Prepared in cooperation with the State of Hawai‘i Department of Hawaiian Home Lands

Availability and Distribution of Low Flow in Anahola Stream, Kaua‘i, Hawai‘i

Scientific Investigations Report 2012–5264

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

Cover:
Kalalea Mountains in northeast Kaua‘i, Hawai‘i. Photographed by Chui Ling Cheng.

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
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)
	Flow rate	
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)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Slope	
foot per mile (ft/mi)	0.1895	meter per kilometer (m/km)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C=(°F-32)/1.8

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.

Availability and Distribution of Low Flow in Anahola Stream, Kaua‘i, Hawai‘i

By Chui Ling Cheng and Reuben H. Wolff

Abstract

Anahola Stream is a perennial stream in northeast Kaua‘i, Hawai‘i, that supports agricultural, domestic, and cultural uses within its drainage basin. Beginning in the late 19th century, Anahola streamflow was diverted by Makee Sugar Company at altitudes of 840 feet (upper intake) and 280 feet (lower intake) for irrigating sugarcane in the Keālia area. When sugarcane cultivation in the Keālia area ceased in 1988, part of the Makee Sugar Company's surface-water collection system (Makee diversion system) in the Anahola drainage basin was abandoned. In an effort to better manage available surface-water resources, the State of Hawai‘i Department of Hawaiian Home Lands is considering using the existing ditches in the Anahola Stream drainage basin to provide irrigation water for Native Hawaiian farmers in the area. To provide information needed for successful management of the surface-water resources, the U.S. Geological Survey investigated the availability and distribution of natural low flow in Anahola Stream and also collected low-flow data in Goldfish Stream, a stream that discharges into Kaneha Reservoir, which served as a major collection point for the Makee diversion system.

Biological surveys of Anahola Stream were conducted as part of a study to determine the distribution of native and nonnative aquatic stream fauna. Results of the biological surveys indicated the presence of the following native aquatic species in Anahola Stream: ‘o‘opu ‘akupa (Sandwich Island sleeper) and ‘o‘opu naniha (Tear-drop goby) in the lower stream reaches surveyed; and ‘o‘opu nākea (Pacific river goby), ‘o‘opu nōpili (Stimpson's goby), and ‘ōpae kala‘ole (Mountain shrimp) in the middle and upper stream reaches surveyed. Nonnative aquatic species were found in all of the surveyed stream reaches along Anahola Stream.

The availability and distribution of natural low flow were determined using a combination of discharge measurements made from February 2011 to May 2012 at low-flow partial-record and seepage-run stations established at locations of interest along study-area streams. Upstream of the upper intake, the estimated natural (undiverted) median flow in Anahola Stream is 2.7 million gallons per day, and the flow is expected to be greater than or equal to 0.97 million gallons per day 95 percent of the time. About 0.7 mile upstream of the lower intake and downstream from the confluence with Kea‘o‘opu Stream, the estimated natural (undiverted) median flow in Anahola Stream is 6.3 million gallons per day, and the flow is expected to be greater than or equal to 2.7 million gallons per day 95 percent of the time. In Goldfish Stream, about 0.4 mile upstream from the point of discharge into Kaneha Reservoir, the estimated natural median flow is 0.54 million gallons per day, and the flow is expected to be greater than or equal to 0.23 million gallons per day 95 percent of the time. The discharge estimates are representative of low-flow conditions in the study-area streams, and they are applicable to the base period (water years 1961–2011) over which they have been computed.

The distribution of natural low flow in Anahola Stream was characterized through data collected during wet- and dry-season seepage runs. Seepage-run results show that Anahola Stream was generally a gaining stream under natural low-flow conditions. During the wet-season seepage run, Anahola Stream at the station located upstream of tributary Ka‘alula Stream had more than five times the flow that was measured upstream from the upper intake. The estimated total gain (including tributary inflow) in the 6.1-mile seepage-run reach was 6.97 million gallons per day; about 42 percent of that gain was groundwater discharge to the main channel of Anahola Stream. During the dry-season seepage run, about 34 percent of the estimated total gain of 3.93 million gallons per day in the same seepage-run reach was groundwater discharge to the main channel of Anahola Stream. A 15-percent seepage loss was estimated in a 0.3-mile reach downstream from the confluence of Anahola and Kea‘o‘opu Streams.

The report summarizes scenarios that describe (1) surface-water availability under regulated conditions of Anahola Stream if the upper and lower intakes are restored in the future; and (2) amount of flow available for agricultural use at the upper intake under a variety of potential instream-flow standards that may be established by the State of Hawai‘i for the protection of instream uses.

Introduction

The surface-water resources of the Anahola Stream drainage basin in northeast Kaua‘i, Hawai‘i (fig. 1), are important for agricultural, domestic, and cultural purposes. Anahola was designated by the Land Act of 1895, which allowed Crown lands to be leased or sold, for Native Hawaiian settlement to promote homestead farming as a means for preserving the Native Hawaiian culture (State of Hawai‘i Department of Hawaiian Home Lands, 2010). In the late 19th century, Makee Sugar Company began diverting surface water from Anahola Stream for the irrigation of sugarcane in the Keālia area. The Makee Sugar Company’s surface-water collection system (hereafter referred to as the Makee diversion system) consisted of a network of ditches and reservoirs in the Anahola and Kapa‘a drainage basins, and depended primarily on Anahola and Keālia Streams for irrigation water (fig. 2). By the early 1900s, the Makee diversion system delivered an average of 30 million gallons per day (Mgal/d) of water and included several reservoirs with a combined capacity of 700 million gallons (Mgal). When Makee Sugar Company was acquired by Līhu‘e Plantation Company in 1933, they were cultivating 7,200 acres with an additional 2,200 acres cultivated primarily by homesteaders in the Anahola and Keālia areas (Wilcox, 1996, p. 73). Līhu‘e Plantation ceased sugarcane cultivation in Anahola and Keālia in 1988—thereby abandoning some parts of the Makee diversion system (Souza and others, 1996).

Presently, the State of Hawai‘i Department of Hawaiian Home Lands (DHHL) owns half of the Anahola Stream drainage basin, and the remaining part—mostly unirrigated lands in the upslope areas—is owned by the State of Hawai‘i and managed by the State of Hawai‘i Department of Land and Natural Resources (DLNR). Part of the Makee diversion system that is located in the Anahola Stream drainage basin and that diverted water from Anahola Stream is abandoned. However, area residents have developed their own systems for diverting surface water from the lower reaches of Anahola Stream for agricultural, domestic, and cultural uses. Anahola remains an important homestead area and has more Native Hawaiians than any other area on the Island of Kaua‘i (State of Hawai‘i Department of Hawaiian Home Lands, 2010).

The DHHL is interested in using part of the Makee diversion system in the Anahola Stream drainage basin to provide irrigation water for Native Hawaiian farmers in the area. In managing water resources, the DHHL utilizes a watershed approach that accounts for the stream ecosystem and water demands of the downstream users. To provide information needed for water-management decisions, the U.S. Geological Survey (USGS), in cooperation with the DHHL, investigated the availability and distribution of low flow and the distribution of aquatic fauna in Anahola Stream. Low-flow data were also collected from an unnamed stream that flows into Kaneha Reservoir. For the purposes of this study, this unnamed stream is referred to as Goldfish Stream, a name commonly used by area residents.

Purpose and Scope

The objectives of this study are to (1) quantify the availability of surface water in Anahola Stream and Goldfish Stream under low-flow conditions upstream of surface-water diversions; (2) characterize the distribution of low flow along Anahola Stream downstream of the diversions; and (3) determine the distribution of native and nonnative aquatic fauna in Anahola Stream. A majority of the field work for this study is focused on Anahola Stream. This study does not evaluate the hydraulic condition of the Makee diversion system or the reservoirs that are part of that diversion system.

The first two objectives of this study were achieved by analyzing historical and current flow data at continuous-record streamflow- and ditch-flow gaging stations, and additional data collected as part of this study, including (1) 10 to 12 discharge measurements at four low-flow partial-record (LFPR) stations established upstream from points of surface-water diversions; and (2) two sets of seepage-run discharge measurements at selected sites along Anahola Stream. The third objective was accomplished through reconnaissance-level biological surveys that documented the presence and absence of aquatic species and number of aquatic species found in Anahola Stream.

Acknowledgments

The authors acknowledge the State of Hawai‘i DHHL and members of the Anahola community for their understanding and support throughout this study. Stephen “Haku” Rivera, Jeff Rivera, Frank Rivera, Sr., John Pia, Harold Ano, Canen Ho‘okano, and Frank Cummings were among the community members that shared information on the Makee diversion system and provided a historical perspective of the Anahola area during the plantation era. The authors appreciate access to homestead lands provided by Frank Rivera, Sr., and Harold Ano. Frank Rivera, Jr., and Frank Rivera, Sr., were most generous with their time as they accompanied USGS personnel during the reconnaissance survey and guided them to the safest hiking trails for accessing the streams. The authors are indebted to Kaipo Duncan and Frank Cummings for their help during difficult situations encountered while driving along the rugged roads of Anahola Valley.

This study could not have been completed without the assistance of an experienced group of USGS personnel. Benjamin H. Shimizu expertly selected and made discharge-measurement sections and conducted discharge measurements during the study. He also served as a mentor to the first author for all field activities. Richard B. Castro, Clarence L. Edwards, Melia K. Iwamoto, and Adam G. Johnson helped with streamflow measurements and other field-related activities. Bobbie L. Arruda helped conduct the biological surveys and assisted with data management. Finally, the authors are grateful to Scot K. Izuka for sharing his knowledge on the geology of the study area, and Delwyn S. Oki and Richard A. Fontaine for their support and guidance in project design and report preparation.

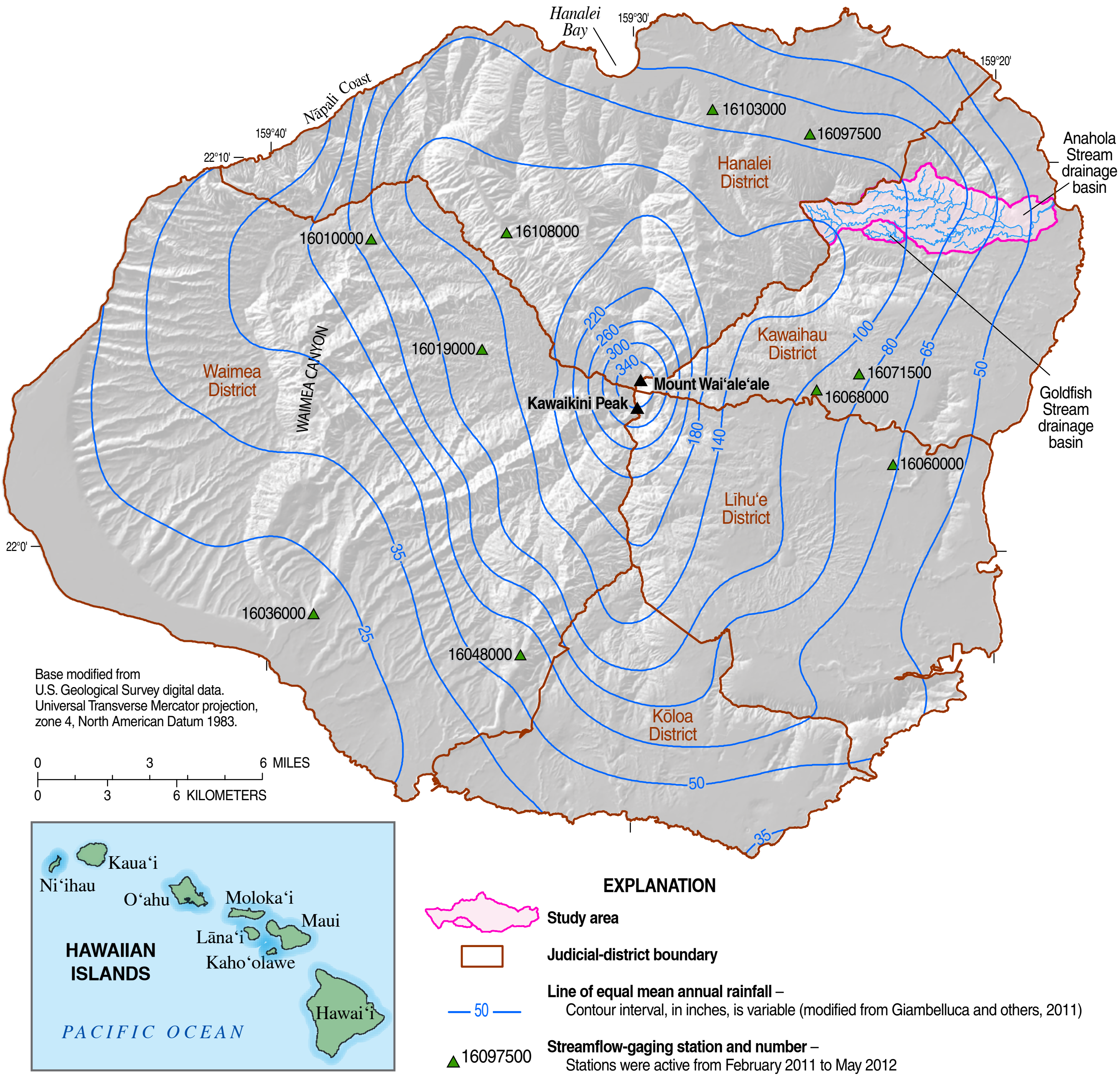


Figure 1. Map showing Anahola and Goldfish Streams study area, Kaua'i, Hawai'i.

Description of the Study Area

Physical Setting

Kaua‘i is the fourth-largest (553 square miles, mi^2) and one of the oldest of the eight major Hawaiian Islands. 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 sea level at Kawaikini Peak, a mile south of Mount Wai‘ale‘ale (fig. 1). The distribution of rainfall on the Island of Kaua‘i is controlled by orographic effects. Orographic rainfall occurs when northeasterly trade winds lift moist air up the windward slopes of the island to higher altitudes where the air is cooled, clouds are formed, and rainfall is generated. Due to the orographic effects, drier air descends down the leeward slopes of the mountains, resulting in decreased rainfall in those areas. Rainfall varies greatly throughout the island, ranging from less than 25 inches per year (in/yr) on the southwestern coast to more than 340 in/yr at Mount Wai‘ale‘ale (Giambelluca and others, 2011). This extreme rainfall variability contributed to the dramatic evolution of the island’s landscapes. The abundant rainfall and resulting streamflow has carved large valleys such as the 14.5-mile (mi) long Waimea Canyon with depths reaching 2,750 ft in some places (Stearns, 1966).

Covering an area of about 10.7 mi^2, the study area encompasses the drainage basins of Anahola Stream and Goldfish Stream, both of which lie on the northeastern or windward side of the Island of Kaua‘i in the district of Kawaihau (fig. 1). The study area is bordered on the east by the coastline of Anahola Bay, on the north by a mountain ridge that extends from the Kalalea Mountains to Namahana Mountains, and on the west-southwest by the Makaleha Mountains. The southern boundary of the study area runs nearly parallel to Kaneha Ditch, which is part of the Makee diversion system (fig. 2). Mean annual rainfall in the study area ranges from about 140 inches at the headwaters to less than 50 inches near the coast (Giambelluca and others, 2011) (fig. 1).

The Anahola Stream drainage basin is the larger of the two basins in the study area and occupies an area of about 10.1 mi^2. Anahola Stream is a perennial stream that flows in an easterly direction for 11.8 mi from its headwaters in the upper slopes of the Namahana Mountains to Anahola Bay (fig. 2). Near the mouth of Anahola Stream is an estuary that extends about three-quarters of a mile inland from the Pacific Ocean. The major tributaries to Anahola Stream include the Kea‘o‘opu Stream, Kaupaku Stream, and Ka‘alula Stream that join the main channel 4.4, 1.8, and 1 mi upstream of the estuary, respectively. From the headwaters at an altitude of 2,450 ft to a waterfall at an altitude 1,050 ft, Anahola Stream flows through a relatively steep valley, descending 1,400 ft over its first 3.3 mi of stream length at an average slope of 420 feet per mile (ft/mi). Downstream of the waterfall to its confluence with Kea‘o‘opu Stream, Anahola Stream flows through a wider valley at an average slope of 190 ft/mi. The remaining 4.4 mi of the stream (excluding the length of the estuary) is wide and flows on a relatively flat terrain with several deep pools along its course to the ocean.

A majority of the Anahola Stream drainage basin supports alien forests and grasslands. Among the more prominent alien plant species are *Psidium guajava* (guava), *Albizia falcataria* (Molucca albizia), and *Caesalpinia decapetala* (cat’s-claw). The guava and Molucca albizia trees are mostly found in the intermediate to upper slopes, whereas the cat’s-claw is more common in the lower slopes of the drainage basin above Kūhiō Highway (fig. 2). Native forests and wetlands are limited to the headwaters and parts of the valley walls surrounding Kea‘o‘opu Stream. The former sugarcane lands located in the center of Anahola Valley, currently owned by the DHHL, are under interim month to month leases and are used primarily for raising cattle. Below Kūhiō Highway and extending outside of the study-area boundary are residential lots; DHHL plans to develop additional residential and agricultural lots in this area (State of Hawai‘i Department of Hawaiian Home Lands, 2010).

The Goldfish Stream drainage basin has an area of 0.6 mi^2 that consists of a network of four tributaries that flow into the main channel (fig. 2). The main channel of Goldfish Stream flows in an easterly direction for 1.8 mi before discharging into Kaneha Reservoir. About 0.3 mi upstream from the reservoir is a small waterfall. From its headwaters at an altitude of 1,350 ft, the stream descends about 350 ft over its first 0.6 mi of stream length at an average slope of 580 ft/mi. Over the remaining 1.2 mi of its course, the stream gradually descends 120 ft to the reservoir. Land cover in this drainage basin is mainly alien forests and shrub lands.

Geologic Setting

Most of Kaua‘i was built by basaltic shield volcanism in the Pliocene. A long period of volcanic inactivity followed the end of shield volcanism; during this time, faulting and erosion created valleys, deep canyons, and other large depressions. Subsequent rejuvenated volcanism, mostly during the late Pliocene and Pleistocene, partially filled the depressions in the original volcano, including the valleys in Anahola (Macdonald and others, 1960; Stearns, 1966; Sherrod and others, 2007).

The volcanic rocks in Anahola are divided into two units of formational rank: the Waimea Canyon Basalt and the Kōloa Volcanics (Langenheim and Clague, 1987; Sherrod and others, 2007). The Waimea Canyon Basalt was formed by shield volcanism that built the bulk of the island and the basement on which younger lavas lie. The predominant unit of the Waimea Canyon Basalt in Anahola is the Nāpali Member, which consists of thin-bedded aa and pāhoehoe flows (Macdonald and others, 1960). The Kōloa Volcanics was formed during the rejuvenated stage of volcanic activity and primarily consists of massive flows and pyroclastic deposits intercalated with sediments (Macdonald and others, 1960; Sherrod and others, 2007).

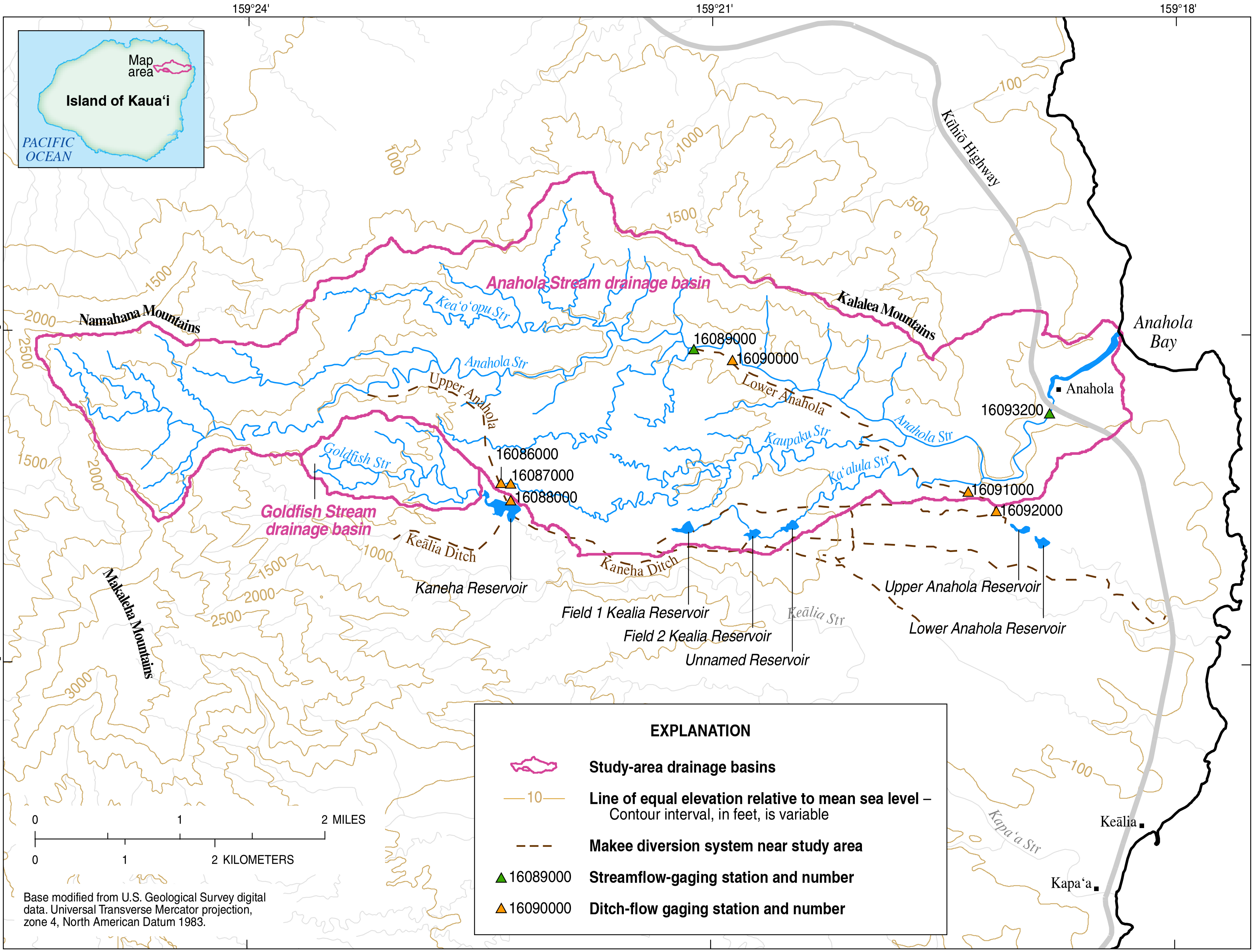


Figure 2. Map showing diversion systems, streamflow and ditch-flow gaging stations in the Anahola and Goldfish Streams study area, Kaua'i, Hawai'i. (Reservoir names from State of Hawai'i, 2012.)

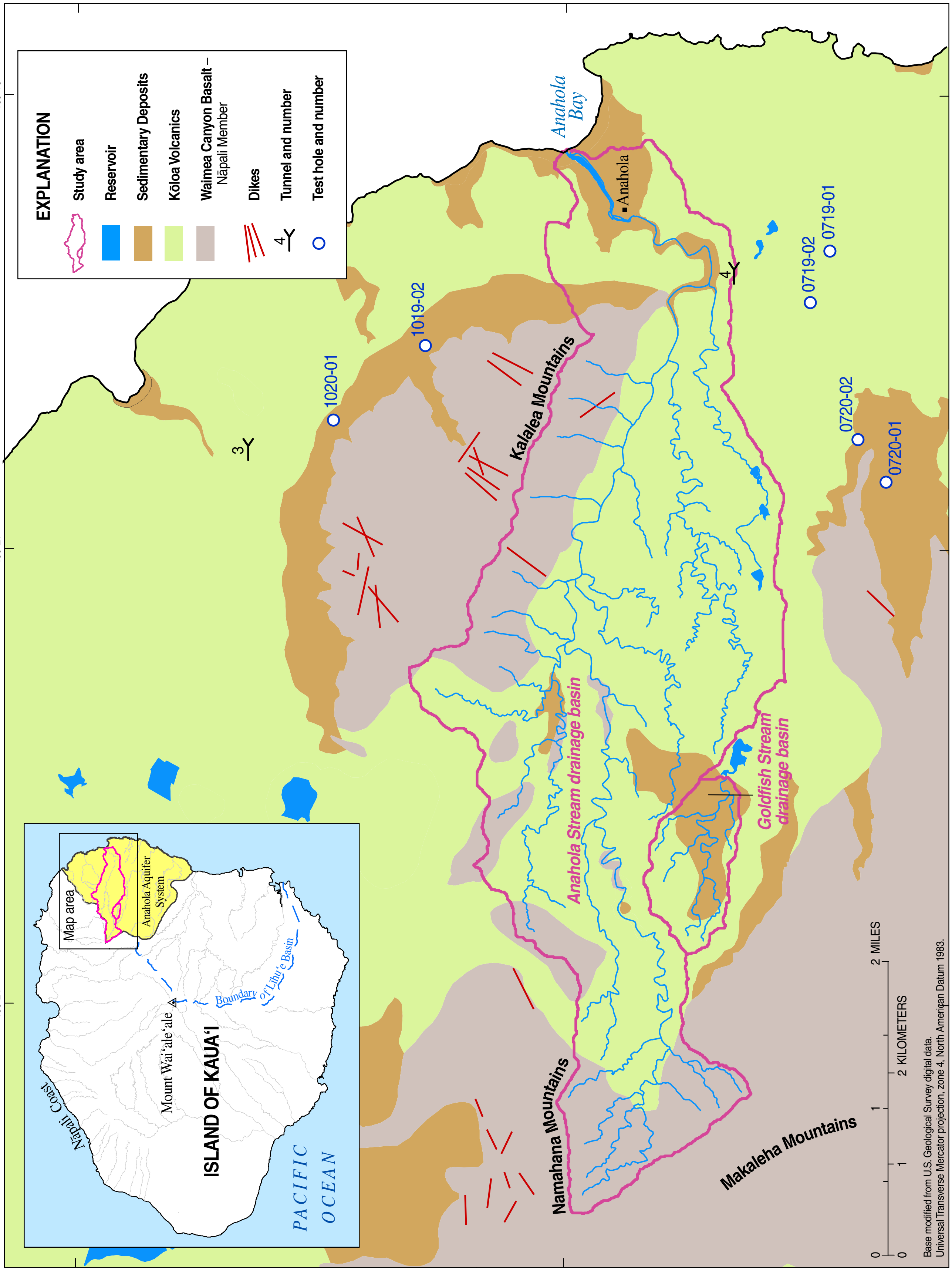


Figure 3. Map showing general geology of the study area, Kaua‘i, Hawai‘i (modified from Macdonald and others, 1960; Sherrod and others, 2007). Anahola aquifer system boundary delineated by State of Hawai‘i Commission on Water Resource Management (2008).

The Anahola Stream drainage basin is formed mainly by Kōloa Volcanics overlying Waimea Canyon Basalt (fig. 3). Along the Kalalea Mountains and Namahana Mountains in the northern drainage-basin boundary and the Makaleha Mountains near the headwaters of Anahola Stream are outcrops of the Waimea Canyon Basalt (Nāpali Member). Sedimentary deposits—principally gravel, sand, and silt—are concentrated in the lower parts of the drainage basin near the estuary, although some of the older alluvium deposits are found between altitudes of 500 to 1,200 ft. The Goldfish Stream drainage basin is formed by Kōloa Volcanics overlying Waimea Canyon Basalt. Older alluvium sedimentary deposits line a majority of the stream length (Macdonald and others, 1960; Sherrod and others, 2007).

Hydrologic Setting

Groundwater

In Hawai‘i, fresh groundwater commonly occurs in a freshwater-lens system in which a lens-shaped body of freshwater floats on underlying, denser saltwater originating from the Pacific Ocean. A zone of brackish water forms where the freshwater and saltwater mix. Groundwater in a freshwater-lens system can discharge to the ocean and to streams and springs where the water table intersects the land surface. In places where the water table is below the stream channel, water that infiltrates moves downward to recharge the aquifer. Freshwater can also occur in a dike-impounded or perched system. A dike-impounded system is created when tabular sheets of low-permeability volcanic rocks (or dikes) intrude other rocks, usually in rift zones and calderas of a volcano. These dikes impede the horizontal movement of groundwater; and where they compartmentalize the more permeable rocks, the water level within the permeable layers can be elevated substantially. Perched-groundwater systems are created where low-permeability strata, such as weathered soil, ash, sedimentary deposits, or dense lava flows, impede the downward movement of water.

Information on the hydrogeology of the Island of Kaua‘i is very limited compared with the existing research available for the more developed areas on O‘ahu. Izuka and Gingerich (2003) studied the complex hydrogeologic characteristics of the southern Līhu‘e Basin (fig. 3), which is characterized by a large region of massive and dense low-permeability (low hydraulic conductivity) Kōloa Volcanics interbedded with sediment, overlying high-permeability Waimea Canyon Basalt. The effect of the low-permeability lava flows paired with the wet climate of the area creates a thick freshwater lens with steep hydraulic gradients, causing water levels to rise to the land surface where groundwater is discharged to springs and streams. As a result, perennial streams within the southern Līhu‘e Basin are supported by substantial amounts of base flow or groundwater discharge.

Anahola Stream and Goldfish Stream lie in the Anahola aquifer system, which has similar rainfall and geologic characteristics as the southern Līhu‘e Basin. Records at test holes 0720-01 and 0720-02 near the easternmost end of the Makaleha Mountains, and test hole 1020-01 at the base of the Kalalea Mountains (fig. 3) show steep vertical and horizontal groundwater hydraulic gradients (Macdonald and others, 1960) that are consistent with a low-permeability (low hydraulic conductivity) aquifer like that found in the southern Līhu‘e Basin. Several dikes intrude the Waimea Canyon Basalt (Nāpali Member) along the southern slopes of the Kalalea Mountains (Sherrod and others, 2007). These dikes most likely do not impound groundwater to levels that reach the land surface because the small tributaries flowing from the ridge to Anahola Stream are intermittent. Although no other dikes have been identified within the study area, the many perennial streams flowing from the Makaleha Mountains suggest that dike-impounded groundwater most likely occurs in the Waimea Canyon Basalt at the headwaters of Anahola Stream.

Historical Streamflow Diversions

Since 1877 when sugarcane was cultivated in the Anahola and Keālia areas, Anahola streamflow was diverted at altitudes of 840 ft (upper intake) and 280 ft (lower intake) (fig. 2). Surface water captured at the upper intake traveled southeast in Upper Anahola Ditch and was discharged into Kaneha Reservoir. A wasteway was located just upstream from the reservoir where some of the flow diverted at the upper intake could be returned to Anahola Stream, about 5.4 mi downstream of the upper intake, by way of tributary Kaupaku Stream. The lower intake, located about 3.6 mi downstream of the upper intake, diverted Anahola streamflow into the Lower Anahola Ditch, which transported the diverted water to the Upper and Lower Anahola Reservoirs (fig. 2). All of the flow in Goldfish Stream discharged into Kaneha Reservoir. With a maximum capacity of 116 Mgal (Souza and others, 1996), Kaneha Reservoir was a collection point for the majority of the surface water diverted by the Makee diversion system. Kaneha Ditch transported the diverted water from the reservoir to several smaller reservoirs along the ditch and ultimately to the sugarcane fields.

The USGS operated six ditch-flow gaging stations in the Upper and Lower Anahola Ditches for parts of the period 1909–2002 (fig. 2). Three stations measured flows within the Upper Anahola Ditch: station 16086000 was located upstream of the wasteway, station 16087000 was located in the wasteway about 300 ft downstream of the wasteway gates, and station 16088000 was located at the point of discharge into Kaneha Reservoir. During the period 1916–21, records at station 16086000 showed that an average daily flow of 4.9 Mgal/d was diverted into the Upper Anahola Ditch before some of the diverted flow was returned to Anahola Stream through the wasteway. When station 16086000 was discontinued, the combined discharges measured at stations

Table 1. Locations and lengths of stream reaches where biological surveys were conducted by the U.S. Geological Survey in Anahola Stream, August 8–12 and September 19–23, 2011, Kauaʻi, Hawaiʻi.

Study reach identifier	Study reach description (Anahola Stream)	Length, in miles	Upstream point			Downstream point		
			Altitude[b], in feet	Latitude[c]	Longitude[c]	Altitude[b], in feet	Latitude[c]	Longitude[c]
Upper 1	Upstream of upper intake	0.55	1,020	22°08'26.5"	159°23'31.2"	830	22°08'37.7"	159°23'14.0"
Upper 2	1.5 miles downstream of upper intake	0.16	540	22°08'44.7"	159°22'25.9"	510	22°08'46.4"	159°22'19.6"
Middle 1	Near Keaʻoʻopu Stream	0.63	430	22°08'44.2"	159°21'53.7"	340	22°08'59.6"	159°21'36.9"
Middle 2[a]	Near lower intake	0.58	310	22°08'58.1"	159°21'15.8"	260	22°08'55.9"	159°20'50.9"
Lower 1	Upstream of Kaʻalula Stream	1.11	180	22°08'32.0"	159°20'07.3"	80	22°08'14.8"	159°19'15.6"
Lower 2	Upstream of estuary	0.22	10	22°08'25.9"	159°18'59.2"	10	22°08'29.6"	159°18'49.8"

[a] Middle 1 study reach includes a 200-foot reach within tributary Keaʻoʻopu Stream immediately upstream of its confluence with Anahola Stream.

[b] Altitude values interpolated from USGS 1:24,000-scale digital hypsography data.

[c] Latitude and longitude coordinates in North American Datum of 1983.

16087000 and 16088000 represented the total amount of surface water diverted at the Upper Anahola Ditch intake, assuming minimal surface-water losses in the wasteway upstream from station 16087000 and in the ditch between the wasteway and station 16088000. During the period 1936–85, the average daily flow at the two stations combined was about 5.4 Mgal/d, and an average daily flow of 2.7 Mgal/d was discharged into Kaneha Reservoir.

The three gaging stations in the Lower Anahola Ditch include station 16090000 about a quarter of a mile downstream from the lower intake, station 16091000 near the end of the ditch, and station 16092000 upstream of Upper Anahola Reservoir. Records at station 16090000 showed that an average daily flow of 5.9 Mgal/d was diverted into Lower Anahola Ditch between 1909 and 1914. During the period 1937–82, an average daily flow of 1.9 Mgal/d was recorded at station 16091000. The difference in average daily flows at stations 16090000 and 16091000 may be attributed to differences in the periods of record and operation and condition of the ditch. Fragmentary record was collected at station 16092000 when it was in operation during 1909–11.

Biological Setting

Isolation of the Hawaiian Islands resulted in the evolution of a unique community of native stream fauna that utilize a variety of macro- and microhabitats within stream ecosystems. Recent human activities have resulted in the introduction of a number of nonnative species into Hawaiʻi, and these nonnative species may compete with native species for available resources, or they may prey on the native species directly. Different natural and human-influenced conditions affect the ability of the amphidromous native stream fauna to recruit, colonize, and flourish in a stream. The amphidromous life history of native species requires stream connectivity to the ocean to enable recruitment. Any condition that impedes connectivity can affect the distribution and abundance of amphidromous fauna.

Reconnaissance-level biological surveys of Anahola Stream were conducted as part of this study to document the distribution of native and nonnative aquatic stream fauna. Six stream reaches along Anahola Stream were surveyed during August 8–12 and September 19–23, 2011 (table 1, fig. 4). The study reaches were selected to represent a variety of habitats available along Anahola Stream, and the reach lengths were determined by time limitations imposed by the difficulty of accessing and traversing the survey sites. In general, the stream water was consistently mildly turbid with a yellowish-orange hue, even during dry-weather conditions. Thick mats of algal growth were present on the rocky substrates in all habitats except those with the fastest flowing water such as cascades. The stream bed in most pools was covered by a layer of leaf litter and other organic debris. Rainfall just prior to the September 19–23, 2011, surveys made Anahola Stream very turbid on the 19th and 20th, limiting the ability to observe the instream fauna in the six surveyed stream reaches.

As part of the biological surveys, the presence or absence and the distribution of aquatic species were determined using snorkel surveys at the six selected reaches on Anahola Stream. During the surveys a snorkeler entered the stream below the downstream end of the reach and slowly moved upstream, photographing and identifying the observed fish, snail, and crustacean species. For some of the native fish species, when possible, the size-class, age (adult or juvenile), and sex were determined. Locations of the observations were recorded with a Global Positioning System (GPS) unit. The snorkel surveys were supplemented by the occasional use of a seine net and hook and line sampling. The presence of some benthic macroinvertebrates was determined by overturning and inspecting rocks while snorkeling. Adult native damselflies, pinao ʻula, of the endemic genus *Megalagrion* were also photographed and identified. Identifications were determined using “Hawaiian Damselflies: a Field Identification Guide” by Polhemus and Asquith (1996). Identifications were verified by Dr. Dan A. Polhemus, Coastal Conservation Program Manager at the Pacific Islands Fish and Wildlife Office, U.S. Fish and Wildlife Service. Additional observations of aquatic biota were made during the biological surveys at various locations along Anahola Stream to provide supplemental information on the distribution of the aquatic fauna. All captured fauna were released unharmed back into the environment from which they were collected. Results of the August and September 2011 biological surveys are described in the following text, summarized in table 2, and illustrated in figures 4 and 5.

Native Species

Eleven native species were observed in the selected reaches of Anahola Stream during the biological surveys (fig. 4; table 2). The endemic Sandwich Island sleeper, *Eleotris sandwicensis* (‘o‘opu ‘akupa), was commonly observed lying in wait amid rocky crevices and leaf litter in pools throughout the Lower 2 study reach, and a single ‘o‘opu ‘akupa was observed in the Lower 1 study reach at an altitude of about 140 ft. Adults and juveniles, males and females of the Pacific river goby, *Awaous guamensis* (‘o‘opu nākea), were numerous within pools, runs, and riffles within each of the six study reaches along Anahola Stream. The endemic Stimpson‘s goby, *Sicyopterus stimpsoni* (‘o‘opu nōpili) were not observed within the Lower 2 study reach and were infrequently observed within the Upper 1 study reach up to an altitude of about 1,000 ft. However, adult and juvenile, male and female ‘o‘opu nōpili were commonly observed in riffles and cascades within the other study reaches. Adults and juveniles of the endemic teardrop goby, *Stenogobius hawaiiensis* (‘o‘opu naniha) were observed in pools and runs within the Lower 2 study reach and were not observed in any of the other study reaches. Schools of the Hawaiian flagtail, *Kuhlia xenura* (āholehole), were commonly observed in pools within the Lower 2 study reach. Smaller schools of āholehole were also commonly observed in pools throughout the Lower 1 study reach and individuals were occasionally observed in pools within the downstream segment of the Middle 2 study reach up to an altitude of about 270 ft. Schools of the striped mullet, *Mugil cephalus* (‘ama‘ama), were commonly observed in pools throughout the Lower 2 study reach but were not observed in any of the other study reaches.

Adult and juvenile mountain shrimp, *Atyoida bisulcata* (‘ōpae kala‘ole), were only observed within the Upper 1 study reach and were common in riffles, runs, and pools above an altitude of about 910 ft. A single ‘ōpae kala‘ole recruit about 0.75 inch long was observed within the Middle 2 study reach, captured from a cascade using a seine net. The endemic river prawn, *Macrobrachium grandimanus* (‘ōpae ‘oeha‘a) was observed in pools within the Lower 2 study reach, and a single ‘ōpae ‘oeha‘a was observed within the Lower 1 study reach near an altitude of 140 ft. The endemic damselflies, *Megalagrion oresitrophum* (Slender Kaua‘i damselfly) and *Megalagrion vagabundum* (Scarlet Kaua‘i damselfly) were commonly observed only within the Upper 1 study reach. Adult males and females of both species were observed flying about the streambank vegetation and basking atop exposed boulders, and were occasionally observed mating. An unidentified *Megalagrion* individual was briefly observed within the riparian vegetation along the Upper 2 study reach.

Four of the commonly observed native stream species, *Neritina granosa* (hīhīwai), *Neritina vespertinus* (hapawai), *Lentipes concolor* (‘o‘opu ‘alamo‘o), and the native chironomid *Telmatogeton,* were conspicuously not observed during the biological surveys in the six study reaches along Anahola Stream. The hīhīwai and hapawai require clean substrate on which to attach (Ford, 1979). The rocky substrate of Anahola Stream tended to be covered by thick algal mats or sediment that may impede the recruitment of these species. The ‘o‘opu ‘alamo‘o also has specific habitat requirements—including clean substrate, high water velocity, and low turbidity that may not have been sufficiently present to allow for substantial recruitment in Anahola Stream (Timbol and others, 1980). Furthermore, they found that streams with the native ‘o‘opu akupa, a top predator in the estuary and lower stream reaches, had few, if any, ‘o‘opu ‘alamo‘o. The ‘o‘opu ‘akupa was observed to be very abundant in the Lower 2 study reach in Anahola Stream during the 2011 biological surveys. The presence of the native aquatic insect *Telmatogeton* was recorded in 1965 (Parham and others, 2008) within the Upper 1 study reach but was not observed during the 2011 biological surveys of the same area.

Nonnative Species

Eleven nonnative species and one cryptogenic (undetermined origin) species were observed in Anahola Stream (fig. 5; table 2). Schools of short-finned mollies, *Poecilia sphenops*, were commonly observed in pools within the Lower 2 study reach but were not observed within any of the other study reaches. The most commonly observed nonnative fish were green swordtails, *Xiphophorus helleri*, which were very abundant in pools and runs throughout the study reaches, except for the Upper 1 study reach where they were only observed up to a cascade or small waterfall near an altitude of 870 ft. These schools consisted of males and females, adults and juveniles, and both green and orange color patterns. Unconfirmed observations of two other nonnative fish species, Chinese catfish, *Clarias fuscus,* and Western mosquitofish, *Gambusia affinis*, were made. These fish were not captured or photographed, and the identifications were made from very brief observations. *Clarias fuscus* was previously captured and identified in Anahola Stream during a survey in 2001 using electrofishing techniques (Brasher and others, 2006), but this cryptic (concealed) fish is difficult to observe using snorkeling techniques. *Gambusia affinis* has not been reported from Anahola Stream, and many of the fish of the family Poeciliidae are similar in appearance at different stages in their development. It is possible that

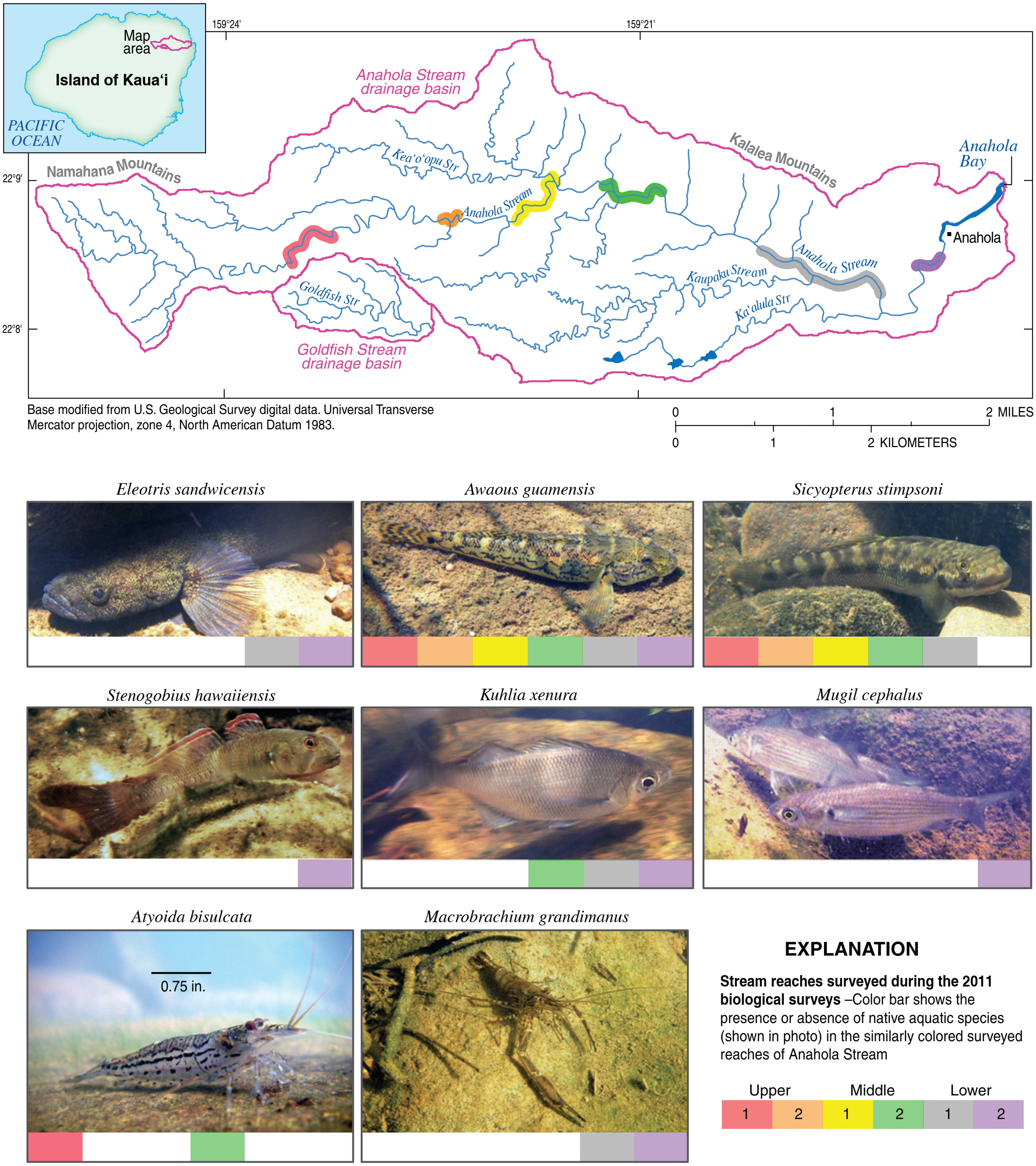


Figure 4. Map showing locations of stream reaches surveyed and the distribution of selected native aquatic species observed during the 2011 U.S. Geological Survey biological surveys in Anahola Stream, Kaua‘i, Hawai‘i. (Aquatic species shown in the photographs without a scale bar generally range from a few inches to one foot.)

Table 2. Species observed during U.S. Geological Survey biological surveys of Anahola Stream, August 8–12 and September 19–23, 2011, Kaua‘i, Hawai‘i.

[Cg, cryptogenic; A, nonnative; N, native; U, uncommon; P, present; C, common; *, unconfirmed observation; --, not observed during surveys]

Phylum / Class / Order / Family / Taxon	Common name	Hawaiian name	Status	Study reach identifier: Upper 1	Upper 2	Middle 1	Middle 2	Lower 1	Lower 2
Chordata									
Osteichthyes									
Cyprinodontiformes									
Poeciliidae									
Gambusia affinis	Western mosquitofish		A	--	--	--	*	*	--
Poecilia sphenops	Short-finned molly		A	--	--	--	--	--	C
Xiphophorus helleri	Green swordtail		A	C	C	C	C	C	C
Perciformes									
Eleotridae									
Eleotris sandwicensis	Sandwich Island sleeper	‘O‘opu ‘akupa	N	--	--	--	--	U	C
Gobiidae									
Awaous guamensis	Pacific river goby	‘O‘opu nākea	N	C	C	C	C	C	C
Sicyopterus stimpsoni	Stimpson's goby	‘O‘opu nōpili	N	P	C	C	C	C	--
Stenogobius hawaiiensis	Teardrop goby	‘O‘opu naniha	N	--	--	--	--	--	C
Kuhliidae									
Kuhlia xenura	Hawaiian flagtail	Āholehole	N	--	--	--	P	C	C
Mugilidae									
Mugil cephalus	Striped mullet	‘Ama‘ama	N	--	--	--	--	--	C
Siluriformes									
Clariidae									
Clarias fuscus	Chinese catfish		A	--	--	--	--	*	--
Amphibia									
Anura									
Bufonidae									
Rhinella marina (Bufo marinus)	Cane toad		A	C	C	C	C	C	C
Ranidae									
Rana catesbeiana	Bullfrog		A	P	P	--	--	P	P
Arthropoda									
Crustacea									
Decapoda									
Atyidae									
Atyoida bisulcata	Mountain shrimp	‘Ōpae kala‘ole	N	C	--	--	U	--	--
Cambaridae									
Procambarus clarkii	Red swamp crayfish		A	--	--	--	U	--	--
Palaemonidae									
Macrobrachium grandimanus	Hawaiian river prawn	‘Ōpae ‘oeha‘a	N	--	--	--	--	P	P
Macrobrachium lar	Tahitian prawn		A	--	C	C	C	C	C
Insecta									
Odonata									
Coenagrionidae									
Megalagrion sp.	Native Hawaiian damselfly	Pinao ‘ula	N	--	P	--	--	--	--
Megalagrion oresitrophum	Slender Kauai damselfly	Pinao ‘ula	N	C	--	--	--	--	--
Megalagrion vagabundum	Scarlet Kauai damselfly	Pinao ‘ula	N	C	--	--	--	--	--
Ischnura posita	Fragile forktail		A	--	P	--	P	P	--
Libellulidae									
Crocothemis servilia	Scarlet skimmer		A	--	P	--	--	--	--
Trichoptera									
Hydropsychidae									
Cheumatopsyche analis	Little sister sedges		A	C	C	C	C	C	C
Mollusca									
Gastropoda									
Basommatophora									
Thiaridae									
Melanoides tuberculata	Red–rimmed melania		Cg	--	--	--	C	C	--
Pelecypoda									
Venerioda									
Corbiculidae									
Corbicula fluminea	Asian clam		A	--	--	--	--	C	P
Platyhelminthes									
Turbellaria									
Tricladida									
Planariidae	Flatworm		A	C	C	C	C	C	C

these observations were of juvenile green swordtails or shortfin mollies. Tadpoles of the Bullfrog, *Rana catesbeiana*, were observed in pools within the upper and lower study reaches. Adult *Rana catesbeiana* were not as common as the tadpoles, but they were observed in some pools—and sounds thought to be adult bullfrogs leaping into the stream were often heard. Tadpoles, toadlets (young toads), and adult cane toads, *Rhinella marina (Bufo marinus)*, were much more abundant than the bullfrogs. Large numbers of *Rhinella marina* tadpoles were commonly observed in pools and habitats with slow flowing water, whereas the toadlets were commonly observed along the streambanks and were very abundant within some study reaches. Adult cane toads were less abundant than the tadpoles and toadlets as they instinctively move away from the stream as adults. They were often observed within all the study reaches and along many of the hiking trails.

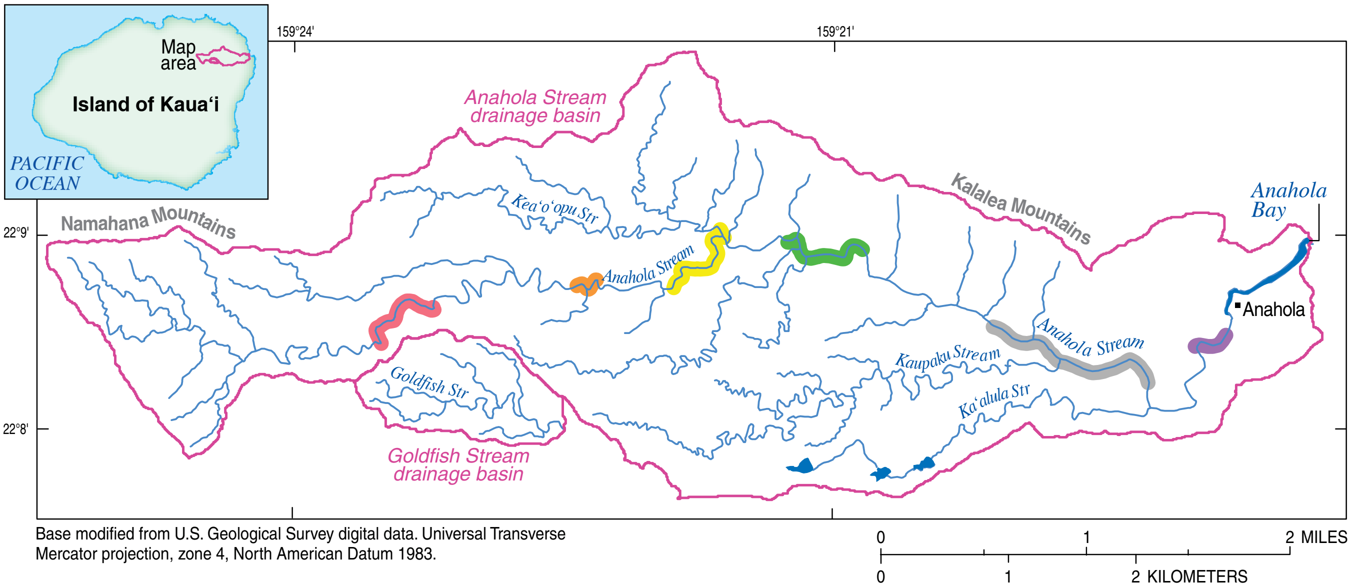
A single specimen of the red swamp crayfish, *Procambarus clarkii*, was briefly observed among the cobbles and boulders along the streambank within the Middle 2 study reach. This observation appears to be the first record of this potentially harmful species in Anahola Stream and indicates that it is not yet established at this time (Yamamoto and Tagawa, 2000). Adults and juveniles of the Tahitian prawn, *Macrobrachium lar*, were also very abundant in pools and habitats with slow flowing water throughout the study reaches except for the Upper 1 study reach. The nonnative damselfly known as the fragile forktail, *Ischnura posita*, was observed in the riparian vegetation within the Lower 1, Middle 2, and Upper 2 study reaches. A nonnative dragonfly known as the Scarlet skimmer, *Crocothemis servilia*, was observed within the Upper 2 study reach. Two small benthic macroinvertebrates were observed on the undersides of cobbles within every study reach. These nonnative invertebrates were insect larvae of the caddisfly known as little sister sedges, *Cheumatopsyche analis*, and a flatworm of the family Planariidae that is probably of the genus *Dugesia*. *Cheumatopsyche analis* larvae were more commonly observed on the undersides of cobbles from riffles and runs with fast flowing water, whereas the flatworms were more commonly observed in pools and on the undersides of cobbles from runs with slow flowing water.

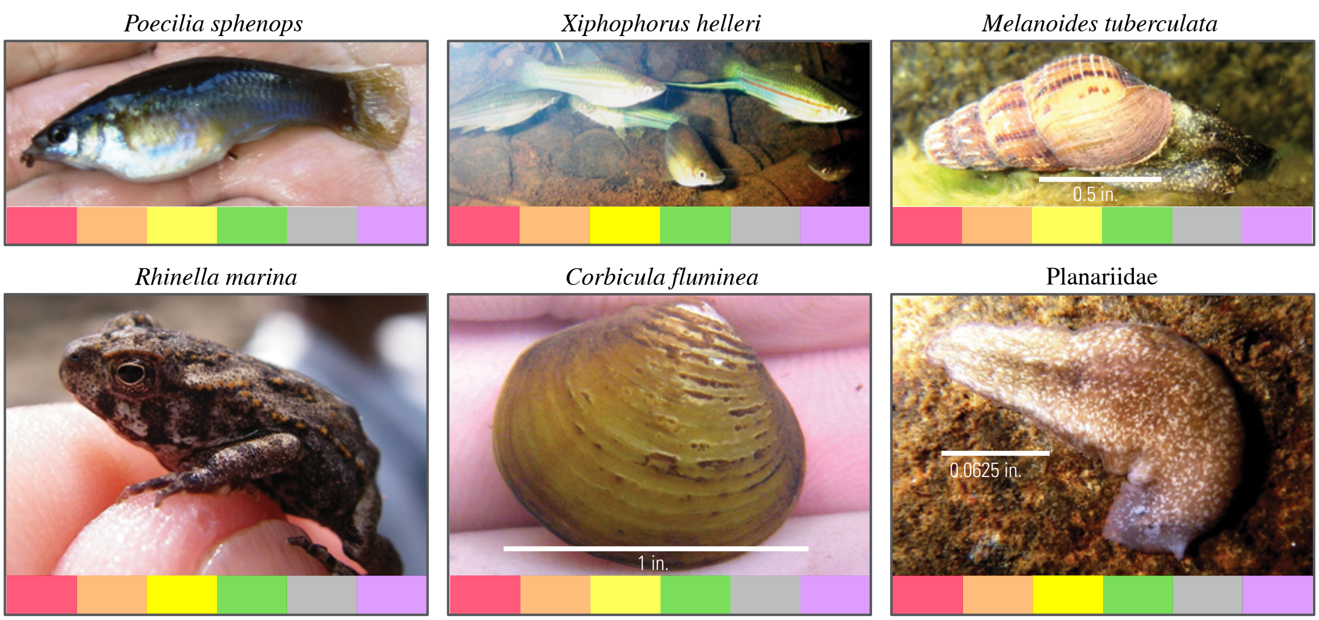
The Asian clam, *Corbicula fluminea*, was observed in pockets of sand within the Lower 1 and 2 study reaches, downstream of the confluence with Kaupaku Stream, and was not observed upstream of the confluence. It is likely this species was introduced sometime in the past into a taro loʻi (irrigated terrace), located near the confluence, as a food resource and it has dispersed into Anahola Stream by way of Kaupaku Stream and has become established downstream of the confluence. However, it is incapable of migrating upstream of the confluence on its own. Conversely, the cryptogenic red-rimmed melania, *Melanoides tuberculata*, were only observed upstream of the confluence attached to cobbles and boulders in pools and habitats with slow flowing water within the Lower 1 and downstream of the Middle 2 study reaches up to an altitude of about 400 ft.

Streamflow Characteristics

Streamflow characteristics at a gaging station are commonly described using a flow-duration curve. A flow-duration curve is a cumulative-frequency distribution that shows the percentage of time that specific discharges (commonly daily mean values) at the gaged site are equaled or exceeded over a specified period of time. The period of time is typically expressed in water years. 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 “2012 water year” is the period October 1, 2011, to September 30, 2012. The most frequently computed flow-duration statistic is the 50th percentile discharge, commonly referred to as median discharge or the Q_{50} flow-duration statistic. The median discharge is the flow that has been equaled or exceeded 50 percent of the time during the specified time period. Low-flow duration discharges are generally considered to be those equal to or less than the Q_{50} flow-duration statistic, and they are represented by the lower end of the flow-duration curve. The slope of the flow-duration curve is affected by hydrologic and geologic characteristics of the drainage basin. A steep slope suggests variable flow conditions in the stream as a result of direct runoff. A flat slope, especially at the low-flow end of the flow-duration curve, suggests perennial-flow conditions in which streamflow is sustained by groundwater discharge.

Base flow is part of the total streamflow that is supported by the discharge of groundwater, which occurs where the stream intersects the water table (Oki, 2003). The base flow of Anahola Stream at the discontinued streamflow-gaging stations was estimated using the automated hydrograph-separation method developed by Wahl and Wahl (1995). The hydrograph-separation method requires two input parameters, N (number of days) and f (turning point factor), defined by the user. The hydrograph-separation method involves dividing the specified time period with daily discharge record (in complete water years) into nonoverlapping increments of N days. The minimum flows within each of the N-day increments (central minimum) are identified. The central minimum is designated as a turning point on the base-flow hydrograph if f times the central minimum is less than the minimum flows in the adjacent increments. The base-flow hydrograph is plotted by drawing straight lines between turning points on semilogarithmic paper. The area beneath the base-flow hydrograph is the volume of base flow for the specified time period. For discontinued Anahola Stream gaging stations, N was determined to be 4 days and f, as recommended by Wahl and Wahl (1995), was 0.9. These input parameters were used in the automated hydrograph-separation method to estimate base flow at the discontinued Anahola Stream gaging stations.





EXPLANATION

Stream reaches surveyed during the 2011 biological surveys –Color bar shows the presence or absence of nonnative aquatic species (shown in photo) in the similarly colored surveyed reaches of Anahola Stream.

Upper		Middle		Lower	
1	2	1	2	1	2

Figure 5. Map showing locations of stream reaches surveyed and the distribution of selected nonnative aquatic species observed during the 2011 U.S. Geological Survey biological surveys in Anahola Stream, Kaua'i, Hawai'i.

Anahola Stream Under Regulated Flow Conditions

Historically, the USGS operated two continuous-record streamflow-gaging stations on Anahola Stream, and both were located downstream from locations where the Makee diversion system was actively diverting surface water for sugarcane cultivation (fig. 2). Because the Makee diversion system in the Anahola Stream drainage basin has been abandoned, historical streamflow records at these stations are not representative of present-day conditions in the valley. Nevertheless, streamflow characteristics at the stations are summarized to provide insight on the regulated conditions of the stream, which may be helpful if parts of the Makee diversion system in the study area are restored in the future. Streamflow statistics provided for Anahola Stream under regulated flow conditions are applicable to the period of record from which the statistics were computed.

One of the continuous-record stations on Anahola Stream (station 16089000) was located at an altitude of 295 ft; this site was downstream from the Upper Anahola Ditch diversion intake and immediately upstream from the Lower Anahola Ditch diversion intake (fig. 2). During the period 1910 and 1913–85 when the station was in operation, 70 complete water years (1914–17 and 1920–85) of streamflow data were collected. During those water years, annual mean discharges ranged from 5.6 Mgal/d in 1984 to 36 Mgal/d in 1969 (fig. 6). Mean monthly discharges show a seasonal pattern in which June to October had the lower flows and November to May had the higher flows (fig. 7). The maximum daily discharge was 1,130 Mgal/d and the minimum daily discharge was 1.0 Mgal/d. The low-flow duration discharges ranged from 1.7 Mgal/d (Q_{99} discharge) to 6.3 Mgal/d (Q_{50} discharge) (table 3, fig. 8).

The other continuous-record station on Anahola Stream (station 16093200) was located about 590 ft upstream from the estuary; streamflow at this location reflected diversion at both the Upper and Lower Anahola Ditches and return flow from the Upper Anahola Ditch wasteway (fig. 2). The station was in operation between 1964 and 1982, during which 17 complete water years (1966–82) of streamflow data were collected. During those water years, annual mean discharges ranged from 12 Mgal/d in 1973 to 50 Mgal/d in 1969 and

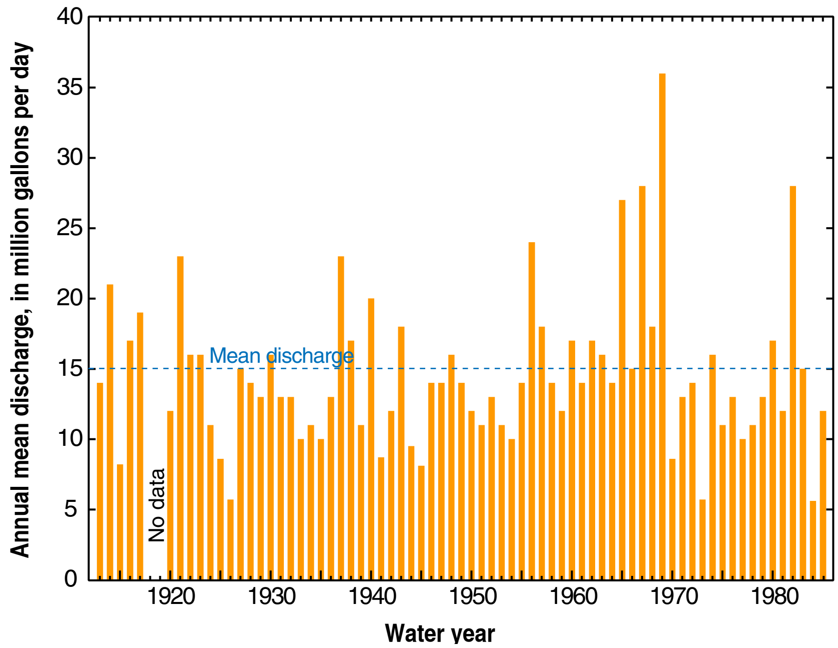


Figure 6. Plot showing annual mean discharges at streamflow-gaging station 16089000 on Anahola Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1913–1985.

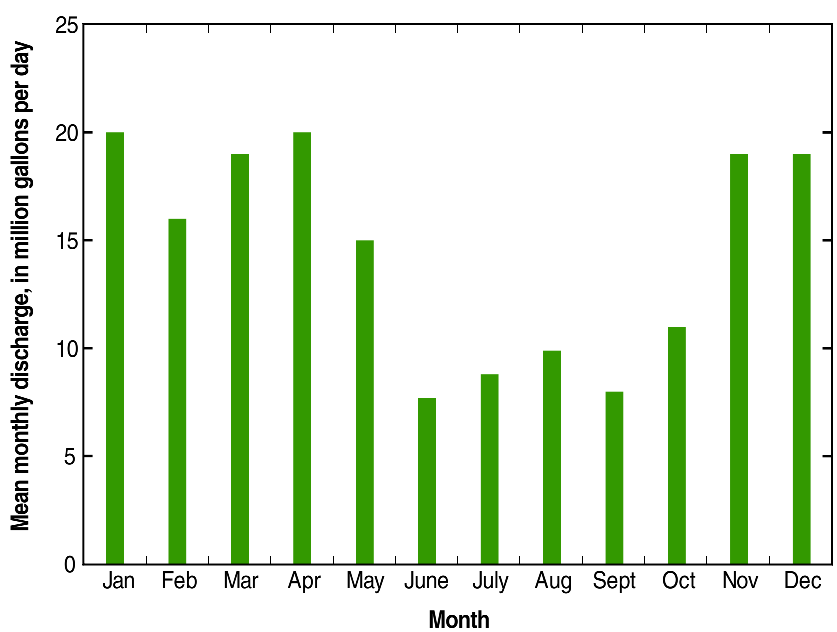


Figure 7. Plot showing mean monthly discharges at streamflow-gaging station 16089000 on Anahola Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1913–1985.

1982 (fig. 9). Mean monthly discharges show a seasonal pattern in which June to October had the lower flows and November to May had the higher flows (fig. 10). The maximum daily discharge was 1,080 Mgal/d and the minimum daily discharge was 1.6 Mgal/d. The low-flow duration discharges ranged from 2.4 Mgal/d (Q_{99} discharge) to 10 Mgal/d (Q_{50} discharge) (table 3, fig. 11).

Study-Area Streams Under Natural Flow Conditions

The primary focus of this study is to characterize the availability and distribution of streamflow in Anahola Stream under natural (undiverted), low-flow conditions. Low-flow availability is determined typically by computing low-flow duration discharges at the sites of interest. Ideally, flow-duration discharges should be computed from streamflow data at a long-term continuous-record station established upstream from points of diversion to accurately describe the availability of natural low flows. Similarly, the distribution of low flows along a stream,

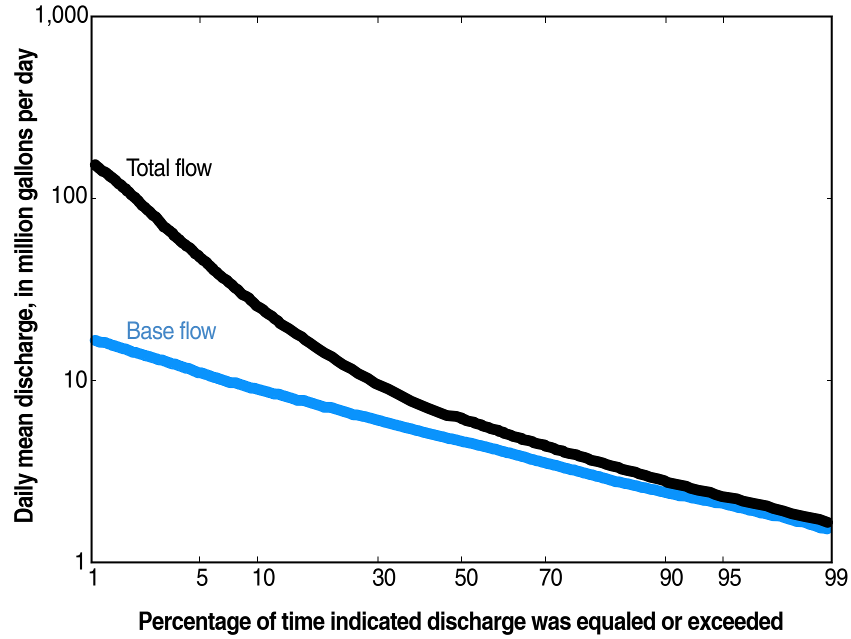


Figure 8. Plot showing flow-duration curves for total flow and base flow at streamflow-gaging station 16089000 on Anahola Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1913–1985.

Table 3. Selected flow-duration discharges for total streamflow at streamflow-gaging stations 16089000 and 16093200 on Anahola Stream, Kaua‘i, Hawai‘i, during indicated period of record with complete water years.

[Mgal/d, million gallons per day; POR, period of record]

Percentage of time indicated flow equaled or exceeded	Discharge (Mgal/d)	
	16089000 POR: 1914–17, 1920–85	16093200 POR: 1966–82
99	1.7	2.4
95	2.3	3.2
90	2.4	3.9
85	3.3	4.5
80	3.7	5.3
75	4.1	5.9
70	4.5	6.5
65	4.8	7.1
60	5.3	7.8
55	5.8	9.0
50	6.3	10

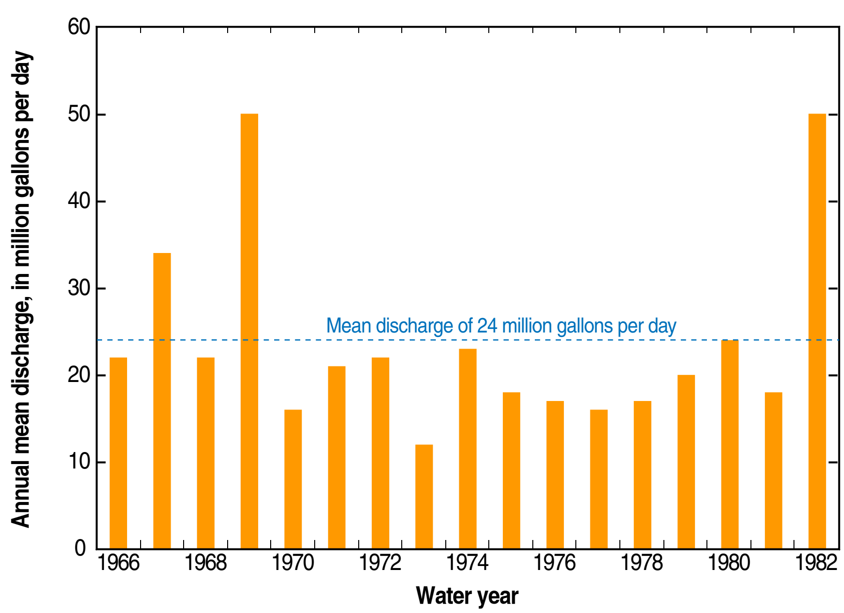


Figure 9. Plot showing annual mean discharges at streamflow-gaging station 16093200 on Anahola Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1966–1982.

which may vary in both time and location due to interactions between surface water and groundwater, can be determined from long-term streamflow data from continuous-record stations established at multiple locations along a stream. However, long-term continuous-record stations are rarely available at all locations where data are desired. Alternatively, the availability and distribution of low flow in a stream can be determined using a combination of discharge measurements made at LFPR and seepage-run stations established at the sites of interest where data are collected over a shorter period of time. The following section of the report includes discussion on using discharge measurements at LFPR stations to determine low-flow availability in Anahola and Goldfish Streams. The method of using discharge measurements at seepage-run stations to describe the distribution of natural low flow in Anahola Stream is discussed in the subsequent section "Natural Low-Flow Distribution."

Natural Low-Flow Availability

Record-augmentation techniques are commonly used to determine flow-duration discharges at sites with either short-term record or partial-record streamflow data. The process of record augmentation involves correlating discharge measurements at the site of interest with the concurrent daily mean discharges at a nearby long-term continuous-record station (index station) to develop a statistical relation. Subsequently, the statistical relation is used to compute flow-duration discharges at the 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. In Hawai‘i, record augmentation has been used by: Fontaine and others (1992) to estimate median streamflows for perennial streams in the State of Hawai‘i; Fontaine (2003) to quantify base-flow availability in Honokōhau Stream, Island of Maui; Oki and others (2006) to characterize low-flow availability in Punalu‘u Stream, Island of O‘ahu; Yeung and Fontaine (2007) to

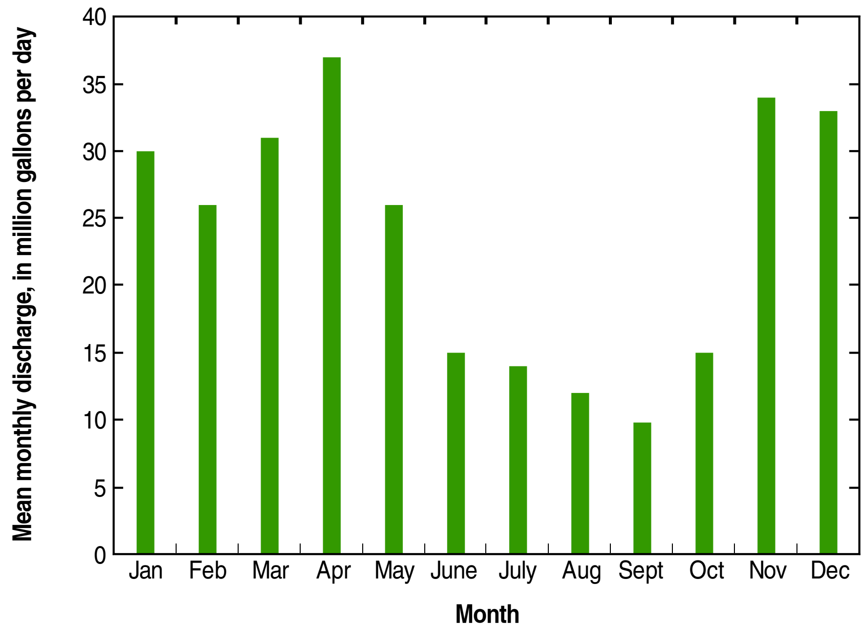


Figure 10. Plot showing mean monthly discharges at streamflow-gaging station 16093200 on Anahola Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1966–1982.

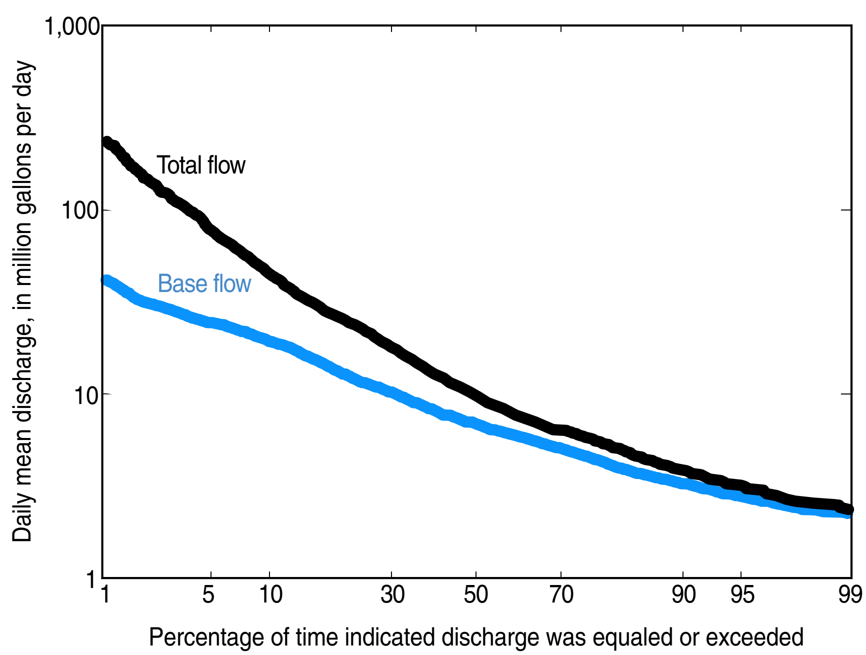


Figure 11. Plot showing flow-duration curves for total flow and base flow at streamflow-gaging station 16093200 on Anahola Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1966–1982.

describe natural and regulated low flows for streams in the windward side of the Island of Oʻahu; and Oki and others (2010) to characterize natural low flows for streams in the Nā Wai ʻEhā area, Island of Maui. For this study, LFPR stations were established at sites of interest along study-area streams where discharge measurements were made for use in record augmentation. The following sections discuss the selection of and data collection at the LFPR stations, the selection of index stations, and the implementation of record-augmentation techniques to determine low-flow availability in the study-area streams.

Low-Flow Partial-Record Stations

No continuous-record stations that measured discharges under natural-flow conditions have been operated in the study-area streams. Available data from the two discontinued stations on Anahola Stream (stations 16089000 and 16093200) reflect regulated-flow conditions, which are not applicable to present-day conditions in the streams. To characterize natural low-flow availability in the study-area streams, LFPR stations were established upstream from points of diversion. The locations of the LFPR stations were selected based on the assumption that one or both of the diversion intakes (upper and lower intakes) on Anahola Stream would likely be restored in the future to provide for surface-water use. Three LFPR stations were established on Anahola Stream: station 16085500 about 450 ft upstream from the Upper Anahola Ditch intake (fig. 12*A*), station 16088300 about 50 ft upstream from the confluence with tributary Keaʻoʻopu Stream (fig. 12*B*), and station 16088500 on tributary Keaʻoʻopu Stream about 80 ft upstream from the confluence with Anahola Stream (fig. 12*C*). By establishing two LFPR stations near the confluence of Anahola and Keaʻoʻopu Streams instead of one LFPR station upstream from the Lower Anahola Ditch intake, low-flow availability could be characterized at the main channel and the

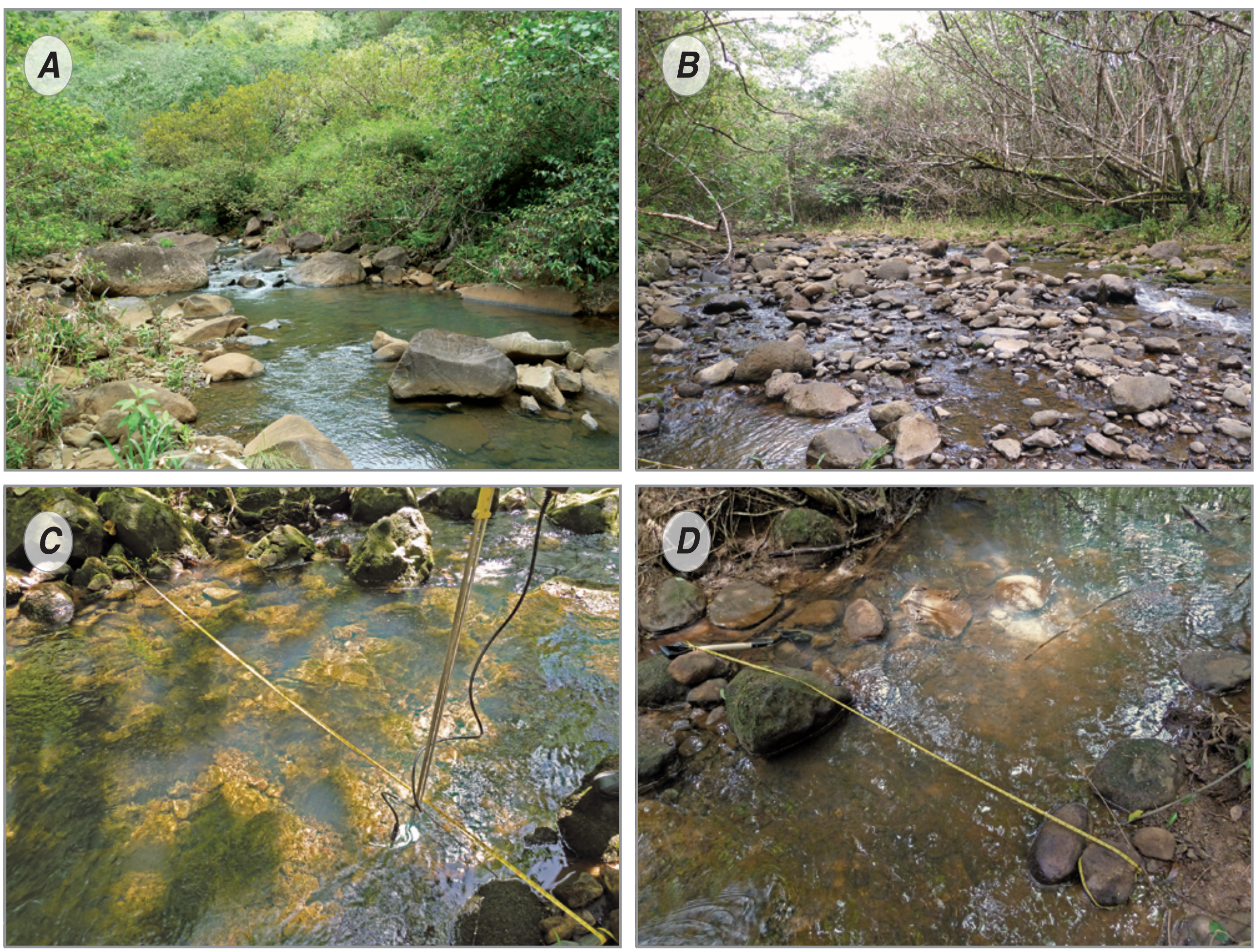


Figure 12. Photographs of low-flow partial-record stations in Anahola and Goldfish Streams, Kauaʻi, Hawaiʻi. *A*. Anahola Stream immediately upstream of station 16085500. *B*. Anahola Stream immediately downstream of station 16088300. *C*. Discharge-measurement cross section of station 16088500 on Keaʻoʻopu Stream. *D*. Discharge-measurement cross section of station 16081500 on Goldfish Stream.

Table 4. Altitude and latitude and longitude coordinates of low-flow partial-record and seepage-run discharge-measurement stations in the Anahola and Goldfish Streams study area, Kaua‘i, Hawai‘i.

[ID, identifier; USGS, U.S. Geological Survey; DS, downstream; alt, altitude]

Station ID	USGS station number	USGS station name, in Kauai, HI	Altitude[a], in feet	Latitude[b]	Longitude[b]
Low-flow partial-record stations					
16081500	16081500	Unnamed Tributary above Kaneha Reservoir	880	22°08'05"	159°22'45"
16085500	16085500	Anahola Stream above upper ditch intake	860	22°08'38"	159°23'18"
16088300	16088300	Anahola Stream near Keaoopu Tributary confluence	350	22°09'00"	159°21'38"
16088500	16088500	Keaoopu Tributary near Anahola Str confluence	350	22°09'02"	159°21'38"
Seepage-run discharge-measurement stations					
1[c]	16085500	Anahola Stream above upper ditch intake	860	22°08'38"	159°23'18"
2	220843159225901	Anahola Stream below upper ditch intake	740	22°08'42.5"	159°22'59.3"
3	220848159224501	Upper Tributary of Anahola Stream	630	22°08'48.0"	159°22'45.4"
4[c]	16088300	Anahola Stream near Keaoopu Trib confluence	350	22°09'00"	159°21'38"
5[c]	16088500	Keaoopu Tributary near Anahola Str confluence	350	22°09'02"	159°21'38"
6	220857159213401	Tributary of Anahola Steam below confluence	340	22°08'56.6"	159°21'33.8"
7	220855159212601	Anahola Stream below confluence at alt 300 ft	330	22°08'55.2"	159°21'25.8"
8	220856159211201	Tributary of Anahola Stream above lower intake	300	22°08'56.0"	159°21'12.0"
9	220854159210601	Anahola Stream below lower ditch intake	280	22°08'54.0"	159°21'05.6"
9a	220854159210501	Lower Anahola Ditch DS of tunnel	280	22°08'53.8"	159°21'04.6"
10	220832159200601	Lower Anahola Stream at alt 200 ft	170	22°08'32.4"	159°20'05.7"
11	220821159194501	Kaupaku Stream near Anahola	140	22°08'21.2"	159°19'45.3"
12	220815159191601	Anahola Stream upstream Kaalula Tributary	70	22°08'15.2"	159°19'15.8"

[a] Altitude values interpolated from USGS 1:24,000-scale digital hypsography data.

[b] Latitude and longitude coordinates in North American Datum of 1983.

[c] Seepage-run stations that were low-flow partial-record stations during the study period of February 2011 to May 2012.

tributary independently. The combined concurrent discharges measured at these two LFPR stations represent the estimated discharge on Anahola Stream immediately downstream from its confluence with Kea‘o‘opu Stream. In Goldfish Stream, LFPR station 16081500 (fig. 12*D*) was established about 0.4 mi upstream from the point of discharge into Kaneha Reservoir (table 4, fig. 13).

For record augmentation, a minimum of about 10 discharge measurements are generally made at LFPR stations 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 recession is the period when streamflows return to low-flow conditions following a period of direct runoff. Hydrographs from nearby, currently active, continuous-record streamflow-gaging stations were checked to determine when recessions were in place in the Anahola and Goldfish Streams study area. The optimal period to make a discharge measurement at the LFPR station is depicted in a streamflow hydrograph as the later phases in the recession limb when the curve begins to level out, eventually reaching base flow. For this study, 10 to 12 discharge measurements were made at each of the LFPR stations between February 2011 and May 2012. Discharge measurements were made with acoustic Doppler velocimeters (ADV) and Price pygmy vertical-axis current meters. Since the LFPR stations were difficult to access, discharge measurements at the stations could not all be made on the same day. A majority of the measurements were made when flows were generally stable. Stable flow conditions were documented by recording the height of water surface, commonly referred to as gage height or stage, during the time when discharge measurements were being made. A few of the measurements were made when gage heights were variable and direct runoff may have been occurring and those measurements were not used to estimate low-flow duration discharges. All of the discharge measurements made at the LFPR stations for this study are presented in tables 5 to 9 and they are stored in the USGS National Water Information System (NWIS) database.

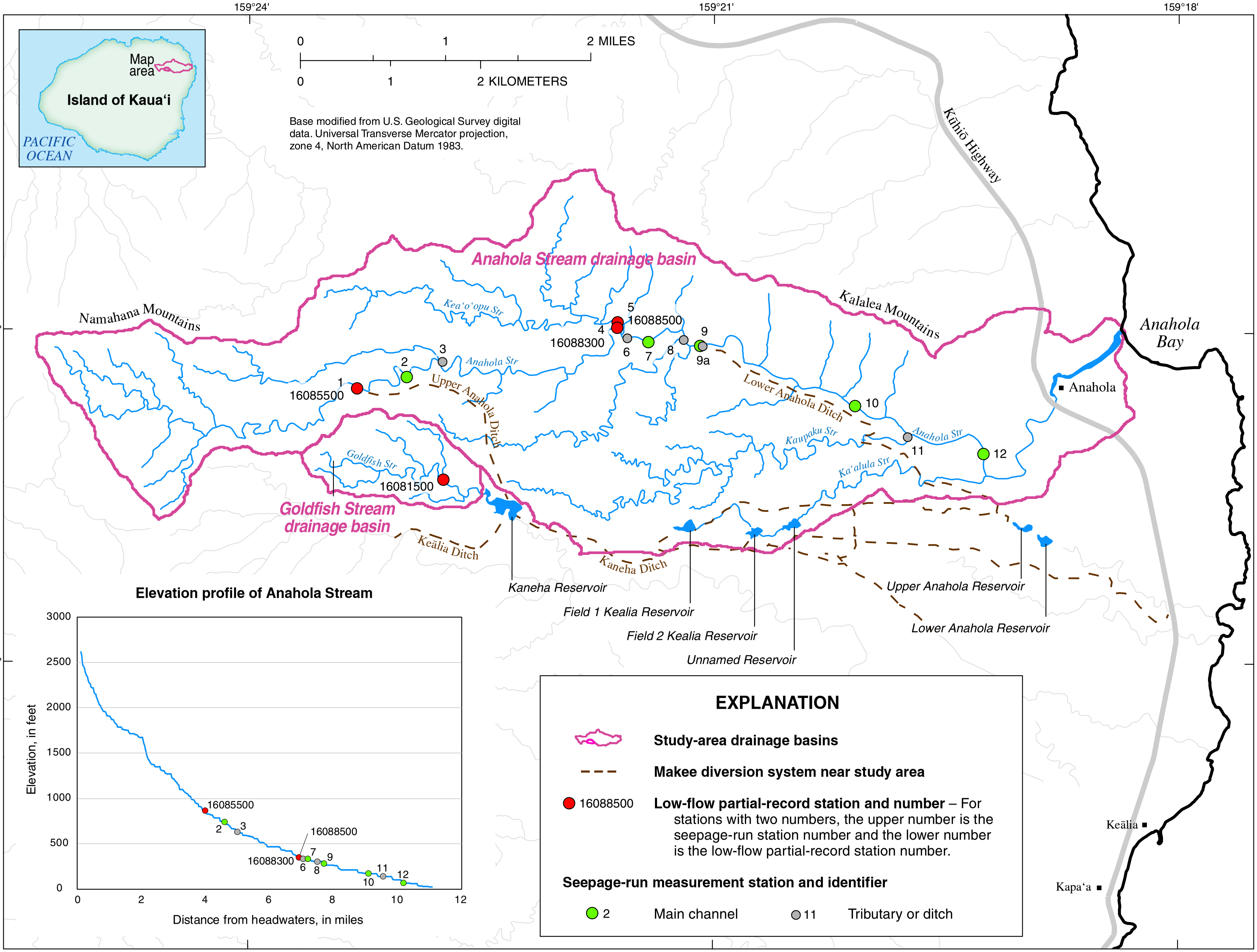


Figure 13. Map showing discharge-measurement stations in the Anahola and Goldfish Streams study area, Kaua'i, Hawai'i. (Reservoir names from State of Hawai'i, 2012.)

Table 5. Measured discharges at low-flow partial-record station 16085500 on Anahola Stream upstream of upper ditch intake and concurrent daily mean discharges at streamflow-gaging station 16097500 on Halaulani Stream, Kaua‘i, Hawai‘i.

[Mgal/d, million gallons per day; discharges not used in record augmentation are underlined]

Date	Daily mean discharge in Mgal/d	
	Station 16097500	Station 16085500
02/23/11	3.9	2.50
03/01/11	3.4	1.51
03/21/11	3.7	2.01
04/13/11	3.4	<u>1.64</u>
04/15/11	3.3	1.50
07/05/11	4.3	2.86
07/28/11	5.7	2.92
08/08/11	4.1	1.66
09/02/11	3.1	1.36
09/26/11	2.6	0.80
05/22/12	3.1	<u>0.72</u>

Table 6. Measured discharges at low-flow partial-record station 16088300 on Anahola Stream near Kea‘o‘opu tributary confluence and concurrent daily mean discharges at streamflow-gaging station 16097500 on Halaulani Stream, Kaua‘i, Hawai‘i.

[Mgal/d, million gallons per day; discharges not used in record augmentation are underlined]

Date	Daily mean discharge in Mgal/d	
	Station 16097500	Station 16088300
02/24/11	7.8	<u>6.85</u>
03/02/11	3.4	2.86
03/22/11	3.9	<u>5.46</u>
04/15/11	3.3	2.66
06/02/11	4.8	4.64
07/05/11	4.3	4.42
07/28/11	5.7	4.69
09/02/11	3.1	2.73
09/26/11	2.6	1.56
04/04/12	4.0	2.81
05/22/12	3.1	1.80

Table 7. Measured discharges at low-flow partial-record station 16088500 on Kea‘o‘opu tributary near Anahola Stream confluence and concurrent daily mean discharges at streamflow-gaging station 16071500 on left branch ‘Ōpaeka‘a Stream, Kaua‘i, Hawai‘i.

[Mgal/d, million gallons per day; discharges not used in record augmentation are underlined]

Date	Daily mean discharge in Mgal/d	
	Station 16071500	Station 16088500
02/24/11	16	<u>3.63</u>
03/02/11	1.9	2.26
03/22/11	2.1	<u>3.33</u>
04/15/11	1.2	1.77
06/02/11	1.6	2.35
07/05/11	1.2	1.52
07/28/11	0.78	1.63
09/02/11	0.46	1.07
09/26/11	0.35	0.74
04/04/12	1.7	2.15
05/22/12	0.58	1.01

Table 8. Combined discharges measured at low-flow partial-record station 16088300 on Anahola Stream near Kea‘o‘opu Stream confluence and low-flow partial-record station 16088500 on Kea‘o‘opu Stream near Anahola Stream confluence, and concurrent daily mean discharges at streamflow-gaging station 16097500 on Halaulani Stream, Kaua‘i, Hawai‘i.

[Mgal/d, million gallons per day; discharges not used in record augmentation are underlined]

Date	Discharge in Mgal/d	
	Daily mean discharge at station 16097500	Combined discharges measured at stations 16088300 and 16088500
02/24/11	7.8	<u>10.5</u>
03/02/11	3.4	5.12
03/22/11	3.9	<u>8.79</u>
04/15/11	3.3	4.43
06/02/11	4.8	6.99
07/05/11	4.3	5.94
07/28/11	5.7	6.32
09/02/11	3.1	3.80
09/26/11	2.6	2.30
04/04/12	4.0	4.96
05/22/12	3.1	2.81

Table 9. Measured discharges at low-flow partial-record station 16081500 on Goldfish Stream and concurrent daily mean discharges at streamflow-gaging station 16071500 on left branch ʻŌpaekaʻa Stream, Kauaʻi, Hawaiʻi.

[Mgal/d, million gallons per day; discharges not used in record augmentation are underlined]

Date	Daily mean discharge in Mgal/d	
	Station 16071500	Station 16081500
02/24/11	16	<u>1.51</u>
03/02/11	1.9	0.73
03/21/11	2.1	1.09
04/12/11	1.2	0.65
06/01/11	1.9	<u>1.45</u>
07/05/11	1.2	0.61
07/29/11	0.84	<u>1.60</u>
08/31/11	0.49	0.34
09/27/11	0.35	0.21
10/31/11	0.39	0.34
04/04/12	1.7	0.66
05/23/12	0.58	0.30

Selection of Index Stations

Streamflow data from an index station are used to compute low-flow duration discharges at the LFPR stations. The index station is usually located along the same stream as the LFPR stations or nearby in drainage basins that are hydrologically similar to that of the LFPR stations. Hydrologic similarity between the drainage basins is defined by Searcy (1959, p. 14) as having the same probability of rainfall, and not necessarily the occurrence of concurrent rainfall events. However, remote index stations as far away as 50 mi have been used to estimate flow-duration discharges when long-term concurrent streamflow data are available at the stations. For this study, index stations were selected from a network of 10 long-term continuous-record streamflow-gaging stations on the Island of Kauaʻi that were active from February 2011 to May 2012 (fig. 1), none of which were located on the study-area streams. Selection of the index stations was based on (1) proximity of the continuous-record stations to the LFPR stations relative to the windward and leeward regions of the island; and (2) a minimum correlation coefficient of 0.80 in the relations between the discharge measurements at the LFPR stations and the concurrent daily mean discharges at the continuous-record stations. The windward and leeward regions of the Island of Kauaʻi are defined in Yamanaga (1972, p.24).

Streamflow-gaging station 16097500 on Halaulani Stream was used as the index station for the two LFPR stations on Anahola Stream, stations 16085500 and 16088300. Correlation coefficients, based on simple linear regression, in the relations between concurrent daily mean discharges at the index station and discharge measurements at the LFPR stations averaged 0.81. Streamflow-gaging station 16071500 on the left branch of ʻŌpaekaʻa Stream was used as the index station for the LFPR stations on Keaʻoʻopu Stream (station 16088500) and on Goldfish Stream (station 16081500). The correlation coefficients, based on simple linear regression, in the relation between concurrent daily mean discharges at the index station and discharge measurements at the LFPR stations averaged 0.91. On Anahola Stream immediately downstream from its confluence with Keaʻoʻopu Stream, the combined concurrent discharges measured at LFPR stations 16088300 and 16088500 were better correlated with the concurrent daily mean discharges at streamflow-gaging station 16097500—correlation coefficient of 0.76—than with the concurrent daily mean discharges at streamflow-gaging station 16071500. Therefore, station 16097500 was used as the index station for this location. Measured discharges at the LFPR stations and the concurrent daily mean discharges at the selected index stations are presented in tables 5 to 9. The base period used to compute low-flow duration discharges at the index stations was water years 1961–2011.

Record-Augmentation Techniques

The two record-augmentation techniques considered for use in this study are (1) the Maintenance of Variance Extension Type 1 (MOVE.1) technique described in Hirsch (1982); and (2) the graphical-correlation technique described in Searcy (1959, p.14). Both record-augmentation techniques assume that the relation between concurrent records at the index and LFPR stations is the same for any time period (Ries, 1993, p.21). Selection of the appropriate record-augmentation technique for estimating low-flow duration discharges depends on the relation between discharge measurements at the LFPR station and the concurrent daily mean discharges at the index station. When little or no curvature is detected in the relation on a logarithmic plot, the MOVE.1 technique is used to estimate low-flow duration discharges. When curvature is evident in the relation, the graphical-correlation technique is used. Only limited curvature was evident in the logarithmic plots in this study and, therefore, the MOVE.1 technique was used to estimate low-flow duration discharges at all four of the LFPR stations.

The MOVE.1 technique applies the line of organic correlation regression method in developing the statistical relation. Compared with ordinary least squares and least normal squares regression methods, the line of organic correlation method has been shown by Hirsch and Gilroy (1984) and Helsel and Hirsch (2002) to be most appropriate in record augmentation. The procedure for the MOVE.1 technique begins by transforming the concurrent discharges at the index and LFPR stations to base-10 logarithms, and computing the means and standard deviations of the logarithms. 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 LFPR stations are determined using the

MOVE.1 formula (equation 1) and then converted to the original (not log-transformed) units of measurement in million gallons per day.

$$Y_i = m_y + \frac{s_y}{s_x}(x_i - m_x) \quad (1)$$

where:

Y_i is the base-10 logarithm of the estimated low-flow duration discharge at the LFPR station,

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 LFPR station,

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 LFPR station, and

s_x is the standard deviation of the base-10 logarithms of the concurrent daily mean discharges at the index station.

The Streamflow Record Extension Facilitator (SREF) is a program developed by the USGS, in cooperation with the Federal Highway Administration and the Rhode Island Water Resources Board, that automates the MOVE.1 record-augmentation technique (Granato, 2009). To help the user evaluate the MOVE.1 results, the SREF program computes several regression statistics. 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) is a measure of the strength of the linear relation between concurrent discharges at the index and LFPR stations. The residual error is the uncertainty in the estimated flow-duration discharges at the LFPR stations. The leverage of a data point measures the influence it has on the final estimates; a high leverage indicates the higher likelihood of an outlier in the discharge measurements made at the LFPR stations. The root mean square error (or standard deviation) is simply the square root of the mean square error (or variance), and it quantifies the difference between the estimated and measured discharges at the LFPR stations. The modified Nash-Sutcliff coefficient of efficiency (Legates and McCabe, 1999) ranges from minus infinity to 1. The closer a coefficient is to 1 the more accurately the statistical relation predicts low-flow duration discharges at the LFPR stations from the low-flow duration discharges at the index station. The equations used to compute these regression statistics can be found in Granato (2009).

Low-Flow Duration Discharges

A summary of the index stations used and selected record-augmentation regression statistics for the LFPR stations in Anahola and Goldfish Streams are included in table 10. Flow-duration curves for index stations 16097500 and 16071500 are provided in figures 14 and 15, respectively. Selected low-flow duration discharges at the index stations and those estimated at the LFPR stations are summarized in table 11. Flow-duration discharge estimates less than the 95th-percentile discharge are not provided because those estimates are outside of the range of discharges measured at the LFPR stations during the study period of February 2011 to May 2012.

Anahola Stream upstream of upper intake.—At LFPR station 16085500, a total of 11 discharge measurements were made during the study period and 9 measurements were used in record augmentation (table 5). Measurements made on April 13 and 15, 2012, were taken during the same streamflow recession and the discharge measured on April 15 was selected to be used in record augmentation because it was taken during a seepage run to identify gains and losses in the stream. The measurement made on May 22, 2012, was not used because it appeared to be an outlier that greatly deviated from the general trend that was consistent with the other nine measurements. Low-flow duration discharges estimated with the MOVE.1 technique ranged from 0.97 Mgal/d (Q_{95} discharge) to 2.7 Mgal/d (Q_{50} discharge). Measured discharges at the LFPR station that were used for record augmentation were between the flow-duration percentiles of 98 and 46 percent; therefore, the measured discharges provide flow-duration estimates that are representative of the low-flow conditions on Anahola Stream upstream of the upper intake.

Anahola Stream at confluence.—At LFPR station 16088300, 11 discharge measurements were made during the study period and 9 of the measurements were used in record augmentation (table 6). Measurements made on February 24 and March 22, 2011, were not used because the hydrograph from index station 16097500 indicated possible runoff occurring during the time that the discharge measurements were being made. Low-flow duration discharges estimated with the MOVE.1 technique ranged from 1.7 Mgal/d (Q_{95} discharge) to 4.2 Mgal/d (Q_{50} discharge). Measured discharges at the LFPR station that were used for record augmentation generally fell between the flow-duration percentiles of 97 and 45 percent; therefore, the measured discharges provide flow-duration estimates that are representative of the low-flow conditions on Anahola Stream immediately upstream of its confluence with Kea‘o‘opu Stream.

Kea‘o‘opu Stream at confluence.—At LFPR station 16088500, 11 discharge measurements were made during the study period, and 9 of the measurements were used in record augmentation (table 7). Discharge measurements made on February 24 and March 22, 2011, were not used because the hydrograph from index station 16071500 indicated possible runoff occurring during the time that the discharge measurements were being made. Only five of the nine usable discharge measurements made at the LFPR station were greater than the median discharge. The highest measured flow was 2.35 Mgal/d, which was about a Q_{20} discharge. Typically, the runoff component of total streamflow, represented in a flow-duration curve as the area between the total-flow and base-flow curves, becomes substantial at discharges greater than the median discharge. This is clearly illustrated in the flow-duration curve for station 16097500 on Halaulani Stream (fig. 14); hence, low-flow duration discharges usually span the range between the Q_{95} to Q_{50} discharges. However, the fairly

Table 10. Index stations, record-augmentation technique, and selected regression statistics for the low-flow partial-record stations in Anahola and Goldfish Streams, Kaua'i, Hawai'i.

[LFPR, low-flow partial-record; ID, identifier; r; correlation coefficient; RMSE, root mean square error; E, modified Nash-Sutcliff coefficient of efficiency (Legates and McCabe, 1999); MOVE.1; Maintenance of Variance Extension Type 1 record-augmentation technique (Hirsch, 1982)]

LFPR station ID	Index station ID	Record-augmentation technique	Regression statistics		
			r	RMSE	E
16085500	16097500	MOVE.1	0.89	0.090	0.51
16088300	16097500	MOVE.1	0.91	0.076	0.52
16088500	16071500	MOVE.1	0.96	0.054	0.70
883+885[a]	16097500	MOVE.1	0.88	0.085	0.50
16081500	16071500	MOVE.1	0.95	0.077	0.69

[a] Flow-duration discharges at Anahola Stream immediately downstream of its confluence with Kea'o'opu Stream were estimated using the combined discharges measured at LFPR stations 16088300 and 16088500 during the study period of February 2011 to May 2012.

Table 11. Selected flow-duration discharges at the index stations and estimated flow-duration discharges at the low-flow partial record stations for water years 1961–2011, Kaua'i, Hawai'i.

[Mgal/d, million gallons per day; --, not applicable]

Percentage of time indicated flow equaled or exceeded	Index stations[a] (Mgal/d)		Low-flow partial-record stations (Mgal/d)				
	16097500	16071500	16085500	16088300	16088500	883+885[b]	16081500
95	2.6	0.33	0.97	1.7	0.76	2.7	0.23
90	2.9	0.41	1.2	2.0	0.87	3.1	0.27
85	3.1	0.47	1.3	2.2	0.96	3.4	0.30
80	3.3	0.53	1.4	2.4	1.0	3.8	0.33
75	3.5	0.59	1.6	2.7	1.1	4.1	0.35
70	3.7	0.65	1.8	3.0	1.2	4.6	0.38
65	3.9	0.78	1.9	3.2	1.3	4.9	0.43
60	4.1	0.84	2.2	3.5	1.4	5.3	0.46
55	4.4	0.90	2.4	3.8	1.5	5.8	0.49
50	4.6	1.0	2.7	4.2	1.6	6.3	0.54
45	--	1.1	--	--	1.7	--	0.56
40	--	1.2	--	--	1.8	--	0.61
30	--	1.5	--	--	2.0	--	0.71
20	--	1.9	--	--	2.4	--	0.84

[a] Selected flow-duration discharges for index stations computed from water years 1961–2011.

[b] Flow-duration discharges at Anahola Stream immediately downstream of its confluence with Kea'o'opu Stream were estimated using the combined discharges measured at LFPR stations 16088300 and 16088500 during the study period of February 2011 to May 2012. These flow-duration estimates may not correspond to the values resulting from the addition of the flow-duration discharges of LFPR stations 16088300 and 16088500 because of differences related to the timing of flows in tributary Kea'o'opu Stream and main channel of Anahola Stream. This is reflected in the use of different index stations for LFPR stations 16088300 and 16088500.

flat slope of the flow-duration curve for index station 16071500 (fig. 15) indicates that low-flow conditions could possibly occur in the range between the Q_{95} to Q_{20} discharges. Low-flow duration discharges estimated with the MOVE.1 technique ranged from 0.76 Mgal/d (Q_{95} discharge) to 2.4 Mgal/d (Q_{20} discharge). All of the discharge measurements made at the LFPR station were between the Q_{96} to Q_{20} discharges; therefore, the measured discharges provide flow-duration estimates that are representative of the low-flow conditions on Kea'o'opu Stream at the confluence.

Anahola Stream immediately downstream of confluence.—On Anahola Stream immediately downstream of its confluence with Kea'o'opu Stream, the concurrent discharge measurements made at LFPR stations 16088300 and 16088500 were combined to represent the estimated discharge at that location (table 8). Eleven concurrent sets of discharge measurements were made at stations 16088300 and 16088500, and nine of those sets were used in record augmentation. Measurements made on February 24 and March 22, 2011, were not used because the hydrograph from index stations 16097500 and 16071500 indicated possible runoff occurring during the time that the discharge measurements were being made. Low-flow duration discharges estimated with the MOVE.1 technique ranged from 2.7 Mgal/d (Q_{95} discharge) to 6.3 Mgal/d (Q_{50} discharge). Combined discharges measured at LFPR stations 16088300 and 16088500 that were used for record augmentation generally were between the flow-duration percentiles of 98 and 45 percent; therefore, the measured discharges provide flow-duration estimates that are representative of the low-flow conditions on Anahola Stream immediately downstream of its confluence with Kea'o'opu Stream.

Goldfish Stream upstream of Kaneha Reservoir.—A total of 12 discharge measurements were made at LFPR station 16081500 during the study period and 9 of the measurements were used in record augmentation (table 9). Discharge measurements made on February 24, June 1, and July 29, 2011, were not used because the hydrograph from index station 16071500 indicated possible runoff occurring during the time that the discharge measurements were being made. Although five of the nine usable measurements made at the LFPR station were higher than the median discharge, low-flow conditions could occur in the range between the Q_{95} to Q_{20} discharges as illustrated in the flow-duration curve for index station 16071500 (fig. 15). Low-flow duration discharges estimated with the MOVE.1 technique ranged from 0.23 Mgal/d (Q_{95} discharge) to 0.84 Mgal/d (Q_{20} discharge). All except one of the discharge measurements made at the LFPR station were between the Q_{97} to Q_{20} discharges. The highest measured flow was 1.09 Mgal/d, which was about a Q_{12} discharge. This measurement was included in the record-augmentation analysis because it was made under stable-flow conditions and runoff appeared to be minimal based on the flow-duration curve for index station 16071500. Therefore, the measured discharges provide flow-duration estimates that are representative of the low-flow conditions on Goldfish Stream.

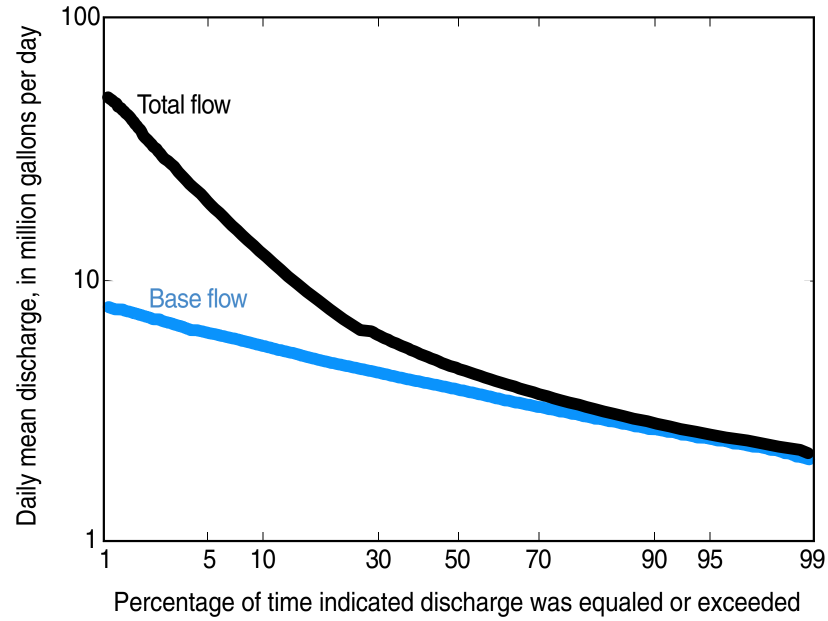


Figure 14. Plot showing flow-duration curves for total flow and base flow at streamflow-gaging station 16097500 on Halaulani Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1961–2011.

Natural Low-Flow Distribution

Local geologic and climatic settings have an effect on groundwater and surface-water flows. The varying interaction of these two bodies of water can affect the distribution of flow along a stream. Different reaches of the same stream can either gain water or lose water. When the water table is above the streambed, the stream can gain water as groundwater discharges into the stream. When the water table is below the streambed, flow in the stream can discharge to the underlying groundwater body.

Seepage Runs

Seepage runs are typically conducted to identify gaining and losing reaches of a stream. A seepage run consists of making multiple discharge measurements, preferably on the same day, at selected sites along the stream. The discharge measurements should be made when

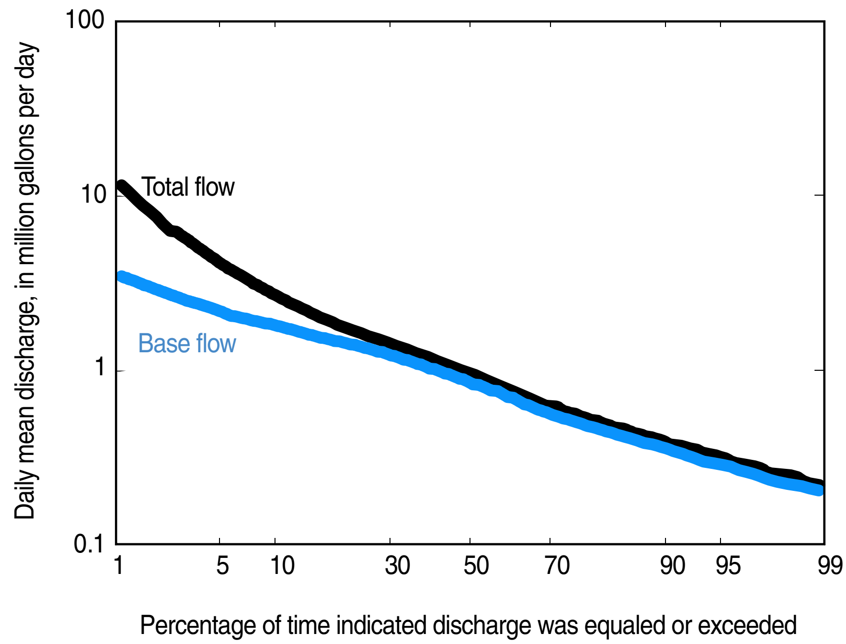


Figure 15. Plot showing flow-duration curves for total flow and base flow at streamflow-gaging station 16071500 on left branch ÿÖpaekaÿa Stream, Kaua‘i, Hawai‘i, for water years with complete record during 1961–2011.

streamflow is generally stable. The existence of stable-flow conditions during a seepage run can be determined by recording the stage during the time when each discharge measurement is being made, and at the beginning and end of the seepage run at a common location with a stable reference point from which the stage could be accurately measured.

For this study, two seepage runs were conducted—one in the wet season and one in the dry season—to characterize seasonal low-flow distribution along Anahola Stream. The wet-season seepage run for Anahola Stream was done on April 15, 2011, and the dry-season seepage run was done on September 2, 2011. The seepage-run stations established for this study are listed in table 4. An abbreviated station identifier (station ID) was assigned to the stations for ease of reference in the report. Discharge measurements were also made at the LFPR stations during the seepage runs. Among the 13 sites where discharges were measured during the seepage runs on Anahola Stream, 7 were in the main channel, 5 were in the tributaries, and 1 was in Lower Anahola Ditch. The station at the highest altitude (860 ft) was LFPR station 16085500 and the station at the lowest altitude (70 ft, station 12) was upstream from the confluence of Anahola Stream and tributary Ka‘alula Stream. The station in Lower Anahola Ditch (station 9a) was established during the dry-season seepage run because water was observed flowing into the ditch at that time.

Flow conditions during the seepage runs were documented by recording the stage during each discharge measurement, and by recording the stage relative to a common reference point at the start and near the end of the seepage runs. The reference point was a pin installed at the discontinued streamflow-gaging station located immediately upstream from the Lower Anahola Ditch diversion intake (station 16089000). All discharge measurements were made during undiverted conditions, or when any streamflow that may have seeped into the abandoned diversion intakes was returned to the stream downstream from the intakes. The existence of potential return flows was documented during the reconnaissance survey, and the seepage run stations were selected accordingly. For both seepage runs, the estimated seepage gains and losses in the main channel of Anahola Stream were computed as the difference between the discharges measured at the upstream and downstream stations, excluding flow contributed from tributaries. During the seepage runs, streamflow gains and losses were estimated along a 6.1-mi reach of Anahola Stream.

Wet Season. —The wet-season seepage run consisted of 12 discharge measurements (table 12, fig. 16). During the period when the first nine measurements were made, stage readings from the reference point and during each discharge measurement did not change, indicating that streamflow was stable despite the light showers that occurred intermittently throughout the morning and early afternoon hours. Discharge measurements in the 0.6-mi reach between stations 1 and 2 indicated a gain in flow of 0.45 Mgal/d, representing a 30-percent increase in flow from the upstream site to the downstream site. This gain included seepage flows observed from the left bank of the stream at altitudes of 790 and 760 ft, which were too low to measure with the available equipment. An unknown amount of flow was diverted into the Upper Anahola Ditch at the diversion intake. Because the ditch was in disrepair, a majority of the diverted flow was observed to have returned to the stream upstream from station 2 at an altitude of 760 ft or about 0.2 mi downstream from the upper intake. In the 2.3-mi reach between stations 2 and 4, the stream had seepage gains of 0.17 Mgal/d, or a 9-percent increase in flow between the two stations—which included several surface inflows along the reach that were too low to measure with the available equipment. In addition to the seepage gains of 0.17 Mgal/d, a tributary on the left bank at an altitude of 680 ft (station 3) contributed an additional 0.54 Mgal/d of flow in the reach. Discharge measurements in the 0.3-mi reach between stations 4 and 7 showed a seepage gain of 0.83 Mgal/d, a 19-percent increase in flow between the upstream and downstream sites. This seepage gain excluded flows contributed from two tributaries within this reach, including Kea‘o‘opu Stream that had a flow of 1.77 Mgal/d (station 5) and a smaller left-bank tributary that had a flow of 0.02 Mgal/d (station 6). In the 0.5-mi reach between stations 7 and 9, the stream lost about 3 percent (0.14 Mgal/d) of its total flow that was measured at the upstream station, excluding inflow of 0.83 Mgal/d from a right-bank tributary (station 8). Station 9 was immediately downstream from a wide raised gravel bed (fig.17) that directed a majority of the flow to the left side of the stream where the discharge measurement was made. The condition may have resulted in an unquantified amount of subsurface flow that bypassed station 9.

Table 12. Wet-season and dry-season seepage-run discharge measurements of Anahola Stream, Kaua‘i, Hawai‘i.

[ID, identifier; Mgal/d, million gallons per day; --, not applicable]

Station ID[a]	Discharge, in Mgal/d	
	Wet season (04/15/2011)	Dry season (09/02/2011)
1	1.50	1.36
2	1.95	1.52
3	0.54	0.43
2	2.66	2.73
3	1.77	1.07
6	0.02	0
7	5.28	3.22
8	0.83	0.36
9	5.97	3.72
9a	--	0.14
10	6.01	4.71
11	0.91	0.72
12	8.47	5.29

[a] Refer to figure 13 for locations of the stations.

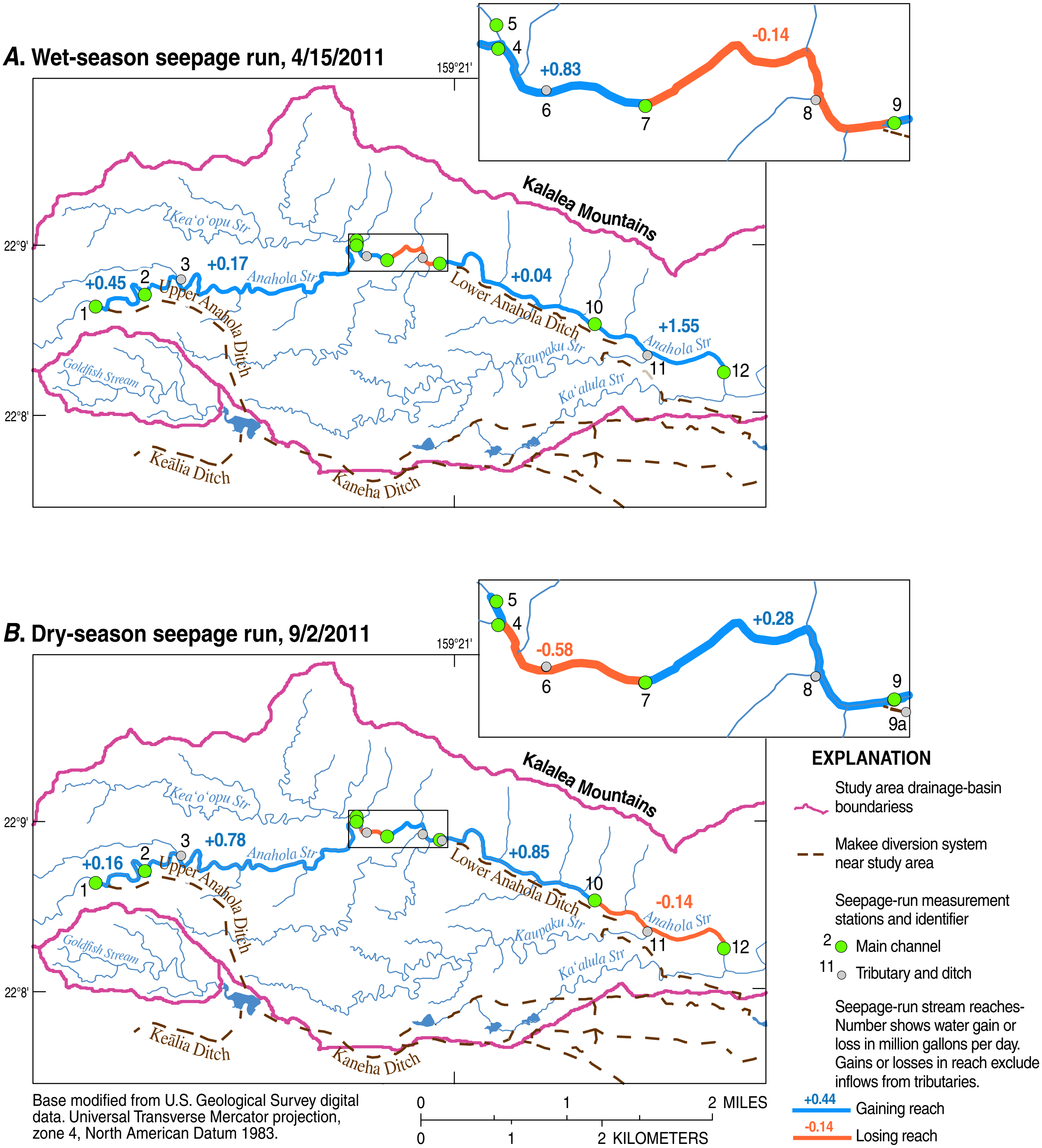


Figure 16. Maps showing results of seepage runs on Anahola Stream, Kaua‘i, Hawai‘i. *A.* Wet-season seepage-run results, 4/15/2011. *B.* Dry-season seepage-run results, 9/2/2011.

Discharge measurements for stations 10, 11, and 12, in the lower reaches of Anahola Stream, were made in the late-afternoon hours when rainfall was more frequent. These measurements indicated Anahola Stream continued to gain flow; however, most of the flow was gained downstream from station 10. In the 1.4-mi reach between stations 9 and 10, the stream gained a flow of 0.04 Mgal/d, representing less than 1-percent increase in flow from the upstream site to the downstream site. In the 1.1-mi reach between stations 10 and 12, the stream gained a flow of 1.55 Mgal/d, or a 26-percent increase in flow between the two stations—which excluded the 0.91 Mgal/d of inflow measured at Kaupaku Stream (station 11). The measured gain downstream from station 10 may have been affected by localized rainfall that occurred during the time when the discharge measurements were made. Two consecutive discharge measurements were made at station 12; the measured flows for the first and second measurements were 8.60 and 8.47 Mgal/d, respectively. The first measurement was made after the field technicians noticed debris flowing downstream, indicating possible runoff that may have caused a rise in stage. The second measurement was made when the stage was receding by 0.03 ft; therefore, this measurement was likely more representative of pre-rain conditions. Although the discharge measurements for stations 10 and 12 were made at nearly the same time, the stage did not change at station 10. This further supported the assumption that localized rainfall may have occurred near tributary Kaupaku Stream, causing the stage in the stream to rise near station 12.

Dry Season. —The dry-season seepage run consisted of 13 discharge measurements (table 12, fig. 16). The measurements were made under stable-flow conditions because no change in stage was detected at the reference point at the start and end of the seepage run, and during the period when each discharge measurement was being made. During the seepage run, all the water in the stream was diverted into the Upper Anahola Ditch at the diversion intake, leaving the stream channel immediately downstream of the upper intake dry. The diverted flow was observed to have returned to the stream at 760 ft altitude or about 0.2 mi downstream from the upper intake. Station 2 was located about 0.3 mi downstream from the location where the diverted flow returned to the stream. Discharge at station 2 was assumed to represent the total natural streamflow in Anahola Stream. Seepage-run discharge measurements show that the 0.6-mi reach between stations 1 and 2 gained a flow of 0.16 Mgal/d, representing a 12-percent increase in flow from the upstream site to the downstream site. All of this gain occurred downstream from the dry reach and between the point of return flow and station 2. Between stations 2 and 4, the 2.3-mi reach had seepage gains of 0.78 Mgal/d, representing a 51-percent increase in flow between the two stations. In addition to the seepage gains of 0.78 Mgal/d, a tributary on the left bank at altitude 680 ft (station 3) contributed an additional 0.43 Mgal/d in this reach. Between stations 4 and 7, tributary Kea‘o‘opu Stream (station 5) contributed 1.07 Mgal/d to the total flow, and Anahola Stream had seepage losses of 15 percent (0.58 Mgal/d) of its total flow in the 0.3-mi reach downstream from the confluence. Station 7 was immediately downstream from a raised gravel bed, similar to the gravel bed upstream of station 9, which directed a majority of the flow to the left side of the stream where the discharge was measured. The condition may have resulted in an unquantified amount of subsurface flow that bypassed station 7. Discharge measurements in the 0.5-mi reach between stations 7 and 9 show a seepage gain in flow of 0.28 Mgal/d, which represents a 9-percent increase in flow from the upstream site to the downstream site. This gain excluded the 0.36 Mgal/d of inflow from the right-bank tributary (station 8). Station 9a was located in Lower Anahola Ditch to measure flow diverted from Anahola Stream into the ditch. A measured flow of about 0.14 Mgal/d at station 9a returned to the stream about 600 ft downstream of the lower intake and downstream from station 9. The combined discharge at stations 9 and 9a was considered the total natural flow in the stream downstream from the lower intake. Between stations 9 and 10, the 1.4-mi reach gained a flow of 0.85 Mgal/d, representing a 22-percent increase in flow from the upstream site to the downstream site. Discharge measurements in the 1.1-mi reach between stations 10 and 12 indicated a seepage loss of 0.14 Mgal/d, representing a 3-percent decrease in flow from the upstream site to the downstream site. Kaupaku Stream (station 11) contributed a flow of 0.72 Mgal/d within this reach.

Results of the seepage runs show that Anahola Stream was generally a gaining stream under natural low-flow conditions. According to the flow-duration discharges estimated with the record-augmentation technique, flows measured at the LFPR stations on the main channel of Anahola Stream during the wet-season seepage run were between the Q_{72} to Q_{78} discharges and flows measured during the dry-season seepage run were at about the Q_{80} discharge. Therefore, discharge measurements taken during the seepage runs were representative of base-flow conditions. During the wet-season seepage run, Anahola Stream at the downstream-most station (upstream of tributary Ka‘alula Stream) had more than five times the flow that was measured at the station upstream of the upper intake (seepage-run station 1). In the 6.1-mi seepage-run reach, the estimated total gain including tributary inflow was 6.97 Mgal/d. About 42 percent of that gain was from groundwater discharge to the main channel of Anahola Stream. During the dry-season seepage run, about 34 percent of the estimated total gain (3.93 Mgal/d) was from groundwater discharge to the main channel of Anahola Stream. The relatively large amounts of groundwater discharge to Anahola Stream is evidence that the aquifer system in the Anahola drainage basin may be similar to that of the southern Līhu‘e Basin, which is characterized by low-permeability (low hydraulic conductivity) lava flows saturated to near land surface.

Streamflow Availability Scenarios

Seepage-run discharge measurements can be used to estimate surface-water availability under regulated conditions of the stream if parts of the Makee diversion system—upper and lower intakes—in the study area are restored in the future. For example, during the wet-season seepage run, 1.50 Mgal/d of flow was measured upstream of the upper intake and 5.97 Mgal/d of flow was measured near the lower intake at station 9 (table 12). In the case that all the water in the stream is diverted at the upper intake, the amount of water remaining in the stream near the lower intake would be 5.97 Mgal/d less 1.50 Mgal/d (amount diverted at the upper intake), or 4.47 Mgal/d. In the case that all the water is diverted at the upper and lower intakes, the amount of water remaining in the stream at the downstream-most discharge-measurement location on Anahola Stream (station 12, fig. 16) would be 8.47 Mgal/d (discharge measured at station 12) less 1.50 Mgal/d (amount diverted at the upper intake) and 4.47 Mgal/d (amount diverted at the lower intake), or 2.50 Mgal/d. These scenarios assume that the groundwater gains observed during the wet-season seepage run are representative of groundwater gains in Anahola Stream for the period when water is diverted.

The Hawaii State Water Code mandates that the Commission on Water Resource Management (CWRM) establish a statewide instream-use protection program (Chapter 174C-71, Hawaii Revised Statutes) for the purpose of protecting instream uses. The principal mechanism that the CWRM has for protecting these instream uses is to establish instream-flow standards. “Each instream flow standard shall describe the flows necessary to protect the public interest in the particular stream. Flows shall be expressed in terms of variable flows of water necessary to protect adequately fishery, wildlife, recreational, aesthetic, scenic, or other beneficial instream uses in the stream in light of existing and potential water developments including the economic impact of restriction of such use” (Chapter 174C-71, Hawaii Revised Statutes). The amount of surface water available for agricultural use in the Anahola Stream drainage basin may be reduced when CWRM establishes an instream-flow standard for Anahola Stream.

Estimated, natural flow-duration curves can be adjusted, based on a given instream-flow standard, to determine how much water is available for agricultural use. A discharge equal to the instream-flow standard is required to remain in the stream at a specific location and, therefore, is not available for offstream uses such as agriculture. The estimated, natural flow-duration discharge less the discharge equal to the instream-flow standard is the amount of water available for agricultural use. Low-flow duration discharges estimated at the LFPR stations can be used to assess the amount of water available under low-flow conditions in the case that the instream-flow standard is established at one of the LFPR stations on Anahola Stream. The amount of surface water available for agricultural use upstream of the upper intake (station 16085500), between 50 and 95 percent of the time, given a variety of instream-flow standards potentially established by the CWRM at that location is shown in figure 18. The estimated, natural flow-duration discharges at this LFPR station that were adjusted to compute surface-water availability for agricultural use are presented in table 11. In the hypothetical case that no instream-flow standard is established

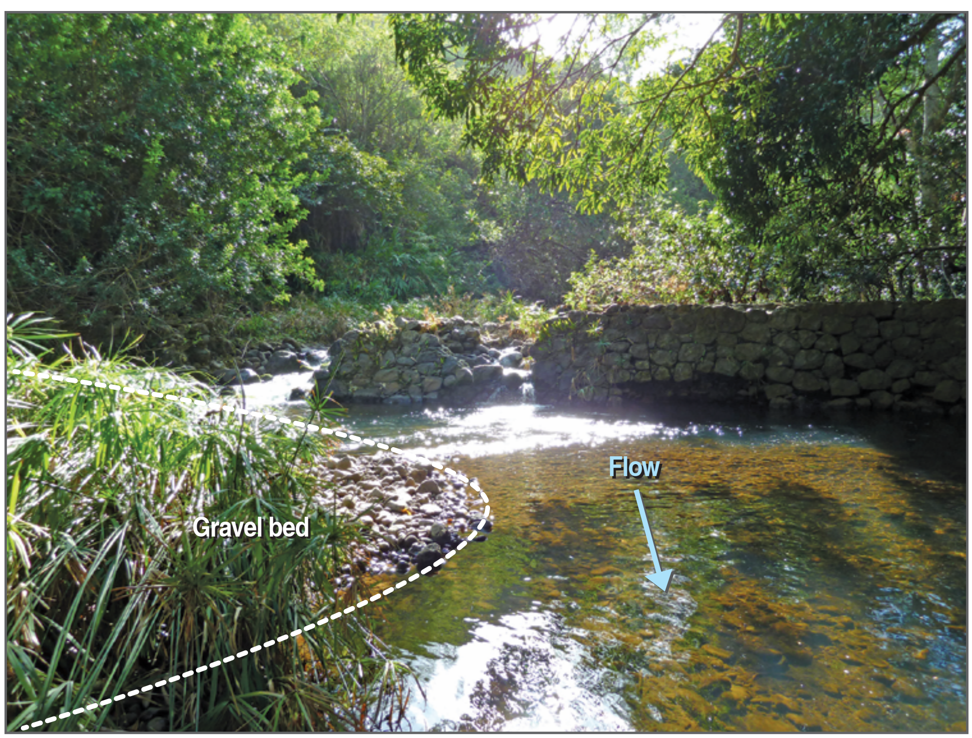


Figure 17. Photograph of raised gravel bed on the right bank immediately upstream of seepage-run measurement station 220854159210601 (station 9) on Anahola Stream, Kaua‘i, Hawai‘i.

in Anahola Stream and the stream is allowed to run dry, the uppermost curve in figure 18 would represent the amount of water available upstream of the upper intake, between 50 and 95 percent of the time, for agricultural use. The four additional curves represent the amount of water available for agricultural use upstream of the upper intake when the Q_{95}, Q_{90}, Q_{80}, and Q_{70} discharges estimated at station 16085500 (table 11) are flows required by CWRM to remain in the stream. For example, if the instream-flow standard established upstream of the upper intake at station 16085500 is the Q_{95} discharge of 0.97 Mgal/d, no diversion of water may occur 5 percent of the time, corresponding to when the flow in the stream is 0.97 Mgal/d or less. The amount of water potentially available for diversion at the upper intake would be greater than or equal to 1.7 Mgal/d 50 percent of the time. If the instream-flow standard established is the Q_{70} discharge of 1.8 Mgal/d, no diversion of water may occur 30 percent of the time, corresponding to when the flow in the stream is 1.8 Mgal/d or less. The amount of water potentially available for diversion at the upper intake would be greater than or equal to 0.90 Mgal/d 50 percent of the time. Generally, the amount of water available for agricultural use would decrease as the amount of water required to remain in the stream increases.

Limitations of Approach

Low-flow duration discharges at the LFPR stations were estimated using the MOVE.1 record-augmentation technique. The accuracy of the estimates is largely associated with (1) the strength of the correlation between concurrent discharges at the index and LFPR stations; (2) the number of LFPR measurements available for record-augmentation analysis; and (3) how accurately the period of record (base period) from which the flow-duration discharges at the index stations were computed represents long-term flow conditions. Selected regression statistics computed by the SREF program that help to evaluate the record-augmentation results are presented in table 10. Correlation coefficients (r) of the MOVE.1 statistical relations are between 0.88 and 0.96, indicating strong correlations between concurrent discharges at the index and LFPR stations. The relatively small RMSE values suggest that the statistical relations generally provide accurate predictions of the flow-duration discharges at the LFPR stations. The MOVE.1 statistical relations with index station 16071500 appear to provide slightly more accurate low-flow duration estimates than the relations with index station 16097500, as indicated by generally higher coefficients of efficiency (E). The uncertainty of flow-duration discharges represented by these regression statistics should be considered minimums because the record-augmentation technique used does not consider the potential errors inherent in the daily mean discharge at the index stations and the discharge measurements made at the LFPR stations (Fontaine, 2003, p.35). A majority of the discharge measurements made at the LFPR stations were rated good or fair, which indicates that measurement errors of 5 to 8 percent were possible.

Each of the MOVE.1 statistical relations was developed based on nine discharge measurements made at the LFPR stations during the study period. These measured discharges were generally within flow percentiles between 95 and 45. Additional discharge measurements may increase the level of confidence of the estimated flow-duration discharges at the LFPR stations. The flow-duration statistics at the index stations and estimates at the LFPR stations are applicable to the base period over which they have been computed. For this study, 51 water years of streamflow data (1961—2011)

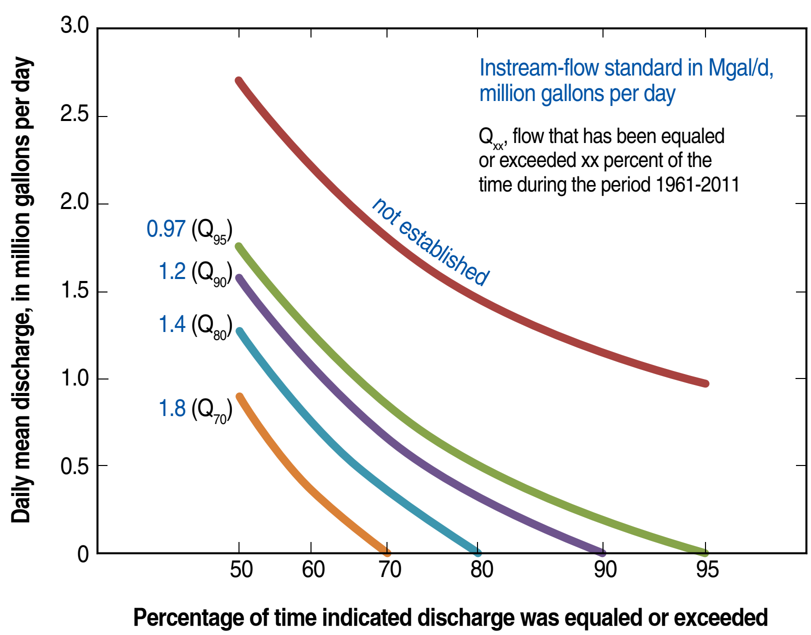


Figure 18. Plot showing flow-duration curves indicating the amount of flow available for agricultural use at the Upper Anahola Ditch diversion intake, Kaua‘i, Hawai‘i, based on data for water years 1961–2011 under a variety of potential instream-flow standards.

were available at the index stations. Considering the length of record, the flow-duration statistics are considered to be reasonably representative of the long-term flow conditions at the index stations and provide flow-duration discharge estimates at the LFPR stations that are representative of long-term flow conditions. Extrapolation of flow-duration statistics beyond the base period assumes that the hydrologic condition of the streams during the extrapolation period is similar to the condition during the past 51 years.

Seepage gains and losses within a reach were computed as the difference between the upstream and downstream discharges, excluding any measured tributary inflows within the reach. Given the potential error inherent in the seepage-run discharge measurements, which could be as much as 5 to 8 percent for measurements rated good and fair, the estimated seepage gains and losses may not accurately reflect the true gain or loss in flow within the reach. Measured tributary inflows within the reach introduce additional errors to the seepage gain and loss estimates. In the upper reaches of Anahola Stream, some of the estimated seepage gains include minor surface inflows from the banks that were too low to measure with the available equipment. Thus, the true gains in flow may be slightly lower than the estimated gains.

Summary and Conclusions

The purpose of this study is to provide information on the availability and distribution of natural low flow in Anahola Stream. Low-flow data were also collected from Goldfish Stream, a stream that discharges into Kaneha Reservoir. This information can be used for water-management decisions for the Anahola drainage basin. The availability and distribution of low flow was determined using a combination of discharge measurements made between February 2011 and May 2012 at low-flow partial-record (LFPR) and seepage-run stations established at sites of interest. Reconnaissance-level biological surveys of Anahola Stream were conducted as part of the study to determine the distribution of native and nonnative aquatic stream fauna. Results of the biological surveys indicated the presence of the following native aquatic species in Anahola Stream: ‘o‘opu ‘akupa and ‘o‘opu naniha in the lower stream reaches surveyed; and ‘o‘opu nākea, ‘o‘opu nōpili, and ‘ōpae kala‘ole in the middle and upper stream reaches surveyed. Nonnative aquatic species were found in all of the surveyed stream reaches along Anahola Stream.

For this study, four LFPR stations were established to characterize natural low-flow availability in the study-area streams. Three stations were established on Anahola Stream, one about 450 ft upstream from the Upper Anahola Ditch intake, one about 50 ft upstream from the confluence with tributary Kea‘o‘opu Stream, and one on tributary Kea‘o‘opu Stream about 80 ft upstream from the confluence with Anahola Stream. One station was established on Goldfish Stream about 0.4 mi upstream from the point of discharge into Kaneha Reservoir. Natural low-flow duration discharges were estimated at the LFPR stations using the MOVE.1 record-augmentation technique. Low-flow conditions at the LFPR stations on the main channel of Anahola Stream were characterized by flow-duration discharges between the 95th (Q_{95} discharge) and 50th (Q_{50} discharge) percentiles. The Q_{95} to Q_{50} discharges at the LFPR station on Anahola Stream upstream of the upper diversion intake ranged from 0.97 to 2.7 Mgal/d, and those at the station on Anahola Stream upstream of the confluence with Kea‘o‘opu Stream ranged from 1.7 to 4.2 Mgal/d. Low-flow conditions at the LFPR stations on Kea‘o‘opu and Goldfish Streams were characterized by flow-duration discharges between the 95th and 20th percentiles. The Q_{95} to Q_{20} discharges at the LFPR station on Kea‘o‘opu Stream ranged from 0.76 to 2.4 Mgal/d, and that at the station on Goldfish Stream ranged from 0.23 to 0.84 Mgal/d. On Anahola Stream immediately downstream of its confluence with Kea‘o‘opu Stream, the Q_{95} to Q_{50} discharges ranged from 2.7 to 6.3 Mgal/d. These flow-duration estimates are applicable to the base period (water years 1961–2011) over which they have been computed. Caution must be used when extrapolating flow-duration statistics beyond the base period as the hydrologic condition of the streams may change in the future.

Wet- and dry-season seepage runs were conducted to characterize seasonal low-flow distribution along Anahola Stream. About 12 to 13 discharge measurements were made during each seepage run. Results of the seepage runs indicate that Anahola Stream was generally a gaining stream under natural flow conditions. Discharges measured in the wet-season seepage run were generally higher and the total amount of groundwater gain was larger than that of the dry-season seepage run. During the wet-season seepage run, Anahola Stream at the downstream-most station had more than five times the flow that was measured at the station upstream of the upper intake. The estimated total gain (including tributary inflow) in the 6.1-mi seepage-run reach was 6.97 Mgal/d and about 42 percent of that gain was from groundwater discharge to the main channel of Anahola Stream. During the dry-season seepage run, about 34 percent of the estimated total gain (3.93 Mgal/d) was from groundwater discharge to the main channel of Anahola Stream. The relatively large amount of base flow (groundwater discharge) observed was a result of local hydrogeologic characteristics of the aquifer system, which may be similar to that of the southern Līhu‘e Basin and characterized by low-permeability (low hydraulic conductivity) lava flows that are saturated to near land surface. In the reaches where estimated seepage flows were within the range of potential error associated with the discharge measurements, the estimated seepage flows may not represent the true seepage flows within the reaches.

Results of this study were used in scenarios that describe (1) surface-water availability under regulated conditions of Anahola Stream if the upper and lower intakes are restored in the future; and (2) amount of flow available for agricultural use at the upper intake under a variety of potential instream-flow standards established by the State of Hawaiʻi for the protection of instream uses. Based on the wet-season seepage-run discharge measurements, in the case that the upper intake diverts all the water (1.50 Mgal/d) in Anahola Stream, the amount of water remaining in the stream near the lower intake would be about 4.47 Mgal/d. The scenario assumes that the groundwater gains observed during the wet-season seepage run are representative of the groundwater gains in Anahola Stream for the period when water is diverted. Low-flow duration discharges estimated upstream of the upper intake on Anahola Stream were used to determine the amount of water available for agricultural use under a variety of instream-flow standard potentially established at that location. If the instream-flow standard established upstream of the upper intake is the Q_{95} discharge of 0.97 Mgal/d, no diversion of water may occur 5 percent of the time, corresponding to when the flow in the stream is 0.97 Mgal/d or less. The amount of water potentially available for diversion at the upper intake would be greater than or equal to 1.7 Mgal/d 50 percent of the time. Generally, the amount of water available for agricultural use would decrease as the amount of water required to remain in the stream increases.

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