa‘i short-term continuous-record stream-gaging station, the estimated natural Q_{95} to Q_{50} discharges range from 0.35 to 3.0 ft^3/s. At station 16049000 on Hanapēpē River, low-flow duration discharges for the base period range from 42 to 69 ft^3/s.

Within the Wailua River basin, the estimated natural Q_{95} to Q_{50} discharges at the established partial-record sites range from 0.48 to 1.1 ft^3/s for right branch ‘Ōpaeka‘a Stream, 17 to 26 ft^3/s for North Fork Wailua River, 2.5 to 7.4 ft^3/s for the confluence of north and south Fork Waikoko Streams, and 7.3 to 11 ft^3/s for ‘Ili‘ili‘ula Stream. Within the Hanamā‘ulu Stream basin, the estimated natural Q_{95} to Q_{50} discharges at the established partial-record sites range from 0.96 to 1.6 ft^3/s for the confluence of north and south fork Hanamā‘ulu Streams and 0.74 to 1.2 ft^3/s for north fork Hanamā‘ulu Stream. Within the Hulē‘ia Stream basin, the estimated natural Q_{95} to Q_{50} discharges at the established partial-record sites range from 1.5 to 5.0 ft^3/s for Pāohia Stream, 4.1 to 11 ft^3/s for Kamo‘oloa Stream, 3.3 to 5.7 ft^3/s for the north tributary Ku‘ia Stream, and 0.018 to 3.2 ft^3/s for the south tributary of Ku‘ia Stream. The estimated natural Q_{95} to Q_{50} discharges at the established partial-record site on Wahiawa Stream range from 1.5 to 3.7 ft^3/s.

Upper-bound estimates of low-flow duration discharges at partial-record sites on south fork Hanamā‘ulu, Hanamā‘ulu tributary, ‘Ōma‘o, and Pō‘ele‘ele Streams were estimated based on the highest discharges measured during the study period that correspond to the concurrent daily mean discharge at each index station that were greater than the median discharge at that index station, which were 0.44, 0.40, 0.19, and 0.22 ft^3/s, respectively. Measured discharges on Nāwiliwili, Pū‘ali, and left branch Wahiawa Stream do not correlate with discharges at any active long-term continuous-record stream-gaging stations that monitored natural flow and therefore flow-duration discharges estimates are not available.

The discharge estimates are representative of the 59-year base period—water years 1961 to 2019—over which they have been computed. Based on the MOVE.1 regression statistics and the range of discharges measured at the partial-record sites (which included the entire low-flow range of interest), the flow-duration discharge estimates at the partial-record sites are considered to be accurate and representative of base-period conditions. Additional discharge measurements will help to increase the level of confidence of the flow-duration discharge estimates at all the partial-record sites. Whether low-flow duration discharges at the index stations provide estimates of streamflow characteristics at the partial-record sites that are representative of future long-term flow conditions is less certain. At the six active long-term continuous-record stream-gaging stations that monitored natural flow, trends in annual total-flow and base-flow statistics—Q_{90}, Q_{70}, and Q_{50} discharges and mean flow—generally were downward. Whether the downward trends in total flow and base flow of streams will continue in the future is unknown as a result of uncertainties associated with potential climate change and watershed response to the changes.

Seepage-run discharge measurements together with low-flow duration discharge estimates at the partial-record sites can provide information on natural streamflow availability in the lower stream reaches and indicate whether the streams support mountain-to-ocean (mauka to makai) flow, which is important for assessing the biological potential of a stream to support native stream fauna. Seepage-run results from previous studies and from this study were analyzed to characterize streamflow gains and losses on selected reaches of streams in the study basins. Gaining and losing reaches were determined by computing the difference between the upstream and downstream discharges, excluding any tributary inflows and diversions of water within the reach when measured. Available seepage-run measurements show that the study-area streams are generally gaining streams in the measured reaches, except for Waikomo Stream and the lower reaches of North Fork Wailua River and Nāwiliwili Stream. Measured seepage-gain rates that considered all inflows and outflows within the measured reaches ranged between 0.03 and 24.3 ft^3/s per mile of stream reach. Seepage gains are presumed to originate mainly from groundwater discharge from a thickly saturated hydrogeologic setting for streams in the Wailua River, Hanamā‘ulu Stream, Nāwiliwili Stream, and Hulē‘ia Stream basins, and from a dike-impounded-groundwater hydrogeologic setting for streams in the Waikomo Stream, Lāwa‘i Stream, Wahiawa Stream, and Hanapēpē River basins. Under the flow conditions of the seepage runs, a majority of the study-area streams flow continuously from mauka to makai. Where a stream discharges into a reservoir—Hanamā‘ulu and Wahiawa Streams—a dry reach may occur immediately downstream from the reservoir to the point of seepage gain in the stream.

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