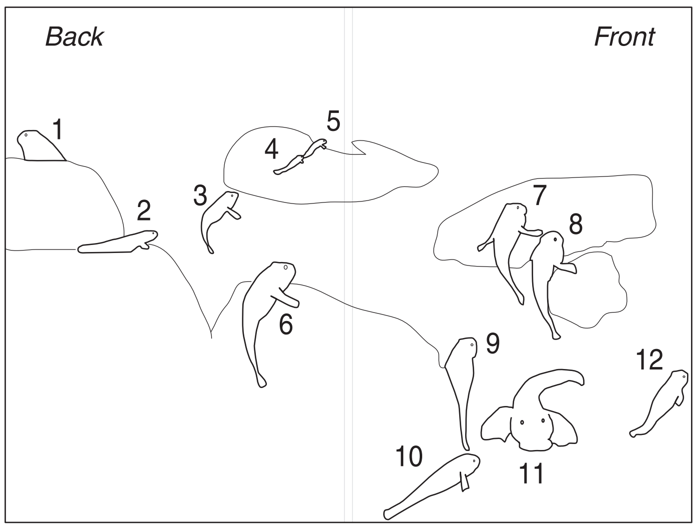
USGS
science for a changing world

Prepared in Cooperation with the County of Maui Office of Economic Development, County of Maui Department of Water Supply, State of Hawai‘i Commission on Water Resource Management, State of Hawai‘i Office of Hawaiian Affairs

Effects of Surface-Water Diversion on Streamflow, Recharge, Physical Habitat, and Temperature, Nā Wai ‘Ehā, Maui, Hawai‘i

Scientific Investigations Report 2010–5011

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



About the cover: Native fish in South Waiehu Stream:
1, 3, 6, 7, 8, and 11, ‘o‘opu nākea;
2, 4, 5, and 10, ‘o‘opu ‘alamo‘o;
9 and 12, ‘o‘opu nōpili.
Photograph by Reuben H. Wolff.

Effects of Surface-Water Diversion on Streamflow, Recharge, Physical Habitat, and Temperature, Nā Wai ‘Ehā, Maui, Hawai‘i

By Delwyn S. Oki, Reuben H. Wolff, and Jeff A. Perreault

Prepared in Cooperation with the County of Maui Office of Economic Development, County of Maui Department of Water Supply, State of Hawai‘i Commission on Water Resource Management, State of Hawai‘i Office of Hawaiian Affairs

Scientific Investigations Report 2010–5011

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

U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

This report and any updates to it are available online at:
http://pubs.usgs.gov/sir/2010/5011/

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications,
visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Oki, D.S., Wolff, R.H., and Perreault, J.A., 2010, Effects of surface-water diversion on streamflow, recharge, physical habitat, and temperature, Nā Wai ʻEhā, Maui, Hawaiʻi: U.S. Geological Survey Scientific Investigations Report 2010–5011, 154 p.

Cataloging-in-publication data are on file with the Library of Congress (http://catalog.loc.gov/).

Executive Summary

This report presents results of a study to characterize the effects of existing surface-water diversions on streamflow, groundwater recharge, physical habitat for native stream fauna, and water temperature in Waiheʻe River, Waiehu Stream, ʻĪao Stream, and Waikapū Stream, collectively known as Nā Wai ʻEhā ("The Four Streams"), Maui, Hawaiʻi (fig. ES1). This study arose out of a need for additional scientific information related to the surface-water resources in the Nā Wai ʻEhā area. Existing diversions are capable of diverting all or nearly all of the dry-weather flows of these streams, leaving some downstream reaches dry. A lack of sufficient water downstream of existing diversions has led to recent conflicts between those currently (2009) diverting or using the water and those desiring sufficient instream flows for protection of traditional and customary Hawaiian rights (including the cultivation of taro), maintenance of habitat for native stream fauna, recreation, and aesthetics. The County of Maui Department of Water Supply currently withdraws groundwater from the aquifers potentially recharged by these streams. Thus, an understanding of the effects of the diversions on groundwater recharge also is essential for proper planning and management of the resource. Factors that likely will play a role in future planning and management decisions include (1) the use of stream water for agriculture, protection of traditional and customary Hawaiian rights, and maintenance of ecologic balance, (2) aesthetic differences between dry and flowing streams, and (3) recreational use of the streams (fishing, swimming). The U.S. Geological Survey (USGS) undertook the present investigation in cooperation with the County of Maui Office of Economic Development, County of Maui Department of Water Supply, State of Hawaiʻi Commission on Water Resource Management, and State of Hawaiʻi Office of Hawaiian Affairs.

General Characteristics of Streams

The streams of the Nā Wai ʻEhā area flow in their upper reaches even during extended dry-weather conditions because of persistent groundwater discharge to the streams. The lower reaches of these streams generally lose water, which may contribute to groundwater recharge. During 1984–2007, Waiheʻe River had the greatest median natural, undiverted flow (upstream of the uppermost diversion) of the four streams. The median undiverted flows during climate years 1984–2007 were 34 Mgal/d (million gallons per day) for Waiheʻe River near an altitude of 605 feet; 25 Mgal/d for ʻĪao Stream near an altitude of 780 feet; and estimated to be about 4.3 Mgal/d for Waikapū Stream near an altitude of 1,160 feet; 3.2 Mgal/d for South Waiehu Stream near an altitude of 870 feet; and 3.2 Mgal/d for North Waiehu Stream near an altitude of 880 feet. As of 2009, water is diverted from each stream by three to five diversion intakes (table ES1; fig. ES2). Hourly photographs collected during 2006–2008 indicate that some stream reaches downstream of diversions are dry more than 50 percent of the time (fig. ES3). Many of these reaches would be perennial or nearly perennial in the absence of diversions.

Stream Fauna

Snorkel surveys during 2008 identified the presence of native fauna in each of the Nā Wai ʻEhā streams. Native fauna observed in the Nā Wai ʻEhā streams include an endemic mountain shrimp (ʻōpae); endemic gobies (ʻoʻopu ʻalamoʻo and ʻoʻopu nōpili); an indigenous goby (ʻoʻopu nākea); and an endemic eleotrid (ʻoʻopu ʻakupa). During the period of this study, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, and ʻoʻopu nākea were observed in each of Waiheʻe River, ʻĪao Stream, and Waiehu Stream (see cover photograph), although only a single unidentified individual ʻoʻopu was observed in Waikapū Stream. The amphidromous life cycle (requiring time in both the ocean and the stream) of the native fauna requires stream connectivity to the ocean to enable recruitment, and any condition that impedes the mauka to makai (mountain to ocean) connectivity can affect the distribution and abundance of the amphidromous fauna.

Mauka to Makai Flows

Each of the Nā Wai ʻEhā streams generally loses water, by infiltration into the streambed, over its lower reaches downstream of diversions. If no water had been diverted from the Nā Wai ʻEhā streams during climate years 1984–2007, Waiheʻe River and ʻĪao Stream would have flowed continuously to the coast; Waiehu Stream would have flowed continuously to the coast at least 95 percent of the time; and Waikapū Stream would have flowed continuously to the coast less than half of the time. The minimum undiverted flows, upstream of the uppermost diversion in each stream, necessary to maintain continuous flow near the coast, are: 1 Mgal/d for Waiheʻe River; 1.3 Mgal/d for North Waiehu Stream and 1.1 Mgal/d for South Waiehu Stream; 5.2 Mgal/d for ʻĪao Stream; and 6.8 Mgal/d for Waikapū Stream.

Groundwater Recharge

Because each stream loses water in its lower reaches, these streams represent potential sources of groundwater recharge for the underlying aquifer. For natural, undiverted

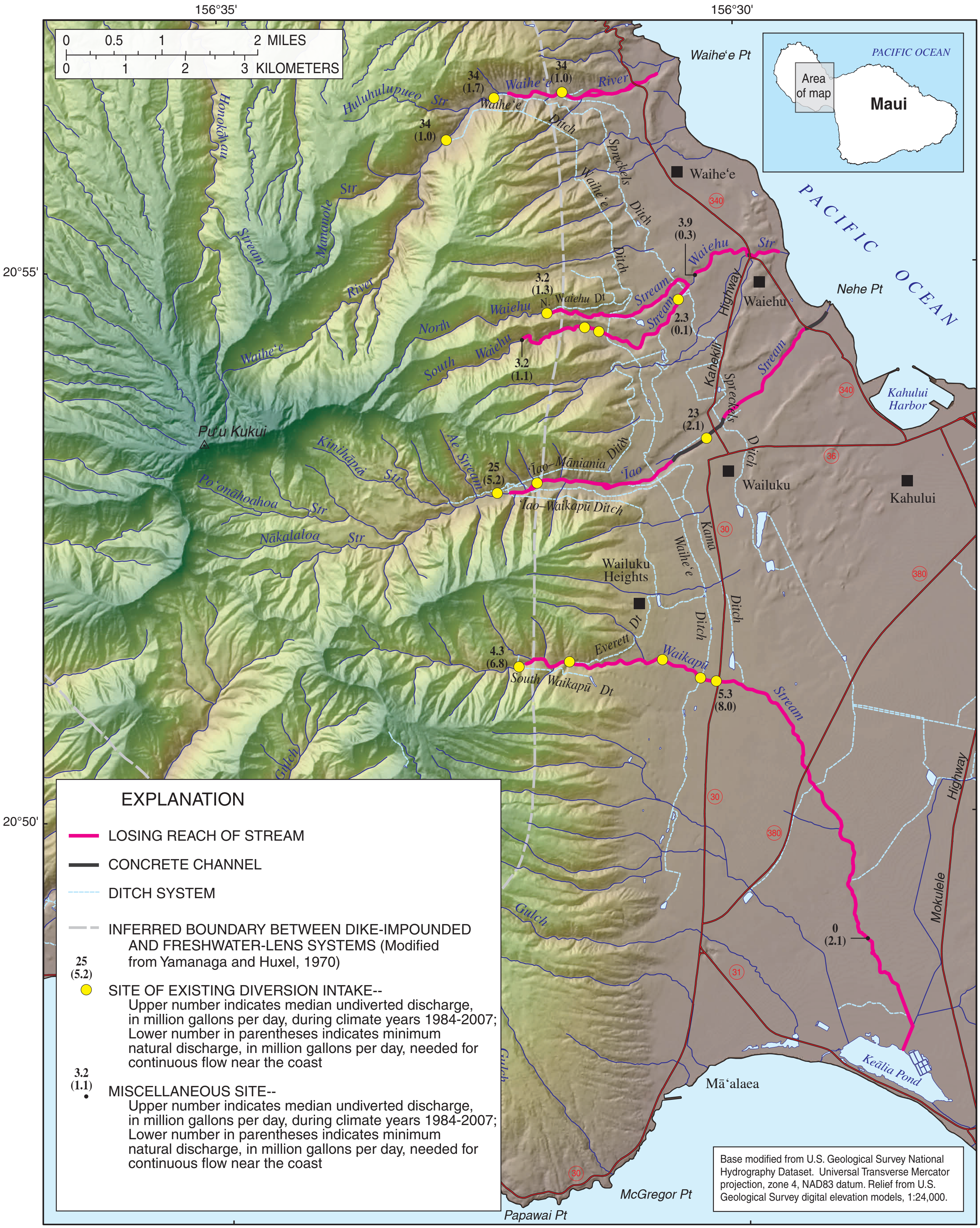


Figure ES1. Streams, diversion intakes, and major ditch systems, Nā Wai ʻEhā area, Maui, Hawaiʻi.

Table ES1. Surface-water diversion intakes, Nā Wai ʻEhā, Maui, Hawaiʻi.

[—, data not available; Mgal/d, million gallons per day]

Intake of ditch system or small private ʻauwai (ditch)	Altitude, in feet[a]	Design capacity, in Mgal/d	Intake capacity setting, in Mgal/d
Waiheʻe River			
Waiheʻe Ditch	600	[b]60	[c]40
Spreckels Ditch	400	[b]30	[c]12
Field 1	260	—	—
North Waiehu Stream			
North Waiehu Ditch	880	—	[c]1.5
South Waiehu Stream			
Left (north) ʻauwai	620	—	—
Right (south) ʻauwai	570	—	—
Spreckels Ditch	270	—[d]	—[d]
ʻĪao Stream			
ʻĪao-Waikapū and ʻĪao-Māniania Ditches	780	[b]60	[c]20
Right (south) ʻauwai	650	—	—
Spreckels Ditch	250	—[e]	—[e]
Waikapū Stream			
South Side Ditch	1,120	[b]5	[c]3
Everett (Palolo) Ditch	900	—	—
Left (north) ʻauwai	560	—	—
Waiheʻe Ditch	440	—[d]	—[d]
Reservoir 6	410	—[d]	—[d]

[a]Altitude determined from topographic map.
[b]Suzuki (2007).
[c]Gate setting (Suzuki, 2007).
[d]Capacity unknown but greater than 1 Mgal/d.
[e]Capacity unknown but likely greater than 10 Mgal/d.

low-flow conditions (when flow is less than or equal to the median flow) the estimated average seepage loss from each stream, downstream of the uppermost diversion, is: 1.7 Mgal/d for Waiheʻe River; 2.9 Mgal/d for North Waiehu Stream, South Waiehu Stream, and Waiehu Stream; 5.6 Mgal/d for ʻĪao Stream; and 4.3 Mgal/d for Waikapū Stream. Existing surface-water diversions in Waiheʻe River, ʻĪao Stream, and Waikapū Stream are capable of reducing the amount of recharge during periods of low flow by more than 80 percent relative to undiverted conditions, and existing diversions in Waiehu Stream are capable of reducing the amount of recharge by more than 33 percent. This potential loss in groundwater recharge may affect the quantity of groundwater that can be developed from the underlying aquifer, which is important to the water supply of the island. This report presents families of curves that show the relation between surface-water diversion capacities and recharge reduction (see figs. 58–61). These curves can be used to assist with water-management decisions by identifying diversion intake capacities that will lead to an acceptable reduction in groundwater recharge.

Figure ES2. Photograph of a typical diversion intake that commonly stretches across the entire low-flow channel of a stream (Reservoir 6 intake on Waikapū Stream, Maui, Hawaiʻi, March 17, 2005). Water that enters the intake grate drains into a collection sump and flows by gravity into a ditch system.

Figure ES3. Photograph of dry streambed caused by upstream diversions, ʻĪao Stream, Maui, Hawaiʻi (September 22, 2006).

Physical Habitat

Diversion of surface water from a stream generally reduces the amount of physical habitat available for native stream fauna during low-flow conditions. A generalized relation between physical habitat and discharge developed for this study indicates that if diversions reduce streamflow to half of the natural, undiverted Q_{70} discharge (discharge that

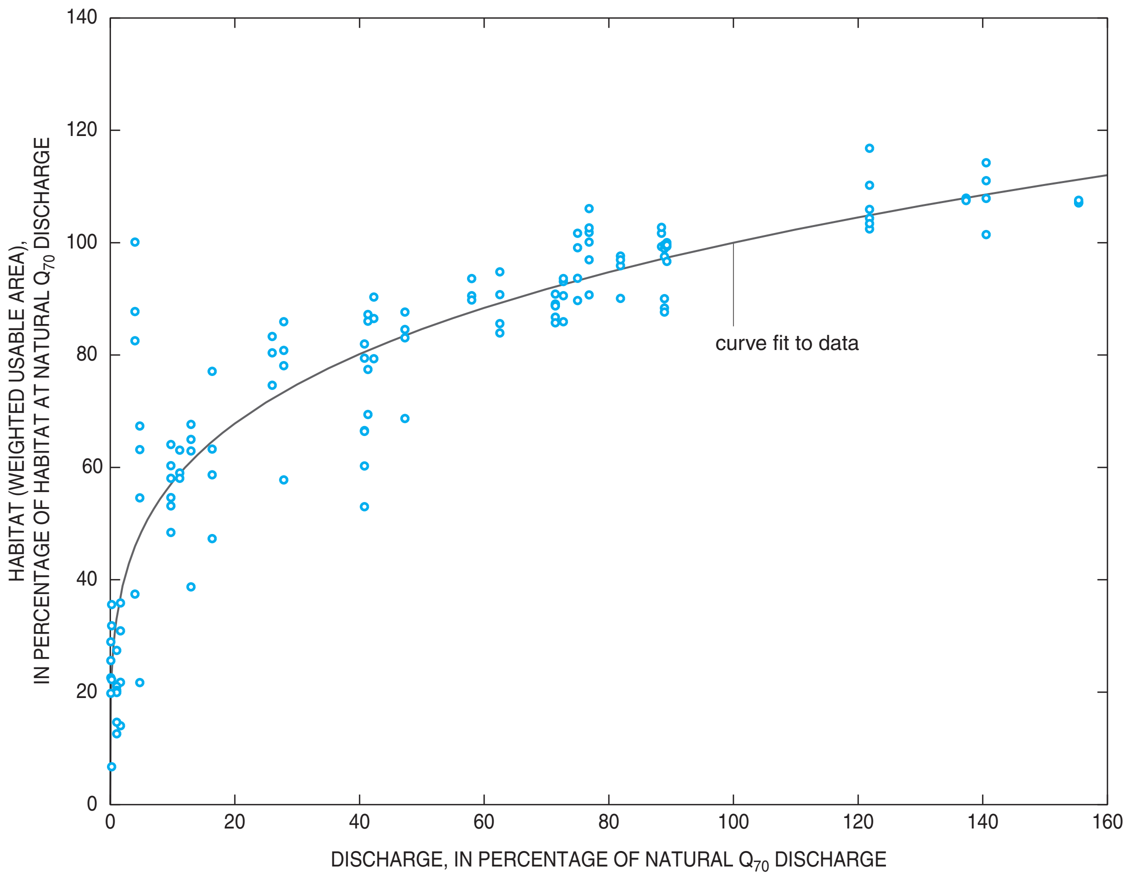


Figure ES4. Generalized relation between habitat and discharge for ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, ʻoʻopu nākea, ʻōpaekalaʻole, and hīhīwai in Waiheʻe River and Waiehu, ʻĪao, and Waikapū Streams, Maui, Hawaiʻi. The Q_{70} discharge is the discharge that is equaled or exceeded 70 percent of the time.

is equaled or exceeded 70 percent of the time), which is an indicator of median base-flow conditions, then habitat will be reduced to about 80 percent of what it would be at the Q_{70} discharge (fig. ES4). During some periods, physical habitat is reduced to zero in stream reaches that are dry because of surface-water diversions. This report presents families of curves for each stream (see figs. 69–72) that can be used to quantify the reduction in habitat downstream of all diversions for different diversion capacities. These curves can be used to assist with water-management decisions by identifying diversion intake capacities that will accommodate a target habitat quantity.

Temperature

During September 2006 to October 2007, when water temperatures in the streams were measured for this study, daily maximum temperatures did not exceed 27°C and daily minimum temperatures did not drop below 15°C at any of the 18 study sites. At all of the study sites, daily maximum temperatures remained below the upper-lethal-temperature limits for native aquatic species, as well as below the temperature that favors Pythium rot of taro. Water temperatures may decrease at some sites downstream of existing diversions if flow is restored to streams, although the effects of reduced temperatures on taro cultiviation were not studied.

Additional Information and Research Needs

Streamflow characteristics estimated for this study can be more precisely determined by establishing long-term, continuous-record stream-gaging stations at selected sites of interest upstream of diversions in Waiehu and Waikapū Streams and downstream of diversions in all streams. These gaging stations also would provide useful information for quantifying streamflow losses and groundwater recharge. Restoration of diverted water at different rates for extended periods (exceeding a few weeks) would allow better characterization of the effects of surface-water diversions on recharge and physical habitat. This study does not predict the effects of flow restoration on native species abundance, nor does this study address water requirements for taro cultivation and aesthetic or recreational uses, algae and invertebrate food sources for native macrofauna, or reproduction of native species.

Contents

Figures

Tables

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
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)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
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)

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 to mean sea level.
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).
Altitude, as used in this report, refers to distance above the vertical datum.

Effects of Surface-Water Diversion on Streamflow, Recharge, Physical Habitat, and Temperature, Nā Wai ʻEhā, Maui, Hawaiʻi

By Delwyn S. Oki, Reuben H. Wolff, and Jeff A. Perreault

Abstract

The perennial flow provided by Waiheʻe River, Waiehu Stream, ʻĪao Stream, and Waikapū Stream, collectively known as Nā Wai ʻEhā ("The Four Streams"), made it possible for widespread agricultural activities to flourish in the eastern part of West Maui, Hawaiʻi. The streams of the Nā Wai ʻEhā area flow in their upper reaches even during extended dry-weather conditions because of persistent groundwater discharge to the streams. Overall, the lower reaches of these streams lose water, which may contribute to groundwater recharge.

During climate years 1984–2007 (when complete streamflow records were available for Waiheʻe River and ʻĪao Stream), Waiheʻe River had the greatest median flow of the four streams upstream of the uppermost diversion on each stream. The median flows, in million gallons per day, during climate years 1984–2007 were: 34 for Waiheʻe River near an altitude of 605 feet; 25 for ʻĪao Stream near an altitude of 780 feet; and estimated to be 4.3 for Waikapū Stream near an altitude of 1,160 feet; 3.2 for North Waiehu Stream near an altitude of 880 feet; and 3.2 for South Waiehu Stream near an altitude of 870 feet. Existing stream diversions in the Nā Wai ʻEhā area have a combined capacity exceeding at least 75 million gallons per day and are capable of diverting all or nearly all of the dry-weather flows of these streams, leaving some downstream reaches dry. Hourly photographs collected during 2006–2008 indicate that some stream reaches downstream of diversions are dry more than 50 percent of the time. Many of these reaches would be perennial or nearly perennial in the absence of diversions.

A lack of sufficient streamflow downstream of existing diversions has led to recent conflicts between those currently diverting or using the water and those desiring sufficient instream flows for protection of traditional and customary Hawaiian rights (including the cultivation of taro), maintenance of habitat for native stream fauna, recreation, aesthetics, and groundwater recharge from loss of water through the streambed. In response to a need for additional information, the U.S. Geological Survey (USGS) undertook the present investigation to characterize the effects of existing surface-water diversions on (1) streamflow, (2) potential groundwater recharge from the streams to the underlying groundwater body, (3) physical habitat for native stream fauna (fish, shrimp, and snails), and (4) instream temperatures.

Information collected for this study includes discharge measurements under different streamflow conditions to characterize streamflow and seepage losses, hourly photographs of stream conditions from mounted cameras, snorkel surveys of stream fauna, measurements of microhabitat (depth, velocity, and substrate) under different flow conditions, and measurements of water temperatures. Families of curves were developed to show the relations between surface-water diversion intake capacity (the maximum rate that an intake can divert) and (1) selected duration discharges for sites near the coast; (2) selected duration discharges for the diversions; (3) groundwater-recharge reduction; and (4) physical-habitat reduction for native stream fauna. These curves may be used by water managers to evaluate the effects of different diversion intake capacities on streamflow, water available for offstream use, groundwater recharge, and habitat for native stream fauna. Results of this study indicate the following:

1. If no water had been diverted from the Nā Wai ʻEhā streams during climate years 1984–2007, Waiheʻe River and ʻĪao Stream would have flowed continuously to the coast; Waiehu Stream would have flowed continuously to the coast at least 95 percent of the time; and Waikapū Stream would have flowed continuously to the coast less than half of the time.
2. The minimum flows upstream of the uppermost diversion in each stream necessary to maintain continuous flow near the coast, assuming no downstream diversions, are: 1 million gallons per day for Waiheʻe River; 1.3 million gallons per day for North Waiehu Stream and 1.1 million gallons per day for South Waiehu Stream; 5.2 million gallons per day for ʻĪao Stream; and 6.8 million gallons per day for Waikapū Stream.
3. For main diversions in their current (2009) configurations (ignoring the smaller private ʻauwai, or ditches, and assuming none of the diverted water is returned to streams), estimated median streamflows are zero for Waiheʻe River near an altitude of 45 feet, ʻĪao Stream near an altitude of 35 feet, and Waikapū Stream near an altitude of 400

feet, and about a third of the natural, undiverted value for Waiehu Stream near an altitude of 20 feet.

4. For natural, undiverted low-flow conditions (when flow is less than or equal to the median flow) the estimated average seepage loss (representing potential groundwater recharge) from each stream, downstream of the uppermost diversion, is: 1.7 million gallons per day for Waiheʻe River; 2.9 million gallons per day for North Waiehu Stream, South Waiehu Stream, and Waiehu Stream; 5.6 million gallons per day for ʻĪao Stream; and 4.3 million gallons per day for Waikapū Stream.
5. For low-flow conditions and main diversions in their current (2009) configurations (ignoring the smaller private ʻauwai and assuming none of the diverted water is returned to streams), surface-water diversions reduce potential groundwater recharge in stream channels by: 1.7 million gallons per day for Waiheʻe River; 1 million gallons per day for North Waiehu Stream, South Waiehu Stream, and Waiehu Stream; 4.8 million gallons per day for ʻĪao Stream; and 4 million gallons per day for Waikapū Stream.
6. Snorkel surveys conducted during 2008 identified the presence of native fauna in each of the Nā Wai ʻEhā streams. Native fauna observed in the Nā Wai ʻEhā streams include the endemic mountain shrimp, ʻōpaekalaʻole (*Atyoida bisulcata*); endemic gobies, ʻoʻopu ʻalamoʻo (*Lentipes concolor*) and ʻoʻopu nōpili (*Sicyopterus stimpsoni*); the indigenous goby, ʻoʻopu nākea (*Awaous guamensis*); and an endemic eleotrid, ʻoʻopu ʻakupa (*Eleotris sandwicensis*).
7. In general, data indicate that physical habitat increases monotonically with discharge up to the median natural discharge. Thus, diversion of surface water from a stream reduces the amount of physical habitat available during low-flow conditions. A generalized relation between physical habitat and discharge was developed for this study.
8. For low-flow conditions and main diversions in their current (2009) configurations (ignoring the smaller private ʻauwai and assuming none of the diverted water is returned to streams), surface-water diversions reduce physical habitat for native stream fauna by: 100 percent for Waiheʻe River near an altitude of 45 feet; more than 60 percent for Waiehu Stream near an altitude of 20 feet; 100 percent for ʻĪao Stream near an altitude of 35 feet; and more than 90 percent for Waikapū Stream near an altitude of 400 feet.
9. During September 2006 to October 2007, when water temperatures were measured for this study, daily maximum temperatures did not exceed 27°C and daily minimum temperatures did not drop below 15°C at any of the study sites. At all of the study sites, daily maximum temperatures remained below the upper-lethal-temperature limits for native aquatic species, as well as below the temperature that favors Pythium rot of taro, although water temperatures were not measured in reaches that commonly had zero flow.

Introduction

The eastern part of West Maui, Hawaiʻi, mainly is drained by Waiheʻe River, Waiehu Stream, ʻĪao Stream, and Waikapū Stream (fig. 1), collectively known as Nā Wai ʻEhā or “The Four Streams” (Handy and Handy, 1991). (ʻĪao Stream is sometimes referred to as Wailuku Stream, but for the purposes of this report it will be referred to as ʻĪao Stream.) The headwaters of Waiheʻe River and ʻĪao Stream extend to or near the summit of the West Maui Mountain at Puʻu Kukui, where mean annual rainfall exceeds 350 in. Waiheʻe River and ʻĪao Stream are among the largest streams, in terms of streamflow, on Maui. North and South Waiehu Streams join near an altitude of about 220 ft to form Waiehu Stream. The headwaters of North and South Waiehu Streams are cut off from the summit area of the West Maui Mountain by the valleys of Waiheʻe River to the north and ʻĪao Stream to the south. Waikapū Stream is the only Nā Wai ʻEhā stream that drains to the southern coast of Maui. The headwater area of Waikapū Stream is truncated by the valleys of ʻĪao Stream to the north and Olowalu Stream to the west.

In the upper reaches where the stream channels intersect the groundwater body, groundwater discharge contributes to streamflow. Groundwater discharge to the streams of the Nā Wai ʻEhā area creates flow in the upper reaches even during extended dry-weather conditions. The dependable flow of water provided by Waiheʻe River, Waiehu Stream, ʻĪao Stream, and Waikapū Stream made it possible for widespread agricultural activities to flourish in the Nā Wai ʻEhā area. The lower reaches of the streams generally lose water because of infiltration into the streambed, and this loss may contribute to groundwater recharge of the underlying aquifer.

Surface water in the Nā Wai ʻEhā area traditionally supported large areas of kalo (taro) cultivation by Native Hawaiians. The area between the valleys of Waiheʻe River and ʻĪao Stream was at one time the largest area of wetland-taro cultivation in the Hawaiian Islands (Handy and Handy, 1991). Taro currently (2009) is cultivated in the Nā Wai ʻEhā area for commercial and individual purposes (fig. 2), although to a much lesser extent than in the past. Starting in the 19th century, large-scale sugarcane plantations began to dominate the landscape at altitudes mainly below about 600 feet in the Nā Wai ʻEhā area. Surface water was diverted from streams to meet irrigation needs for sugarcane cultivation (Wilcox, 1996; Yamanaga and Huxel, 1970). Yamanaga and Huxel (1970) indicated that an average of about 67 million gallons per day (Mgal/d) was diverted, mainly for sugarcane irrigation, from Waiheʻe River, Waiehu Stream, ʻĪao Stream, and Waikapū Stream. (Discharge is measured by the U.S. Geological Survey [USGS] in terms of cubic feet per second [ft^3/s], and all

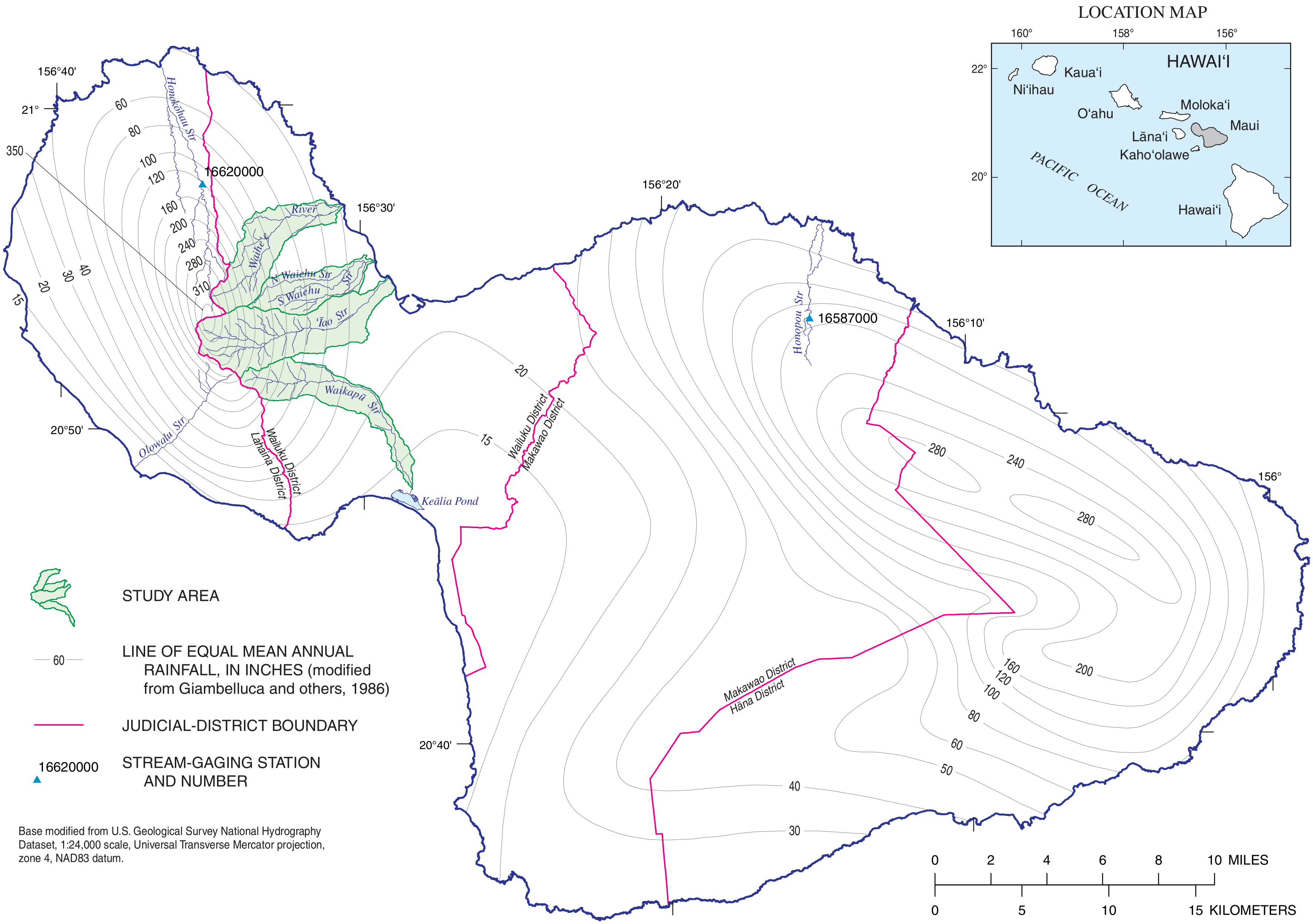


Figure 1. Nā Wai 'Ehā study area, Maui, Hawai'i.

Figure 2. Photograph of taro being cultivated near Waiheʻe River, Maui, Hawaiʻi (June 8, 2006).

computations in this report were made in terms of ft^3/s. Where applicable, discharge values are reported in the original ft^3/s units as well as the converted units of Mgal/d.)

In 1987, about 53 percent of the diverted water from the Nā Wai ʻEhā streams was used by Wailuku Sugar Company, 35 percent by Hawaiian Sugar and Commercial Company (HC&S), 10 percent by small private users, and 2 percent by Maui County (Chumbley, 2007). In 1988, Wailuku Sugar Company, the main user of the diverted water, shut down operations in the Nā Wai ʻEhā area (Dorrance and Morgan, 2000), where it had been irrigating about 5,250 acres of sugarcane (Chumbley, 2007). Some of the land previously cultivated in sugarcane by Wailuku Sugar Company was later used for macadamia nuts and pineapples by Wailuku Agribusiness Company, Inc., or leased by HC&S for sugarcane.

In 2005, about 79 percent of the diverted water from the Nā Wai ʻEhā streams was used by HC&S, 10 percent by small private users, 4 percent by Maui County, and the remaining 7 percent was for various users with water delivery agreements with Wailuku Water Company, LLC (WWC) (Chumbley, 2007). (Predecessors to Wailuku Water Company, LLC, include Wailuku Agribusiness Company, Inc., Wailuku Sugar Company, and C. Brewer and Company, Limited.) As of 2009, water continued to be diverted from streams in the Nā Wai ʻEhā area for sugarcane irrigation in the central isthmus area by HC&S and for municipal and domestic uses, golf-course and landscape irrigation, maintaining pastures for cattle grazing, and other agricultural uses. The main ditch systems currently are owned and maintained by WWC. HC&S assists in the maintenance of some of the ditch systems.

Existing diversions are capable of diverting all or nearly all of the dry-weather flows of the Nā Wai ʻEhā streams, which leaves some downstream reaches completely dry (fig. 3). A lack of sufficient water downstream of existing diversions has led to recent conflicts between those currently diverting or using the water and those desiring sufficient instream flows for protection of traditional and customary Hawaiian rights (including the cultivation of taro), maintenance of habitat for native stream fauna, recreation, and aesthetics. The County of Maui Department of Water Supply currently withdraws groundwater from the aquifers potentially recharged by these streams. Thus, an understanding of the effects of the diversions on streamflow characteristics and groundwater recharge is essential for proper planning and management of the resource. It is becoming increasingly apparent that competition exists for the limited surface-water resources in Hawaiʻi, and this competition will likely play a role in future planning and management decisions.

The State Water Code mandates that the State of Hawaiʻi Commission on Water Resource Management (CWRM) establish a statewide instream use protection program (State Water Code, Hawaiʻi Revised Statutes, chapter 174C, section 71). The main mechanism that the CWRM has for protection of instream uses is to establish instream flow standards that describe the flows necessary to protect the public interest in the particular stream in light of existing and potential water developments, including the economic effect of restriction of such use (State Water Code, Hawaiʻi Revised Statutes, chapter 174C, section 71[1][C]). The CWRM has recognized certain instream uses as beneficial, including: (1) maintenance of fish and wildlife habitat, (2) outdoor recreational activities, (3) maintenance of ecosystems, such as estuaries, wetlands, and stream vegetation, (4) aesthetic values, such as waterfalls and scenic waterways, (5) maintenance of water quality, (6) the conveyance of irrigation and domestic water supplies to downstream points of diversion, and (7) the protection of traditional and customary Hawaiian rights.

Figure 3. Photograph of ʻĪao Stream channel near an altitude of 160 feet, Maui, Hawaiʻi, during diverted conditions on June 6, 2006.

On October 19, 1988, the CWRM set interim instream flow standards for all streams in West Maui. The interim instream flow standard was defined as “that amount of water flowing in each stream on the effective date of this standard, and as that flow may naturally vary throughout the year and from year to year without further amounts of water being diverted offstream through new or expanded diversions, and under the stream conditions existing on the effective date of the standard * * *” (Hawai‘i Administrative Rules, chapter 169, section 13-169-48). The interim instream flow standards essentially allowed diversions existing at the time to continue operating unless a petition was filed with the CWRM to reduce diversions and restore water to the stream.

Since 1988, interim instream flow standards have been challenged as demand for water has increased and the ecological, cultural, and aesthetic significance of streams has become increasingly recognized. In June 2004, Earthjustice filed a petition with the CWRM, on behalf of Hui o Nā Wai ‘Ehā and Maui Tomorrow Foundation, Inc., to amend the interim instream flow standards for Waihe‘e River, Waiehu Stream, ‘Īao Stream, and Waikapū Stream, and in December 2007 a contested-case hearing was initiated by the CWRM to address this issue. The results generated by the present cooperative study will help the CWRM to fulfill its obligation to determine technically defensible instream flow standards for the streams of Nā Wai ‘Ehā by providing scientific information addressing the hydrologic and aquatic-habitat aspects of the standards.

Purpose and Scope

In response to a need for additional information on the Nā Wai ‘Ehā streams, the U.S. Geological Survey (USGS) undertook the present investigation from 2006 to 2009 in cooperation with the County of Maui Office of Economic Development, County of Maui Department of Water Supply, State of Hawai‘i Commission on Water Resource Management, and State of Hawai‘i Office of Hawaiian Affairs. The objective of this study on Waihe‘e River, Waiehu Stream, ‘Īao Stream, and Waikapū Stream is to characterize the effects of existing surface-water diversions on (1) streamflow, (2) potential groundwater recharge from the streams to the underlying groundwater body, (3) physical habitat for native stream fauna (fish, shrimp, and snails), and (4) instream temperatures. This study does not predict the effects of flow restoration on native species abundance, nor does this study address water requirements for taro cultivation and aesthetic or recreational uses, algae and invertebrate food sources for native macrofauna, or reproduction of native species.

Acknowledgments

This study was conducted in cooperation with the County of Maui Office of Economic Development, County of Maui Department of Water Supply, State of Hawai‘i Commission on Water Resource Management, and State of Hawai‘i Office of Hawaiian Affairs. Access to study sites was graciously provided by the following entities and individuals: Maui Coastal Land Trust (Dale Bonar and Scott Fisher), John Varel, Harry Apolo, and other residents along Waihe‘e River; Patricia Bragg, Stanley Izumigawa, and Paul Higashino for Waiehu Stream; John and Rose Duey, Nani Santos, Bob Horcajo, Vernon Lindsey, Tropical Gardens of Maui, Inc. (Bernie Graham), and the Hawai‘i Nature Center (J.D. Wyatt) for ‘Īao Stream; and David Niehaus, Noho‘ana Farm, LLC (Victor Pellegrino and Hōkūao Pellegrino), Ione Shimizu, Hawaiian Sugar and Commercial Company, and Maui Flavors Catering for Waikapū Stream. The Wailuku Water Company, LLC, also provided access to stream sites and their schedule of when water would be restored temporarily to streams during ditch-maintenance periods. We also benefitted much from discussions with the following individuals: Skippy Hau, Jonathan Kurtz, Megan Wells, Francis Cerizo, Zac and Val Kanoa, Duke Sevilla, David Ivy, and Frank Rocha and Kim Gaines.

This study could not have been completed without assistance from the following U.S. Geological Survey personnel. Phillip C. Teeters, Matt A. Wong, and James W. Nelson maintained stream-gaging stations in Waihe‘e River and ‘Īao Stream. Sarah N. Rosa, Stephen B. Gingerich, Kolja Rotzoll, and Gordon Tribble assisted in making discharge measurements and other field activities. Tracy-Joy I. Saguibo processed temperature records and discharge measurements and interpreted photographs with the assistance of Craig A. Senter. John A. Engott assisted in stream reconnaissance at the onset of the study.

Setting

The Island of Maui, the second largest of the Hawaiian Islands, occupies an area of 727.3 mi^2 (Juvik and Juvik, 1998) between latitudes 20°30′ and 21°05′ N. and between longitudes 156°45′ and 155°55′ W. (fig. 1). The island is composed mainly of two shield volcanoes (Stearns and Macdonald, 1942): the older West Maui Volcano (West Maui Mountain), which rises to an altitude of 5,788 ft, and the younger East Maui Volcano (Haleakalā), which rises to an altitude of 10,023 ft. The interior parts of the West Maui Mountain are relatively rugged and steep in comparison to the gently sloping central saddle or isthmus that connects the East and West Maui Volcanoes. The central isthmus was formed by Haleakalā lava flows that banked up against and were deflected by the preexisting West Maui Mountain and were later buried by marine and terrestrial sedimentary deposits. The interior parts of West Maui Mountain are mainly forested conservation areas, the central isthmus mainly is used for agricultural purposes, and the coastal areas commonly are developed for residential or other urban uses.

The Kahului and Wailuku areas of north-central Maui are the main population centers near the study area.

The Nā Wai ʻEhā study area includes the Waiheʻe River, and Waiehu, ʻĪao, and Waikapū Streams, which drain the eastern part of West Maui Mountain. These streams have eroded deep valleys that are incised to depths of a few thousand feet in places. The drainage basins of Waiheʻe River, Waiehu Stream, and ʻĪao Stream, respectively, are 7.0, 4.7, and 11.4 mi^2. Part of the southwestern slope of Haleakalā drains into the lowest reach of Waikapū Stream near Keālia Pond. Inland from Keālia Pond, and upstream of where the slopes of Haleakalā drain into Waikapū Stream, Waikapū Stream drains the West Maui Mountain only and this part of the drainage basin is about 6.9 mi^2.

Land Use

Before the start of large-scale sugarcane plantation agriculture in the study area during the mid-19th century, the Nā Wai ʻEhā area supported the largest continuous area of wetland-taro cultivation in the Hawaiian Islands (Handy and Handy, 1991). Native Hawaiians likely also cultivated sweet potatoes, dry-land taro, bananas, breadfruit, coconuts, and other subsistence, medicinal, ceremonial, ornamental, and utilitarian plants in the Nā Wai ʻEhā area (see, for example, Handy and Handy, 1991; Kelly and others, 1978; Creed, 1993). The earliest available population estimates for the Nā Wai ʻEhā area were from the 1831–32 census (Schmitt, 1973): the populations of Waiheʻe, Waiehu, ʻĪao (Wailuku), and Waikapū communities, respectively, were 827, 355, 2,256, and 733. Native Hawaiian populations may have been greater before western contact in the late 18th century, although precontact population estimates are uncertain (Schmitt, 1971).

Sugarcane is not native to Hawaiʻi, although it was introduced to Hawaiʻi centuries before western contact. The following brief summary of sugarcane operations in the Nā Wai ʻEhā area mainly is from Silva (1962) and Dorrance and Morgan (2000). The first sugar mill in the Nā Wai ʻEhā area began operation in 1823, and King Kamehameha III built the King's Mill sometime during 1839–40 in Wailuku. During 1839, about 80 acres were planted in sugarcane, presumably for processing by the King's Mill, and in 1841 Hung and Company produced sugar from its 150-acre plantation in Wailuku (Maclennan, 1995). During 1862 three sugarcane plantations (Waiheʻe, Wailuku, and Waikapū Sugar Companies) in the Nā Wai ʻEhā area were formed, which marked the beginnings of large-scale commercial sugarcane operations in the area. Other sugarcane plantations in the Nā Wai ʻEhā area included those of Bal and Adams, as well as E. Bailey and Son, both of which were sold to Wailuku Sugar Company in 1877. By 1879, Maclennan (1997) estimated that about 1,950 acres were planted in sugarcane in the Nā Wai ʻEhā area. In 1894, Wailuku Sugar Company purchased both Waiheʻe and Waikapū Sugar Companies, and total production was 4,349 tons of sugar.

Maps showing generalized land use in the Nā Wai ʻEhā area are available for 1900, 1906, 1920, 1930, 1937, 1956, 1975, 1976, 1982, 1980–84, 1985–89, 1990–99, 2000–2004, 2001, and 2005 (Hawaiʻi Territorial Planning Board, 1939; Coulter, 1940; Harland Bartholomew and Associates, 1957; Mitchell and others, 1977; U.S. Department of Agriculture, 1982; Engott and Vana, 2007; National Oceanic and Atmospheric Administration, 2001, 2005). Available land-use maps from 1930 and earlier indicate areas of wetland crops of taro and rice in addition to large areas of sugarcane cultivation in the Nā Wai ʻEhā area. Before the 1988 shutdown of sugarcane operations by Wailuku Sugar Company (Dorrance and Morgan, 2000), some of the land previously used for sugarcane cultivation in the Nā Wai ʻEhā area was converted to macadamia nut orchards. Wailuku Agribusiness Company, Inc., irrigated about 1,580 acres of macadamia nuts with about 8 Mgal/d of water during the 1980s and about 1,900 acres of pineapples with about 6 Mgal/d during the early 1990s (Chumbley, 2007). By about 2000, however, macadamia nuts and pineapples were no longer being actively cultivated on a large-scale commercial basis in the Nā Wai ʻEhā area.

Since 1900, land-use patterns on Maui have reflected increases in population and decreases in large-scale agricultural operations over time. The resident population on Maui increased from fewer than 28,000 in 1900 to 117,644 in 2000 (State of Hawaiʻi, 2007). In 2000, about 10 percent of the State's population resided on Maui, and about 52 percent of the residents on Maui were in the Wailuku District (fig. 1). Between 1980 and 2000, the resident population in the Wailuku District increased 91 percent, from 32,111 to 61,346, which is consistent with the 87 percent increase of the resident population on Maui between 1980 (62,823) and 2000 (117,644) (State of Hawaiʻi, 2007). Toward the latter part of the 20th century, the general trend of land use on Maui shifted from large-scale plantation agriculture to other land uses. Although one large sugarcane plantation (Hawaiian Commercial and Sugar Company) continues to operate in central Maui, much of the land previously used for sugarcane cultivation in the Nā Wai ʻEhā area has been developed for urban uses or is used for grazing and diversified agriculture.

Climate

The climate on Maui is characterized by mild temperatures, cool and persistent trade winds, a rainy winter season from October through April, and a dry summer season from May through September (Blumenstock and Price, 1967; Sanderson, 1993). The climate is controlled primarily by topography and the position of the North Pacific anticyclone and other migratory weather systems relative to the island. During the dry season, the stability of the North Pacific anticyclone produces persistent northeasterly winds known locally as trade winds. Summer trade winds blow 80 to 95 percent of the time. During the rainy season, frequent passage of migratory weather systems near the Hawaiian Islands results in less persistent trade winds. Winter trade winds blow 50 to 80 percent of the time. Southerly winds associated with low-pressure systems can bring heavy rains to the island.

Rainfall

The central interior part of West Maui Mountain receives the highest mean annual rainfall on the island, a pattern controlled by the orographic lifting of moisture-laden northeasterly trade winds along the windward slope of the mountain. The moisture-laden air mass cools as it rises up the slopes of the mountain, resulting in condensation, cloud formation, and high rainfall near the topographic peak of the mountain. Rainfall on West Maui is characterized by maxima at high altitudes and steep spatial gradients in the interior areas (fig. 1). Maximum mean annual rainfall is more than 350 in. near the summit of West Maui Mountain (Giambelluca and others, 1986). Mean annual rainfall over coastal areas of West Maui is much lower, ranging from 40 to 60 in. over the northwestern part to less than 15 in. over the southern part. In comparison, mean annual rainfall over the open ocean is estimated at 22 to 28 in. (Dorman and Bourke, 1979; Elliot and Reed, 1984). Mean annual rainfall over West Maui Mountain can vary by more than 200 in. over a mile of horizontal distance in the wetter interior areas. Over the drier central isthmus, the mean annual rainfall is much more uniform, varying by less than 5 in. over a mile of horizontal distance in places.

Within the drainage basin of Waihe‘e River, mean annual rainfall ranges from less than 30 in. near the coast to more than 310 in. near the headwater area. Within the drainage basin of Waiehu Stream, mean annual rainfall ranges from less than 30 in. near the coast to more than 160 in. near the headwater area. Within the drainage basin of ‘Īao Stream, mean annual rainfall ranges from less than 30 in. near the coast to more than 350 in. near the headwater area. Within the drainage basin of Waikapū Stream, mean annual rainfall ranges from less than 15 in. near the coast to about 160 in. near the headwater area.

Within the study area, the seasonal pattern of rainfall is most pronounced in areas of low to moderate rainfall (fig. 4). In areas of low to moderate rainfall, the wettest months are from October through April and the driest months are from May through September. In wetter areas, variability in rainfall throughout the year is much less pronounced (fig. 4). The annual pattern of rainfall in wetter areas is characterized by three minima and three maxima (Giambelluca and others, 1986).

Hydrogeologic Setting

The valleys of Waihe‘e River, Waiehu Stream, ‘Īao Stream, and Waikapū Stream have been deeply eroded, exposing volcanic dikes. The erosion likely was enhanced by high rainfall in the interior part of West Maui Mountain. Within the study area, the geologic setting consists of volcanic rocks overlain by sedimentary deposits at lower altitudes. Exposed volcanic rocks in the study area mainly are from the shield-building stage of the West Maui Volcano. A coastal plain formed by sedimentary deposits is about one-half mile wide near Waihe‘e Stream and about 2 miles wide near ‘Īao Stream. The sedimentary deposits are continuous to the south in the central isthmus and are truncated to the north by sea cliffs. The hydrogeologic setting controls the occurrence of and interaction between surface water and groundwater in the study area. In some places, the presence of low-permeability rocks that impede groundwater flow may create high groundwater levels and result in discharge of groundwater to streams and perennial streamflow.

Geology

The geologic setting of the Island of Maui has been described in detail by numerous investigators (for example, Stearns and Macdonald, 1942; Yamanaga and Huxel, 1970; Macdonald and others, 1983; Stearns, 1985). Langenheim and Clague (1987) described and renamed the stratigraphic framework of volcanic rocks on Maui. The exposed rocks of West Maui Volcano (fig. 5) are named the Wailuku Basalt, the Honolua Volcanics, and the Lahaina Volcanics, respectively representing the shield stage and postshield caldera-filling phase, the postshield stage, and the rejuvenated stage of volcanism. The Wailuku Basalt consists of shield-stage lava of tholeiitic basalt, olivine tholeiitic basalt, and picritic tholeiitic basalt and postshield-stage caldera-filling lava of alkalic basalt; the Honolua Volcanics consists of postshield-stage lava of mugearite, trachyte, and hawaiite; and the Lahaina Volcanics consists of rejuvenated-stage lava of basanite and pricritic basanite (Langenheim and Clague, 1987). No mapped Lahaina Volcanics exists in the study area.

The shield stage represents the most voluminous phase of eruptive activity of the West Maui Volcano, during which more than 95 percent of the volcano was formed, mainly by thousands of relatively thin basalt lava flows. These flows emanated from a central caldera area near the heads of ‘Īao and Waikapū Stream Valleys and from fissures and vents radiating outward from the central caldera (Stearns and Macdonald, 1942). Individual lava flows of the shield-stage Wailuku Basalt range in thickness from about 1 to 100 ft, averaging about 15 ft, and dip from 5 to 20 degrees away from their sources (Stearns and Macdonald, 1942). Shield-stage volcanism ended about 1.35 million years ago and was followed by postshield-stage volcanism (Sherrod and others, 2006). The postshield stage is marked by a change in lava chemistry and character that led to the formation of massive lava flows. A thin red soil as much as 5 ft thick may separate older shield-stage Wailuku Basalt from postshield-stage Honolua Volcanics in places. Individual lava flows of Honolua Volcanics generally are thicker than those of the Wailuku Basalt and form an incomplete veneer over Wailuku Basalt. Individual lava flows of Honolua Volcanics range in thickness from about 25 to 300 ft, averaging about 75 ft, and dip from 3 to 20 degrees depending on the preexisting slopes over which they flowed (Stearns and Macdonald, 1942). Within the study area, Honolua Volcanics is limited to small areas in the drainage basins of Waiheʻe River and Waikapū Stream. Postshield-stage volcanism ended about 1.2 million years ago (Sherrod and others, 2006), and following the postshield stage, streams incised deep valleys (as much as 2,000 to 4,000 ft deep in places) into the volcano (Stearns and Macdonald, 1942).

The central part of the West Maui Volcano contains numerous intrusive volcanic dikes that generally trend radially outward from the central caldera area. Two main rift zones trending nearly north and south-southeastward from the central caldera are marked by numerous volcanic vents and dikes (Stearns and Macdonald, 1942; Sherrod and others, 2007), and the trends of these two rift zones are consistent with measured gravity anomalies (Kinoshita and Okamura, 1965). Macdonald and others (1983) indicated that the rift zones of West Maui are less well defined than those of most Hawaiian volcanoes, and that two additional rift zones (trending northeastward and southwestward) may exist. The boundary separating the dike-intruded and dike-free volcanic rocks is less than 1.5 mi inland from the coast near Waiheʻe River and is progressively farther inland to the south (Yamanaga and Huxel, 1970) (fig. 5). The dikes are visible in water-development tunnels or where they have been exposed by erosion in valleys. Dikes of the Wailuku Basalt generally are less than 10 ft wide and average about 1.5 ft, whereas dikes of the Honolua Volcanics range from about 8 to 25 ft wide (Stearns and Macdonald, 1942).

Sedimentary deposits of consolidated older alluvium exist on the interfluves between Waiheʻe and Waikapū Streams at altitudes from about 100 to 1,000 ft. The older alluvium extends inland to altitudes greater than 2,000 ft in Waiheʻe and ʻĪao Stream Valleys. Stearns and Macdonald (1942) indicate that these sedimentary deposits may have been emplaced during a period of submergence, when relative sea level stood

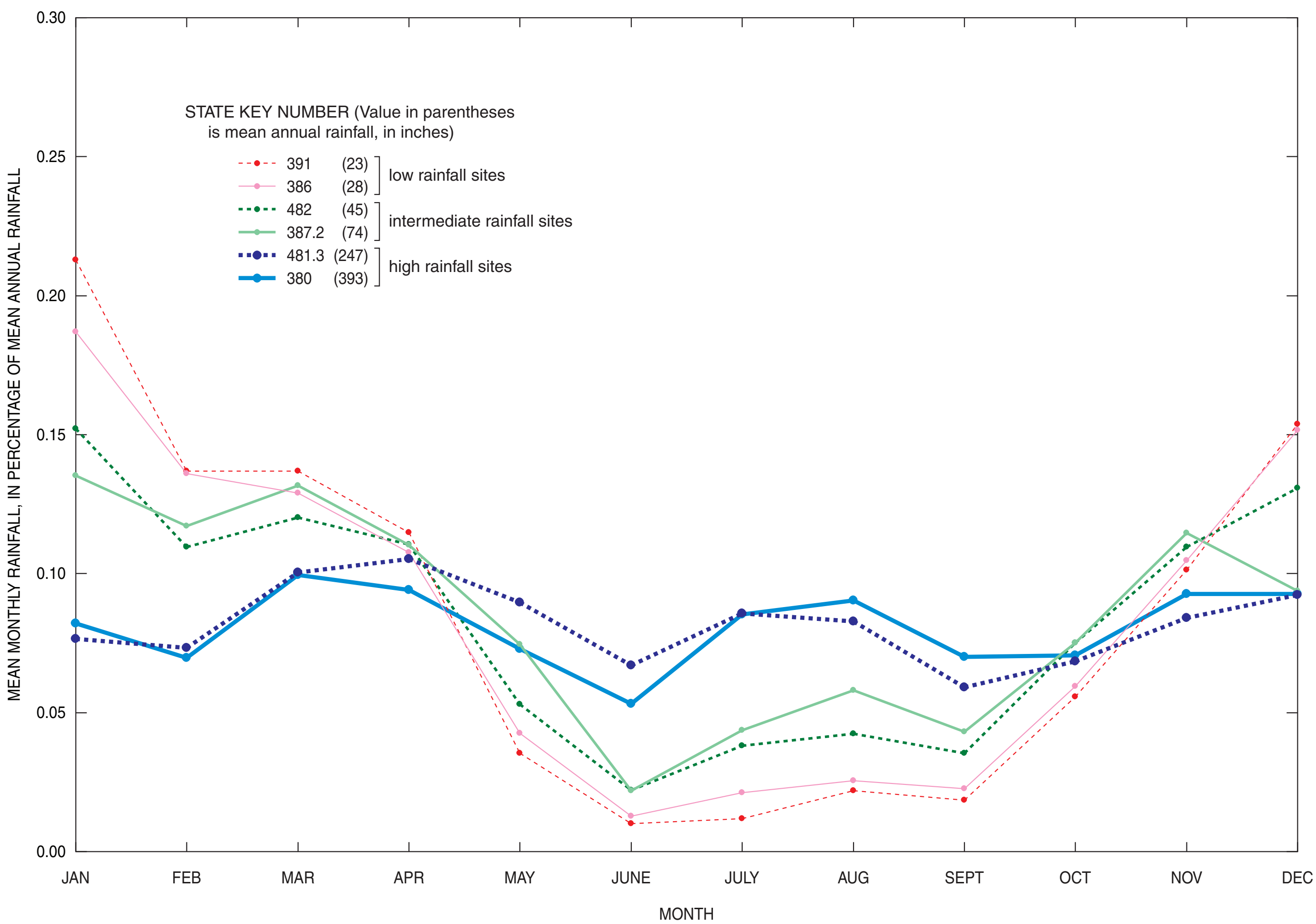


Figure 4. Mean monthly rainfall at selected rain-gaging stations, Maui, Hawaiʻi (data from Giambelluca and others, 1986).

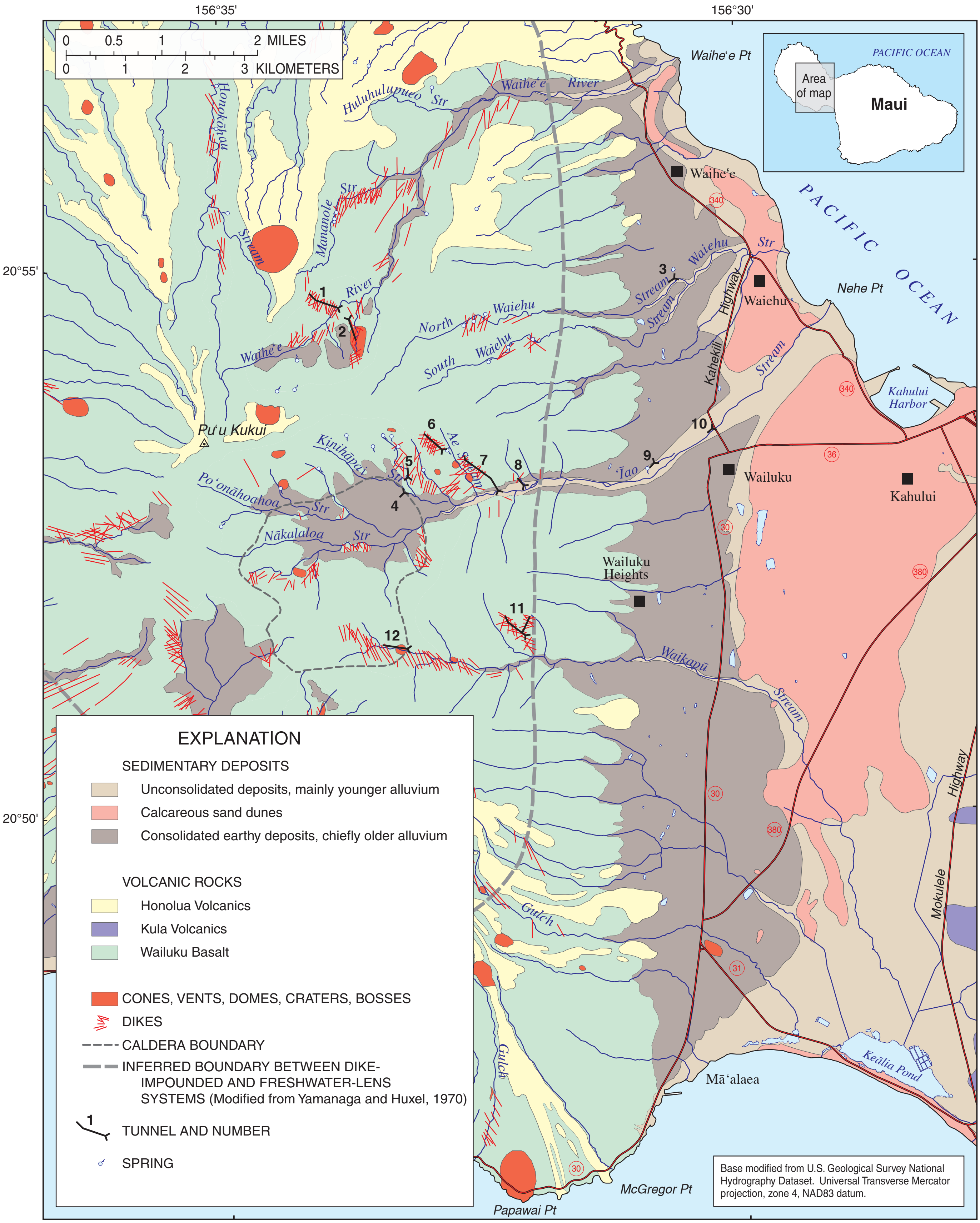


Figure 5. Generalized geology, central Maui, Hawaiʻi (modified from Stearns and Macdonald, 1942; Sherrod and others, 2007).

higher than it does today. The older alluvium is a poorly sorted, consolidated conglomerate, consisting of particles ranging from fine-grained particles to boulders (Yamanaga and Huxel, 1970). These deposits are thickest near the axes of large stream valleys. Information from a test hole near the lower reaches of ʻĪao Stream indicates that older alluvium extends to an altitude of at least 524 ft below sea level (Yamanaga and Huxel, 1970).

Older dune deposits and unconsolidated younger alluvium generally are at altitudes below about 300 ft, except in stream valleys where younger alluvium may extend to higher altitudes. The older dune deposits veneer the older alluvium between Waiheʻe River and ʻĪao Stream and in the western part of the isthmus east and south of ʻĪao Stream. The dune deposits are visible in the lower reaches of Waiehu, ʻĪao, and Waikapū Streams. Stearns and Macdonald (1942, p. 151) indicated that migrating dunes may have blocked the original northern course of Waikapū Stream, which is marked by an abandoned channel entering Kahului Bay, diverting it to the south, where it currently discharges near Keālia Pond. The younger alluvium consists of deposits in stream channels and at the seaward extent of the older alluvium. Unconsolidated sedimentary deposits in stream channels range from fine-grained particles to large boulders. A cobble beach (fig. 6) that is more than a mile long extends south from Waiheʻe Point (Stearns and Macdonald, 1942). Near the shore, terrestrial sedimentary deposits may be interbedded with marine deposits (Yamanaga and Huxel, 1970).

Permeability describes the ease with which fluid can move through rock. The permeability of volcanic rocks is variable and depends on many factors, including the mode of emplacement and amount of weathering. Weathered volcanic rocks generally have a much lower permeability than unweathered volcanic rocks. Lava chemistry and topography also can affect permeability. In the study area, dike-free volcanic rocks are much more permeable than intrusive dikes and older sedimentary deposits and are limited to areas seaward of the dike-intruded area (fig. 5). Hydraulic conductivity is a quantitative measure of permeability. Rotzoll and others (2007) estimated the hydraulic conductivity of Wailuku Basalt to be comparable to other permeable dike-free volcanic rocks in Hawaiʻi.

Within the dike-intruded area, dikes reduce overall permeability of the volcanic rocks and impede flow of groundwater. In general, the overall permeability of a dike-intruded area decreases as the number of dike intrusions within the area increases. Although the thickness of individual dikes generally is less than 10 ft, dikes are hydrologically significant because they tend to impede the movement of groundwater, resulting in groundwater levels that are hundreds of feet above sea level within dike compartments.

Older alluvium generally is poorly permeable and, in the study area, acts as a confining unit over the volcanic-rock aquifer that retards the discharge of groundwater to the ocean. The dune deposits are more permeable than the older alluvium. Dune deposits may be hydrologically significant

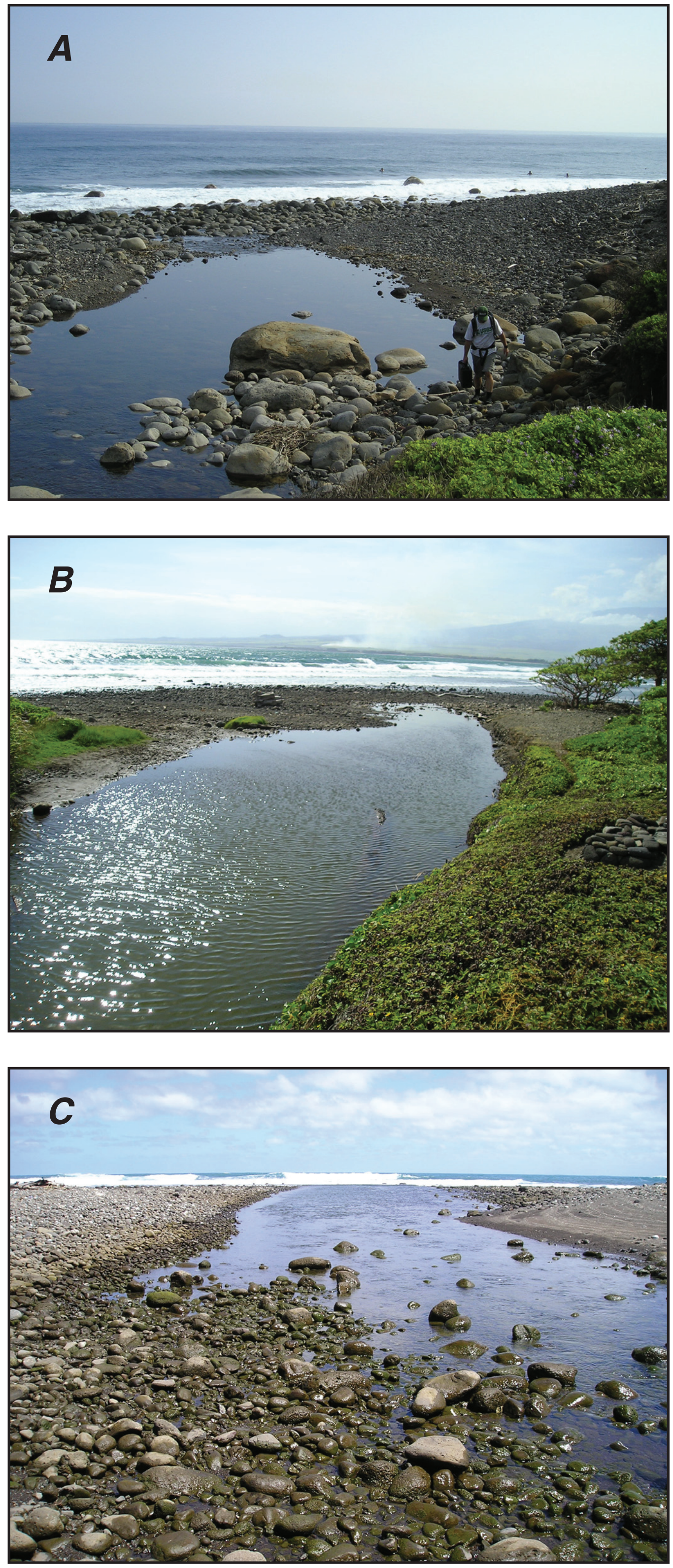


Figure 6. Photographs of cobble beach near the mouths of selected streams, Maui, Hawaiʻi. *A*, Waiheʻe River (February 5, 2007). *B*, Waiehu Stream (June 30, 2006). *C*, ʻĪao Stream (March 17, 2005).

because water in streams may infiltrate into them and recharge underlying groundwater bodies. Younger alluvium commonly occurs in or near stream valleys.

Surface-Water Resources

Upstream of existing diversions, Waihe‘e River and Waiehu, ‘Īao, and Waikapū Streams flow perennially because of sustained groundwater discharge and persistent rainfall. The natural median streamflows in Waihe‘e River and ‘Īao Stream may exceed 20 Mgal/d in places and are considerably greater than in Waiehu and Waikapū Streams, where natural median streamflows are less than 10 Mgal/d. All four streams are characterized by steep gradients in the mountainous headwater areas and flatter gradients near the coast.

These streams are flashy because rainfall is intense, drainage basins are small, basins and streams are steep, and channel storage is limited. Stream stage, or water level, can rise several feet in less than an hour during periods of intense rainfall. Streamflow generated during periods of heavy rainfall has led to loss of human lives and property in the Nā Wai ‘Ehā area. In January 2002, three people lost their lives attempting to drive across a flooded stream crossing in the Waiehu area.

Perennial flows in the upper reaches of the streams represent a reliable source of water for agricultural and other purposes. Native Hawaiians used surface water in the Nā Wai ‘Ehā area to cultivate large areas of taro, although the locations of many ancient ‘auwai (ditches) are largely unknown. For more than a century, ditch systems (figs. 7, A1) have diverted water by gravity from streams in the Nā Wai ‘Ehā area for large-scale sugarcane cultivation. An average of about 67 Mgal/d of water was diverted from Waihe‘e River and Waiehu, ‘Īao, and Waikapū Streams for sugarcane irrigation (Yamanaga and Huxel, 1970). About 40 Mgal/d was diverted from Waihe‘e River; 3 Mgal/d from North Waiehu Stream; 3 Mgal/d from South Waiehu Stream; 18 Mgal/d from ‘Īao Stream; and 3 Mgal/d from Waikapū Stream (Yamanaga and Huxel, 1970).

As of 2009, water continues to be diverted from each of the streams in the Nā Wai ‘Ehā area. Currently, three known diversions exist on Waihe‘e River, one on North Waiehu Stream, three on South Waiehu Stream, three on ‘Īao Stream, and five on Waikapū Stream (table 1). A brief description of these diversions is provided in this section. Additional details and photographs of the diversions are available in appendix A.

Three known diversions currently exist on Waihe‘e River: Waihe‘e Ditch, with an intake near an altitude of 600 ft; Spreckels Ditch, with an intake near an altitude of 400 ft; and the Field 1 diversion, with an intake near an altitude of 260 ft (fig. 7). The main diversions from Waihe‘e River are the Waihe‘e and Spreckels Ditches. The Waihe‘e Ditch has two intake grates in Waihe‘e River in a reach that is bifurcated by an island. The Waihe‘e Ditch intakes have a combined design capacity of 60 Mgal/d, although a downstream control gate limits flow in the ditch to about 40 Mgal/d (Suzuki, 2007). The Spreckels Ditch intake in Waihe‘e River has a design capacity of 30 Mgal/d, although a control gate limits flow in the ditch to about 12 Mgal/d (Suzuki, 2007). About 6 Mgal/d of the water diverted by the Waihe‘e Ditch commonly discharges into the Spreckels Ditch (Suzuki, 2007), about 2,000 ft downstream of the Spreckels Ditch intake. The capacity and frequency of use of the Field 1 intake are unknown.

The only known existing diversion on North Waiehu Stream is the North Waiehu Ditch (fig. 7), which has an intake near an altitude of 880 ft. A downstream control gate is set to limit flow in the North Waiehu Ditch to about 1.5 Mgal/d (Suzuki, 2007). Three known diversions currently exist on South Waiehu Stream: two ‘auwai for private use, with intakes near altitudes of 620 ft (north side of stream) and 570 ft (south side of stream), and the Spreckels Ditch, with an intake near an altitude of 270 ft. The capacities of the diversions on South Waiehu Stream are not known. Limited measurements indicate (1) less than 0.5 Mgal/d flow in each of the two ‘auwai and (2) the Spreckels Ditch intake is capable of diverting all of the low flow of South Waiehu Stream up to at least 1 Mgal/d.

Three known diversion intakes currently exist on ‘Īao Stream: the ‘Īao-Waikapū and ‘Īao-Māniania Ditches, which share a common intake near an altitude of 780 ft; Spreckels Ditch, with an intake near an altitude of 250 ft; and a small private intake near an altitude of 650 ft. The intake for the ‘Īao-Waikapū and ‘Īao-Māniania Ditches has a design capacity of 60 Mgal/d, although a downstream control gate limits combined flow in the ‘Īao-Waikapū and ‘Īao-Māniania Ditches to about 20 Mgal/d (18 Mgal/d to the ‘Īao-Waikapū Ditch and 2 Mgal/d to the ‘Īao-Māniania Ditch) (Suzuki, 2007). The capacity of the intake for Spreckels Ditch is unknown, although it likely exceeds 10 Mgal/d on the basis of available discharge measurements and observations. The capacity of the intake for the small private ‘auwai with intake near an altitude of 650 ft is unknown, although two measurements (September 21, 2004, and July 24, 2006) indicated flows ranging from 0.054 to 0.090 Mgal/d (0.083 to 0.14 ft^3/s) in the system.

Five known diversion intakes currently exist on Waikapū Stream: (1) the South Side Ditch (also referred to as South Waikapū Ditch) is the most upstream diversion, with an intake near an altitude of 1,120 ft; (2) the Everett Ditch (also referred to as Palolo Ditch) intake is near an altitude of 900 ft; (3) a private, community ‘auwai diverts water near an altitude of 560 ft; (4) the Waihe‘e Ditch intake is near an altitude of 440 ft; and (5) the Reservoir 6 intake is near an altitude of 410 ft. The intake for the South Side Ditch has a design capacity of about 5 Mgal/d (Suzuki, 2007), although a control gate is set to limit flow in the South Side Ditch to about 3 Mgal/d (Suzuki, 2007). The capacity of the Everett Ditch intake is unknown but is less than the typical low flow of Waikapū Stream. During April 29 and 30, 2008, discharges in the Everett Ditch near gaging station 16649000 (fig. 7) were 0.36 and 0.14 Mgal/d (0.56 and 0.21 ft^3/s), respectively. Measured discharges in Waikapū Stream, about 600 ft upstream of the Everett Ditch intake,

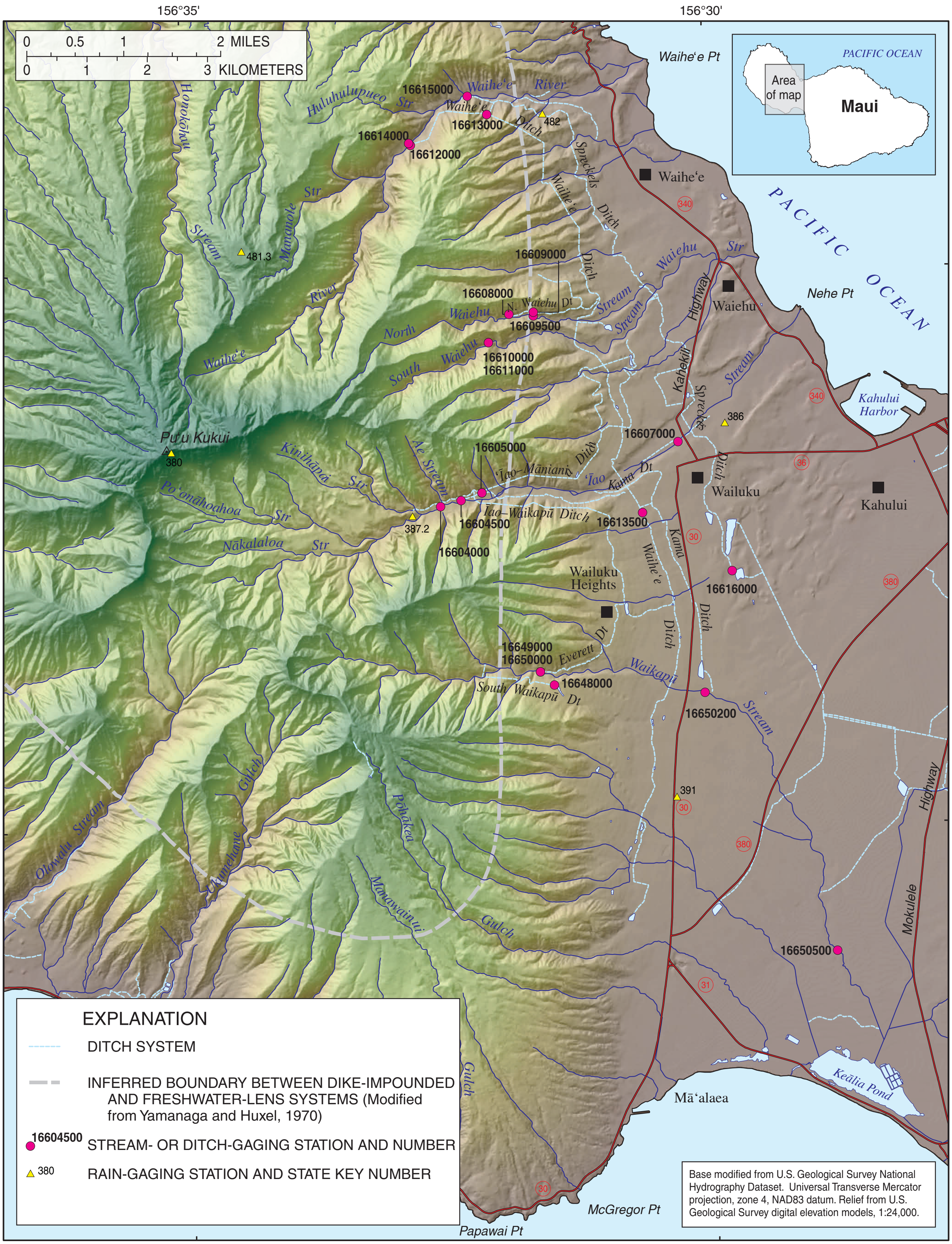


Figure 7. Ditch systems, stream-gaging stations, and selected rain-gaging stations, Nā Wai ʻEhā area, Maui, Hawaiʻi.

Table 1. Surface-water diversion intakes, Nā Wai ʻEhā, Maui, Hawaiʻi.

[—, data not available; Mgal/d, million gallons per day]

Intake of ditch system or small private ʻauwai (ditch)	Altitude, in feet[a]	Design capacity, in Mgal/d	Intake capacity setting, in Mgal/d
Waiheʻe River			
Waiheʻe Ditch	600	[b]60	[c]40
Spreckels Ditch	400	[b]30	[c]12
Field 1	260	—	—
North Waiehu Stream			
North Waiehu Ditch	880	—	[c]1.5
South Waiehu Stream			
Left (north) ʻauwai	620	—	—
Right (south) ʻauwai	570	—	—
Spreckels Ditch	270	—[d]	—[d]
ʻĪao Stream			
ʻĪao-Waikapū and ʻĪao-Māniania Ditches	780	[b]60	[c]20
Right (south) ʻauwai	650	—	—
Spreckels Ditch	250	—[e]	—[e]
Waikapū Stream			
South Side Ditch	1,120	[b]5	[c]3
Everett (Palolo) Ditch	900	—	—
Left (north) ʻauwai	560	—	—
Waiheʻe Ditch	440	—[d]	—[d]
Reservoir 6	410	—[d]	—[d]

[a]Altitude determined from topographic map.
[b]Suzuki (2007).
[c]Gate setting (Suzuki, 2007).
[d]Capacity unknown but greater than 1 Mgal/d.
[e]Capacity unknown but likely greater than 10 Mgal/d.

were 3.19 and 1.29 Mgal/d (4.93 and 1.99 ft^3/s), respectively, on April 29 and 30, 2008. The capacity of the private ʻauwai with an intake near an altitude of 560 ft is unknown, although measurements from October 28, 2004, indicate that 0.66 Mgal/d (1.02 ft^3/s) was diverted and about 0.42 Mgal/d (0.65 ft^3/s) of this leaked or was returned back to the stream. The capacities of the Waiheʻe Ditch and Reservoir 6 intakes each exceed 1 Mgal/d but are otherwise unknown.

Groundwater Resources

The Nā Wai ʻEhā area contains three types of fresh groundwater systems: (1) dike-impounded groundwater; (2) a freshwater lens floating on saltwater; and (3) perched water (Gingerich and Oki, 2000). Dike-impounded groundwater occurs inland at relatively high altitudes and consists of freshwater contained in dike compartments. Closer to the coast, a freshwater-lens system is contained in dike-free volcanic rocks and sedimentary deposits. Perched water also can occur in the sedimentary deposits where low-permeability rocks impede the downward movement of groundwater sufficiently to allow a saturated water body to develop in otherwise unsaturated rocks.

In the Nā Wai ʻEhā area, water enters and recharges the freshwater-lens system by direct infiltration of precipitation and irrigation water, seepage from flowing streams where the water table is below the streambed, and inflow from upgradient groundwater bodies (for example, dike-impounded and perched water bodies). The low-permeability coastal sedimentary deposits impede the discharge of freshwater from, and the inflow of saltwater to, the freshwater-lens system.

Significant development of groundwater from the Nā Wai ʻEhā area began with the construction of tunnels to divert dike-impounded groundwater (Meyer and Presley, 2001). Twelve tunnels are known to have been excavated in the Nā Wai ʻEhā area between 1900 and 1926 (fig. 5) (Stearns and Macdonald, 1942). Eight of the tunnels were excavated in the dike complex and tap dike-impounded groundwater. The other four tunnels were excavated mainly in alluvium. About 9 Mgal/d of dike-impounded groundwater was developed by tunnels (table 2), although most of the water (7.5 Mgal/d) might have discharged naturally to streams below the level of the tunnels had the water not been intercepted by the tunnels (Stearns and Macdonald, 1942; Yamanaga and Huxel, 1970). Most of the dike-impounded groundwater developed (intercepted) by tunnels likely discharges back into the streams.

The large-scale withdrawal of groundwater from the freshwater lens in the Nā Wai ʻEhā area began in 1948 in the ʻĪao area (Meyer and Presley, 2001). The freshwater lens in the Waiheʻe area, which is adjacent to the ʻĪao area, was developed beginning in 1997. Currently (2009), groundwater is pumped by five major wells or well fields in the ʻĪao area and two well fields in the Waiheʻe area. In general, groundwater levels in the ʻĪao and Waiheʻe areas have declined, the chloride concentration of water pumped by some wells has increased, and, as indicated by salinity profiles from an existing deep monitor well in the ʻĪao area, the brackish-water transition zone between the freshwater and the underlying saltwater has risen (Meyer and Presley, 2001; Gingerich, 2008).

Interaction Between Groundwater and Surface Water

Groundwater and surface water interact in different ways, depending on the geology and hydrology of an area. In the dike-impounded groundwater system, the low permeability of the dikes causes groundwater levels to build up behind them, typically on the order of hundreds or thousands of feet above sea level. In the Nā Wai ʻEhā area, stream erosion has carved deeply incised valleys in which the stream channels have been lowered below the level of the water table of the dike-impounded groundwater body, creating the opportunity for streams to drain dike-impounded groundwater (fig. 8). In reaches where the groundwater table is higher than the adjacent stream channel, the streams are

Table 2. Water-development tunnels, Nā Wai ʻEhā, Maui, Hawaiʻi.

[Refer to fig. 5 for locations; —, not applicable or data not available; Mgal/d, million gallons per day]

Tunnel no.	Year constructed	Altitude, in feet[a]	Length, in feet[b]	Tunnel discharge, in Mgal/d: August 1911 (Martin and Pierce, 1913)	Tunnel discharge, in Mgal/d: Stearns and Macdonald, 1942[c]	Geologic description
Waiheʻe						
1	1909	1,625	2,200	5.2	4.6	Older alluvium and dike-intruded Wailuku Basalt
2	1909	1,650	2,500	0.38	1.0	Older alluvium, dike-intruded Wailuku Basalt, breccia
Waiehu						
3	1902	300	500	—	0.25	Alluvium
ʻĪao						
4	1906	1,425	[d]2,500	0.40	0.075	Dike-intruded caldera complex
5	1906	1,475	caved	0.62	caved	Dike-intruded caldera complex
6	1926	1,305	1,413	—	[e]0	Dike-intruded Wailuku Basalt
7	1938, 1945	787	2,630	—	[f]2.3	Dike-intruded Wailuku Basalt
8	1900	700	caved	—	caved	Alluvium and Wailuku Basalt
9	1900	444	1,000	—	0.15	Alluvium
10	1900	240	2,000	—	0.25	Alluvium
Waikapū						
11	1900, 1906	1,800	2,943	1.7	1.0	Dike-intruded Wailuku Basalt
12	1905	1,770	[g]1,650	—	0.007	Dike-intruded vent breccia of caldera
Total	—	—	—	—	9.6	—

[a]Altitude determined by barometer, except for tunnel 6, for which altitude was determined by level line (Stearns and Macdonald, 1942)
[b]Includes laterals, if any.
[c]Mostly estimated.
[d]Tunnel is caved in at 650 feet from portal; cuts 21 dikes in first 650 feet.
[e]Reported discharge was 0.60 Mgal/d before construction of tunnel 7 (Stearns and Macdonald, 1942). Tunnel 6 was dry after construction of tunnel 7 (Yamanaga and Huxel, 1970).
[f]Reported discharge from 1951 was 2.3 Mgal/d (Yamanaga and Huxel, 1970). Measured discharge was 2.0 Mgal/d on December 27, 1940, before tunneling by Wailuku Sugar Company. Records of discharge kept during excavation indicate a maximum flow of 4 Mgal/d (Stearns and Macdonald, 1942)
[g]Tunnel is caved in at 1,500 feet from portal; water slightly thermal and gas present. Another tunnel reported to be in this area was not found.

said to be "gaining" because groundwater contributes to streamflow.

In general, Waiheʻe River and Waiehu, ʻĪao, and Waikapū Streams are gaining in reaches where they intersect the dike-impounded water body (fig. 5). Discharge from the dike-impounded water body maintains perennial flow in these streams. Streamflow may vary in response to rainfall, but flow continues even during extended dry-weather periods because of sustained groundwater discharge to the stream.

In lower altitude areas lying above the freshwater lens, the stream channels generally are above the groundwater table. At these lower altitudes, the water table is only a few feet or tens of feet above sea level, as opposed to hundreds or thousands of feet in the dike-impounded system. Where an unsaturated zone exists between the stream and water table, a stream may lose water and act as a source of groundwater recharge for the freshwater-lens system. Waiheʻe River and ʻĪao, Waiehu, and Waikapū Streams may lose water in reaches overlying the freshwater-lens system where the channel bottoms are above the water table.

In places, shallow groundwater in the alluvium within stream channels also may discharge to the stream. Groundwater within the alluvium may be hydraulically connected to and part of a dike-impounded groundwater body or freshwater-lens system. Groundwater within the alluvium also may be perched on low-permeability material and separated from an underlying dike-impounded groundwater body or freshwater-lens system by a zone of unsaturated rock. At low altitudes close to the coast in the Nā Wai ʻEhā area, stream channels may intersect the water table in sedimentary deposits, causing some streams to gain near their mouths. Where the pressure in the groundwater system is high enough to raise the water to the land surface, groundwater also can discharge in the form of coastal springs or seeps that are not within defined stream channels.

Potential Effects of Groundwater Withdrawals on Streamflow

Groundwater withdrawals can affect streamflow in reaches where the groundwater body is hydraulically connected to the stream, and this also may cause streamflow to be affected in downstream reaches. When withdrawal

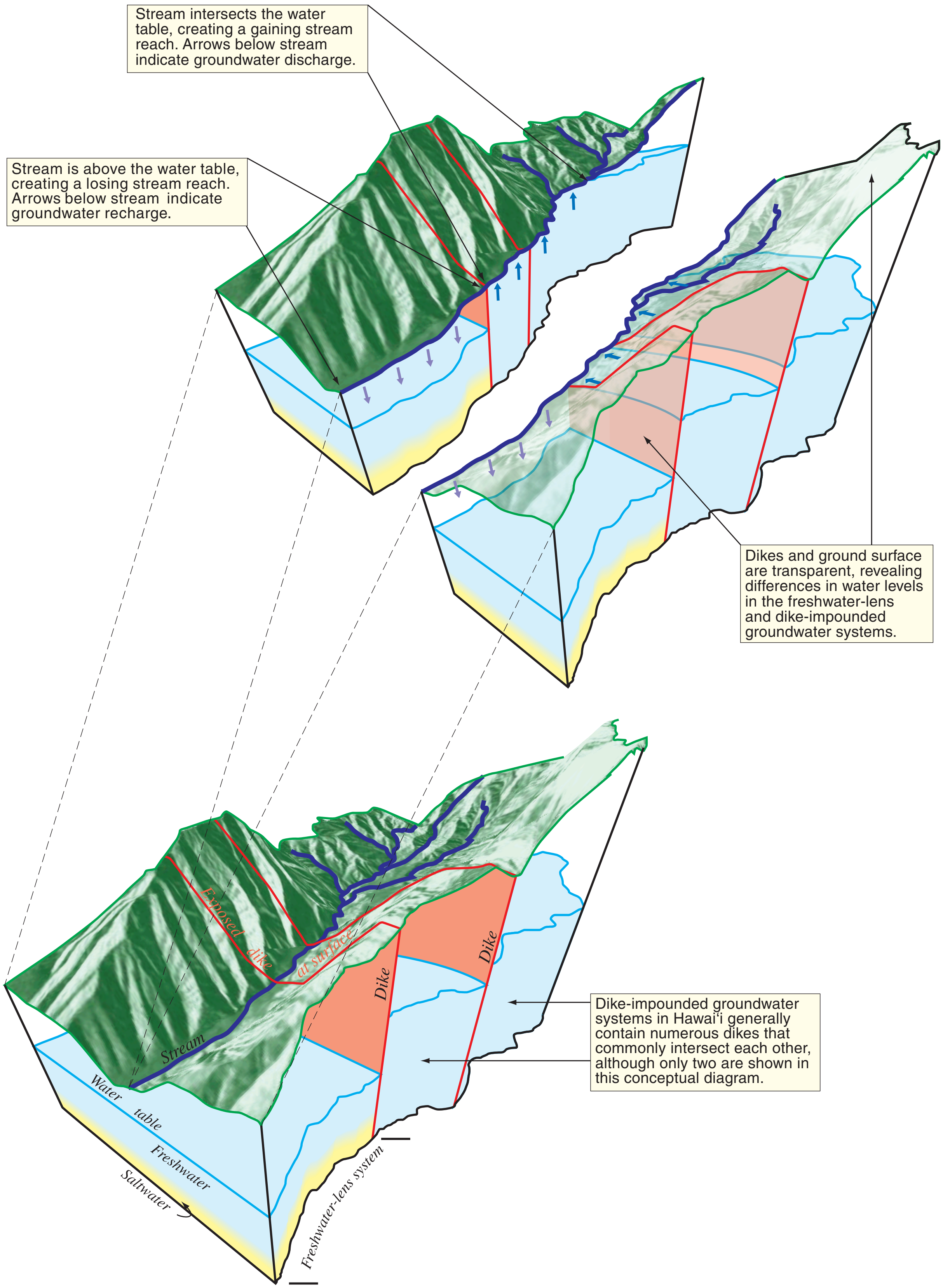


Figure 8. Conceptual diagram showing relation between surface water and groundwater within the drainage basin of a stream. The cutaway views at the top are split along the main stream.

from a well begins, water is initially removed from aquifer storage, and groundwater levels in the vicinity of the well begin to decline. If withdrawal is stopped and groundwater recharge remains steady, water lost from storage eventually will be regained and groundwater levels will recover as the system returns to prewithdrawal conditions. If withdrawal from the well continues at a steady rate, the zone over which groundwater levels decline expands outward from the well as additional water is removed from storage. Water-level decline is greatest at the withdrawal site and decreases outward from the well, forming what is known as a cone of depression. The cone of depression eventually reaches areas where water is discharging to the ocean or streams, or where recharge to the groundwater body can occur. The shape of the cone of depression surrounding the withdrawal site generally is not symmetrical, because of the presence of inhomogeneities (for example, low-permeability geologic features), anisotropy, or recharge and discharge boundaries. As groundwater levels decline near a discharge area, the rate of discharge in that area decreases. As water levels decline near a potential recharge area, the rate of recharge in that area may increase.

Long-term steady withdrawal of groundwater by a well is eventually balanced by enhanced recharge or loss of natural discharge (provided the rate of withdrawal is not greater than the possible balancing sources of water), and water levels cease to decline further. Long-term withdrawal may enhance recharge in areas where water may otherwise have been (1) lost to evapotranspiration where plants extract groundwater from below the water table, or (2) discharged to springs or streams (see, for example, Lohman, 1979). Long-term withdrawal may lower the water table below the roots of plants or below the level of spring-discharge sites, creating a condition that could lead to enhanced recharge. Where long-term steady withdrawal by a well does not result in enhanced recharge, natural discharge is reduced by an amount equal to the withdrawal (provided none of the water that is withdrawn contributes to recharge). In Hawaiʻi, long-term withdrawal of groundwater generally results in a reduction of groundwater discharge to the ocean or streams.

If the zone of groundwater-level declines caused by withdrawal extends to a stream that is hydraulically connected to the groundwater body, streamflow may be reduced by (1) a reduction of groundwater discharge to the stream where the water level in the adjacent aquifer is higher than the stream or (2) enhanced opportunity for surface-water losses through the streambed where the water level in the adjacent aquifer is lower than the stream. Development tunnels, wells, and shafts that withdraw groundwater from the dike-impounded groundwater body or freshwater-lens system all can cause such reductions in streamflow.

Stream Fauna

Both native and non-native aquatic species can be found in Nā Wai ʻEhā streams. The isolation of the Hawaiian Islands has resulted in the evolution of a unique native stream community. Recent human activities have resulted in the introduction of a number of non-native species into the Nā Wai ʻEhā area, and these non-native species may compete with native species for available resources or may prey on the native species directly. Native stream fauna utilize a variety of macro- and microhabitats within stream ecosystems. The availability of suitable habitat for native fish, snails, and shrimp species found in the Nā Wai ʻEhā area is examined in a later section (“Effects of Surface-Water Diversions on Physical Habitat”) of this report.

Native Species

In Hawaiʻi, native invertebrate (mollusks and crustaceans) species include the endemic (found only in Hawaiʻi) freshwater snail, *Neritina granosa* Sowerby, 1825, commonly referred to by the Hawaiian name hīhīwai; the endemic brackish-water snail, *Neritina vespertinus* (Sowerby, 1849), referred to as hapawai; the endemic prawn, *Macrobrachium grandimanus* (Randall, 1840), referred to as ʻōpae ʻoehaʻa; and the endemic mountain shrimp, *Atyoida bisulcata* (Randall, 1840), referred to as ʻōpaekalaʻole or mountain ʻōpae. Native vertebrate species include fish, collectively referred to as ʻoʻopu wai. The five ʻoʻopu include an endemic eleotrid (family: Eleotridae), *Eleotris sandwicensis* (Vaillant and Sauvage, 1875), referred to as ʻoʻopu ʻakupa (or ʻōkuhe), and fishes in the family Gobiidae, collectively referred to as gobies, including the endemic gobies *Lentipes concolor* (Gill, 1860), known as ʻoʻopu ʻalamoʻo (or hiʻukole); *Sicyopterus stimpsoni* (Gill, 1860), known as ʻoʻopu nōpili; *Stenogobius hawaiiensis*, the teardrop goby also known as ʻoʻopu naniha (Watson, 1991); and the indigenous (native to Hawaiʻi and elsewhere) goby *Awaous guamensis* (Valenciennes, 1837), also known as ʻoʻopu nākea. The juveniles of an endemic nearshore marine fish species, *Kuhlia xenura* (Jordan and Gilbert, 1882), also known as the Hawaiian flagtail or āholehole, are commonly found in lower stream reaches and estuaries. Each of the native species listed above has been observed in at least one stream in the Nā Wai ʻEhā area in the past (tables 3–6).

The Nā Wai ʻEhā watersheds also are inhabited by native Hawaiian damselflies of the endemic genus *Megalagrion* referred to as pinao ʻula. The larvae of most of the 23 described species are aquatic, and many adults are observed on plants and rocks in and around streams (Polhemus and Asquith, 1996). Because of habitat loss and degradation and predation by alien species, *Megalagrion* damselfly populations have been in decline and some species have been extirpated from entire islands (Polhemus, 1993). Because of their sensitivity to environmental disturbance, the *Megalagrion* damselflies are considered indicators of ecosystem health (DiSalvo and others, 2003). The damselflies that were observed during this study in the Nā Wai ʻEhā watersheds include *M. blackburni* McLachlan, 1883 (Blackburn’s Hawaiian Damselfly), *M. hawaiiense* (McLachlan, 1883) (Hawaiian Upland

Table 3. Native aquatic species observed in Waihe‘e River from surveys during 1978–2008, Maui, Hawai‘i.

[HSA, Hawai‘i Stream Assessment (Hawai‘i Cooperative Park Service Unit, 1990); DAR, Hawai‘i Department of Land and Natural Resources, Division of Aquatic Resources; spp., more than one species; NG1, native species group 1; NG2, native species group 2; End, endemic; Ind, indigenous; p, present; a, abundant; va, very abundant; —, no data]

Class	Family	Genus/Species	Hawaiian name	HSA classification	Status	Observations			
						HSA	DAR	Ford[1]	This study
Gastropoda	Neritidae	*Neritina vespertinus*	hapawai	NG2	End	—	—	—	—
Gastropoda	Neritidae	*Neritina granosa*	hīhīwai	NG1	End	—	1995(p)[2]	—	—
Crustacea	Atyidae	*Atyoida bisulcata*	‘ōpaekala‘ole	NG2	End	1978(a)	2008(a)[3]	2007(a)	2008(a)
Crustacea	Palaemonidae	*Macrobrachium grandimanus*	‘ōpae ‘oeha‘a	NG2	Ind	—	—	—	—
Insecta	Coenagrionidae	*Megalagrion* spp.	pinao ‘ula	—	End	—	(p)[4]	2007(p)	2008(a)
Osteichthyes	Eleotridae	*Eleotris sandwicensis*	‘o‘opu ‘akupa	NG2	End	—	—	—	2008(p)
Osteichthyes	Gobiidae	*Stenogobius hawaiiensis*	‘o‘opu naniha	NG2	End	—	—	—	—
Osteichthyes	Gobiidae	*Awaous guamensis*	‘o‘opu nākea	NG1	Ind	1989(p)	2008(a)[3]	2007(a)	2008(va)
Osteichthyes	Gobiidae	*Sicyopterus stimpsoni*	‘o‘opu nōpili	NG1	End	1978(a)	2008(a)[3]	2007(a)	2008(va)
Osteichthyes	Gobiidae	*Lentipes concolor*	‘o‘opu ‘alamo‘o	NG1	End	1978(a)	2008(a)[3]	2007(va)	2008(va)
Osteichthyes	Kuhliidae	*Kuhlia xenura*[5]	āholehole	NG2	End	—	—	—	2008(a)

[1]Ford and others (2008).
[2]DAR observation (State of Hawai‘i, 2004).
[3]DAR observation (D. Polhemus, written commun., 2009).
[4]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).
[5]Revised name for species previously identified as *K. sandvicensis*.

Table 4. Native aquatic species observed in Waiehu Stream from surveys during 1961–2008, Maui, Hawai‘i.

[HSA, Hawai‘i Stream Assessment (Hawai‘i Cooperative Park Service Unit, 1990); DAR, Hawai‘i Department of Land and Natural Resources, Division of Aquatic Resources; spp., more than one species; NG1, native species group 1; NG2, native species group 2; End, endemic; Ind, indigenous; p, present; a, abundant; —, no data]

Class	Family	Genus/Species	Hawaiian name	HSA classification	Status	Observations			
						HSA	DAR	Ford[1]	This Study
Gastropoda	Neritidae	*Neritina vespertinus*	hapawai	NG2	End	—	(p)[2]	—	—
Gastropoda	Neritidae	*Neritina granosa*	hīhīwai	NG1	End	—	(p)[2]	—	—
Crustacea	Atyidae	*Atyoida bisulcata*	‘ōpaekala‘ole	NG2	End	1961(a)	2008(p)[3]	2007(a)	2008(p)
Crustacea	Palaemonidae	*Macrobrachium grandimanus*	‘ōpae ‘oeha‘a	NG2	Ind	—	—	—	—
Insecta	Coenagrionidae	*Megalagrion* spp.	pinao ‘ula	—	End	—	(p)[2]	2007(a)	2008(a)
Osteichthyes	Eleotridae	*Eleotris sandwicensis*	‘o‘opu ‘akupa	NG2	End	—	(p)[2]	—	—
Osteichthyes	Gobiidae	*Stenogobius hawaiiensis*	‘o‘opu naniha	NG2	End	—	—	—	—
Osteichthyes	Gobiidae	*Awaous guamensis*	‘o‘opu nākea	NG1	Ind	1961(p)	2008(p)[3]	2007(p)	2008(a)
Osteichthyes	Gobiidae	*Sicyopterus stimpsoni*	‘o‘opu nōpili	NG1	End	1961(a)	2008(p)[3]	2007(p)	2008(a)
Osteichthyes	Gobiidae	*Lentipes concolor*	‘o‘opu ‘alamo‘o	NG1	End	—	2008(p)[3]	2007(a)	2008(a)
Osteichthyes	Kuhliidae	*Kuhlia xenura*[4]	āholehole	NG2	End	—	(p)[2]	—	—

[1]Ford and others (2008).
[2]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).
[3]DAR observation (D. Polhemus, written commun., 2009).
[4]Revised name for species previously identified as *K. sandvicensis.*

Table 5. Native aquatic species observed in ʻĪao Stream from surveys during 1970–2008, Maui, Hawaiʻi.

[HSA, Hawaiʻi Stream Assessment (Hawaiʻi Cooperative Park Service Unit, 1990); DAR, Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources; spp., more than one species; NG1, native species group 1; NG2, native species group 2; End, endemic; Ind, indigenous; p, present; a, abundant; va, very abundant; —, no data]

Class	Family	Genus/Species	Hawaiian name	HSA classification	Status	Observations			
						HSA	DAR	Ford[1]	This study
Gastropoda	Neritidae	*Neritina vespertinus*	hapawai	NG2	End	—	—	—	—
Gastropoda	Neritidae	*Neritina granosa*	hīhīwai	NG1	End	—	(p)[2]	—	2006(p)
Crustacea	Atyidae	*Atyoida bisulcata*	ʻōpaekalaʻole	NG2	End	1989(va)	1994(p)[3]	2007(va)	2008(p)
Crustacea	Palaemonidae	*Macrobrachium grandimanus*	ʻōpae ʻoehaʻa	NG2	Ind	—	—	—	—
Insecta	Coenagrionidae	*Megalagrion* spp.	pinao ʻula	—	End	—	(p)[2]	2007(p)	2008(p)
Osteichthyes	Eleotridae	*Eleotris sandwicensis*	ʻoʻopu ʻakupa	NG2	End	—	(p)[2]	—	—
Osteichthyes	Gobiidae	*Stenogobius hawaiiensis*	ʻoʻopu naniha	NG2	End	—	(p)[2]	—	—
Osteichthyes	Gobiidae	*Awaous guamensis*	ʻoʻopu nākea	NG1	Ind	1989(p)	1994(p)[3]	2007(p)	2008(a)
Osteichthyes	Gobiidae	*Sicyopterus stimpsoni*	ʻoʻopu nōpili	NG1	End	1970(p)	(p)[2]	2007(p)	2008(a)
Osteichthyes	Gobiidae	*Lentipes concolor*	ʻoʻopu ʻalamoʻo	NG1	End	—	1994(p)[3]	2007(p)	2008(a)
Osteichthyes	Kuhliidae	*Kuhlia xenura*[4]	āholehole	NG2	End	1989(p)	(p)[2]	—	—

[1]Ford and others (2008).
[2]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).
[3]DAR observation from tributary of ʻĪao Stream (State of Hawaiʻi, 2004).
[4]Revised name for species previously identified as *K. sandvicensis*.

Table 6. Native aquatic species observed in Waikapū Stream from surveys during 1961–2008, Maui, Hawaiʻi.

[HSA, Hawaiʻi Stream Assessment (Hawaiʻi Cooperative Park Service Unit, 1990); DAR, Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources; spp., more than one species; NG1, native species group 1; NG2, native species group 2; End, endemic; Ind, indigenous; p, present; a, abundant; ?, uncertain identification; —, no data]

Class	Family	Genus/Species	Hawaiian name	HSA classification	Status	Observations			
						HSA	DAR	Ford[1]	This study
Gastropoda	Neritidae	*Neritina vespertinus*	hapawai	NG2	End	—	(p)[2]	—	—
Gastropoda	Neritidae	*Neritina granosa*	hīhīwai	NG1	End	—	—	—	—
Crustacea	Atyidae	*Atyoida bisulcata*	ʻōpaekalaʻole	NG2	End	1961(a)	(p)[2]	2007(a)	2008(a)
Crustacea	Palaemonidae	*Macrobrachium grandimanus*	ʻōpae ʻoehaʻa	NG2	Ind	—	(p)[2]	—	—
Insecta	Coenagrionidae	*Megalagrion* spp.	pinao ʻula	—	End	—	(p)[2]	2007(a)	2008(a)
Osteichthyes	Eleotridae	*Eleotris sandwicensis*	ʻoʻopu ʻakupa	NG2	End	—	—	—	—
Osteichthyes	Gobiidae	*Stenogobius hawaiiensis*	ʻoʻopu naniha	NG2	End	—	—	—	—
Osteichthyes	Gobiidae	*Awaous guamensis*	ʻoʻopu nākea	NG1	Ind	1961(p)	(p)[2]	—	—
Osteichthyes	Gobiidae	*Sicyopterus stimpsoni*	ʻoʻopu nōpili	NG1	End	1961(p)	(p)[2]	—	2008(?)
Osteichthyes	Gobiidae	*Lentipes concolor*	ʻoʻopu ʻalamoʻo	NG1	End	—	—	—	2008(?)
Osteichthyes	Kuhliidae	*Kuhlia xenura*[3]	āholehole	NG2	End	—	(p)[2]	—	—

[1]Ford and others (2008).
[2]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).
[3]Revised name for species previously identified as *K. sandvicensis*.

Damselfly), and *M. nigrohamatum nigrohamatum* (Blackburn, 1884) (Blackhook Hawaiian Damselfly).

Life-History Characteristics of Native Species

A number of life-history characteristics factor into the habitat selection of native stream fauna in Hawai‘i (summarized in Fitzsimons and others, 2007). First, having evolved from marine ancestors, the species of interest for this study are all amphidromous, retaining a marine larval stage (McDowall, 1993; McDowall, 2003). Amphidromy is a type of diadromy, which is a life-history type that requires fauna to migrate between freshwater and saltwater. Females deposit their eggs in streams, the eggs hatch, and the larvae are carried downstream to the ocean, where they live as zooplankton for a species-specific period of time. They then migrate back to freshwater and metamorphose into postlarvae commonly called hinana. The postlarvae then make their way upstream, where they eventually mature into adults and live for the remainder of their lives (Ego, 1956; Tomihama, 1972; Ford and Kinzie, 1982; Kinzie and Ford, 1982; Kinzie, 1988; McDowall, 1988; Radtke and others, 1988; Tate and others, 1992; Radtke and others, 2001; McRae, 2007a). For these Hawaiian species, unlike salmon, no evidence indicates that the postlarvae recruit back to their natal streams. The amphidromous life cycle requires unimpeded access to and from the ocean.

Another relevant life-history characteristic is the upstream migratory ability of the different species. Four of the five ‘o‘opu (‘o‘opu ‘alamo‘o, ‘o‘opu nōpili, ‘o‘opu nākea, and ‘o‘opu naniha) are true gobies and have fused pelvic fins. The fused pelvic fin forms a suction disk that enables these fishes to attach themselves to stream substrate and climb cascades and waterfalls (Kinzie and Ford, 1982; Schoenfuss and Blob, 2003; Blob and others, 2006). Differences in clinging and climbing abilities have allowed the native fish species to migrate upstream and inhabit stream reaches according to their relative abilities to cling to the stream substrate. ‘O‘opu ‘akupa is not a true goby and lacks the fused pelvic fin and, therefore, is restricted to the lowest stream reaches, stream mouths, and estuaries. ‘O‘opu naniha has the weakest climbing ability of the true gobies and also is confined to the lower stream reaches, stream mouths, and estuaries. ‘O‘opu nākea, the largest of the native fish species, is a moderate climber and commonly is found in lower and middle stream reaches. ‘O‘opu nōpili often inhabits the middle stream reaches, whereas ‘o‘opu ‘alamo‘o, the best climber of the native fish species, typically is found in middle and upper stream reaches (Nishimoto and Fitzsimons, 1986; Fitzsimons and Nishimoto, 1990; Kinzie, 1990). The mountain ‘ōpae, ‘ōpaekala‘ole, has exceptional climbing ability and most often inhabits the upper stream reaches (Couret, 1976; Kinzie, 1990). Hīhīwai generally inhabit lower and middle stream reaches, preferring cold, well-oxygenated waters (Ford, 1979; Kinzie, 1990). Hapawai and ‘ōpae ‘oeha‘a are restricted to the lower stream reaches and estuaries. Segregation along elevation and longitudinal gradients reduces the amount of competition among native species for resources. Exceptions to the general segregation along elevation and longitudinal gradients, however, are known to exist. For example, adult ‘o‘opu nōpili were commonly observed near the mouth of Waihe‘e River during this study. The reasons these ‘o‘opu nōpili do not migrate farther upstream are unknown.

Another factor in habitat selection involves territoriality. Mature ‘o‘opu ‘alamo‘o males have been observed to aggressively defend territories against male conspecifics (males of the same species), whereas females tend to move freely about the stream (Lau, 1973; Maciolek, 1977; Nishimoto and Fitzsimons, 1986; Fitzsimons and Nishimoto, 1991). Similarly, male ‘o‘opu nōpili aggressively defend territories, with larger fish defending larger territories (Fitzsimons and Nishimoto, 1990; Fitzsimons and others, 1993). The normally docile ‘o‘opu nākea exhibits aggressive territoriality toward conspecifics as well as other species during the fall spawning season (Fitzsimons and Nishimoto, 1990).

Dietary preferences of the stream fauna also can influence habitat selection. The heterogeneous nature of streams may make it possible for species to occupy the same stream macrohabitats, because microhabitats commonly have different dietary resources. Morphological adaptations of the fishes may have functionally served to reduce interspecific competition for resources and allow the fish species to coexist (Kido, 1996, 1997a,b). Heterogeneous algal and invertebrate assemblages in Hawaiian streams provide a diversity of dietary resources for fish species of various age classes to utilize.

Non-Native Species

Over the years, many non-native species have been introduced into Hawaiian streams. More than 50 aquatic animal species, excluding insects, have become established in Hawai‘i (Brock, 1960; Kanayama, 1967; Maciolek, 1984; Devick, 1991; Brasher and others, 2006). The list of non-native species observed in Nā Wai ‘Ehā streams include: Thiaridae snails, including the red rimmed melania, *Melanoides tuberculata* (Müller, 1774), and the quilted melania, *Tarebia granifera* (Lamarck, 1822); Physidae pouch snail species, *Physa* Draparnaud, 1801; the Asiatic clam, *Corbicula fluminea* (Müller, 1774); crustaceans, including the amphidromous Tahitian prawn, *Macrobrachium lar* (Fabricius, 1798), and the Louisiana crayfish, *Procambarus clarkii* (Girard, 1852); fish from the family Poeciliidae, including the western mosquitofish, *Gambusia affinis* (Baird and Girard, 1853), guppies, *Poecilia reticulata* Peters, 1859, and green swordtails, *Xiphophorus helleri* Heckel, 1848; the Chinese catfish, *Clarias fuscus* (Lacepède, 1803), and the Channel catfish, *Ictalurus punctatus* (Rafinesque, 1818) (tables 7–10). Some of these species, such as *G. affinis*, were intentionally released for mosquito control, whereas others, such as *Physa* spp., may be accidental introductions from home aquaria (Van Dine, 1907; Devick, 1991; Yamamoto and Tagawa, 2000; Cowie, 2000). Some of these species, such as the catfish, can directly affect the native fauna by

Table 7. Non-native aquatic species observed in Waiheʻe River from surveys during 1978–2008, Maui, Hawaiʻi.

[HSA, Hawaiʻi Stream Assessment (Hawaiʻi Cooperative Park Service Unit, 1990); DAR, Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources; sp., species place holder for determinations to generic level only; spp., more than one species; IG1, introduced species group 1; IG2, introduced species group 2; p, present; a, abundant; va, very abundant;—, no data]

Class	Family	Genus/Species	Common name	HSA classification	Observations			
					HSA	DAR	Ford[1]	This study
Gastropoda	Thiaridae	*Melanoides tuberculata*	Red rimmed melania	IG2	—	—	—	—
Gastropoda	Thiaridae	*Tarebia granifera*	Quilted melania	IG2	—	—	—	—
Gastropoda	Physidae	*Physa* spp.	Pouch snail	IG2	—	2008(p)[2]	—	2008(a)
Gastropoda	Planorbidae	*Planorbella duryi*	Ramshorn snail	IG2	—	—	—	—
Gastropoda	Viviparidae	*Cipangopaludina chinensis*	Chinese mystery snail	IG2	—	(p)[3]	—	
Pelecypoda	Corbiculidae	*Corbicula fluminea*	Asiatic clam	IG1	—	—	—	—
Crustacea	Cambaridae	*Procambarus clarkii*	Louisiana crayfish	IG2	—	—	—	—
Crustacea	Palaemonidae	*Macrobrachium lar*	Tahitian prawn	IG2	1978(a)	2008(p)[2]	2007(p)	2008(a)
Osteichthyes	Poeciliidae	*Gambusia affinis*	Western mosquitofish	IG1	—	—	—	—
Osteichthyes	Poeciliidae	*Poecilia reticulata*	Guppy	IG1	1978(a)	—	—	2008(va)
Osteichthyes	Poeciliidae	*Xiphophorus helleri*	Green swordtail	IG1	—	—	—	2008(va)
Osteichthyes	Poeciliidae	*Poecilia* sp.	Poeciliids	IG1	—	—	—	2008(va)
Osteichthyes	Cichlidae	*Tilapia* sp.	Tilapia	IG1	—	—	—	—
Osteichthyes	Ictaluridae	*Ictalurus punctatus*	Channel catfish	IG2	—	(p)[3]	—	—

[1]Ford and others (2008).
[2]DAR observation (D. Polhemus, written commun., 2009).
[3]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).

Table 8. Non-native aquatic species observed in Waiehu Stream from surveys during 1961–2008, Maui, Hawaiʻi.

[HSA, Hawaiʻi Stream Assessment (Hawaiʻi Cooperative Park Service Unit, 1990); DAR, Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources; sp., species place holder for determinations to generic level only; spp., more than one species; IG1, introduced species group 1; IG2, introduced species group 2; p, present; a, abundant; va, very abundant;—, no data]

Class	Family	Genus/Species	Common name	HSA classification	Observations			
					HSA	DAR	Ford[1]	This study
Gastropoda	Thiaridae	*Melanoides tuberculata*	Red rimmed melania	IG2	—	—	—	2008(a)
Gastropoda	Thiaridae	*Tarebia granifera*	Quilted melania	IG2	—	2008(p)[2]	—	2008(a)
Gastropoda	Physidae	*Physa* spp.	Pouch snail	IG2	—	2008(p)[2]	—	2008(a)
Gastropoda	Planorbidae	*Planorbella duryi*	Ramshorn snail	IG2	—	—	—	2008(a)
Gastropoda	Ampullariidae	*Pomacea canaliculata*	Channeled apple snail	IG2	—	(p)[3]	—	—
Pelecypoda	Corbiculidae	*Corbicula fluminea*	Asiatic clam	IG1	—	2008(p)[2]	—	—
Crustacea	Cambaridae	*Procambarus clarkii*	Louisiana crayfish	IG2	—	(p)[3]	2007(a)	—
Crustacea	Palaemonidae	*Macrobrachium lar*	Tahitian prawn	IG2	—	2008(p)[2]	2007(p)	2008(a)
Osteichthyes	Poeciliidae	*Gambusia affinis*	Western mosquitofish	IG1	—	—	2007(a)	—
Osteichthyes	Poeciliidae	*Poecilia reticulata*	Guppy	IG1	—	2008(a)[2]	—	2008(va)
Osteichthyes	Poeciliidae	*Xiphophorus helleri*	Green swordtail	IG1	—	2008(p)[2]	—	2008(va)
Osteichthyes	Poeciliidae	*Poecilia* sp.	Poeciliids	IG1	—	2008(p)[2]	—	2008
Osteichthyes	Cichlidae	*Tilapia* sp.	Tilapia	IG1	—	—	—	—
Osteichthyes	Clariidae	*Clarias fuscus*	Chinese catfish	IG2	—	(p)[3]	—	—

[1]Ford and others (2008).
[2]DAR observation (D. Polhemus, written commun., 2009).
[3]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).

Table 9. Non-native aquatic species observed in ʻĪao Stream from surveys during 1961–2008, Maui, Hawaiʻi.

[HSA, Hawaiʻi Stream Assessment (Hawaiʻi Cooperative Park Service Unit, 1990); DAR, Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources; sp., species place holder for determinations to generic level only; spp., more than one species; IG1, introduced species group 1; IG2, introduced species group 2; p, present; a, abundant; va, very abundant; —, no data]

Class	Family	Genus/Species	Common name	HSA classification	Observations			
					HSA	DAR	Ford[1]	This study
Gastropoda	Thiaridae	*Melanoides tuberculata*	Red rimmed melania	IG2	—	—	—	2008(a)
Gastropoda	Thiaridae	*Tarebia granifera*	Quilted melania	IG2	—	—	—	2008(a)
Gastropoda	Physidae	*Physa* spp.	Pouch snail	IG2	—	(p)[2]	2007(a)	2008(a)
Gastropoda	Planorbidae	*Planorbella duryi*	Ramshorn snail	IG2	—	—	—	2008(a)
Pelecypoda	Corbiculidae	*Corbicula fluminea*	Asiatic clam	IG1	—	—	—	—
Crustacea	Cambaridae	*Procambarus clarkii*	Louisiana crayfish	IG2	—	—	—	—
Crustacea	Palaemonidae	*Macrobrachium lar*	Tahitian prawn	IG2	1989(p)	(p)[2]	2007 (p)	2008(a)
Osteichthyes	Poeciliidae	*Gambusia affinis*	Western mosquitofish	IG1	1989(p)	(p)[2]	—	—
Osteichthyes	Poeciliidae	*Poecilia reticulata*	Guppy	IG1	—	(p)[2]	2007(va)	2008(va)
Osteichthyes	Poeciliidae	*Xiphophorus helleri*	Green swordtail	IG1	—	(p)[2]	—	2008(va)
Osteichthyes	Poeciliidae	*Poecilia* sp.	Poeciliids	IG1	—	(p)[2]	2007(va)	2008(va)
Osteichthyes	Cichlidae	*Tilapia* sp.	Tilapia	IG1	—	(p)[2]	—	—
Osteichthyes	Ictaluridae	*Ictalurus punctatus*	Channel catfish	IG2	—	—	—	—

[1]Ford and others (2008).
[2]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).

Table 10. Non-native aquatic species observed in Waikapū Stream from surveys during 1961–2008, Maui, Hawaiʻi.

[HSA, Hawaiʻi Stream Assessment (Hawaiʻi Cooperative Park Service Unit, 1990); DAR, Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources; sp., species place holder for determinations to generic level only; spp., more than one species; IG1, introduced species group 1; IG2, introduced species group 2; p, present; a, abundant;—, no data]

Class	Family	Genus/Species	Common name	HSA classification	Observations			
					HSA	DAR	Ford[1]	This study
Gastropoda	Thiaridae	*Melanoides tuberculata*	Red rimmed melania	IG2	—	(p)[2]	—	—
Gastropoda	Thiaridae	*Tarebia granifera*	Quilted melania	IG2	—	—	—	—
Gastropoda	Physidae	*Physa* spp.	Pouch snail	IG2	—	—	2008(p)	2008(a)
Gastropoda	Planorbidae	*Planorbella duryi*	Ramshorn snail	IG2	—	—	—	—
Pelecypoda	Corbiculidae	*Corbicula fluminea*	Asiatic clam	IG1	—	(p)[2]	2008(p)	—
Crustacea	Cambaridae	*Procambarus clarkii*	Louisiana crayfish	IG2	—	(p)[2]	2007(p)	2008(a)
Crustacea	Palaemonidae	*Macrobrachium lar*	Tahitian prawn	IG2	—	—	—	—
Osteichthyes	Poeciliidae	*Gambusia affinis*	Western mosquitofish	IG1	—	(p)[2]	—	—
Osteichthyes	Poeciliidae	*Poecilia reticulata*	Guppy	IG1	—	—	2007(a)	—
Osteichthyes	Poeciliidae	*Xiphophorus helleri*	Green swordtail	IG1	—	—	—	—
Osteichthyes	Poeciliidae	*Poecilia* sp.	Poeciliids	IG1	—	—	—	—
Osteichthyes	Cichlidae	*Tilapia* sp.	Tilapia	IG1	—	(p)[2]	—	—
Osteichthyes	Ictaluridae	*Ictalurus punctatus*	Channel catfish	IG2	—	(p)[2]	—	—

[1]Ford and others (2008).
[2]Undated DAR observation from the Atlas of Hawaiian Watersheds and Their Aquatic Resources (Parham and others, 2008).

preying on small fishes, crustaceans, and insects (Yamamoto and Tagawa, 2000). The HSA classified non-native species into two groups based on their potential to threaten native species (Hawaiʻi Cooperative Park Service Unit, 1990). Non-native species group 1 (IG1) included non-native species that threaten native species by predation or competition. Non-native species group 2 (IG2) included non-native species that are not harmful to native species.

Aquatic Fauna in Nā Wai ʻEhā Streams

As part of this study, the presence or absence and distribution of aquatic species were determined using snorkel surveys at selected reaches on Nā Wai ʻEhā streams during 2008 (tables 3–10; figs. 9–15). In conducting these surveys, a snorkeler entered the stream below the downstream end of the reach and slowly moved upstream and photographed and identified the observed fish, snail, and crustacean species. Locations of the observations were recorded with a GPS (global positioning system) unit. The presence of hīhīwai was determined by sight and by overturning and inspecting rocks while snorkeling. Adult native damselflies, pinao ʻula, of the endemic genus *Megalagrion* also were photographed and identified. Additional observations of the aquatic biota were made throughout the study period at various locations along the Nā Wai ʻEhā streams to provide supplemental information on the distribution of the aquatic fauna.

Native Species

Each of the four streams has different natural and human-influenced conditions affecting the ability of the amphidromous native stream fauna to recruit, colonize, and flourish along the length of the stream. The amphidromous life cycle requires stream connectivity to the ocean to enable recruitment, and any condition that impedes that connectivity can affect the distribution and abundance of the amphidromous fauna.

Waiheʻe River

The Timbol and Maciolek (1978) inventory listed Waiheʻe River as having five diversions and five road crossings. In 1990, the Hawaiʻi Stream Assessment (HSA), a cooperative project that attempted to identify streams and rivers in Hawaiʻi with significant native aquatic biodiversity, rated Waiheʻe River as having “Outstanding” aquatic resources and “Good” native diversity (Hawaiʻi Cooperative Park Service Unit, 1990). The HSA aquatic biota surveys of Waiheʻe River included three Native Group 1 (NG1) species (“indicator species” considered representative of potentially high-quality stream ecosystems), ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, and ʻoʻopu nākea, and one Native Group 2 (NG2) species (species considered more common and typical of a healthy native stream ecosystem), ʻōpaekalaʻole. Data from Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources (DAR) point-quadrat surveys (Baker and Foster, 1992) conducted in Waiheʻe River in 1995 identified ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, ʻoʻopu nākea, and hīhīwai (State of Hawaiʻi, 2004). More recently, Ford and others (2008) observed ʻōpaekalaʻole and ʻoʻopu ʻalamoʻo in the upper reaches (altitude 1,600 ft) and ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, and ʻoʻopu nākea in the middle (420–620 ft) and lower (100 ft) reaches. DAR point-quadrat surveys conducted in 2008 also identified ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, and ʻoʻopu nākea in Waiheʻe River (D. Polhemus, written commun., 2009). Stream surveys conducted by the USGS in 2008, as part of this study, identified ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, ʻoʻopu nākea, ʻoʻopu ʻakupa, and āholehole at various locations along Waiheʻe River (figs. 9–13). Waiheʻe River also has been the site of stream fauna studies involving benthic macroinvertebrate assemblages (McIntosh and others, 2008).

Waiehu Stream

The Timbol and Maciolek (1978) inventory listed Waiehu Stream as having five diversions and eight road crossings. The HSA determined Waiehu Stream as having “Substantial” aquatic resources and “Good” native diversity, including two NG1 species, ʻoʻopu nōpili and ʻoʻopu nākea, and one NG2 species, ʻōpaekalaʻole (Hawaiʻi Cooperative Park Service Unit, 1990). More recently, DAR point-quadrat surveys conducted in 2008 identified ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, and ʻoʻopu nākea in Waiehu Stream (D. Polhemus, written commun., 2009). The DAR “Atlas of Hawaiian Watersheds and Their Aquatic Resources” also has records of ʻoʻopu ʻakupa, hapawai, hīhīwai, and āholehole in the Waiehu watershed (Parham and others, 2008). Ford and others (2008) observed ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, and ʻoʻopu nākea in North Waiehu Stream at an altitude of 875 ft and ʻoʻopu nōpili downstream of an altitude of 100 ft. Stream surveys conducted by the USGS in 2008, as part of this study, identified ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, ʻoʻopu nākea, and āholehole at various locations along Waiehu Stream (figs. 9–13).

ʻĪao Stream

The Timbol and Maciolek (1978) inventory listed ʻĪao Stream as having nine diversions and six road crossings. The HSA rated ʻĪao Stream as having “Substantial” aquatic resources and “Excellent” native diversity (Hawaiʻi Cooperative Park Service Unit, 1990). The HSA aquatic biota surveys of ʻĪao Stream included two NG1 species, ʻoʻopu nōpili and ʻoʻopu nākea, and two NG2 species, ʻōpaekalaʻole and āholehole. Data from the DAR Freshwater Database (State of Hawaiʻi, 2004) recorded in 1994 observations of ʻōpaekalaʻole and ʻoʻopu ʻalamoʻo in Poʻonāhoahoa Stream and ʻōpaekalaʻole and ʻoʻopu nākea in Nākalaloa Stream, both tributaries of ʻĪao

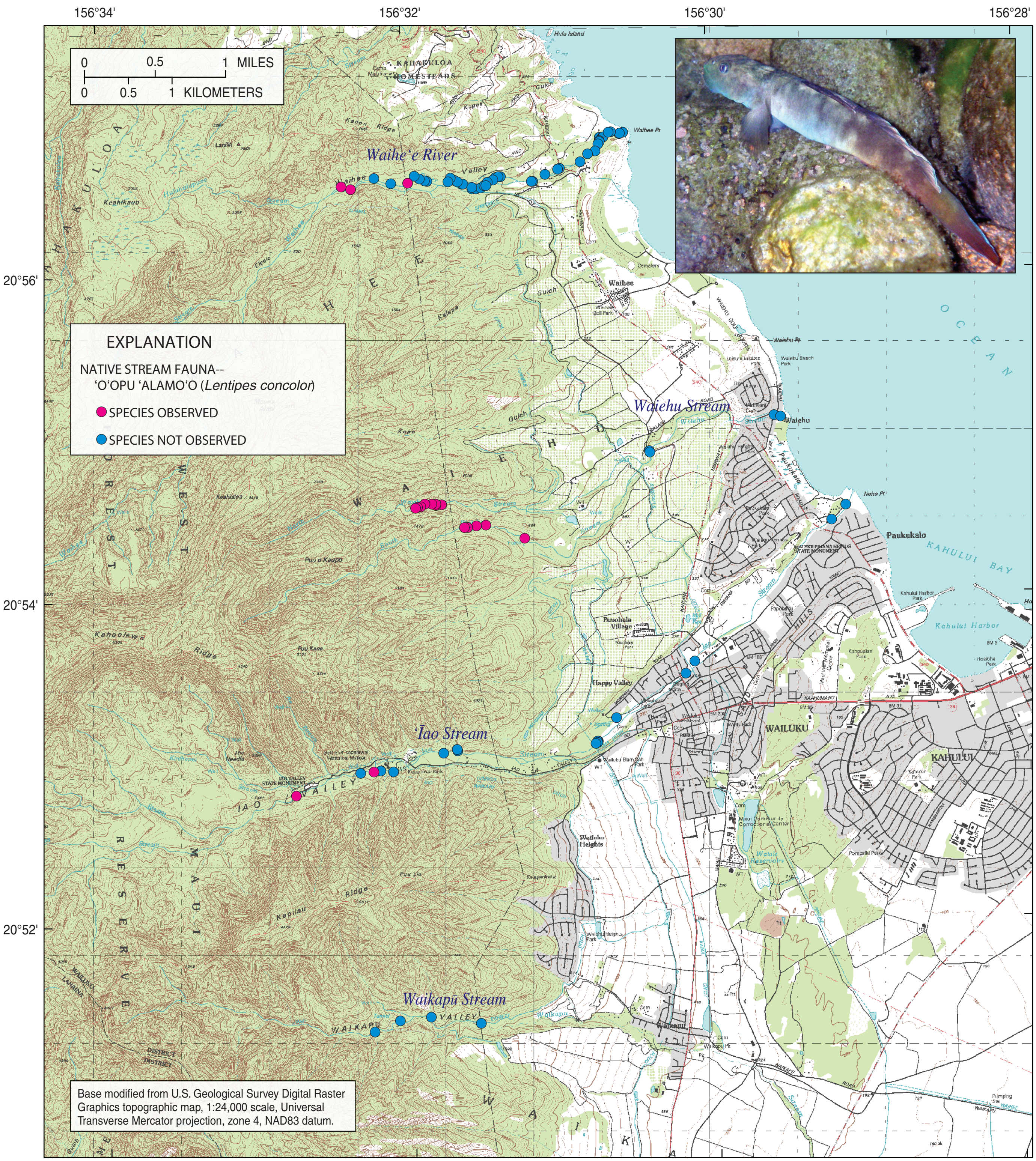


Figure 9. Distribution of ʻoʻopu ʻalamoʻo (*Lentipes concolor*, shown in inset photograph) from stream surveys during August and September 2008, Nā Wai ʻEhā, Maui, Hawaiʻi.

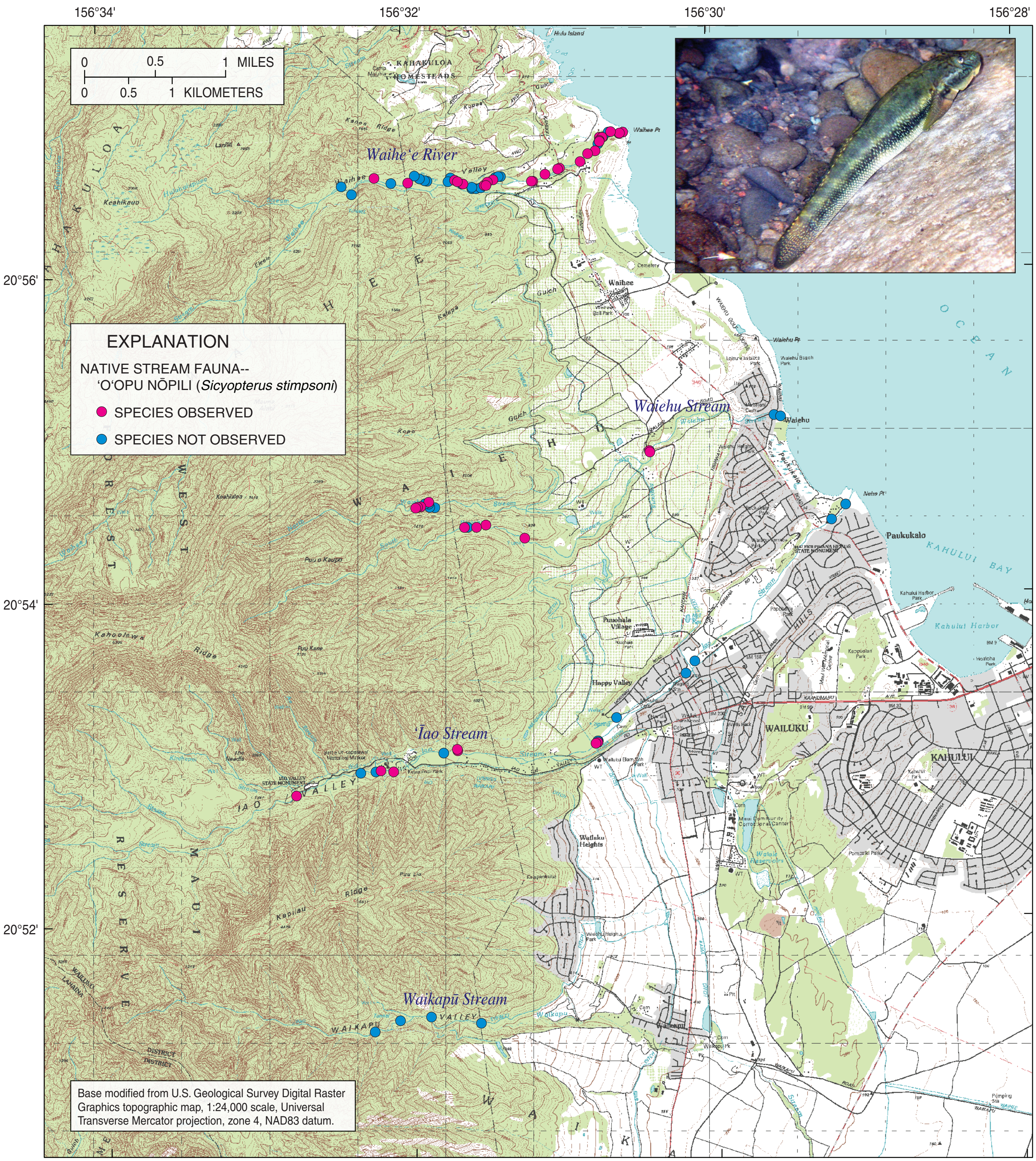


Figure 10. Distribution of ʻoʻopu nōpili (*Sicyopterus stimpsoni*, shown in inset photograph) from stream surveys during August and September 2008, Nā Wai ʻEhā, Maui, Hawaiʻi.

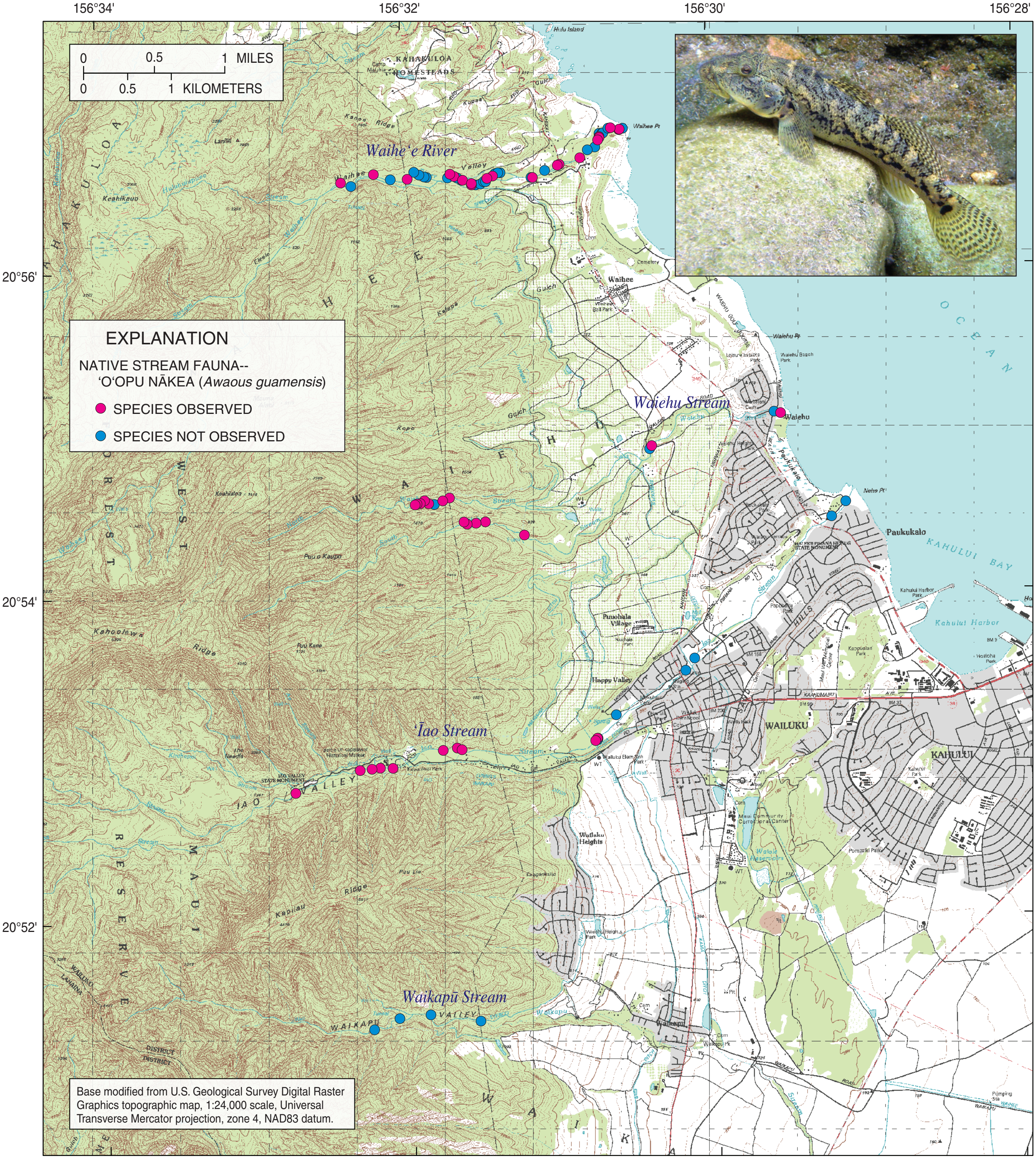


Figure 11. Distribution of ʻoʻopu nākea (*Awaous guamensis*, shown in inset photograph) from stream surveys during August and September 2008, Nā Wai ʻEhā, Maui, Hawaiʻi.

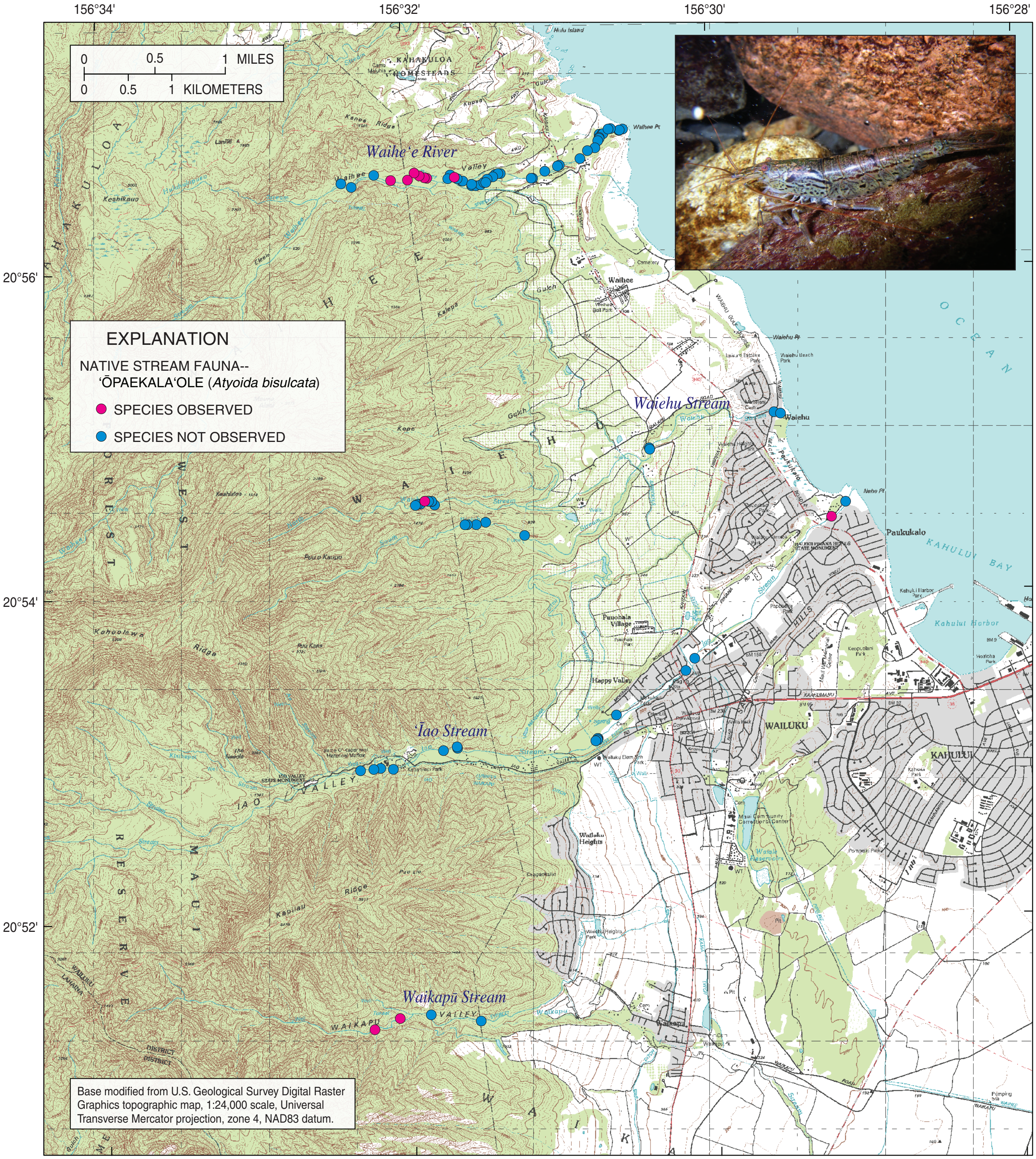


Figure 12. Distribution of ʻōpaekalaʻole (*Atyoida bisulcata*, shown in inset photograph) from stream surveys during August and September 2008, Nā Wai ʻEhā, Maui, Hawaiʻi.

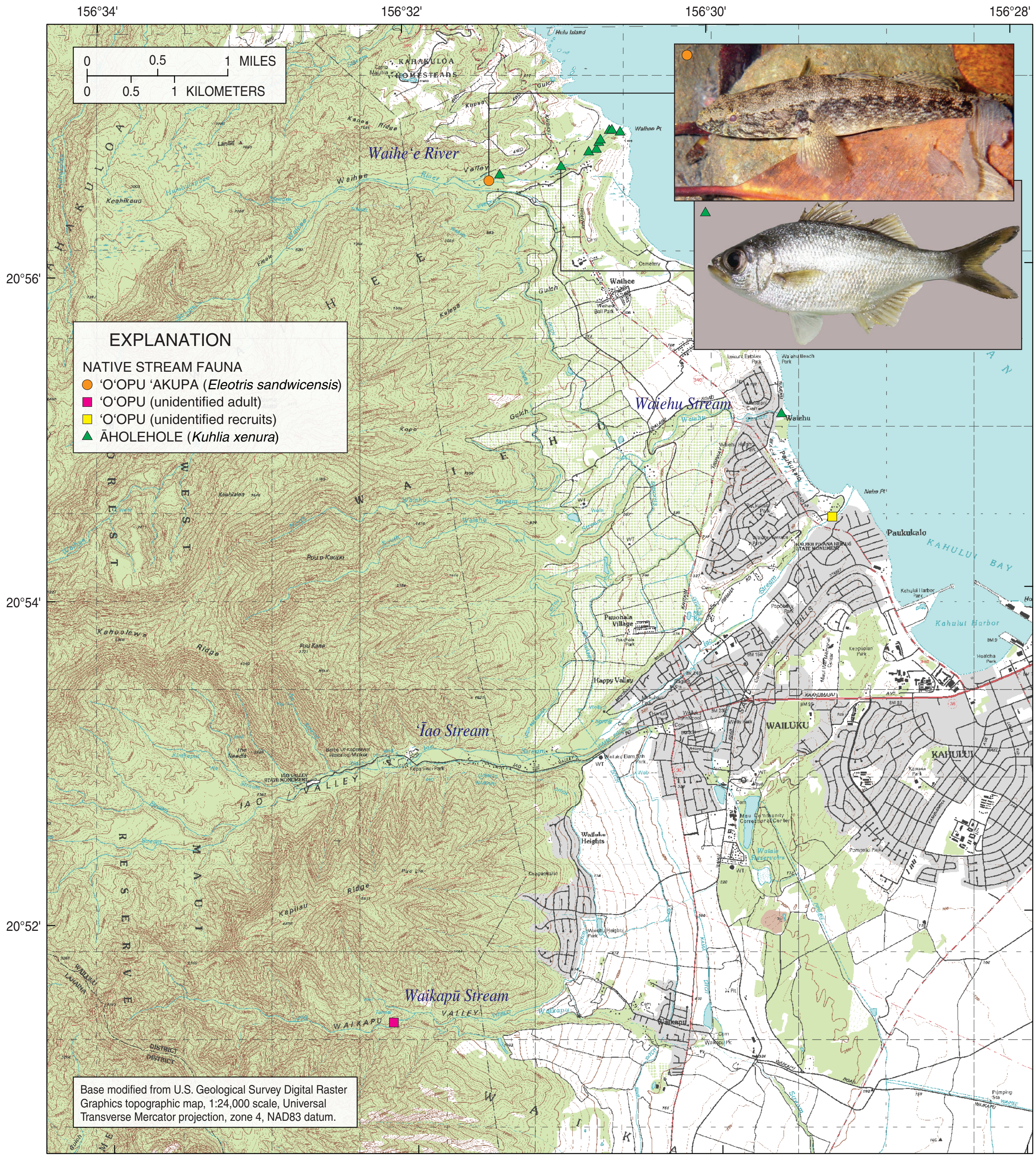


Figure 13. Selected native stream fauna, including ʻoʻopu ʻakupa (*Eleotris sandwicensis*, shown in upper inset photograph), āholehole (*Kuhlia xenura*, shown in lower inset photograph), and unidentified ʻoʻopu, observed during 2008, Nā Wai ʻEhā, Maui, Hawaiʻi.

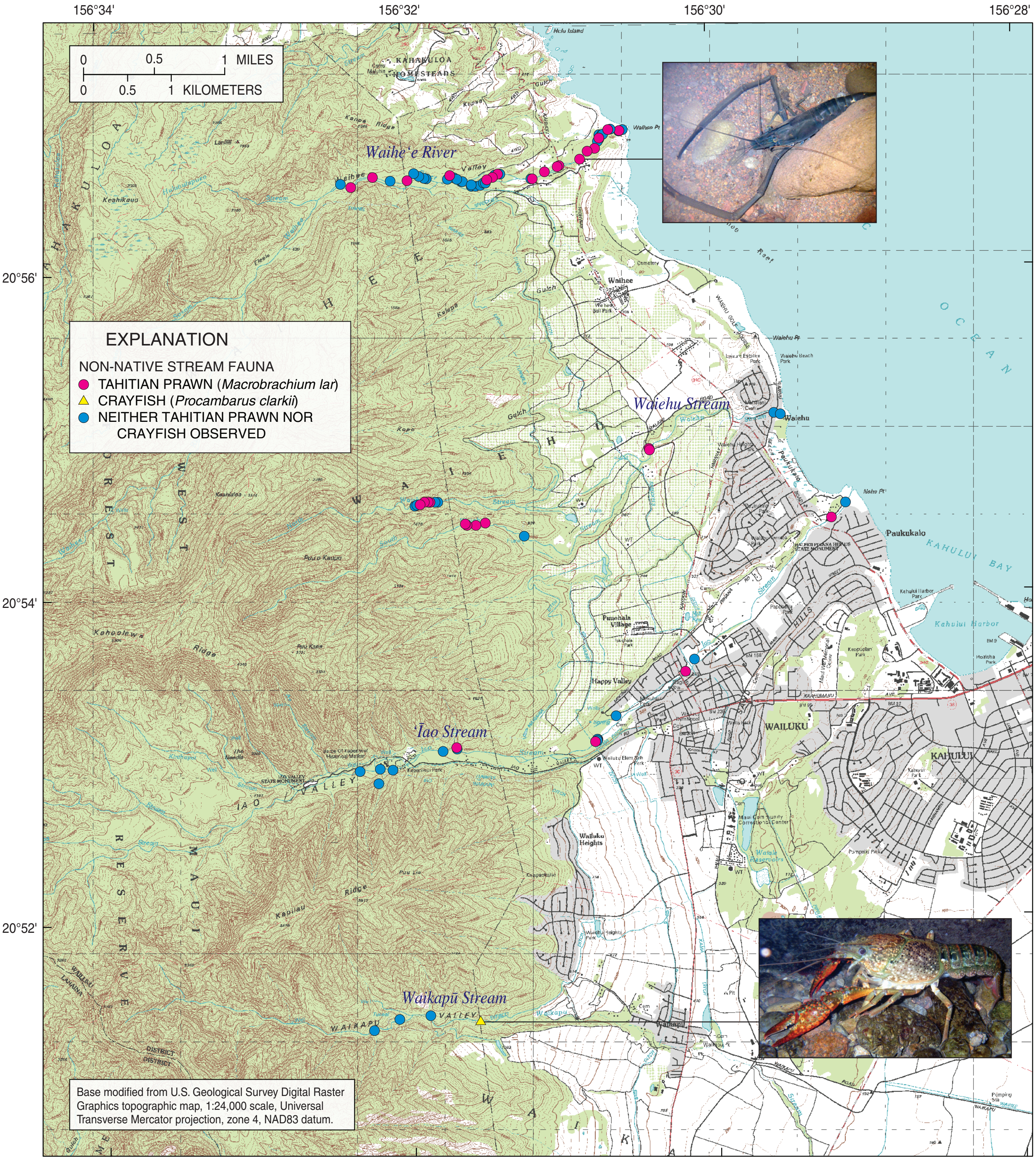


Figure 14. Distribution of Tahitian prawn (*Macrobrachium lar*, shown in upper inset photograph) and crayfish (*Procambarus clarkii*, shown in lower inset photograph) from stream surveys during August and September 2008, Nā Wai ʻEhā, Maui, Hawaiʻi.

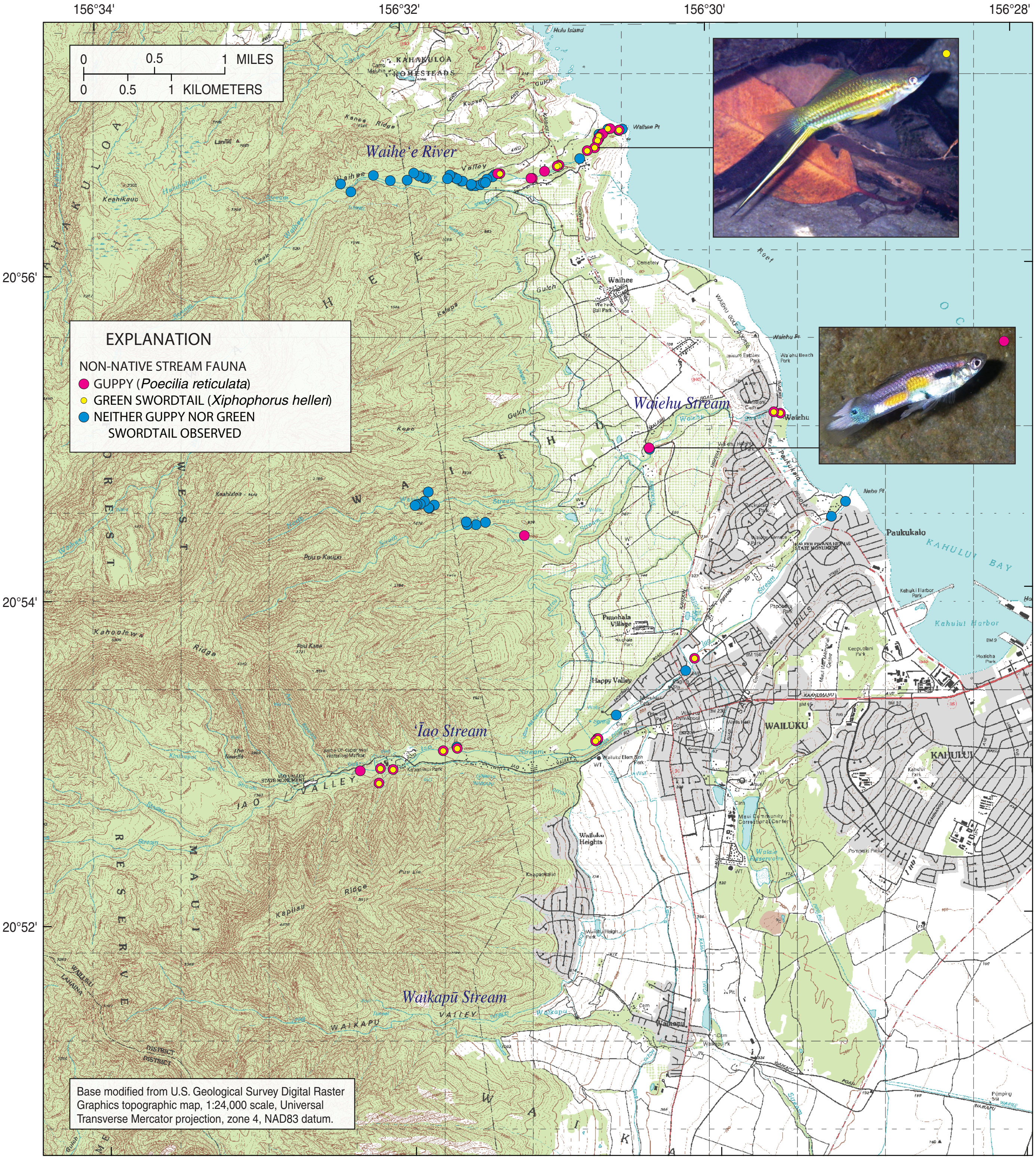


Figure 15. Distribution of green swordtails (*Xiphophorus helleri*, shown in upper inset photograph) and guppies (*Poecilia reticulata*, shown in lower inset photograph) from stream surveys during August and September 2008, Nā Wai ‘Ehā, Maui, Hawai‘i.

Stream, during point-quadrat count surveys. The DAR "Atlas of Hawaiian Watersheds and Their Aquatic Resources" also has records of ʻoʻopu naniha, ʻoʻopu ʻakupa, and āholehole in the ʻĪao watershed (Parham and others, 2008). In 2007, Ford and others (2008) observed ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, and ʻoʻopu nōpili in the upper reaches (1,600 ft) and ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, and ʻoʻopu nākea in the middle reaches (760–1,200 ft) of ʻĪao Stream. Stream surveys conducted by the USGS in 2008, as part of this study, identified ʻōpaekalaʻole, ʻoʻopu ʻalamoʻo, ʻoʻopu nōpili, and ʻoʻopu nākea at various locations along ʻĪao Stream (figs. 9–13).

ʻĪao Stream has been the site of many stream fauna studies involving (1) recruitment of hīhīwai (Hau, 2007), ʻoʻopu (State of Hawaiʻi, 2000; Benbow, 2001; Benbow and others, 2004a,b), and ʻōpaekalaʻole (Benbow and others, 2004a); (2) migration of hīhīwai (Benbow, 2001; Jennings and others, 2002); and (3) benthic macroinvertebrate assemblages (McIntosh and others, 2002, 2003; Benbow and others, 2003, 2005).

Waikapū Stream

The Timbol and Maciolek (1978) inventory listed Waikapū Stream as having nine diversions and nine road crossings. The HSA determined Waikapū Stream as having "Substantial" aquatic resources and "Good" native diversity, including two NG1 species, ʻoʻopu nōpili and ʻoʻopu nākea, and one NG2 species, ʻōpaekalaʻole (Hawaiʻi Cooperative Park Service Unit, 1990). The DAR "Atlas of Hawaiian Watersheds and Their Aquatic Resources" also has records of ʻōpaekalaʻole, ʻōpae ʻoehaʻa, ʻoʻopu nōpili, ʻoʻopu nākea, āholehole, and hapawai in the Waikapū watershed (Parham and others, 2008). More recently, Ford and others (2008) observed ʻōpaekalaʻole near an altitude of 1,180 ft, upstream and downstream of the South Side Ditch intake, and no native species at and downstream of an altitude of 410 ft. Stream surveys conducted by the USGS in 2008, as part of this study, identified ʻōpaekalaʻole at various locations along Waikapū Stream (figs. 9–13). A juvenile ʻoʻopu also was observed and photographed by the USGS in the pool just downstream of the South Side Ditch intake (fig. 13) during April 2008 and was identified as either ʻoʻopu ʻalamoʻo or ʻoʻopu nōpili (D.P. Lindstrom, oral commun., 2009).

Non-Native Species

The Nā Wai ʻEhā streams have a number of non-native aquatic species (tables 7–10; figs. 14–15). Non-native species have been introduced into Hawaiian streams either purposefully, with or without government sponsorship, for reasons such as mosquito control, weed control, fishing, food, or for ornamental ponds, or accidentally by escaping from aquaculture facilities, being brought in with aquatic plants or ballast water, or being released from home aquaria (Brock, 1960; Kanayama, 1967; Maciolek, 1984; Devick, 1991; Yamamoto and Tagawa, 2000).

Waiheʻe River

HSA surveys of Waiheʻe River in 1978 included records of the IG1 species *Poecilia reticulata* and the IG2 species the Tahitian prawn (Hawaiʻi Cooperative Park Service Unit, 1990). DAR point-quadrat surveys conducted in Waiheʻe River in 1995 identified the Tahitian prawn (State of Hawaiʻi, 2004). DAR point-quadrat surveys conducted in 2008 identified the Tahitian prawn and non-native Physidae (D. Polhemus, written commun., 2009). The "Atlas of Hawaiian Watersheds and Their Aquatic Resources" also has records of the Chinese mystery snail, *Cipangopaludina chinensis* (Gray, 1834), in the Waiheʻe watershed (Parham and others, 2008). Ford and others (2008) observed no non-native fauna in the upper reaches (1,600 ft) and the Tahitian prawn in the middle (420–620 ft) and lower (100 ft) reaches. Stream surveys conducted by the USGS in 2008, as part of this study, identified guppies, green swordtails, Physidae snails, and the Tahitian prawn at various locations along Waiheʻe River (figs. 14–15).

Waiehu Stream

HSA surveys of Waiehu Stream in 1961 had no records of non-native species (Hawaiʻi Cooperative Park Service Unit, 1990). DAR point-quadrat surveys conducted in 2008 identified green swordtails, guppies, the Tahitian prawn, and non-native mollusks, including the Asiatic clam, *Tarebia granifera*, and Physidae species (D. Polhemus, written commun., 2009). In addition to these observations, the "Atlas of Hawaiian Watersheds and Their Aquatic Resources" also has records of the Louisiana crayfish and the Chinese catfish (Parham and others, 2008). Ford and others (2008) observed the Tahitian prawn in North Waiehu Stream at an altitude of 875 ft and the western mosquitofish, the Louisiana crayfish, and the Tahitian prawn downstream of an altitude of 100 ft. Stream surveys conducted by the USGS in 2008, as part of this study, identified guppies, green swordtails, and the Tahitian prawn at various locations along Waiehu Stream (figs. 14–15).

ʻĪao Stream

HSA surveys of ʻĪao Stream in 1989 included records of the IG1 species the western mosquitofish and the IG2 species the Tahitian prawn (Hawaiʻi Cooperative Park Service Unit, 1990). In addition to these species, the "Atlas of Hawaiian Watersheds and Their Aquatic Resources" also has records of guppies, green swordtails, a species of tilapia, Physidae snail species, and other non-native snails in the ʻĪao watershed (Parham and others, 2008). No non-native species were recorded during DAR point-quadrat surveys conducted in ʻĪao Stream in 1994 (State of Hawaiʻi, 2004). Stream surveys conducted by the USGS in 2008, as part of this study, identified guppies, green swordtails, the Tahitian prawn, Physidae snails, Thiaridae snails, and ramshorn snails at various locations along ʻĪao Stream (figs. 14–15). During 2006, the USGS observed and photographed a turtle identified as a red-eared slider, *Chrysemys scripta elegans* (Wied-Neuwied, 1839), near an altitude of 570 ft. The red-eared slider is a common pet species that has become established at locations on Oahu (Yamamoto and Tagawa, 2000).

Waikapū Stream

HSA surveys of Waikapū Stream in 1961 had no records of non-native species (Hawaiʻi Cooperative Park Service Unit, 1990). The "Atlas of Hawaiian Watersheds and Their Aquatic Resources" has records of the Asiatic clam, the Louisiana crayfish, the western mosquitofish, the Chinese catfish, and a species of tilapia. Ford and others (2008) observed the Louisiana crayfish and a Lymnaeid snail species near an altitude of 1,180 ft, the Louisiana crayfish and guppies near an altitude of 410 ft, and the Asiatic clam and Physidae snails near an altitude of 200 ft. Stream surveys conducted by the USGS in 2008, as part of this study, identified the Louisiana crayfish and Physidae snails at various locations along Waikapū Stream (fig. 14).

Potential Factors Affecting Abundances of Native Species

The availability of physical habitat and water temperature may affect the abundance of native species in Nā Wai ʻEhā streams. The relations between streamflow and physical habitat for selected native species and measured stream temperatures along Nā Wai ʻEhā streams are described in later sections of this report. In addition to physical habitat and temperature, other factors that may affect the abundance of native species in Nā Wai ʻEhā streams include, but are not limited to, the presence of non-native species, channelization, water removal, and land-use activities in areas adjacent to the stream (Brasher, 2003).

Waiheʻe River

The intakes for the Waiheʻe Ditch are steel grates that are capable of diverting all of the dry-weather flow of Waiheʻe River. Water being diverted into the intake grates can create a tremendous downward force on the small, bottom-dwelling fish and shrimp that attempt to traverse the grate. Postlarvae recruits may become entrained in the diverted water and subsequently constrained to move within the ditch system to points of discharge. Larval ʻoʻopu, ʻōpae, and hīhīwai heading downstream to the ocean also may become entrained in the diverted water, removing them from the gene pool (Benstead and others, 1999). All diversion intakes similar to the Waiheʻe Ditch intakes can affect the abundances of native species.

In its natural state, using the ecosystem classification developed by Polhemus and others (1992), Waiheʻe River would be classified as a continuous perennial stream, but because of the diversion of surface water it is classified as an artificially interrupted perennial stream. Stream reaches downstream of the Waiheʻe and Spreckels Ditch intakes sometimes were dry during the course of this study. These dry reaches can impede the upstream migration of amphidromous species. Adult ʻoʻopu must find cool, persistent pools during dry-weather periods or perish.

Waiehu Stream

A potential factor affecting the distribution and abundance of native aquatic biota in Waiehu Stream is the diversion of water for offstream uses. In its natural state, this stream mainly would be classified as a continuous perennial stream, but because of the diversion of surface water it is classified as an artificially interrupted perennial stream. The upstream water removal causes the stream to be dry at lower altitudes, which affects the timing and duration of stream connectivity to the ocean and consequently limits the opportunity for the amphidromous species to successfully recruit and migrate upstream. Adult ʻoʻopu may perish in isolated pools because of elevated temperatures or insufficient dissolved oxygen (fig. 16). The vertical wall (about 10 to 15 ft high) of the Spreckels Ditch diversion structure on South Waiehu Stream (fig. 17) also could impede the upstream migration of the amphidromous species.

ʻĪao Stream

Two factors that potentially affect the distribution and abundance of native fauna in ʻĪao Stream are: (1) diversions that commonly cause some stream reaches to be dry, and (2) the sections of modified, concrete-lined stream channel. These two factors interact to affect the timing and duration of stream connectivity to the ocean and consequently limit the opportunity for the amphidromous species postlarvae to successfully recruit and migrate upstream (Hau, 2007). In its natural state, ʻĪao Stream would be classified as a continuous perennial stream, flowing continuously to the ocean over its entire course, but the diversions have changed the classification to that of an artificially interrupted perennial stream, with dry reaches downstream of diversions. The common intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches commonly diverts all of the dry-weather flow of ʻĪao Stream. Two sections of ʻĪao Stream currently are lined with concrete. Between altitudes of about 310 and 220 ft, ʻĪao Stream consists of a 1,100-ft-long concrete-lined channel with several chutes and a vertical drop structure (fig. 18), about 20 ft high, near the downstream end of the reach (Lencioni, 2000). From an altitude of about 35 ft down to its mouth, ʻĪao Stream consists of a 1,700-ft-long concrete-lined channel (fig. 19).

ʻĪao Stream flows to the ocean only during periods of moderate or heavy rainfall or ditch maintenance, when water is returned to the stream. This temporary connectivity can end abruptly, because the concrete channel was engineered as a flood control project meant to quickly transport the water out to the ocean. Larval animals that do not make it successfully to the ocean may perish. Migrating postlarvae need to negotiate the concrete channel to upstream areas with more persistent flow in order to survive. On a number of occasions since 2005, USGS personnel observed recruiting ʻoʻopu and ʻōpaekalaʻole in small, disconnected puddles in the concrete channel near the stream mouth. As these puddles heat up in the sun and evaporate, the postlarvae recruits die (fig. 19). Even in stream reaches with natural channels, downstream of the intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches, the ʻoʻopu must find cool, persistent pools during dry-weather periods or perish.

Other impediments to upstream migration include a vertical drop in the concrete channelized section near an altitude of 220 ft (fig. 18), a subvertical drop near an altitude of 370 ft upstream of a debris basin (fig. 20), and the grate-type intake structures. Water being diverted into an intake grate may entrain postlarvae recruits, removing them from the stream, or larval ʻoʻopu, ʻōpae, and hīhīwai heading downstream to the ocean, removing them from the gene pool.

Figure 16. Photographs of isolated shallow pool of water with ʻoʻopu near an altitude of 20 feet, Waiehu Stream, Maui, Hawaiʻi. *A*, Shallow pool at the left (north) edge of the channel beneath bridge (June 30, 2006). *B*, Dead and living ʻoʻopu in shallow pool (June 30, 2006).

Figure 17. Photograph of dam structure just downstream of the Spreckels Ditch diversion intake near an altitude of 270 feet, South Waiehu Stream, Maui, Hawaiʻi (July 17, 2006).

Figure 18. Photograph of vertical drop structure in concrete-lined channel near an altitude of 220 feet, ʻĪao Stream, Maui, Hawaiʻi (August 13, 2008).

Waikapū Stream

Unlike the other streams in this study, Waikapū Stream flows south and discharges into the Kēalia Pond National Wildlife Refuge, an important home to endangered native wetland birds. Waikapū Stream would be classified as a naturally interrupted perennial stream (Polhemus and others, 1992), with perennial flow in its upper reaches and naturally dry lower reaches. Connectivity to Kēalia Pond only occurs during and following periods of rainfall, and connectivity to the ocean also requires Kēalia Pond to discharge to the ocean. Recruitment and upstream migration to the perennial stream reaches may be possible only during extended wet periods, when continuous flow to the ocean is maintained for a sufficient duration. However, the presence of amphidromous species in the perennial reaches may be from human intervention or passage through the ditch system, as discussed below.

Artificial Transport of Postlarvae

The Hawaiʻi DAR and other individuals have been involved with transporting postlarvae recruits, collected from stream mouths, to stream reaches upstream of the dry reaches of ʻĪao Stream and Waikapū Stream (Polhemus, 2007; Skippy

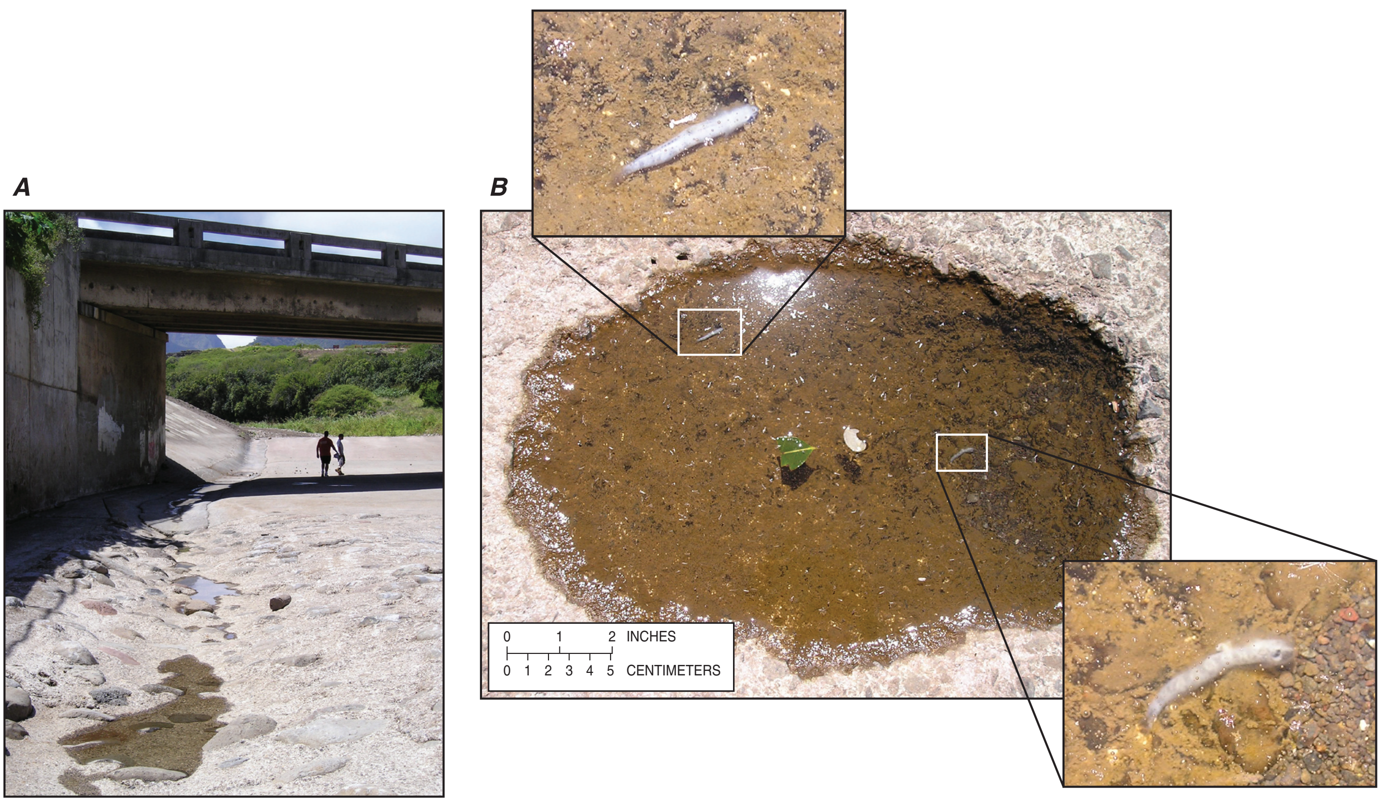


Figure 19. Photograph of concrete-lined channel of ʻĪao Stream near an altitude of 30 feet, Maui, Hawaiʻi. *A*, Disconnected puddles of water may exist following a period of rainfall (March 17, 2005). *B*, Migrating postlarvae ʻoʻopu recruits may die in these puddles as water temperatures rise to lethal levels (March 17, 2005).

Hau, written commun., 2009). This artificial transport of recruits to enhance upstream populations of native species also may increase the reproductive output of the streams and thus increase the populations of nearshore postlarvae. However, this effort can confound analyses of stream-fauna surveys by artificially increasing the abundances of native species in areas upstream of existing impediments to migration.

Ditch System

The system of ditches that interconnects the four streams in the Nā Wai ʻEhā area removes water from streams for offstream uses. Both native and non-native species have been observed in the ditches during the period of this study. These ditches may enable some aquatic biota to travel from one stream to another. It may be possible for some organisms to enter the ditch system from one stream and exit the system into another stream. Within the ditch system, this movement can be either in an upstream or downstream direction. Similar to the upstream relocation of the postlarvae, species movement within the ditch system can increase the species abundances in areas upstream of existing impediments to migration. The ditch system also may act as a conduit that allows some non-native species to move into areas they could not otherwise reach.

Larvae and Postlarvae

The system of ditches and ditch intakes efficiently diverts surface water for delivery to offstream uses. The ditch system also may divert large percentages of larval ʻoʻopu, ʻōpae, and hīhīwai that were headed downstream to the ocean, removing them from the gene pool (Benstead and others, 1999). The ditches prevent the larvae from reaching the population of marine-phase larvae, which could consequently decrease the number of locally available postlarvae recruits. Additionally, reduced streamflow caused by diversions results in lower water velocity that potentially increases the length of time it takes for larvae to reach the ocean, thus increasing the chance that the larvae may die from starvation (Lindstrom and Brown, 1996; Iguchi and Mizuno, 1999; Iguchi, 2007; McRae, 2007b). These effects may function to reduce the contribution of larvae from these streams to the nearshore population of potential recruits. The removal of the amphidromous larvae by the ditch system and the increased mortality caused by reduced streamflow may have transformed some of the upstream habitats from source habitats to sink habitats (McRae, 2007b).

Another effect of reduced streamflow is a reduction in the size of the estuary and the freshwater plume that extends into the marine environment. The native amphidromous species cue on the freshwater plume to begin their recruitment to the stream mouths (Tate and others, 1992). Reductions in the size and frequency of the freshwater plumes may reduce the overall number of postlarvae recruits to the dewatered streams.

Figure 20. Photograph of subvertical drop near an altitude of 370 feet, ʻĪao Stream, Maui, Hawaiʻi (June 6, 2006).

Other Issues Not Investigated

Ecosystems in the Nā Wai ʻEhā streams are composed of complex webs of interconnected hydrological, chemical, and biological processes. This study only addresses a part of the ecological composition. Factors that were not investigated during this study include, but are not limited to, the reproduction, larval dispersal, and recruitment of the amphidromous species; the effects of non-native amphibians such as frogs and toads; water chemistry and water-quality parameters; parasites; non-native marine species; and benthic algal and macroinvertebrate assemblages.

Natural, Undiverted Low-Flow Characteristics

Natural, undiverted streamflows can be characterized using data from historical and active USGS gaging stations (table 11). Data from these stations can be extrapolated to other reaches using additional discharge measurements (figs. 21–24; table 12, placed at the end of the report as appendix B) that quantify gains and losses in the stream channels and tributary inflows.

Gaging-Station Data

Since 1983, the USGS has maintained two continuous-record stream-gaging stations in the Nā Wai ʻEhā area:

station 16614000 (Waiheʻe River above Waiheʻe Ditch intake near Waiheʻe, Maui, Hawaiʻi) and station 16604500 (ʻĪao Stream at Kepaniwai Park near Wailuku, Maui, Hawaiʻi) (fig. 7). Data from these two stations can be used to characterize the natural, undiverted flows in Waiheʻe River and ʻĪao Stream for recent conditions. Complete data are available for stations 16614000 and 16604500 during climate years 1984–2007, and this common period is used for characterizing flows in this report. A climate year starts on April 1 and ends on March 31 of the following year and is named according to the calendar year in which it starts. Climate years maintain the integrity of the dry season, which occurs during May through September in the study area (fig. 4), and therefore are useful for characterizing low-flow characteristics.

On the basis of long-term data available from Honokōhau Stream (station 16620000, fig. 1, northwest of Waiheʻe River), mean flow during climate years 1984–2007 was 24 Mgal/d (37 ft^3/s), compared to 25 Mgal/d (39 ft^3/s) during climate years 1914–2007 (complete data during climate years 1920–22 and 1988–90 were not available). Thus, data from 1984–2007 appear to provide a reasonable proxy for long-term data in the study area. Continuous streamflow data for Waiehu and Waikapū Streams during climate years 1984–2007 are not available, although flow statistics for these streams can be estimated using record-extension methods.

Waiheʻe River

During climate years 1984–2007, the mean discharge measured at gaging station 16614000 was 47.3 Mgal/d (73.2 ft^3/s) and annual mean discharges at station 16614000 ranged from 31.8 Mgal/d (49.2 ft^3/s) in 1984 to 70.5 Mgal/d (109 ft^3/s) in 1987 (fig. 25). Daily mean discharges in Waiheʻe River over the same period are much more variable than annual mean discharges, ranging from 14 to 750 Mgal/d (22 to 1,160 ft^3/s).

During climate years 1984–2007, mean monthly discharge in Waiheʻe River (station 16614000) was greatest during March and April (54.6 Mgal/d; 84.5 ft^3/s) toward the end of the wet season and least during October (42.3 Mgal/d; 65.4 ft^3/s) at the start of the wet season (fig. 26). The pattern of mean monthly streamflow generally is consistent with the pattern of mean monthly rainfall measured by rain gages near the wetter, mountainous interior parts of the Nā Wai ʻEhā area (fig. 4).

A flow-duration curve for daily mean discharges is a cumulative-frequency curve that shows the percentage of days specified discharges were equaled or exceeded during a given time period. Although a flow-duration curve does not account for the actual sequence of flows being characterized, it does provide insight into the availability and variability of flows at a site. The median discharge, or Q_{50}, during a specified period is the discharge that is equaled or exceeded 50 percent of the time. Similarly, the Q_{95} discharge during a specified period is the discharge that is equaled or exceeded 95 percent of the time and, therefore, represents a lower discharge than the Q_{50} discharge. The flow-duration curve (based on daily mean discharges) for station 16614000 for climate years 1984–2007 indicates that the median discharge was 34 Mgal/d (52 ft^3/s) and the Q_{95} discharge was 22 Mgal/d (34 ft^3/s) (fig. 27; table 13). For climate years 1984–2007 for station 16614000, the overall ratio of the Q_{95} to the Q_{50} discharges was 0.65. In contrast to the mean monthly discharges, which were greatest during March and April and least during October, the median monthly discharges generally were greatest during July or August and least during February (fig. 26). The median monthly discharges are less variable than the mean monthly discharges, which are more affected by periods of high discharge.

ʻĪao Stream

During climate years 1984–2007, the mean discharge measured at gaging station 16604500 was 41.5 Mgal/d (64.2 ft^3/s) and annual mean discharges at station 16604500 ranged from 20.8 Mgal/d (32.2 ft^3/s) in 1984 to 57.1 Mgal/d (88.3 ft^3/s) in 1987 (fig. 25). Daily mean discharges in ʻĪao Stream during the same period are much more variable than annual mean discharges, ranging from 6.1 to 1,100 Mgal/d (9.4 to 1,700 ft^3/s).

During climate years 1984–2007, mean monthly discharge in ʻĪao Stream (station 16604500) was greatest during March (54.2 Mgal/d; 83.8 ft^3/s) toward the end of the wet season and least during September (30.2 Mgal/d; 46.7 ft^3/s) toward the end of the dry season (fig. 26). The pattern of mean monthly streamflow generally is consistent with the pattern of mean monthly rainfall measured by rain gages near the wetter, mountainous interior parts of the Nā Wai ʻEhā area (fig. 4).

The flow-duration curve for station 16604500 for climate years 1984–2007 indicates that the median discharge was 25 Mgal/d (39 ft^3/s) and the Q_{95} discharge was 11 Mgal/d (17 ft^3/s) (fig. 27; table 13). For climate years 1984–2007 for station 16604500, the overall ratio of the Q_{95} to the Q_{50} discharges was 0.44, reflecting more low-flow variability than at station 16614000 on Waiheʻe River. In contrast to the mean monthly discharges, which were greatest during March and least during September, the median monthly discharges were greatest during April or August and least during October (fig. 26).

Waiehu and Waikapū Streams

Complete records of discharge from stream-gaging stations on North Waiehu, South Waiehu, and Waikapū Streams during climate years 1984–2007 are unavailable to define natural-flow characteristics for these streams. Continuous-record stream-gaging stations currently are not being operated on these streams, although historical daily streamflow data for these streams from about 1911 to 1917 have been published by the U.S. Geological Survey (Martin

Table 11. Selected active and historical U.S. Geological Survey (USGS) gaging stations in and near the Nā Wai ʻEhā, Maui, Hawaiʻi.

[SW, continuous-record stream-gaging station; CSG, crest-stage gage; p, present (2009); station names are as they appear in the USGS National Water Information System database]

USGS site number	Station name	Altitude, in feet	Period of record	Station type	Comment
16587000	Honopou Stream near Huelo, Maui, HI	1,208	1910–p	SW[1]	outside of study area
16604000	IAO STREAM NR WAILUKU, MAUI, HI	860	1910–15	SW[1]	natural, undiverted flow
16604500	Iao Stream at Kepaniwai Park nr Wailuku, Maui, HI	780	1983–p	SW[1]	natural, undiverted flow
16605000	MANIANIA DITCH NR WAILUKU,MAUI,HI	740	1910–13	Ditch	ditch flow
16607000	Iao Stream at Wailuku, Maui, HI	250	1950–51;1950–p	SW; CSG[2]	downstream of diversions
16608000	NORTH WAIEHU STREAM NR WAILUKU, MAUI, HI	880	1912–15	SW	natural, undiverted flow
16609000	N WAIEHU DITCH NR WAILUKU,MAUI,HI	840	1910–11; 1916–17	Ditch	ditch flow
16609500	N WAIEHU STR BL N WAIEHU DITCH NR WAILUKU, MAUI	730	1910–11	SW	downstream of diversion
16610000	SOUTH WAIEHU STREAM NR WAILUKU, MAUI, HI	870	1910–17	SW	natural, undiverted flow
16611000	S WAIEHU DITCH NR WAILUKU,MAUI,HI	860	1912–13	Ditch	ditch flow
16612000	WAIHEE RIVER NR WAIHEE, MAUI, HI	620	1913–17	SW[1]	natural, undiverted flow
16613000	WAIHEE CANAL NR WAIHEE,MAUI,HI	600	1910–12	Ditch	ditch flow
16613500	WAIHEE CANAL AT WAIALE WEIR NR WAILUKU,MAUI,HI	450	1911–12	Ditch	ditch flow
16614000	Waihee Rv abv Waihee Dtch intk nr Waihee, Maui, HI	605	1983–p	SW[1]	natural, undiverted flow
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	380	1910–13	Ditch	ditch flow
16616000	SPRECKLES DITCH AT WAIALE WEIR NR WAILUKU,MAUI	230	1910–11	Ditch	ditch flow
16620000	Honokohau Stream near Honokohau, Maui, HI	870	1911–p[3]	SW[1]	outside of study area
16648000	SOUTH SIDE WAIKAPU DITCH NR WAIKAPU, MAUI, HI	1,100	1910–17	Ditch[4]	ditch flow
16649000	PALOLO DITCH NR WAIKAPU, MAUI, HI	880	1910–17	Ditch[4]	ditch flow
16650000	WAIKAPU STREAM NR WAIKAPU,MAUI,HI	880	1910–17	SW[4]	downstream of diversions
16650200	Waikapu Stream at Waikapu, Maui, HI	340	2002–p	CSG	downstream of diversions
16650500	Waikapu Stream at Waikapu, Maui, HI	340	1963–97	CSG	downstream of diversions

[1]Station used as an index station for record extension purposes.
[2]SW station 1950–51; CSG station 1950–present.
[3]No data available during calendar years 1912, 1921, and 1989.
[4]Data from stations 16648000, 16649000, and 16650000 combined to estimate discharge in Waikapū Stream near an altitude of 880 feet.

and Pierce, 1913; Pierce and Larrison, 1914; Larrison, 1915; Grover and Larrison, 1917a,b, 1918; Wells, 1961). These historical records can be extended to provide estimates of natural-flow characteristics that reflect recent conditions (1984–2007 climate years). The recent base period covering the 1984–2007 climate years is used for the record extension of historical data from North Waiehu, South Waiehu, and Waikapū Streams. On the basis of available data from Honokōhau Stream (station 16620000), mean flow during the 1984–2007 base period was 24 Mgal/d (37 ft^3/s), compared to 36 Mgal/d (55 ft^3/s) during climate years 1914–17. Thus, historical data from Waiehu and Waikapū Streams may reflect a wetter period relative to the 1984–2007 base period.

Daily streamflow data for North Waiehu, South Waiehu, and Waikapū Streams are available during the period from about 1911 to 1917, although the records have numerous data gaps (fig. 28). In some cases, discharge data from stream-gaging stations upstream of diversions can be used to estimate natural flow characteristics. In other cases, discharge data from a stream-gaging station (downstream of diversions) and ditch-gaging stations can be combined to estimate natural-flow characteristics for the stream.

Daily discharge data from additional gaging stations (index stations) are needed to extend the records of North Waiehu, South Waiehu, and Waikapū Streams. For each index station, at least two years of concurrent (relative to the records of North Waiehu, South Waiehu, and Waikapū Streams) historical data were considered the minimum to include the index station in the analysis. Data from index stations on Waiheʻe River and ʻĪao, Honokōhau, and Honopou Streams can be correlated with concurrent data from North Waiehu, South Waiehu, and Waikapū Streams for record extension. Because of limitations described below, data from all four index stations were used to provide a range of estimated natural-flow characteristics for the recent base period 1984–2007. All index stations had complete (or nearly complete in the case of Honokōhau Stream) data during the 1984–2007 base period.

North Waiehu Stream.—Historical data that can be used to estimate natural-flow characteristics of North

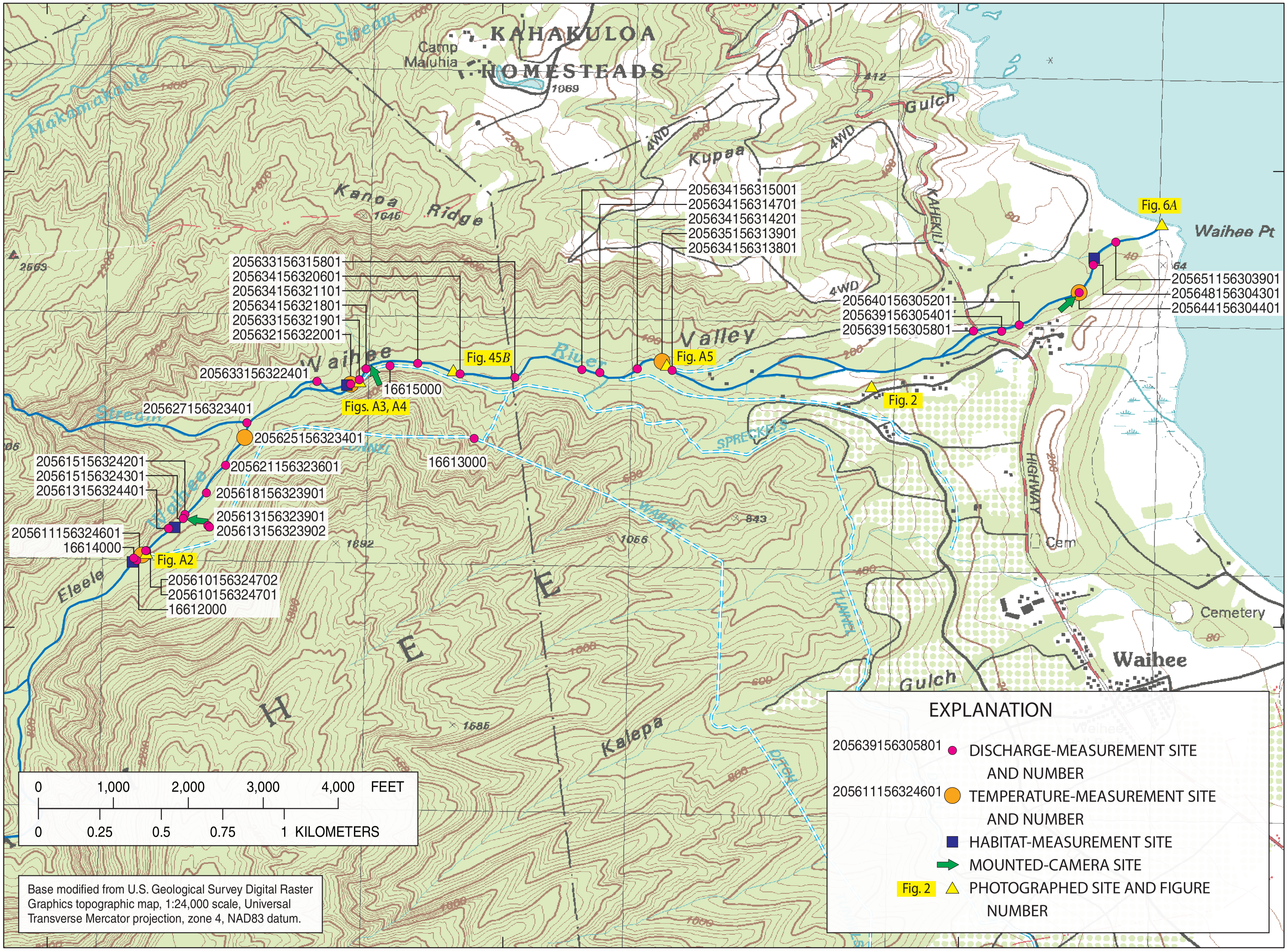


Figure 21. Discharge-, temperature-, and habitat-measurement sites, mounted-camera sites, and photographed sites, Waiheʻe River, Maui, Hawaiʻi.

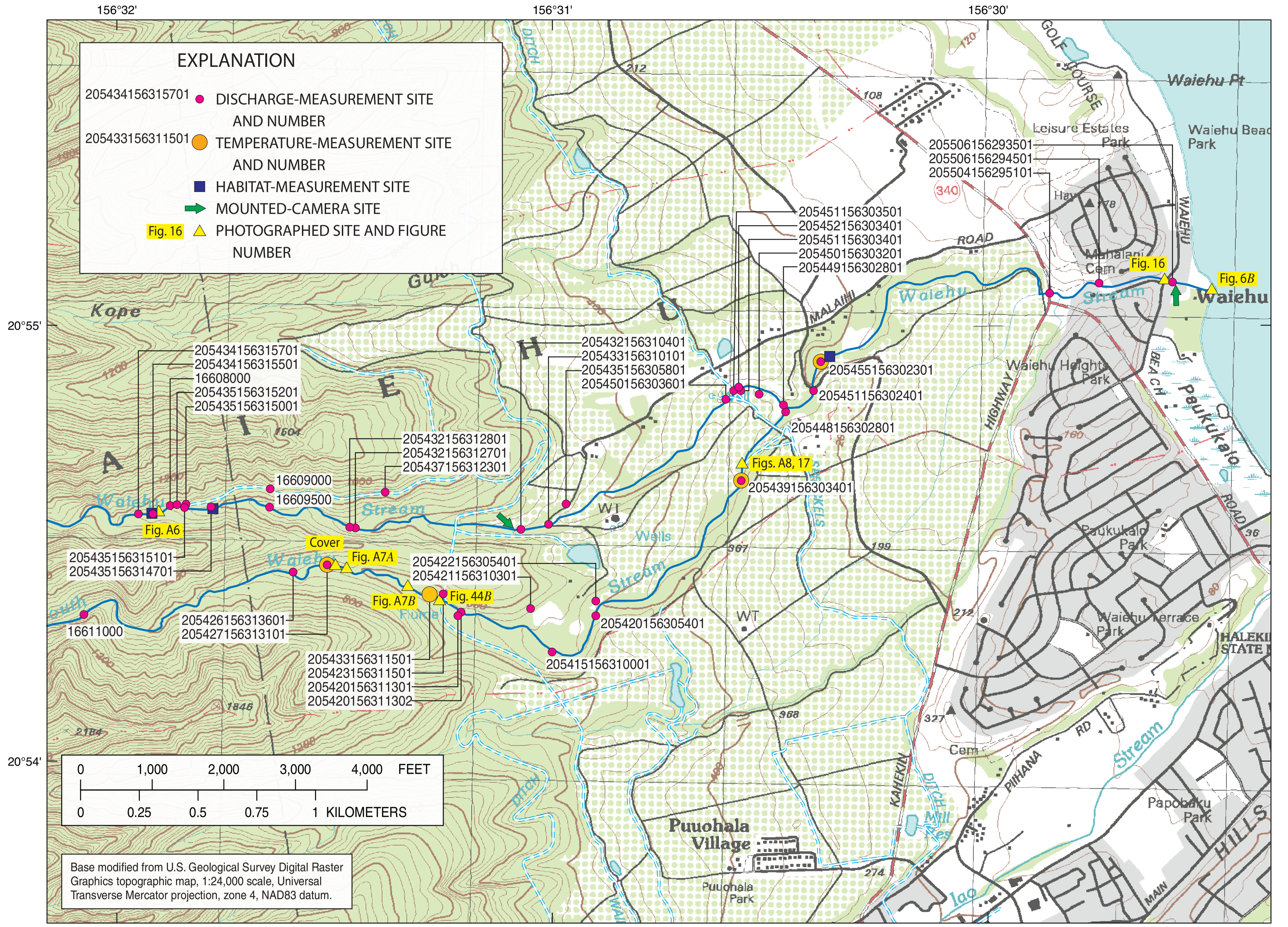


Figure 22. Discharge-, temperature-, and habitat-measurement sites, mounted-camera sites, and photographed sites, Waiehu Stream, Maui, Hawaiʻi.

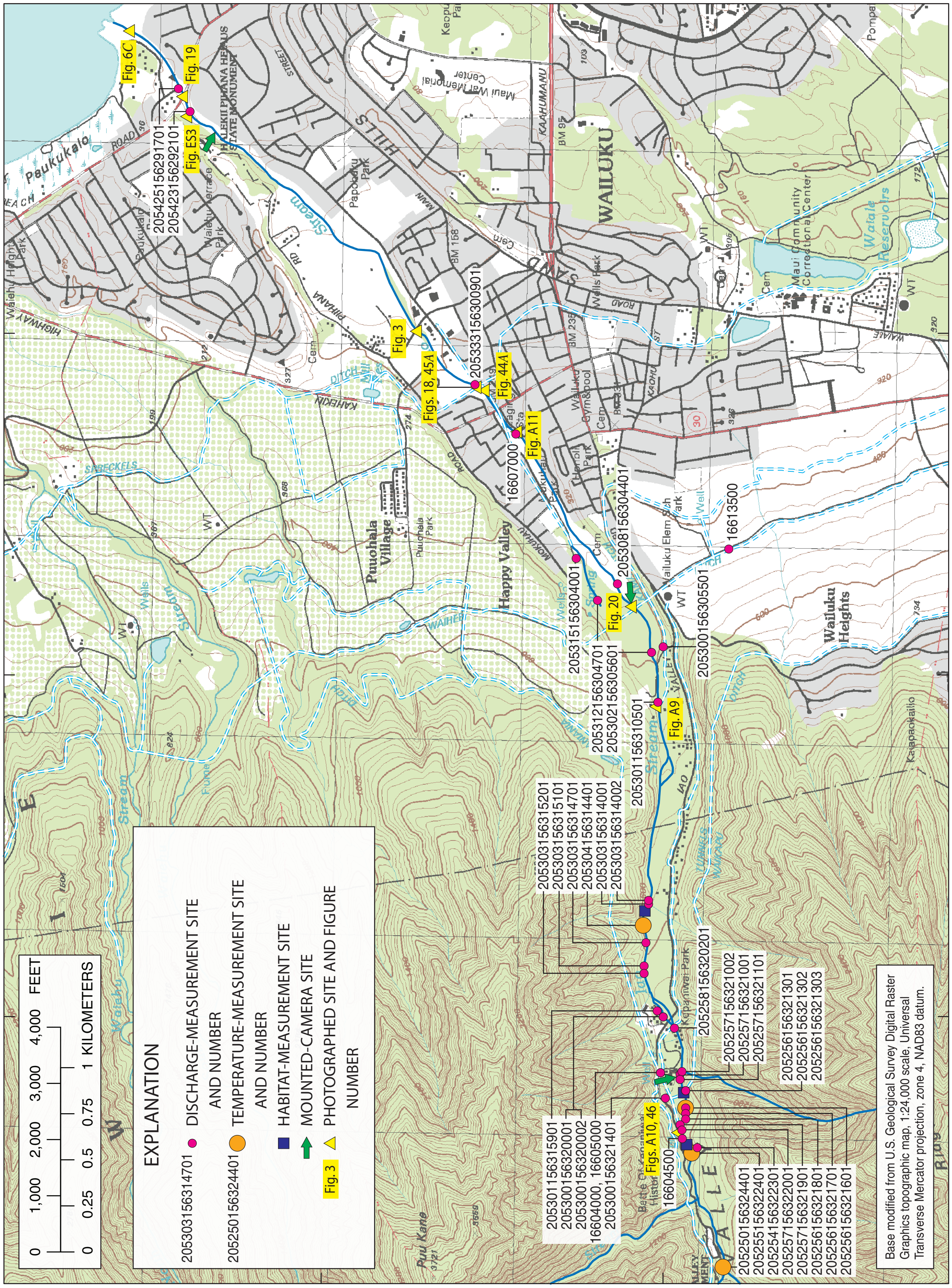


Figure 23. Discharge-, temperature-, and habitat-measurement sites, mounted-camera sites, and photographed sites, ʻĪao Stream, Maui, Hawaiʻi.

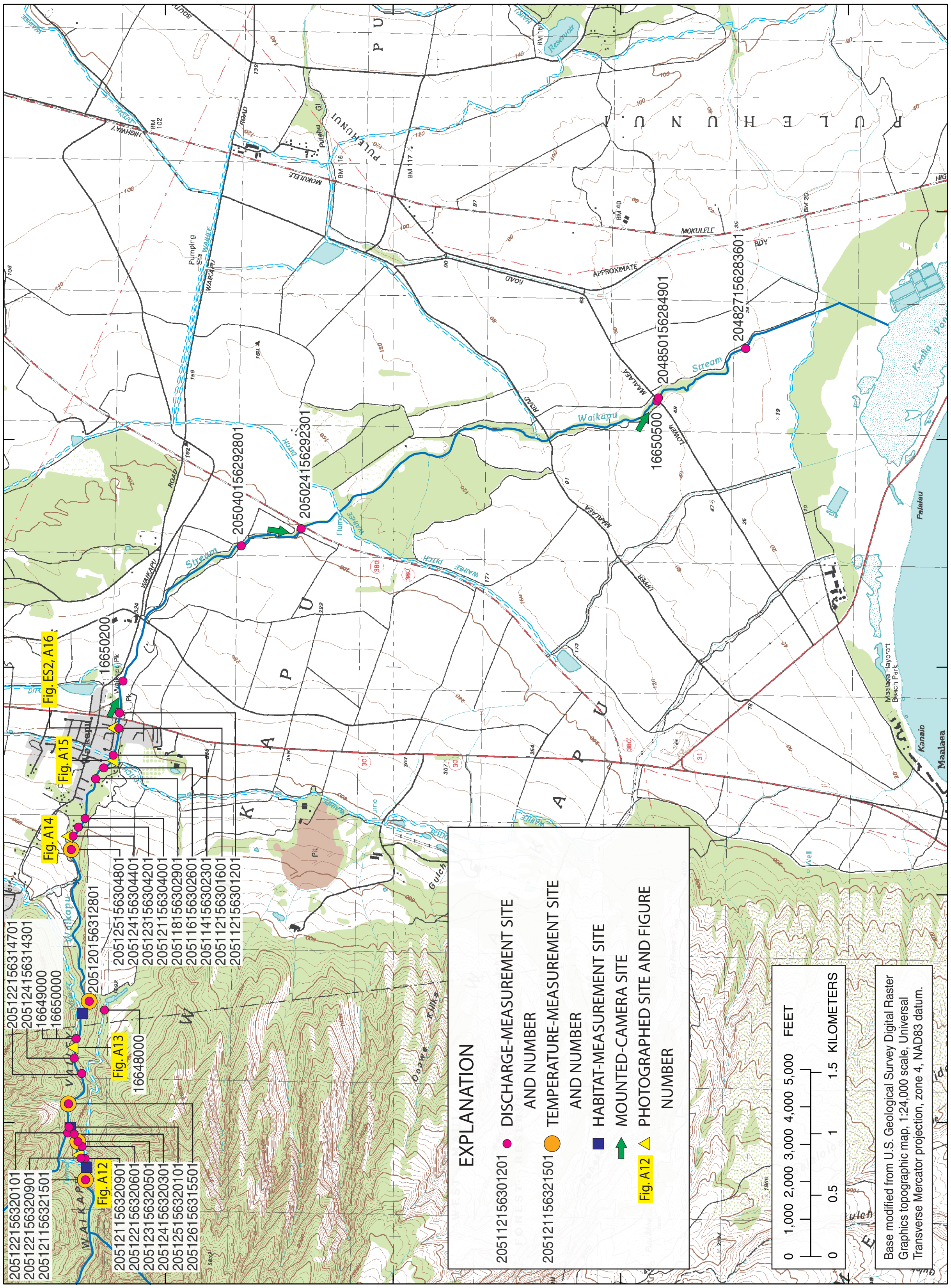


Figure 24. Discharge-, temperature-, and habitat-measurement sites, mounted-camera sites, and photographed sites, Waikapū Stream, Maui, Hawaiʻi.

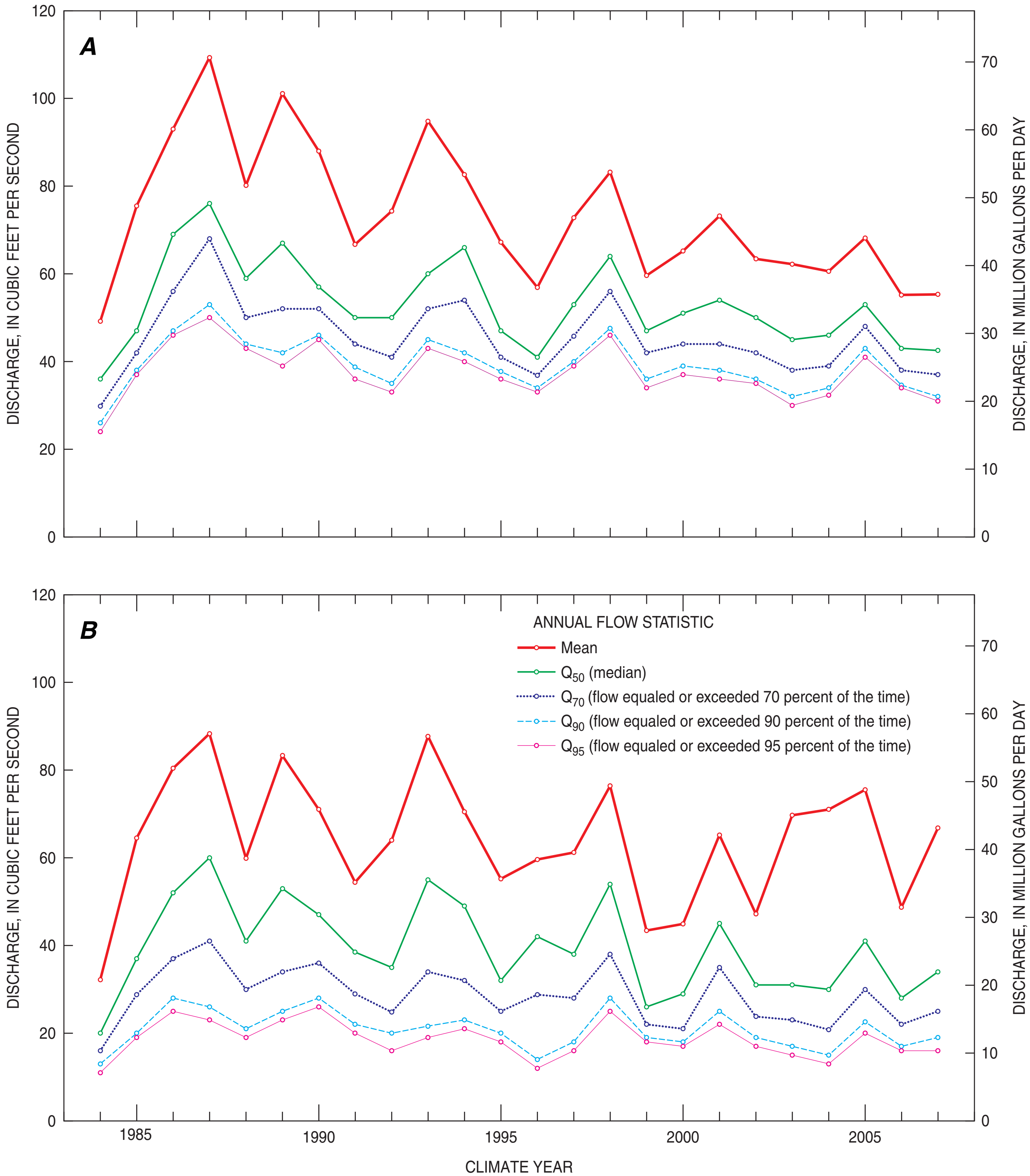


Figure 25. Annual flow statistics (climate years 1984–2007) for Waiheʻe River and ʻĪao Stream, Maui, Hawaiʻi. *A*, Waiheʻe River, gaging station 16614000. *B*, ʻĪao Stream, gaging station 16604500.

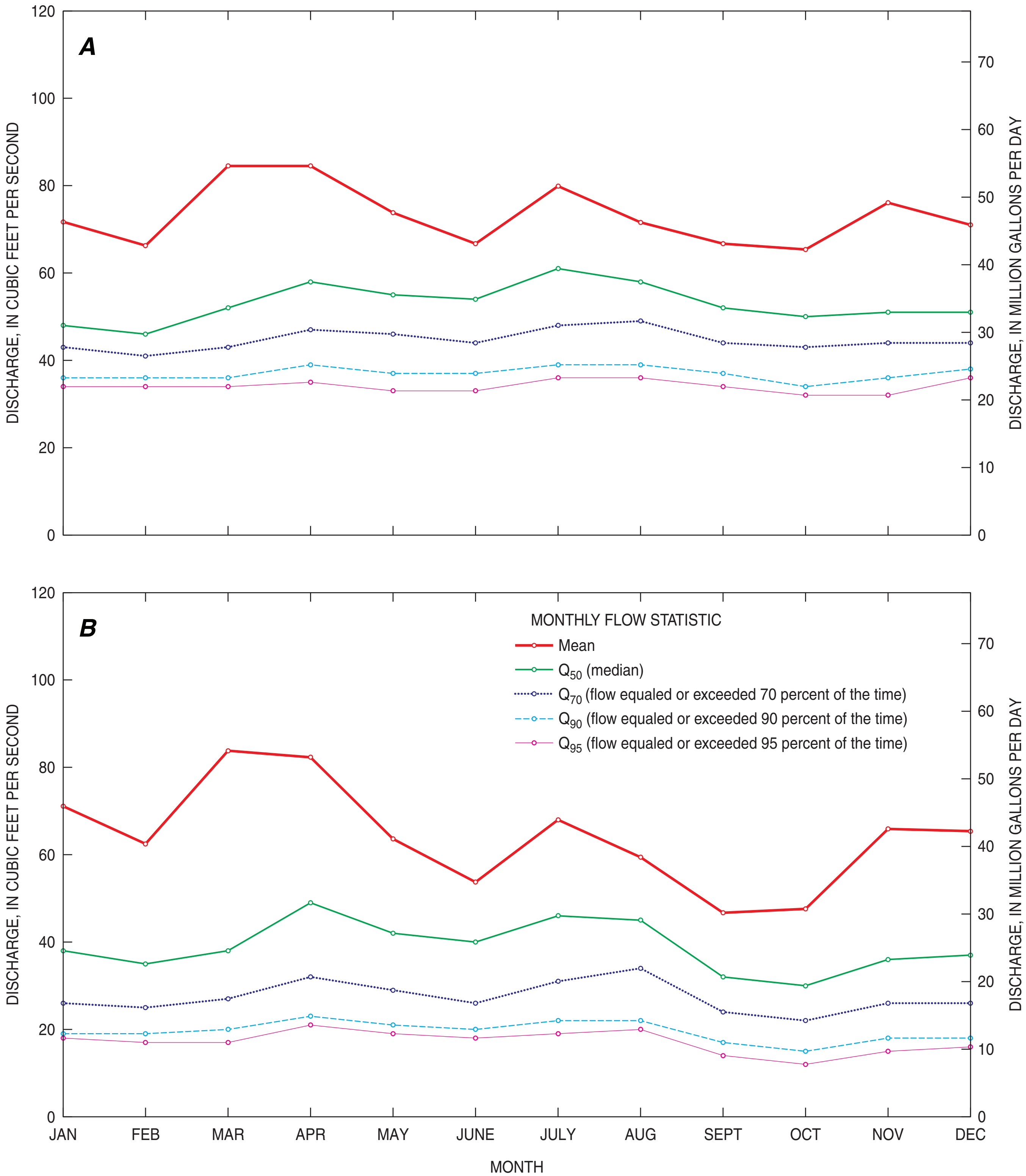


Figure 26. Monthly flow statistics (climate years 1984–2007) for Waiheʻe River and ʻĪao Stream, Maui, Hawaiʻi. *A*, Waiheʻe River, gaging station 16614000. *B*, ʻĪao Stream, gaging station 16604500.

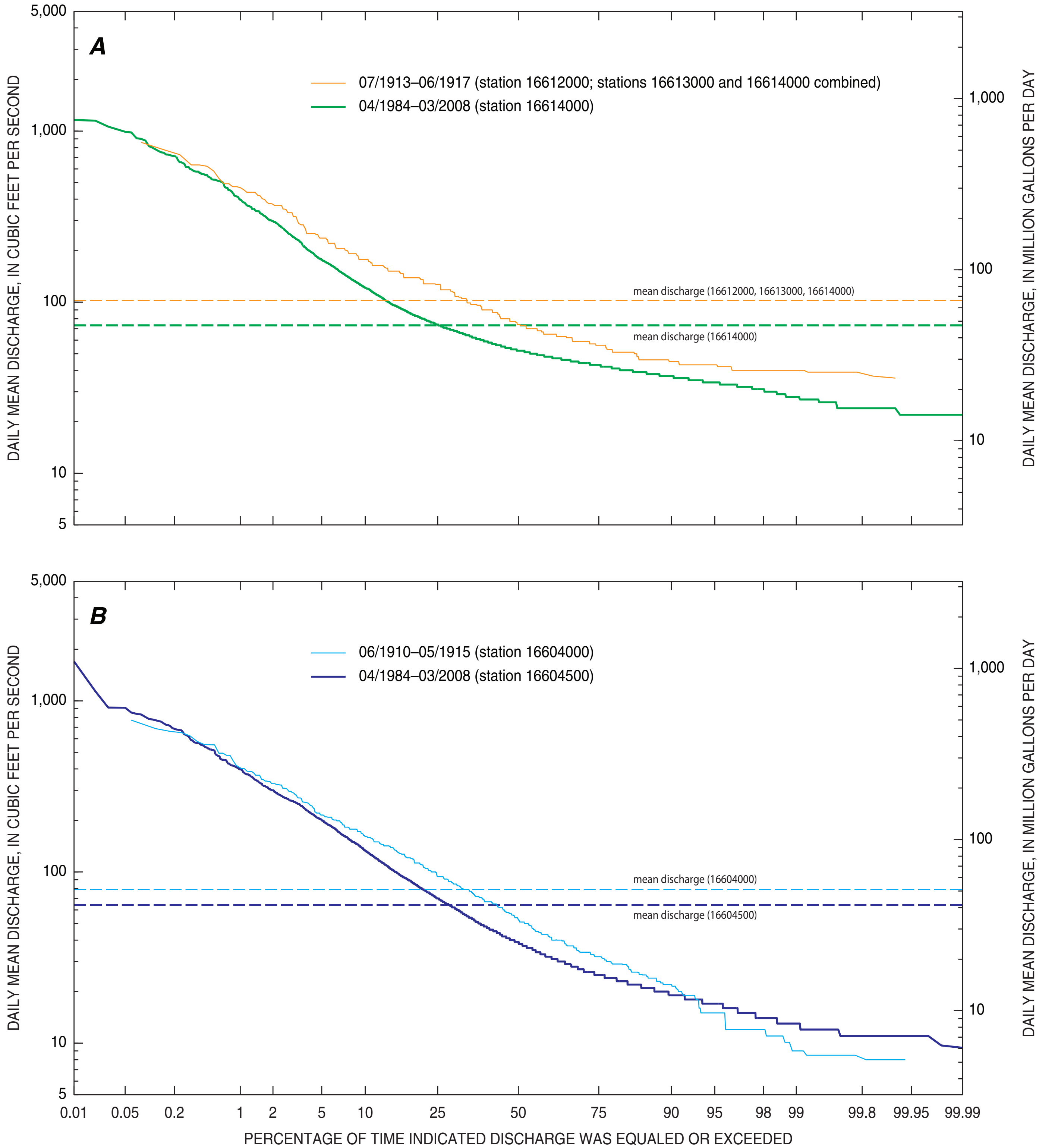


Figure 27. Flow-duration curves for early historical period and climate years 1984–2007, Waihe‘e River and ‘Īao Stream, Maui, Hawai‘i. *A*, Waihe‘e River, gaging stations 16612000, 16613000, and 16614000. *B*, ‘Īao Stream, gaging stations 16604000 and 16604500.

Table 13. Selected duration discharges (natural, undiverted conditions) for Waihe‘e River and ‘Īao, Honokōhau, and Honopou Streams during climate years 1984–2007, Maui, Hawai‘i.

[Mgal/d, million gallons per day]

Flow-duration percentile	Duration discharge for indicated stream and gaging station, in Mgal/d (values in parentheses are in cubic feet per second)			
	Waihe‘e River (16614000)	‘Īao Stream (16604500)	Honopou Stream (16587000)	Honokōhau Stream (16620000)[1]
50	34 (52)	25 (39)	1.4 (2.1)	14 (22)
55	32 (50)	23 (35)	1.2 (1.9)	14 (21)
60	31 (48)	21 (32)	1.0 (1.6)	12 (19)
65	30 (46)	19 (30)	0.90 (1.4)	12 (18)
70	28 (44)	17 (27)	0.84 (1.3)	11 (17)
75	28 (43)	16 (25)	0.71 (1.1)	10 (16)
80	27 (41)	15 (23)	0.58 (0.90)	9.7 (15)
85	25 (39)	14 (21)	0.49 (0.76)	9.0 (14)
90	24 (37)	12 (19)	0.39 (0.61)	8.4 (13)
95	22 (34)	11 (17)	0.32 (0.49)	7.8 (12)
99	18 (28)	8.4 (13)	0.17 (0.26)	6.3 (9.8)

[1]Climate years 1984–87, 1991–2007.

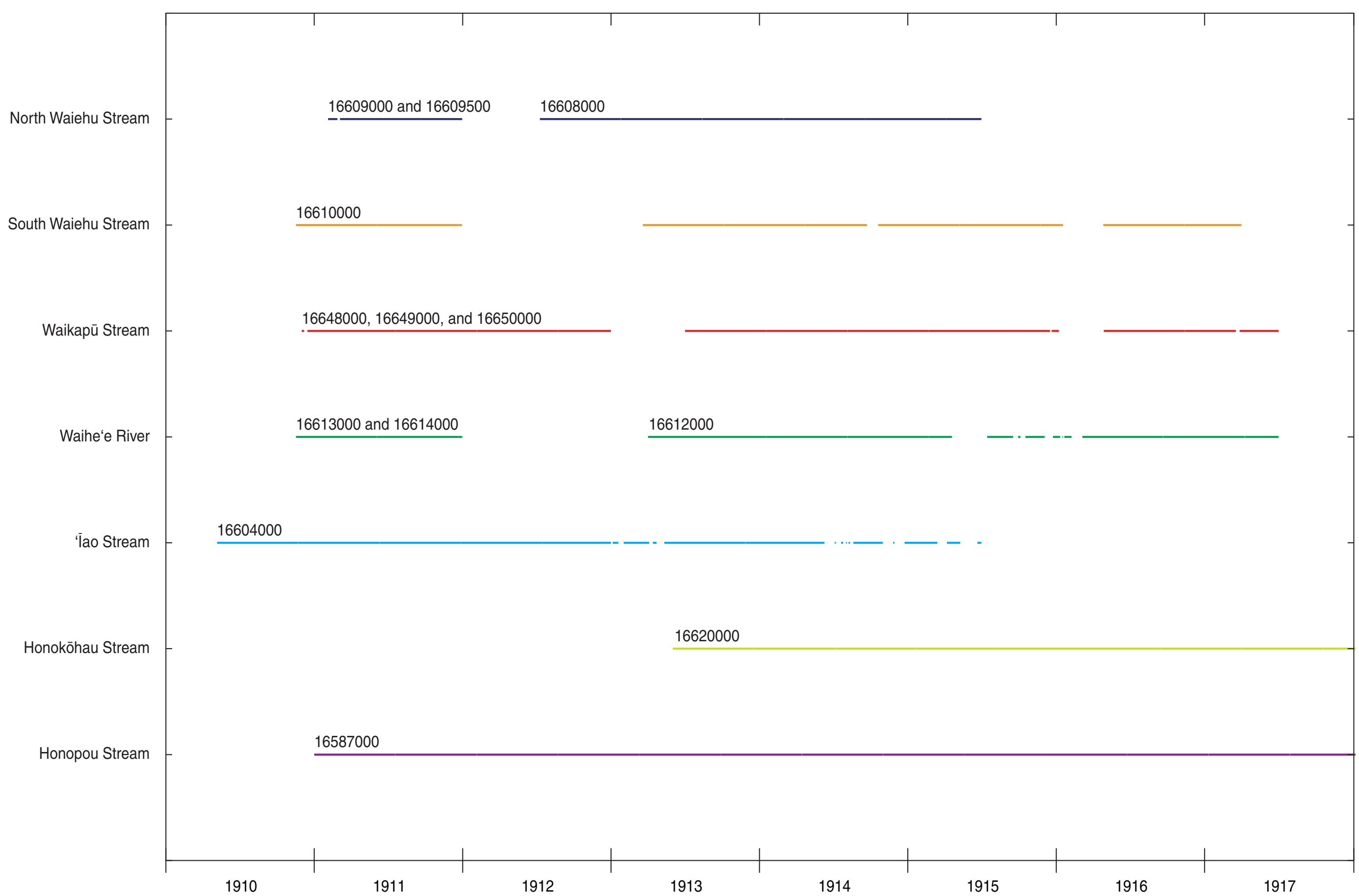


Figure 28. Time lines of available data from selected gaging stations (numbers on lines) during 1910–17, Maui, Hawai‘i.

Waiehu Stream are available from gaging stations 16608000, 16609000, and 16609500. Gaging station 16608000 measured the natural flow in North Waiehu Stream at an altitude of about 880 ft, upstream of all diversions. Gaging station 16609000 measured the flow in North Waiehu Ditch, which diverted water from North Waiehu Stream about 50 ft downstream of gaging station 16608000 (Wells, 1961). Gaging station 16609500 measured the flow remaining in North Waiehu Stream at an altitude of about 730 ft, downstream of the North Waiehu Ditch diversion. Combining the concurrent flows measured at gaging stations 16609000 and 16609500 provides an estimate of the natural flow in the stream near an altitude of 730 ft. However, because of unquantified losses in the reach between altitudes of 880 and 730 ft, the combined flows from stations 16609000 and 16609500 were not used in the analysis. During the period of record for gaging station 16608000 (1912–15), the minimum reported flow based on stage readings made twice daily (Grover and Larrison, 1917a) was 1.6 Mgal/d (2.5 ft^3/s) during March 1915.

South Waiehu Stream.— Historical data that can be used to estimate natural-flow characteristics of South Waiehu Stream are available from gaging station 16610000. Gaging station 16610000 measured the flow in South Waiehu Stream at an altitude of about 870 ft, upstream of most diversions. A small taro ditch diverted about 0.06–0.2 Mgal/d (0.1–0.3 ft^3/s) at typical stages upstream of station 16610000 (Larrison, 1915; Grover and Larrison, 1917a,b, 1918; Wells, 1961). For the purposes of this study, data from gaging station 16610000 are assumed to be representative of natural-flow conditions in South Waiehu Stream. During the period of record for gaging station 16610000 (1910–11, 1913–17), the minimum reported flow based on stage readings made twice daily (Grover and Larrison, 1917a) was 1.5 Mgal/d (2.3 ft^3/s) during July 1913.

Waikapū Stream.— Historical data that can be used to estimate natural-flow characteristics of Waikapū Stream are available from gaging stations 16648000, 16649000, and 16650000 during 1910–17. Two water-development tunnels driven in 1905 and 1906 at altitudes of about 1,800 and 1,770 ft, respectively, may have contributed to measured flow in Waikapū Stream, although the tunnel at an altitude of 1,770 ft produced only about 0.007 Mgal/d (0.01 ft^3/s) (table 2). Gaging station 16648000 measured the flow in the South Side Ditch, which diverted water from Waikapū Stream at an altitude of about 1,120 ft. Gaging station 16649000 measured the flow in the Everett Ditch (also referred to as the Palolo Ditch), which diverted water from Waikapū Stream at an altitude of about 900 ft. Gaging station 16650000 measured the flow remaining in Waikapū Stream at an altitude of about 880 ft, downstream of the South Side Ditch and Everett Ditch diversions (Wells, 1961). Combining the concurrent flows measured at gaging stations 16648000, 16649000, and 16650000 provides an estimate of the natural flow in Waikapū stream near an altitude of 880 ft. This estimate assumes no losses or return flows between the South Side Ditch diversion and station 16650000 during the period when the gaging stations were operated. Recent U.S. Geological Survey seepage-run data (see section below on “Seepage-Run Measurements”) support the assumption of relatively small loss between the South Side Ditch diversion and station 16650000. During the period of record of gaging stations 16648000, 16649000, and 16650000 (1910–17), the minimum estimated combined discharge at these stations, based on stage readings made twice daily, was 3.3 Mgal/d (5.1 ft^3/s) during October 1912.

Waiheʻe River.— Historical data from Waiheʻe River that can be correlated with data from North Waiehu, South Waiehu, and Waikapū Streams are available from gaging stations 16612000, 16613000, and 16614000. Two water-development tunnels driven in 1909 at altitudes of about 1,625 and 1,650 ft may have contributed to measured flow in Waiheʻe River, although flow in the river may not have been appreciably increased after the initial storage of groundwater developed by the tunnels had been depleted (Stearns and Macdonald, 1942, p. 195–196). Gaging station 16612000 measured the flow in Waiheʻe River at an altitude of about 620 ft, upstream of all diversions. Gaging station 16613000 measured the flow in the Waiheʻe Ditch, which diverted water from Waiheʻe River at an altitude of about 600 ft. Before 1913, gaging station 16614000 measured the flow remaining in Waiheʻe River, downstream of the Waiheʻe Ditch diversion. Combining the historical concurrent flows measured at gaging stations 16613000 and 16614000 provides an estimate of the flow in Waiheʻe River at an altitude of about 605 ft, upstream of all diversions. Gaging station 16614000 was reestablished in 1983, after which it measured the flow in Waiheʻe River at an altitude of about 605 ft, upstream of all diversions. Stations 16612000 and 16614000 (at its current location) are within a few hundred feet of each other, and therefore data from these two stations are assumed to represent equivalent conditions.

ʻĪao Stream.—Historical data from ʻĪao Stream that can be correlated with data from North Waiehu, South Waiehu, and Waikapū Streams are available from gaging station 16604000. Gaging station 16604000 measured the flow in ʻĪao Stream at an altitude of about 860 ft, upstream of all diversions. Two water-development tunnels were driven in 1906 near altitudes of 1,425 and 1,475 ft, upstream of gaging station 16604000, and may have affected measured flow at the gaging station, although no information is available to quantify the effects. For the purposes of this study, flow measured at gaging station 16604000 is assumed to represent the natural flow in ʻĪao Stream at an altitude of about 860 ft. Active (2009) gaging station 16604500 was established in 1983 at an altitude of about 780 ft, upstream of all diversions. In addition to the two water-development tunnels mentioned above, another water-development tunnel at an altitude of about 787 ft may affect flow measured at gaging station 16604500, although no information is available to quantify the effects. The tunnel at an altitude of about 787 ft caused another nearby tunnel at an altitude of 1,305 ft to cease flowing (Yamanaga and Huxel, 1970). For the purposes of this study, flow measured at gaging station 16604500 is assumed to represent natural flow in

ʻĪao Stream at an altitude of about 780 ft. Data from gaging stations 16604000 and 16604500 are assumed to represent equivalent conditions, although station 16604500 is about 1,000 ft downstream of where station 16604000 was located. Data are unavailable to determine whether ʻĪao Stream gains or loses water in this 1,000-ft reach, although the reach is within an area of mapped dikes and high groundwater levels and therefore likely gains water. Because of uncertainty in the equivalence of flow conditions at gaging stations 16604000 and 16604500, use of these index stations is considered least reliable.

Honokōhau Stream.—Historical data from Honokōhau Stream that can be correlated with data from North Waiehu, South Waiehu, and Waikapū Streams are available from gaging station 16620000. Gaging station 16620000 is an active (2009) station that measures the natural flow in Honokōhau Stream at an altitude of about 870 ft, upstream of all diversions.

Honopou Stream.—Historical data from Honopou Stream that can be correlated with data from North Waiehu, South Waiehu, and Waikapū Streams are available from gaging station 16587000. Gaging station 16587000 is an active (2009) station that measures the natural flow in Honopou Stream at an altitude of about 1,210 ft, upstream of all diversions.

Record-Extension Method

The record-extension method used for this study is described by Ries (1993) and is summarized in the steps below.

1. Selected duration discharges between the median (Q_{50}) and Q_{99} discharges were computed for the period formed by years with complete and nearly complete record for each short-term, historical gaged site. The Q_{50} discharge represents the discharge that is equaled or exceeded 50 percent of the time, and the Q_{99} discharge represents the discharge that is equaled or exceeded 99 percent of the time. The selected duration discharges (Q_{50}, Q_{55}, Q_{60}, Q_{65}, Q_{70}, Q_{75}, Q_{80}, Q_{85}, Q_{90}, Q_{93}, Q_{95}, Q_{97}, Q_{98}, and Q_{99}) represent discharges from the lower half of a flow-duration curve (Searcy, 1959). Because limited data were available for analysis, years with as many as 48 days of missing record were included (table 14).
2. The selected duration discharges listed above were computed for concurrent periods (relative to the periods for each short-term, historical gaged site) for each of the index stations.
3. Correlation coefficients between the base-10 logarithms of the duration discharges for the concurrent period at a short-term site and each index site were computed. For this study, all correlation coefficients between data from short-term and index sites exceeded 0.8. All index stations were therefore retained for analysis.
4. Concurrent duration discharges for each pairing of short-term gaged site and index station were plotted in log-space to test for curvature in the relation between the two sites.

The graphical-correlation method (Searcy, 1959) was used to estimate selected duration discharges at the short-term site for the base period. The graphical-correlation method, instead of the MOVE.1 method (Hirsch, 1982), was necessitated because some measure of curvature was detected in all relations from step 4. The graphical-correlation method involves (1) drawing a smooth curve through the plotted points of the concurrent duration discharges at the short-term site and index station, (2) estimating selected duration discharges for the base period (1984–2007) at the index station, (3) estimating the selected duration discharges at the short-term site during the base period from the smooth curve by reading the discharge (at the short-term site) corresponding to the base period duration discharges at the index station. For the purposes of estimating the selected duration discharges at the short-term site during the base period, data were replotted on an arithmetic scale (figs. 29–31) to reduce extreme low-end curvature and simplify extrapolations to low flows.

Estimated Streamflow During 1984–2007

For this study, selected duration discharges from the Q_{50} to the Q_{99} discharges were estimated for the base period for sites on North Waiehu, South Waiehu, and Waikapū Streams. These estimated flow characteristics generally are representative of natural-flow conditions during the 1984–2007 base period. Different estimates for the 1984–2007 base-period duration discharges are available, depending on the index station used. Because of the limited data available for analysis and uncertainty associated with the estimated duration discharges for the sites on North Waiehu, South Waiehu, and Waikapū Streams, values based on each of the four index stations for the 1984–2007 base period are presented (tables 15–17). In general, the largest estimated duration discharges during the base period are associated with the index station on ʻĪao Stream, and the smallest estimated duration discharges are associated with the index station on Honokōhau Stream (tables 15–17). Estimated duration discharges using the index stations on ʻĪao Stream are considered least reliable because of possible streamflow gain between historical station 16604000 and active station 16604500 and were not used to compute average estimates (tables 15–17). Estimated duration discharges below the Q_{90} discharge (that is, Q_{93}, Q_{95}, Q_{97}, Q_{98}, and Q_{99}) are considered least reliable, because extrapolation of curves was necessary to make estimates in some cases.

Index Stations.—Complete data from gaging stations 16614000 on Waiheʻe River, 16604500 on ʻĪao Stream, and 16587000 on Honopou Stream are available during the 1984–2007 base period (table 13). For gaging station 16614000 on Waiheʻe River, the Q_{99} and Q_{50} duration

Table 14. Concurrent periods used for extension of records from North Waiehu, South Waiehu, and Waikapū Streams, West Maui, Hawaiʻi.

[values in parentheses indicate number of missing days in the year]

Stream and index station(s)	Periods of historical data available for record extension for indicated gaging stations		
	North Waiehu Stream station 16608000	South Waiehu Stream station 16610000	Waikapū Stream stations 16648000, 16649000, 16650000
Waiheʻe River, stations 16612000, 16613000, 16614000	04/1913 to 03/1914 04/1914 to 03/1915	01/1911 to 12/1911 04/1913 to 03/1914 04/1914 to 03/1915 (26) 04/1916 to 03/1917 (24)	01/1911 to 12/1911 01/1914 to 12/1914 05/1916 to 04/1917 (9)
ʻĪao Stream, station 16604000	07/1912 to 06/1913 (48) 07/1913 to 06/1914 (21)	01/1911 to 12/1911 06/1913 to 05/1914	01/1911 to 12/1911 01/1912 to 12/1912 07/1913 to 06/1914 (21)
Honokōhau Stream, station 16620000	06/1913 to 05/1914 06/1914 to 05/1915	06/1913 to 05/1914 01/1915 to 12/1915 04/1916 to 03/1917 (24)	07/1913 to 06/1914 07/1914 to 06/1915 (5) 07/1916 to 06/1917 (9)
Honopou Stream, station 16587000	07/1912 to 06/1913 (8) 07/1913 to 06/1914 07/1914 to 06/1915	01/1911 to 12/1911 04/1913 to 03/1914 01/1915 to 12/1915 04/1916 to 03/1917 (24)	01/1911 to 12/1911 01/1912 to 12/1912 07/1913 to 06/1914 07/1914 to 06/1915 (5) 05/1916 to 04/1917 (9)

discharges during 1984–2007 were 18 and 34 Mgal/d (28 and 52 ft^3/s), respectively. For gaging station 16604500 on ʻĪao Stream, the Q_{99} and Q_{50} duration discharges during 1984–2007 were 8.4 and 25 Mgal/d (13 and 39 ft^3/s), respectively. For gaging station 16587000 on Honopou Stream, the Q_{99} and Q_{50} duration discharges during 1984–2007 were 0.17 and 1.4 Mgal/d (0.26 and 2.1 ft^3/s), respectively. For gaging station 16620000 on Honokōhau Stream, the Q_{99} to Q_{50} duration discharges were computed for the period 1984–87 and 1991–2007 (complete data during climate years 1988–90 were not available) and ranged from 6.3 to 14 Mgal/d (9.8 to 22 ft^3/s) (table 13). Duration discharges for Waiheʻe River and ʻĪao Stream were computed for the 1984–2007 base period both with and without data from climate years 1988–90, and the resulting duration discharges (less than or equal to the Q_{50}) for the incomplete period generally were less than, but within 5 percent of, the corresponding duration discharges for the complete period. Thus, incomplete data from Honokōhau Stream during 1984–2007 are considered representative of the entire base period. The base-period duration discharges from the index stations were used in conjunction with the curves of concurrent duration discharges (figs. 29–31) to estimate the base-period duration discharges near gaging stations 16608000 (North Waiehu Stream), 16610000 (South Waiehu Stream), and 16650000 (Waikapū Stream) (tables 15–17).

North Waiehu Stream.—For North Waiehu Stream near gaging station 16608000, the estimated median (Q_{50}) discharges during 1984–2007, using the index stations from Waiheʻe River, Honokōhau Stream, and Honopou Stream only, ranged from 2.8 to 3.5 Mgal/d (4.4 to 5.4 ft^3/s) and averaged 3.2 Mgal/d (4.9 ft^3/s) (table 15). The estimated Q_{70} discharges during 1984–2007 ranged from 2.1 to 2.7 Mgal/d (3.2 to 4.2 ft^3/s), and the estimated Q_{90} discharges ranged from 1.2 to 2.2 Mgal/d (1.8 to 3.4 ft^3/s) (table 15).

South Waiehu Stream.— For South Waiehu Stream near gaging station 16610000, the estimated median (Q_{50}) discharges during 1984–2007, using the index stations from Waiheʻe River, Honokōhau Stream, and Honopou Stream only, ranged from 2.4 to 4.0 Mgal/d (3.7 to 6.2 ft^3/s) and averaged 3.2 Mgal/d (5.0 ft^3/s) (table 16). The estimated Q_{70} discharges during 1984–2007 ranged from 1.8 to 2.8 Mgal/d (2.8 to 4.3 ft^3/s), and the estimated Q_{90} discharges ranged from 1.2 to 1.6 Mgal/d (1.9 to 2.4 ft^3/s) (table 16).

Waikapū Stream.— For Waikapū Stream near gaging station 16650000, the estimated median (Q_{50}) discharges during 1984–2007, using the index stations from Waiheʻe River, Honokōhau Stream, and Honopou Stream only, ranged from 4.8 to 6.1 Mgal/d (7.5 to 9.5 ft^3/s) and averaged 5.6 Mgal/d (8.6 ft^3/s) (table 17). The estimated Q_{70} discharges during 1984–2007 ranged from 3.7 to 5.0 Mgal/d (5.8 to 7.8 ft^3/s), and the estimated Q_{90} discharges ranged from 3.1 to 4.1 Mgal/d (4.8 to 6.3 ft^3/s) (table 17).

Limitations

The estimates of duration discharges for the base period for North Waiehu, South Waiehu, and Waikapū Streams are uncertain because of several data limitations. These limitations are described below.

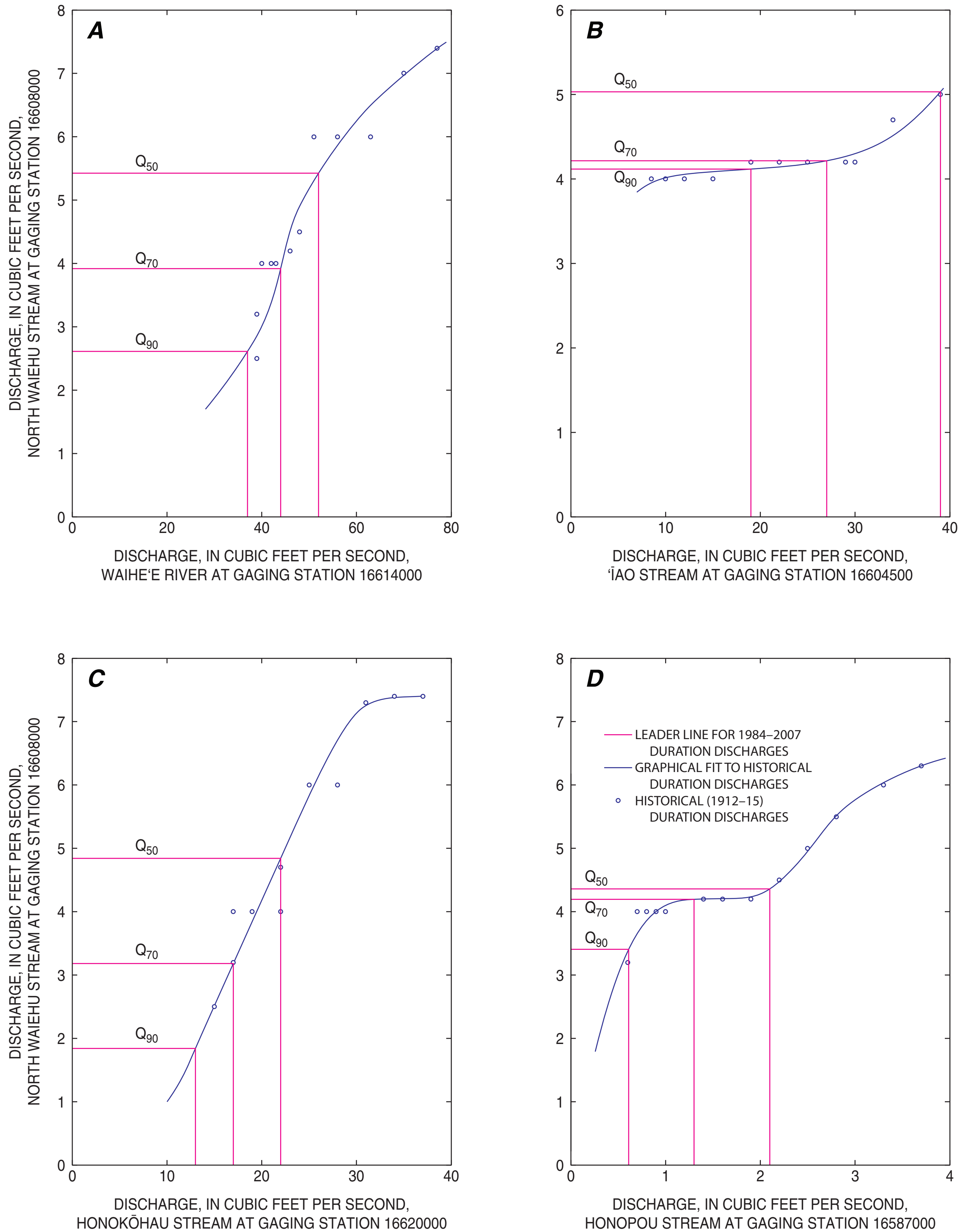


Figure 29. Relation between concurrent duration discharges for North Waiehu Stream and index stations during the period 1912–15, and selected duration discharges for North Waiehu Stream and index stations during the 1984–2007 base period, Maui, Hawai‘i. *A*, Index station 16614000, Waihe‘e River. *B*, Index station 16604500, ‘Īao Stream. *C*, Index station 16620000, Honokōhau Stream. *D*, Index station 16587000, Honopou Stream.

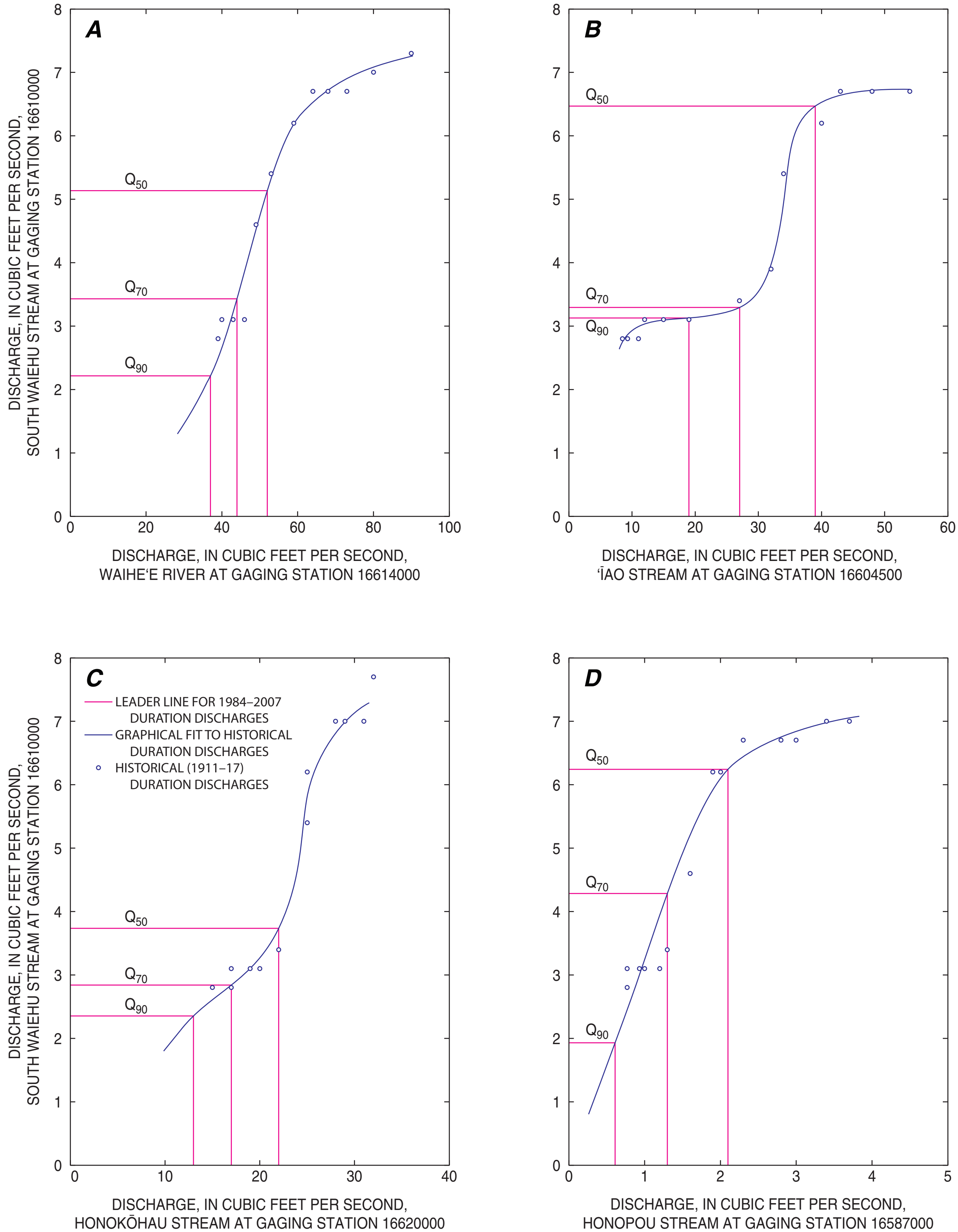


Figure 30. Relation between concurrent duration discharges for South Waiehu Stream and index stations during the period 1911–17, and selected duration discharges for South Waiehu Stream and index stations during the 1984–2007 base period, Maui, Hawaiʻi. *A*, Index station 16614000, Waiheʻe River. *B*, Index station 16604500, ʻĪao Stream. *C*, Index station 16620000, Honokōhau Stream. *D*, Index station 16587000, Honopou Stream.

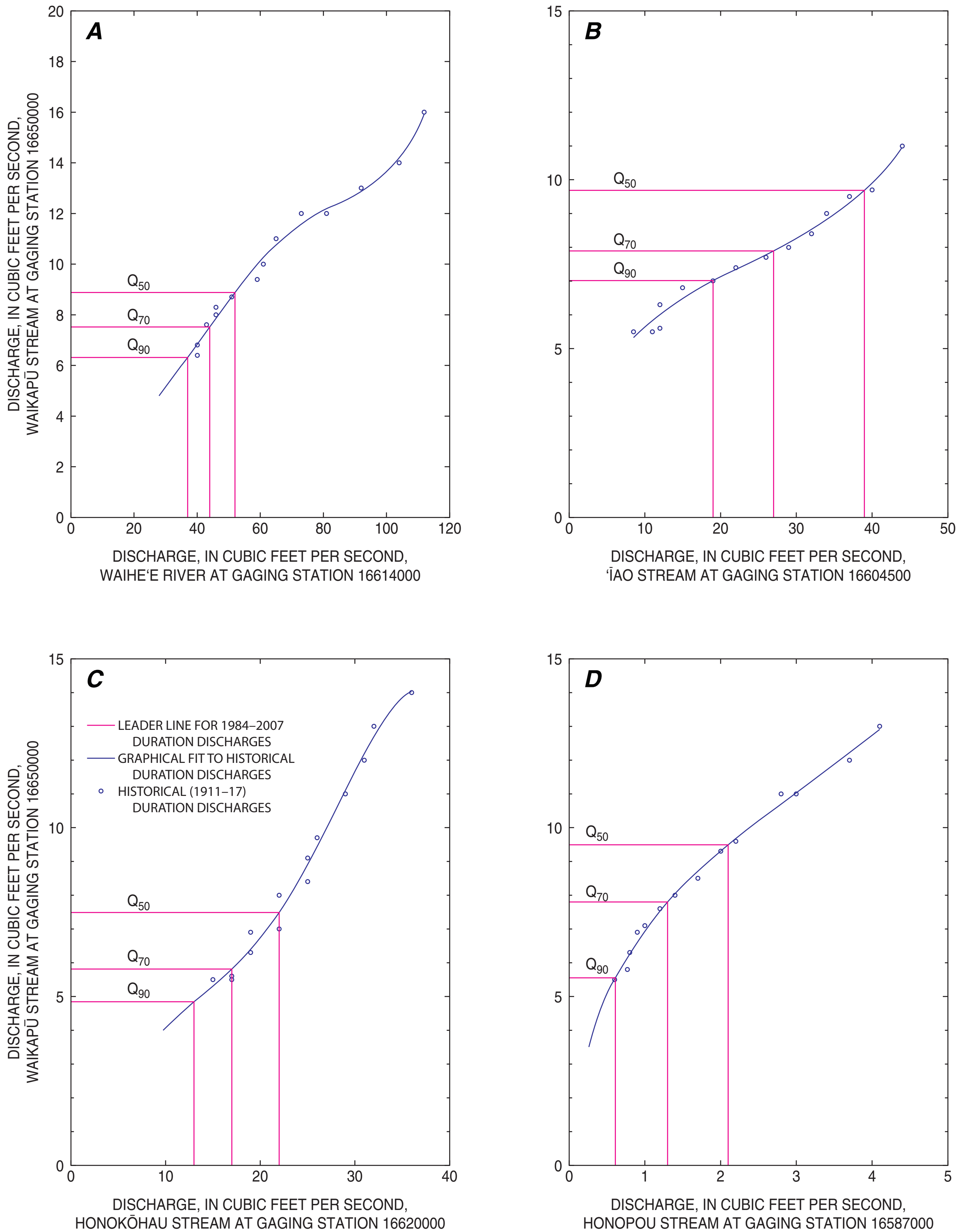


Figure 31. Relation between concurrent duration discharges for Waikapū Stream and index stations during the period 1911–17, and selected duration discharges for Waikapū Stream and index stations during the 1984–2007 base period, Maui, Hawai‘i. *A*, Index station 16614000, Waihe‘e River. *B*, Index station 16604500, ‘Īao Stream. *C*, Index station 16620000, Honokōhau Stream. *D*, Index station 16587000, Honopou Stream.

Table 15. Selected duration discharges (natural, undiverted conditions) estimated for North Waiehu Stream near an altitude of 880 feet during climate years 1984–2007, Maui, Hawai‘i.

[Mgal/d, million gallons per day]

Flow-duration percentile	Duration discharges for North Waiehu Stream using indicated index station, in Mgal/d (values in parentheses are in cubic feet per second)				
	Waihe‘e River (16614000)	Honokōhau Stream (16620000)	Honopou Stream (16587000)	‘Īao Stream (16604500)	Average (excluding ‘Īao Stream)
50	3.5 (5.4)	3.1 (4.8)	2.8 (4.4)	3.2 (5.0)	3.2 (4.9)
55	3.4 (5.2)	2.9 (4.5)	2.7 (4.2)	3.0 (4.6)	3.0 (4.6)
60	3.2 (4.9)	2.5 (3.8)	2.7 (4.2)	2.8 (4.4)	2.8 (4.3)
65	2.9 (4.5)	2.3 (3.5)	2.7 (4.2)	2.8 (4.3)	2.7 (4.1)
70	2.5 (3.9)	2.1 (3.2)	2.7 (4.2)	2.7 (4.2)	2.5 (3.8)
75	2.3 (3.6)	1.8 (2.8)	2.7 (4.2)	2.7 (4.2)	2.3 (3.5)
80	2.1 (3.2)	1.6 (2.5)	2.6 (4.0)	2.7 (4.2)	2.1 (3.2)
85	1.9 (2.9)	1.4 (2.2)	2.5 (3.8)	2.7 (4.1)	1.9 (3.0)
90	1.7 (2.6)	1.2 (1.8)	2.2 (3.4)	2.7 (4.1)	1.7 (2.6)
95	1.5 (2.3)	0.97 (1.5)	1.9 (3.0)	2.7 (4.1)	1.5 (2.3)
99	1.1 (1.7)	0.65 (1.0)	1.2 (1.8)	2.7 (4.1)	0.97 (1.5)

Table 16. Selected duration discharges (natural, undiverted conditions) estimated for South Waiehu Stream near an altitude of 870 feet during climate years 1984–2007, Maui, Hawai‘i.

[Mgal/d, million gallons per day]

Flow-duration percentile	Duration discharges for South Waiehu Stream using indicated index station, in Mgal/d (values in parentheses are in cubic feet per second)				
	Waihe‘e River (16614000)	Honokōhau Stream (16620000)	Honopou Stream (16587000)	‘Īao Stream (16604500)	Average (excluding ‘Īao Stream)
50	3.3 (5.1)	2.4 (3.7)	4.0 (6.2)	4.2 (6.5)	3.2 (5.0)
55	3.0 (4.7)	2.3 (3.5)	3.8 (5.9)	3.7 (5.7)	3.0 (4.7)
60	2.8 (4.3)	2.0 (3.1)	3.4 (5.2)	2.6 (4.0)	2.7 (4.2)
65	2.5 (3.9)	1.9 (3.0)	3.0 (4.6)	2.3 (3.5)	2.5 (3.8)
70	2.2 (3.4)	1.8 (2.8)	2.8 (4.3)	2.1 (3.3)	2.3 (3.5)
75	2.1 (3.2)	1.7 (2.7)	2.3 (3.6)	2.1 (3.2)	2.1 (3.2)
80	1.8 (2.8)	1.7 (2.6)	1.9 (2.9)	2.1 (3.2)	1.8 (2.8)
85	1.6 (2.5)	1.6 (2.5)	1.6 (2.4)	2.0 (3.1)	1.6 (2.5)
90	1.4 (2.2)	1.6 (2.4)	1.2 (1.9)	2.0 (3.1)	1.4 (2.2)
95	1.2 (1.9)	1.4 (2.2)	0.97 (1.5)	2.0 (3.1)	1.2 (1.9)
99	0.84 (1.3)	1.2 (1.8)	0.52 (0.81)	2.0 (3.1)	0.84 (1.3)

Table 17. Selected duration discharges (natural, undiverted conditions) estimated for Waikapū Stream near an altitude of 880 feet during climate years 1984–2007, Maui, Hawaiʻi.

[Mgal/d, million gallons per day]

Flow-duration percentile	Duration discharges for Waikapū Stream using indicated index station, in Mgal/d (values in parentheses are in cubic feet per second)				
	Waiheʻe River (16614000)	Honokōhau Stream (16620000)	Honopou Stream (16587000)	ʻĪao Stream (16604500)	Average (excluding ʻĪao Stream)
50	5.8 (8.9)	4.8 (7.5)	6.1 (9.5)	6.3 (9.7)	5.6 (8.6)
55	5.5 (8.5)	4.6 (7.1)	5.9 (9.1)	5.8 (9.0)	5.3 (8.2)
60	5.3 (8.2)	4.1 (6.4)	5.5 (8.5)	5.5 (8.5)	5.0 (7.7)
65	5.1 (7.9)	3.9 (6.1)	5.2 (8.0)	5.4 (8.3)	4.7 (7.3)
70	4.8 (7.5)	3.7 (5.8)	5.0 (7.8)	5.1 (7.9)	4.5 (7.0)
75	4.7 (7.3)	3.6 (5.6)	4.7 (7.2)	5.0 (7.7)	4.3 (6.7)
80	4.5 (7.0)	3.4 (5.3)	4.3 (6.6)	4.8 (7.4)	4.1 (6.3)
85	4.3 (6.7)	3.3 (5.1)	3.9 (6.1)	4.7 (7.2)	3.9 (6.0)
90	4.1 (6.3)	3.1 (4.8)	3.6 (5.6)	4.5 (7.0)	3.6 (5.6)
95	3.7 (5.8)	3.0 (4.6)	3.2 (5.0)	4.4 (6.8)	3.3 (5.1)
99	3.1 (4.8)	2.6 (4.0)	2.3 (3.5)	4.0 (6.2)	2.7 (4.1)

Limited concurrent data for the short-term, historical gaged sites and index stations were available for analysis. Two to five years of concurrent data were available from the gaged sites. Most of the concurrent years of data were complete, although one year contained 48 days of missing data. The limited historical data lead to unquantified uncertainty in estimated duration discharges for the 1984–2007 base period.

In some cases, concurrent discharge data from ditch- and stream-gaging stations were combined to estimate the total natural flow in the stream. Natural flows estimated by combining concurrent data in this manner may contain error related to losses or ditch return flows in the stream reach between the diversion intake and stream-gaging station.

Selected historical daily discharge values may be subject to error because the values were based on instantaneous stage measurements at specified times during the day. The uncertainty associated with this limitation cannot be accurately quantified.

The correlation coefficients between concurrent daily discharge values from each short-term, historical gaged site and each index station generally were less than 0.3, which necessitated use of the graphical-correlation method. The poor correlation between concurrent daily discharge values from short-term, historical gaged sites and each index station may indicate that daily discharge values at the index stations are poor predictors of daily discharge at the other sites.

Some of the reported daily discharge values may have been affected by diversions or unquantifiable contributions from upstream water-development tunnels, which leads to additional uncertainty in estimated duration discharges. The estimated duration discharges for South Waiehu Stream may need to be adjusted upward by 0.06–0.2 Mgal/d (0.1–0.3 ft^3/s) to reflect the known diversion upstream of gaging station 16610000 (Larrison, 1915; Grover and Larrison, 1917a,b, 1918; Wells, 1961), although the actual diversion rate is poorly known.

In some cases (Waiheʻe River and ʻĪao Stream), data from two nearby stream-gaging stations were assumed to represent common hydrologic conditions to enhance the amount of data available for analysis, even though the stream-gaging stations were not colocated. The sites may have been separated by a gaining or losing reach, although information is not currently available to accurately quantify the gain or loss in flow.

The concurrent periods of record for the short-term gaged site and the index sites were wetter than the 1984–2007 base period. Thus, curves relating the duration discharges for the concurrent periods required extrapolation to obtain some of the base-period low-flow estimates, particularly those less than the Q_{90} discharge. These extrapolated low-flow estimates contain unquantifiable uncertainty. The low-flow characteristics can be determined best by establishing long-term, continuous-record stream-gaging stations in North Waiehu, South Waiehu, and Waikapū Streams.

Seepage-Run Measurements

Same-day discharge measurements were made along selected reaches of each stream to determine the magnitude of streamflow gains or losses over each reach. These same-day discharge measurements form what commonly is called a seepage run. Seepage-run measurements are used in this study to estimate (1) natural streamflow characteristics at ungaged sites downstream of existing and historical gaging stations, (2) the minimum natural flows necessary to establish continuous surface flows from the mountains to the ocean (mauka to makai) in the Nā Wai ‘Ehā area (assuming no water is diverted from the streams), (3) the reduction of recharge from the stream to the underlying groundwater system caused by diversion of surface water, and (4) the reduction of physical habitat for native stream fauna caused by diversion of surface water. For each seepage run, estimated gains or losses in the main channel of each stream exclude the contributions from tributaries or ditch return flows. For this study, discharge measurements were made with acoustic-Doppler velocity (ADV) meters using methods described by Rantz and others (1982).

Seepage-run measurements were made on days when flow generally was stable and direct runoff was considered to be negligible. In some cases, seepage-run measurements were made during ditch-maintenance periods, when diverted water was restored to streams for several days. During periods of flow restoration, seepage-run measurements were repeated on several days to characterize potential changes in loss rates over time. The effects of losses related to evaporation and transpiration associated with riparian vegetation are small at the time and length scales of the seepage-run measurements and are not considered.

Because of frequent rainfall within the study area, particularly near the mountainous interior areas, scheduling seepage-run measurements for periods with zero antecedent rainfall was not always possible. Thus, in some cases the seepage-run measurements may have been made during a recession period when streamflow was slowly declining following a period of rainfall. During these recession periods, multiple measurements were made, if possible, at the same sites (on the same day) in an attempt to bracket the loss estimates over a reach for that day. For example, during January 14–18, 2008, flow was restored to ‘Īao Stream for ditch maintenance and multiple measurements were made on January 16, 2008, during a slight recession. On January 16, 2008, discharge in ‘Īao Stream near an altitude of 395 ft was 18.7 Mgal/d (28.9 ft^3/s) at 9:14 a.m., discharge near an altitude of 595 ft was 20.4 Mgal/d (31.6 ft^3/s) at 10:55 a.m., and discharge near an altitude of 395 ft was 17.5 Mgal/d (27.0 ft^3/s) at 12:35 p.m. (all discharge values were computed from the sum of two values, one from a measurement in the stream and the second from an estimated inflow of much smaller magnitude). Thus, on January 16, 2008, the estimated loss rate between altitudes of 595 and 395 ft ranged from 1.7 Mgal/d (= 20.4-18.7) to 2.9 Mgal/d (= 20.4-17.5). The estimated loss rate may be underestimated if direct runoff, in the form of interflow, entered the stream between altitudes of 595 and 395 ft. Because of uncertainty in the estimated gains and losses in a reach, bracketing values for most reaches were defined to provide upper and lower estimates of natural streamflow characteristics.

Linear relations were developed between the upstream flow (independent variable) and downstream flow (dependent variable) for reaches over which gains or losses were measured. In most cases, the slope of the linear relation was set equal to 1 because the loss showed poor correlation with the upstream flow. For reaches in which the slope of the linear relation between upstream and downstream flows was set equal to 1, loss in the reach is constant and equal to the average value. For two reaches (North Waiehu Stream between altitudes of 920 and 475 ft and Waiehu Stream between altitudes of 190 and 20 ft) in which upstream and downstream flows were measured for a relatively wide range of conditions, the linear relation was defined by regression. Linear regression was used for these two reaches, even though limited data were available, because it produced a more reasonable estimate of loss over the range of available measurements relative to using the average loss. In terms of the loss in the reach, (1) a slope less than 1 indicates that loss in the reach increases as the upstream flow increases; (2) a slope equal to 1 indicates a constant loss in the reach, regardless of upstream flow; and (3) a slope greater than 1 indicates that loss in the reach decreases as the upstream flow increases. A slope less than 1 is expected in losing reaches that remain hydraulically disconnected from groundwater as the upstream flow increases. A slope greater than 1 may exist in losing reaches within which the hydraulic connection to groundwater is enhanced as the upstream flow increases.

Available seepage-run measurements from Waihe‘e River indicate a gaining reach between the diversion intakes for Waihe‘e and Spreckels Ditches and a generally losing reach between the intake for Spreckels Ditch and an altitude of 45 ft, although localized gaining reaches may exist (fig. 32). Seepage-run measurements indicate that North and South Waiehu, ‘Īao, and Waikapū Streams mainly lose water downstream of their uppermost diversions, although localized gaining reaches may exist in each of these streams (figs. 33–35). Measured loss rates in some reaches of these streams exceeded 1 Mgal/d per mile of stream (1.5 ft^3/s per mile) (figs. 32–35).

Measured losses, in terms of percentage of upstream flow, commonly exceeded 10 percent in reaches of Waiehu, ‘Īao, and Waikapū Streams but were less than 10 percent in reaches of Waihe‘e River. In some stream reaches small relative differences between measured upstream and downstream flows reflect potential uncertainty associated with characterizing losses. If errors associated with discharge measurements are less than 5 percent of the actual discharge values, then according to the rules of error propagation, losses less than 7 percent of the discharge in the reach of interest may not be reliably detected (LaBaugh and Rosenberry, 2008). Similarly, if errors associated with discharge measurements are less than 8 percent of the actual discharge values, then losses less than 11 percent of the discharge in the reach of interest may not be reliably detected. Repeated seepage-run measurements in a stream reach increase the level of confidence in, and the reliability of, loss estimates in the reach.

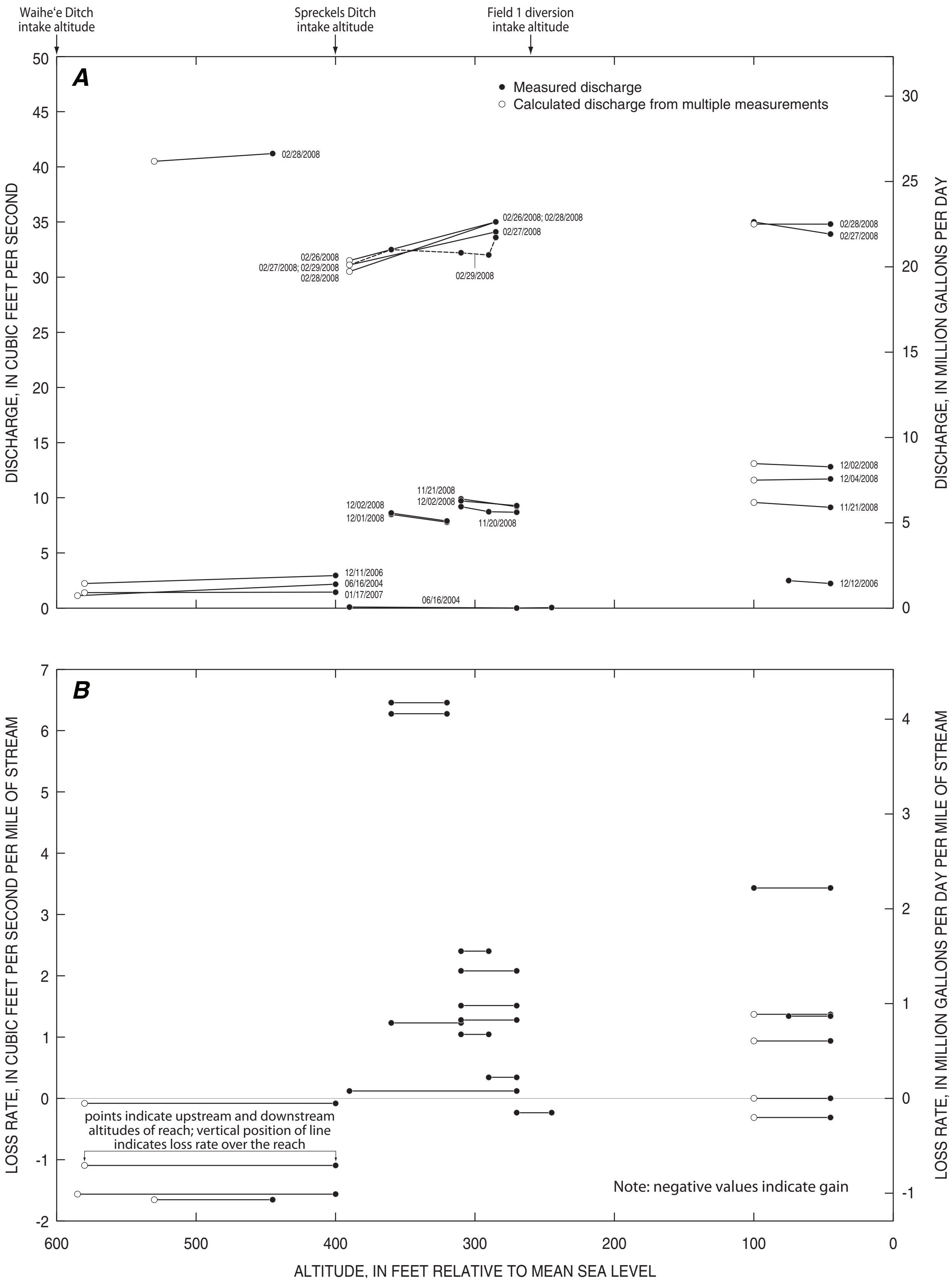


Figure 32. Seepage-run measurements over selected reaches, Waiheʻe River, Maui, Hawaiʻi. *A*, Discharge variation with altitude. *B*, Loss-rate variation with altitude. Repeat measurement from 02/26/2008 at an altitude of 285 feet not shown.

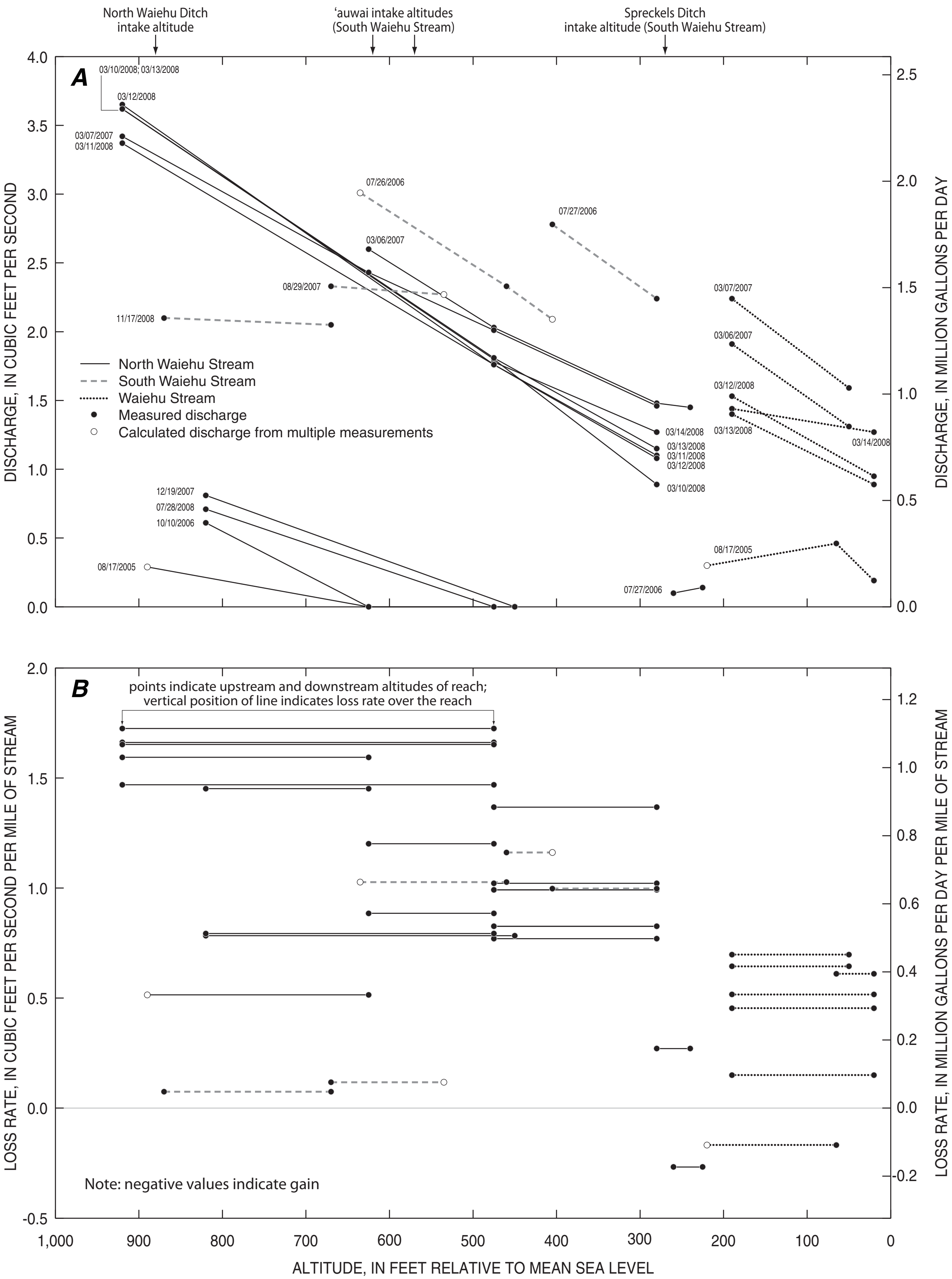


Figure 33. Seepage-run measurements over selected reaches, Waiehu Stream, Maui, Hawaiʻi. *A*, Discharge variation with altitude. *B*, Loss-rate variation with altitude.

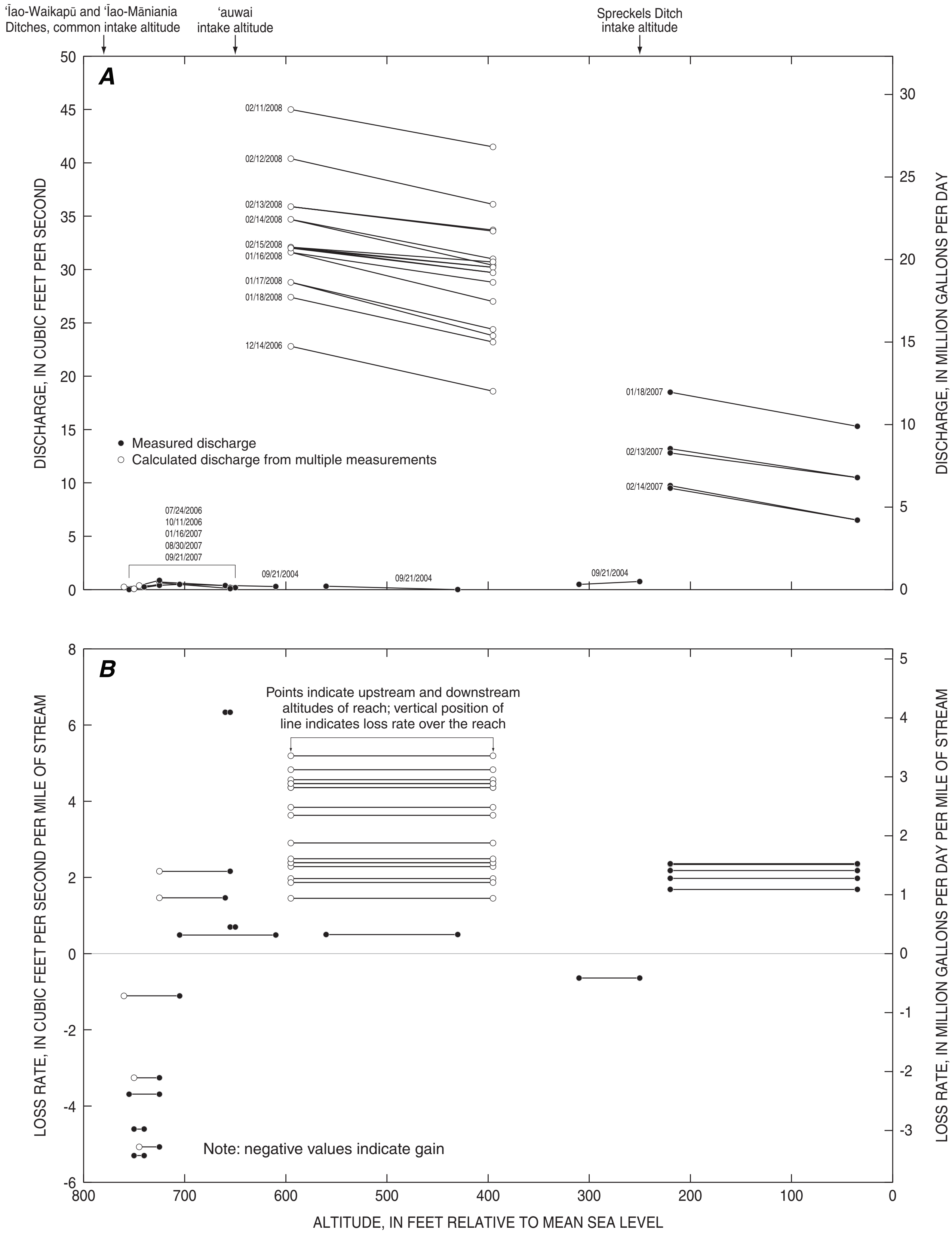


Figure 34. Seepage-run measurements over selected reaches, ʻĪao Stream, Maui, Hawaiʻi. *A*, Discharge variation with altitude. *B*, Loss-rate variation with altitude.

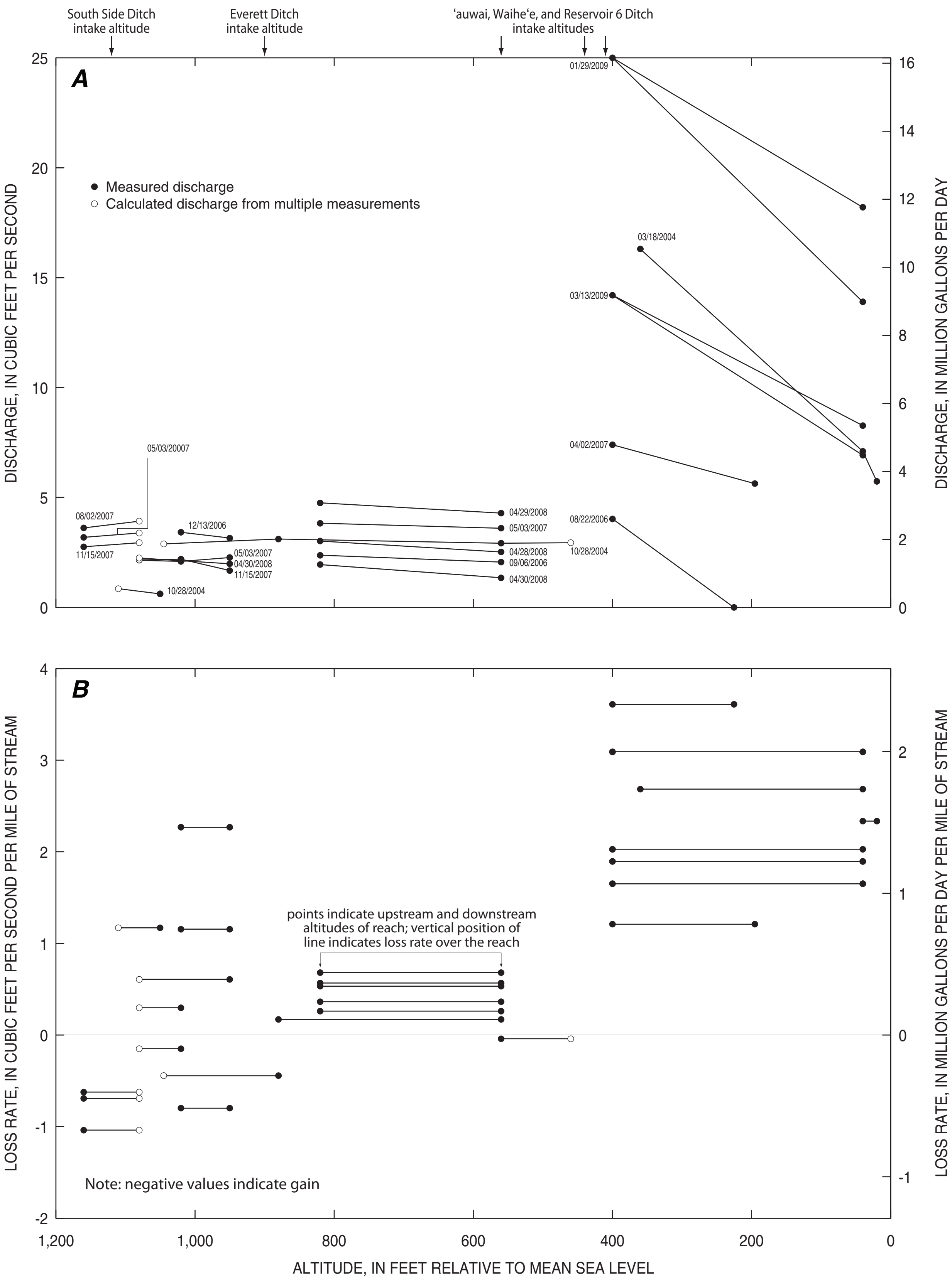


Figure 35. Seepage-run measurements over selected reaches, Waikapū Stream, Maui, Hawaiʻi. *A*, Discharge variation with altitude. *B*, Loss-rate variation with altitude.

Waiheʻe River

Seepage-run measurements were made during typical diverted conditions, as well as during periods of about a week in duration when flow was partially or almost fully restored to Waiheʻe River. Temporary periods of flow restoration in Waiheʻe River occurred during February, November, and December 2008. Flow was restored to Waiheʻe River near an altitude of 560 ft (February 2008), near an altitude of 315 ft (November 2008), or near both altitudes (December 2008). Seepage-run measurements were made about one to several days following the initiation of the flow restorations. Near an altitude of 45 ft in Waiheʻe River, increased streamflow caused by the temporary restorations was observed from about (1) 3:00 p.m. on February 24, 2008, before the seepage-run measurements during February 26–29, 2008; (2) 5:30 p.m. on November 16, 2008, before the seepage-run measurements of November 20–21, 2008; and (3) 5:30 p.m. on November 30, 2008, before the seepage-run measurements of December 1–4, 2008. Rainfall occurred on November 18 and 19, 2008, before the measurements of November 20–21, 2008, and caused a rise in flow in Waiheʻe River, although measurements used to characterize gains and losses in Waiheʻe River were not affected by changing stage.

Stream Altitudes of 585 to 400 Feet

Seepage-run measurements between altitudes of 585 and 400 ft indicate a gaining reach in Waiheʻe River, downstream of the intake for Waiheʻe Ditch and upstream of the intake for Spreckels Ditch. Available measurements indicate an average gain of about 0.39 Mgal/d (0.61 ft^3/s) in this reach of Waiheʻe River. Measured gains between altitudes of 585 and 400 ft ranged from 0.03 to 0.68 Mgal/d (0.05 to 1.05 ft^3/s), and this range is assumed to bracket the true gain in the reach (fig. 32). Seepage-run measurements between altitudes of 585 and 400 ft are available for diverted conditions, when flow was less than about 2 Mgal/d (3 ft^3/s). In addition, seepage-run measurements made at altitudes of 530 and 445 ft are available for nearly undiverted conditions. On February 28, 2008, when nearly all of the water diverted from Waiheʻe River near an altitude of 600 ft was returned to Waiheʻe River near an altitude of 560 ft, the measured gain between altitudes of 530 and 445 ft was 0.45 Mgal/d (0.70 ft^3/s) (fig. 32).

Huluhulupueo Stream is a tributary of Waiheʻe River and enters the north side of the main stream near an altitude of about 490 ft. Available discharge measurements from Huluhulupueo Stream range from 0.033 to 0.50 Mgal/d (0.051 to 0.78 ft^3/s), with an average flow of 0.17 Mgal/d (0.27 ft^3/s), and do not indicate a strong correlation between the tributary inflow and corresponding daily mean discharge of Waiheʻe River at gaging station 16614000. Two small tributaries on the south side of Waiheʻe River, between altitudes of about 500 and 560 ft, contribute about 0.1 Mgal/d (0.2 ft^3/s).

Stream Altitudes of 400 to 100 Feet

Available seepage-run measurements downstream of an altitude of 400 ft, downstream of the Spreckels Ditch intake, indicate that Waiheʻe River generally loses water, although localized gaining reaches may exist immediately downstream of the dams associated with the intakes for Spreckels and Field 1 Ditches. For the purposes of this study, the reach between altitudes of 400 and 360 ft is assumed to neither gain nor lose water, although the stream may gain a small amount of water downstream of the dam for Spreckels Ditch. On the basis of limited data, the loss between altitudes of 360 and 310 ft (including the measurements between altitudes of 360 and 320 ft) ranged from about 0.19 to 0.47 Mgal/d (0.30 to 0.72 ft^3/s), and the average of the maximum and minimum loss values is 0.33 Mgal/d (0.51 ft^3/s) (fig. 32). The loss between altitudes of 310 and 270 ft ranged from 0.28 to 0.45 Mgal/d (0.43 to 0.70 ft^3/s), and the average of the maximum and minimum loss values is 0.36 Mgal/d (0.56 ft^3/s) (fig. 32).

Gains or losses between altitudes of about 270 and 100 ft were not directly measured, because of numerous return flows that were considered too difficult to accurately quantify. For this study, the loss between altitudes of about 270 and 100 ft was estimated on the basis of data from upstream and downstream reaches. On the basis of measurements from three separate days, the loss rate between altitudes of 310 and 270 ft ranged from 0.84 to 1.4 Mgal/d per mile of stream (1.3 to 2.1 ft^3/s per mile), and the average of the maximum and minimum loss rates is about 1.1 Mgal/d per mile of stream (1.7 ft^3/s per mile). (For the reach between altitudes of 310 and 270 ft, loss rates were measured on November 20 and 21, 2008, but only data from November 21, 2008, were included in computing the average to avoid giving too much weight to potentially nonindependent values.) The loss rate between altitudes of 100 and 45 ft ranged from -0.20 to 2.2 Mgal/d per mile of stream (-0.31 to 3.4 ft^3/s per mile), with an average loss rate of about 0.71 Mgal/d per mile of stream (1.1 ft^3/s per mile). Using the average loss rates from the upstream and downstream reaches and a reach length of about 4,700 ft between altitudes of 270 and 100 ft, the estimated loss between altitudes of 270 and 100 ft ranges from about 0.28 to 1.58 Mgal/d (0.43 to 2.44 ft^3/s) and averages about 0.80 Mgal/d (1.25 ft^3/s). (The minimum loss was estimated from the average of the minimum loss rates from the upstream and downstream reaches. Similarly, the maximum loss was estimated from the average of the maximum loss rates from the upstream and downstream reaches.)

Seepage-run measurements from February 26–29, 2008, indicate a gaining reach between altitudes of 390 and 285 ft, although the gain could not be confirmed by subsequent measurements during November 20–21 and December 1–4, 2008. Furthermore, many dry reaches and no obvious significant gaining reaches were observed between altitudes of 390 and 285 ft during a reconnaissance survey on August 12, 2008. Thus, measurements made during February 26–29, 2008, near altitudes of 390 and 285 ft may not accurately reflect losses or gains within this reach.

Stream Altitudes of 100 to 45 Feet

In general, the reach of Waihe‘e River between altitudes of 100 and 45 ft loses water, although seepage-run measurements from February 28, 2008, indicate no gain or loss and measurements from December 4, 2008, indicate a small gain of less than 1 percent of the upstream flow. The difference in flow between altitudes of 100 and 45 ft ranged from a gain of 0.065 Mgal/d (0.10 ft^3/s) to a loss of 0.71 Mgal/d (1.10 ft^3/s). Because of the wide range of differences between upstream and downstream flows, the average difference was estimated from all available data and indicated a loss of about 0.23 Mgal/d (0.35 ft^3/s) (fig. 32).

Waiehu Stream

Seepage-run measurements were made on selected reaches of North Waiehu Stream, South Waiehu Stream, and Waiehu Stream. The seepage-run measurements most representative of natural-flow conditions in North Waiehu Stream and Waiehu Stream were made during periods when flow was temporarily restored to North Waiehu Stream during March 2007 and March 2008.

North Waiehu Stream

During March 2007 and March 2008, diverted flow was temporarily restored to North Waiehu Stream through a release gate just downstream of the diversion dam for the North Waiehu Ditch. Seepage-run measurements were made about one to several days following the initiation of the temporary flow restorations. (North Waiehu Stream was flowing near an altitude of 475 ft during March 4 and 5, 2007, before the seepage-run measurements on March 6 and 7, 2007. North Waiehu Stream was flowing near an altitude of 475 ft after 2:00 p.m. on March 9, 2008, before the seepage-run measurements on March 10–14, 2008.) Data from the March 14, 2008, seepage run appear to have been affected by rainfall and were not used in the analysis.

Stream Altitudes of 920 to 475 Feet

During the periods of flow restoration in March 2007 and March 2008, the measured natural flow in North Waiehu Stream near an altitude of 920 ft ranged from 2.18 to 2.36 Mgal/d (3.37 to 3.65 ft^3/s). The overall loss between altitudes of 920 and 475 ft ranged from 0.91 to 1.22 Mgal/d (1.41 to 1.89 ft^3/s), representing 41 to 52 percent of the available upstream flow (fig. 33). The overall loss rates between altitudes of 920 and 475 ft ranged from 0.84 to 1.1 Mgal/d per mile of stream (1.3 to 1.7 ft^3/s per mile). On March 10, 11, 12, and 13, 2008, the loss rates between altitudes of 920 and 475 ft were, respectively, 1.1, 0.97, 1.1, and 1.0 Mgal/d per mile of stream (1.7, 1.5, 1.7, and 1.6 ft^3/s per mile).

For dry-weather conditions during the 2006–2008 data-collection period, diversion of water from North Waiehu Stream near an altitude of 880 ft commonly caused the stream to be dry (zero flow) at some point upstream of an altitude of 450 ft, where an existing road crosses the stream. Visual observations on August 17, 2005, and October 10, 2006, indicated zero flow at an altitude of about 625 ft. On December 19, 2007, measured flow near an altitude of 820 ft was 0.52 Mgal/d (0.81 ft^3/s) and zero flow was observed near an altitude of 450 ft. On July 1, 2008, measured flow near an altitude of 820 ft was 1.00 Mgal/d (1.55 ft^3/s) and flow was observed at least as far downstream as an altitude of 490 ft. Thus, a flow between about 0.52 and 1.00 Mgal/d (0.81 and 1.55 ft^3/s) near an altitude of 820 ft is required to initiate flow near altitudes of 490 to 450 ft, and these flows are used to bracket the flow at an altitude of 920 ft necessary to initiate flow at an altitude of 475 ft (fig. 36*A*).

For the losing reach between stream altitudes of 920 and 475 ft, the regression line fit to the available pairs of upstream and downstream flows has a slope less than 1 (fig. 36*A*), indicating that the loss increases as the upstream flow increases. For the flow-restoration period during March 2008, only data from March 13, 2008, were used in the linear regression analysis. Data from March 13, 2008, were collected toward the end of the March 2008 flow-restoration period and were considered most representative for estimating loss in the reach. Data from March 10–12, 2008, were collected during the same flow-restoration period, show similar losses, and do not represent independent conditions. Therefore, they were excluded from the regression analysis.

Because the relation between upstream and downstream flows in the reach between altitudes of 920 and 475 ft is poorly known, bracketing lines were developed to describe the range of downstream flows that are possible for a given upstream flow (fig. 36*A*). The upper bracketing line was established by connecting the two points that define the upper limit of the available data. The lower bracketing line was established by using the linear regression slope and forcing the line to pass through the point that causes the line to define the lower limit of the available data.

For this study, the natural discharge in North Waiehu Stream was measured near an altitude of 920 ft, upstream of the North Waiehu Ditch intake, which is near an altitude of 880 ft. Because the discharge-measurement site near an altitude of 920 ft is within a few hundred feet of the North Waiehu Ditch intake near an altitude of 880 ft, the natural, undiverted discharges at altitudes of 920 and 880 ft in North Waiehu Stream are considered equal for this study.

Stream Altitudes of 475 to 280 Feet

Same-day measurements at altitudes of 475 and 280 ft are available only for a small range of upstream flows. On the basis of available data, the loss between altitudes of 475 and 280 ft ranged from about 0.36 to 0.59 Mgal/d (0.55 to 0.91 ft^3/s). The average loss from measurements on March 7, 2007, and March 13, 2008, was 0.39 Mgal/d (0.61 ft^3/s). Available data from March 7, 2007, and March 13, 2008, were considered most

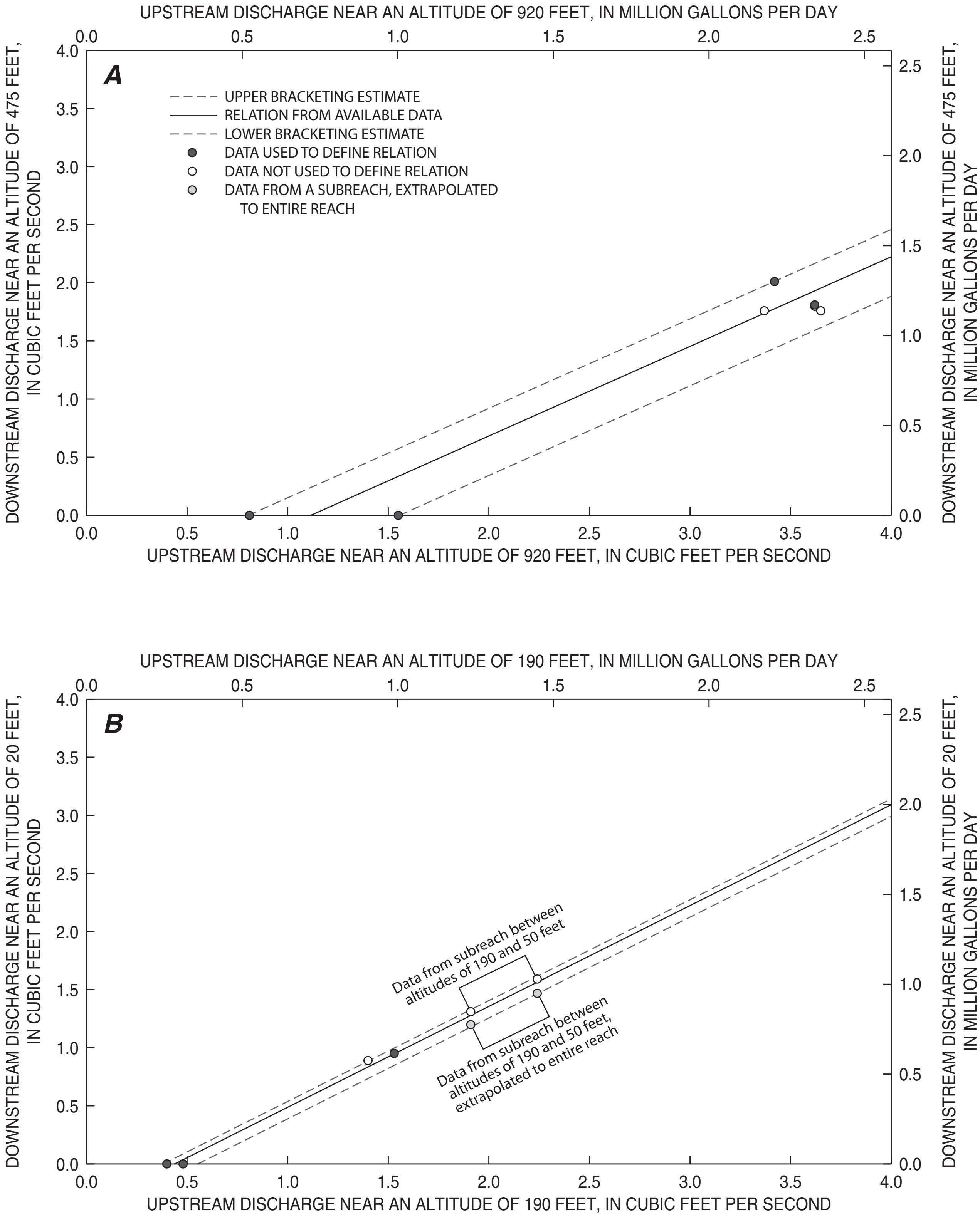


Figure 36. Relation between undiverted streamflows at an upstream and downstream site, Waiehu Stream, Maui, Hawaiʻi. *A*, Altitudes of 920 and 475 feet, North Waiehu Stream. *B*, Altitudes of 190 and 20 feet, Waiehu Stream. (Discharge near an altitude of 920 feet in North Waiehu Stream is assumed to be equal to discharge near an altitude of 880 feet.)

representative for estimating the loss during their respective flow-restoration periods.

Stream Altitudes of 280 to 220 Feet

Downstream of an altitude of about 280 ft to the confluence of North and South Waiehu Streams near an altitude of 220 ft, North Waiehu Stream appears to gain water. The source of the gain may be related to shallow groundwater or subsurface leakage from the Spreckels Ditch pipeline beneath and near North Waiehu Stream. Irrigation water returned to the stream also may be a source of the apparent gain. On the basis of seepage-run measurements from July 27, 2006, the average gain between altitudes of 260 and 225 ft is about 1 percent of the flow in North Waiehu Stream near an altitude of 900 ft measured 2 days earlier. (For the purposes of this study, the flow near an altitude of 900 ft is assumed to be equal to the flow near an altitude of 920 ft, which is reasonable given that the two sites are separated by less than 200 ft of stream length. Furthermore, the gain between altitudes of 260 and 225 ft is assumed to be representative of the gain between altitudes of 280 and 220 ft.) Measurements are not available to define a range of gains in this reach. The bracketing values for the gain in this reach are assumed to range from 0 to 2 percent of the flow in North Waiehu Stream near an altitude of 920 ft, and these values represent -100 to +100 percent of the estimate of 1 percent of the flow near an altitude of 920 ft.

South Waiehu Stream

The limited seepage-run data that were collected for South Waiehu Stream indicate that South Waiehu Stream neither gains nor loses large volumes of water between altitudes of 870 and 535 ft. South Waiehu Stream loses about 1 Mgal/d (1.5 ft^3/s) between altitudes of 535 and 280 ft.

Stream Altitudes of 870 to 670 Feet

On the basis of measurements made on November 17, 2008, the estimated loss between altitudes of 870 and 670 ft in South Waiehu Stream was only 0.03 Mgal/d (0.05 ft^3/s), indicating a relatively neutral reach that does not gain or lose a large volume of water. Measurements are not available to define a range of losses in this reach. The bracketing values for the loss in this reach are assumed to be 0 to 0.06 Mgal/d (0 to 0.1 ft^3/s), and these values represent -100 to +100 percent of the estimate of 0.03 Mgal/d (0.05 ft^3/s).

Stream Altitudes of 670 to 535 Feet

On the basis of measurements made on August 29, 2007, the estimated loss between altitudes of 670 and 535 ft in South Waiehu Stream was only 0.04 Mgal/d (0.06 ft^3/s), indicating a relatively neutral reach that does not gain or lose a large volume of water. Measurements are not available to define a range of losses in this reach. The bracketing values for the loss in this reach are assumed to be 0 to 0.08 Mgal/d (0 to 0.12 ft^3/s), and these values represent -100 to +100 percent of the estimate of 0.04 Mgal/d (0.06 ft^3/s). Assuming a uniform loss per mile of stream length, about 24 percent of the loss takes place between altitudes of 670 and 635 ft, and the remaining 76 percent of the loss takes place between altitudes of 635 and 535 ft.

Stream Altitudes of 535 to 405 Feet

Between altitudes of 635 and 405 ft, the measured loss on July 26, 2006, was 0.59 Mgal/d (0.92 ft^3/s). Available information on losses between altitudes of 670 and 405 ft indicates that nearly all of the measured loss in the reach between altitudes of 635 and 405 ft takes place downstream of an altitude of 535 ft. The estimated loss between altitudes of 635 and 535 ft is about 0.03 Mgal/d (0.05 ft^3/s) (see previous discussion for stream altitudes of 670 to 535 ft), and the estimated loss between altitudes of 535 and 405 ft is 0.56 Mgal/d (0.87 ft^3/s). Measurements are not available to define a range of losses in this reach. The bracketing values for the loss in the reach between altitudes of 535 and 405 ft are assumed to be 0 to 1.12 Mgal/d (0 to 1.74 ft^3/s), and these values represent -100 to +100 percent of the estimate of 0.56 Mgal/d (0.87 ft^3/s).

Stream Altitudes of 405 to 280 Feet

On the basis of measurements made on July 27, 2006, the estimated loss between altitudes of 405 and 280 ft in South Waiehu Stream was 0.35 Mgal/d (0.54 ft^3/s). Measurements are not available to define a range of losses in this reach. The bracketing values for the loss in this reach are assumed to be 0 to 0.70 Mgal/d (0 to 1.08 ft^3/s), and these values represent -100 to +100 percent of the estimate of 0.35 Mgal/d (0.54 ft^3/s).

Stream Altitudes of 280 to 220 Feet

Measurements are not available to characterize gains or losses in the reach of South Waiehu Stream between an altitude of 280 ft and the confluence with North Waiehu Stream near an altitude of 220 ft. For the purposes of this study, this reach is assumed to neither gain nor lose water, although the stream may gain a small amount of water downstream of the dam for Spreckels Ditch.

Waiehu Stream

Limited seepage-run measurements were made on Waiehu Stream upstream of an altitude of 190 ft. Available seepage-run measurements downstream of an altitude of 190 ft indicate that Waiehu Stream loses water in its lower reaches.

Stream Altitudes of 220 to 190 Feet

Seepage-run measurements from August 17, 2005, indicate a possible gaining reach in Waiehu Stream between an altitude of 220 ft, near the confluence of North and South Waiehu Streams, and an altitude of 65 ft. Although measurements are not available to definitively constrain the location of the gaining reach, the presence of a gaining reach between the confluence of North and South Waiehu Streams and an altitude of 190 ft is consistent with visual observations of seepage from the stream banks upstream of an altitude of 190 ft and available data that indicate a losing reach downstream of an altitude of 190 ft.

On the basis of seepage-run measurements from August 17, 2005, the average gain between altitudes of 220 and 65 ft is about 5 percent of the flow in North Waiehu Stream near an altitude of 920 ft. For the purposes of this study, all of the gain is attributed to the reach between altitudes of 220 and 190 ft, and losses between altitudes of 190 and 65 ft are assumed to be small. Measurements are not available to define a range of gain in the reach between altitudes of 220 and 190 ft. The bracketing values for the gain in this reach are assumed to range from 0 to 10 percent of the flow in North Waiehu Stream near an altitude of 920 ft, and these values represent -100 to +100 percent of the estimate of 5 percent of the flow near an altitude of 920 ft.

Stream Altitudes of 190 to 20 Feet

During periods of flow restoration to North Waiehu Stream in March 2007 and March 2008, seepage-run measurements were made in Waiehu Stream downstream of an altitude of 190 ft. During these periods of flow restoration, measured flow in Waiehu Stream near an altitude of 190 ft ranged from 0.90 to 1.45 Mgal/d (1.40 to 2.24 ft^3/s). On March 6 and 7, 2007, upstream flows near an altitude of 190 ft were 1.23 and 1.45 Mgal/d (1.91 and 2.24 ft^3/s), respectively, and losses between 190 and 50 ft were 0.39 and 0.42 Mgal/d (0.60 and 0.65 ft^3/s), or about 0.41 and 0.45 Mgal/d per mile of stream (0.64 and 0.70 ft^3/s per mile). Measured losses between altitudes of 190 and 50 ft represent about 30 percent of the upstream flow at 190 ft. On March 12 and 13, 2008, upstream flows near an altitude of 190 ft were 0.99 and 0.90 Mgal/d (1.53 and 1.40 ft^3/s), respectively, and losses between 190 and 20 ft were 0.37 and 0.33 Mgal/d (0.58 and 0.51 ft^3/s), or about 0.34 and 0.29 Mgal/d per mile of stream (0.52 and 0.45 ft^3/s per mile). Measured losses between altitudes of 190 and 20 ft represent about 37 percent of the upstream flow at 190 ft.

The increase in loss from March 6 to March 7, 2007, may reflect a higher discharge at the upstream site near an altitude of 190 ft on March 7 (1.45 Mgal/d; 2.24 ft^3/s) relative to March 6 (1.23 Mgal/d; 1.91 ft^3/s). The reduction in loss from March 12 to March 13, 2008, may reflect a lower discharge at the upstream site near an altitude of 190 ft on March 13 (0.90 Mgal/d; 1.40 ft^3/s) relative to March 12 (0.99 Mgal/d; 1.53 ft^3/s), or a reduction in loss as the streambed became saturated.

On September 21, 2007, measured flow near an altitude of 190 ft was 0.26 Mgal/d (0.40 ft^3/s) and zero flow was observed (based on photographic data from a mounted camera) near an altitude of 20 ft. On April 2, 2007, measured flow near an altitude of 190 ft was 0.31 Mgal/d (0.48 ft^3/s) and nonzero flow (very low flow, based on photographic data from a mounted camera) was observed near an altitude of 20 ft. Thus, a flow between about 0.26 and 0.31 Mgal/d (0.40 and 0.48 ft^3/s) near an altitude of 190 ft is required to initiate flow near an altitude of 20 ft. No known diversions exist downstream of the confluence of North and South Waiehu Streams.

For the losing reach between stream altitudes of 190 and 20 ft, the regression line fit to the available pairs of upstream and downstream flows has a slope less than 1 (fig. 36*B*), indicating that the loss increases as the upstream flow increases. For the flow-restoration period during March 2008, only data from March 12 were used in the linear regression analysis. Data from March 12 were considered most representative for estimating loss in the reach because of the timing of the upstream and downstream measurements during a slight flow-recession period. On March 12 the upstream measurement was made about 2 hours before the downstream measurement, whereas on March 13 the upstream and downstream measurements were made at about the same time. Thus, the loss estimated from measurements on March 13, 2008, could underestimate the actual loss.

Because the relation between upstream and downstream flows in the reach between altitudes of 190 and 20 ft is poorly known, bracketing lines were developed to describe the range of downstream flows that are possible for a given upstream flow (fig. 36*B*). The lower bracketing line was established using the same slope as the linear-regression slope, and it was forced to pass through the March 7, 2007, data (upstream flow at 190 ft and downstream flow at 50 ft) that were extrapolated to the entire reach from altitudes of 190 to 20 ft. For this case, the extrapolation was made by assuming that the loss rate is linearly related to flow. The upper bracketing line also used the same slope as the linear-regression slope, and the intercept was defined by assuming the regression line passes through the data from March 13, 2008.

‘Īao Stream

Seepage-run measurements were made during typical diverted conditions, as well as during periods when flow was partially or almost fully restored to ‘Īao Stream. The seepage-run measurements most representative of natural-flow conditions in ‘Īao Stream were made when flow was temporarily restored to ‘Īao Stream during December 14, 2006; January 18, 2007; January 16–18, 2008; and February 11–15, 2008.

Variability in measured loss rates for a reach may reflect variable antecedent conditions or variable flow rates among the different measurement days. On the basis of available antecedent photographic data near an altitude of 370 ft, ʻĪao Stream was flowing at various rates before the discharge measurements near altitudes of 595 and 395 ft on December 14, 2006 (flowing since November 27, 2006), and on January 16–18, 2008, and February 11–15, 2008 (flowing since December 2, 2007). On the basis of available antecedent photographic data near an altitude of 50 ft, ʻĪao Stream was flowing at various rates before the discharge measurements near altitudes of 220 and 35 ft on January 18, 2007 (since January 17, 2007), and February 13–14, 2008 (since January 26, 2008).

Downstream of an altitude of 780 ft, ʻĪao Stream generally loses water, although localized gaining reaches exist. For example, a pool at the base of a near-vertical drop in the steam channel near an altitude of 370 ft persists during dry-weather conditions because of shallow subsurface flow and seepage. An apparent gaining reach between altitudes of 310 and 250 ft in a concrete-lined channel is caused by subsurface water that emerges through cracks and holes in the concrete. Mapped tunnels and a spring on the north side of ʻĪao Stream between altitudes of about 400 and 250 ft are consistent with observed gains in this area (Stearns and Macdonald, 1942).

Stream Altitudes of 780 to 725 Feet

Seepage-run measurements for subreaches between altitudes of 780 and 725 ft indicate a gaining reach in ʻĪao Stream, downstream of the intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches, although available measurements are for diverted conditions when flow was less than 0.65 Mgal/d (1 ft^3/s). On the basis of measurements from September 21, 2004; July 24, 2006; October 11, 2006; and January 16, 2007, subreaches between altitudes of 780 and 725 ft gained between 1.2 and 2.2 percent of the upstream, undiverted flow near an altitude of 780 ft (gaging station 16604500), with an average gain of 1.8 percent. In addition to the gain in the main stream channel, an unnamed tributary that enters the south side of ʻĪao Stream near an altitude of 710 ft contributes inflow. Available discharge values for this tributary range from 0.03 to 0.11 Mgal/d (0.04 to 0.17 ft^3/s), with an average flow of about 0.05 Mgal/d (0.07 ft^3/s), and do not indicate a strong correlation with the corresponding daily mean discharge from ʻĪao Stream at gaging station 16604500.

Stream Altitudes of 725 to 595 Feet

Seepage-run measurements between altitudes of 725 and 610 ft indicate a losing reach in ʻĪao Stream, although these measurements are available only for diverted conditions, when flow was less than 0.46 Mgal/d (0.71 ft^3/s). On the basis of discharge measurements from July 24 and October 11, 2006, the estimated lower bracketing value of loss in this reach is about 0.32 Mgal/d (0.50 ft^3/s). By extrapolating the loss rate, assuming uniform loss per mile of stream length, from the reach between altitudes of 595 and 395 ft, which generally has a higher loss rate than the reach between altitudes of 725 and 595 ft, the upper bracketing value of loss in the reach between altitudes of 725 and 595 ft is estimated to be about 1.25 Mgal/d (1.94 ft^3/s). The average of the estimated lower and upper bracketing losses in this reach is 0.79 Mgal/d (1.22 ft^3/s).

Stream Altitudes of 595 to 395 Feet

Measurements to estimate losses between altitudes of 595 and 395 ft are available for periods when flow was partially restored to ʻĪao Stream during December 14, 2006; January 16–18, 2008; and February 11–15, 2008. Measured losses between altitudes of 595 and 395 ft, for upstream flows ranging from 14.7 to 29.1 Mgal/d (22.8 to 45.0 ft^3/s), ranged from 0.90 to 3.2 Mgal/d (1.4 to 5.0 ft^3/s) (fig. 34), or about 1.0 to 3.4 Mgal/d per mile of stream (1.5 to 5.2 ft^3/s per mile). Measured losses between altitudes of 595 and 395 ft range from about 4 to 18 percent of the upstream flow at 595 ft. For the flow-restoration period during January 2008, the loss of 3.0 Mgal/d (4.6 ft^3/s) measured on January 16, 2008, was considered most representative for estimating loss in the reach because of the timing of the upstream and downstream measurements during a period of near-stable discharge. Similarly, for the flow-restoration period during February 2008, the loss of 1.5 Mgal/d (2.3 ft^3/s) measured on February 13, 2008, was considered most representative for estimating loss in the reach. The average loss between altitudes of 595 and 395 ft computed from measurements on December 14, 2006, January 16, 2008, and February 13, 2008, is 2.4 Mgal/d (3.7 ft^3/s), or about 2.5 Mgal/d per mile of stream (3.8 ft^3/s per mile) (fig. 37*A*).

Stream Altitudes of 395 to 360 Feet

Measurements are not available to quantify the loss in the reach between altitudes of 395 and 360 ft. For the purposes of this study, the loss in this reach is estimated by multiplying the loss rate (loss per mile of stream length) from the upstream reach between altitudes of 595 and 395 ft by the stream distance (about 820 ft) between altitudes of 395 and 360 ft.

Stream Altitudes of 360 to 220 Feet

On the basis of visual observations and measurements from September 21, 2004, the reach between altitudes of 360 and 220 ft gains water. Seepage-run measurements from September 21, 2004, indicate a gain of about 0.18 Mgal/d

(0.28 ft^3/s), or about 2.2 percent of the daily mean flow at ʻĪao Stream gaging station 16604500 on that day.

A spring on the north side of ʻĪao Stream also contributes flow in this reach. The spring discharge is poorly correlated with the corresponding daily mean flow at ʻĪao Stream gaging station 16604500. The correlation is improved by considering the average flow over a period of 8 days (including the current day and the 7 previous days) at ʻĪao Stream gaging station 16604500 (fig. 38). The upper and lower bracketing lines were assumed to have the same slope as the regression line.

Stream Altitudes of 220 to 35 Feet

Measurements to estimate losses between altitudes of 220 and 35 ft are available for periods when flow was partially restored to ʻĪao Stream during January 18, 2007, and February 11–15, 2008. Measured losses between altitudes of 220 and 35 ft, for upstream flows ranging from 6.14 to 12.0 Mgal/d (9.50 to 18.5 ft^3/s), ranged from 1.5 to 2.1 Mgal/d (2.3 to 3.23 ft^3/s) (fig. 34), or about 1.1 to 1.6 Mgal/d per mile of stream (1.7 to 2.4 ft^3/s per mile). Measured losses between altitudes of 220 and 35 ft range from about 17 to 33 percent of the upstream flow at 220 ft. For the flow-restoration period during February 2008, the loss of 2.09 Mgal/d (3.23 ft^3/s) measured on February 14, 2008, was considered most representative for estimating loss in the reach because of the timing of the upstream and downstream measurements during a period of near-stable discharge. The average loss between altitudes of 220 and 35 ft computed from measurements on January 18, 2007, and February 14, 2008, is 2.1 Mgal/d (3.2 ft^3/s), or about 1.5 Mgal/d per mile of stream (2.3 ft^3/s per mile). Because the upper bracketing value of loss for this reach is nearly equal to the average value, an assumed upper bracketing value was set equal to 2.7 Mgal/d (4.1 ft^3/s). The upper and lower bracketing values of loss are thus equidistant from the average value (fig. 37*B*).

Waikapū Stream

Waikapū Stream may flow continuously to Keālia Pond during periods of high flow. Full restoration of flow to Waikapū Stream during extended dry-weather conditions would establish whether Waikapū Stream flows continuously to Keālia Pond for natural, undiverted, low-flow conditions. Full restoration of flow was not known to have occurred during the period of this study and, thus, data representative of diverted conditions and periods of recession were used to provide an indication of conditions needed to establish flow to Keālia Pond.

Stream Altitudes of 1,160 to 1,080 Feet

Seepage-run measurements between altitudes of 1,160 and 1,080 ft indicate a gaining reach in Waikapū Stream, after accounting for diversion of water by the South Side Ditch intake. Measured gains between altitudes of 1,160 and 1,080 ft, for upstream flows of 1.78 to 2.34 Mgal/d (2.76 to 3.62 ft^3/s), ranged from 0.12 to 0.19 Mgal/d (0.18 to 0.30 ft^3/s), or about 0.40 to 0.67 Mgal/d per mile of stream (0.62 to 1.04 ft^3/s per mile). The average measured gain between altitudes of 1,160 and 1,080 ft was about 7 percent of the upstream flow, with bracketing values of 6 and 9 percent.

Stream Altitudes of 1,080 to 950 Feet

For stream reaches between altitudes of 1,080 and 950 ft, available data from March 3, 2007; November 15, 2007; and April 30, 2008, indicate that Waikapū Stream may either gain or lose water, which may be reflective of the transition from a gaining reach upstream to a losing reach downstream. The difference in measured flow between altitudes of 1,080 and 950 ft ranged from a loss of 0.31 Mgal/d (0.48 ft^3/s) to a gain of 0.078 Mgal/d (0.12 ft^3/s). The gain of 0.078 Mgal/d (0.12 ft^3/s) represents about 4 percent of the flow near an altitude of 1,160 ft. The average measured difference indicates a loss of about 0.14 Mgal/d (0.21 ft^3/s) (fig. 35).

A tributary that enters the north (left) side of Waikapū Stream near an altitude of about 1,050 ft contributes an average of about 1.16 Mgal/d (1.80 ft^3/s) to the main stream. The tributary inflow ranged from about 0.99 to 1.47 Mgal/d (1.53 to 2.27 ft^3/s) and is not strongly correlated to the undiverted flow in Waikapū Stream near an altitude of 1,160 ft.

Stream Altitudes of 950 to 820 Feet

Everett Ditch diverts water from and returns water to the stream in this reach. The diffuse return flow from Everett Ditch could not be accurately measured, although most of the diverted water probably returns to the stream. Seepage-run measurements from November 15, 2007, and April 30, 2008, can be used to provide an upper estimate of the loss in this reach. (Discharge measurements near stream altitudes of 950 and 820 ft also are available from March 3, 2007; August 1, 2007; and April 29, 2008, but return flow from the South Side Ditch within this reach was not quantified on these days.) The measured losses for this reach were 0.02 and 0.09 Mgal/d (0.025 and 0.14 ft^3/s) on November 15, 2007, and April 30, 2008, respectively, and averaged 0.05 Mgal/d (0.08 ft^3/s). The assumed lower bracketing value for the loss in this reach is zero, and the upper bracketing value corresponds to the greatest measured loss of 0.09 Mgal/d (0.14 ft^3/s).

Stream Altitudes of 820 to 560 Feet

Seepage-run measurements between altitudes of 820 and 560 ft indicate a losing reach. Measured losses between altitudes of 820 and 560 ft, for upstream flows of 1.26 to 3.08 Mgal/d (1.95 to 4.76 ft^3/s), ranged from 0.15 to 0.39 Mgal/d (0.23 to 0.60 ft^3/s), or about 0.17 to 0.44 Mgal/d per mile of

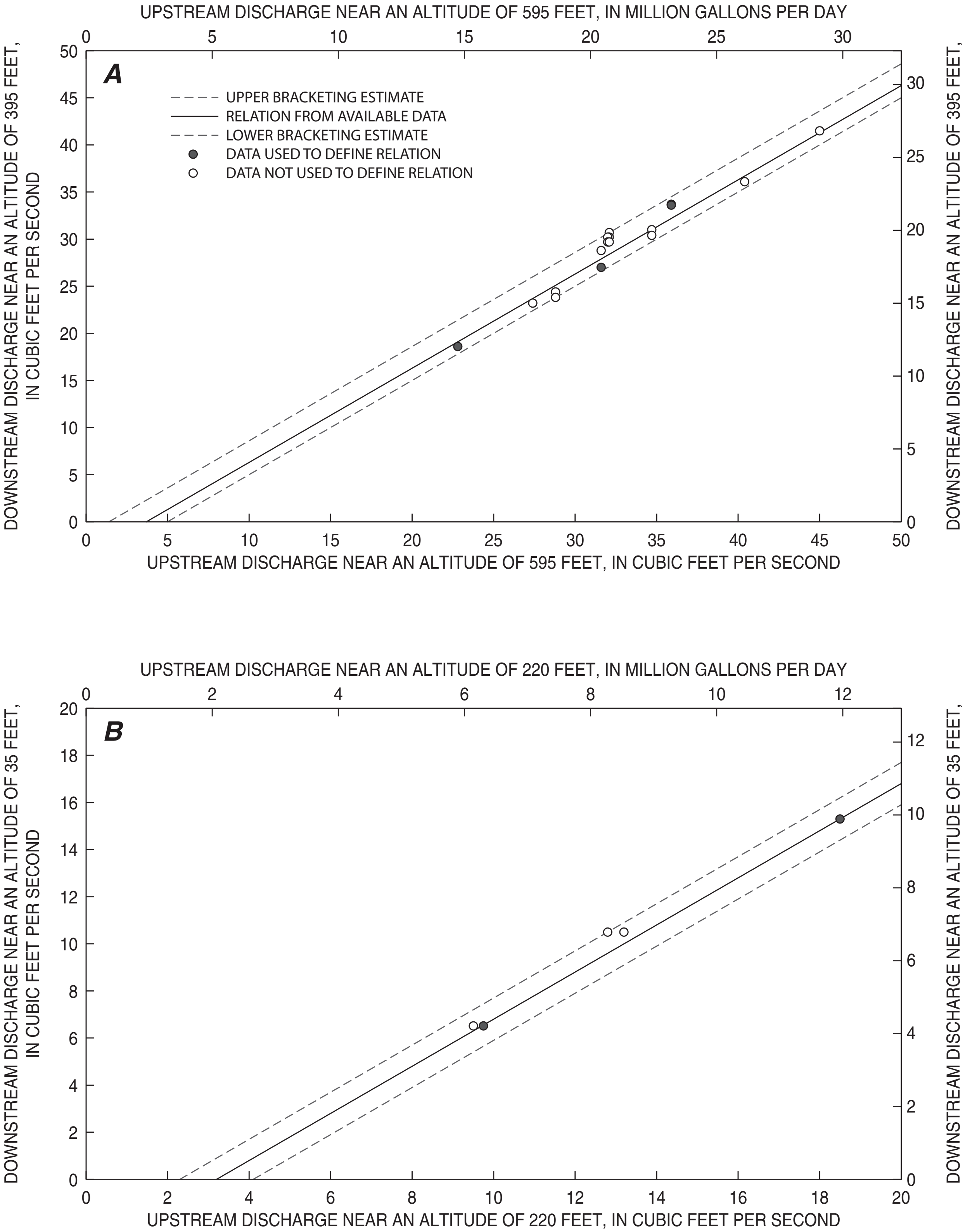


Figure 37. Relation between undiverted streamflows at an upstream and downstream site, ʻĪao Stream, Maui, Hawaiʻi. *A*, Altitudes of 595 and 395 feet. *B*, Altitudes of 220 and 35 feet.

stream (0.26 to 0.68 ft^3/s per mile). The average measured loss between altitudes of 820 and 560 ft was about 0.27 Mgal/d (0.42 ft^3/s), or about 0.31 Mgal/d per mile of stream (0.48 ft^3/s per mile) (fig. 39*A*). Three measurements of loss were made during April 2008, when upstream flows were varied on separate days because of ditch-maintenance activities.

Stream Altitudes of 560 to 400 Feet

Seepage-run measurements from October 28, 2004, between altitudes of 560 and 460 ft indicate a reach that neither gains nor loses appreciable amounts of water. The estimated lower bracketing loss and average loss in the reach between altitudes of 560 and 400 ft were thus assumed to be zero. The upper bracketing loss rate from the upstream reach between altitudes of 820 and 560 ft was used to characterize the upper bracketing loss in the reach between altitudes of 560 and 400 ft. The reach between altitudes of 820 and 560 ft more closely resembles the reach between altitudes of 560 and 400 ft, in terms of slope and channel material, than the downstream reach between altitudes of 400 and 40 ft. Applying the upper bracketing loss rate between altitudes of 820 and 560 ft to the reach between altitudes of 560 and 400 ft results in an estimated upper bracketing loss of 0.35 Mgal/d (0.54 ft^3/s) between altitudes of 560 and 400 ft.

Stream Altitudes of 400 to 40 Feet

Downstream of an altitude of 400 ft, only limited data are available to evaluate stream loss rates because steady flow in the lower reaches of Waikapū Stream was rarely observed. In general, loss rates downstream of an altitude of 400 ft are higher than loss rates farther upstream, which may reflect (1) higher flow conditions associated with the measurements downstream of an altitude of 400 ft, (2) more permeable sedimentary deposits in and beneath the streambed downstream of an altitude of 400 ft relative to farther upstream, or (3) reduced channel gradient downstream of an altitude of 400 ft. Seepage-run measurements downstream of an altitude of 400 ft were made on March 18, 2004, during a likely recession period; on August 22, 2006, and April 2, 2007, when flows for characterizing loss rates were observed; and on January 29 and March 13, 2009, during streamflow recessions. The measurements from January 29 and March 13, 2009, covered the entire reach between altitudes of 400 and 40 ft, whereas the measurements on the other days covered only partial reaches between altitudes of 400 and 40 ft. On the basis of available information described below, the loss between altitudes of 400 and 40 ft ranged from 2.81 to 8.40 Mgal/d (4.34 to 13.0 ft^3/s), corresponding to loss rates of 0.78 to 2.3 Mgal/d per mile of stream (1.2 to 3.6 ft^3/s per mile). The average loss in this reach, estimated

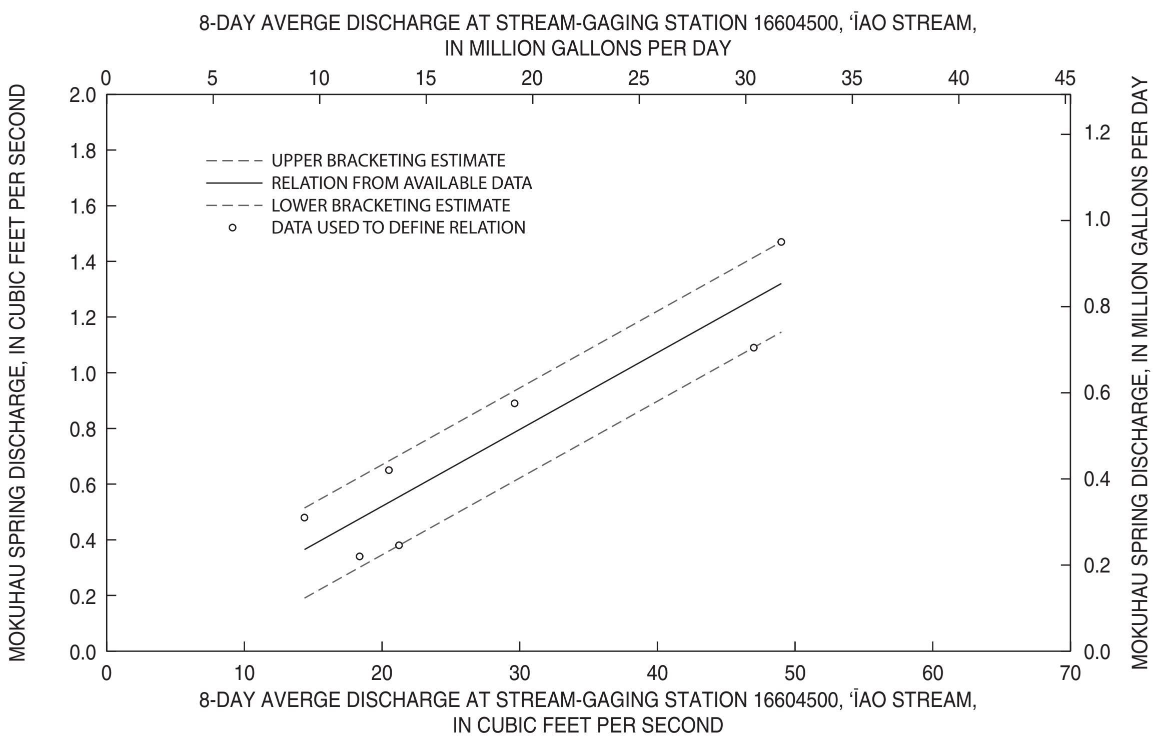


Figure 38. Relation between discharge from the Mokuhau Spring and discharge at stream-gaging station 16604500, ʻĪao Stream, Maui, Hawaiʻi. Eight-day average discharge for stream-gaging station 16604500 computed from current (same day as Mokuhau Spring measurement) and seven previous days.

from the higher of two loss values measured on each day (January 29 and March 13, 2009), was 5.9 Mgal/d (9.2 ft^3/s), corresponding to a loss rate of 1.7 Mgal/d per mile of stream (2.6 ft^3/s per mile) (fig. 39).

On March 18, 2004, measured flows in Waikapū Stream near altitudes of 360 and 40 ft respectively were 10.5 and 4.59 Mgal/d (16.3 and 7.10 ft^3/s). The measured loss rate between altitudes of 360 and 40 ft was 1.7 Mgal/d per mile of stream (2.6 ft^3/s per mile). The measurement near an altitude of 40 ft was made about an hour before the measurement near an altitude of 360 ft. The timing of the measurements during a likely recession indicates that the measured loss between 360 and 40 ft may be low relative to the expected loss for steady flow conditions. Applying the measured loss rate between altitudes of 360 and 40 ft to the reach between altitudes of 400 and 40 ft results in an estimated flow of 10.8 Mgal/d (16.7 ft^3/s) at an altitude of 400 ft needed for a flow of 4.59 Mgal/d (7.10 ft^3/s) near an altitude of 40 ft.

On August 22, 2006, the measured flow near an altitude of 400 ft was 2.60 Mgal/d (4.03 ft^3/s), and flow near an altitude of about 225 ft was zero, corresponding to a loss rate of about 2.3 Mgal/d per mile of stream (3.6 ft^3/s per mile). Flow near an altitude of 400 ft was visibly higher 14 hours before the measurement on August 22, 2006. Applying the measured loss rate between altitudes of 400 and 225 ft to the reach between altitudes of 400 and 40 ft results in an estimated flow of 8.40 Mgal/d (13.0 ft^3/s) at an altitude of 400 ft needed to initiate flow near an altitude of 40 ft.

On April 2, 2007, the measured loss between altitudes of 400 and 195 ft was 1.14 Mgal/d (1.77 ft^3/s), or about 0.78 Mgal/d per mile of stream (1.2 ft^3/s per mile), for an upstream flow of 4.78 Mgal/d (7.40 ft^3/s); the loss of 1.14 Mgal/d (1.77 ft^3/s) represents 24 percent of the upstream flow in the reach. Photographic data indicate that flow at the two sites was relatively steady during the period of measurement, although flow appeared to have receded over the period from 6 hours to 1 hour before the measurement period. Applying the measured loss rate between altitudes of 400 and 195 ft to the reach between altitudes of 400 and 40 ft results in an estimated flow of 1.98 Mgal/d (3.06 ft^3/s) near an altitude of 40 ft for a flow of 4.78 Mgal/d (7.40 ft^3/s) near an altitude of 400 ft.

On January 29, 2009, and March 13, 2009, discharge measurements were made in Waikapū Stream near altitudes of 40 ft and 400 ft. Because flow was receding on both days, measurements were made, in order, at the downstream site, the upstream site, and then again at the downstream site. On January 29, 2009, the measured loss between altitudes of 400 and 40 ft ranged from 4.4 to 7.17 Mgal/d (6.8 to 11.1 ft^3/s), representing 27 to 44 percent of the upstream flow in the reach. On March 13, 2009, the measured loss between altitudes of 400 and 40 ft ranged from 3.8 to 4.7 Mgal/d (5.9 to 7.3 ft^3/s), representing 42 to 51 percent of the upstream flow in the reach. Because of the distance between the upstream and downstream sites and the timing of the measurements, the estimated losses from these measurements may be less than would be expected during steady flow conditions.

Stream Altitudes of 40 to 20 Feet

On March 18, 2004, measured flows in Waikapū Stream near altitudes of 40 and 20 ft were, respectively, 4.59 and 3.71 Mgal/d (7.10 and 5.74 ft^3/s). The measured loss rate between altitudes of 40 and 20 ft was 1.5 Mgal/d per mile of stream (2.3 ft^3/s per mile). The measurement near an altitude of 40 ft was made about an hour before the measurement near an altitude of 20 ft. The timing of the measurements during a likely recession indicates that the measured loss between 40 and 20 ft may be a reasonable estimate of the expected loss for steady flow conditions. Applying the average loss rate between altitudes of 400 and 40 ft to the reach between altitudes of 40 and 20 ft results in an estimated loss of 0.92 Mgal/d (1.43 ft^3/s) between altitudes of 40 and 20 ft. The extrapolated loss of 0.92 Mgal/d (1.43 ft^3/s) is similar to the measured loss of 0.88 Mgal/d (1.36 ft^3/s) for the reach between altitudes of 40 and 20 ft. Bracketing estimates of the loss between altitudes of 40 and 20 ft also were estimated by extrapolating the bracketing loss rates between altitudes of 400 and 40 ft. The resulting bracketing estimates for the loss between altitudes of 40 and 20 ft ranged from 0.45 to 1.34 Mgal/d (0.69 to 2.08 ft^3/s).

Stream Altitudes of 20 to 10 Feet

Measurements are not available to characterize the loss in the reach between altitudes of 20 and 10 ft. For this study, the loss for the reach between altitudes of 20 and 10 ft was estimated by extrapolation of the loss rate between altitudes of 400 and 40 ft. The estimated average loss in the reach between altitudes of 20 and 10 ft is 1.29 Mgal/d (1.99 ft^3/s), ranging from 0.63 to 1.87 Mgal/d (0.97 to 2.89 ft^3/s).

Natural, Undiverted Flow Characteristics at Ungaged Sites

Natural, undiverted streamflows at ungaged sites downstream of existing diversions can be estimated using information from the seepage runs in conjunction with data from the active and historical stream-gaging stations. Selected duration discharges (Q_{50}, Q_{55}, Q_{60}, Q_{65}, Q_{70}, Q_{75}, Q_{80}, Q_{85}, Q_{90}, Q_{95}, and Q_{99}) were estimated at sites downstream of the uppermost diversions on each stream. Because of uncertainty in the estimated losses, upper and lower bounding estimates also were developed (tables 18–21).

For each stream, duration discharges computed using records from an existing gaging station (station 16614000 on Wahie‘e River and station 16604500 on ‘Īao Stream) or derived from record-extension methods using historical data from previously operated gaging stations (station 16608000 on North Waiehu Stream; station 16610000 on South Waiehu Stream; and stations 16648000, 16649000, and 16650000 on Waikapū Stream) were used as a starting point for determining duration discharges at selected ungaged sites on each stream. Estimated gains or losses from seepage-run measurements were used with the duration

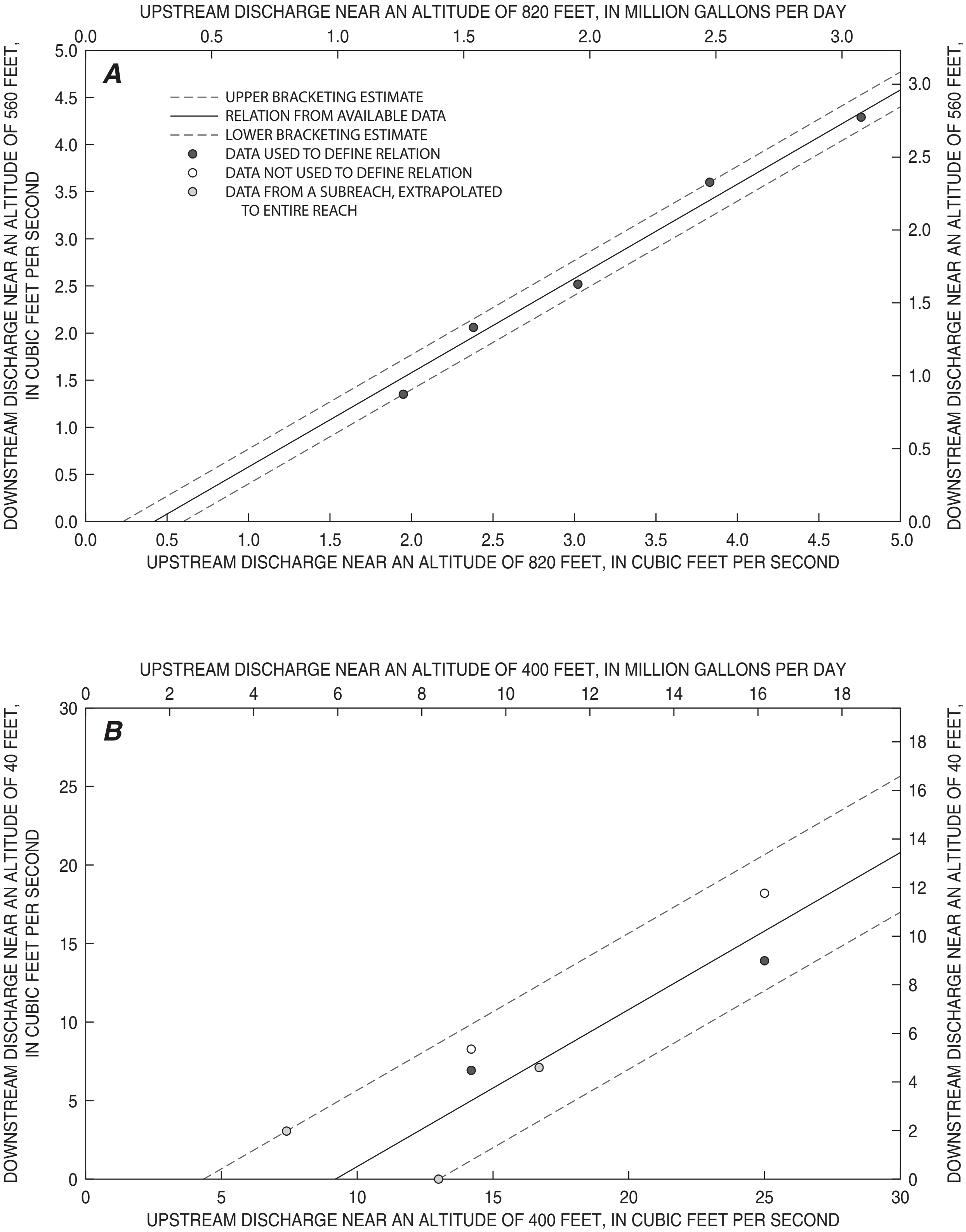


Figure 39. Relation between undiverted streamflows at an upstream and downstream site, Waikapū Stream, Maui, Hawaiʻi. *A*, Altitudes of 820 and 560 feet. *B*, Altitudes of 400 and 40 feet.

Table 18. Selected duration discharges (natural, undiverted conditions) for Waihe‘e River during climate years 1984–2007, Maui, Hawai‘i.

[Mgal/d, million gallons per day; ft, feet; values in light grey text are lower and upper bracketing values]

Flow-duration percentile	Duration discharges for selected altitudes of Waihe‘e River, in Mgal/d (values in parentheses are in cubic feet per second)					
	605 ft[1]	400 ft	310 ft	270 ft	100 ft	45 ft
50	34 (52)	34 (52) 34 (53) 35 (54)	34 (52) 34 (53) 35 (54)	33 (51) 34 (52) 34 (53)	31 (48) 33 (51) 34 (53)	30 (47) 32 (50) 34 (53)
55	32 (50)	32 (50) 33 (51) 34 (52)	32 (50) 33 (51) 34 (52)	32 (49) 32 (50) 33 (51)	30 (46) 32 (49) 33 (51)	29 (45) 31 (48) 33 (51)
60	31 (48)	31 (48) 32 (49) 32 (50)	31 (48) 32 (49) 32 (50)	30 (47) 31 (48) 32 (49)	28 (44) 30 (47) 32 (49)	28 (43) 30 (46) 32 (49)
65	30 (46)	30 (46) 30 (47) 31 (48)	30 (46) 30 (47) 31 (48)	29 (45) 30 (46) 30 (47)	27 (42) 29 (45) 30 (47)	27 (41) 28 (44) 30 (47)
70	28 (44)	28 (44) 29 (45) 30 (46)	28 (44) 29 (45) 30 (46)	28 (43) 28 (44) 29 (45)	26 (40) 28 (43) 29 (45)	25 (39) 27 (42) 29 (45)
75	28 (43)	28 (43) 28 (44) 29 (45)	28 (43) 28 (44) 29 (45)	27 (42) 28 (43) 28 (44)	25 (39) 27 (42) 28 (44)	25 (38) 27 (41) 28 (44)
80	27 (41)	27 (41) 27 (42) 28 (43)	27 (41) 27 (42) 28 (43)	26 (40) 27 (41) 27 (42)	24 (37) 26 (40) 27 (42)	23 (36) 25 (39) 27 (42)
85	25 (39)	25 (39) 26 (40) 27 (41)	25 (39) 26 (40) 27 (41)	25 (38) 25 (39) 26 (40)	23 (35) 25 (38) 26 (40)	22 (34) 24 (37) 26 (40)
90	24 (37)	24 (37) 25 (38) 25 (39)	24 (37) 25 (38) 25 (39)	23 (36) 24 (37) 25 (38)	21 (33) 23 (36) 25 (38)	21 (32) 23 (35) 25 (38)
95	22 (34)	22 (34) 23 (35) 23 (36)	22 (34) 23 (35) 23 (36)	21 (33) 22 (34) 23 (35)	19 (30) 21 (33) 23 (35)	19 (29) 21 (32) 23 (35)
99	18 (28)	18 (28) 19 (29) 19 (30)	18 (28) 19 (29) 19 (30)	17 (27) 18 (28) 19 (29)	16 (24) 17 (27) 19 (29)	15 (23) 17 (26) 19 (29)

[1]From record of gaging station 16614000.

Table 19. Selected duration discharges (natural, undiverted conditions) for Waiehu Stream during climate years 1984–2007, Maui, Hawaiʻi.

[Mgal/d, million gallons per day; ft, feet; values in light grey text are lower and upper bracketing values]

Flow-duration percentile	Duration discharges for selected altitudes of Waiehu Stream, in Mgal/d (values in parentheses are in cubic feet per second)						
	North Waiehu Stream			South Waiehu Stream		Waiehu Stream	
	880 ft[1]	475 ft	280 ft	870 ft[2]	280 ft	190 ft	20 ft
50	3.2 (4.9)	1.7 (2.6) 1.9 (2.9) 2.1 (3.2)	1.1 (1.7) 1.5 (2.3) 1.7 (2.6)	3.2 (5.0)	1.3 (2.0) 2.3 (3.5) 3.2 (5.0)	2.3 (3.6) 3.9 (6.1) 5.6 (8.7)	1.7 (2.7) 3.2 (4.9) 4.7 (7.3)
55	3.0 (4.6)	1.5 (2.3) 1.7 (2.7) 1.9 (2.9)	0.90 (1.4) 1.4 (2.1) 1.6 (2.4)	3.0 (4.7)	1.1 (1.7) 2.1 (3.2) 3.0 (4.7)	2.0 (3.1) 3.6 (5.5) 5.3 (8.2)	1.4 (2.2) 2.8 (4.4) 4.4 (6.8)
60	2.8 (4.3)	1.4 (2.1) 1.6 (2.5) 1.7 (2.7)	0.78 (1.2) 1.2 (1.8) 1.4 (2.1)	2.7 (4.2)	0.78 (1.2) 1.7 (2.7) 2.7 (4.2)	1.6 (2.4) 3.1 (4.8) 4.8 (7.4)	1.0 (1.6) 2.5 (3.8) 3.9 (6.1)
65	2.7 (4.1)	1.3 (2.0) 1.5 (2.3) 1.6 (2.5)	0.71 (1.1) 1.1 (1.7) 1.3 (2.0)	2.5 (3.8)	0.49 (0.76) 1.5 (2.3) 2.5 (3.8)	1.2 (1.8) 2.7 (4.2) 4.4 (6.8)	0.71 (1.1) 2.1 (3.3) 3.6 (5.6)
70	2.5 (3.8)	1.1 (1.7) 1.4 (2.1) 1.5 (2.3)	0.53 (0.82) 0.97 (1.5) 1.2 (1.8)	2.3 (3.5)	0.30 (0.46) 1.3 (2.0) 2.3 (3.5)	0.84 (1.3) 2.4 (3.7) 4.1 (6.3)	0.41 (0.63) 1.8 (2.8) 3.3 (5.1)
75	2.3 (3.5)	0.97 (1.5) 1.2 (1.8) 1.4 (2.1)	0.38 (0.59) 0.78 (1.2) 0.97 (1.5)	2.1 (3.2)	0.10 (0.16) 1.1 (1.7) 2.1 (3.2)	0.48 (0.75) 2.0 (3.1) 3.7 (5.7)	0.11 (0.17) 1.5 (2.3) 3.0 (4.6)
80	2.1 (3.2)	0.84 (1.3) 1.0 (1.6) 1.2 (1.8)	0.23 (0.36) 0.65 (1.0) 0.84 (1.3)	1.8 (2.8)	0 0.84 (1.3) 1.8 (2.8)	0.23 (0.36) 1.6 (2.5) 3.2 (5.0)	0 1.1 (1.8) 2.6 (4.0)
85	1.9 (3.0)	0.71 (1.1) 0.97 (1.5) 1.1 (1.7)	0.13 (0.20) 0.54 (0.84) 0.71 (1.1)	1.6 (2.5)	0 0.63 (0.98) 1.6 (2.5)	0.13 (0.20) 1.3 (2.0) 3.0 (4.6)	0 0.90 (1.4) 2.3 (3.6)
90	1.7 (2.6)	0.52 (0.80) 0.71 (1.1) 0.90 (1.4)	0 0.34 (0.53) 0.54 (0.83)	1.4 (2.2)	0 0.44 (0.68) 1.4 (2.2)	0 0.90 (1.4) 2.5 (3.9)	0 0.52 (0.81) 1.9 (3.0)
95	1.5 (2.3)	0.37 (0.57) 0.59 (0.91) 0.78 (1.2)	0 0.19 (0.30) 0.39 (0.60)	1.2 (1.9)	0 0.25 (0.38) 1.2 (1.9)	0 0.53 (0.82) 2.1 (3.3)	0 0.21 (0.33) 1.7 (2.6)
99	0.97 (1.5)	0 0.19 (0.30) 0.35 (0.54)	0 0 0	0.84 (1.3)	0 0 0.84 (1.3)	0 0.058 (0.090) 1.3 (2.0)	0 0 0.90 (1.4)

[1]From extension of record of gaging station 16608000 (based on average value, excluding ʻĪao Stream index stations). Discharge assumed to be equal to discharge at an altitude of 920 feet.

[2]From extension of record of gaging station 16610000 (based on average value, excluding ʻĪao Stream index stations).

Table 20. Selected duration discharges (natural, undiverted conditions) for ‘Īao Stream during climate years 1984–2007, Maui, Hawai‘i.

[Mgal/d, million gallons per day; ft, feet; values in light grey text are lower and upper bracketing values]

Flow-duration percentile	Duration discharges for selected altitudes of ‘Īao Stream, in Mgal/d (values in parentheses are in cubic feet per second)						
	780 ft[1]	725 ft	595 ft	395 ft	260 ft	220 ft	35 ft
50	25 (39)	26 (40) 26 (40) 26 (40)	25 (38) 25 (39) 26 (40)	21 (33) 23 (35) 25 (38)	21 (33) 23 (36) 26 (40)	21 (33) 23 (36) 26 (40)	19 (29) 21 (33) 25 (38)
55	23 (35)	23 (35) 23 (36) 23 (36)	22 (34) 22 (34) 23 (35)	19 (29) 20 (31) 22 (34)	19 (29) 21 (32) 23 (36)	19 (29) 21 (32) 23 (36)	16 (25) 19 (29) 21 (33)
60	21 (32)	21 (32) 21 (33) 21 (33)	19 (30) 20 (31) 21 (32)	16 (25) 18 (28) 20 (31)	17 (26) 19 (29) 21 (32)	17 (26) 19 (29) 21 (32)	14 (22) 16 (25) 19 (30)
65	19 (30)	19 (30) 20 (31) 20 (31)	18 (28) 19 (29) 19 (30)	15 (23) 17 (26) 19 (29)	16 (24) 17 (27) 19 (30)	16 (24) 17 (27) 19 (30)	13 (20) 15 (23) 18 (28)
70	17 (27)	17 (27) 18 (28) 18 (28)	16 (25) 17 (26) 17 (27)	13 (20) 15 (23) 17 (26)	14 (21) 15 (23) 17 (27)	14 (21) 15 (23) 17 (27)	11 (17) 13 (20) 16 (25)
75	16 (25)	16 (25) 17 (26) 17 (26)	15 (23) 16 (24) 16 (25)	12 (18) 14 (21) 16 (24)	12 (19) 14 (21) 16 (25)	12 (19) 14 (21) 16 (25)	9.7 (15) 12 (18) 15 (23)
80	15 (23)	15 (23) 15 (23) 16 (24)	14 (21) 14 (22) 15 (23)	10 (16) 12 (19) 14 (22)	10 (16) 12 (19) 15 (23)	10 (16) 12 (19) 15 (23)	7.8 (12) 10 (16) 13 (20)
85	14 (21)	14 (21) 14 (21) 14 (22)	12 (19) 13 (20) 14 (21)	9.0 (14) 11 (17) 13 (20)	9.0 (14) 11 (17) 14 (21)	9.0 (14) 11 (17) 14 (21)	6.5 (10) 9.0 (14) 12 (18)
90	12 (19)	12 (19) 12 (19) 13 (20)	11 (17) 12 (18) 12 (19)	7.8 (12) 9.0 (14) 12 (18)	7.8 (12) 9.7 (15) 12 (19)	7.8 (12) 9.7 (15) 12 (19)	5.2 (8.1) 7.8 (12) 10 (16)
95	11 (17)	11 (17) 11 (17) 12 (18)	9.7 (15) 10 (16) 11 (17)	6.5 (10) 7.8 (12) 10 (16)	6.5 (10) 8.4 (13) 10 (16)	6.5 (10) 8.4 (13) 10 (16)	3.9 (6.0) 6.1 (9.5) 9.0 (14)
99	8.4 (13)	8.4 (13) 8.4 (13) 8.4 (13)	7.1 (11) 7.8 (12) 8.4 (13)	4.1 (6.3) 5.4 (8.4) 7.8 (12)	3.8 (5.9) 5.4 (8.4) 7.8 (12)	3.8 (5.9) 5.4 (8.4) 7.8 (12)	1.2 (1.8) 3.4 (5.2) 6.3 (9.8)

[1]From record of gaging station 16604500.

Table 21. Selected duration discharges (natural, undiverted conditions) for Waikapū Stream during climate years 1984–2007, Maui, Hawaiʻi.

[Mgal/d, million gallons per day; ft, feet; values in light grey text are lower and upper bracketing values]

Flow-duration percentile	Duration discharges for selected altitudes of Waikapū Stream, in Mgal/d (values in parentheses are in cubic feet per second)							
	1,160 ft	1,080 ft	950 ft	820 ft	560 ft	400 ft	40 ft	10 ft
	3.6 (5.6)	4.5 (7.0)	5.2 (8.0)	5.1 (7.9)	4.7 (7.3)	4.4 (6.8)	0	0
50	4.3 (6.6)	4.6 (7.1)	5.6 (8.7)	5.6 (8.6)	5.3 (8.2)	5.3 (8.2)	0	0
	4.7 (7.2)	4.7 (7.2)	6.3 (9.7)	6.3 (9.7)	6.1 (9.5)	6.1 (9.5)	3.4 (5.2)	2.3 (3.5)
	3.4 (5.2)	4.3 (6.6)	4.9 (7.6)	4.8 (7.5)	4.5 (6.9)	4.1 (6.3)	0	0
55	4.0 (6.2)	4.3 (6.6)	5.3 (8.2)	5.2 (8.1)	5.0 (7.7)	5.0 (7.7)	0	0
	4.4 (6.8)	4.4 (6.8)	6.0 (9.3)	6.0 (9.3)	5.8 (9.0)	5.8 (9.0)	3.0 (4.7)	1.9 (3.0)
	3.1 (4.8)	3.9 (6.0)	4.6 (7.1)	4.5 (7.0)	4.1 (6.4)	3.7 (5.8)	0	0
60	3.7 (5.7)	3.9 (6.1)	5.0 (7.7)	4.9 (7.6)	4.7 (7.2)	4.7 (7.2)	0	0
	4.1 (6.3)	4.0 (6.2)	5.6 (8.7)	5.6 (8.7)	5.5 (8.5)	5.5 (8.5)	2.7 (4.1)	1.6 (2.5)
	2.9 (4.5)	3.7 (5.7)	4.4 (6.8)	4.3 (6.6)	3.9 (6.0)	3.6 (5.5)	0	0
65	3.5 (5.4)	3.7 (5.8)	4.8 (7.4)	4.7 (7.3)	4.5 (6.9)	4.5 (6.9)	0	0
	3.9 (6.0)	3.8 (5.9)	5.4 (8.4)	5.4 (8.4)	5.2 (8.1)	5.2 (8.1)	2.5 (3.8)	1.4 (2.1)
	2.7 (4.2)	3.5 (5.4)	4.2 (6.5)	4.1 (6.3)	3.7 (5.7)	3.4 (5.2)	0	0
70	3.3 (5.1)	3.6 (5.5)	4.5 (7.0)	4.5 (7.0)	4.2 (6.5)	4.2 (6.5)	0	0
	3.7 (5.7)	3.6 (5.6)	5.2 (8.0)	5.2 (8.0)	5.0 (7.8)	5.0 (7.8)	2.3 (3.5)	1.2 (1.8)
	2.5 (3.9)	3.3 (5.1)	3.9 (6.1)	3.9 (6.0)	3.5 (5.4)	3.2 (4.9)	0	0
75	3.1 (4.8)	3.3 (5.1)	4.3 (6.7)	4.3 (6.6)	4.0 (6.2)	4.0 (6.2)	0	0
	3.5 (5.4)	3.4 (5.2)	5.0 (7.7)	5.0 (7.7)	4.8 (7.5)	4.8 (7.5)	2.0 (3.1)	0.97 (1.5)
	2.3 (3.6)	3.0 (4.7)	3.7 (5.7)	3.6 (5.6)	3.2 (5.0)	2.8 (4.4)	0	0
80	2.8 (4.4)	3.0 (4.7)	4.1 (6.3)	4.0 (6.2)	3.7 (5.8)	3.7 (5.8)	0	0
	3.2 (5.0)	3.1 (4.8)	4.7 (7.2)	4.7 (7.2)	4.5 (7.0)	4.5 (7.0)	1.7 (2.7)	0.65 (1.0)
	2.1 (3.3)	2.9 (4.5)	3.6 (5.5)	3.5 (5.4)	3.1 (4.8)	2.7 (4.2)	0	0
85	2.7 (4.2)	2.9 (4.5)	3.9 (6.1)	3.9 (6.0)	3.6 (5.6)	3.6 (5.6)	0	0
	3.0 (4.7)	3.0 (4.6)	4.5 (7.0)	4.5 (7.0)	4.4 (6.8)	4.4 (6.8)	1.6 (2.4)	0.51 (0.79)
	1.9 (2.9)	2.6 (4.0)	3.3 (5.1)	3.2 (4.9)	2.8 (4.3)	2.5 (3.8)	0	0
90	2.5 (3.8)	2.7 (4.1)	3.7 (5.7)	3.6 (5.6)	3.4 (5.2)	3.4 (5.2)	0	0
	2.8 (4.4)	2.7 (4.1)	4.3 (6.6)	4.3 (6.6)	4.1 (6.3)	4.1 (6.3)	1.3 (2.0)	0.22 (0.34)
	1.6 (2.5)	2.3 (3.5)	2.9 (4.5)	2.8 (4.4)	2.5 (3.8)	2.1 (3.3)	0	0
95	2.1 (3.3)	2.3 (3.5)	3.3 (5.1)	3.2 (5.0)	3.0 (4.6)	3.0 (4.6)	0	0
	2.5 (3.9)	2.3 (3.6)	3.9 (6.0)	3.9 (6.0)	3.7 (5.8)	3.7 (5.8)	0.90 (1.4)	0
	1.0 (1.6)	1.6 (2.5)	2.3 (3.6)	2.3 (3.5)	1.9 (2.9)	1.5 (2.3)	0	0
99	1.6 (2.4)	1.7 (2.6)	2.7 (4.2)	2.7 (4.1)	2.4 (3.7)	2.4 (3.7)	0	0
	1.9 (2.9)	1.7 (2.6)	3.2 (5.0)	3.2 (5.0)	3.1 (4.8)	3.1 (4.8)	0.27 (0.41)	0

discharges from gaged sites to determine duration discharges at ungaged sites. The method to estimate duration discharges at ungaged sites is described in detail below for Waiheʻe River.

Waiheʻe River

For Waiheʻe River at gaging station 16614000 near an altitude of 605 ft, the median (Q_{50}) discharge during climate years 1984–2007 was 34 Mgal/d (52 ft^3/s); the Q_{70} discharge was 28 Mgal/d (44 ft^3/s); and the Q_{90} discharge was 24 Mgal/d (37 ft^3/s) (tables 12, 18). The duration discharges for Waiheʻe River near an altitude of 605 ft were adjusted by estimated gains or losses in downstream reaches to determine the duration discharges at ungaged, downstream sites. Data are not available to define gains or losses in the reach between altitudes of 605 and 585 ft. Thus, duration discharges near an altitude of 605 ft are assumed to be representative of duration discharges near an altitude of 585 ft.

In the reach between altitudes of 585 and 400 ft, Waiheʻe River gains an average of about 0.39 Mgal/d (0.61 ft^3/s). In addition, Huluhulupueo Stream on the north side and two small tributaries on the south side of Waiheʻe River contribute about 0.30 Mgal/d (0.47 ft^3/s) in the reach between altitudes of 585 and 400 ft. Thus, duration discharges for Waiheʻe River near an altitude of 400 ft reflect an increase of about 0.70 Mgal/d (1.08 ft^3/s) relative to the duration discharges near an altitude of 605 ft. (For this gaining reach, the increase was assumed to be constant and unaffected by upstream flow rate. For other gaining reaches, the gain generally was assumed to be a percentage of the upstream, natural discharge.) Near an altitude of 400 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 34, 29, and 25 Mgal/d (53, 45, and 38 ft^3/s) (table 18). The upper and lower bracketing estimates of duration discharges near an altitude of 400 ft account for increases of 1.31 and 0.19 Mgal/d (2.03 and 0.30 ft^3/s), respectively, relative to the duration discharges near an altitude of 605 ft.

In the reach between altitudes of 400 and 310 ft, Waiheʻe River loses an average of about 0.33 Mgal/d (0.51 ft^3/s), and the duration discharges near an altitude of 310 ft are less than the duration discharges near an altitude of 400 ft by this constant amount. Near an altitude of 310 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 34, 29, and 25 Mgal/d (53, 45, and 38 ft^3/s) (table 18). The upper and lower bracketing estimates of duration discharges near an altitude of 310 ft account for losses of 0.19 and 0.47 Mgal/d (0.30 and 0.72 ft^3/s), respectively, relative to the duration discharges near an altitude of 400 ft.

In the reach between altitudes of 310 and 270 ft, Waiheʻe River loses an average of about 0.36 Mgal/d (0.56 ft^3/s), and the duration discharges near an altitude of 270 ft are less than the duration discharges near an altitude of 310 ft by this constant amount. Near an altitude of 270 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 34, 28, and 24 Mgal/d (52, 44, and 37 ft^3/s) (table 18). The upper and lower bracketing estimates of duration discharges near an altitude of 270 ft account for losses of 0.28 and 0.45 Mgal/d (0.43 and 0.70 ft^3/s), respectively, relative to the duration discharges near an altitude of 310 ft.

In the reach between altitudes of 270 and 100 ft, Waiheʻe River loses an average of about 0.80 Mgal/d (1.25 ft^3/s), and the duration discharges near an altitude of 100 ft are less than the duration discharges near an altitude of 270 ft by this constant amount. Near an altitude of 100 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 33, 28, and 23 Mgal/d (51, 43, and 36 ft^3/s) (table 18). The upper and lower bracketing estimates of duration discharges near an altitude of 100 ft account for losses of 0.28 and 1.58 Mgal/d (0.43 and 2.44 ft^3/s), respectively, relative to the duration discharges near an altitude of 270 ft.

In the reach between altitudes of 100 and 45 ft, Waiheʻe River loses an average of about 0.23 Mgal/d (0.35 ft^3/s), and the duration discharges near an altitude of 45 ft are less than the duration discharges near an altitude of 100 ft by this constant amount. Near an altitude of 45 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 32, 27, and 23 Mgal/d (50, 42, and 35 ft^3/s) (table 18). The upper and lower bracketing estimates of duration discharges near an altitude of 45 ft account for a gain of 0.065 Mgal/d (0.10 ft^3/s) and a loss of 0.71 Mgal/d (1.10 ft^3/s), respectively, relative to the duration discharges near an altitude of 100 ft.

Waiehu Stream

To estimate the flow-duration discharges in Waiehu Stream, the flow-duration discharges at common duration percentiles were assumed to occur concurrently in North and South Waiehu Streams near altitudes of 880 (station 16608000) and 870 ft (station 16610000), respectively. For North Waiehu Stream at gaging station 16608000 near an altitude of 880 ft, the estimated median discharge during climate years 1984–2007 was 3.2 Mgal/d (4.9 ft^3/s); the estimated Q_{70} discharge was 2.5 Mgal/d (3.8 ft^3/s); and the estimated Q_{90} discharge was 1.7 Mgal/d (2.6 ft^3/s) (table 15). (The average values from the record extension analysis, excluding values resulting from using ʻĪao Stream as an index station, were assumed to be the most representative for all subsequent analyses.) For South Waiehu Stream at gaging station 16610000 near an altitude of 870 ft, the estimated median discharge during climate years 1984–2007 was 3.2 Mgal/d (5.0 ft^3/s); the estimated Q_{70} discharge was 2.3 Mgal/d (3.5 ft^3/s); and the estimated Q_{90} discharge was 1.4 Mgal/d (2.2 ft^3/s) (table 16). Downstream of the confluence of North and South Waiehu Streams, near an altitude of 20 ft, the estimated undiverted

Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 3.2, 1.8, and 0.52 Mgal/d (4.9, 2.8, and 0.81 ft^3/s) (table 19).

ʻĪao Stream

For ʻĪao Stream at gaging station 16604500 near an altitude of 780 ft, the estimated median discharge during climate years 1984–2007 was 25 Mgal/d (39 ft^3/s); the estimated Q_{70} discharge was 17 Mgal/d (27 ft^3/s); and the estimated Q_{90} discharge was 12 Mgal/d (19 ft^3/s) (tables 13, 20). Farther downstream, near an altitude of 35 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 21, 13, and 7.8 Mgal/d (33, 20, and 12 ft^3/s) (table 20).

Waikapū Stream

For Waikapū Stream near an altitude of 880 ft, the estimated median discharge (Q_{50}) during climate years 1984–2007 was 5.6 Mgal/d (8.6 ft^3/s); the estimated Q_{70} discharge was 4.5 Mgal/d (7.0 ft^3/s); and the estimated Q_{90} discharge was 3.6 Mgal/d (5.6 ft^3/s) (table 17). Upstream, near an altitude of 1,160 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were, respectively, 4.3, 3.3, and 2.5 Mgal/d (6.6, 5.1, and 3.8 ft^3/s) (table 21). Downstream of an altitude of 40 ft, the estimated undiverted Q_{50}, Q_{70}, and Q_{90} discharges were zero (table 21). Thus, on the basis of this analysis, Waikapū Stream would not have flowed continuously to the coast during climate years 1984–2007 in the absence of diversions (or additions) of water. Creed (1993, p. 10) indicated that Waikapū Stream "flows continuously to the sea, above ground in the valley, and underground in portions of the isthmus * * *," and this statement seems to be consistent with results from this study. However, Sterling (1998, p. 63) indicated that Waikapū Stream may be the only constantly flowing stream near Māʻalaea. Maciolek (1971) also indicated that Waikapū Stream flowed continuously throughout its course in a natural state. Neither Sterling (1998) nor Maciolek (1971) provide supporting information for their statements regarding flow in Waikapū Stream.

Maintaining Continuous Flows to the Ocean

Maintaining continuous surface flows from the mountains to the ocean (mauka to makai) in the Nā Wai ʻEhā area may be important for upstream migration of native stream fauna. To estimate the minimum flow necessary to maintain continuous mauka to makai flow in each stream, gains and losses determined from the seepage-run measurements were used to develop relations between the flow upstream of all diversions and the downstream flow near the coast (figs. 40–43). These relations were developed for natural, undiverted conditions (tables 18–21). Because of uncertainty in the estimated losses, upper and lower bounding relations also were developed (figs. 40–43) using the upper and lower bracketing flow estimates at the upstream and downstream sites (tables 18–21). The upper and lower bounding relations for Waikapū Stream (fig. 43) indicate greatest uncertainty mainly because seepage-run measurements to constrain losses in the lower reaches (downstream of an altitude of 400 ft) were collected during periods of recession. Estimates of losses in the lower reaches of Waikapū Stream can be improved by restoring all flow to the stream for a period sufficient to attain steady flow conditions.

Waiheʻe River

For Waiheʻe River, a minimum flow of about 1 Mgal/d (1.6 ft^3/s) near an altitude of 605 ft, corresponding to minimum flows of about 1.7 Mgal/d (2.7 ft^3/s) near an altitude of 400 ft and 1 Mgal/d (1.6 ft^3/s) near an altitude of 270 ft, is needed to initiate flow near the coast at an altitude of 45 ft, assuming no diversions exist in Waiheʻe River downstream of an altitude of 605 ft or in any tributaries to Waiheʻe River (fig. 40). The minimum flow estimate of 1 Mgal/d (1.6 ft^3/s) for Waiheʻe River near an altitude of 605 ft is much less than the minimum recorded flow of 14 Mgal/d (22 ft^3/s) during climate years 1984–2007 near an altitude of 605 ft. Thus, during climate years 1984–2007, Waiheʻe River would have flowed continuously to the coast at all times if no diversions existed.

Waiehu Stream

To estimate the flows in Waiehu Stream near the coast, the flow-duration discharges at common duration percentiles were assumed to occur concurrently in North and South Waiehu Streams. With this approximation, the flow in Waiehu Stream, downstream of the confluence of North and South Waiehu Streams, could be estimated (fig. 41). For Waiehu Stream, a minimum flow of 1.3 Mgal/d (2.1 ft^3/s) near an altitude of 880 ft in North Waiehu Stream, corresponding to a flow of about 1.1 Mgal/d (1.7 ft^3/s) in South Waiehu Stream near an altitude of 870 ft, is needed to initiate flow near the coast at an altitude of 20 ft, assuming no diversions exist downstream of an altitude of 880 ft in North Waiehu Stream and 870 ft in South Waiehu Stream (fig. 41). (For the purposes of this study, the flows at altitudes of 920 and 880 ft in North Waiehu Stream are considered equal.) The minimum flow estimate of 1.3 Mgal/d (2.1 ft^3/s) for North Waiehu Stream near an altitude of 880 ft is between the estimated Q_{95} and Q_{99} flows during climate years 1984–2007. Thus, during climate years 1984–2007, Waiehu Stream would have flowed continuously to the coast at least 95 percent of the time if no diversions existed. The minimum flows near altitudes of 880 ft in North Waiehu Stream and 870 ft in South Waiehu Stream needed to initiate flow near the coast at an altitude of 20 ft correspond to minimum flows of about 0.1 Mgal/d (0.2 ft^3/s) near an altitude of 280 ft in South Waiehu Stream and 0.3 Mgal/d (0.4 ft^3/s) near an altitude of 190 ft in Waiehu Stream.

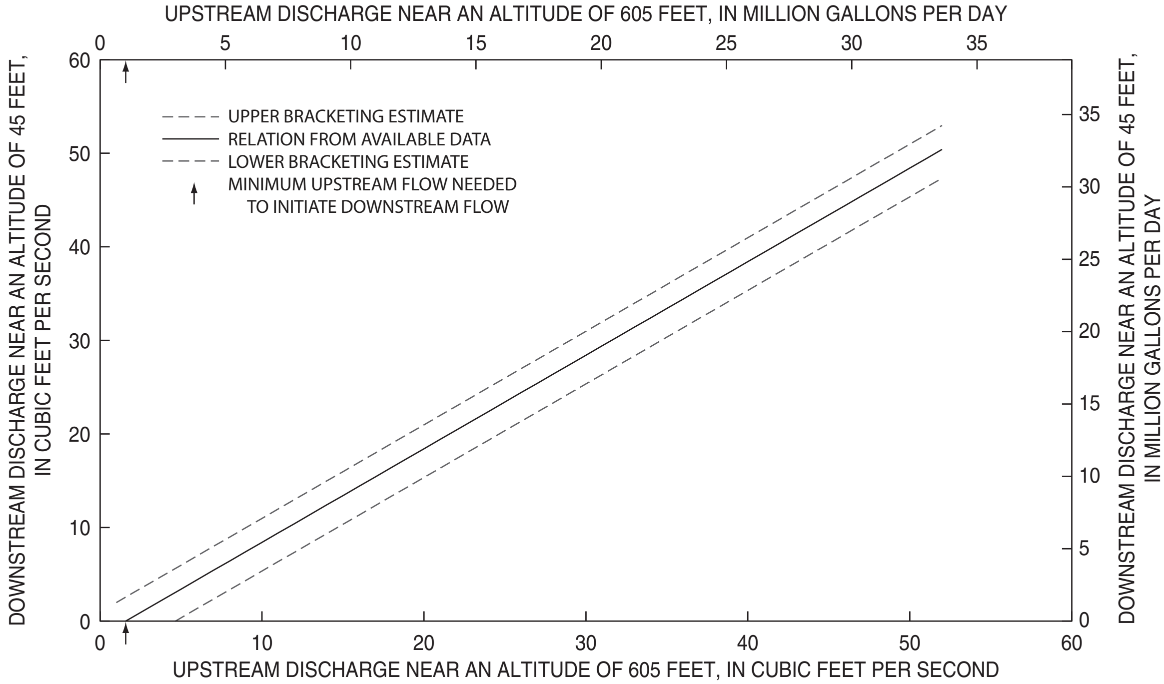


Figure 40. Relation between discharge near an altitude of 605 feet and discharge near an altitude of 45 feet for natural, undiverted conditions, Waihe‘e River, Maui, Hawai‘i.

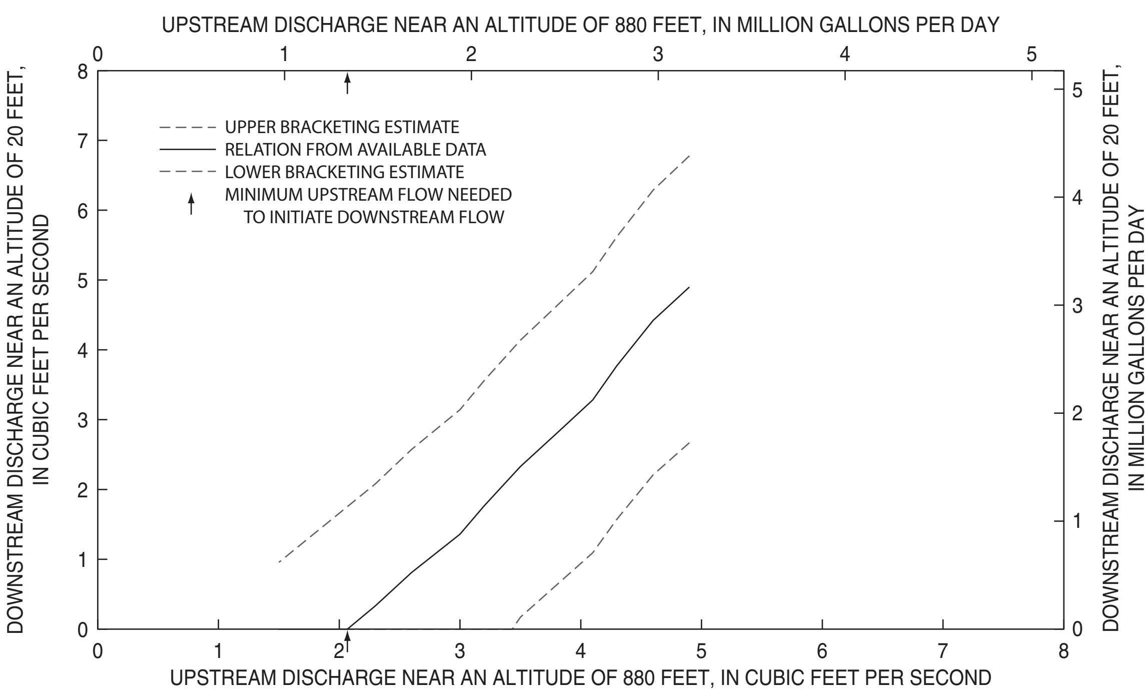


Figure 41. Relation between discharge near an altitude of 880 feet in North Waiehu Stream and discharge near an altitude of 20 feet in Waiehu Stream for natural, undiverted conditions, Maui, Hawai‘i.

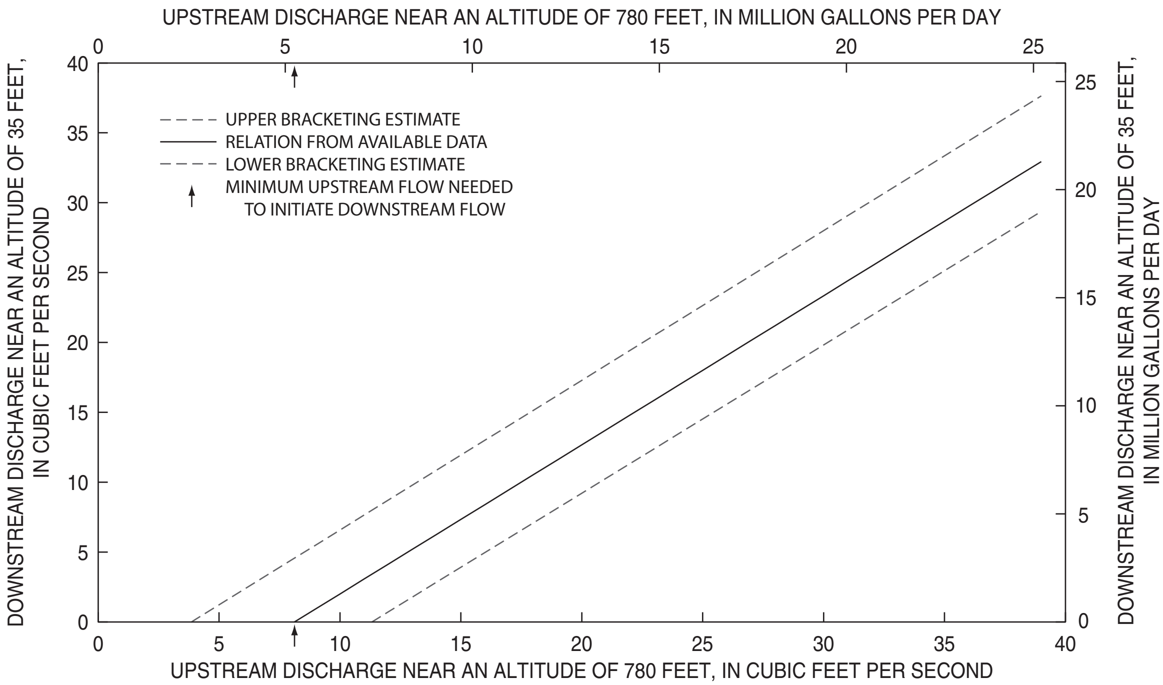


Figure 42. Relation between discharge near an altitude of 780 feet and discharge near an altitude of 35 feet for natural, undiverted conditions, ʻĪao Stream, Maui, Hawaiʻi.

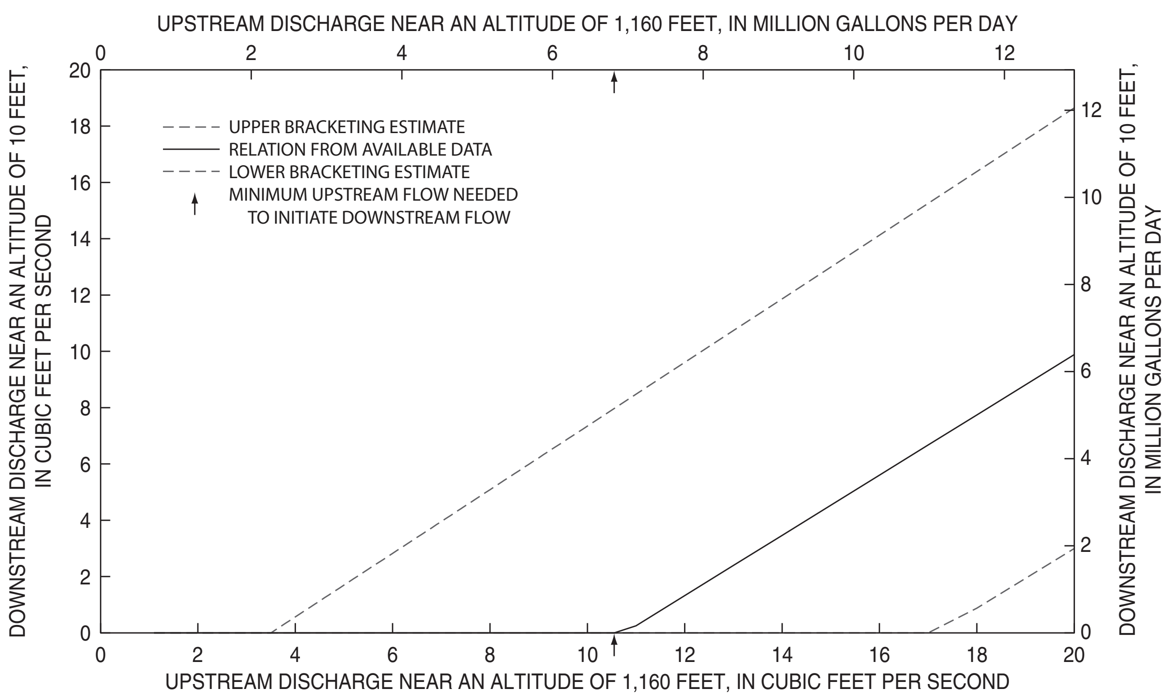


Figure 43. Relation between discharge near an altitude of 1,160 feet and discharge near an altitude of 10 feet for natural, undiverted conditions, Waikapū Stream, Maui, Hawaiʻi.

ʻĪao Stream

For ʻĪao Stream, a minimum flow of about 5.2 Mgal/d (8.1 ft^3/s) near an altitude of 780 ft, corresponding to a minimum flow of about 2.1 Mgal/d (3.2 ft^3/s) near an altitude of 220 ft, is needed to initiate flow near the coast at an altitude of 35 ft, assuming no diversions exist downstream of an altitude of 780 ft or in any tributaries to ʻĪao Stream (fig. 42). The minimum flow estimate of 5.2 Mgal/d (8.1 ft^3/s) for ʻĪao Stream near an altitude of 780 ft is less than the minimum recorded flow of 6.1 Mgal/d (9.4 ft^3/s) during climate years 1984–2007. Thus, during climate years 1984–2007, ʻĪao Stream would have flowed continuously to the coast at all times if no diversions existed.

Waikapū Stream

For Waikapū Stream, a minimum flow of about 6.8 Mgal/d (11 ft^3/s) near an altitude of 1,160 ft, corresponding to minimum flows of about 8.0 Mgal/d (12 ft^3/s) near an altitude of 400 ft and 2.1 Mgal/d (3.2 ft^3/s) near an altitude of 40 ft, is needed to initiate flow near the coast at an altitude of 10 ft, assuming no diversions exist downstream of an altitude of 1,160 ft or in the unnamed tributary that enters Waikapū Stream near an altitude of 1,050 ft (fig. 43). The minimum flow estimate of 6.8 Mgal/d (11 ft^3/s) for Waikapū Stream near an altitude of 1,160 ft is greater than the estimated median undiverted flow (4.3 Mgal/d; 6.6 ft^3/s) (table 21) during climate years 1984–2007 at an altitude of 1,160 ft. Thus, during climate years 1984–2007, Waikapū Stream would have flowed continuously to the coast less than half of the time if no diversions existed. The relation between upstream flow near an altitude of 1,160 ft and downstream flow near an altitude of 10 ft for Waikapū Stream (fig. 43) required extrapolation or use of seepage-run measurements for flows exceeding the median flow and, thus, this relation may not accurately reflect low-flow conditions and contains much uncertainty.

Recent Diverted Low-Flow Characteristics in Streams

During dry-weather conditions in 2006–2008, some reaches in each of the Nā Wai ʻEhā area streams have been observed to be dry (no visible water). Waiheʻe River was occasionally dry in some reaches immediately downstream of the Waiheʻe Ditch intakes and between the Spreckels Ditch intake near an altitude of 400 ft and the Field 1 intake near an altitude of 260 ft. North Waiehu Stream commonly was dry between altitudes of 490 and 280 ft. On the basis of a limited number of measurements (table 12) and additional visual observations made during this study, diversion of water from South Waiehu Stream through two private ʻauwai near altitudes of 620 and 570 ft was not known to have caused South Waiehu Stream to cease flowing upstream of an altitude of 270 ft during the 2006–2008 data-collection period. Near an altitude of 270 ft, Spreckels Ditch commonly diverts all of the dry-weather flow in South Waiehu Stream, although streamflow immediately downstream of the intake may exist because of leakage through or subsurface flow beneath the dam near the intake. Waiehu Stream was never observed to be dry immediately downstream of the confluence of North and South Waiehu Streams, although Waiehu Stream commonly was dry farther downstream near an altitude of 20 ft. ʻĪao Stream commonly was observed to be dry near altitudes of 370 and 50 ft. Waikapū Stream commonly was dry downstream of an altitude of 200 ft. Each stream flows continuously from mauka to makai during large storms. Waiheʻe River and ʻĪao Stream flow continuously from mauka to makai during dry-weather conditions when sufficient flow is restored to the stream.

Following a discharge peak in an undiverted stream, streamflow will gradually recede over a period of time that is dependent on factors including the volume and duration of rainfall, drainage-basin size and steepness, stream-channel storage, and permeability of rocks and sedimentary deposits through which interflow occurs. In a diverted stream with an intake capable of diverting all streamflow below a particular level, the recession period immediately downstream of the intake will tend to be abruptly truncated. That is, once streamflow recedes to a level less than the intake capacity, flow passing the diversion intake will cease. Thus, in a diverted stream with an intake capable of diverting all of the low flow in a stream, recession periods generally will be shortened, and this will tend to reduce the time available for upstream migration of native stream fauna following a freshet.

Water that originally was diverted from one stream can be discharged to another stream, either intentionally through release gates in the ditch system or by overflow of ditch or flume systems. For example, the Spreckels Ditch flume over ʻĪao Stream transports water diverted from Waiheʻe River and South Waiehu Stream and commonly was observed to overflow into ʻĪao Stream during periods of high flow in Waiheʻe River (fig. 44). In addition, the Waiheʻe Ditch flumes over North and South Waiehu Streams may overflow (fig. 44), and discharge from the Spreckels Ditch siphon across South Waiehu Stream can exceed the capacity of the system and overflow into South Waiehu Stream.

Low-Flow Partial-Record Stations

Continuous-record stream-gaging stations downstream of diversions currently (2009) do not exist in the Nā Wai ʻEhā area. Gaging-station records from 1910–17 can be used to characterize historical diverted streamflows, although conditions during 1910–17 may not be relevant today because diversion configurations and operations may have changed. Low-flow partial-record (LFPR) stations commonly are used to estimate low-flow statistics at sites without a long-term stream-gaging station. For example, Fontaine and others (1992) used data from LFPR stations on windward Oahu perennial streams to estimate median discharges at ungaged, regulated sites. Fontaine (2003) also used LFPR stations to estimate regulated discharges, within the Q_{50} to Q_{95} range, in Honokōhau Stream.

At LFPR stations, a minimum of about 10 discharge measurements generally are made during periods of low flow. These measurements are best made during independent recessions following periods of direct runoff and cover a range of low-flow conditions. The measured discharges at each LFPR station are correlated with the concurrent daily mean discharges at a long-term index station with hydrologically similar characteristics. For this study, LFPR stations were established on each stream and the measured discharges were correlated with concurrent daily mean discharges from ʻĪao Stream (16604500) and Waiheʻe River (16614000). Discharges at the LFPR stations affected by diversions were poorly correlated (correlation coefficients commonly less than 0.5 and in some cases less than 0.1) with concurrent discharges at the index stations for a number of reasons: (1) some of the diversion intakes are capable of diverting all of the dry-weather low flow of the stream, and this results in sites downstream of the intakes having near-zero flow for a range of low flows at the index station; (2) ditches and flumes that carry water from one stream (for example Waiheʻe River) may overflow into another stream (for example South Waiehu Stream or ʻĪao Stream) and affect the flow characteristics of the receiving stream (fig. 44); (3) during ditch-maintenance periods, flow may be restored temporarily to a stream for periods of various lengths (fig. 45);

Figure 44. Photographs of overflowing flumes discharging water originating from one stream into another stream, Maui, Hawaiʻi. *A*, Spreckels Ditch overflowing into ʻĪao Stream near an altitude of 220 feet (September 19, 2007). *B*, Waiheʻe Ditch overflowing into South Waiehu Stream near an altitude of 550 feet (July 17, 2006).

Figure 45. Photographs of diverted water being returned to streams during periods of ditch maintenance, Maui, Hawaiʻi. *A*, Water being returned to ʻĪao Stream near an altitude of 220 feet (February 13, 2008). *B*, Water being returned to Waiheʻe River near an altitude of 320 feet (November 17, 2008).

(4) return of diverted water to streams may be affected by the size of the opening of the return gate, which can be manually raised or lowered; (5) intake grates may divert variable rates of water for the same upstream flow because of natural clogging by rocks and debris or human activities (fig. 46); and (6) the amount of water diverted by North Waiehu Ditch was dependent on both streamflow and the condition of the rock-wall diversion dam. Thus, estimates of diverted-flow statistics from the LFPR stations were not made for this study.

Flow Characterization from Mounted Cameras

Hourly photographs from cameras mounted at 11 sites downstream of existing diversions were used to characterize how frequently each stream was dry (no visible water) near the camera site. For each stream, a camera was mounted at low altitude to provide information on how frequently the stream flowed near the coast. Additional cameras were mounted immediately downstream of selected diversion intakes and at other sites where access was safe, a suitable mounting structure was available, and where the camera would not be readily detected. In some cases, photographs were limited to daylight hours. In addition, hourly photographs sometimes were not taken by the cameras, even though they were programmed to record on an hourly basis.

Waiheʻe River

Cameras were mounted a few hundred feet downstream of the intakes for both the Waiheʻe and Spreckels Ditches, respectively near altitudes of 560 and 390 ft, and farther downstream near an altitude of 45 ft in Waiheʻe River. Photographs are available from October 2006 to April 2008 near an altitude of 560 ft; from October 2006 to December 2008 near an altitude of 390 ft; and from September 2006 to September 2008 near an altitude of 45 ft. The camera mounted near an altitude of 560 ft was vandalized sometime between May 1 and May 28, 2008.

None of the photographs indicate completely dry stream reaches, although photographs from altitudes of 560 and 390 ft commonly show highly diverted flow conditions with estimated flows less than 0.06 Mgal/d (0.1 ft^3/s). Photographs from the camera near an altitude of 45 ft indicate continuous flow.

Figure 46. Photograph of partially covered (with blue tarp) diversion intake common to the ʻĪao-Māniania and ʻĪao-Waikapū Ditches near an altitude of 780 feet, ʻĪao Stream, Maui, Hawaiʻi (July 30, 2007).

Waiehu Stream

Cameras were mounted near an altitude of 490 ft in North Waiehu Stream and near an altitude of 20 ft in Waiehu Stream. Photographs are available from September 2006 to July 2008 near an altitude of 490 ft in North Waiehu Stream and from February 2007 to December 2008 near an altitude of 20 ft in Waiehu Stream. Available photographs indicate that North Waiehu Stream was dry about 75 percent of the time and Waiehu Stream was dry about 57 percent of the time during the periods of record. During the 2007 climate year (April 1, 2007, through March 31, 2008), North Waiehu Stream was dry 77 percent of the time and Waiehu Stream was dry 45 percent of the time.

ʻĪao Stream

Cameras were mounted near altitudes of 720, 370, and 50 ft in ʻĪao Stream. Photographs are available from September 2006 to October 2008 near an altitude of 720 ft; from September 2006 to December 2008 near an altitude of 370 ft; and from September 2006 to May 2008 near an altitude of 50 ft. The camera mounted near an altitude of 50 ft was first noted missing on July 1, 2008. Available photographs indicate that ʻĪao Stream was never completely dry near an altitude of 720 ft, mainly because ʻĪao Stream gains water between the common intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and the camera site (fig. 34). Near altitudes of 370 and 50 ft, ʻĪao Stream was dry about 28 and 66 percent of the time, respectively, during the periods of record at each site. During the 2007 climate year, ʻĪao Stream was dry about 20 and 66 percent of the time near altitudes of 370 and 50 ft, respectively. The intake for Spreckels Ditch on ʻĪao Stream is between the camera sites near altitudes of 370 and 50 ft.

Waikapū Stream

Cameras were mounted near altitudes of 400, 200, and 40 ft in Waikapū Stream. Photographs are available from August 2006 to May 2009 near an altitude of 400 ft; from August 2006 to April 2009 near an altitude of 200 ft; and from April 2008 to May 2009 near an altitude of 40 ft. Available photographs indicate that near altitudes of 400, 200, and 40 ft, Waikapū Stream was dry about 3, 44, and 76 percent of the time, respectively, during the periods of record at each site. During the 2007 climate year, Waikapū Stream was dry about 1 and 28 percent of the time near altitudes of 400 and 200 ft, respectively. Available data during the 2008 climate year indicate that Waikapū Stream was dry about 7, 63, and 78 percent of the time near altitudes of 400, 200, and 40 ft, respectively. (The camera near an altitude of 40 ft was installed on April 29, 2008, and, thus, data during April 1 thru April 28, 2008, are not available.)

The increased frequency of dry conditions in a downstream direction is consistent with the presence of a losing reach between altitudes of 400 and 40 ft (fig. 35). The lack of continuous flow to the ocean from Waikapū Stream is consistent with observations by Martin and Pierce (1913, p. 225), who indicated that only storm water reaches the ocean from Waikapū Stream.

Effects of Surface-Water Diversions on Streamflow

Diversion of surface water from a stream reduces the amount of water available at downstream sites. The seepage-run measurements were used to develop relations between upstream and downstream flows of selected reaches in each stream (see section on “Seepage-Run Measurements” and figs. 32–39), and these relations were used to estimate the effects of surface-water diversions on streamflow at selected sites downstream of diversions. The method used to estimate streamflow at sites downstream of diversions is similar to the method used to estimate natural, undiverted flows at ungaged sites, except that water diverted from streams must be considered. For each stream, natural flows upstream of existing diversions were used as a starting point for determining selected duration discharges for sites downstream of diversions (tables 18–21).

As the capacity of a diversion intake increases, the reduction in streamflow at downstream sites generally increases. To estimate the effects of surface-water diversions on streamflow for this study, diversions are assumed to be capable of diverting water at a rate up to, but not exceeding, the diversion intake capacity. Thus, if streamflow immediately upstream of an intake is less than or equal to the intake capacity, all available streamflow is assumed to be diverted. (In reality, some flow may bypass the diversion intake for upstream flows less than the intake capacity, although the relation between upstream flow and bypass flow is not known. Thus, for the purposes of this study, the simplifying assumption was made that this bypass flow is small.) At some level of diversion intake capacity the diversions may cause downstream sites to be dry, and increased diversion intake capacity has no further effect on reducing streamflow during dry-weather, low-flow conditions. The effects of the diversions on streamflow at downstream sites were determined at selected upstream flows equal to and less than the median flow. For the purposes of this analysis, none of the diverted water is assumed to return to the stream, and the intake capacity of a diversion is assumed to be unaffected by water, possibly derived from another stream, already in the ditch system.

Using the natural flows upstream of existing diversions and estimated gains or losses from seepage-run measurements, duration discharges at downstream sites were determined for selected diversion intake capacities. For most cases, estimated losses in a reach were assumed to be constant, independent of flow rate, and uniformly distributed along the reach. Thus, if a diversion intake is located in the middle of a reach, then half of the loss is assumed to occur upstream and half of the loss is assumed to occur downstream of the intake. If the intake is capable of diverting all of the flow remaining in the stream, after accounting for losses in the upstream reach, then streamflow and losses downstream of the intake are zero. For two reaches (one between altitudes of 880 and 475 ft on North Waiehu Stream and the other between altitudes of 190 and 20 ft on Waiehu Stream), estimated losses are assumed to be a function of streamflow at the upstream end of the reach (fig. 36). The intake for the North Waiehu Ditch is at the upstream end of the reach on North Waiehu Stream between altitudes of 880 and 475 ft and, thus, diversion amounts are simply subtracted from the natural, undiverted upstream flow. No diversions are known to exist in the reach on Waiehu Stream between altitudes of 190 and 20 ft.

Waihe‘e River

Selected duration discharges (Q_{50}, Q_{70}, and Q_{90}) for Waihe‘e River near altitudes of 590, 390, and 45 ft were determined for diversion intake capacities of 0 to 39 Mgal/d (0 to 60 ft^3/s) for the Waihe‘e Ditch; 0 to 39 Mgal/d (0 to 60 ft^3/s) for Spreckels Ditch; and 0 or 3.2 Mgal/d (0 or 5 ft^3/s) for the Field 1 intake (figs. 47–48). The intake capacity for the Field 1 diversion is unknown and, thus, the use of 3.2 Mgal/d (5 ft^3/s) for the intake capacity of the Field 1 intake is arbitrary. For each duration discharge (Q_{50}, Q_{70}, or Q_{90}) near altitudes of 390 and 45 ft, a family of curves, with each curve corresponding to a particular flow near an altitude of 390 ft (fig. 47*B*) or near the coast at an altitude of 45 ft (fig. 48), was developed to show the relation between diversion intake capacities and streamflow.

Using the approximate diversion capacity settings of 40 Mgal/d (62 ft^3/s) for the Waihe‘e Ditch and 12 Mgal/d (18 ft^3/s) for Spreckels Ditch (Suzuki, 2007), estimated median streamflows near altitudes of 390 and 45 ft are zero (figs. 47–48). Thus, if both Waihe‘e and Spreckels Ditches divert at their reported capacities and no water is returned to Waihe‘e River, then zero flow may occur at least 50 percent of the time downstream of the Spreckels Ditch intake (assuming no subsurface leakage immediately downstream of existing diversion structures contributes to streamflow).

Combinations of diversion intake capacities that result in a specified flow near the coast at an altitude of 45 ft can be estimated using the family of curves (fig. 48). For example, to maintain a median flow of 12.9 Mgal/d (20 ft^3/s) near an altitude of 45 ft, assuming no water is diverted at the Field 1 intake, different combinations of diversion intake capacities for

Waiheʻe and Spreckels Ditches equal to 19.6 Mgal/d (30.4 ft^3/s) are possible (see fig. 48*A*, Q_{50}). Thus, if the intake capacity for the Waiheʻe Ditch is19.6 Mgal/d (30.4 ft^3/s) and no water is diverted by Spreckels Ditch or the Field 1 intake, then the estimated median flow is 12.9 Mgal/d (20 ft^3/s) near an altitude of 45 ft (fig. 48*A*, Q_{50}). Similarly, if the intake capacities for the Waiheʻe and Spreckels Ditches are each 9.8 Mgal/d (15.2 ft^3/s), then the estimated median flow remains 12.9 Mgal/d (20 ft^3/s) near an altitude of 45 ft (fig. 48*A*). For combinations of diversion intake capacities from Waiheʻe and Spreckels Ditches equal to 19.6 Mgal/d (30.4 ft^3/s), the corresponding Q_{70} and Q_{90} discharges near an altitude of 45 ft, assuming no water is diverted at the Field 1 intake, are estimated to be about 7.8 and 3.2 Mgal/d (12.0 and 5.0 ft^3/s), respectively (fig. 48*A*).

Waiehu Stream

To estimate the streamflow in Waiehu Stream downstream of diversions from North and South Waiehu Streams, natural flows (upstream of all diversions) in each stream at common flow-duration percentiles were assumed to occur concurrently. Selected duration discharges (Q_{50}, Q_{70}, and Q_{90}) for Waiehu Stream near altitudes of 190 and 20 ft were determined for diversion intake capacities of 0 to 3.2 Mgal/d (0 to 5 ft^3/s) for North Waiehu Ditch, North Waiehu Stream; 0 to 3.2 Mgal/d (0 to 5 ft^3/s) for Spreckels Ditch, South Waiehu Stream; and 0 or 0.32 Mgal/d (0 or 0.5 ft^3/s) each for two existing private ʻauwai with intakes near altitudes of 620 and 570 ft, South Waiehu Stream (figs. 49–50). The diversion intake capacities for the two existing private ʻauwai are unknown and variable, depending on the condition of the intakes. For this study, the intake capacity of each private ʻauwai was assumed

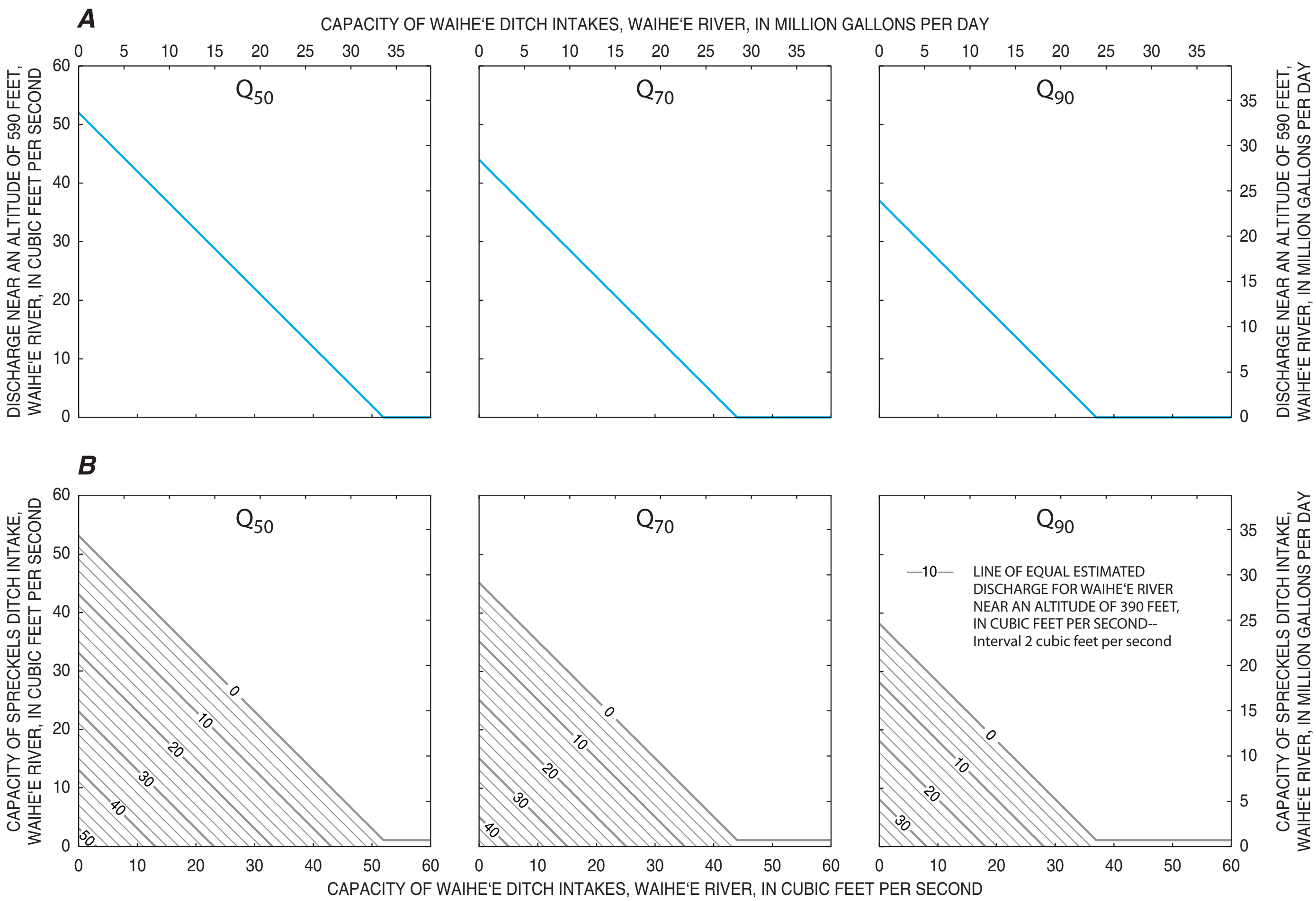


Figure 47. Estimated discharges (Q_{50}, Q_{70}, and Q_{90}) in Waiheʻe River, Maui, Hawaiʻi, resulting from diversions into the Waiheʻe Ditch and Spreckels Ditch with indicated hypothetical intake capacities. *A*, Near an altitude of 590 feet, downstream of the intakes for the Waiheʻe Ditch. *B*, Near an altitude of 390 feet, downstream of the intake for Spreckels Ditch. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

to be either 0 or 0.32 Mgal/d (0 or 0.5 ft^3/s), which generally represents the range of available measured diversion rates during this study (table 12). For each duration discharge (Q_{50}, Q_{70}, or Q_{90}) near altitudes of 190 and 20 ft, a family of curves, with each curve corresponding to a particular flow near an altitude of 190 ft (fig. 49) or near the coast at an altitude of 20 ft (fig. 50), was developed to show the relation between diversion intake capacities and streamflow.

Using the reported diversion capacity of 1.5 Mgal/d (2.3 ft^3/s) for the North Waiehu Ditch (Suzuki, 2007) and a diversion intake capacity of 1.3 Mgal/d (2 ft^3/s) for Spreckels Ditch, estimated median streamflows in Waiehu Stream near altitudes of 190 and 20 ft were about a third of the values for natural, undiverted conditions (assuming no water is returned to the stream, no water is diverted by each of the two existing private ʻauwai on South Waiehu Stream, and no leakage immediately downstream of diversion structures contributes to streamflow) (figs. 49–50). Using the reported diversion capacity of 1.5 Mgal/d (2.3 ft^3/s) for the North Waiehu Ditch (Suzuki, 2007), diversion intake capacities of 0.32 Mgal/d (0.5 ft^3/s) each for two existing private ʻauwai with intakes near altitudes of 620 and 570 ft in South Waiehu Stream, and a diversion intake capacity of 1.3 Mgal/d (2 ft^3/s) for Spreckels Ditch, estimated median streamflows in Waiehu Stream near altitudes of 190 and 20 ft were less than 1 Mgal/d (1.5 ft^3/s) (assuming no water is returned to the stream) (figs. 49–50). For these diversion intake capacities, Waiehu Stream may have zero flow at least 30 percent of the time near an altitude of 20 ft (fig. 50*B*). Even for the case of no diversions, available data indicate that Waiehu Stream near an altitude of 20 ft may have zero flow between 1 and 5 percent of the time (table 19).

Combinations of diversion intake capacities that result in a specified flow near the coast at an altitude of 20 ft can be estimated using the family of curves (fig. 50). For example, to maintain a median flow of 0.65 Mgal/d (1 ft^3/s) near an altitude of 20 ft, assuming diversion intake capacities of 0.32 Mgal/d (0.5

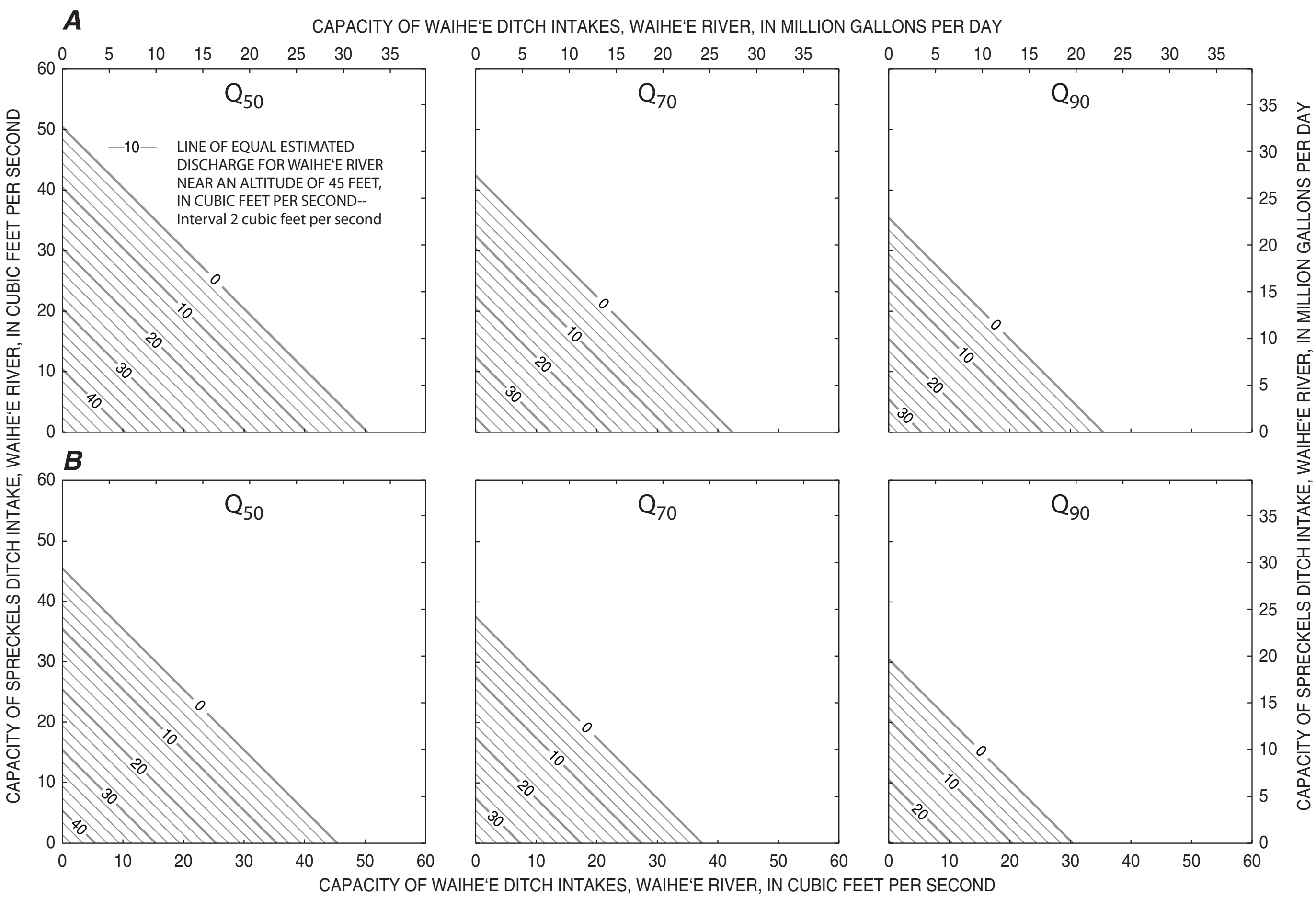


Figure 48. Estimated discharges (Q_{50}, Q_{70}, and Q_{90}) in Waiheʻe River near an altitude of 45 feet, Maui, Hawaiʻi, resulting from diversions into the Waiheʻe Ditch and Spreckels Ditch with indicated hypothetical intake capacities. *A*, Zero diversion into the Field 1 intake. *B*, Diversion capacity of 3.2 million gallons per day (5 cubic feet per second) for the Field 1 intake. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

ft^3/s) each for the two existing private ‘auwai with intakes near altitudes of 620 and 570 ft in South Waiehu Stream, different combinations of diversion intake capacities for North Waiehu and Spreckels Ditches are possible (see fig. 50*B*, Q_{50}). For a diversion intake capacity of 0.85 Mgal/d (1.31 ft^3/s) for North Waiehu Ditch and diversion intake capacities of 0.32 Mgal/d (0.5 ft^3/s) each for the two existing private ‘auwai in South Waiehu Stream, a diversion intake capacity of at least 1.60 Mgal/d (2.48 ft^3/s) for Spreckels Ditch will result in a median flow of 0.65 Mgal/d (1 ft^3/s) near an altitude of 20 ft. Diversion intake capacities greater than 1.60 Mgal/d (2.48 ft^3/s) for Spreckels Ditch cause median flow in South Waiehu Stream to be zero downstream of the Spreckels Ditch intake, and, thus, diversion intake capacities greater than 1.60 Mgal/d (2.48 ft^3/s) for Spreckels Ditch do not reduce further the low flow in Waiehu Stream. This is shown by the vertical lines (fig. 50*B*, Q_{50}) for diversion intake capacities greater than 1.60 Mgal/d (2.48 ft^3/s) for Spreckels Ditch. For a diversion intake capacity of at least 1.94 Mgal/d (3.00 ft^3/s) for North Waiehu Ditch and diversion intake capacities of 0.32 Mgal/d (0.5 ft^3/s) each for the two existing private ‘auwai in South Waiehu Stream, a diversion intake capacity of 0.76 Mgal/d (1.18 ft^3/s) for Spreckels Ditch also will result in a median flow of 0.65 Mgal/d (1 ft^3/s) near an altitude of 20 ft. Diversion intake capacities greater than 1.94 Mgal/d (3.00 ft^3/s) for North Waiehu Ditch cause flow in North Waiehu Stream to be zero downstream of an altitude of 280 ft, and, thus, diversion intake capacities greater than 1.94 Mgal/d (3.00 ft^3/s) for North Waiehu Ditch do not reduce further the low flow in Waiehu Stream. This is shown by the horizontal lines (fig. 50*B*, Q_{50}) for diversion intake intake capacities greater than 1.94 Mgal/d (3.00 ft^3/s) for North Waiehu Ditch. For diversion intake capacities that result in a median discharge of 0.65 Mgal/d (1 ft^3/s) near an altitude of 20 ft, (1) the estimated Q_{70} discharge near an altitude of 20 ft ranges from zero to 0.14 Mgal/d (0.21 ft^3/s), depending on the diversion intake capacities of North Waiehu and Spreckels Ditches, and (2) the estimated Q_{90} discharge near an altitude of 20 ft is zero (fig. 50*B*).

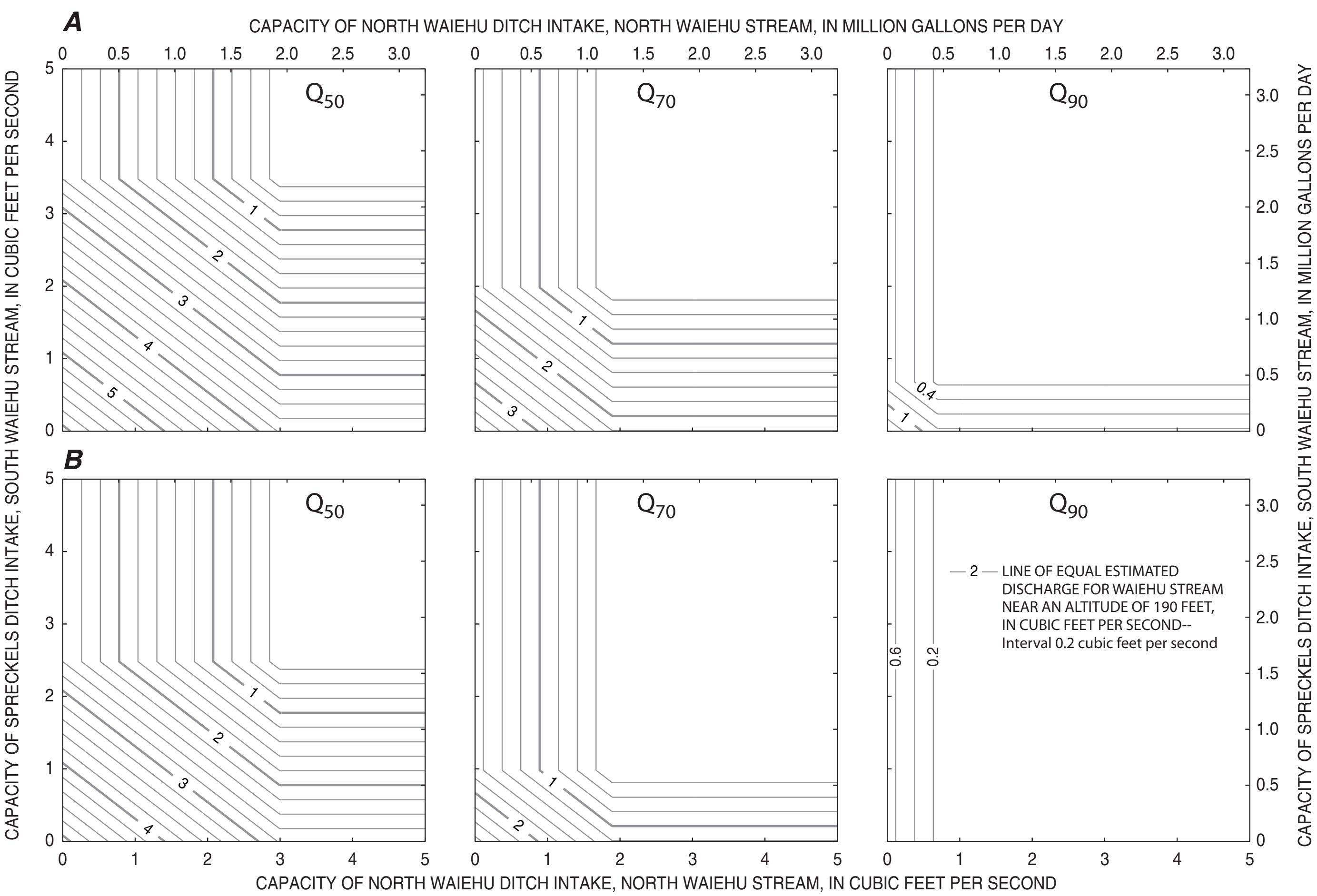


Figure 49. Estimated discharges (Q_{50}, Q_{70}, and Q_{90}) in Waiehu Stream near an altitude of 190 feet, Maui, Hawai‘i, resulting from diversions into the North Waiehu Ditch and Spreckels Ditch with indicated hypothetical intake capacities. *A*, Zero diversion into two private ‘auwai (ditches) near altitudes of 620 and 570 feet, South Waiehu Stream. *B*, Combined diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for two private ‘auwai near altitudes of 620 and 570 feet, South Waiehu Stream. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

ʻĪao Stream

Selected duration discharges (Q_{50}, Q_{70}, and Q_{90}) for ʻĪao Stream near altitudes of 220 and 35 ft were determined for diversion intake capacities of 0 to 26 Mgal/d (0 to 40 ft^3/s) for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches; 0 to 26 Mgal/d (0 to 40 ft^3/s) for Spreckels Ditch; and 0 or 0.65 Mgal/d (0 or 1 ft^3/s) for an existing private ʻauwai with an intake at an altitude of about 650 ft (figs. 51–52). The diversion intake capacity for the existing private ʻauwai is unknown but much less than the current diversion intake capacities for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and Spreckels Ditch. The range selected for the private ʻauwai covers the range of available measured diversion rates (table 12). For each duration discharge (Q_{50}, Q_{70}, or Q_{90}) near altitudes of 220 and 35 ft, a family of curves, with each curve corresponding to a particular flow near an altitude of 220 ft (fig. 51) or near the coast at an altitude of 35 ft (fig. 52), was developed to show the relation between diversion intake capacities and streamflow.

Using the reported diversion capacity for the common intake of the ʻĪao-Waikapū and ʻĪao-Māniania Ditches of 20 Mgal/d (31 ft^3/s) (Suzuki, 2007) and a diversion intake capacity of 3.9 Mgal/d (6 ft^3/s) for Spreckels Ditch, estimated median streamflows near altitudes of 220 and 35 ft are zero, assuming no water is returned to the stream (figs. 51–52). For the case of no diversions, ʻĪao Stream near an altitude of 35 ft is estimated to have a Q_{99} flow of 3.4 Mgal/d (5.2 ft^3/s) (table 20).

Combinations of diversion intake capacities that result in a specified flow near the coast at an altitude of 35 ft can be estimated using the family of curves (fig. 52). For example, to maintain a median flow of 6.5 Mgal/d (10 ft^3/s) near an altitude of 35 ft, assuming an intake capacity of 0.65 Mgal/d (1 ft^3/s) for the private ʻauwai near an altitude of 650 ft, different combinations of diversion intake capacities for the

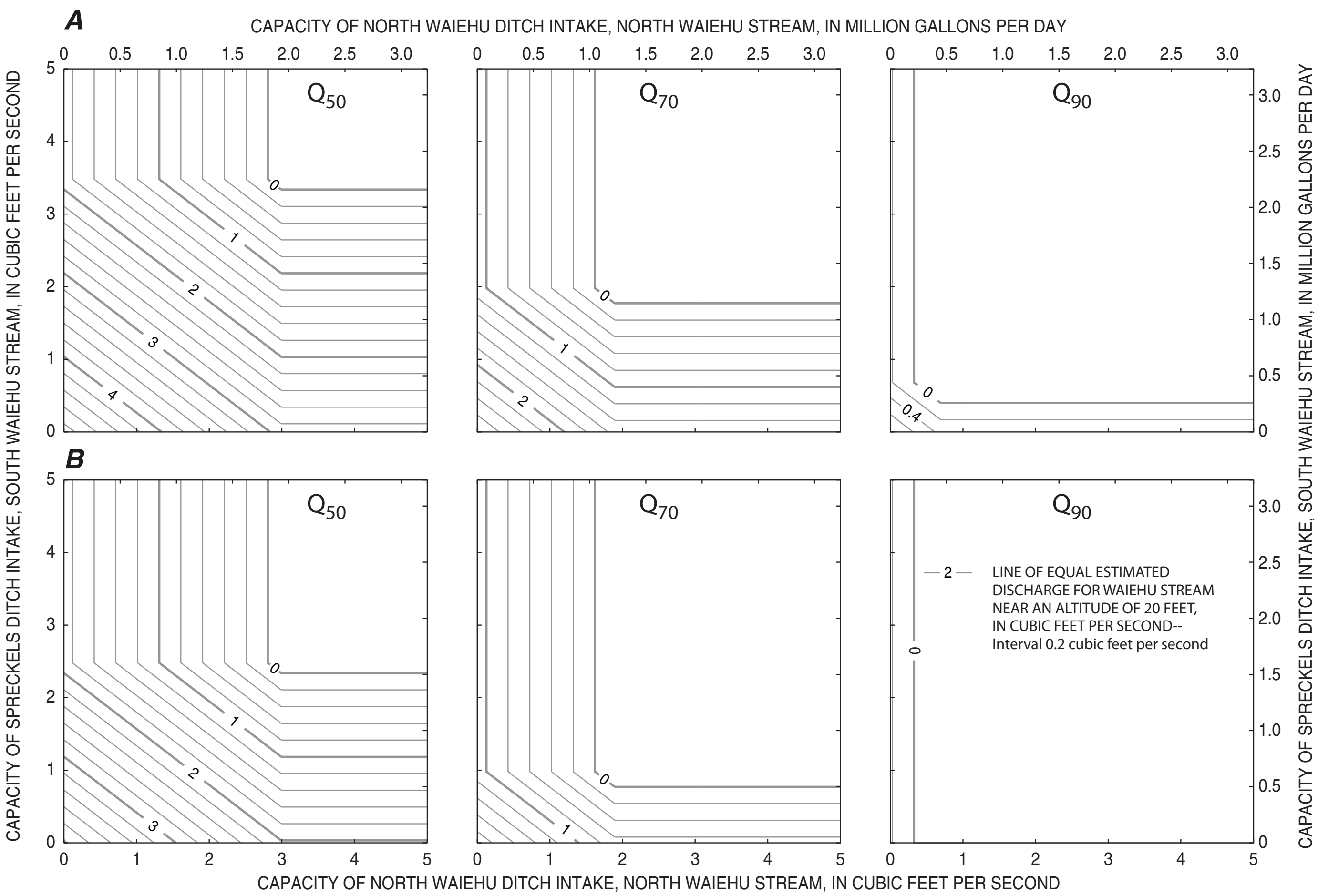


Figure 50. Estimated discharges (Q_{50}, Q_{70}, and Q_{90}) in Waiehu Stream near an altitude of 20 feet, Maui, Hawaiʻi, resulting from diversions into the North Waiehu Ditch and Spreckels Ditch with indicated hypothetical intake capacities. *A*, Zero diversion into two private ʻauwai (ditches) near altitudes of 620 and 570 feet, South Waiehu Stream. *B*, Combined diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for two private ʻauwai near altitudes of 620 and 570 feet, South Waiehu Stream. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

ʻĪao-Waikapū and ʻĪao-Māniania Ditches and Spreckels Ditch equal to 14.2 Mgal/d (21.9 ft^3/s) are possible (see fig. 52*B*, Q_{50}). All combinations of diversion intake capacities that result in a median flow of 6.5 Mgal/d (10 ft^3/s) near an altitude of 35 ft result in Q_{70} and Q_{90} discharges near an altitude of 35 ft of zero (fig. 52).

Waikapū Stream

Selected duration discharges (Q_{50}, Q_{70}, and Q_{90}) for Waikapū Stream near an altitude of 400 ft were determined for diversion intake capacities of 0 to 6.5 Mgal/d (0 to 10 ft^3/s) for the South Side Ditch; 0 to 6.5 Mgal/d (0 to 10 ft^3/s) for the combined capacity of a private ʻauwai with an intake near an altitude of 560 ft, Waiheʻe Ditch, and the Reservoir 6 diversion; and 0 or 0.65 Mgal/d (0 or 1 ft^3/s) for Everett Ditch. The diversion intake capacity of the Everett Ditch is unknown and, thus, values that cover the range of available measured diversion rates (table 12) were used. For each duration discharge (Q_{50}, Q_{70}, or Q_{90}) near an altitude of 400 ft, a family of curves, with each curve corresponding to a particular flow near an altitude of 400 ft (fig. 53), was developed to show the relation between diversion intake capacities and streamflow.

For natural-flow conditions, Waikapū Stream may flow continuously to an altitude of 400 ft, although the estimated median flow downstream near an altitude of 40 ft is zero (table 21). Using the reported diversion capacity of the South Side Ditch of 3 Mgal/d (4.6 ft^3/s) (Suzuki, 2007) and a combined diversion intake capacity of at least 2.6 Mgal/d (4 ft^3/s) for the private ʻauwai near an altitude of 560 ft, Waiheʻe Ditch, and the Reservoir 6 diversion, the estimated median flow near an altitude of 400 ft is zero, assuming no water is returned to the stream (fig. 53).

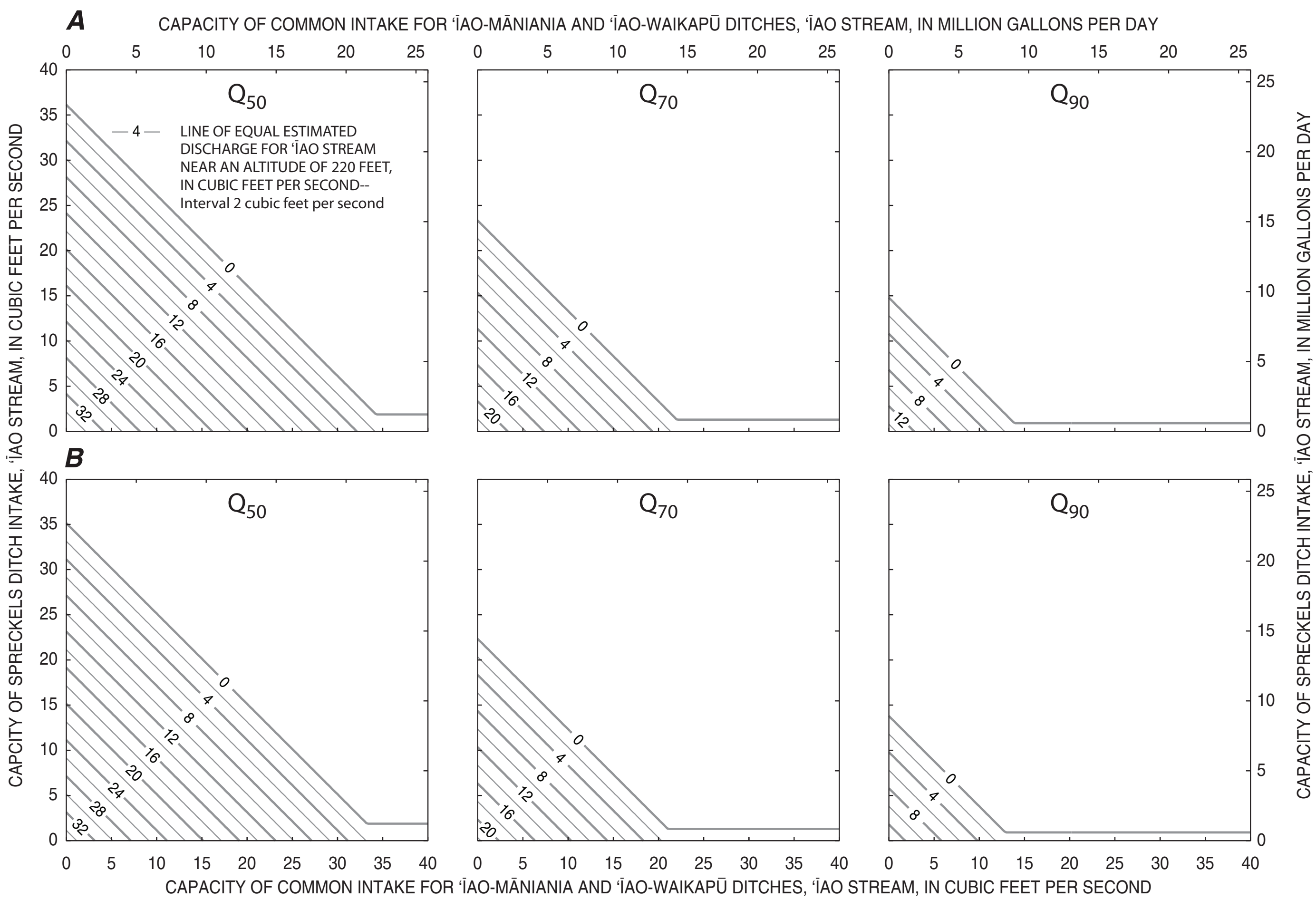


Figure 51. Estimated discharges (Q_{50}, Q_{70}, and Q_{90}) in ʻĪao Stream near an altitude of 220 feet, Maui, Hawaiʻi, resulting from diversions into the ʻĪao-Māniania and ʻĪao-Waikapū Ditches and Spreckels Ditch with indicated hypothetical intake capacites. *A*, Zero diversion into a private ʻauwai (ditch) near an altitude of 650 feet. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for a private ʻauwai near an altitude of 650 feet. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

Combinations of diversion intake capacities that result in a specified flow near an altitude of 400 ft can be estimated using the family of curves (fig. 53). For example, to maintain a median flow of 1.3 Mgal/d (2 ft^3/s) near an altitude of 400 ft, assuming a diversion intake capacity of 0.65 Mgal/d (1 ft^3/s) for the Everett Ditch, different combinations of the diversion intake capacity for the South Side Ditch and combined diversion intake capacity for the private ʻauwai near an altitude of 560 ft, Waiheʻe Ditch, and the Reservoir 6 diversion are possible (see fig. 53*B*, Q_{50}). Thus, if the intake capacity for the South Side Ditch is 3.32 Mgal/d (5.13 ft^3/s) and no water is diverted by the private ʻauwai near an altitude of 560 ft, Waiheʻe Ditch, and the Reservoir 6 diversion, then the estimated median flow is 1.3 Mgal/d (2 ft^3/s) near an altitude of 400 ft (fig. 53*B*, Q_{50}). Similarly, if the intake capacity for the South Side Ditch is 1.66 Mgal/d (2.56 ft^3/s) and the combined intake capacity for the private ʻauwai near an altitude of 560 ft, Waiheʻe Ditch, and the Reservoir 6 diversion also is 1.66 Mgal/d (2.56 ft^3/s), then the estimated median flow remains 1.3 Mgal/d (2 ft^3/s) near an altitude of 400 ft (fig. 53*B*). For diversion intake capacities that result in a median discharge of 1.3 Mgal/d (2 ft^3/s) near an altitude of 400 ft, (1) the estimated Q_{70} discharge near an altitude of 400 ft is 0.26 Mgal/d (0.40 ft^3/s) and (2) the estimated Q_{90} discharge near an altitude of 400 ft ranges from zero to 0.16 Mgal/d (0.25 ft^3/s), depending on the diversion intake capacity of the South Side Ditch and combined diversion intake capacity for the private ʻauwai near an altitude of 560 ft, Waiheʻe Ditch, and the Reservoir 6 diversion (fig. 53*B*).

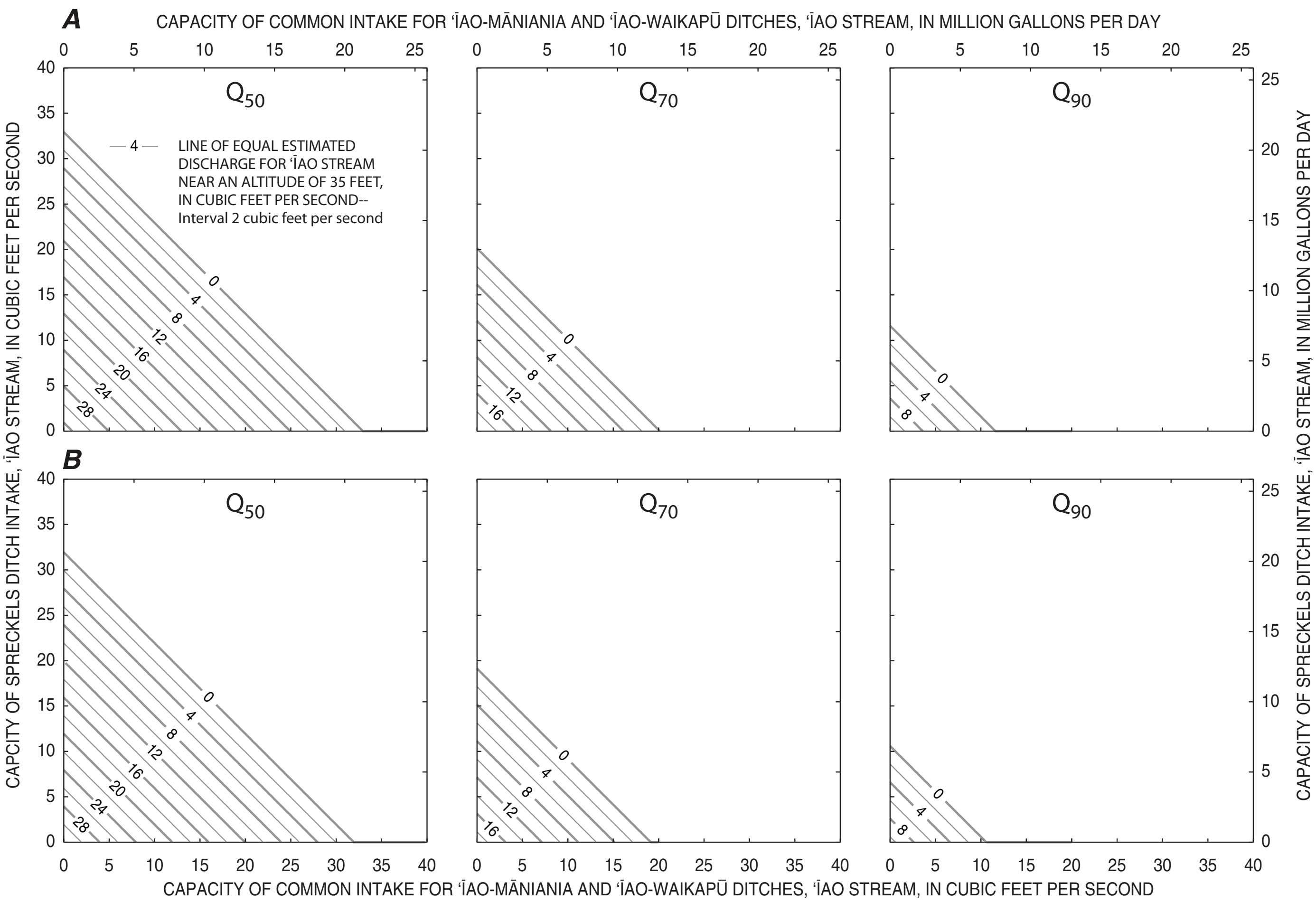


Figure 52. Estimated discharges (Q_{50}, Q_{70}, and Q_{90}) in ʻĪao Stream near an altitude of 35 feet, Maui, Hawaiʻi, resulting from diversions into the ʻĪao-Māniania and ʻĪao-Waikapū Ditches and Spreckels Ditch with indicated hypothetical intake capacites. *A*, Zero diversion into a private ʻauwai (ditch) near an altitude of 650 feet. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for a private ʻauwai near an altitude of 650 feet. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

Ditch-Flow Relations

The flow characteristics for a ditch system are dependent on the streamflow characteristics immediately upstream of the diversion intake, as well as on the diversion intake capacity. For this study, diversions are assumed to be capable of diverting water at a rate up to, but not exceeding, the diversion intake capacity. If streamflow immediately upstream of an intake is less than or equal to the intake capacity, all available streamflow is assumed to be diverted. For the purposes of this study, none of the diverted water is assumed to return to the stream and the intake capacity of a diversion is assumed to be unaffected by water, possibly derived from another stream, already in the ditch system.

Waiheʻe River

The Waiheʻe Ditch is the uppermost surface-water diversion on Waiheʻe River. Estimated duration discharges for the Waiheʻe Ditch are equal to the diversion intake capacity, but do not exceed the corresponding duration discharges for Waiheʻe River immediately upstream of the intake (fig. 54*A*). For example, the median (Q_{50}) discharge for the Waiheʻe Ditch increases linearly, at a one-to-one slope, as the intake capacity is assumed to increase (fig. 54*A*). However, the median discharge for Waiheʻe Ditch is limited by the median discharge in Waiheʻe River immediately upstream of the diversion intake. If the diversion intake capacity equals or exceeds the

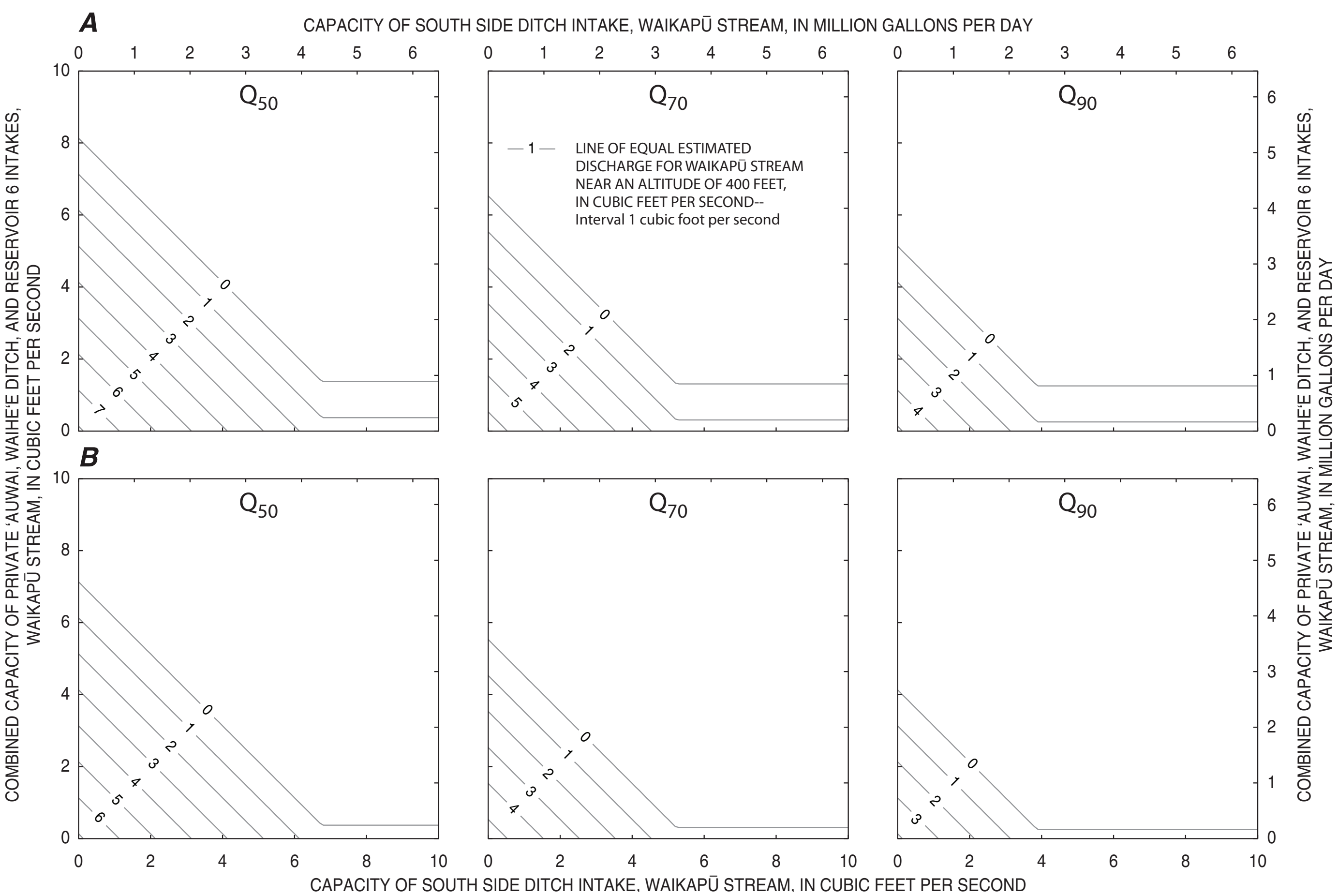


Figure 53. Estimated discharges (Q_{50}, Q_{70}, and Q_{90}) in Waikapū Stream near an altitude of 400 feet, Maui, Hawaiʻi, resulting from diversion into the South Side Ditch and combined diversions into a private ʻauwai (ditch) near an altitude of 560 feet, Waiheʻe Ditch, and Reservoir 6 Ditch with indicated hypothetical intake capacities. *A*, Zero diversion into Everett Ditch. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for Everett Ditch. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

median discharge in Waihe‘e River immediately upstream of the intake (34 Mgal/d; 52 ft^3/s), the median discharge for Waihe‘e Ditch is equal to the median discharge in Waihe‘e River (34 Mgal/d; 52 ft^3/s). Similar relations among diversion intake capacity, streamflow characteristics, and ditch-flow characteristics exist for other duration discharges, including the Q_{70} and Q_{90} discharges (fig. 54*A*).

The Spreckels Ditch is downstream of the Waihe‘e Ditch. Thus, water available for diversion by the Spreckels Ditch is dependent not only on the diversion intake capacity of Spreckels Ditch, but also on the characteristics of the upstream diversion and streamflow gains in the intervening reach. A family of curves, with each curve corresponding to a particular flow in Spreckels Ditch, was developed to show the relation between diversion intake capacities and selected duration discharges (Q_{50}, Q_{70}, and Q_{90}) for Spreckels Ditch (fig. 54*B*).

Combinations of diversion intake capacities that result in a specified flow in Spreckels Ditch can be estimated using the family of curves (fig. 54*B*). For example, to maintain a median flow of 2.6 Mgal/d (4 ft^3/s) in Spreckels Ditch, different combinations of diversion intake capacities for Waihe‘e and Spreckels Ditches are possible (see fig. 54*B*, Q_{50}). If the intake capacity for the Waihe‘e Ditch is less than 32 Mgal/d (49 ft^3/s) and the intake capacity of Spreckels Ditch is 2.6 Mgal/d (4.0 ft^3/s), then the estimated median flow in Spreckels Ditch is 2.6 Mgal/d (4.0 ft^3/s). If the intake capacity for the Waihe‘e Ditch is equal to 32 Mgal/d (49 ft^3/s) and the intake capacity of Spreckels Ditch is greater than 2.6 Mgal/d (4.0 ft^3/s), then the estimated median flow in Spreckels Ditch also is 2.6 Mgal/d (4.0 ft^3/s).

If the diversion intake capacity for Waihe‘e Ditch exceeds the flow in Waihe‘e River immediately upstream of the intake, then the available flow for Spreckels Ditch is limited to the gain and tributary inflows that occur in the reach between the two diversions. The curves (fig. 54*B*) change from horizontal to vertical lines at a point at which zero flow is expected to occur immediately downstream of the Spreckels Ditch

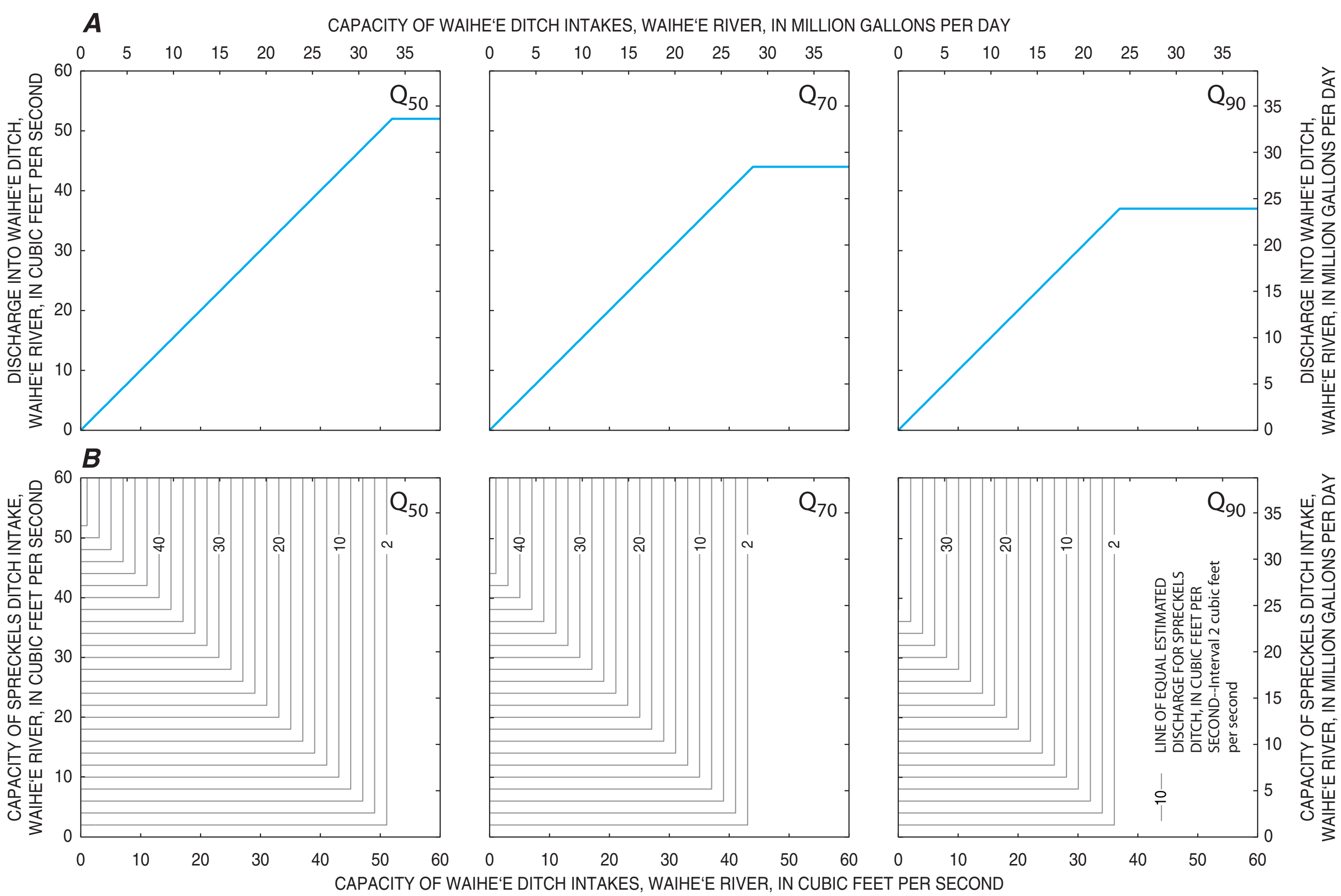


Figure 54. Estimated diversion discharges (Q_{50}, Q_{70}, and Q_{90}) for the Waihe‘e Ditch and Spreckels Ditch, Waihe‘e River, Maui, Hawai‘i, for indicated intake capacities. *A*, Waihe‘e Ditch. *B*, Spreckels Ditch. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

diversion intake (ignoring any subsurface leakage immediately downstream of the Spreckels Ditch dam that may contribute to streamflow downstream of the intake for Spreckels Ditch).

Waiehu Stream

The North Waiehu Ditch is the only known existing surface-water diversion on North Waiehu Stream. Estimated duration discharges for the North Waiehu Ditch are equal to the diversion intake capacity but do not exceed the corresponding duration discharges for North Waiehu Stream immediately upstream of the intake (fig. 55*A*). For example, the median (Q_{50}) discharge for the North Waiehu Ditch increases linearly, at a one-to-one slope, as the intake capacity increases (fig. 55*A*). However, the median discharge for North Waiehu Ditch is limited by the median discharge in North Waiehu Stream immediately upstream of the diversion intake. If the diversion intake capacity equals or exceeds the median discharge in North Waiehu Stream immediately upstream of the intake (3.2 Mgal/d; 4.9 ft^3/s) (table 19), the median discharge for North Waiehu Ditch is equal to the median discharge in North Waiehu Stream (3.2 Mgal/d; 4.9 ft^3/s). Similar relations among diversion intake capacity, streamflow characteristics, and ditch-flow characteristics exist for other duration discharges, including the Q_{70} and Q_{90} discharges (fig. 55*A*).

The Spreckels Ditch is downstream of two private ‘auwai on South Waiehu Stream. Thus, water diverted by the

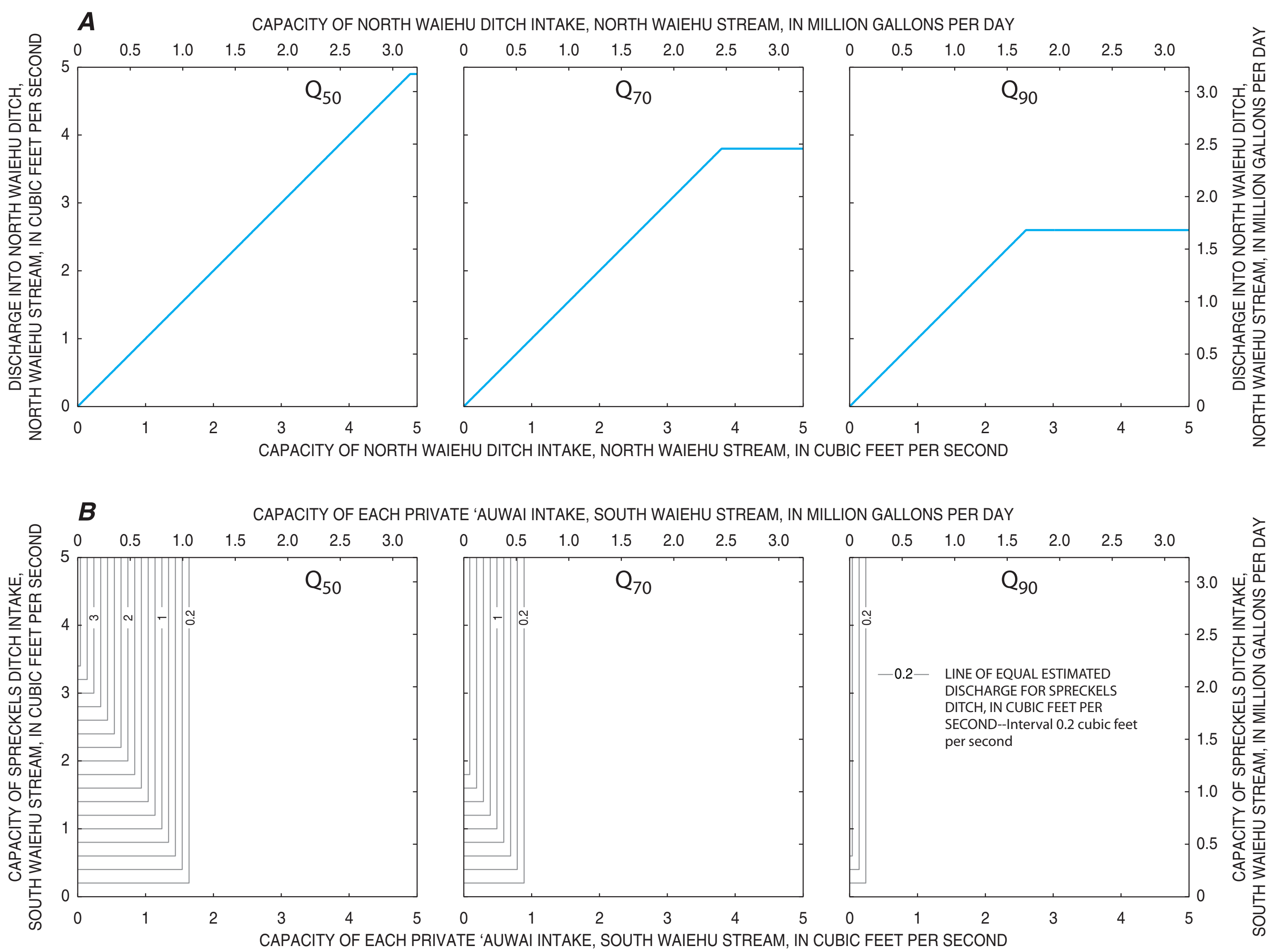


Figure 55. Estimated diversion discharges (Q_{50}, Q_{70}, and Q_{90}) for the North Waiehu Ditch, North Waiehu Stream, and Spreckels Ditch, South Waiehu Stream, Maui, Hawai‘i, for indicated intake capacities. *A*, North Waiehu Ditch. *B*, Spreckels Ditch. Two private ‘auwai (ditches), near altitudes of 620 and 570 feet, exist upstream of the Spreckels Ditch intake on South Waiehu Stream. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

Spreckels Ditch is dependent not only on the diversion intake capacity of Spreckels Ditch, but also on the characteristics of the upstream diversions. A family of curves, with each curve corresponding to a particular flow diverted into Spreckels Ditch from South Waiehu Stream, was developed to show the relation between diversion intake capacities and selected duration discharges (Q_{50}, Q_{70}, and Q_{90}) for Spreckels Ditch (fig. 55*B*). Because South Waiehu Stream loses water in the reach between the downstream private ʻauwai and Spreckels Ditch, the available flow for Spreckels Ditch is estimated to be zero if the capacities of the private ʻauwai exceed the streamflow of South Waiehu Stream. The curves (fig. 55*B*) change from horizontal to vertical lines at a point at which zero flow is expected to occur immediately downstream of the Spreckels Ditch diversion intake (ignoring any subsurface leakage immediately downstream of the Spreckels Ditch dam that may contribute to streamflow downstream of the intake for Spreckels Ditch).

ʻĪao Stream

The common intake of the ʻĪao-Waikapū and ʻĪao-Māniania Ditches is the uppermost surface-water diversion intake on ʻĪao Stream. Estimated duration discharges for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches are equal to the diversion intake capacity but do not exceed the corresponding duration discharges for ʻĪao Stream immediately upstream of the intake (plot not shown).

The Spreckels Ditch is downstream of the common intake of the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and a private ʻauwai. Thus, water available for diversion by the Spreckels Ditch is dependent on the diversion intake capacity of Spreckels Ditch, the characteristics of the upstream diversions, and streamflow losses in the intervening reaches. A family of curves, with each curve corresponding to a particular flow into Spreckels Ditch, was developed to show the relation between diversion intake capacities and selected duration discharges (Q_{50}, Q_{70}, and

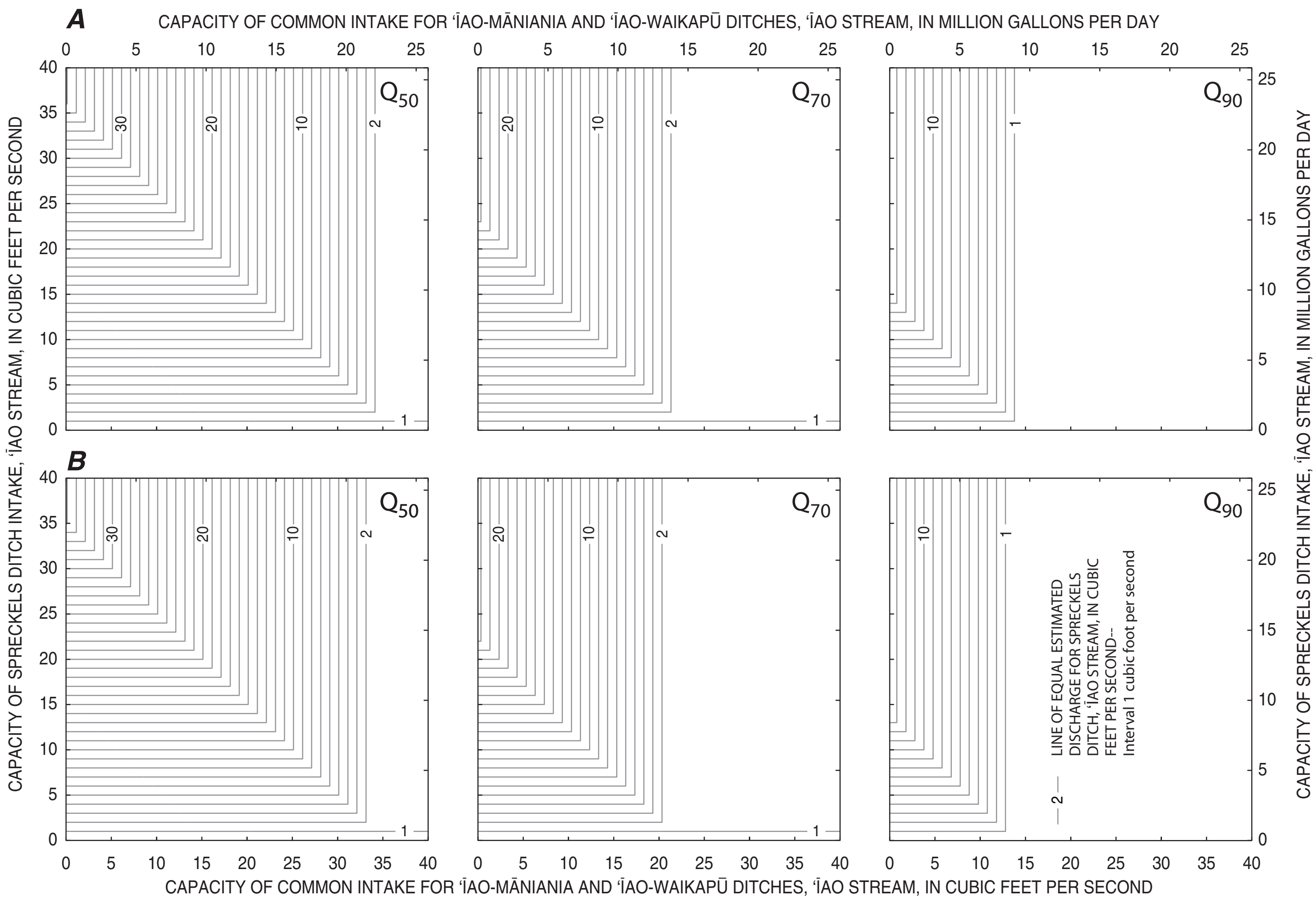


Figure 56. Estimated diversion discharges (Q_{50}, Q_{70}, and Q_{90}) for the Spreckels Ditch, ʻĪao Stream, Maui, Hawaiʻi, for indicated intake capacities. *A*, Zero diversion into a private ʻauwai (ditch) near an altitude of 650 feet. *B*, Diversion of 0.65 million gallons per day (1 cubic foot per second) into a private ʻauwai near an altitude of 650 feet. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

Q_{90}) for Spreckels Ditch (fig. 56). The curves (fig. 56) change from horizontal to vertical lines at a point at which zero flow is expected to occur immediately downstream of the Spreckels Ditch diversion intake (ignoring any leakage that may contribute to streamflow downstream of Spreckels Ditch). The diversion intake capacity for the existing private ‘auwai is unknown but much less than the current diversion intake capacities for the ‘Īao-Waikapū and ‘Īao-Māniania Ditches and Spreckels Ditch. For this study, the intake capacity of the private ‘auwai was assumed to be either 0 (fig. 56*A*) or 0.65 Mgal/d (1 ft^3/s) (fig. 56*B*), which covers the range of available measured diversion rates.

Waikapū Stream

The South Side Ditch is the uppermost surface-water diversion intake on Waikapū Stream. Estimated duration discharges for the South Side Ditch are equal to the diversion intake capacity but do not exceed the corresponding duration discharges for Waikapū Stream immediately upstream of the intake (plot not shown).

The diversion intakes for the private ‘auwai near an altitude of 560 ft, Waihe‘e Ditch, and the Reservoir 6 diversion are downstream of the diversion intakes for the South Side and Everett Ditches. Thus, water available for diversion by the private ‘auwai, Waihe‘e Ditch, and the Reservoir 6 diversion is dependent not only on the diversion intake capacities of these systems, but also on the characteristics of the upstream diversions and streamflow losses in the intervening reaches. A family of curves, with each curve corresponding to a particular combined flow into the private ‘auwai near an altitude of 560 ft, Waihe‘e Ditch, and the Reservoir 6 diversion, was developed to show the relation between diversion intake capacities and selected duration discharges (Q_{50}, Q_{70}, and Q_{90}) for these diversions (fig. 57). The curves (fig. 57) change from horizontal to vertical lines at a point at which zero flow is expected to occur immediately downstream of the Reservoir 6 diversion intake (ignoring any leakage that may contribute to streamflow downstream of the Reservoir 6 intake). The diversion intake capacity of the Everett Ditch is unknown. For this study, the intake capacity of Everett Ditch was assumed to be either 0 (fig. 57*A*) or 0.65 Mgal/d (1 ft^3/s) (fig. 57*B*), which covers the range of available measured diversion rates.

Effects of Surface-Water Diversions on Recharge

For streams in which all of the dry-weather flow is diverted, infiltration of water in losing reaches downstream of diversions may be reduced to zero during dry-weather conditions. Dry stream reaches of varying lengths were observed in each of the Nā Wai ‘Ehā streams downstream of existing diversions during the 2006–2008 data-collection period. For natural, undiverted conditions, many of these same stream reaches would not be dry. Thus, these dry stream reaches created by diversions represent a potential loss of recharge to the underlying groundwater body. The loss of recharge immediately beneath diverted streams is offset to some extent by enhanced recharge associated with ditch transmission losses and reservoir seepage (Broadbent, 1988) or irrigation return flow (Engott and Vana, 2007), although the location where the recharge takes place will change. The effects of recharge distribution on the groundwater system can be evaluated using a numerical groundwater model that accounts for the spatial distribution of groundwater recharge (Gingerich, 2008).

The amount of recharge that takes place along losing stream reaches is dependent on a number of factors, including (1) the amount of flow available in the stream (the loss may be limited by the upstream flow), (2) the antecedent moisture of the channel sediments (dry antecedent conditions may be associated with high infiltration rates during the early period when a stream first begins to flow), (3) channel slope, geometry, and wetted perimeter, (4) the presence of a poorly permeable streambed-clogging layer of fine sedimentary materials or biofilm growth, which can be modified during periods of high flow, (5) the hydraulic properties of the sediments beneath and near the streambed, and (6) the presence of a shallow groundwater body near the stream (Sophocleous, 2002; Vázquez-Suñé and others, 2007). These factors may contribute to variability in measured gains or losses within a stream reach. Because the existing diversions have a reduced effect on potential groundwater recharge during periods of high flow, the effects of diversions on recharge are considered only for low-flow conditions.

The seepage-run measurements were used to develop relations between upstream and downstream flows of selected reaches in each stream (see section on “Seepage-Run Measurements” and figs. 32–39), and these relations were used to estimate the effects of surface-water diversions on recharge beneath the stream channels during low-flow conditions. The effects of the diversions on recharge were determined at selected upstream flows equal to and less than the median flow (Q_{50}, Q_{55}, Q_{60}, Q_{65}, Q_{70}, Q_{75}, Q_{80}, Q_{85}, Q_{90}, Q_{95}, and Q_{99}). The reductions in recharge were integrated to provide an overall estimate of the reduction in recharge during low-flow conditions. At each duration discharge, the recharge reduction was weighted by the percentage of time that flow occurs during low-flow conditions. The overall percentage of time that each selected flow occurs was determined to be half of the difference between duration percentiles of adjacent duration discharges. For example, the overall percentage of time that the Q_{55} flow was assumed to occur was equal to (60-50)/2, or 5 percent. Similarly, the overall percentage of time that the Q_{50} flow was assumed to occur was equal to (55-50)/2, or 2.5 percent. For this study, reductions in recharge were computed only for low-flow conditions and, thus, the overall percentage of time that each flow was assumed to occur was doubled. During low-flow conditions, when flow is less than the median flow, the Q_{50} flow occurs 5 (=2.5×2) percent of the time. Thus, for the Q_{50} flow, the recharge reduction was multiplied by 0.05 (equal to 5 percent of the time during low-flow conditions); for the Q_{55} to Q_{90} flows, the recharge reductions were multiplied by 0.1; for the Q_{95} flow, the recharge reduction was multiplied by 0.09; and for the Q_{99} flow, the recharge reduction was multiplied by 0.06. The sum of the weights is equal to 1, reflecting 100 percent of the time during low-flow conditions.

Diversion of surface water from a stream reduces the amount of water available for infiltration and recharge beneath the stream channel. Thus, as the capacity of the diversion intakes increase, the reduction in potential recharge generally increases. At some level of diversion intake capacity, the reach immediately downstream of the diversion may have zero flow, the effects of diversions on recharge reduction may reach a maximum value, and increased diversion intake capacity has no further effect on reducing recharge. The reported recharge reductions represent average values over periods when the upstream, undiverted flows are less than or equal to the median flow, which occurs 50 percent of the time. Also, for the purposes of this analysis, none of the diverted water is assumed to return to the stream and no leakage immediately downstream of diversion structures is assumed to contribute to streamflow.

Waiheʻe River

For natural, undiverted low-flow conditions, the estimated seepage loss from Waiheʻe River downstream of the intakes for the Waiheʻe Ditch is about 1.7 Mgal/d (2.7 ft^3/s). This seepage loss takes place entirely downstream of an altitude of 400 ft and represents potential groundwater recharge. The effects of diversions on recharge beneath

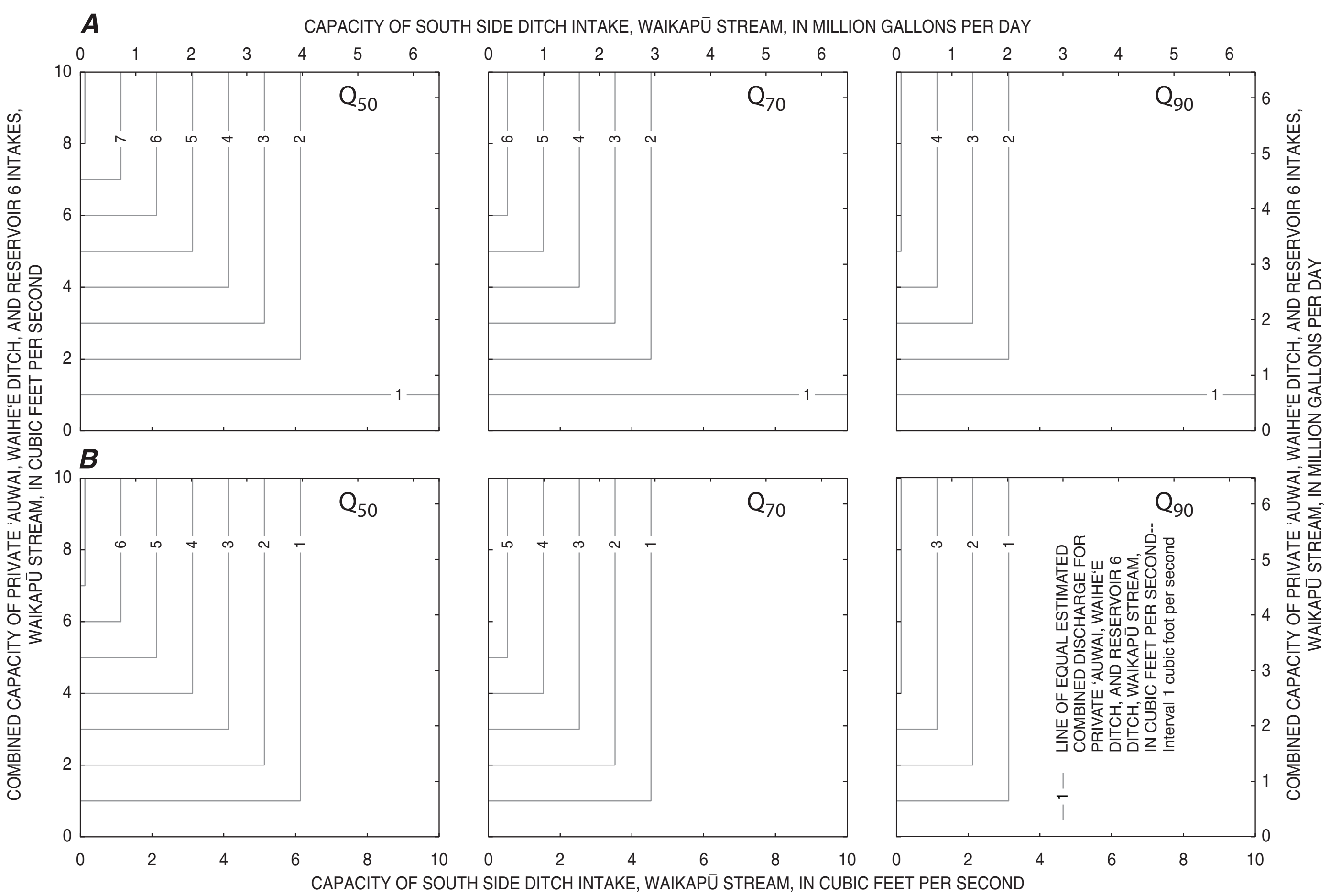


Figure 57. Estimated combined diversion discharges (Q_{50}, Q_{70}, and Q_{90}) for a private ʻauwai (ditch) near an altitude of 560 feet, Waiheʻe Ditch, and Reservoir 6 Ditch, Waikapū Stream, Maui, Hawaiʻi, for indicated intake capacities. *A*, Zero diversion into Everett Ditch. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for Everett Ditch. The Q_{50}, Q_{70}, and Q_{90} discharges represent the discharges that are equaled or exceeded 50, 70, and 90 percent of the time, respectively. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

Waiheʻe River were evaluated for diversion intake capacities of 0 to 39 Mgal/d (0 to 60 ft^3/s) for the Waiheʻe Ditch; 0 to 39 Mgal/d (0 to 60 ft^3/s) for Spreckels Ditch; and 0 or 3.2 Mgal/d (0 or 5 ft^3/s) for the Field 1 intake (fig. 58). The intake capacity for the Field 1 diversion is unknown and, thus, the use of 3.2 Mgal/d (5 ft^3/s) for the intake capacity of the Field 1 intake is arbitrary. The family of curves (fig. 58), with each curve corresponding to a selected value of groundwater-recharge reduction, shows the relation between capacities of the diversion intakes and recharge reduction. For the diversion intake capacities tested, the maximum overall reduction in recharge is 1.7 Mgal/d (2.7 ft^3/s) for different combinations of diversion intake capacities (fig. 58). The reduction in recharge represents the average value during low-flow conditions when the upstream, undiverted streamflow is less than the median flow. For combinations of diversion intake capacities up to about 17 Mgal/d (26 ft^3/s), the overall reduction in recharge may be zero (fig. 58). Overall reduction in recharge may be zero if available streamflow in reaches downstream of diversions exceeds maximum loss rates (and losses are assumed to be independent of streamflow).

Using the approximate diversion capacity settings of 40 Mgal/d (62 ft^3/s) for the Waiheʻe Ditch and 12 Mgal/d (18 ft^3/s) for Spreckels Ditch (Suzuki, 2007), and either 0 or 3.2 Mgal/d (0 or 5 ft^3/s) for the Field 1 intake, the estimated overall reduction in recharge is 1.7 Mgal/d (2.7 ft^3/s) (fig. 58). This reduction in recharge corresponds to the maximum estimated value. The reduction in recharge takes place downstream of the intake for Spreckels Ditch.

Waiehu Stream

For natural, undiverted low-flow conditions, the estimated seepage loss (potential groundwater recharge) from North Waiehu, South Waiehu, and Waiehu Streams downstream of an altitude of about 880 ft is about 2.9 Mgal/d (4.5 ft^3/s). About 83 percent of the seepage loss takes place upstream of an altitude of 280 ft, and the remaining 17 percent takes place downstream of an altitude of 190 ft.

To estimate the reduction in recharge caused by diversions from North and South Waiehu Streams, natural flows (upstream of all diversions) in each stream at common flow-duration percentiles were assumed to occur concurrently. The effects of diversions on recharge were evaluated for the following diversion intake capacities: 0 to 3.2 Mgal/d (0 to 5 ft^3/s) for North Waiehu Ditch, North Waiehu Stream; 0 to 3.2 Mgal/d (0 to 5 ft^3/s) for Spreckels Ditch, South Waiehu Stream; and 0 or 0.32 Mgal/d (0 or 0.5 ft^3/s) each for two existing private ʻauwai with intakes near altitudes of 620 and 570 ft, South Waiehu Stream. The diversion intake capacities for the two existing private ʻauwai are unknown and variable, depending on the condition of the intakes. For this study, the intake capacity of each private ʻauwai was assumed to be either 0 (fig. 59*A*) or 0.32 Mgal/d (0.5 ft^3/s) (fig. 59*B*), which generally represents the range of available measured diversion rates. The family of curves (fig. 59), with each curve corresponding to a selected value of groundwater-recharge reduction, shows the relation between capacities of the diversion intakes and recharge reduction. For the diversion intake capacities tested, the maximum overall reduction in recharge is 1.9 Mgal/d (3.0 ft^3/s) (fig. 59).

Using the reported diversion capacity of North Waiehu Ditch of 1.5 Mgal/d (2.3 ft^3/s) (Suzuki, 2007) and a diversion intake capacity of 1.3 Mgal/d (2.0 ft^3/s) for Spreckels Ditch, the overall reduction in recharge during low-flow periods is 1.0 Mgal/d (1.6 ft^3/s) if no water is diverted by each of the two existing private ʻauwai. Using the reported diversion capacity of North Waiehu Ditch of 1.5 Mgal/d (2.3 ft^3/s) (Suzuki, 2007) and a diversion intake capacity of 1.3 Mgal/d (2.0 ft^3/s) for Spreckels Ditch, the overall reduction in recharge during low-flow periods is 1.2 Mgal/d (1.8 ft^3/s) if 0.32 Mgal/d (0.5 ft^3/s) is diverted by each of the two existing private ʻauwai. For these diversion intake capacities, about 70 percent of the overall reduction in recharge takes place upstream of an altitude of 280 ft.

ʻĪao Stream

For natural, undiverted low-flow conditions, the estimated seepage loss (potential groundwater recharge) from ʻĪao Stream downstream of the common intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches is about 5.6 Mgal/d (8.7 ft^3/s). About 63 percent of the seepage loss takes place upstream of an altitude of 360 ft, and the remaining 37 percent takes place downstream of an altitude of 220 ft.

The effects of diversions on potential recharge beneath ʻĪao Stream were evaluated for the following diversion intake capacities: 0 to 26 Mgal/d (0 to 40 ft^3/s) for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches; 0 to 26 Mgal/d (0 to 40 ft^3/s) for Spreckels Ditch; and 0 or 0.65 Mgal/d (0 or 1 ft^3/s) for an existing private ʻauwai with an intake at an altitude of about 650 ft (fig. 60). The diversion intake capacity for the existing private ʻauwai is unknown but much less than the current diversion intake capacities for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and Spreckels Ditch. For this study, the intake capacity of the private ʻauwai was assumed to be either 0 (fig. 60*A*) or 0.65 Mgal/d (1 ft^3/s) (fig. 60*B*), which covers the range of available measured diversion rates. The family of curves (fig. 60), with each curve corresponding to a selected value of groundwater-recharge reduction, shows the relation between capacities of the diversion intakes and recharge reduction. For the diversion intake capacities tested, the maximum overall reduction in recharge is 5.3 Mgal/d (8.2 ft^3/s) for different combinations of diversion intake capacities (fig. 60). For combinations of diversion intake capacities up to about 3.2 Mgal/d (5 ft^3/s), the overall reduction in recharge may be zero (fig. 60). Overall reduction in recharge may be zero if available streamflow in reaches

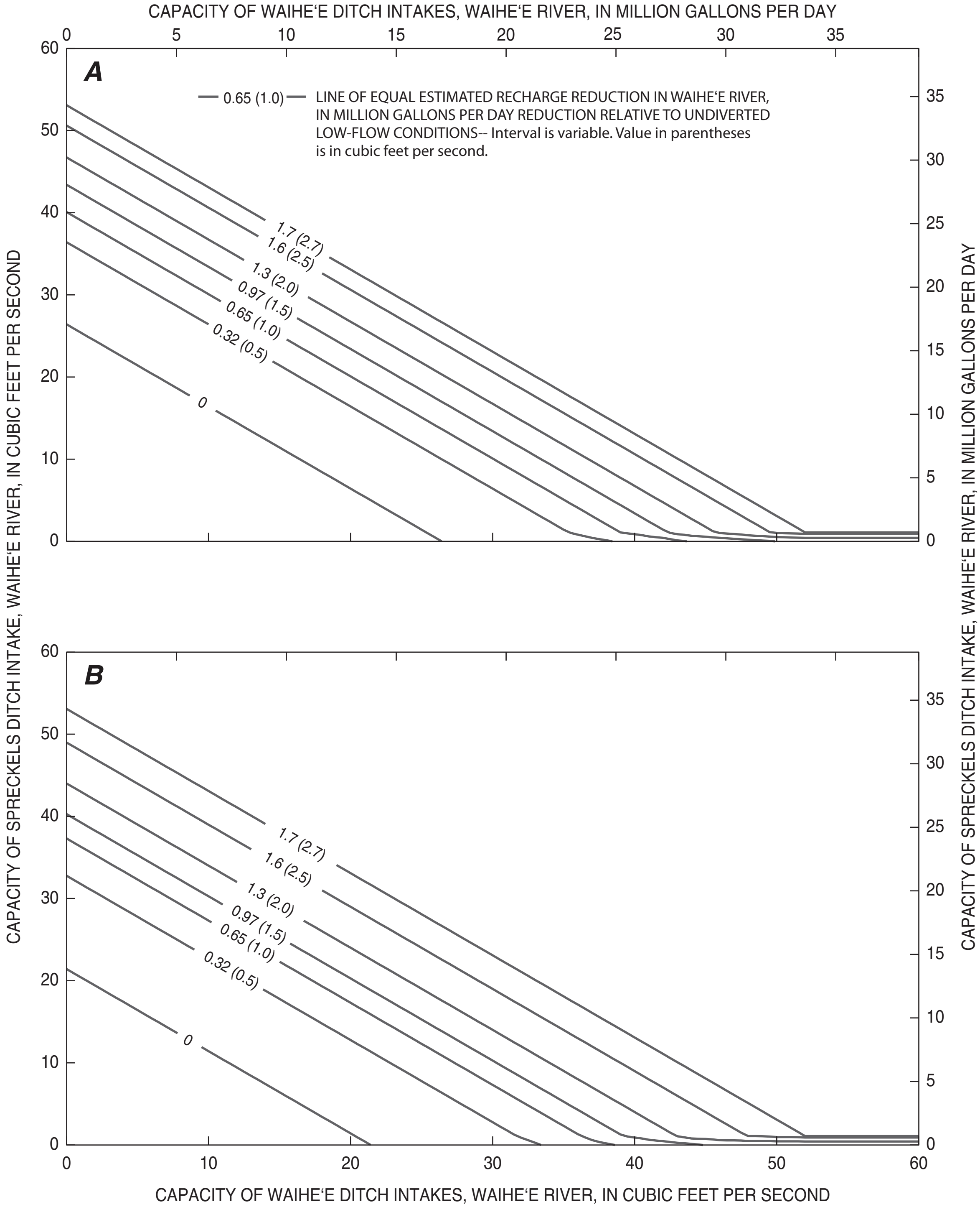


Figure 58. Reduction in potential groundwater recharge, relative to undiverted conditions, caused by diversions into the Waiheʻe Ditch and Spreckels Ditch with indicated intake capacities, Waiheʻe River, Maui, Hawaiʻi. *A*, Zero diversion into the Field 1 intake. *B*, Diversion capacity of 3.2 million gallons per day (5 cubic feet per second) for the Field 1 intake. Recharge reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

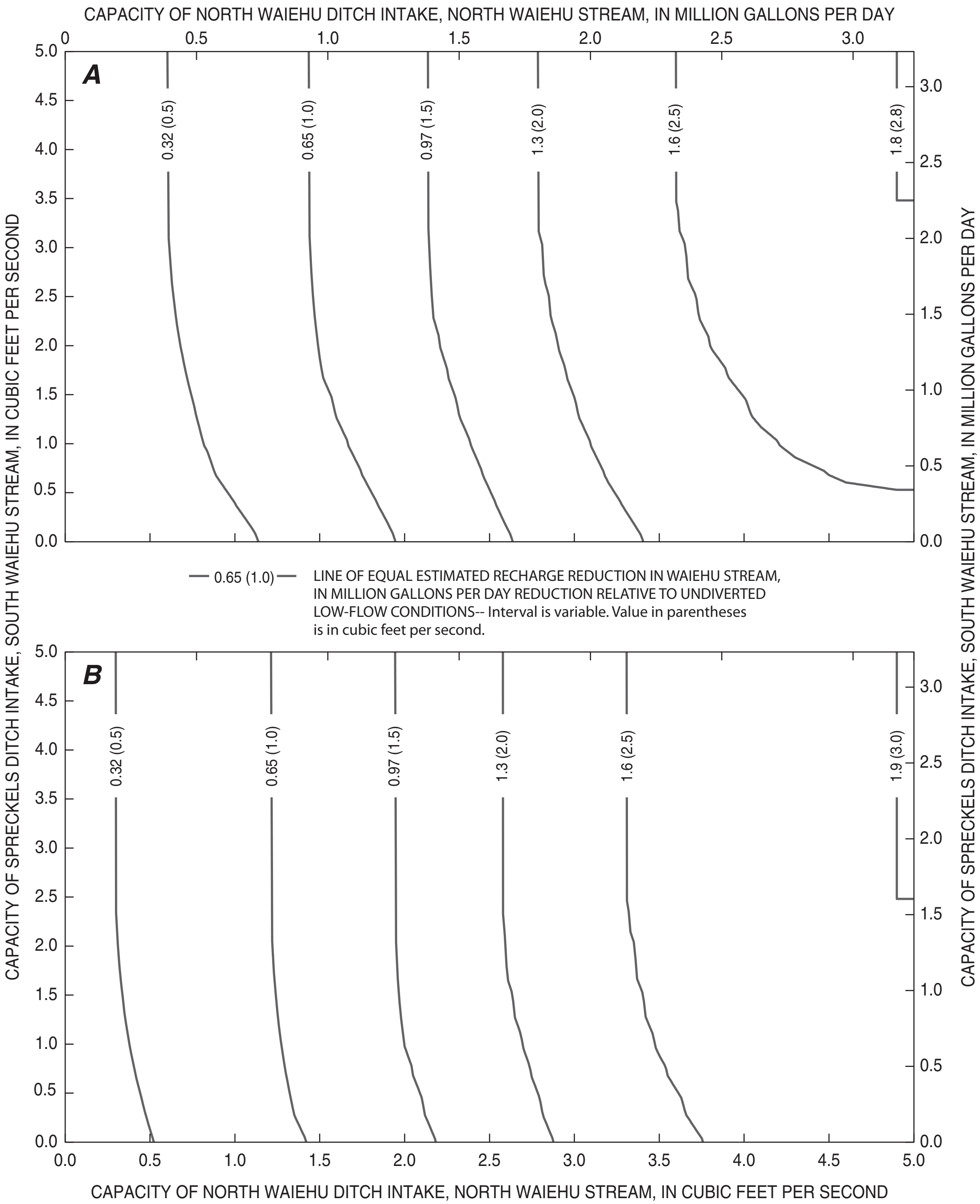


Figure 59. Reduction in potential groundwater recharge, relative to undiverted conditions, caused by diversions into the North Waiehu and Spreckels Ditches with indicated intake capacities, Waiehu Stream, Maui, Hawai‘i. *A*, Zero diversion into two private ‘auwai (ditches) near altitudes of 620 and 570 feet, South Waiehu Stream. *B*, Combined diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for two private ‘auwai near altitudes of 620 and 570 feet, South Waiehu Stream. Recharge reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

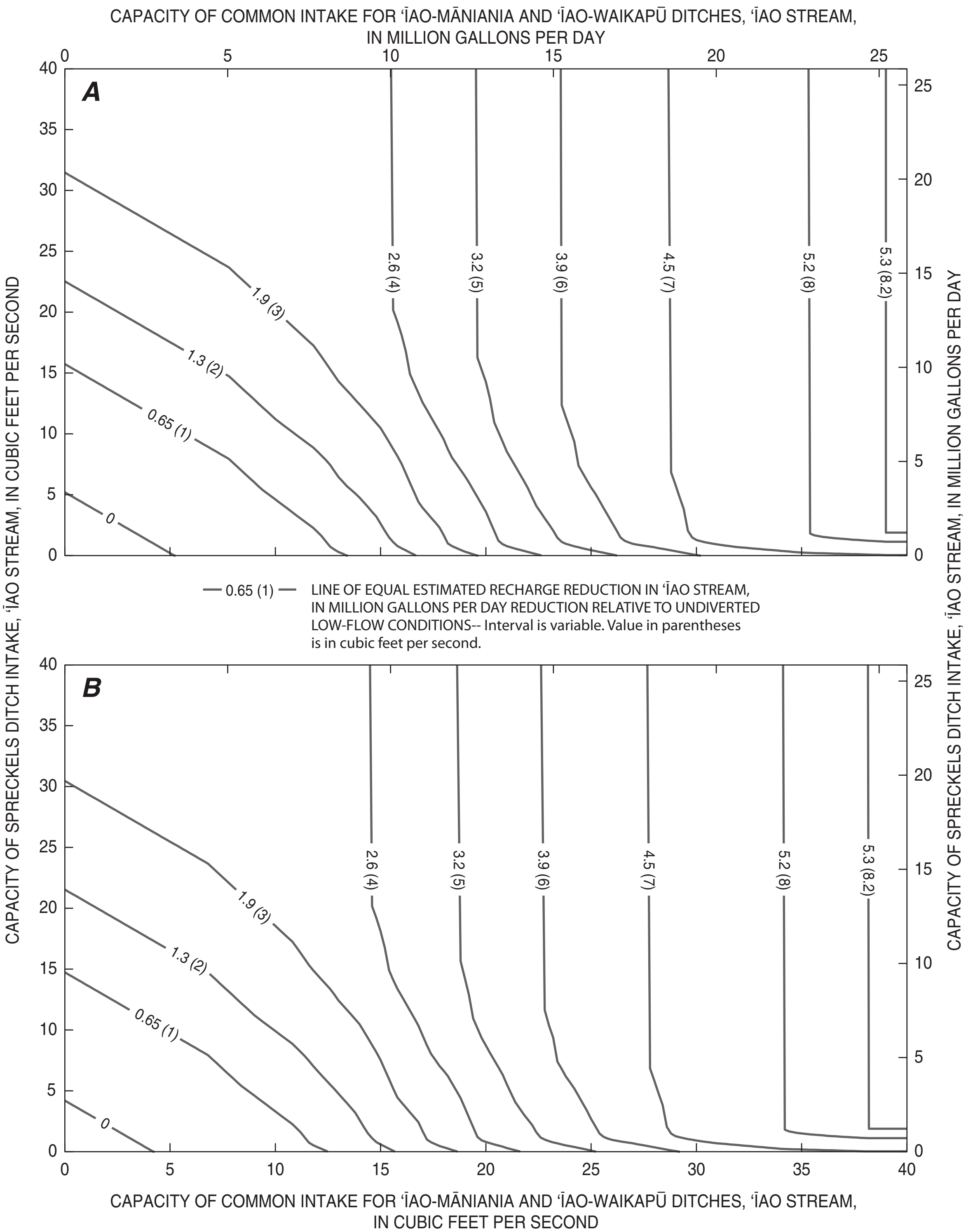


Figure 60. Reduction in potential groundwater recharge, relative to undiverted conditions, caused by diversions into the ʻĪao-Māniania and ʻĪao-Waikapū Ditches and Spreckels Ditch with indicated intake capacities, ʻĪao Stream, Maui, Hawaiʻi. *A*, Zero diversion into a private ʻauwai (ditch) near an altitude of 650 feet. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for a private ʻauwai near an altitude of 650 feet. Recharge reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

downstream of diversions exceeds maximum loss rates (and losses are assumed to be independent of streamflow).

Using the reported diversion capacity of the ʻĪao-Waikapū and ʻĪao-Māniania Ditches of 20 Mgal/d (31 ft^3/s) (Suzuki, 2007) and a diversion intake capacity of at least 3.9 Mgal/d (6 ft^3/s) for Spreckels Ditch, the overall reduction in recharge is 4.8 Mgal/d (7.4 ft^3/s) if no water is diverted by the existing private ʻauwai. For these diversion intake capacities, about 55 percent of the overall reduction in recharge takes place upstream of an altitude of 360 ft.

Waikapū Stream

For natural, undiverted low-flow conditions, the estimated seepage loss (potential groundwater recharge) from Waikapū Stream downstream of the intake for the South Side Ditch is about 4.3 Mgal/d (6.7 ft^3/s). About 8 percent of the seepage loss takes place upstream of an altitude of 400 ft, and the remaining 92 percent takes place downstream of an altitude of 400 ft.

The effects of diversions on recharge beneath Waikapū Stream were evaluated for the following diversion intake capacities: 0 to 6.5 Mgal/d (0 to 10 ft^3/s) for the South Side Ditch; 0 to 6.5 Mgal/d (0 to 10 ft^3/s) for the combined capacity of a private ʻauwai with an intake near an altitude of 560 ft, Waiheʻe Ditch, and the Reservoir 6 diversion; and 0 or 0.65 Mgal/d (0 or 1 ft^3/s) for Everett Ditch. The diversion intake capacity of the Everett Ditch is unknown. For this study, the intake capacity of Everett Ditch was assumed to be either 0 (fig. 61*A*) or 0.65 Mgal/d (1 ft^3/s) (fig. 61*B*), which covers the range of available measured diversion rates. The family of curves (fig. 61), with each curve corresponding to a selected value of groundwater-recharge reduction, shows the relation between capacities of the diversion intakes and recharge reduction. For the diversion intake capacities tested, the maximum overall reduction in recharge is 4.0 Mgal/d (6.2 ft^3/s) for different combinations of diversion intake capacities (fig. 61).

Using the approximate diversion capacity of the South Side Ditch of 3 Mgal/d (4.6 ft^3/s) (Suzuki, 2007) and a combined diversion intake capacity of at least 2.3 Mgal/d (3.6 ft^3/s) for the private ʻauwai, Waiheʻe Ditch, and the Reservoir 6 diversion, the overall reduction in recharge is 4.0 Mgal/d (6.2 ft^3/s) for diversion intake capacities of 0 or 0.65 Mgal/d (0 or 1 ft^3/s) for Everett Ditch (fig. 61). For these diversion intake capacities, the overall reduction in recharge takes place entirely downstream of an altitude of 400 ft.

Effects of Surface-Water Diversions on Physical Habitat

Changes in streamflow may affect the quantity and quality of physical habitat used by native stream fauna (see, for example, Gingerich and Wolff, 2005; Oki and others, 2006). This section addresses the effects that streamflow reduction, caused by diverting water, will have on physical habitat in Waiheʻe River and Waiehu, ʻĪao, and Waikapū Streams. Groundwater withdrawals that affect streamflow also can affect physical habitat used by the native fauna. However, determination of the effects of groundwater withdrawal on physical habitat used by the native fauna is beyond the scope of this study.

The Instream Flow Incremental Methodology (IFIM) is a tool used to quantify the effects of incremental changes in streamflow, and was developed to assess instream flow issues and assist in water-management decisions (Bovee, 1982). The development of many small hydropower projects and expanding urban development encroaching on river and stream systems in the United States during the 1970s and 1980s led to the design and refinement of tools that evaluate instream-habitat quality and predict how the populations and communities of fish inhabiting the streams and rivers would be affected.

A number of these tools are referred to as habitat-selection models, preference models, or habitat-index models. The Physical Habitat Simulation System (PHABSIM) (Bovee, 1986, 1997; Bovee and others, 1998) is an example of a habitat-selection model for stream organisms and has been used in many studies to assist in management decisions (Railsback and others, 2003). In Hawaiʻi, Gingerich and Wolff (2005) and Oki and others (2006) used PHABSIM to evaluate the effects of surface-water diversions on physical habitat.

Habitat-selection modeling combines elements of biology and hydrology that may be related to the population of an aquatic species. In terms of biology, these models commonly account for the frequency of microhabitat utilization of a target species. This is often compared with a measurement of microhabitat availability to define preference or habitat-suitability criteria. The preferred microhabitat is assumed to be the most advantageous for a specific activity and life stage of the target species. In terms of hydrology, these models commonly account for streamflow characteristics and stream geomorphology. Computer models like PHABSIM are used to merge these components to estimate the changes in the quantity of preferred microhabitat area available for the target species with incremental changes in streamflow.

For this study, the effects of changes in streamflow on physical habitat were evaluated using the PHABSIM approach. Measurements of microhabitat under different flow conditions were combined with habitat-suitability criteria modified from those developed for streams in northeast Maui (Gingerich and Wolff, 2005). Habitat-suitability criteria developed for northeast Maui streams are transferable, in some cases, to other areas of the State (Gingerich and Wolff, 2005). Habitat-suitability criteria specific to the Nā Wai ʻEhā area were not developed for this study because existing populations of native species within the study reaches were considered too small for development of site-specific criteria.

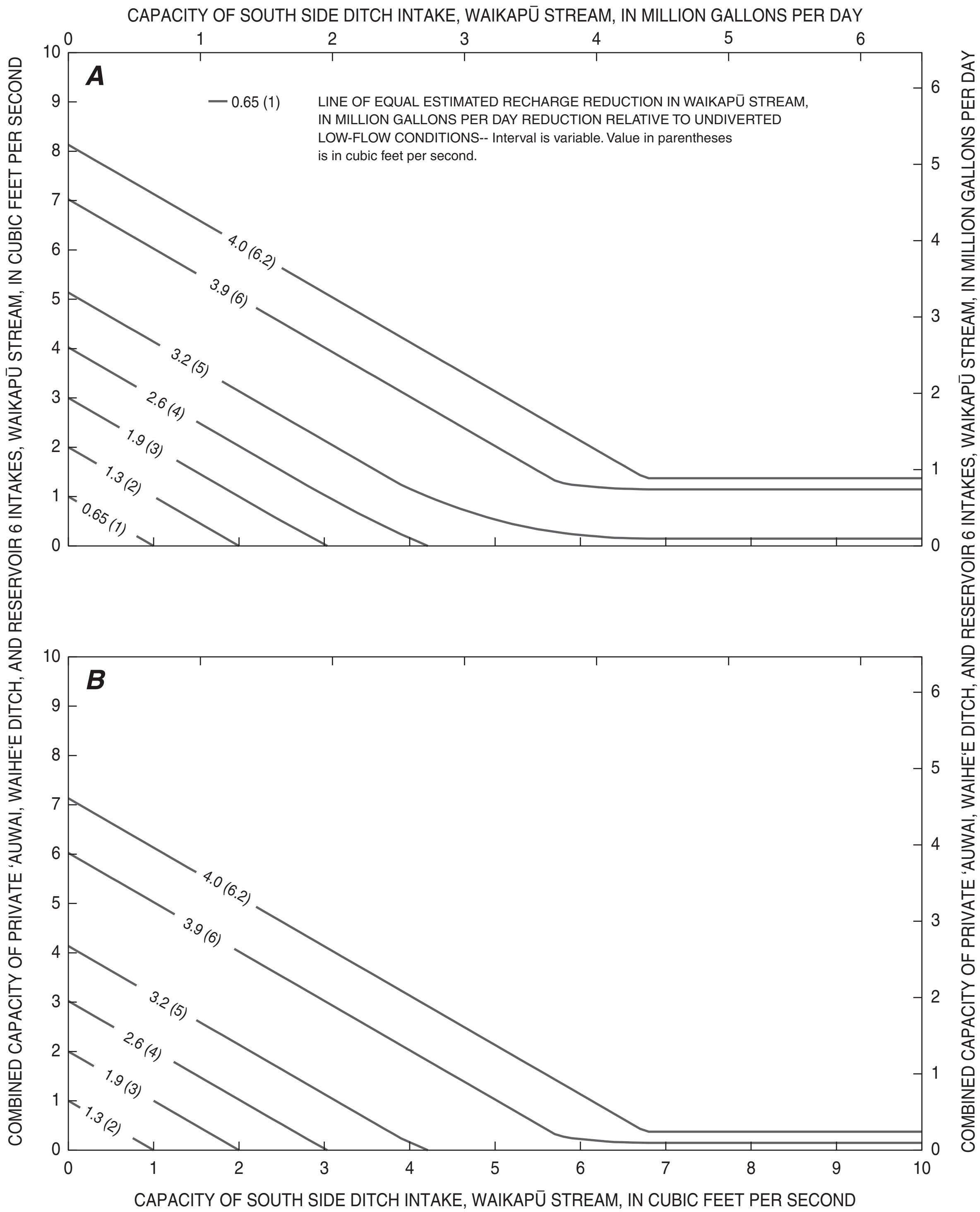


Figure 61. Reduction in potential groundwater recharge, relative to undiverted conditions, caused by diversion into the South Side Ditch and combined diversions into a private ‘auwai (ditch) near an altitude of 560 feet, Waihe‘e Ditch, and Reservoir 6 Ditch with indicated intake capacities, Waikapū Stream, Maui, Hawai‘i. *A*, Zero diversion into Everett Ditch. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for Everett Ditch. Recharge reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

Stream Habitat Data Collection

Habitat data were collected at two or three reaches in each stream (figs. 21–24). Study reaches, each about 300 ft in length, were located at stream altitudes ranging from about 30 to 1,140 ft. In each reach, measurements of microhabitat characteristics (depth, velocity, and substrate) generally were made at 10 cross sections for at least two different flow conditions.

Study Reaches

Study reaches were selected on the basis of hydrologic, ecologic, access, and safety considerations. Because of uncertainty related to availability of streamflow, reaches that commonly were dry were not selected. The boundaries of each 300-ft study reach were selected to exclude tributaries or diversions. Reaches immediately upstream and downstream of the uppermost diversions were assumed to be comparable in terms of habitat characteristics.

Cross Sections

Cross-section locations within each reach were determined using a stratified-random design. Study reaches were stratified at the level of three habitat types: riffle, run, and pool. Riffles were defined as stream sections with high gradient and shallow, fast-moving turbulent water. Runs were defined as stream sections with moderate- to fast-flowing water with minimal turbulence. Pools were defined as low gradient, deeper stream sections with low water velocity. Within each reach, the length and location of each discrete riffle, run, and pool were determined. The individual lengths were summed by habitat type, and the proportion of each habitat type within the reach was calculated (table 22). Ten cross sections were located within each reach. The number of cross sections per habitat type was calculated on the basis of the proportion of the habitat type within the reach. Once it was determined how many cross sections per habitat type were to be established, the location of each cross section was determined using computer-generated random numbers. Brightly colored vinyl flagging tape was labeled and placed on the stream bank to mark the location of each cross section. At each cross-section location, semipermanent boundary markers also were established on each stream bank. These semipermanent markers made it possible to reestablish cross-section locations throughout the period of study. Each cross section was oriented perpendicular to flow and stretched across the entire width of the low-flow channel of the stream.

For the reach near an altitude of 185 ft in Waiehu Stream, 10 cross sections originally were defined, but the lowermost section became inaccessible during 2008 because of a fallen tree. Data from the remaining nine cross sections were used in the habitat modeling. For this reach, 50 percent of the total length was characterized as riffle habitat. Because one of the five riffle sections was not available on all microhabitat measurement dates, habitat from the remaining four riffle sections was weighted by a factor of 1.25 to reflect the percentage of riffle habitat in the reach and to account for the missing tenth cross section.

Information on microhabitat availability was recorded at each cross section. Each cross section was subdivided into rectangular cells 1 ft wide and extending 1 ft downstream and 1 ft upstream of a line connecting the ends of the section. Thus, each 1-ft-wide cell represents an area of 2 ft^2. The habitat variables (depth, velocity, and substrate) were measured within each individual cell. Water depth was determined as the distance between the water surface and the stream bottom at the center of the cell. Measured water depths ranged from 0 to about 4 ft. In general, velocity was determined at the center of the cell at a depth (as measured from the water surface) of 0.6 times the total water-column depth, although in some cells where depths exceeded 1.5 ft, velocity was measured at 0.2 and 0.8 depths. The measurement depths were selected because they provide a representation of the mean velocity in the vertical water column at a site (Rantz and others, 1982). All velocities were measured with acoustic-Doppler velocity (ADV) meters. Average velocity generally was determined over a 40-second interval, although time constraints sometimes dictated a shorter interval of either 20 or 30 seconds. Measured water velocities ranged from zero in pool areas or near stream edges to more than 3 ft/s in other areas. The dominant substrate (table 23) was determined within each cell, and the percentage of each cell that was not completely submerged was recorded where applicable.

Quantification of Suitable Habitat

For this study, suitable physical habitat was quantified using the PHABSIM approach (U.S. Geological Survey, 2001). Habitat-suitability criteria modified from Gingerich and Wolff (2005) were used to determine the effects of incremental changes in streamflow on physical habitat for selected native species. Froude number and depth habitat-suitability criteria developed originally for streams in northeast Maui (Gingerich and Wolff, 2005) were modified and used for this study. The modifications are related to the bin widths used for the frequency distributions and the specified minimum suitability index. For this study, the bin width for Froude number frequency distributions was standardized to 0.05, with the first bin range of 0–0.025, and the bin width for depth frequency distributions was standardized to 0.20 ft, with the first bin range of 0–0.10 ft. The previously applied minimum suitability index of 0.20 (Gingerich and Wolff, 2005) was not used in this study. Instead, the minimum suitability-index values for Froude number and depth were determined from the nonparametric tolerance limits.

Table 22. Percentage of riffle, run, and pool habitat within studied stream reaches, Maui, Hawaiʻi.

Altitude near downstream end of stream reach, in feet	Percentage of habitat in 300-foot reach			
	Riffle	Run	Pool	Total
Waiheʻe River				
[a]610	43	57	0	100
570	29	71	0	100
405	38	62	0	100
30	53	47	0	100
North Waiehu Stream				
[a]900	51	49	0	100
820	43	57	0	100
Waiehu Stream				
185	47	53	0	100
ʻĪao Stream				
[a]790	55	45	0	100
730	48	44	8	100
570	42	43	15	100
Waikapū Stream				
[a]1,140	68	32	0	100
1,050	64	36	0	100
840	68	32	0	100

[a]Reach is upstream of uppermost diversion and is assumed to represent comparable habitat to the reach immediately downstream.

Physical habitat for ʻoʻopu ʻalamoʻo and ʻōpaekalaʻole was modeled only at the uppermost reaches in each stream; physical habitat for ʻoʻopu nākea was modeled at all reaches; physical habitat for ʻoʻopu nōpili was modeled at all reaches except the uppermost reaches of Waiheʻe River and Waikapū Stream; and physical habitat for hīhīwai was modeled only in the two lower reaches of Waiheʻe River and the one reach in Waiehu Stream. Physical habitat for *Eleotris sandwicensis* (ʻoʻopu ʻakupa) and *Stenogobius hawaiiensis* (ʻoʻopu naniha) was not modeled because habitat-suitability criteria were neither available nor developed in this study, although ʻoʻopu ʻakupa was observed in Waiheʻe River. Habitat-suitability criteria for hīhīwai developed by Gingerich and Wolff (2005) were based on observations during daytime hours, although hīhīwai apparently are more active during nighttime hours (Brasher, 1997).

The habitat-suitability curves define weights, which may range in value from 0 (unusable habitat) to 1 (preferred habitat), for selected microhabitat parameters. For this study, the dominant substrate category (table 23), dimensionless Froude number (fig. 62), and depth (fig. 63) were used to define microhabitat characteristics within each 1-ft-wide cell of each cross section. The Froude number represents the ratio of inertia force to gravity force and is defined as

$$F = v/(dg)^{1/2},$$

where

F is the dimensionless Froude number,
v is the water velocity [L/T],
d is the water depth [L],
g is the acceleration due to gravity [L/T^2],
L represents units of length, and
T represents units of time.

If the Froude number is less than 1, flow is characterized as subcritical or tranquil, whereas if the Froude number is greater than 1, flow is supercritical, rapid, or shooting. A Froude number of 1 indicates critical flow (flow at minimum specific energy) (see, for example, Olson, 1980). Froude numbers computed from velocity and depth measurements ranged from 0 in areas with standing water to greater than 1 in sections with rapidly flowing water.

For each 1-ft-wide cell, a composite suitability was determined as

$$C_i = F_i \times D_i \times S_i,$$

where

C_i is the composite suitability of cell i,
F_i is the suitability associated with the Froude number in cell i,
D_i is the suitability associated with depth in cell i, and
S_i is the suitability associated with the dominant substrate category in cell i.

The composite-suitability value may range from 0 (unusable habitat) to 1 (preferred habitat). Because the Froude number may be zero for different values of depth, the composite suitability included depth to account for different habitat suitability for different depths with zero velocity. The weighted usable area for a cell (*wua*), which is a measure of suitable physical habitat, is then computed from

$$wua_i = A_i \times C_i \times E_i,$$

where

wua_i is the weighted usable area of cell i [L^2],
A_i is the area of cell i [L^2],
C_i is the composite suitability of cell i, and
E_i is the fraction of cell i that is submerged.

For this study, each cell had a total area of 2 ft^2. The weighted usable area for each cross section was determined by adding the weighted-usable-area values for each cell in that cross section. Total weighted usable area (WUA) for the reach was then determined by summing the weighted-usable-area values for the 10 cross sections, which are representative of the reach. Because each 1-ft-wide cell in a cross section is 2 ft long, the computed WUA value for a reach with 10 cross sections is expressed in terms of square feet per 20 ft of stream length. By multiplying the WUA for the reach by a factor of 50, the WUA also can be expressed in terms of square feet per 1,000 ft of stream. Because a stratified-random design was used to select cross sections, riffles, runs, and

Table 23. Substrate size categories and dominant substrate suitability values for selected native species (Gingerich and Wolff, 2005).

[>, greater than; in., inches]

Species	Dominant substrate suitability value						
	Silt and organic detritus	Sand (>0.002 to 0.08 in.)	Gravel (>0.08 to 0.8 in.)	Cobble (>0.8 to 4 in.)	Small boulder (>4 to 12 in.)	Large boulder (>12 in.)	Bedrock or compact alluvium
ʻōpaekalaʻole (*Atyoida bisulcata*)	0.2	0.2	0.2	0.2	0.5	1	0.2
ʻoʻopu ʻalamoʻo, adult (*Lentipes concolor*)	0.2	0.2	0.2	0.2	0.2	1	0.2
ʻoʻopu ʻalamoʻo, juvenile (*Lentipes concolor*)	0.2	0.2	0.2	0.2	0.5	1	0.2
ʻoʻopu nōpili, adult (*Sicyopterus stimpsoni*)	0.2	0.2	0.2	1	1	1	0.2
ʻoʻopu nōpili, juvenile (*Sicyopterus stimpsoni*)	0.2	0.2	0.2	0.5	1	1	0.2
ʻoʻopu nākea, adult (*Awaous guamensis*)	0.2	0.2	0.5	1	1	1	0.2
hīhīwai (*Neritina granosa*)	0.2	0.2	0.2	0.5	0.5	1	0.2

pools were appropriately weighted according to availability in determining the WUA for each reach.

WUA was computed for each study reach at each of two to five different measured discharge rates (figs. 64–67). At some sites, habitat data were collected over reaches (300 ft in length) immediately upstream and downstream of a diversion to characterize habitat over a range of discharge rates. For these cases, habitat data from the upstream reach were assumed to be representative of conditions at the downstream reach at comparable flows because of the close proximity of the upstream and downstream reaches, although the percentages of riffles, runs, and pools may have differed between the upstream and downstream reaches (table 22). This approach was necessitated because reaches immediately downstream of diversions generally lacked flows at the higher end of the low-flow range (near the median flow).

In general, data indicate that WUA increases monotonically with discharge up to the median natural discharge (figs. 64–67). Most studies using PHABSIM incorporate hydraulic modeling to estimate depths and velocities, and also WUA, for different flow conditions. However, hydraulic modeling was not incorporated in this study because (1) stream-channel modifications following large storms made it too difficult to collect reliable data for model calibration and (2) the complexity of the velocity distributions in the stream caused by the uneven nature of the channel bottoms makes hydraulic modeling results tenuous. Thus, for this study, power functions of the form $y=ax^b$ were fit to the available data to provide consistent estimates of WUA throughout the range of discharges from zero to the median natural discharge. A power function monotonically increases (or decreases) with increasing values in the dependent variable, which is not always the case with a quadratic function. Because available data generally indicate increasing WUA with discharge within the low-flow range of interest (figs. 64–67), fitting the data to a power function was considered appropriate.

The relations between WUA and discharge are steepest between discharge rates of zero and a few million gallons per day, which indicates that the rate of increase in WUA is greatest as discharge increases from zero to a few million gallons per day (and the rate of decrease in WUA is greatest as discharge decreases from a few million gallons per day to zero). WUA values range from zero at no flow to more than

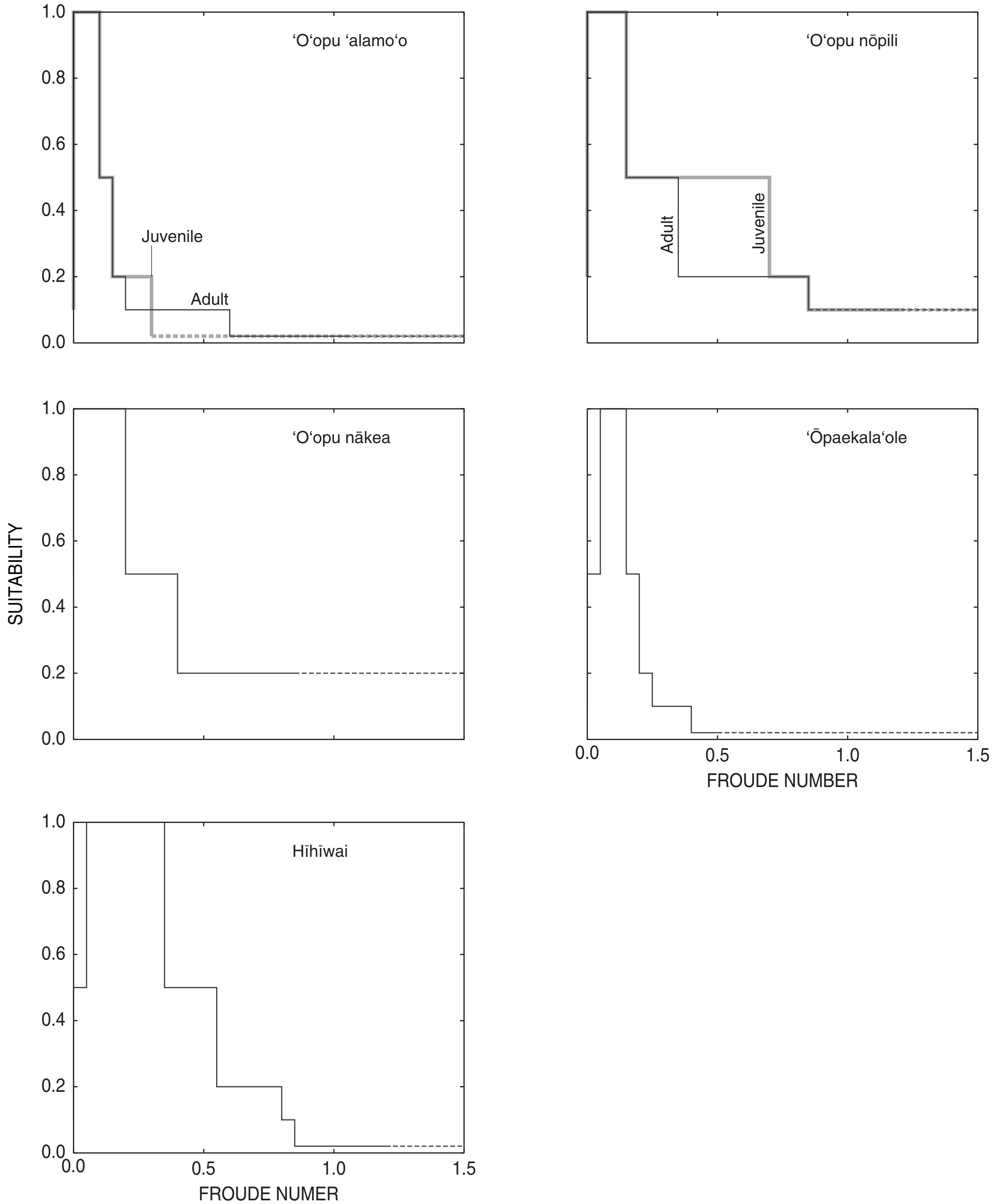


Figure 62. Froude number suitability curves for selected native stream fauna, Maui, Hawaiʻi (modified from Gingerich and Wolff, 2005). Curves dashed where extrapolated.

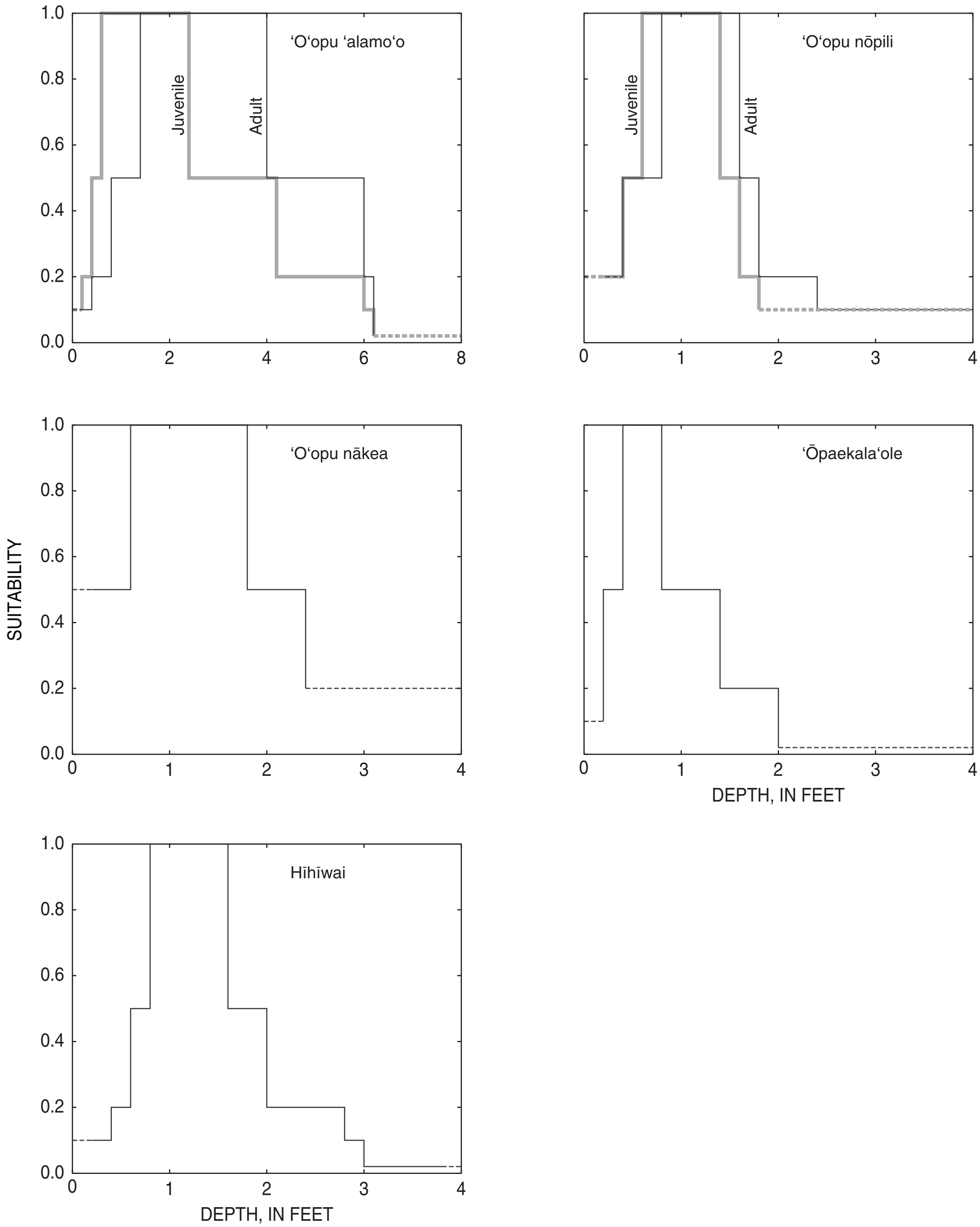


Figure 63. Depth suitability curves for selected native stream fauna, Maui, Hawai‘i (modified from Gingerich and Wolff, 2005). Curves dashed where extrapolated.

10,000 ft[2] per 1,000 ft of stream for some species and flows (figs. 64–67).

Available hydrograph-separation analyses for undiverted Hawaiian streams indicate that median base flow values generally are in the range of the Q_{60} to Q_{80} duration flows (Fontaine, 2003; Oki, 2004; Gingerich, 2005; Oki and others, 2006). For this study, normalized relations between habitat and discharge were developed by dividing habitat values by the habitat at the natural, undiverted Q_{70} discharge and by dividing discharge values by the natural, undiverted Q_{70} discharge (figs. 64–67). (The natural, undiverted Q_{70} discharge for each habitat study reach was determined from the nearest available site at which flow characteristics were estimated (tables 18–21). Flow characteristics were estimated for sites within or immediately upstream or downstream of each study reach.) Normalizing the relations between habitat and discharge allowed comparisons to be made among species and streams. Available data from the different species and streams were used to develop a generalized relation between habitat and discharge (fig. 68). This generalized relation indicates increased physical habitat for increased discharge, which is consistent with the individual relations (figs. 64–67). The generalized relation indicates that at a discharge equal to 20 percent of the Q_{70} discharge, the physical habitat (WUA)

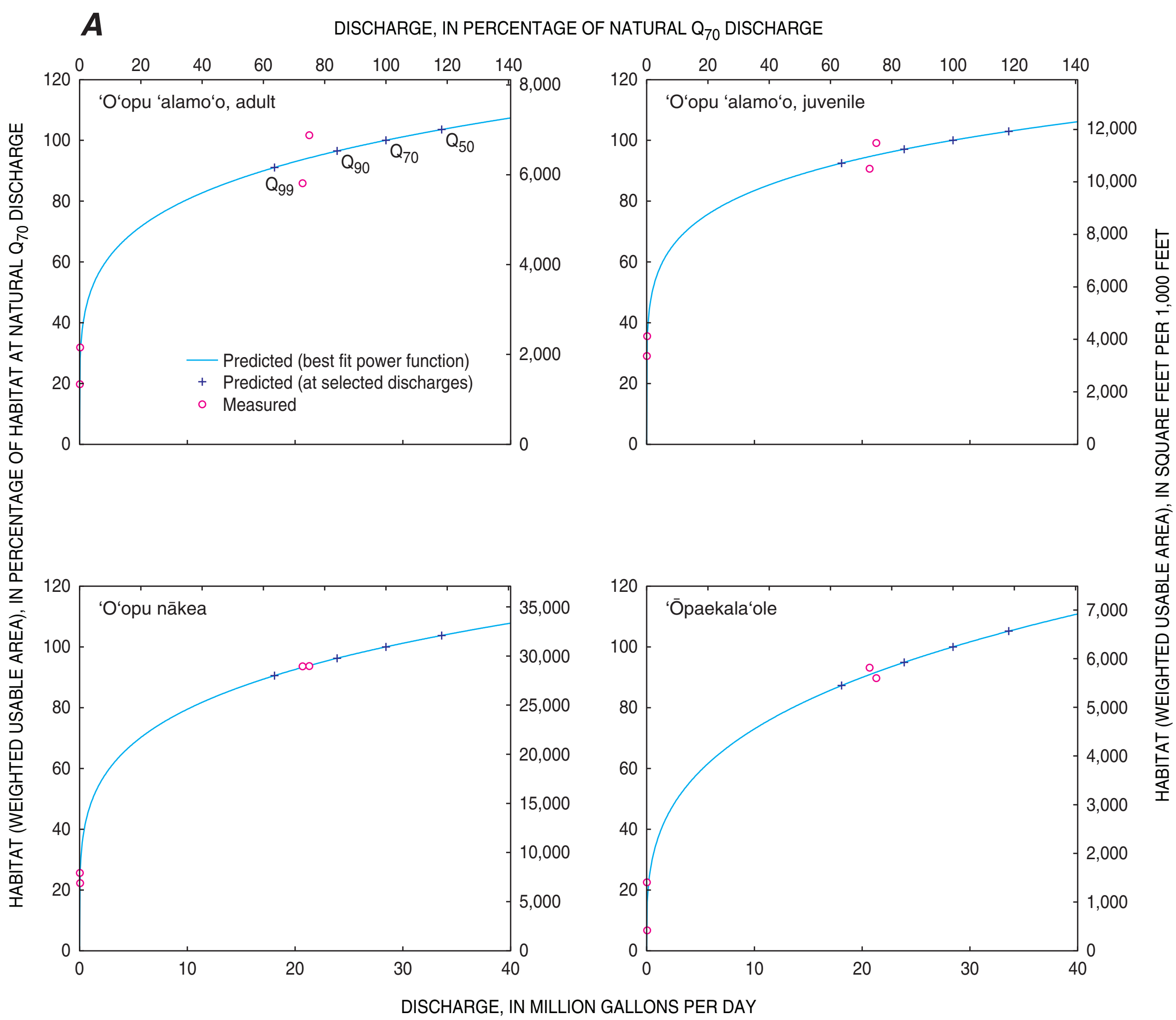


Figure 64. Relations between habitat (weighted usable area) for selected native species and discharge in Waihe‘e River, Maui, Hawai‘i. *A*, Altitude of 570 feet. *B*, Altitude of 405 feet. *C*, Altitude of 30 feet. The Q_p discharge is the discharge equaled or exceeded p percent of the time. The natural, undiverted flow characteristics at an altitude of 570 feet are assumed to be equivalent to those at an altitude of 605 feet, and the natural, undiverted flow characteristics at an altitude of 30 feet are assumed to be equivalent to those at an altitude of 45 feet.

is about 67 percent of the habitat at the Q_{70} discharge; at a discharge equal to 50 percent of the Q_{70} discharge, WUA is about 84 percent of the habitat at the Q_{70} discharge. The relation between physical habitat and discharge developed for this study generally is consistent with results from Gingerich and Wolff (2005). Results for a specific species and site may vary from the generalized relation, as indicated by the scatter in the data (fig. 68). For example, the generalized relation may predict greater habitat, for a given discharge, than data for hīhīwai indicate (fig. 68). However, the generalized relation is useful as an indicator of how habitat varies with discharge, particularly for sites without available data.

Reduction of Habitat Caused by Diversions

To evaluate the effects of existing surface-water diversions on physical habitat, the generalized relation between habitat and discharge (fig. 68) was used in conjunction with estimates of streamflow for different diversion intake capacities (see previous section on "Effects of Surface-Water Diversions on Streamflow"). The weighted-average physical habitat (in terms of WUA) available during low-flow conditions at selected sites downstream of diversions was computed for both undiverted and diverted conditions, and the percentage reduction in habitat between undiverted

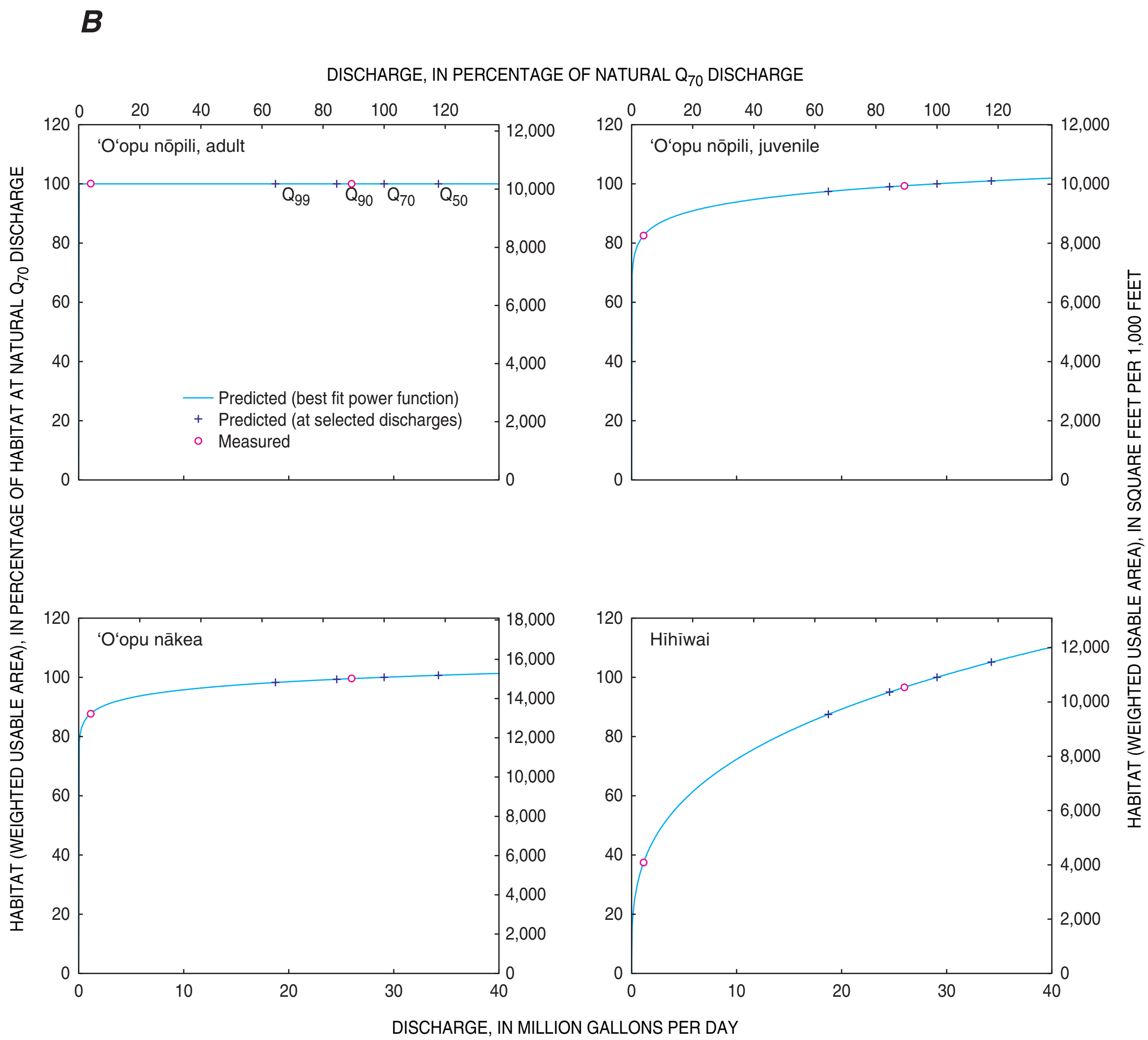


Figure 64.—Continued.

and diverted conditions was computed. The effects of the diversions on habitat were determined at selected flows equal to and less than the median flow (Q_{50}, Q_{55}, Q_{60}, Q_{65}, Q_{70}, Q_{75}, Q_{80}, Q_{85}, Q_{90}, Q_{95}, and Q_{99}). At each flow, the habitat was weighted by the percentage of time that flow occurs during low-flow conditions to provide an estimate of the weighted-average habitat available during low-flow conditions. The percentage of time that each selected flow occurs was determined by half of the difference between duration percentiles of adjacent duration discharges. For example, the percentage of time that the Q_{55} flow was assumed to occur was equal to (60-50)/2, or 5 percent. During low-flow conditions, when flow is less than the median flow, the Q_{55} flow occurs 10 (=5×2) percent of the time. The percentage of time that the Q_{50} flow was assumed to occur was equal to (55-50)/2, or 2.5 percent. During low-flow conditions, when flow is less than the median flow, the Q_{50} flow occurs 5 (=2.5×2) percent of the time. Thus, for the Q_{50} flow, the habitat was multiplied by 0.05 (equal to 5 percent of the time during low-flow conditions); for the Q_{55} to Q_{90} flows, the habitat was multiplied by 0.1; for the Q_{95} flow, the habitat was multiplied by 0.09; and for the Q_{99} flow, the habitat was multiplied by 0.06. The sum of the weights is equal to 1.

Diversion of surface water from a stream generally reduces the amount of physical habitat available during low-flow conditions. Thus, as the capacity of the diversion intakes increase, the reduction in habitat generally increases. At some level of diversion intake capacity, the reach immediately downstream of the diversion may have zero flow during dry-weather conditions, the effects of diversions on habitat reduction may reach a maximum value, and increased diversion intake capacity has no further effect on reducing habitat during dry-weather conditions. The reported habitat reductions are for periods when the upstream, undiverted flows are less than or equal to the median flow, which occurs 50 percent of the time. Also, for the purposes of this analysis, none of the diverted water is assumed to return to the stream.

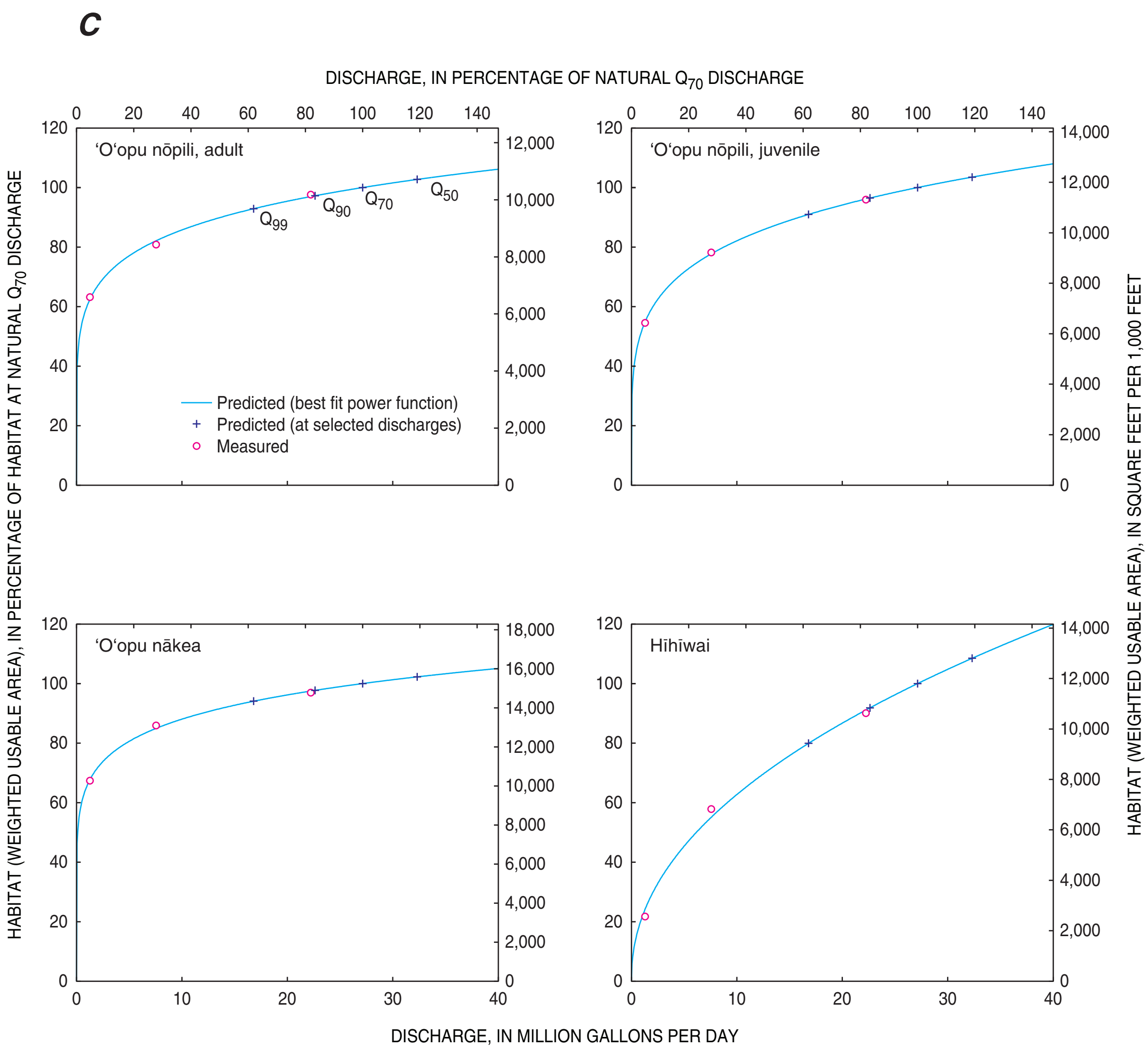


Figure 64.—Continued.

Waiheʻe River

Reduction in physical habitat (WUA), relative to undiverted low-flow conditions, caused by diversions into the Waiheʻe, Spreckels, and Field 1 intakes was estimated for Waiheʻe River near an altitude of 45 ft (fig. 69) using the generalized relation between habitat and discharge. The effects of diversions on physical habitat near an altitude of 45 ft in Waiheʻe River were evaluated for diversion intake capacities of 0 to 39 Mgal/d (0 to 60 ft^3/s) for the Waiheʻe Ditch; 0 to 39 Mgal/d (0 to 60 ft^3/s) for Spreckels Ditch; and 0 or 3.2 Mgal/d (0 or 5 ft^3/s) for the Field 1 intake. The intake capacity for the Field 1 diversion is unknown and, thus, the use of 3.2 Mgal/d (5 ft^3/s) for the intake capacity of the Field 1 intake is arbitrary. The family of curves (fig. 69), with each curve corresponding to a selected value of habitat reduction, shows the relation between capacities of the diversion intakes and habitat reduction during low-flow conditions. If no water is diverted at the Field 1 intake, then combinations of diversion intake capacities for Waiheʻe and Spreckels Ditches equal to 32.6 Mgal/d (50.4 ft^3/s) result in 100 percent reduction in physical habitat near an altitude of 45 ft (fig. 69*A*). Thus, if the intake capacity of Waiheʻe Ditch is 32.6 Mgal/d (50.4 ft^3/s) and no water is diverted by Spreckels Ditch, then physical habitat will be reduced by 100 percent near an altitude of 45 ft. Similarly, if the intake capacity of Waiheʻe Ditch is 16.3 Mgal/d (25.2 ft^3/s) and the intake capacity of Spreckels Ditch is the same, then physical habitat also will be reduced by 100 percent near an altitude of 45 ft (fig. 69*A*). Existing diversions by Waiheʻe and Spreckels Ditches, with reported intake capacities of 40 and 12 Mgal/d (62 and 19 ft^3/s), respectively, reduce physical habitat near an altitude of 45 ft by 100 percent during low-flow periods if no water is diverted at the Field 1 intake and if no water is returned to the stream upstream of an altitude of 45 ft (fig. 69*A*).

If no water is diverted at the Field 1 intake, then combinations of diversion intake capacities for Waiheʻe and Spreckels Ditches equal to 22.9 Mgal/d (35.4 ft^3/s) result in 50 percent reduction in physical habitat near an altitude of 45 ft (fig. 69*A*). If 3.2 Mgal/d (5 ft^3/s) is diverted at the Field 1 intake, then combinations of diversion intake capacities for Waiheʻe and Spreckels Ditches equal to 19.6 Mgal/d (30.4 ft^3/s) result in 50 percent reduction in physical habitat near an altitude of 45 ft (fig. 69*B*).

Waiehu Stream

Reduction in physical habitat (WUA), relative to undiverted low-flow conditions, caused by diversions into the North Waiehu Ditch, Spreckels Ditch, and two existing private ʻauwai with intakes near altitudes of 620 and 570 ft in South Waiehu Stream was estimated for Waiehu Stream near an altitude of 20 ft (fig. 70) using the generalized relation between habitat and discharge. The effects of diversions on physical habitat near an altitude of 20 ft in Waiehu Stream were evaluated for diversion intake capacities of 0 to 3.2 Mgal/d (0 to 5 ft^3/s) for North Waiehu Ditch, North Waiehu Stream; 0 to 3.2 Mgal/d (0 to 5 ft^3/s) for Spreckels Ditch, South Waiehu Stream; and 0 or 0.32 Mgal/d (0 or 0.5 ft^3/s) each for two existing private ʻauwai with intakes near altitudes of 620 and 570 ft, South Waiehu Stream. The diversion intake capacities for the two existing private ʻauwai are unknown and variable, depending on the condition of the intakes. For this study, the intake capacity of each private ʻauwai was assumed to be either 0 (fig. 70*A*) or 0.32 Mgal/d (0.5 ft^3/s) (fig. 70*B*), which generally represents the range of available measured diversion rates. The family of curves (fig. 70), with each curve corresponding to a selected value of habitat reduction, shows the relation between capacities of the diversion intakes and habitat reduction during low-flow conditions. Existing diversions by the North Waiehu Ditch, with a reported capacity of 1.5 Mgal/d (2.3 ft^3/s), and Spreckels Ditch, with a capacity that exceeds 1 Mgal/d (1.5 ft^3/s), reduce physical habitat near an altitude of 20 ft by at least 60 percent, even if no water is diverted by each of the two private ʻauwai and if no water is returned to the stream upstream of an altitude of 20 ft (fig. 70*A*).

If no water is diverted by the two private ʻauwai, then different combinations of diversion intake capacities for North Waiehu and Spreckels Ditches may result in 50 percent reduction in physical habitat near an altitude of 20 ft (fig. 70*A*). For example, if the intake capacity for North Waiehu Ditch is 0.65 Mgal/d (1.0 ft^3/s) and the intake capacity for Spreckels Ditch is about 1.1 Mgal/d (1.7 ft^3/s), then physical habitat will be reduced by 50 percent near an altitude of 20 ft (fig. 70*A*). Similarly, if the intake capacity for North Waiehu Ditch is 1.3 Mgal/d (2.0 ft^3/s) and the intake capacity for Spreckels Ditch is about 0.65 Mgal/d (1.0 ft^3/s), then physical habitat also will be reduced by 50 percent near an altitude of 20 ft (fig. 70*A*).

If 0.32 Mgal/d (0.5 ft^3/s) is diverted by each of the two existing private ʻauwai of South Waiehu Stream, then different combinations of diversion intake capacities for North Waiehu and Spreckels Ditches may result in 50 percent reduction in physical habitat near an altitude of 20 ft (fig. 70*B*). For example, if the intake capacity for North Waiehu Ditch is 0.65 Mgal/d (1.0 ft^3/s) and the intake capacity for Spreckels Ditch is about 0.43 Mgal/d (0.67 ft^3/s), then physical habitat will be reduced by 50 percent near an altitude of 20 ft (fig. 70*B*). Similarly, if the intake capacity for North Waiehu Ditch is 1.3 Mgal/d (2.0 ft^3/s) and the intake capacity for Spreckels Ditch is about 0.03 Mgal/d (0.05 ft^3/s), then physical habitat also will be reduced by 50 percent near an altitude of 20 ft (fig. 70*B*).

ʻĪao Stream

Reduction in physical habitat (WUA), relative to undiverted low-flow conditions, caused by diversions into the

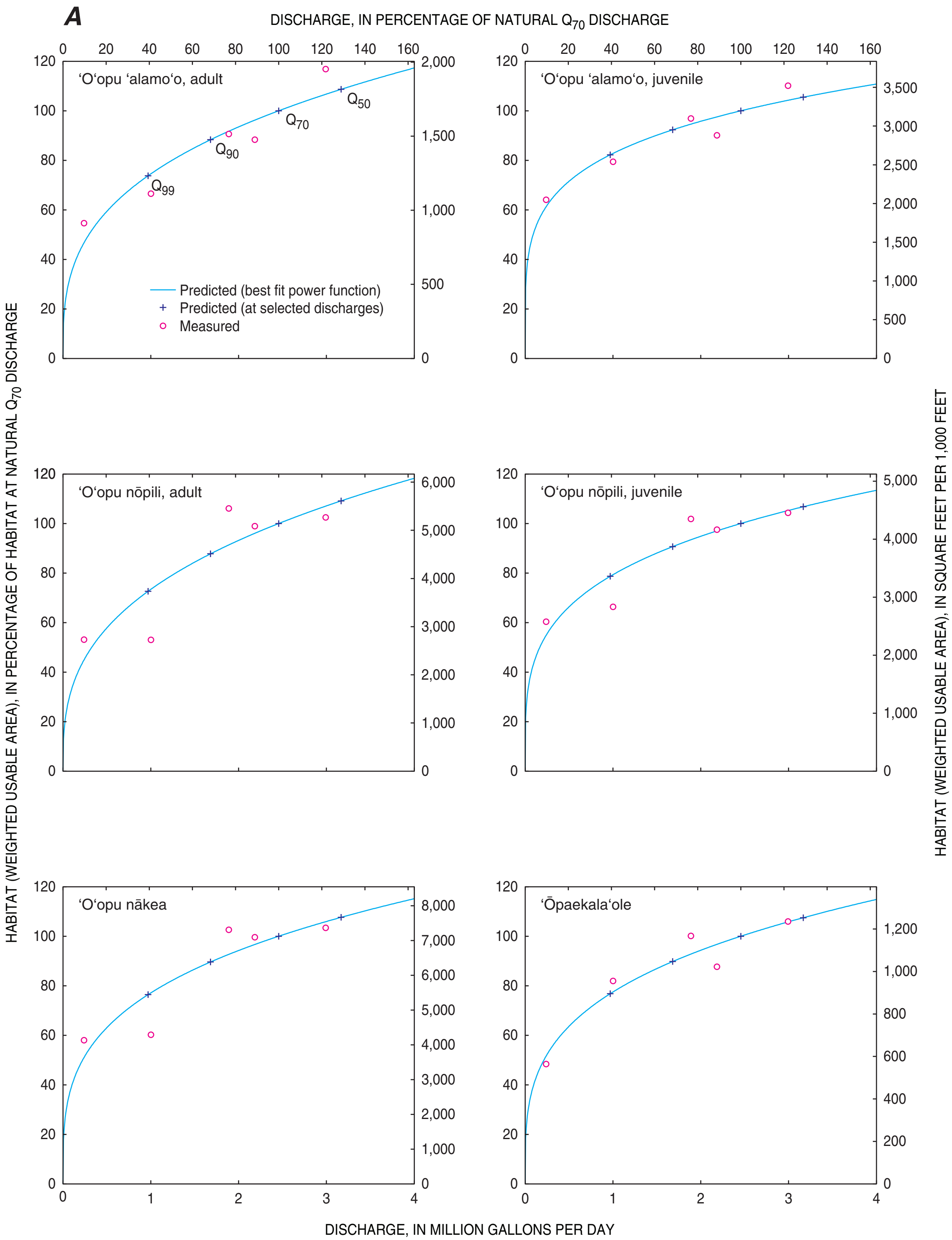


Figure 65. Relations between habitat (weighted usable area) for selected native species and discharge in Waiehu Stream, Maui, Hawaiʻi. *A*, Altitude of 820 feet in North Waiehu Stream. *B*, Altitude of 185 feet in Waiehu Stream. The Q_p discharge is the discharge equaled or exceeded p percent of the time. The natural, undiverted flow characteristics of North Waiehu Stream at an altitude of 820 feet are assumed to be equivalent to those at an altitude of 880 feet, and the natural, undiverted flow characteristics of Waiehu Stream at an altitude of 185 feet are assumed to be equivalent to those at an altitude of 190 feet.

ʻĪao-Waikapū and ʻĪao-Māniania Ditches, Spreckels Ditch, and an existing private ʻauwai was estimated for ʻĪao Stream near an altitude of 35 ft (fig. 71) using the generalized relation between habitat and discharge. The effects of diversions on physical habitat near an altitude of 35 ft in ʻĪao Stream were evaluated for diversion intake capacities of 0 to 26 Mgal/d (0 to 40 ft^3/s) for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches; 0 to 26 Mgal/d (0 to 40 ft^3/s) for Spreckels Ditch; and 0 or 0.65 Mgal/d (0 or 1 ft^3/s) for an existing private ʻauwai with an intake at an altitude of about 650 ft. The diversion intake capacity for the existing private ʻauwai is unknown but much less than the current diversion intake capacities for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and Spreckels Ditch. For this study, the intake capacity of the private ʻauwai was assumed to be either 0 (fig. 71*A*) or 0.65 Mgal/d (1 ft^3/s) (fig. 71*B*), which covers the range of available measured diversion rates. The family of curves (fig. 71), with each curve corresponding to a selected value of habitat reduction, shows the relation between capacities of the diversion intakes and habitat reduction during low-flow conditions. If no water is diverted by the existing private ʻauwai, then combinations of diversion intake capacities for ʻĪao-Waikapū and ʻĪao-Māniania Ditches and Spreckels Ditch equal to 21.2 Mgal/d (32.9 ft^3/s) result in 100 percent reduction in physical habitat near an altitude of 35 ft (fig. 71*A*). Existing diversions by the ʻĪao-Waikapū and ʻĪao-Māniania Ditches, with a reported capacity of 20 Mgal/d (31 ft^3/s), and Spreckels Ditch, with an intake capacity that likely exceeds several Mgal/d, reduce physical habitat near an altitude of 35 ft by 100 percent during low-flow periods if no water is returned to ʻĪao Stream upstream of an altitude of 35 ft (fig. 71*A*).

If no water is diverted by the existing private ʻauwai, then combinations of diversion intake capacities for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and Spreckels Ditch

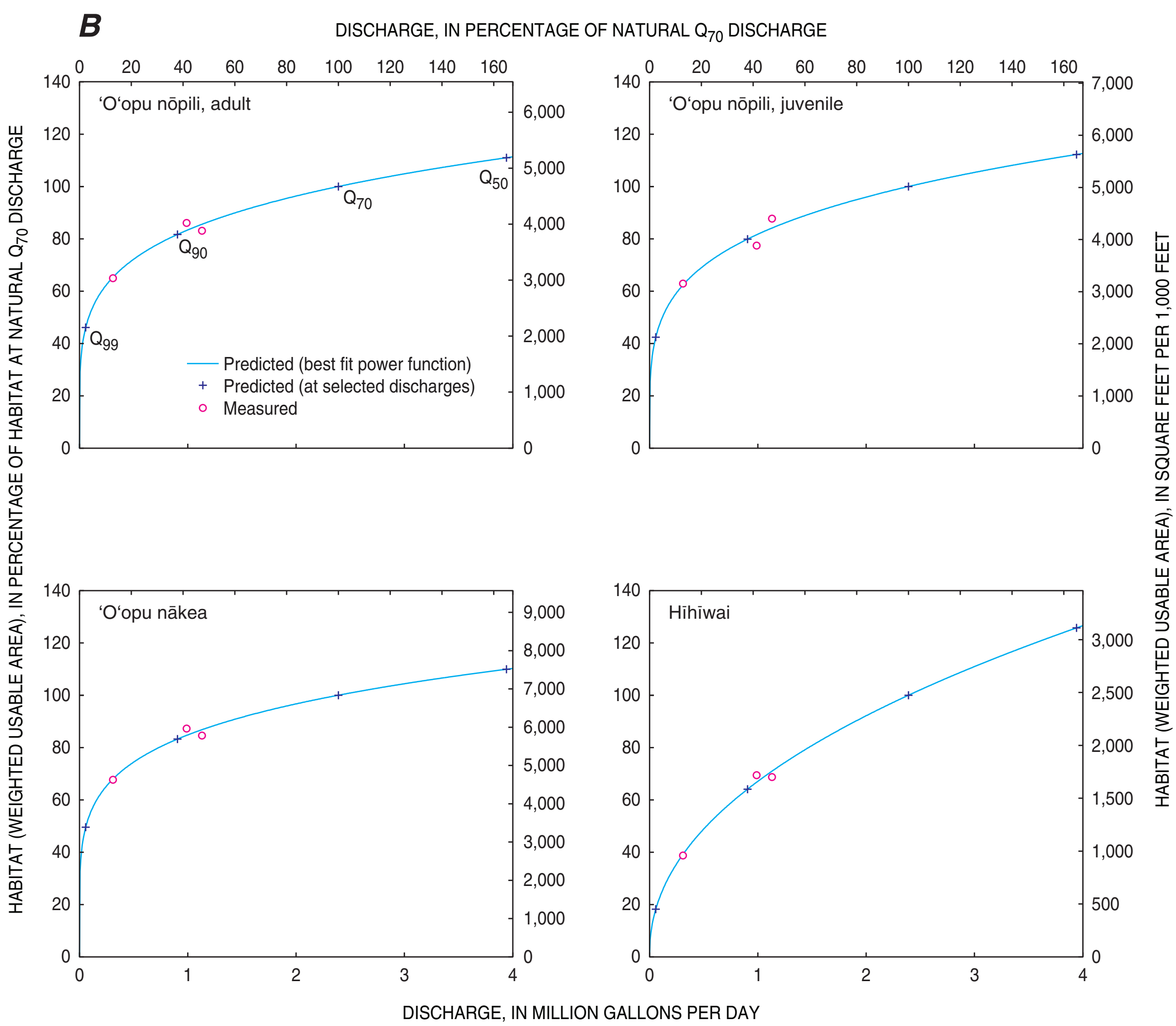


Figure 65.—Continued.

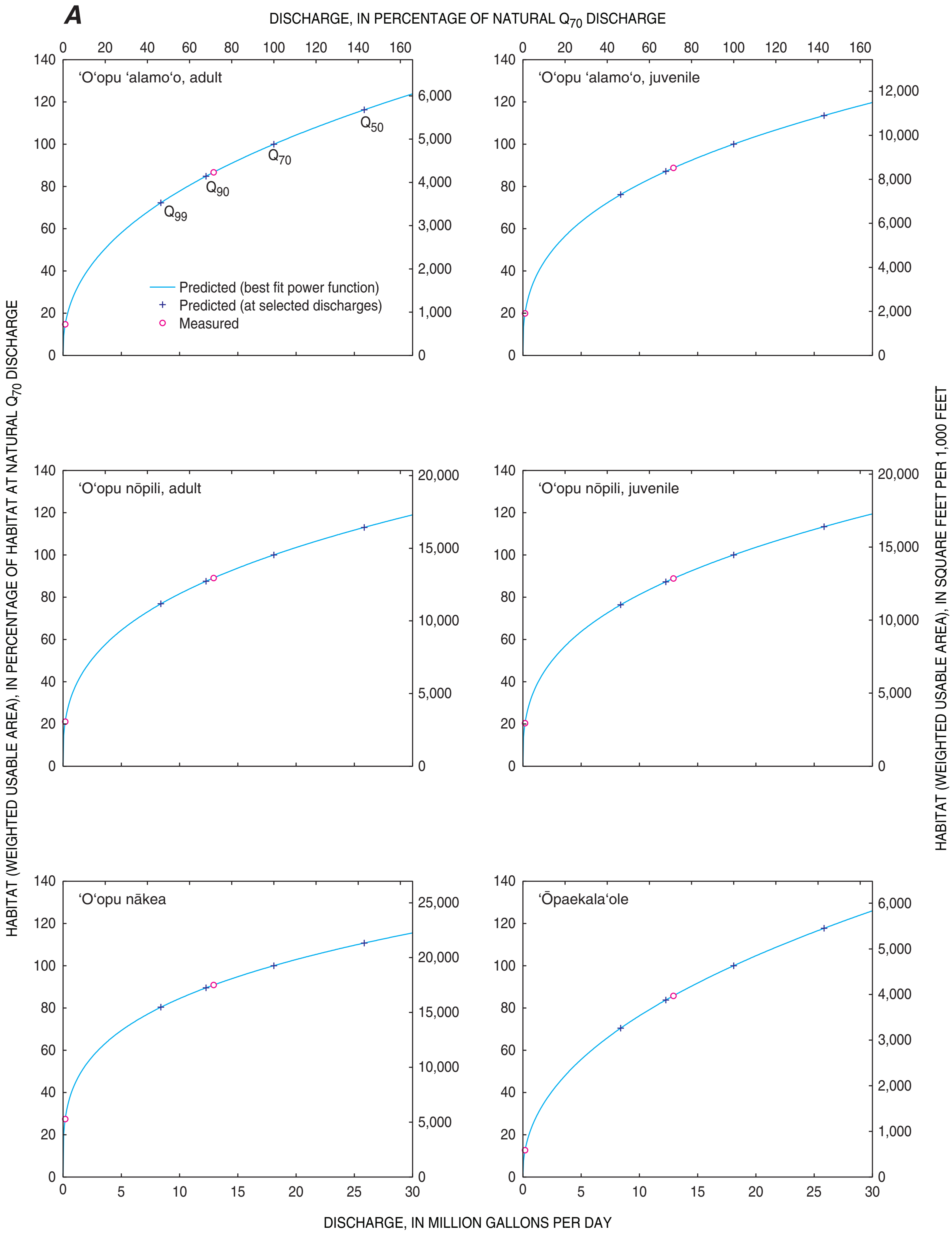


Figure 66. Relations between habitat (weighted usable area) for selected native species and discharge in ʻĪao Stream, Maui, Hawaiʻi. *A*, Altitude of 730 feet. *B*, Altitude of 570 feet. The Q_p discharge is the discharge equaled or exceeded p percent of the time. The natural, undiverted flow characteristics at an altitude of 730 feet are assumed to be equivalent to those at an altitude of 725 feet, and the natural, undiverted flow characteristics at an altitude of 570 feet are assumed to be equivalent to those at an altitude of 595 feet.

equal to 9.8 Mgal/d (15.2 ft^3/s) result in 50 percent reduction in physical habitat near an altitude of 35 ft (fig. 71*A*). If 0.65 Mgal/d (1 ft^3/s) is diverted by the existing private ‘auwai, then combinations of diversion intake capacities for the ‘Īao-Waikapū and ‘Īao-Māniania Ditches and Spreckels Ditch equal to 9.2 Mgal/d (14.2 ft^3/s) result in 50 percent reduction in physical habitat near an altitude of 45 ft (fig. 71*B*).

Waikapū Stream

Reduction in physical habitat (WUA), relative to undiverted low-flow conditions, caused by diversions into the South Side Ditch, Everett Ditch, an existing private ‘auwai with an intake near an altitude of 560 ft, Waihe‘e Ditch, and the Reservoir 6 Ditch was estimated for Waikapū Stream near an altitude of 400 ft (fig. 72) using the generalized relation between habitat and discharge. The effects of diversions on physical habitat near an altitude of 400 ft in Waikapū Stream were evaluated for diversion intake capacities of 0 to 6.5 Mgal/d (0 to 10 ft^3/s) for the South Side Ditch; 0 to 6.5 Mgal/d (0 to 10 ft^3/s) for the combined capacity of a private ‘auwai with an intake near an altitude of 560 ft, Waihe‘e Ditch, and the Reservoir 6 diversion; and 0 or 0.65 Mgal/d (0 or 1 ft^3/s) for Everett Ditch. For this study, the intake capacity of Everett Ditch was assumed to be either 0 (fig. 72*A*) or 0.65 Mgal/d (1 ft^3/s) (fig. 72*B*), which covers the range of available measured diversion rates. The family of curves (fig. 72), with each curve corresponding to a selected value of habitat reduction, shows the relation between capacities of the diversion intakes and habitat reduction during low-flow conditions. Existing diversions by the South Side Ditch, with a reported capacity of 3 Mgal/d (4.6 ft^3/s), and the private ‘auwai with intake near an altitude of 560 feet, Waihe‘e Ditch, and Reservoir 6 Ditch,

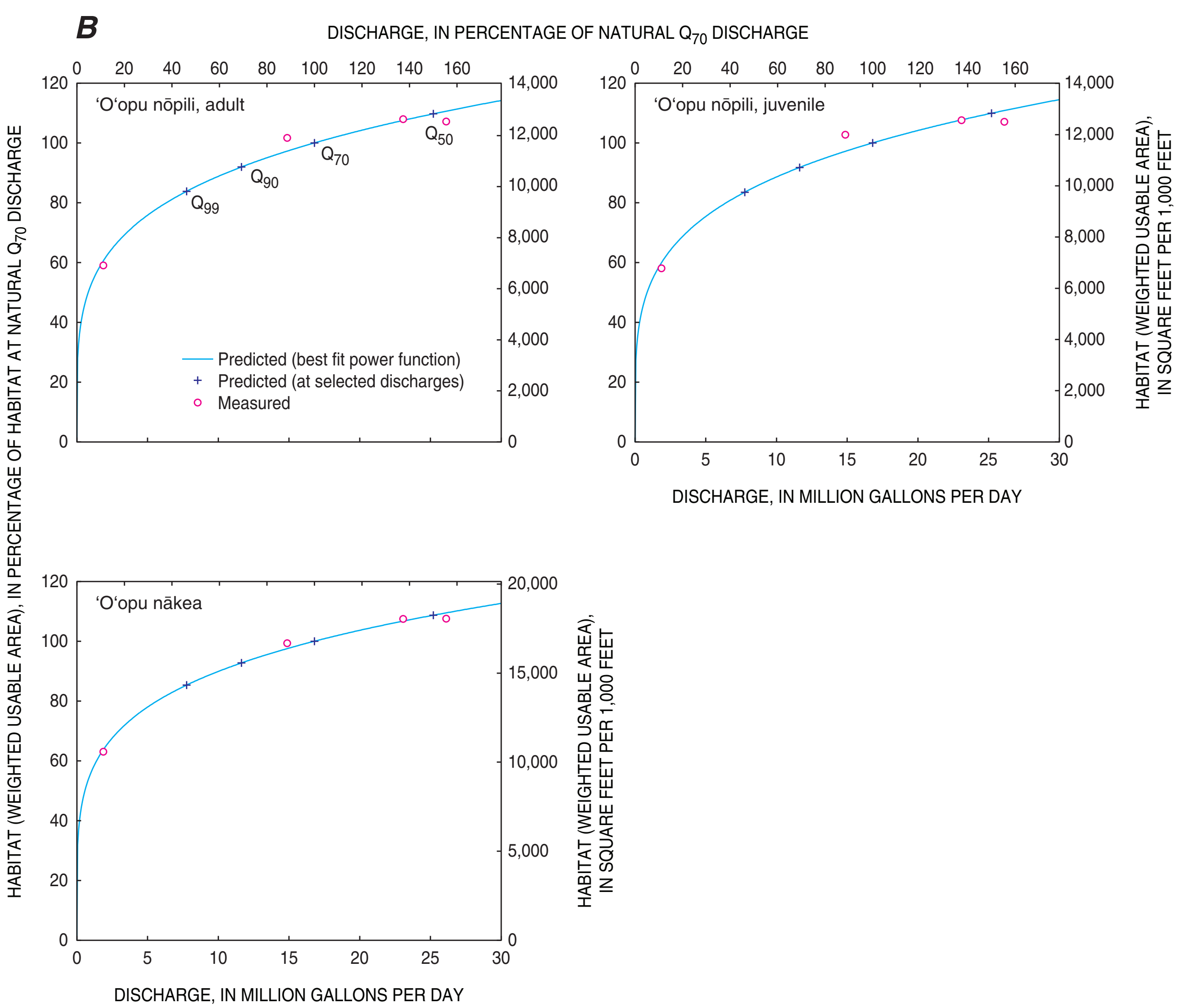


Figure 66.—Continued.

with a combined intake capacity that likely exceeds 2 Mgal/d (3.1 ft^3/s), reduce physical habitat near an altitude of 400 ft by more than 90 percent during low-flow periods if no water is diverted by the Everett Ditch and if no water is returned to the stream upstream of an altitude of 400 feet (fig. 72*A*).

If no water is diverted by Everett Ditch, then different combinations of diversion intake capacity for the South Side Ditch and combined intake capacity for the existing private ʻauwai, Waiheʻe Ditch, and Reservoir 6 Ditch may result in 50 percent reduction in physical habitat near an altitude of 400 ft (fig. 72*A*). For example, if the intake capacity for the South Side Ditch is 0.65 Mgal/d (1.0 ft^3/s) and the combined capacity for the intakes of the existing private ʻauwai, Waiheʻe Ditch, and Reservoir 6 Ditch is about 2.8 Mgal/d (4.3 ft^3/s), then physical habitat will be reduced by 50 percent near an altitude of 400 ft (fig. 72*A*). Similarly, if the intake capacity for the South Side Ditch is 1.9 Mgal/d (3.0 ft^3/s) and the combined capacity for the intakes of the existing private ʻauwai, Waiheʻe Ditch, and Reservoir 6 Ditch is about 1.5 Mgal/d (2.3 ft^3/s), then physical habitat also will be reduced by 50 percent near an altitude of 400 ft (fig. 72*A*).

If the intake capacity for the Everett Ditch is 0.65 Mgal/d (1 ft^3/s), then different combinations of diversion intake capacity for the South Side Ditch and combined intake capacity

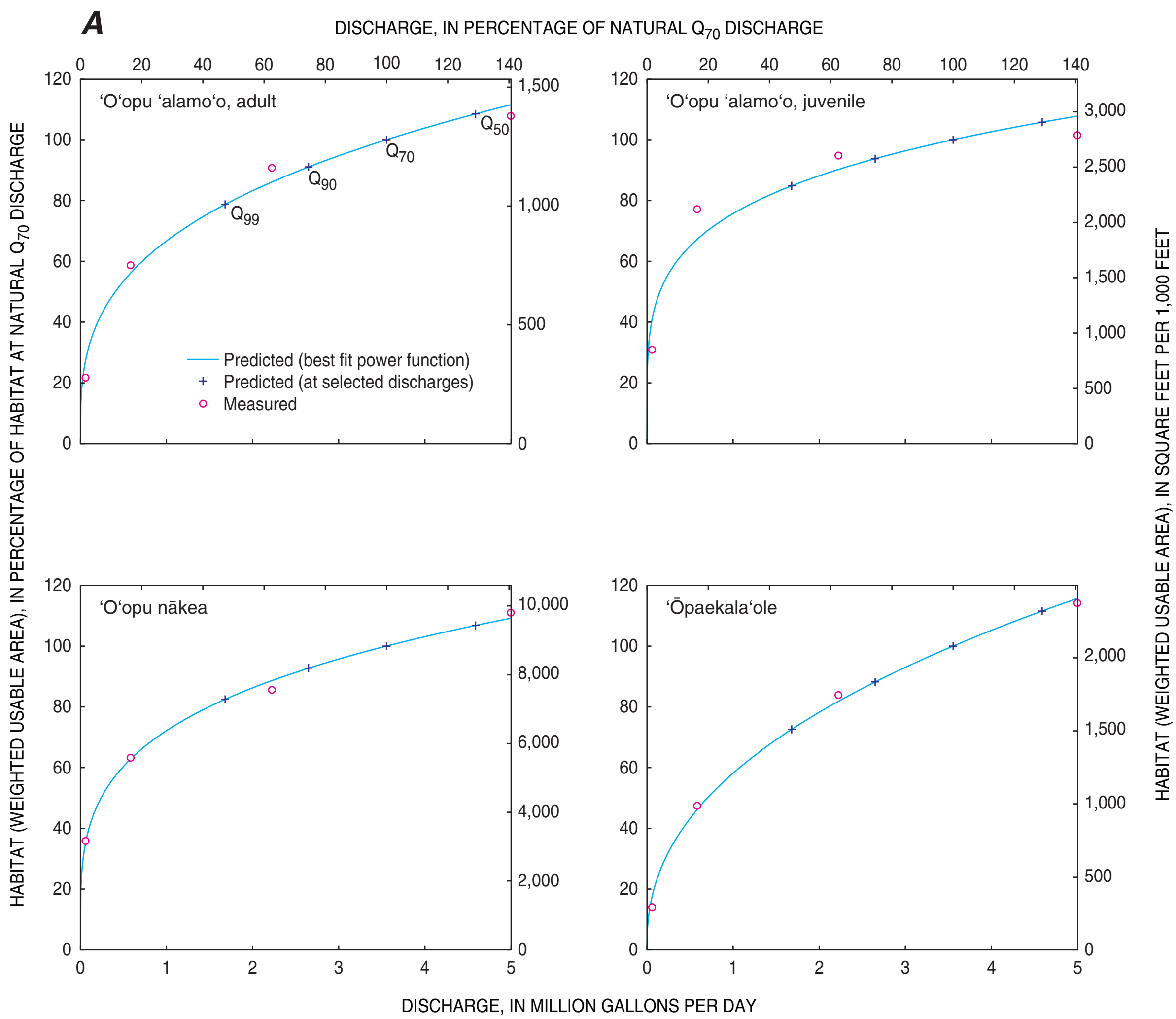


Figure 67. Relations between habitat (weighted usable area) for selected native species and discharge in Waikapū Stream, Maui, Hawaiʻi. *A*, Altitude of 1,050 feet. *B*, Altitude of 840 feet. The Q_p discharge is the discharge equaled or exceeded p percent of the time. The natural, undiverted flow characteristics at an altitude of 1,050 feet are assumed to be equivalent to those at an altitude of 1,080 feet, and the natural, undiverted flow characteristics at an altitude of 840 feet are assumed to be equivalent to those at an altitude of 820 feet.

for the existing private ‘auwai, Waihe‘e Ditch, and Reservoir 6 Ditch may result in 50 percent reduction in physical habitat near an altitude of 400 ft (fig. 72*B*). For example, if the intake capacity for the South Side Ditch is 0.65 Mgal/d (1.0 ft^3/s) and the combined capacity for the intakes of the existing private ‘auwai, Waihe‘e Ditch, and Reservoir 6 Ditch is about 2.1 Mgal/d (3.3 ft^3/s), then physical habitat will be reduced by 50 percent near an altitude of 400 ft (fig. 72*B*). Similarly, if the intake capacity for the South Side Ditch is 1.9 Mgal/d (3.0 ft^3/s) and the combined capacity for the intakes of the existing private ‘auwai, Waihe‘e Ditch, and Reservoir 6 Ditch is about 0.84 Mgal/d (1.3 ft^3/s), then physical habitat also will be reduced by 50 percent near an altitude of 400 ft (fig. 72*B*).

Effects of Surface-Water Diversions on Water Temperature

Upstream diversion of surface water results in decreased flow and, possibly, increased stream temperatures in downstream reaches. Reduced streamflow will lead to lower water velocities and longer traveltimes for water to flow to the ocean. Because of the longer traveltimes, water is exposed to potential heating from the sun for longer periods. In stream reaches that gain water, upstream diversion of surface water may result in decreased water temperatures if local

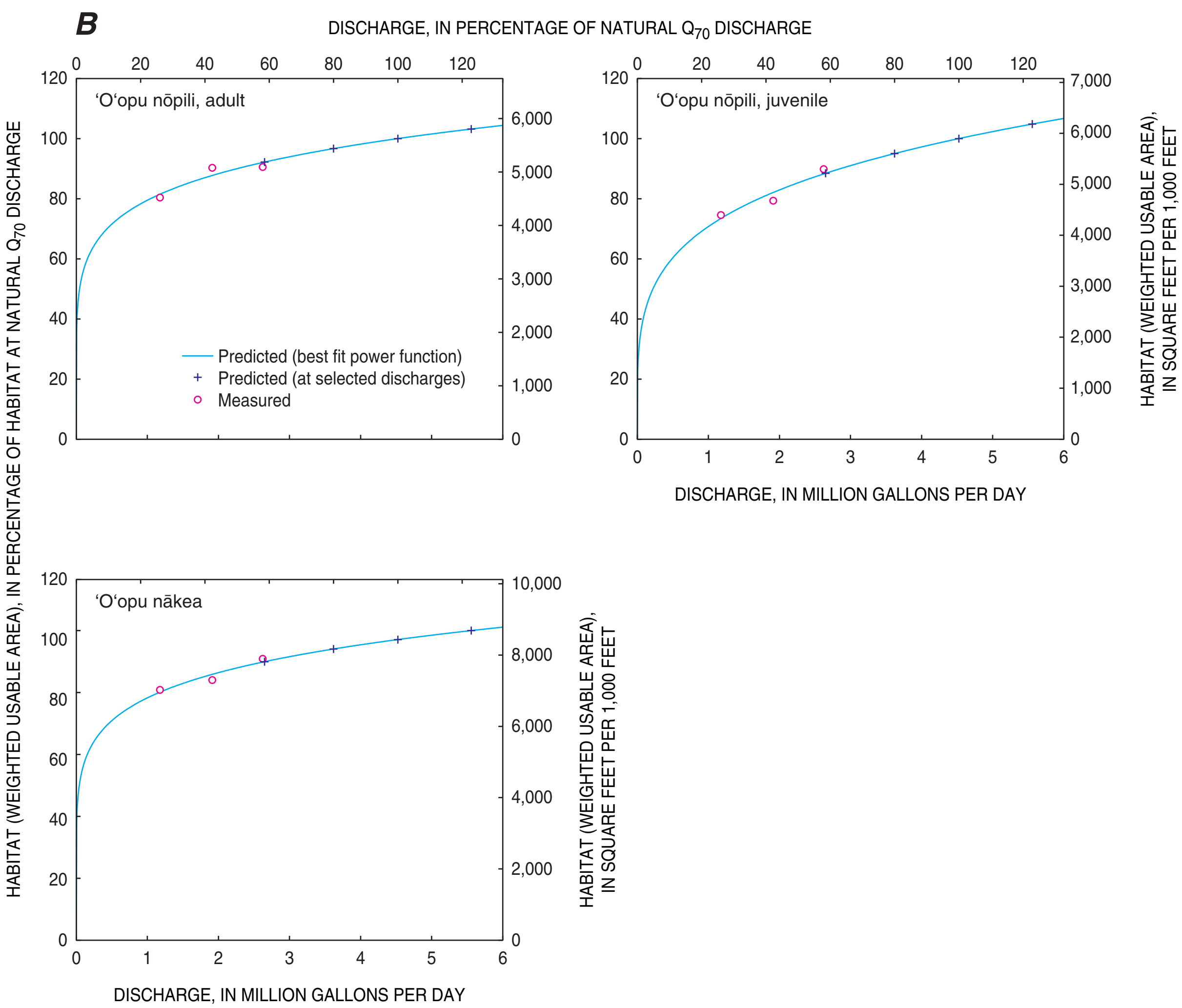


Figure 67.—Continued.

groundwater discharge that is cooler than the diverted water becomes the dominant source of water in the stream.

Stream temperature is a factor that could potentially affect the abundance and distribution of native aquatic species and wetland-taro production. Hathaway (1978) indicated that the upper lethal temperature limits for native aquatic species generally range from about 35°C to 40°C. Wetland-taro agriculture commonly is dependent on surface water from streams for irrigation water. Ooka (1994) indicated that water temperatures exceeding 27°C favors Pythium rot, which transforms the normally firm flesh of the corm of taro into a soft, mushy, often malodorous mass. Pardales and others (1982) indicated that water temperatures above 29°C seemed to be detrimental to root growth in newly planted taro.

To evaluate the effects of diversion of water on stream temperatures in the Nā Wai ‘Ehā area, temperature-recording sensors were placed immediately upstream of all diversions and at selected downstream sites. Temperature was monitored at a total of 18 sites: 4 each on ‘Īao and Waiehu Streams, and 5 each on Waikapū Stream and Waihe‘e River (figs. 21–24, table 24). The sensors generally were placed near the stream thalweg (low point in the stream) to ensure that they remained submerged for all flow conditions that occurred during the study period and that water continuously flowed past the sensors. Sensors were placed in shaded or partially shaded locations where possible. All temperature-recording sensors were programmed to measure temperature at 15-minute intervals during the period between September 2006 and October 2007. At some sites, data were lost because of vandalism, equipment failure, or loss of equipment during periods of high flow.

Daily Mean Temperatures

During the period when temperatures were measured for this study, daily mean water temperatures at the studied sites ranged from 16.5°C to 24.8°C (figs. 73–76). The lowest daily

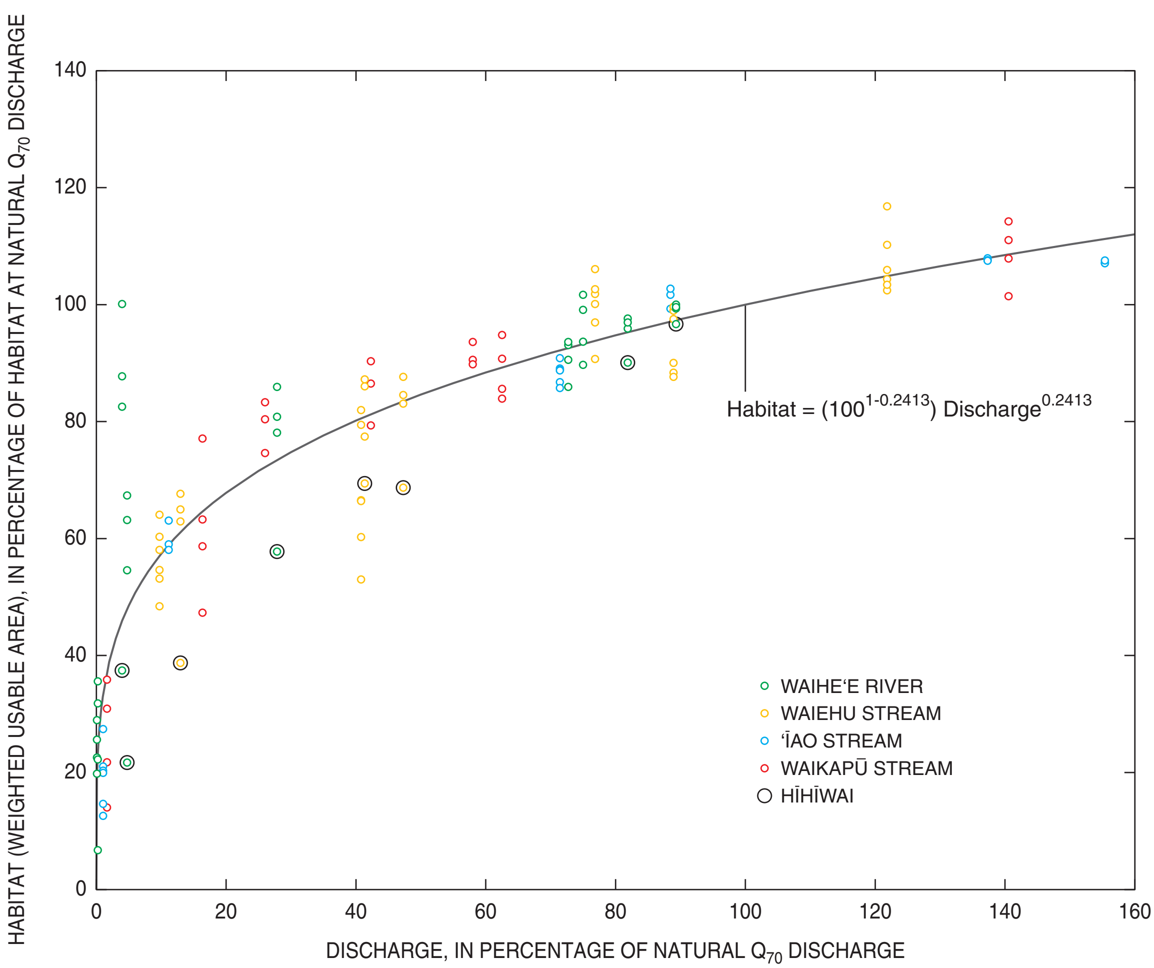


Figure 68. Generalized relation between habitat and discharge for ‘o‘opu ‘alamo‘o, ‘o‘opu nōpili, ‘o‘opu nākea, ‘ōpaekala‘ole, and hīhīwai in Waihe‘e River and Waiehu, ‘Īao, and Waikapū Streams, Maui, Hawai‘i.

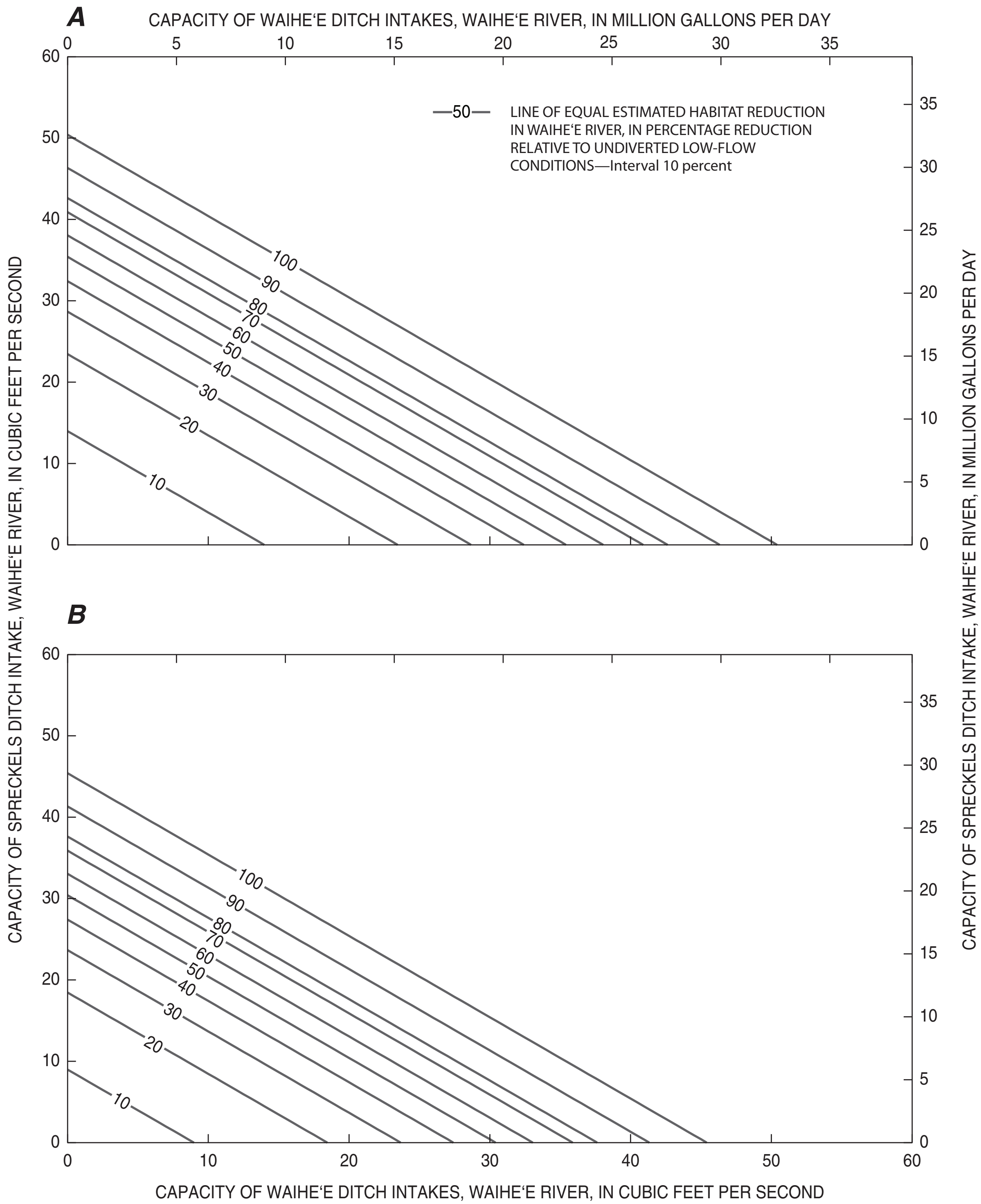


Figure 69. Reduction in physical habitat (average weighted usable area), relative to undiverted conditions, caused by diversions into the Waihe‘e Ditch and Spreckels Ditch with indicated intake capacities, Waihe‘e River near an altitude of 45 feet, Maui, Hawai‘i. *A*, Zero diversion into the Field 1 intake. *B*, Diversion capacity of 3.2 million gallons per day (5 cubic feet per second) for the Field 1 intake. Habitat reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge, using generalized relation between habitat and discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

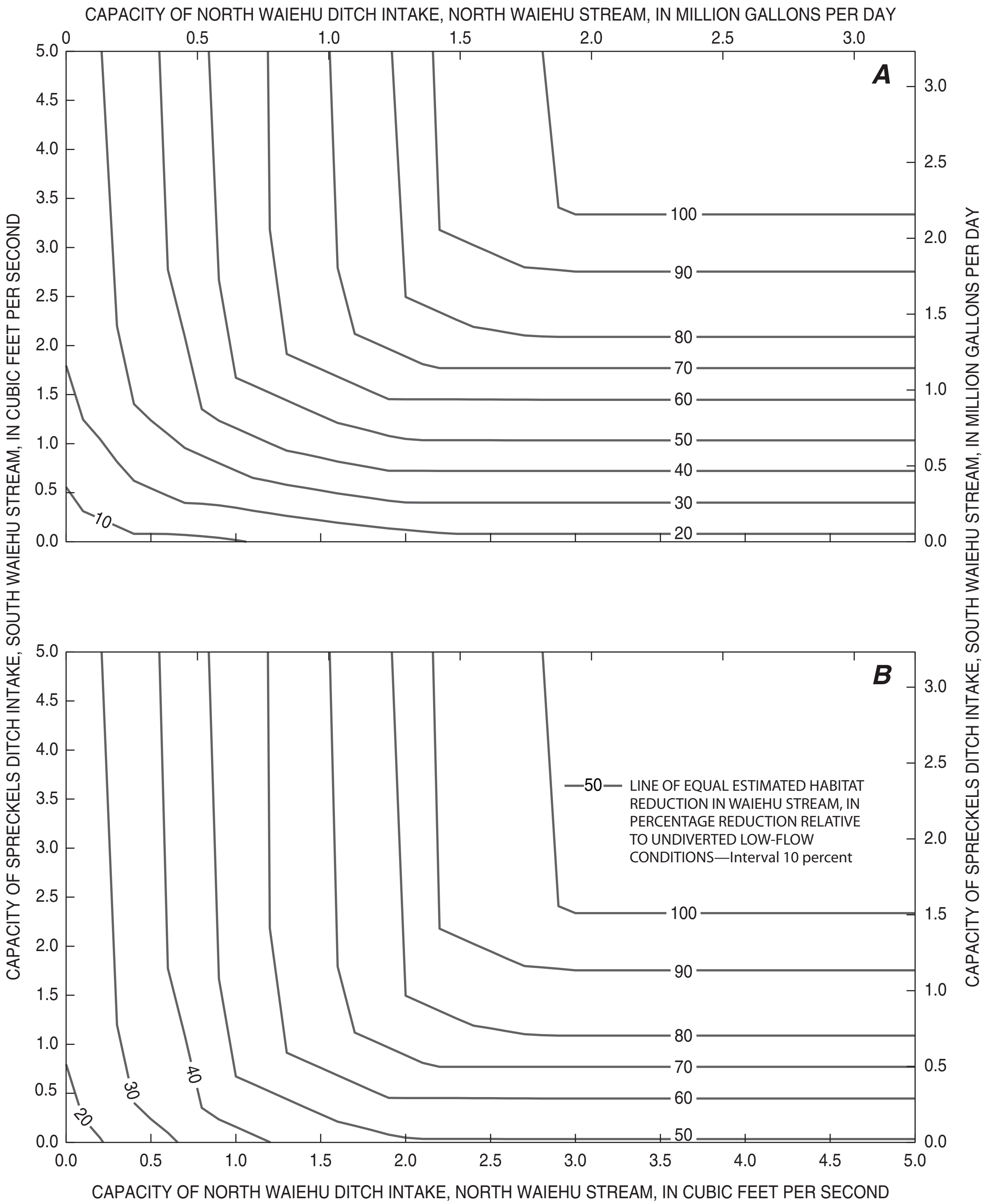


Figure 70. Reduction in physical habitat (average weighted usable area), relative to undiverted conditions, caused by diversions into the North Waiehu and Spreckels Ditches with indicated intake capacities, Waiehu Stream near an altitude of 20 feet, Maui, Hawaiʻi. *A*, zero diversion into two private ʻauwai (ditches) near altitudes of 620 and 570 feet, South Waiehu Stream. *B*, Combined diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for two private ʻauwai near altitudes of 620 and 570 feet, South Waiehu Stream. Habitat reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge, using generalized relation between habitat and discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

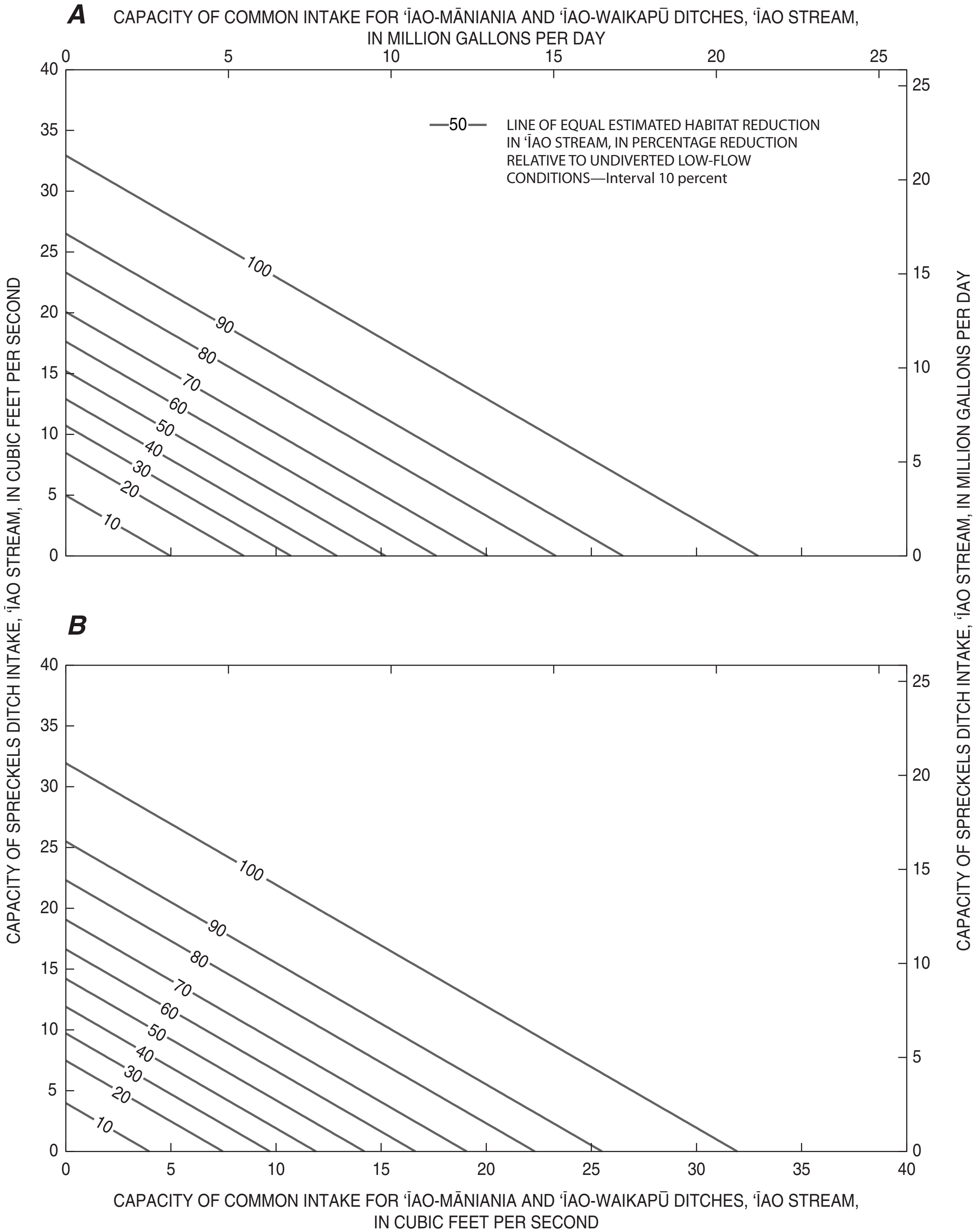


Figure 71. Reduction in physical habitat (average weighted usable area), relative to undiverted conditions, caused by diversions into the ʻĪao-Māniania and ʻĪao-Waikapū Ditches and Spreckels Ditch with indicated intake capacities, ʻĪao Stream near an altitude of 35 feet, Maui, Hawaiʻi. *A*, Zero diversion into a private ʻauwai (ditch) near an altitude of 650 feet. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for a private ʻauwai near an altitude of 650 feet. Habitat reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge, using generalized relation between habitat and discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

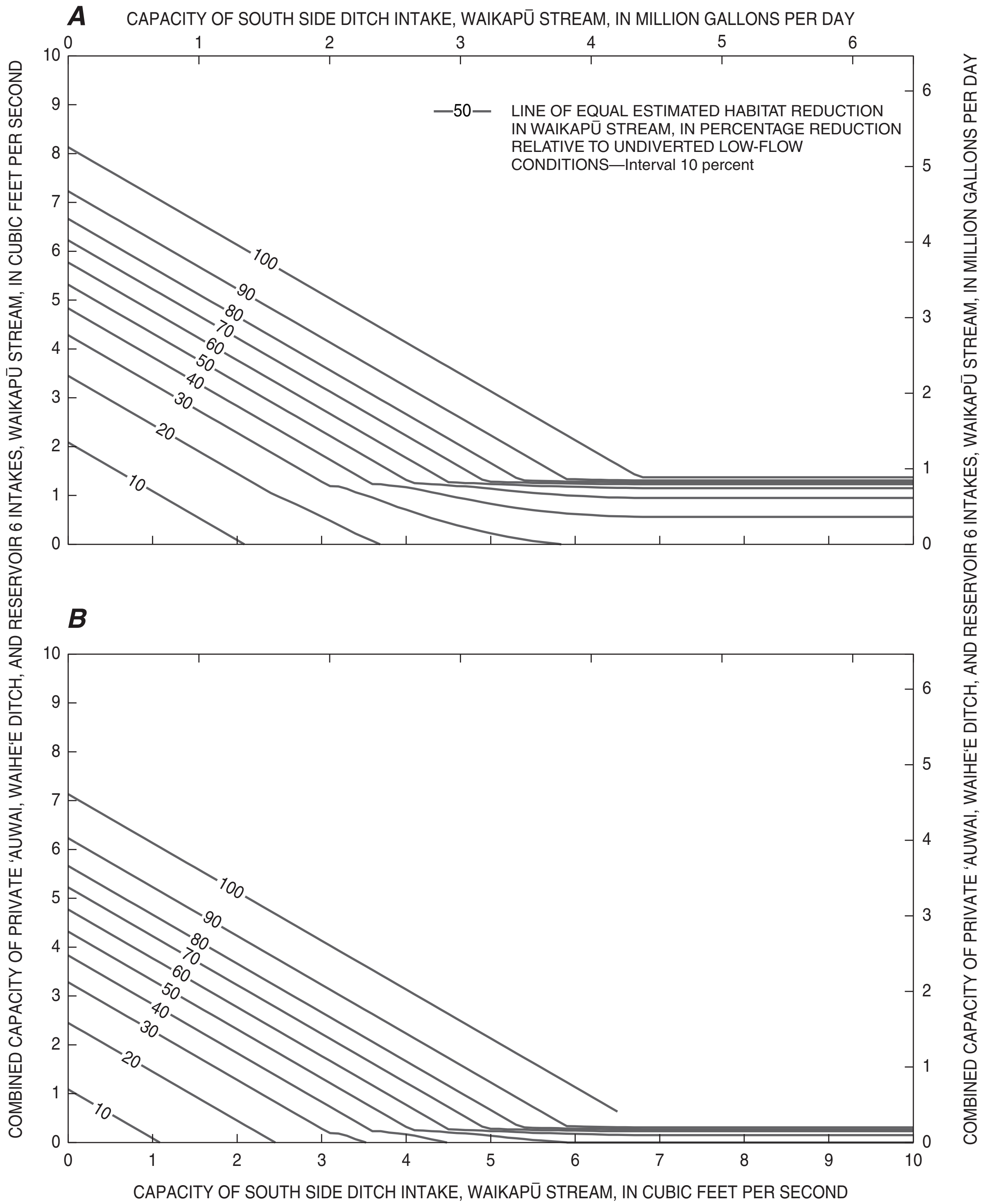


Figure 72. Reduction in physical habitat (average weighted usable area), relative to undiverted conditions, caused by diversion into the South Side Ditch and combined diversions from a private ʻauwai (ditch) near an altitude of 560 feet, Waiheʻe Ditch, and Reservoir 6 Ditch with indicated intake capacities, Waikapū Stream near an altitude of 400 feet, Maui, Hawaiʻi. *A*, Zero diversion into Everett Ditch. *B*, Diversion capacity of 0.65 million gallons per day (1 cubic foot per second) for Everett Ditch. Habitat reduction computed for low-flow periods, when streamflow is less than or equal to the median discharge, using generalized relation between habitat and discharge. A ditch intake is assumed to divert at a rate up to, but not exceeding, the indicated capacity (if streamflow is less than the indicated capacity, then all streamflow at the ditch intake is assumed to be diverted).

mean temperature (16.5°C) was measured during February 2007 at three sites in Waikapū Stream, near altitudes of 1,160 ft, 1,080 ft, and 820 ft. The highest daily mean temperature (24.8°C) was measured during July 2007 in Waiheʻe River near an altitude of 45 ft, downstream of all diversions. Data from all sites indicate that daily mean temperatures were higher (ranging from 19.1°C to 24.8°C) during the months of June through September, which are part of the dry season, and lower (ranging from 16.5°C to 22.5°C) during the months of December through March, which are part of the wet season (figs. 73–76).

In general, stream temperatures increase in a downstream direction (figs. 73–76). An increase in water temperature in a downstream direction is caused partly by an increase in air temperature in a downstream direction, frictional heating, and exposure of the water to solar radiation, which may be enhanced by upstream diversion of water. An increase in water temperature in a downstream direction also may be related to inflows of warmer water from different sources, including natural tributaries, return flows or leakage from ditches, irrigation water that is returned to the stream, and possibly a shallow groundwater body. In some cases, stream temperatures may decrease in a downstream direction because of inflow of relatively cold water between an upstream and downstream measurement site (fig. 76).

Differences in daily mean water temperatures between the uppermost site in a stream and the downstream sites in the same stream generally were larger during the months of June through September and smaller during the months of December through March (figs. 73–76), which may be related to reduced solar radiation during the months of December through March (National Renewable Energy Laboratory, 2009). The longitudinal temperature differences were reduced during periods of heavy rainfall, as indicated by periods of high streamflow (figs. 73, 75). The reduced longitudinal temperature differences during rainy periods may be related to factors including: (1) direct runoff of nearly uniform temperature entering along the length of the stream; (2) a smaller altitudinal air-temperature gradient during rainy periods; (3) a reduced effect of ditch-return flows and irrigation water entering the stream; and (4) increased water velocities and shorter traveltimes, which reduce the possibility for warming of water.

Waiheʻe River

Five temperature-monitoring sites were established in Waiheʻe River near altitudes ranging from 600 to 45 ft. The uppermost site near an altitude of 600 ft was about 15 ft upstream of the left branch intake of Waiheʻe Ditch. The other four sites were located about 1,900, 3,800, 8,200, and 14,000 ft downstream of the uppermost site: the site near an altitude of 500 ft was between the diversion intakes for Waiheʻe and Spreckels Ditches, and downstream of where water is sometimes returned to Waiheʻe River from the Waiheʻe Ditch; the site near an altitude of 400 ft was immediately upstream of the intake for Spreckels Ditch; the site near an altitude of 260 ft was 4,400 ft downstream of the intake for Spreckels Ditch; and the site near an altitude of 45 ft was about 1,500 ft upstream of the coast.

During the period March through September 2007, for which complete records are available at all five sites, the overall average water temperatures were 19.5, 20.4, 21.2, 21.9, and 22.7°C near stream altitudes of 600, 500, 400, 260, and 45 ft, respectively (table 24). Between altitudes of 600 and 500 ft, the average temperature gradient (temperature change per 1,000 feet of stream length) during March through September 2007 was 0.5°C per 1,000 ft; between altitudes of 500 and 400 ft, the average temperature gradient was 0.4°C per 1,000 ft; between altitudes of 400 and 260 ft, the average temperature gradient was 0.2°C per 1,000 ft; and between altitudes of 260 and 45 ft, the average temperature gradient was 0.1°C per 1,000 ft. The average temperature gradient between adjacent sites was greatest between altitudes of 600 and 500 ft, which bracket the diversion intakes for the Waiheʻe Ditch. Daily mean temperatures near an altitude of 600 ft were less than corresponding daily mean temperatures at all downstream sites (fig. 73).

Downstream increases in temperature potentially could be reduced if no water is diverted from the stream. For example, during June 15–20, 2007, photographic data indicate that water diverted from Waiheʻe River by the Waiheʻe Ditch was returned to Waiheʻe River about 400 ft downstream of the diversion intakes, and the restored flow continued past the lowest measurement site near an altitude of 45 ft. During this period, measured temperatures decreased by about 2–3°C, relative to the period just before the flow restoration, at sites downstream of where water was returned to Waiheʻe River (fig. 73). Also during this period, temperature increases between the upstream site and the downstream sites were reduced (fig. 73), which may be partly explained by the flow restoration. During June 16–19, 2007 (flow was restored on only parts of June 15 and 20, 2007), the average water temperatures were 19.5, 19.6, 19.9, 20.5, and 21.2°C near stream altitudes of 600, 500, 400, 260, and 45 ft, respectively. During the June 16–19, 2007, period of flow restoration, the difference between average water temperatures near altitudes of 45 and 600 ft was 1.7°C, whereas during the period March through September 2007, the difference was 3.2°C.

South Waiehu Stream

Three temperature-monitoring sites were established in South Waiehu Stream near altitudes of 635, 555, and 290 ft, and one site was established in Waiehu Stream near an altitude of 190 ft. The uppermost site near an altitude of 635 ft was upstream of all known existing diversions. The other three sites were located 1,600, 7,300, and 9,600 ft downstream of the uppermost site: the site near an altitude of 555 ft was about 150 ft upstream of the Waiheʻe Ditch flume over South

Table 24. Temperature-monitoring sites, Nā Wai ʻEhā, Maui, Hawaiʻi.

[—, more than one missing daily mean value during the period March through September, 2007; ft, feet]

Site	USGS site no.	Altitude, in feet	Average temperature, in degrees Celsius[1]	Average diurnal temperature variation, in degrees Celsius[2]	Description
Waiheʻe River					
1	205611156324601	600	19.5	1.5	15 feet upstream of Waiheʻe Ditch intakes
2	205625156323401	500	20.4	1.6	1,900 feet downstream of Waiheʻe Ditch intakes
3	205632156322001	400	21.2	2.2	50 feet upstream of Spreckels Ditch intake
4	205635156313901	260	21.9	1.4	4,400 feet downstream of Spreckels Ditch intake
5	205644156304401	45	22.7	2.9	1,500 feet upstream of coast
South Waiehu Stream					
1	205427156313101	635	19.9	1.0	upstream of private ʻauwai intakes
2	205433156311501	555	20.4	1.4	downstream of private ʻauwai intakes
3	205439156303401	290	21.0	1.7	400 feet upstream of Spreckels Ditch intake
4 (Waiehu Stream)	205455156302301	190	22.2	2.4	downstream of confluence of North and South Waiehu Streams
ʻĪao Stream					
1	205250156324401	920	19.8	2.2	2,400 feet upstream of ʻĪao-Waikapū Ditch intake[3]
2	205255156322401	810	19.9	2.2	400 feet upstream of ʻĪao-Waikapū Ditch intake[3]
3	205256156321601	740	20.4	1.0	500 feet downstream of ʻĪao-Waikapū Ditch intake[3]
4	205304156314401	580	21.2	2.3	4,000 feet downstream of ʻĪao-Waikapū Ditch intake[3]
Waikapū Stream					
1	205121156321501	1,160	19.2	1.1	700 feet upstream of South Side Ditch intake
2	205123156320501	1,080	—	—	800 feet downstream of South Side Ditch intake
3	205126156315501	1,020	18.9	1.1	600 feet downstream of unnamed tributary inflow
4	205120156312801	820	19.5	1.5	1,300 feet downstream of Everett Ditch intake
5	205125156304801	560	20.3	2.0	upstream of private ʻauwai intake

[1]Average water temperature during March through September, 2007.
[2]Average difference between daily maximum and minimum water temperatures during March through September, 2007.
[3]The ʻĪao-Waikapū Ditch shares a common intake with the ʻĪao-Māniania Ditch.

Waiehu Stream; the site near an altitude of 290 ft was about 400 ft upstream of the diversion intake for Spreckels Ditch; and the site in Waiehu Stream near an altitude of 190 ft was downstream of all known diversions.

During the period March through September 2007, for which complete records are available at all four sites, the overall average water temperatures were 19.9, 20.4, 21.0, and 22.2°C near stream altitudes of 635, 555, 290, and 190 ft, respectively (table 24). Between altitudes of 635 and 555 ft, the average temperature gradient during March through September 2007 was 0.3°C per 1,000 ft; between altitudes of 555 and 290 ft, the average temperature gradient was 0.1°C per 1,000 ft; and between altitudes of 290 and 190 ft, the average temperature gradient was 0.5°C per 1,000 ft. The average temperature gradient between adjacent sites was greatest between altitudes of 290 and 190 ft, which bracket the diversion intake for Spreckels Ditch in South Waiehu Stream. Daily mean temperatures at an altitude of 635 ft were less than corresponding daily mean temperatures at all downstream sites (fig. 74).

ʻĪao Stream

Four temperature-monitoring sites were established in ʻĪao Stream near altitudes of 920, 810, 740, and 580 ft. The two upper sites were upstream of the common intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and were established to evaluate the natural change in temperature in ʻĪao Stream. The sites near altitudes of 920 and 810 ft were, respectively, about 2,400 and 400 ft upstream of the diversion intake, and the sites near altitudes of 740 and 580 ft were, respectively, about 500 and 4,000 ft downstream of the intake.

To evaluate the natural change in temperature in ʻĪao Stream upstream of the common intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches, temperature sensors were placed near stream altitudes of 920 and 810 ft. On average, daily mean temperatures at the downstream site were about 0.1°C warmer than at the upstream site, located about 2,000 ft upstream. This natural increase in temperature in ʻĪao Stream

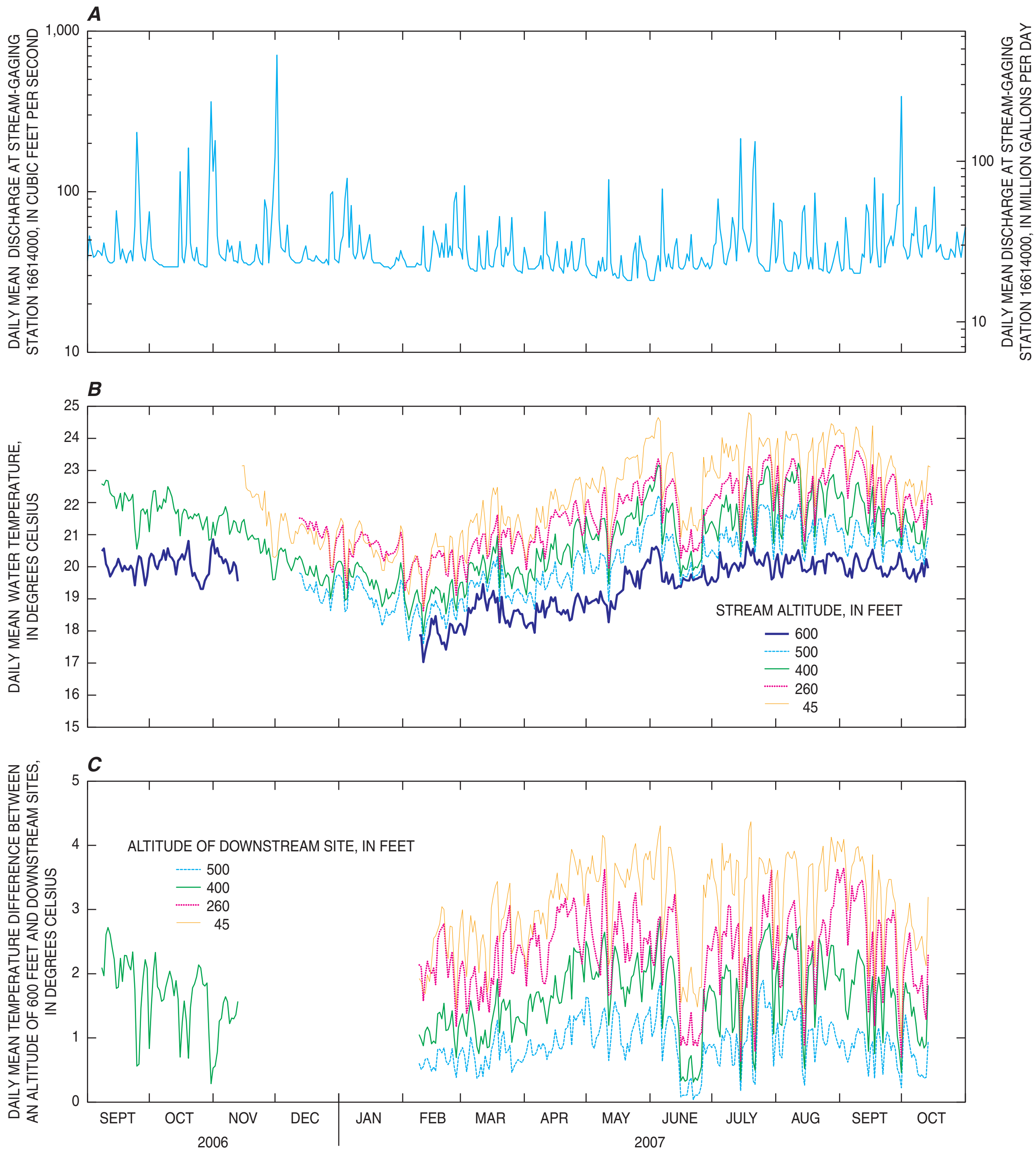


Figure 73. Daily mean discharge and water temperatures, Waihe‘e River, Maui, Hawai‘i. *A*, Daily mean discharge at stream-gaging station 16614000. *B*, Daily mean water temperatures between altitudes of 600 and 45 feet. *C*, Daily mean temperature difference between an altitude of 600 feet (upstream of the Waihe‘e Ditch intakes) and downstream sites. A positive temperature difference indicates water temperature at downstream site is greater than water temperature at an altitude of 600 feet.

in a downstream direction could be affected by inflow of colder groundwater between the two measurement sites (the sites are in the area of dike-impounded groundwater, where groundwater levels are expected to be high), although no measurements of streamflow gain between these two sites were made during the study.

During the period March through September 2007, for which nearly complete records are available at all four sites (the site at an altitude of 810 ft has one missing daily mean temperature value), the overall average water temperatures were 19.8, 19.9, 20.4, and 21.2°C near stream altitudes of 920, 810, 740, and 580 ft, respectively (table 24). Between altitudes of 920 and 810 ft, the average temperature gradient during March through September 2007 was 0.05°C per 1,000 ft; between altitudes of 810 and 740 ft, the average temperature gradient was 0.6°C per 1,000 ft; and between altitudes of 740 and 580 ft, the average temperature gradient was 0.2°C per 1,000 ft. The average temperature gradient between adjacent sites was greatest between altitudes of 810 and 740 ft, which bracket the diversion intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches. Daily mean temperatures at an altitude of 920 ft generally were less than corresponding daily mean temperatures at the downstream sites, although the daily mean temperature near an altitude of 920 ft was sometimes higher than that near an altitude of 740 ft (fig. 75), and this condition may be related to diversion of water (see following section entitled "Diurnal Temperature Variations").

Waikapū Stream

Five temperature-monitoring sites were established in Waikapū Stream near altitudes ranging from 1,160 to 560 ft. The uppermost site near an altitude of 1,160 ft was about 700 feet upstream of the intake for the South Side Ditch. The other four sites were located about 1,500, 2,600, 5,900,

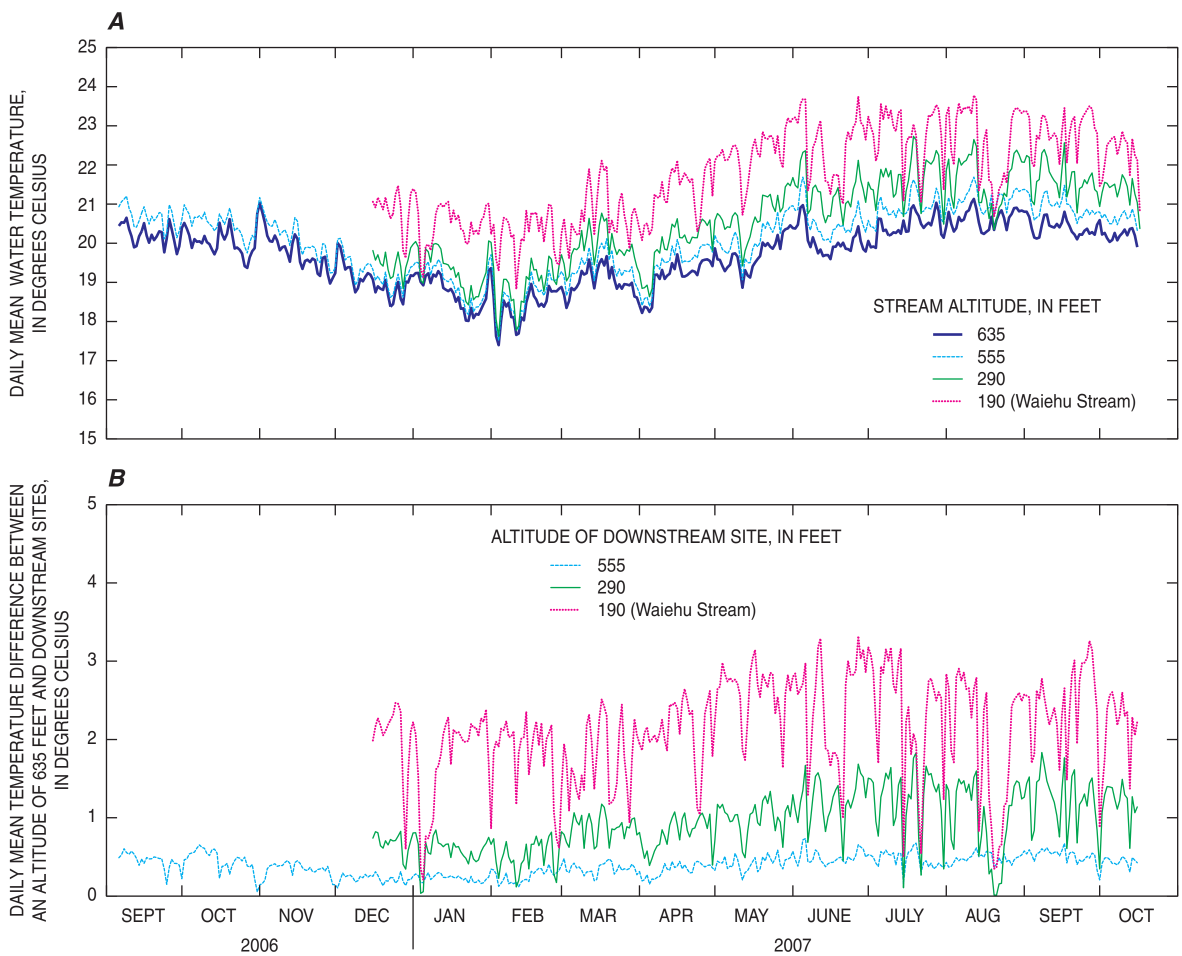


Figure 74. Daily mean water temperatures between altitudes of 635 and 190 feet, South Waiehu Stream, Maui, Hawaiʻi. *A*, Daily mean water temperatures. *B*, Daily mean temperature difference between an altitude of 635 feet (upstream of diversions) and downstream sites. A positive temperature difference indicates water temperature at downstream site is greater than water temperature at an altitude of 635 feet.

and 11,000 ft downstream of the uppermost site: the site near an altitude of 1,080 ft was about 800 ft downstream of the intake for the South Side Ditch; the site near an altitude of 1,020 ft was about 600 ft downstream of the confluence of Waikapū Stream and an unnamed tributary; the site near an altitude of 820 ft was about 1,300 ft downstream of the intake for the Everett Ditch; and the site near an altitude of 560 ft was about 100 ft upstream of the intake for an existing community ‘auwai.

During the period March through September 2007, for which complete records are available at four of the five sites, the overall average water temperatures were 19.2, 18.9, 19.5, and 20.3°C near stream altitudes of 1,160, 1,020, 820, and 560 ft, respectively (table 24). Between altitudes of 1,160 and 1,020 ft, the average temperature gradient during March through September 2007 was −0.1°C per 1,000 ft; between altitudes of 1,020 and 820 ft, the average temperature gradient was 0.2°C per 1,000 ft; and between altitudes of 820 and 560 ft, the average temperature gradient was 0.2°C per 1,000 ft. The average temperature gradient was greatest downstream of the diversion intake for the South Side Ditch and also downstream of the unnamed tributary that enters the north side (left side as viewed downstream) of Waikapū Stream near an altitude of 1,050 ft.

Daily mean temperatures near an altitude of 1,160 ft were less than corresponding daily mean temperatures near an altitude of 560 ft and generally were less than daily mean temperatures near an altitude of 820 ft (fig. 76). However, daily mean temperatures near an altitude of 1,160 ft commonly were higher than daily mean temperatures near an altitude of 1,020 ft (fig. 76). Stream temperatures decreased in a downstream direction between altitudes of 1,160 and 1,020 ft because of inflow of relatively cold water from the unnamed tributary between the upstream and downstream sites.

Diurnal Temperature Variations

Because exposure to lethal temperatures for short durations, in some cases less than 30 minutes (Hathaway, 1978), can cause death in native aquatic species, maximum and minimum daily temperatures were considered. Temperatures vary on a diurnal basis because of diurnal variations in energy (in the form of solar radiation and longwave radiation) received in the stream valleys. During daytime hours, incoming solar radiation causes stream temperatures to increase, whereas during the nighttime, loss of infrared energy from the surface causes stream temperatures to decrease. During the periods when measured temperatures were available, daily maximum temperatures did not exceed 27°C and daily minimum temperatures did not drop below 15°C at any of the study sites (figs. 77–80). At all of the study sites, daily maximum temperatures remained below the upper-lethal-temperature limits for native aquatic species (Hathaway, 1978), as well as below the temperature (27°C) that favors Pythium rot of taro (Ooka, 1994). In general, maximum temperatures occurred during the afternoon hours (between about 1:00 p.m. and 6:00 p.m.) and minimum temperatures occurred in the morning hours (between about 3:00 a.m. and 8:00 a.m.). Differences between measured daily maximum and minimum temperatures generally are greatest at the lowest site and least at the highest site on a stream and were enhanced during warm, dry periods and reduced during cool, wet periods (fig. 77).

Waihe‘e River

During the period March through September 2007, the average differences between measured daily maximum and minimum temperatures were 1.5, 1.6, 2.2, 1.4, and 2.9 °C near stream altitudes of 600, 500, 400, 260, and 45 ft, respectively (table 24). During low-flow conditions, surface flows past the Waihe‘e Ditch and Spreckels Ditch diversion intakes in Waihe‘e River were typically zero when available streamflow did not exceed the capacity of the intakes. As a result, at some reaches downstream of diversions, standing water and low flows during dry-weather conditions were sustained mainly by local groundwater discharge. For sites near sources of groundwater discharge, diurnal temperature variations may be small because temporal variations in groundwater temperatures are relatively small. The site near an altitude of 260 ft has a smaller average diurnal temperature variation than the upstream sites, which may reflect a local source of groundwater input to the stream that is the main source of water during low-flow conditions when water was being diverted upstream. Flow past the lowest measurement site near an altitude of 45 ft is sustained mainly by return of irrigation water to Waihe‘e River upstream of this site and downstream of the site near an altitude of 260 ft.

South Waiehu Stream

During the period March through September 2007, the average differences between measured daily maximum and minimum temperatures were 1.0, 1.4, 1.7, and 2.4°C near stream altitudes of 635, 555, 290, and 190 ft, respectively (table 24). The average difference between measured daily maximum and minimum temperatures increases in a downstream direction.

‘Īao Stream

During the period March through September 2007, the average differences between measured daily maximum and minimum temperatures were 2.2, 2.2, 1.0, and 2.3°C near stream altitudes of 920, 810, 740, and 580 ft, respectively (table

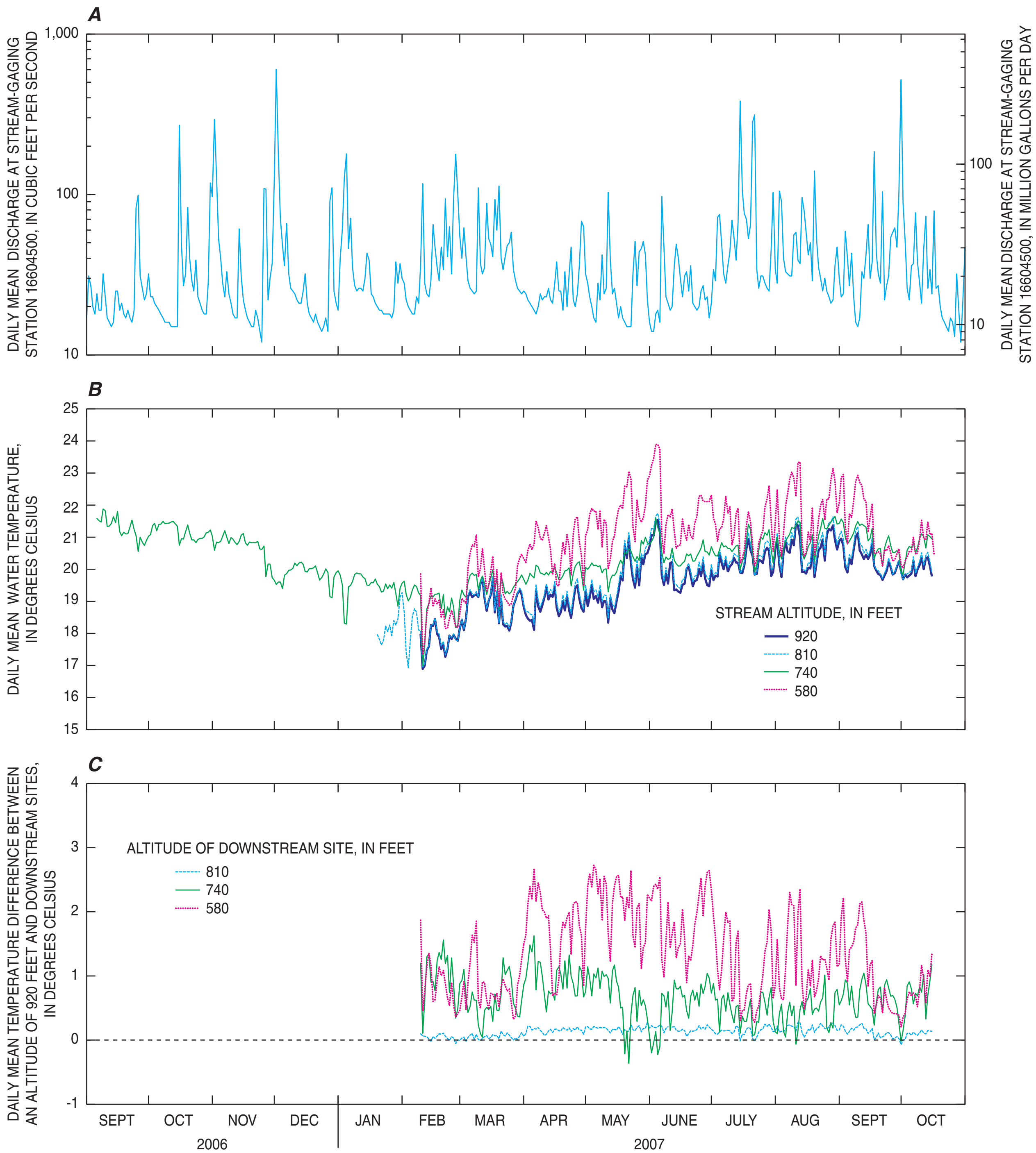


Figure 75. Daily mean discharge and water temperatures, ‘Īao Stream, Maui, Hawai‘i. *A*, Daily mean discharge at stream-gaging station 16604500. *B*, Daily mean water temperatures between altitudes of 920 and 580 feet. *C*, Daily mean temperature difference between an altitude of 920 feet (upstream of the ‘Īao-Waikapū and ‘Īao-Māniania Ditch intakes) and downstream sites. A positive temperature difference indicates water temperature at downstream site is greater than water temperature at an altitude of 920 feet.

24). During low-flow conditions, surface flows in ʻĪao Stream past the intake for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches were typically zero when available streamflow did not exceed the capacity of the intake. As a result, low flows immediately downstream of the intake during dry-weather conditions were sustained mainly by local groundwater discharge. The site near an altitude of 740 ft has a smaller average diurnal temperature variation than the upstream sites, which may reflect a local source of groundwater input to the stream that is the main source of water during low-flow periods when water was being diverted upstream.

Waikapū Stream

During the period March through September 2007, the average differences between measured daily maximum and minimum temperatures were 1.1, 1.1, 1.5, and 2.0°C near stream altitudes of 1,160, 1,020, 820, and 560 ft, respectively (table 24). The average difference between measured daily maximum and minimum temperatures generally increases in a downstream direction, although the average differences at 1,160 and 1,020 ft are the same, possibly because of the inflow of relatively cold water from an unnamed tributary between the two sites.

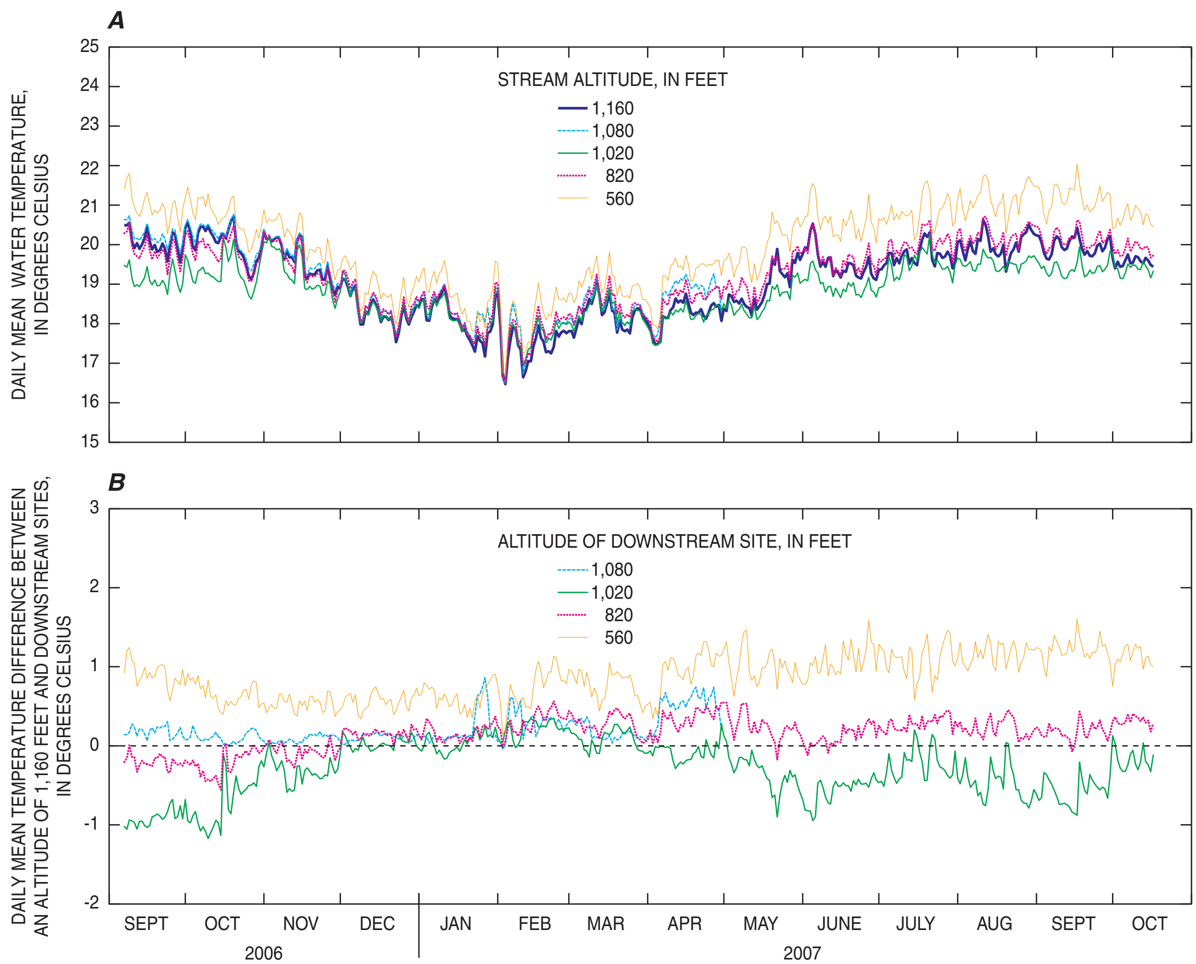


Figure 76. Daily mean water temperatures between altitudes of 1,160 and 560 feet, Waikapū Stream, Maui, Hawaiʻi. *A*, Daily mean water temperatures. *B*, Daily mean temperature difference between an altitude of 1,160 feet (upstream of the South Side Ditch intake) and downstream sites. A positive temperature difference indicates water temperature at downstream site is greater than water temperature at an altitude of 1,160 feet.

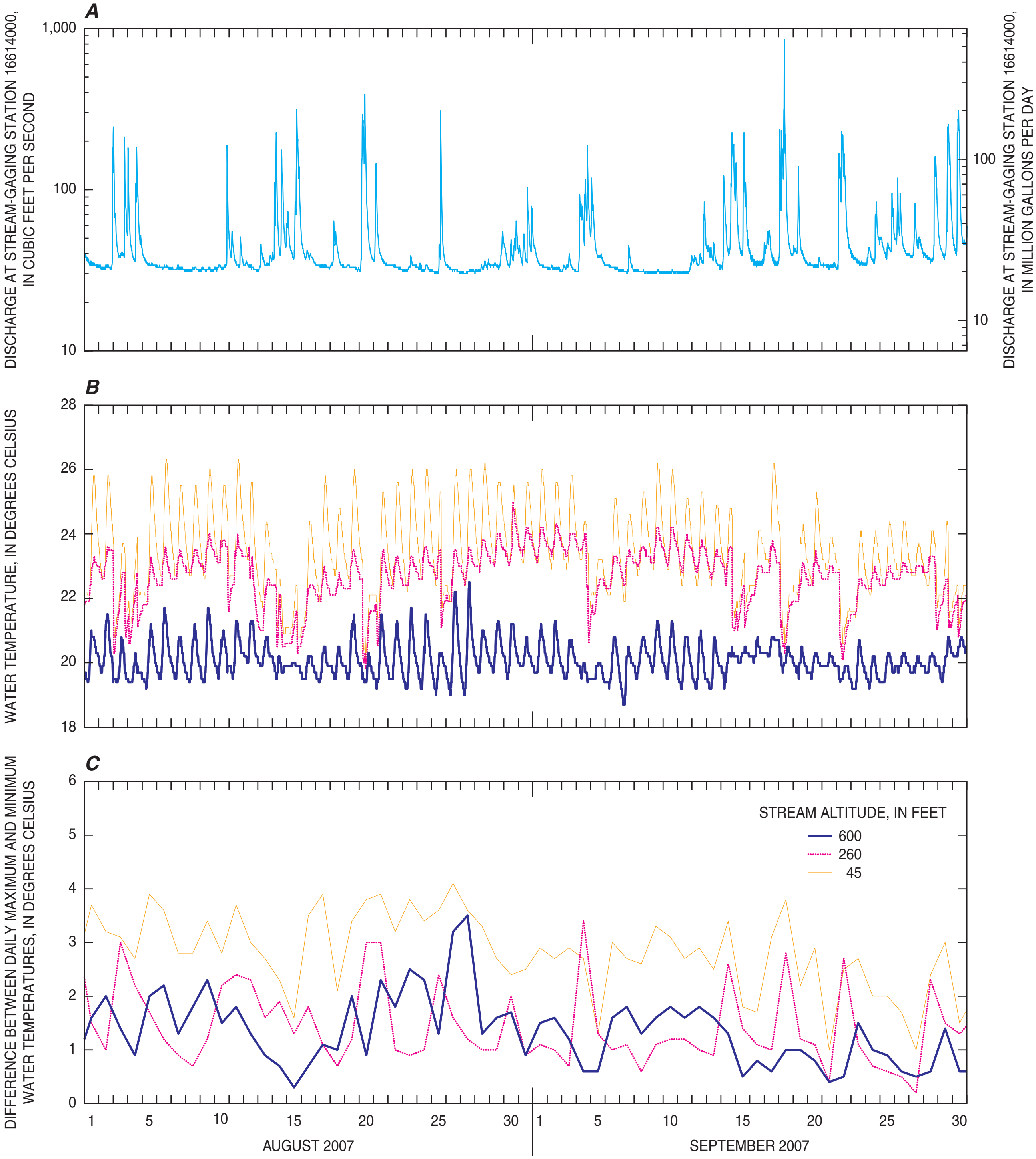


Figure 77. Discharge and water temperatures during August and September, 2007, Waiheʻe River, Maui, Hawaiʻi. *A*, Discharge at stream-gaging station 16614000. *B*, Water temperatures (measured at 15-minute intervals) between altitudes of 600 and 45 feet. *C*, Difference between daily maximum and minimum water temperatures.

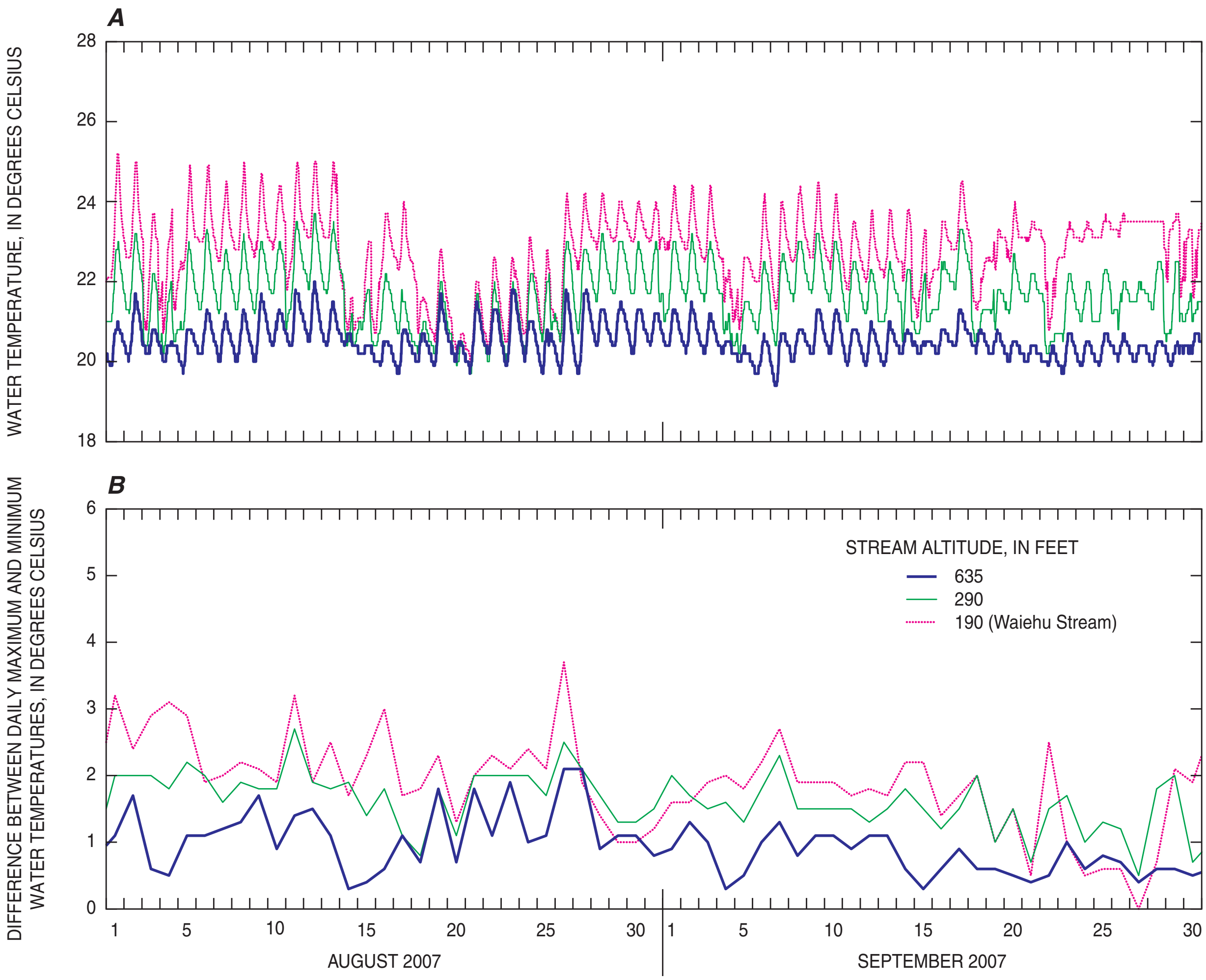


Figure 78. Water temperatures during August and September, 2007, South Waiehu Stream, Maui, Hawai‘i. *A*, Water temperatures (measured at 15-minute intervals) between altitudes of 635 and 190 feet. *B*, Difference between daily maximum and minimum water temperatures.

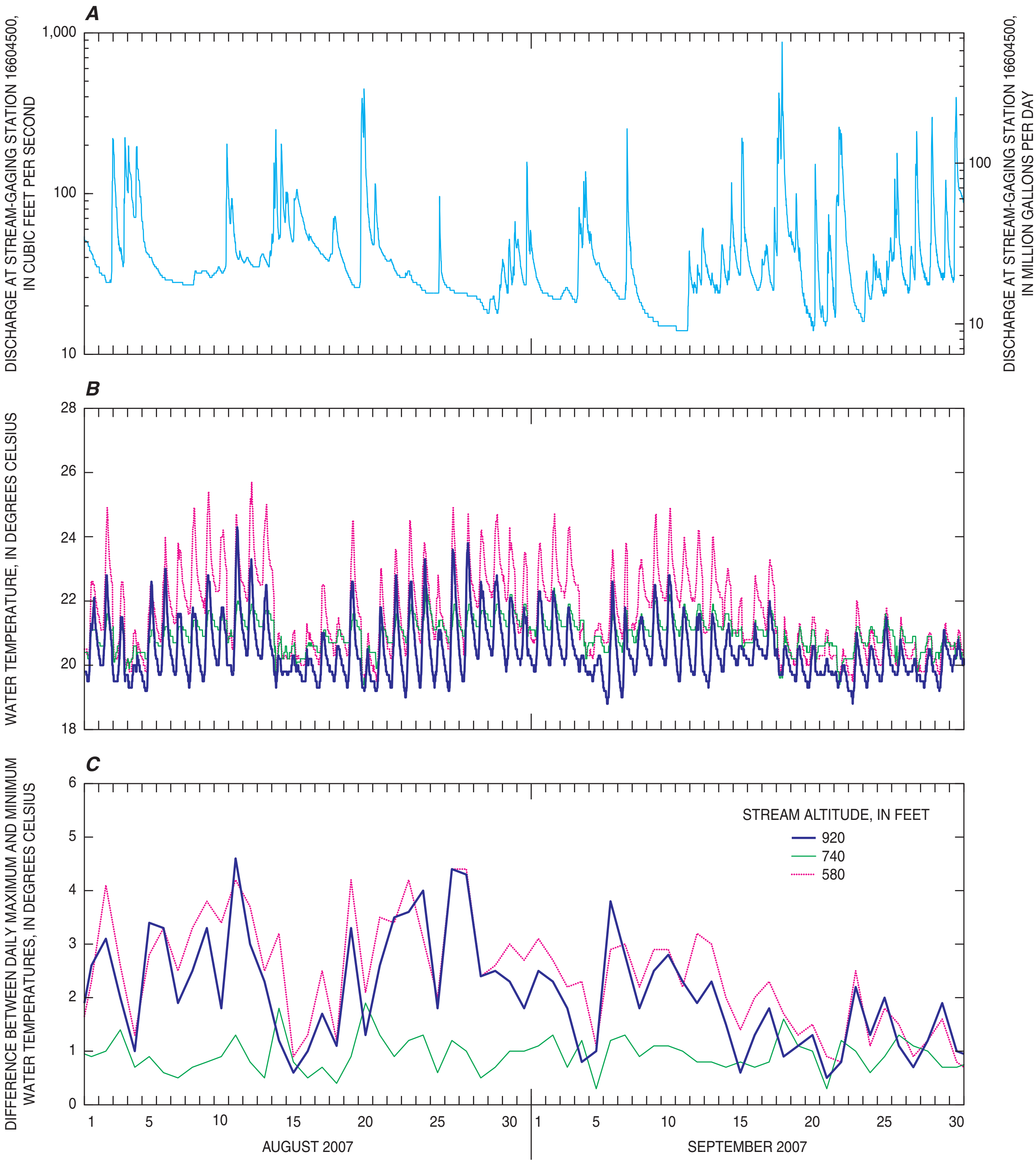


Figure 79. Discharge and water temperatures during August and September, 2007, ʻĪao Stream, Maui, Hawaiʻi. *A*, Discharge at stream-gaging station 16604500. *B*, Water temperatures (measured at 15-minute intervals) between altitudes of 920 and 580 feet. *C*, Difference between daily maximum and minimum water temperatures.

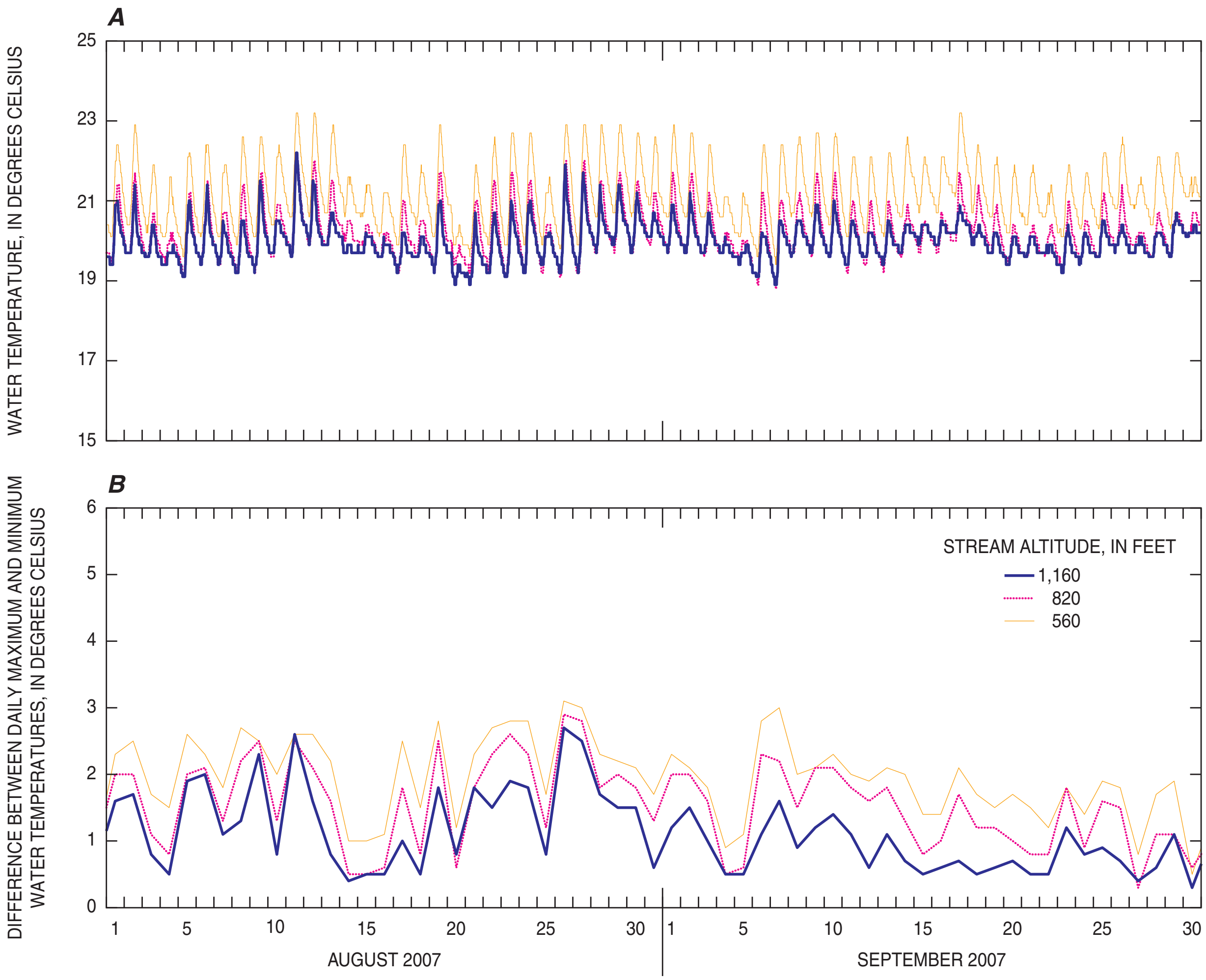


Figure 80. Water temperatures during August and September, 2007, Waikapū Stream, Maui, Hawai‘i. *A*, Water temperatures (measured at 15-minute intervals) between altitudes of 1,160 and 560 feet. *B*, Difference between daily maximum and minimum water temperatures.

Summary

The dependable flow of water provided by Waihe‘e River, Waiehu Stream, ‘Īao Stream, and Waikapū Stream, collectively known as Nā Wai ‘Ehā (“The Four Streams”), made it possible for widespread agricultural activities to flourish in the eastern part of West Maui, Hawai‘i. The streams of the Nā Wai ‘Ehā area flow in their upper reaches even during extended dry-weather conditions because of persistent groundwater discharge to the streams. The lower reaches of these streams lose water by infiltration into the streambed, which may contribute to groundwater recharge. Surface water in the Nā Wai ‘Ehā area traditionally supported large areas of kalo (taro) cultivation for Native Hawaiians. Starting in the 19th century, large-scale sugarcane plantations began to dominate the landscape in the Nā Wai ‘Ehā area. Before 1970, an average of about 67 Mgal/d was diverted, mainly for sugarcane irrigation, from Waihe‘e River, Waiehu Stream, ‘Īao Stream, and Waikapū Stream. In 1988, Wailuku Sugar Company, the main user of the diverted water at the time, shut down operations. As of 2009, water continued to be diverted from streams in the Nā Wai ‘Ehā area for sugarcane irrigation in central Maui by Hawaiian Sugar and Commercial Company, for municipal and domestic uses, golf-course and landscape irrigation, maintaining pastures for cattle grazing, and other agricultural uses.

Daily mean discharge data from a continuous-record stream-gaging station in Waihe‘e River (16410000) near an altitude of 605 ft, upstream of existing diversions, indicate that the long-term median (Q_{50}) discharge was 34 Mgal/d (52 ft^3/s) during climate years 1984–2007. Seepage-run measurements were used to estimate the minimum flow near an altitude of 605 ft necessary for Waihe‘e River to maintain continuous flow to the ocean. A minimum flow of about 1 Mgal/d (1.6 ft^3/s) near an altitude of 605 ft is needed to initiate flow near the coast at an altitude of 45 ft, assuming no diversions exist. This minimum flow estimate of 1 Mgal/d (1.6 ft^3/s) for Waihe‘e River is much less than the minimum recorded flow of 14 Mgal/d (22 ft^3/s) during climate years 1984–2007 near an altitude of 605 ft. Thus, during climate years 1984–2007, Waihe‘e River would have flowed continuously to the coast at all times if no diversions existed.

Daily mean discharge data from ʻĪao Stream (gaging station 16604500) near an altitude of 780 ft, upstream of existing diversions, indicate that the long-term median discharge was 25 Mgal/d (39 ft^3/s) during climate years 1984–2007. For ʻĪao Stream, a minimum flow of about 5.2 Mgal/d (8.1 ft^3/s) near an altitude of 780 ft is needed to initiate flow near the coast at an altitude of 35 ft, assuming no diversions exist. This minimum flow estimate of 5.2 Mgal/d (8.1 ft^3/s) for ʻĪao Stream is less than the minimum recorded flow of 6.1 Mgal/d (9.4 ft^3/s) during climate years 1984–2007 near an altitude of 780 ft. Thus, during climate years 1984–2007, ʻĪao Stream would have flowed continuously to the coast at all times if no diversions existed.

Active continuous-record stream-gaging stations are not available for Waiehu or Waikapū Streams, although historical data from the early part of the 20th century are available to estimate the low-flow characteristics of these streams during climate years 1984–2007. For North Waiehu Stream near an altitude of 880 ft, upstream of existing diversions, the estimated median discharge is 3.2 Mgal/d (4.9 ft^3/s). For South Waiehu Stream near an altitude of 870 ft, upstream of existing diversions, the estimated median discharge is 3.2 Mgal/d (5.0 ft^3/s). For Waiehu Stream, a minimum flow of 1.3 Mgal/d (2.1 ft^3/s) near an altitude of 880 ft in North Waiehu Stream, corresponding to a flow of 1.1 Mgal/d (1.7 ft^3/s) in South Waiehu Stream near an altitude of 870 ft, is needed to initiate flow near the coast at an altitude of 20 ft, assuming no diversions exist. The minimum flow estimate of 1.3 Mgal/d (2.1 ft^3/s) for North Waiehu Stream is between the estimated Q_{95} and Q_{99} flows during climate years 1984–2007 near an altitude of 880 ft. Thus, during climate years 1984–2007, Waiehu Stream would have flowed continuously to the coast at least 95 percent of the time if no diversions existed.

For Waikapū Stream near an altitude of 1,160 ft, the estimated median undiverted discharge is 4.3 Mgal/d (6.6 ft^3/s) for climate years 1984–2007. A minimum flow of about 6.8 Mgal/d (11 ft^3/s) near an altitude of 1,160 ft is needed to initiate flow near the coast at an altitude of 10 ft, assuming no diversions exist. This minimum flow estimate of 6.8 Mgal/d (11 ft^3/s) for Waikapū Stream is greater than the estimated median flow. Thus, during climate years 1984–2007, Waikapū Stream would have flowed continuously to the coast less than half of the time if no diversions existed.

Currently, the main diversions from Waiheʻe River are the Waiheʻe and Spreckels Ditches, with intakes near altitudes of about 600 and 400 ft, respectively. In addition, the Field 1 diversion intake and dam exist near an altitude of 260 ft in Waiheʻe River. The North Waiehu Ditch has an intake near an altitude of 880 ft and is the only existing diversion from North Waiehu Stream. Three known diversions exist on South Waiehu Stream: two ʻauwai (ditches) for private use with intakes near altitudes of 620 ft (north side of stream) and 570 ft (south side of stream) and the Spreckels Ditch with an intake near an altitude of 270 ft. The main diversions in ʻĪao Stream are the ʻĪao-Waikapū and ʻĪao-Māniania Ditches, which share a common intake near an altitude of 780 ft, and the Spreckels Ditch with an intake in a concrete-lined channel near an altitude of 250 ft. A small private intake exists near an altitude of 650 ft and diverts water through a pipe for use on the south side of ʻĪao Stream. Five known diversion intakes exist on Waikapū Stream: (1) the South Side Ditch is the most upstream diversion, with an intake near an altitude of 1,120 ft; (2) the Everett Ditch intake is near an altitude of 900 ft; (3) a private, community ʻauwai diverts water near an altitude of 560 ft; (4) the Waiheʻe Ditch intake is near an altitude of 440 ft; and (5) the Reservoir 6 intake is near an altitude of 410 ft.

Existing diversions are capable of diverting all or nearly all of the dry-weather flows of these streams, leaving some downstream reaches completely dry. Hourly photographs collected during 2006–2008 indicate that some stream reaches downstream of diversions are dry more than 50 percent of the time. Many of these reaches would be perennial or nearly perennial in the absence of diversions.

For streams in which all of the dry-weather flow is diverted, infiltration of water in losing reaches downstream of diversions may be reduced to zero during dry-weather conditions. For natural, undiverted conditions, many of these dry stream reaches would not exist. Thus, these dry stream reaches represent a potential loss of recharge to the underlying groundwater body. Seepage-run measurements were used to estimate the effects of surface-water diversions on recharge beneath the stream channels during low-flow conditions, assuming none of the diverted water is returned to the streams. For Waiheʻe River, existing diversions by the Waiheʻe and Spreckels Ditches reduce potential groundwater recharge by 1.7 Mgal/d (2.7 ft^3/s). For Waiehu Stream, existing diversions by the North Waiehu Ditch and Spreckels Ditch reduce potential groundwater recharge by about 1 Mgal/d (0.65 ft^3/s), even if no water is diverted by each of two private ʻauwai on South Waiehu Stream. For ʻĪao Stream, existing diversions by the ʻĪao-Waikapū and ʻĪao-Māniania Ditches and Spreckels Ditch reduce potential groundwater recharge by about 4.8 Mgal/d (7.4 ft^3/s). For Waikapū Stream, existing diversions by the South Side Ditch, private ʻauwai with intake near an altitude of 560 ft, Waiheʻe Ditch, and Reservoir 6 Ditch reduce potential groundwater recharge by about 4 Mgal/d (6 ft^3/s), even if no water is diverted by the Everett Ditch. Families of curves were developed for each stream to show the relation between surface-water diversion intake capacities and recharge reduction. These curves can be used to assist with water-management decisions by identifying diversion intake capacities that will lead to an acceptable reduction in groundwater recharge.

The streams in the Nā Wai ʻEhā area provide habitat for native stream fauna. Snorkel surveys at selected stream reaches during 2008 identified the presence of native fauna in each of the Nā Wai ʻEhā streams. Native fauna observed in the Nā Wai ʻEhā streams include the endemic mountain shrimp, ʻōpaekalaʻole (*Atyoida bisulcata*); endemic gobies ʻoʻopu ʻalamoʻo (*Lentipes concolor*) and ʻoʻopu nōpili (*Sicyopterus stimpsoni*); the indigenous goby ʻoʻopu nākea (*Awaous guamensis*); and an endemic eleotrid, ‘o‘opu ‘akupa (*Eleotris sandwicensis*). The amphidromous life cycle of native stream fauna requires unimpeded access to and from the ocean.

Changes in streamflow may affect the quantity and quality of physical habitat used by native stream fauna. For this study, the effects of changes in streamflow on physical habitat, in terms of weighted usable area (WUA) were evaluated using the Physical Habitat Simulation System (PHABSIM) approach. Measurements of microhabitat under different flow conditions were combined with habitat-suitability criteria modified from those developed for streams in northeast Maui. In general, data indicate that physical habitat increases monotonically with discharge up to the median natural discharge. A generalized relation between physical habitat and discharge developed for this study indicates that if diversions reduce streamflow to 20 percent of the natural, undiverted Q_{70} discharge (discharge that is equaled or exceeded 70 percent of the time), which is an indicator of median base-flow conditions, then habitat will be reduced by about 33 percent; if diversions reduce streamflow to 50 percent of the natural, undiverted Q_{70} discharge, habitat will be reduced by about 16 percent.

To evaluate the effects of existing surface-water diversions on physical habitat during low-flow conditions, the generalized relation between habitat and discharge was used in conjunction with estimates of streamflow for different diversion intake capacities, assuming none of the diverted water is returned to the stream. For Waihe‘e River near an altitude of 45 ft, existing diversions by Waihe‘e and Spreckels Ditches reduce physical habitat by 100 percent during low-flow periods. For Waiehu Stream near an altitude of 20 ft, existing diversions by the North Waiehu Ditch and Spreckels Ditch reduce physical habitat by more than 60 percent during low-flow periods if no water is diverted by each of two private ‘auwai on South Waiehu Stream. For ‘Īao Stream near an altitude of 35 ft, existing diversions by the ‘Īao-Waikapū and ‘Īao-Māniania Ditches and Spreckels Ditch reduce physical habitat by 100 percent during low-flow periods. For Waikapū Stream near an altitude of 400 ft, existing diversions by the South Side Ditch, private ‘auwai with intake near an altitude of 560 ft, Waihe‘e Ditch, and Reservoir 6 Ditch reduce physical habitat by more than 90 percent during low-flow periods if no water is diverted by the Everett Ditch. Families of curves were developed for sites near the coast on each stream to show the relation between surface-water diversion intake capacities and habitat reduction. These curves can be used to assist with water-management decisions by identifying diversion intake capacities that will lead to an acceptable reduction in physical habitat.

Stream temperature is a factor that potentially could affect the abundance and distribution of native aquatic species and wetland-taro production. The upper-lethal-temperature limits for native aquatic species generally range from about 35°C to 40°C. Wetland-taro agriculture commonly is dependent on surface water with temperatures that do not exceed about 27°C to 29°C. During the period from September 2006 to October 2007, water temperatures immediately upstream of all diversions and at selected downstream sites were recorded every 15 minutes. Exposure to lethal temperatures for short durations, in some cases less than 30 minutes, can cause death in native aquatic species. During the periods when measured temperatures were available, daily maximum temperatures did not exceed 27°C and daily minimum temperatures did not drop below 15°C at any of the study sites. At all of the study sites, daily maximum temperatures remained below the upper-lethal-temperature limits for native aquatic species, as well as below the temperature that favors Pythium rot of taro, although temperatures were not measured in reaches that sometimes were dry.

References Cited

Bailey, E., 1878, Map of the Wailuku Plantation: map no. 17 of Wailuku Water Company, LLC collection on loan to the Bailey House Museum, Maui, Hawai‘i, map scale 1:3,168 (4 chains to the inch).

Baker, J.A., and Foster, S.A., 1992, Estimating density and abundance of endemic fishes in Hawaiian streams: Hawai‘i Department of Land and Natural Resources, Division of Aquatic Resources, 50 p.

Benbow, M.E., 2001, Endemic amphidromous postlarval recruitment and migration patterns in West Maui Streams: Prepared for Earthwatch Institute and the Center for Field Studies, 31 p.

Benbow, M.E., Burky, A.J., and Way, C.M., 2003, Life cycle of a torrenticolous Hawaiian chironomid (*Telmatogeton torrenticola*); stream flow and microhabitat effects: Annales de Limnologie–International Journal of Limnology, v. 39, p. 103–114.

Benbow, M.E., Burky, A.J., and Way, C.M., 2004a, The use of two modified Breder traps to quantitatively study amphidromous upstream migration: Hydrobiologia, v. 527, p. 139–151.

Benbow, M.E., Burky, A.J., and Way, C.M., 2004b, Morphological characteristics and species separation of Hawaiian postlarval amphidromous fishes: Micronesica, v. 37, p. 127–143.

Benbow, M.E., McIntosh, M.D., Burky, A.J., and Way, C.M., 2005, The influence of stream flow reduction on the energetics of endemic Hawaiian torrenticolous aquatic insects, *Telmatogeton* Schiner and *Procanace* Hendel: Journal of Insect Conservation, v. 9, p. 175–185.

Benstead, J.P., March, J.G., Pringle, C.M., and Scatena, F.N., 1999, Effects of a low-head dam and water abstraction on migratory tropical stream biota: Ecological Applications, v. 9, p. 656–668.

Blob, R.W., Rai, R., Julius, M.L., and Schoenfuss, H.L., 2006, Functional diversity in extreme environments; effects of locomotor style and substrate texture on the waterfall-climbing performance of Hawaiian gobiid fishes: Journal of

Zoology, v. 268, p. 315–324.

Blumenstock, D.I., and Price, S., 1967, Climate of Hawaii, *in* Climates of the States, no. 60–51, Climatography of the United States: Washington, D.C., U.S. Department of Commerce.

Bovee, K.D., 1982, A guide to stream habitat analysis using the instream flow incremental methodology: U.S. Fish and Wildlife Service, Office of Biological Services, Instream Flow Information Paper No. 12, FWS/OBS–82/26, 248 p.

Bovee, K.D., 1986, Development and evaluation of habitat suitability criteria for use in the Instream Flow Incremental Methodology: U.S. Fish and Wildlife Service, Instream Flow Information Paper No. 21, Biological Report 86, no. 7, 235 p.

Bovee, K.D., 1997, Data collection procedures for the physical habitat simulation system: Fort Collins, Colo., U.S. Geological Survey, Mid-Continent Ecological Science Center, 146 p., [http://www.fort.usgs.gov/Products/Publications/20002/20002.pdf, accessed December 9, 2009].

Bovee, K.D., Lamb, B.L., Bartholow, J.M., Stalnaker, C.B., Taylor, J., and Henriksen, J., 1998, Stream habitat analysis using the instream flow incremental methodology: U.S. Geological Survey, Biological Resources Division Information and Technology Report USGS/BRD–1998–0004, 131 p.

Brasher, A.M., 1997, Life history characteristics of the native Hawaiian stream snail *Neritina granosa* (hihiwai): Cooperative National Park Resources Studies Unit Hawaii Technical Report 114, 46 p.

Brasher, A.M.D., 2003, Impacts of human disturbances on biotic communities in Hawaiian streams: BioScience, v. 53, p. 1,052–1,060.

Brasher, A.M.D., Luton, C., Goodbred, S., and Wolff, R.H., 2006, Invasion patterns along elevation and urbanization gradients in Hawaiian streams: Transactions of the American Fisheries Society, v. 135, p. 1,109–1,129.

Broadbent, E.W., 1988, Report on losses in and kuleana uses from ditch systems, losses in reservoirs, condition of flow measurement stations of Wailuku Agribusiness Company, Inc.: 21 p. plus appendix material.

Brock, V.E., 1960, The introduction of aquatic animals into Hawaiian waters: Internationale Revue der gesamten Hydrobiologie, v. 45, p. 463–480.

Chumbley, A.B., 2007, Direct testimony before the Commission on Water Resource Management, State of Hawaiʻi, case no. CCH-MA06-01, Iao Ground Water Management Area high-level source water use permit applications and petition to amend interim instream flow standards of Waiheʻe, Waiehu, Iao & Waikapu Streams contested case hearing: 17 p.

Coulter, J.W., 1940, Agricultural land-use planning in the Territory of Hawaii: University of Hawaiʻi Agricultural Extension Service, Extension Bulletin no. 35, 124 p.

Couret, C.L., Jr., 1976, The biology and taxonomy of a freshwater shrimp, *Atya bisulcata*, Randall, endemic to the Hawaiian islands: Honolulu, University of Hawaiʻi at Mānoa, M.S. thesis, 168 p.

Cowie, R.H., 2000, Non-indigenous land and freshwater molluscs in the islands of the Pacific; conservation impacts and threats, *in* Sherley, G., ed., Invasive species in the Pacific; a technical review and draft regional strategy: South Pacific Regional Environment Programme, Samoa, p. 143–172.

Creed, V.S., 1993, Settlement pattern for Waikapū, Wailuku District, Maui, Hawaii, v.1: Cultural Surveys Hawaii, 100 p.

Devick, W.S., 1991, Patterns of introductions of aquatic organisms to Hawaiian freshwater habitats, *in* Devick, W.S., ed., New directions in research, management and conservation of Hawaiian freshwater stream ecosystems: Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources, Proceedings of the 1990 Symposium on Freshwater Stream Biology and Fisheries Management, p. 189–213.

DiSalvo, C., Orr, R., and Foote, D., 2003, Dragonflies and damselflies—invertebrate indicators of ecological health: U.S. National Park Service, Natural Resource Year in Review–2003, p. 86–87.

Dorman, C.E., and Bourke, R.H., 1979, Precipitation over the Pacific Ocean, 30°S to 60°N: Monthly Weather Review, v. 107, no. 7, p. 896–910.

Dorrance, W.H., and Morgan, F.S., 2000, Sugar islands; the 165-year story of sugar in Hawaiʻi: Honolulu, Mutual Publishing, 259 p.

Ego, K., 1956, Life history of freshwater gobies: State of Hawaiʻi, Department of Land and Natural Resources, Freshwater Game Fish Management Research, Project No. F–4–R, 24 p.

Elliot, W.P., and Reed, R.K., 1984, A climatological estimate of precipitation for the world ocean: Journal of Applied Meteorology, v. 23, no. 3, p. 434–439.

Engott, J.A., and Vana, T.T., 2007, Effects of agricultural land-use changes and rainfall on ground-water recharge in central and west Maui, Hawaiʻi, 1926–2004: U.S. Geological Survey Scientific Investigations Report 2007–5103, 56 p.

Fitzsimons, J.M., and Nishimoto, R.T., 1990, Territories and site tenacity in males of the Hawaiian stream goby, *Lentipes concolor* (Pisces: Gobiidae): Ichthyological Exploration of Freshwaters, v. 1, p. 185–189.

Fitzsimons, J.M., and Nishimoto, R.T., 1991, Behavior of gobioid fishes from Hawaiian fresh waters, *in* Devick, W.S., ed., New directions in research, management and conservation of Hawaiian freshwater stream ecosystems: Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources, Proceedings of the 1990 Symposium on Freshwater Stream Biology and Fisheries Management, p. 106–124.

Fitzsimons, J.M., Nishimoto, R.T., and Yuen, A.R., 1993, Courtship and territorial behavior in the native Hawaiian stream goby, *Sicyopterus stimpsoni*: Ichthyological Exploration of Freshwaters, v. 4, p. 1–10.

Fitzsimons, J.M., McRae, M.G., and Nishimoto, R.T., 2007, Behavioral ecology of indigenous stream fishes in Hawaiʻi, *in* Evenhuis, N.L., and Fitzsimons, J.M., eds., Biology of

Hawaiian streams and estuaries: Honolulu, Bishop Museum Bulletin in Cultural and Environmental Studies, p. 11–21.

Fontaine, R.A., 2003, Availability and distribution of base flow in lower Honokohau Stream, Island of Maui, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 03–4060, 37 p.

Fontaine, R.A., Wong, M.F., and Matsuoka, I., 1992, Estimation of median streamflows at perennial stream sites in Hawaii: U.S. Geological Survey Water-Resources Investigations Report 92–4099, 37 p.

Ford, J.I., 1979, Biology of a Hawaiian fluvial gastropod *Neritina granosa* Sowerby (Prosobranchia: Neritidae): Honolulu, University of Hawai‘i at Mānoa, M.S. thesis, 92 p.

Ford, J.I., and Kinzie, R.A., III, 1982, Life crawls upstream: Natural History, v. 91, p. 61–66.

Ford, J., Kinzie, R.A., III, Thair, T., and Taira, R., 2008, Survey of native Hawaiian stream fauna in Nā Wai ‘Ehā, West Maui: Prepared for Cades Schutte, LLC, by SWCA Environmental Consultants, 52 p.

Gay, J.N., 1875, Plan of Waihee, Maui: Hawai‘i Department of Accounting and General Services, Land Survey Division, Government Survey Registered map 771, 28 x 48 inches.

Giambelluca, T.W., Nullet, M.A., and Schroeder, T.A., 1986, Rainfall atlas of Hawai‘i: Hawai‘i Department of Land and Natural Resources Report R76, 267 p.

Gingerich, S.B., 2005, Median and low-flow characteristics for streams under natural and diverted conditions, Northeast Maui, Hawaii: U.S. Geological Survey Scientific Investigations Report 2004–5262, 72 p.

Gingerich, S.B., 2008, Ground-water availability in the Wailuku area, Maui, Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2008–5236, 95 p.

Gingerich, S.B., and Oki, D.S., 2000, Ground water in Hawaii: U.S. Geological Survey Fact Sheet 126–00, 6 p.

Gingerich, S.B., and Wolff, R.H., 2005, Effects of surface-water diversions on habitat availability for native macrofauna, Northeast Maui, Hawaii: U.S. Geological Survey Scientific Investigations Report 2005–5213, 93 p.

Grover, N.C., and Larrison, G.K., 1917a, Surface water supply of Hawaii July 1, 1913, to June 30, 1915: U.S. Geological Survey Water-Supply Paper 430, 329 p.

Grover, N.C., and Larrison, G.K., 1917b, Surface water supply of Hawaii July 1, 1915 to June 30, 1916: U.S. Geological Survey Water-Supply Paper 445, 224 p.

Grover, N.C., and Larrison, G.K., 1918, Surface water supply of Hawaii July 1, 1916 to June 30, 1917: U.S. Geological Survey Water-Supply Paper 465, 191 p.

Handy, E.S.C, and Handy, E.G., 1991, Native planters in old Hawaii—their life, lore, and environment: Honolulu, Bishop Museum Press, Bernice P. Bishop Museum Bulletin 253, 676 p.

Harland Bartholomew and Associates, 1957, An inventory of available information on land use in Hawaii, vol. 1; evaluation and recommendations: Honolulu, Hawaii, 100 p.

Hathaway, C.B., 1978, Stream channel modification in Hawaii, Part C; tolerance of native stream species to observed levels of environmental variability: U.S. Fish and Wildlife Service National Stream Alteration Team, Columbia, Mo., FWS/OBS–78/18, 59 p.

Hau, S., 2007, Hīhīwai (*Neritina granosa* Sowerby) recruitment in ‘Iao and Honomanū streams on the island of Maui, Hawai‘i, *in* Evenhuis, N.L., and Fitzsimons, J.M., eds., Biology of Hawaiian Streams and Estuaries: Bishop Museum Bulletin in Cultural and Environmental Studies, Honolulu, p. 171–181.

Hawai‘i Cooperative Park Service Unit, 1990, Hawaii stream assessment; a preliminary appraisal of Hawaii's stream resources: State of Hawai‘i Department of Land and Natural Resources, Commission on Water Resource Management, Report R84, 294 p.

Hawai‘i Territorial Planning Board, 1939, An historic inventory of the physical, social and economic and industrial resources of the Territory of Hawaii, first progress report: Honolulu, Advertiser Publishing Co., Ltd., 322 p. + supplement.

Hirsch, R.M., 1982, A comparison of four streamflow record extension techniques: Water Resources Research, v. 18, no. 4, p. 1,081–1,088.

Iguchi, K., 2007, Limitations of early seaward migration success in amphidromous fishes, *in* Evenhuis, N.L., and Fitzsimons, J.M., eds., Biology of Hawaiian Streams and Estuaries: Bishop Museum Bulletin in Cultural and Environmental Studies, Honolulu, p. 75–85.

Iguchi, K., and Mizuno, N., 1999, Early starvation limits survival in amphidromous fishes: Journal of Fish Biology, v. 54, p. 705–712.

Jennings, K.R., Fernandes, T.M., Boreman, J., Hanlin, A., Mikelatis, C., Mountcastle, A., Rider, M., Stengel, C., Benbow, M.E., McIntosh, M.D., and Burky, A.J., 2002, Effects of stream size and water withdrawal on *Neritina granosa* (Sowerby) spat dispersion and migration in the Iao watershed, Maui, Hawaii [abs.]: Ohio Journal of Science, v. 102, p. A–19.

Juvik, S.O., and Juvik, J.O., 1998, Atlas of Hawai‘i (3d ed.): Honolulu, University of Hawai‘i Press, 333 p.

Kanayama, R.K., 1967, Hawaii's aquatic animal introductions: Presented at the 47th annual conference of the Western Association of State Game and Fish Commissioners, 8 p.

Kelly, M., Hee, C., and Cordy, R., 1978, Cultural reconnaissance of hydroelectric power plant sites–Waihe‘e Valley, Maui; Lumaha‘i Valley, Kaua‘i: Honolulu, Hawai‘i, Bernice P. Bishop Museum, Department of Anthropology, 95 p.

Kido, M.H., 1996, Diet and food selection in the endemic Hawaiian amphidromous goby, *Sicyopterus stimpsoni* (Pisces: Gobiidae): Environmental Biology of Fishes, v. 45, p. 199–209.

Kido, M.H., 1997a, Food webs and feeding dynamics of coexisting native Hawaiian stream gobies: Micronesica, v. 30, p. 71–82.

Kido, M.H., 1997b, Food relations between coexisting native

Hawaiian stream fishes: Environmental Biology of Fishes, v. 49, p. 481–494.

Kinoshita, W.T., and Okamura, R.T., 1965, A gravity survey of the Island of Maui, Hawaii: Pacific Science, v. XIX, no. 3, p. 341–342.

Kinzie, R.A., III, 1988, Habitat utilization by Hawaiian stream fishes with reference to community structure in oceanic island streams: Environmental Biology of Fishes, v. 22, p. 179–192.

Kinzie, R.A., III, 1990, Species profiles; life histories and environmental requirements of coastal vertebrates and invertebrates, Pacific Ocean Region; Report 3, amphidromous macrofauna of island streams: Vicksburg, Miss., U.S. Army Engineer Waterways Experiment Station, Technical Report EL–89–10, 28 p.

Kinzie, R.A., III, and Ford, J.I., 1982, Population biology in small Hawaiian streams: University of Hawaiʻi Water Resources Research Center Technical Report No. 147, 60 p.

LaBaugh, J.W., and Rosenberry, D.O., 2008, Introduction and characteristics of flow, chap. 1 *of* Rosenberry, D.O. and LaBaugh, J.W., eds., Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods 4–D2, 128 p.

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain, part II, stratigraphic framework of volcanic rocks of the Hawaiian Islands, chap. 1 *of* Decker, R.W., Wright, T.L., and Stauffer, P.H., eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 55–84.

Larrison, G.K., 1915, Water resources of Hawaii 1913: U.S. Geological Survey Water-Supply Paper 373, 190 p.

Lau, E.Y., 1973, Dimorphism and speciation in the Hawaiian freshwater goby genus *Lentipes*: Honolulu, University of Hawaiʻi at Mānoa, B.A. Honors Thesis, 83 p.

Lencioni, J., 2000, Introduction, chap. 1 *of* Copeland, R.R., and McComas, D.N., eds., Channel stability problems, Iao Stream, Maui, Hawaii: U.S. Army Engineer Committee on Channel Stabilization Report of the 64th meeting–September 1999, ERDC/CHL SR–00–2, p. 1–3.

Lewers Plantation, 1868, Map of Lewers' Plantation: map no. 27 of Wailuku Water Company, LLC collection on loan to the Bailey House Museum, Maui, Hawaiʻi, map scale 1:6,336 (8 chains to the inch).

Lindstrom, D.P., and Brown, C.L., 1996, Captive breeding and rearing of native amphidromous Hawaiian gobioids; ramifications for ecosystem management, *in* Devick, W.S., ed., Will stream restoration benefit freshwater, estuarine, and marine fisheries? Proceedings of the Hawaii Stream Restoration Symposium: Hawaiʻi Department of Land and Natural Resources, Technical Report 96–01, Honolulu, Hawaiʻi, p. 112–131.

Lohman, S.W., 1979, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Macdonald, G.A., Abbott, A.T., and Peterson, F.L., 1983, Volcanoes in the sea; the geology of Hawaii (2d ed.): Honolulu, University of Hawaiʻi Press, 517 p.

Maciolek, J., 1971, Aquatic ecosystems of Kealia floodplain and Maalaea Bay, Maui; evaluation for perpetuation and public use: University of Hawaiʻi, Hawaiʻi Institute of Marine Biology Technical Report no. 27, 42 p.

Maciolek, J.A., 1977, Taxonomic status, biology, and distribution of Hawaiian *Lentipes*, a diadromous goby: Pacific Science, v. 31, p. 355–362.

Maciolek, J.A., 1984, Exotic fishes in Hawaii and other islands of Oceania, *in* Courtenay, W.R., Jr., and Stauffer, J.R., Jr., eds., Distribution, biology, and management of exotic fishes: Baltimore, Md., The Johns Hopkins University Press, p. 131–161.

Maclennan, C.A., 1995, Foundation of sugar's power; early Maui plantations, 1840–1860: The Hawaiian Journal of History, v. 29, p. 33–56.

Maclennan, C.A., 1997, Hawaiʻi turns to sugar; the rise of plantation centers, 1860–1880: The Hawaiian Journal of History, v. 31, p. 97–125.

Martin, W.F., and Pierce, C.H., 1913, Water resources of Hawaii 1909–1911: U.S. Geological Survey Water-Supply Paper 318, 552 p.

McDowall, R.M., 1988, Diadromy in fishes: Portland, Oregon, Timber Press, 308 p.

McDowall, R.M., 1993, A recent marine ancestry for diadromous fishes? sometimes yes, but mostly no!: Environmental Biology of Fishes, v. 37, p. 329–335.

McDowall, R.M., 2003, Hawaiian biogeography and the islands' freshwater fish fauna: Journal of Biogeography, v. 30, p. 703–710.

McIntosh, M.D., Benbow, M.E., and Burky, A.J., 2002, Effects of stream diversion on riffle macroinvertebrate communities in a Maui, Hawaii, stream: River Research and Applications, v. 18, p. 569–581.

McIntosh, M.D., Benbow, M.E., and Burky, A.J., 2003, Effect of water removal on introduced caddisflies from a tropical mountain stream: Annales de Limnologie–International Journal of Limnology, v. 39, p. 297–306.

McIntosh, M.D., Schmitz, J.A., Benbow, M.E., and Burky, A.J., 2008, Structural and functional changes of tropical riffle macroinvertebrate communities associated with stream flow withdrawal: River Research and Applications, v. 24, p. 1,045–1,055.

McRae, M.G., 2007a, Watershed-scale patterns of seaward migration in *Lentipes concolor*, a Hawaiian stream goby: Baton Rouge, Louisiana State University, Ph.D. dissertation, 71 p.

McRae, M.G., 2007b, The potential for source-sink population dynamics in Hawaii's amphidromous fishes, *in* Evenhuis, N.L., and Fitzsimons, J.M., eds., Biology of Hawaiian Streams and Estuaries: Honolulu, Bishop Museum Bulletin in Cultural and Environmental Studies, p. 87–98.

Meyer, W., and Presley, T.K., 2001, The response of the Iao Aquifer to ground-water development, rainfall, and land-use practices between 1940 and 1998, Island of Maui, Hawaii: USGS Water-Resources Investigations Report 00–4223, 60 p.

Mitchell, W.B., Guptill, S.C., Anderson, E., Fegeas, R.G., and Hallam, C.A., 1977, GIRAS—a geographic information retrieval and analysis system for handling land use and land cover data: U.S. Geological Survey Professional Paper 1059, 16 p.

Monsarrat, M.D., 1882, Map of a portion of Wailuku, Maui: Hawaiʻi Department of Accounting and General Services, Land Survey Division, Government Survey Registered map 1261.

Monsarrat, M.D., 1894, Map of cane fields of Waikapu, Maui: map no. 14 of Wailuku Water Company, LLC collection on loan to the Bailey House Museum, Maui, Hawaiʻi, map scale 1:3,600 (300 feet to the inch).

National Oceanic and Atmospheric Administration, 2001, Land cover analysis, Hawaii land cover: Coastal Services Center [http://www.csc.noaa.gov/crs/lca/hawaii.html, accessed March 25, 2009].

National Oceanic and Atmospheric Administration, 2005, Land cover analysis, Maui county land cover: Coastal Change Analysis Program [http://www.csc.noaa.gov/ccap/pacific/maui, accessed March 25, 2009].

National Renewable Energy Laboratory, 2009, U.S. solar radiation resource maps: [http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/, accessed October 28, 2009].

Nishimoto, R.T., and Fitzsimons, J.M., 1986, Courtship, territoriality, and coloration in the endemic Hawaiian freshwater goby, *Lentipes concolor*: Indo-Pacific Fish Biology, Proceedings of the Second International Conference on Indo-Pacific Fishes, p. 811–817.

Oki, D.S., 2004, Trends in streamflow characteristics at long-term gaging stations, Hawaii: U.S. Geological Survey Scientific Investigations Report 2004–5080, 120 p.

Oki, D.S., Wolff, R.H., and Perreault, J.A., 2006, Effects of surface-water diversion and ground-water withdrawal on streamflow and habitat, Punaluu Stream, Oahu, Hawaii: U.S. Geological Survey Scientific Investigations Report 2006–5153, 104 p.

Olson, R.M., 1980, Essentials of engineering fluid mechanics: New York, Harper & Row, 583 p.

Ooka, J.J., 1994, Taro diseases; a guide for field identification: Honolulu, University of Hawaiʻi College of Tropical Agriculture and Human Resources, Research Extension Series 148, 13 p.

Pardales, J.R., Melchor, F.M., and de la Peña, R.S., 1982, Effects of water temperature on the early growth and development of taro: Annals of Tropical Research, v. 4, no. 4, p. 231–238.

Parham, J.E., Higashi, G.R., Lapp, E.K., Kuamoʻo, D.G.K., Nishimoto, R.T., Fitzsimons, J.M., Polhemus, D.A., and Devick, W.S., 2008, Atlas of Hawaiian watersheds and their aquatic resources: Bishop Museum and Hawaiʻi Division of Aquatic Resources [http://www.hawaiiwatershedatlas.com/, accessed March 25, 2010].

Pierce, C.H., and Larrison, G.K., 1914, Water resources of Hawaii 1912: U.S. Geological Survey Water-Supply Paper 336, 392 p.

Polhemus, D.A., 1993, Damsels in distress; a review of the conservation status of Hawaiian *Megalagrion* damselflies (Odonata: Coenagrionidae): Aquatic Conservation, Marine and Freshwater Ecosystems, v. 3, p. 343–349.

Polhemus, D.A., 2007, Oral testimony at contested case hearing, Case No. CCH-MA06-01, ʻIao Ground Water Management Area High Level Source Water Use Permit Applications and Petition to Amend Interim Instream Flow Standards of Waiheʻe, Waiehu, ʻIao and Waikapū Streams Contested Case Hearing, December 12, 2007, Wailuku, Maui.

Polhemus, D.A., and Asquith, A., 1996, Hawaiian damselflies—a field identification guide: Honolulu, Hawaiʻi, Bishop Museum Press, 122 p.

Polhemus, D.A., Maciolek, J., and Ford, J., 1992, An ecosystem classification of inland waters for the tropical Pacific Islands: Micronesica, v. 25, p. 155–173.

Radtke, R.L., Kinzie, R.A., III, and Folsom, S.D., 1988, Age at recruitment of Hawaiian freshwater gobies: Environmental Biology of Fishes, v. 23, p. 205–213.

Radtke, R.L., Kinzie, R.A., III, and Shafer, D.J., 2001, Temporal and spatial variation in length of larval life and size at settlement of the Hawaiian amphidromous goby *Lentipes concolor*: Journal of Fish Biology, v. 59, p. 928–938.

Railsback, S.F., Stauffer, H.B., and Harvey, B.C., 2003, What can habitat preference models tell us? tests using a virtual trout population: Ecological Applications, v. 13, p. 1,580–1,594.

Rantz, S.E., and others, 1982, Measurement and computation of streamflow, volumes 1 and 2: U.S. Geological Survey Water-Supply Paper 2175, 631 p.

Ries, K.G., III, 1993, Estimation of low-flow duration discharges in Massachusetts: U.S Geological Survey Open-File Report 93–38, 59 p.

Rotzoll, K., El-Kadi, A.I., and Gingerich, S.B., 2007, Estimating hydraulic properties of volcanic aquifers using constant-rate and variable-rate aquifer tests: Journal of the American Water Resources Association, v. 43, no. 2, p. 334–345.

Sanderson, M., 1993, Prevailing trade winds, weather and climate in Hawaiʻi: Honolulu, University of Hawaiʻi Press, 126 p.

Schmitt, R.C., 1971, New estimates of the pre-censal population of Hawaii: The Journal of the Polynesian Society, v. 80, no. 2, p. 237–243.

Schmitt, R.C., 1973, The missionary censuses of Hawaii: Honolulu, Hawaiʻi, Bernice P. Bishop Museum, Department of Anthropology, Pacific Anthropological Records, No. 20, 49 p.

Schoenfuss, H.L., and Blob, R.W., 2003, Kinematics of waterfall climbing in Hawaiian freshwater fishes (Gobiidae); vertical propulsion at the aquatic-terrestrial interface: Journal of Zoology, London, v. 261, p. 191–205.

Searcy, J.K., 1959, Flow-duration curves, manual of hydrology—part 2. Low-flow techniques: U.S. Geological Survey Water-Supply Paper 1542–A, p. 1–33.

Sherrod, D.R., Murai, T., and Tagami, T., 2006, New K-Ar ages for calculating end-of-shield extrusion rates at West Maui volcano, Hawaiian island chain: Bulletin of Volcanology, v. 69,

p. 627–642.

Sherrod, D.R., Sinton, J.M., Watkins, S.E., and Brunt, K.M., 2007, Geologic map of the State of Hawaiʻi: U.S. Geological Survey Open-File Report 2007–1089, 83 p.

Silva, A.K., 1962, Wailuku Sugar Company centennial, November 1862–1962, a century of progress in sugar cane cultivation: Wailuku, Maui, Hawaiʻi, Maui Publishing Co., Ltd., 67 p.

Sophocleous, M., 2002, Interactions between groundwater and surface water; the state of the science: Hydrogeology Journal, v. 10, p. 52–67.

State of Hawaiʻi, 2000, Freshwater fisheries research and surveys; surveys, monitoring and habitat studies of native freshwater species on the island of Maui: Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources, Job No. 5 (Study VII), 5 p.

State of Hawaiʻi, 2004, Hawaiʻi freshwater database: Hawaiʻi Department of Land and Natural Resources, Division of Aquatic Resources, database [http://www.hawaii.gov/dlnr/dar/streams_data.html, downloaded May 30, 2004].

State of Hawaiʻi, 2007, The State of Hawaii data book 2006: Department of Business, Economic Development, and Tourism, Research and Economic Analysis Division, Statistics and Data Support Branch [http://hawaii.gov/dbedt/info/economic/databook/db2006/, accessed April 8, 2008].

Stearns, H.T., 1985, Geology of the State of Hawaii (2d ed.): Palo Alto, Calif., Pacific Books, 335 p.

Stearns, H.T., and Macdonald, G.A., 1942, Geology and groundwater resources of the island of Maui, Hawaii: Hawaiʻi Division of Hydrography Bulletin 7, 344 p.

Sterling, E.P., 1998, Sites of Maui: Honolulu, Bishop Museum Press, 285 p.

Suzuki, C., 2007, Direct testimony before the Commission on Water Resource Management, State of Hawaiʻi, case no. CCH–MA06–01, Iao Ground Water Management Area high-level source water use permit applications and petition to amend interim instream flow standards of Waiheʻe, Waiehu, Iao & Waikapu Streams contested case hearing, 16 p.

Tate, D.C., Fitzsimons, J.M., and Cody, R.P., 1992, Hawaiian freshwater fishes (Osteichthyes, Gobioidei); a field key to the species of larvae and postlarvae during recruitment into fresh waters: Baton Rouge, Louisiana State University, Occasional Papers of the Museum of Natural Science, v. 65, p. 1–10.

Thrum, T.G., 1908, New irrigation works, the new Waihee canal: The Hawaiian Annual, p. 156–157.

Timbol, A.S., and Maciolek, J.A., 1978, Stream channel modification in Hawaii. Part A, statewide inventory of streams; habitat factors and associated biota: U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS–78/16, 158 p.

Tomihama, M.T., 1972, The biology of *Sicydium stimpsoni*; freshwater goby endemic to Hawaii: Honolulu, University of Hawaiʻi at Mānoa, B.S. Honors Thesis, 123 p.

U.S. Department of Agriculture, 1982, Agricultural land use in the State of Hawaii, Island of Maui: Soil Conservation Service, map 4–R–37 965, scale not specified.

U.S. Geological Survey, 2001, PHABSIM for Windows—user's manual and exercises: Open-File Report 01–340, 288 p.

Van Dine, B.L., 1907, The introduction of top-minnows into the Hawaiian Islands: Hawaiʻi Agricultural Experiment Station, Press Bulletin No. 20, 10 p.

Vázquez-Suñé, E., Capino, B., Abarca, E., and Carrera, J., 2007, Estimation of recharge from floods in disconnected stream-aquifer systems: Ground Water, v. 45, no. 5, p. 579–589.

Wailuku Water Company, LLC, undated, Map showing location of Waiehu: map no. 33 of Wailuku Water Company, LLC collection on loan to the Bailey House Museum, Maui, Hawaiʻi, working sheets, map scale 1:480 (40 feet to the inch).

Wells, J.V.B., 1961, Compilation of records of surface water of Hawaii through June 1950: U.S. Geological Survey Water-Supply Paper 1319, 316 p.

Wilcox, C., 1996, Sugar water; Hawaii's plantation ditches: Honolulu, University of Hawaiʻi Press, 191 p.

Yamamoto, M.N., and Tagawa, A.W., 2000, Hawaii's native and exotic freshwater animals: Honolulu, Hawaiʻi, Mutual Publishing, 200 p.

Yamanaga, G., and Huxel, C.J., Jr., 1970, Preliminary report on the water resources of the Wailuku area, Maui: Honolulu, Hawaiʻi, Hawaiʻi Department of Land and Natural Resources, Division of Water and Land Development, Circular C61, 43 p.

Appendix A. Surface-Water Diversions

As of 2009, three known diversions existed on Waiheʻe River, one on North Waiehu Stream, three on South Waiehu Stream, three on ʻĪao Stream, and five on Waikapū Stream. Each of these diversions is described briefly in this appendix. Historically, additional diversions existed on each stream, and those that have been mapped or documented also are described briefly.

Waiheʻe River

Silva (1962, p. 14) describes a "broad and deep ditch four miles long" that was dug in 1866 to bring water to Waiheʻe Plantation, although the locations of the intake and ditch are not known. A map from 1868 (Lewers Plantation, 1868) shows what appear to be two ditches that divert water from the south side of Waiheʻe River, and the upstream diversion may be the 1866 ditch that Silva (1962) described. A dam and what appears to be a ditch shown downstream of Huluhulupueo Stream (near the location of the current intake of Spreckels Ditch) is indicated on a Government Survey map from 1875 of the Waiheʻe area (Gay, 1875) and also may be related to the 1866 ditch that Silva (1962) described. Martin and Pierce (1913) show locations of Waiheʻe and Spreckels Ditches and two smaller, unnamed ditches that diverted water from Waiheʻe River (fig. A1). Martin and Pierce (1913, p. 257) measured discharges in the "Native" (south side) and "Kapuna" (north side) Ditches that diverted water from Waiheʻe River, and these may be the two unnamed ditches (fig. A1).

Currently (2009), the main diversions from Waiheʻe River are the Waiheʻe and Spreckels Ditches, with intakes near altitudes of 600 and 400 ft, respectively (fig. 7). Spreckels Ditch was constructed in 1882 and Waiheʻe Ditch was completed in 1907 (Silva, 1962). These ditches currently are maintained by Wailuku Water Company, LLC (WWC) with assistance from Hawaiian Sugar and Commercial Company (HC&S). The Field 1 diversion ditch is much smaller than either Waiheʻe Ditch or Spreckels Ditch and has an intake near an altitude of 260 ft (fig. 7).

The original intake for Waiheʻe Ditch was near an altitude of 650 ft. The 10.62-mile-long Waiheʻe Ditch system originally consisted of 22 tunnels, varying in length from 155 to 2,246 ft, 39 flumes totaling 2,764 ft, 1,253 ft of pipelines, and 35,549 ft of open ditch (Thrum, 1908). Construction of a new intake for the Waiheʻe Ditch was started in 1935 (Silva, 1962). Currently (2009), the Waiheʻe Ditch has two intake grates in Waiheʻe River in a reach that is bifurcated by an island. The intake grates are near the crests of dams and consist of parallel steel bars roughly aligned in the direction of flow. Open spaces between bars are about 0.15 ft wide and 3 to 7 ft long (in the direction of flow). The intake grate for the right (south) branch of Waiheʻe River stretches about 25 ft across the entire low-flow channel and has 74 openings between steel bars and at the grate edges (fig. A2). The intake grate for the left (north) branch of Waiheʻe River stretches about 44 ft across the entire low-flow channel, with 121 openings between steel bars and at the grate edges (fig. A2). Water that enters the intake grates drains into a collection sump and flows by gravity into the ditch system. The Waiheʻe Ditch intakes have a combined design capacity of 60 Mgal/d, although a downstream control gate limits flow in the ditch to about 40 Mgal/d (Suzuki, 2007).

The intake for Spreckels Ditch (fig. A3) is located near the right (south) edge of Waiheʻe River and on the upstream side of a dam that stretches across the entire low-flow channel (fig. A4). The intake gate for Spreckels Ditch is about 6.5 ft wide, although only the right half of the gate is currently (2009) open to accept water. The Spreckels Ditch intake in Waiheʻe River has a design capacity of 30 Mgal/d, although a control gate limits flow in the ditch to about 12 Mgal/d (Suzuki, 2007). About 6 Mgal/d of the water diverted by the Waiheʻe Ditch commonly discharges into the Spreckels Ditch (Suzuki, 2007), about 2,000 ft downstream of the Spreckels Ditch intake.

The Field 1 diversion intake and dam exists near an altitude of 260 ft. In its recent (2009) configuration, the Field 1 diversion intake gate opening is about 1.7 ft wide and 1.2 ft high (fig. A5), but the capacity of the intake is unknown. The ditch associated with the Field 1 intake is on the north side of Waiheʻe River and currently (2009) also receives water from Spreckels Ditch through a pipeline.

Waiehu Stream

A map from 1868 of the Waiehu area (Lewers Plantation, 1868) shows what appears to be the North Waiehu Ditch that starts in North Waiehu Stream and a second ditch that either terminates or starts in North Waiehu Stream near the current location of Spreckels Ditch. Martin and Pierce (1913) show a single diversion (North Waiehu Ditch) from North Waiehu Stream near an altitude of about 880 ft and a single diversion (South Waiehu Ditch) from South Waiehu Stream near an altitude of about 860 ft, although they also indicate that water is diverted from both North and South Waiehu Streams "for irrigation through several ditches at various levels" (fig. A1). For example, a small ditch upstream of an altitude of 870 ft diverted about 0.2 Mgal/d from South Waiehu Stream for irrigation of taro (Grover and Larrison, 1917a). In addition, an undated map (Wailuku Water Company, LLC, undated) that shows both Spreckels and Waiheʻe Ditches also shows two unnamed ditches that appear to start in Waiehu Stream. This same undated map of Waiehu also shows one unnamed ditch each in the valleys of North and South Waiehu Streams that appear to start below the level of the Waiheʻe Ditch but are unconnected at their upstream ends to either a stream or the Waiheʻe Ditch. Thus, the source of water for these two unnamed ditches is uncertain.

Currently (2009), the North Waiehu Ditch (fig. 7) is the only known diversion from North Waiehu Stream and

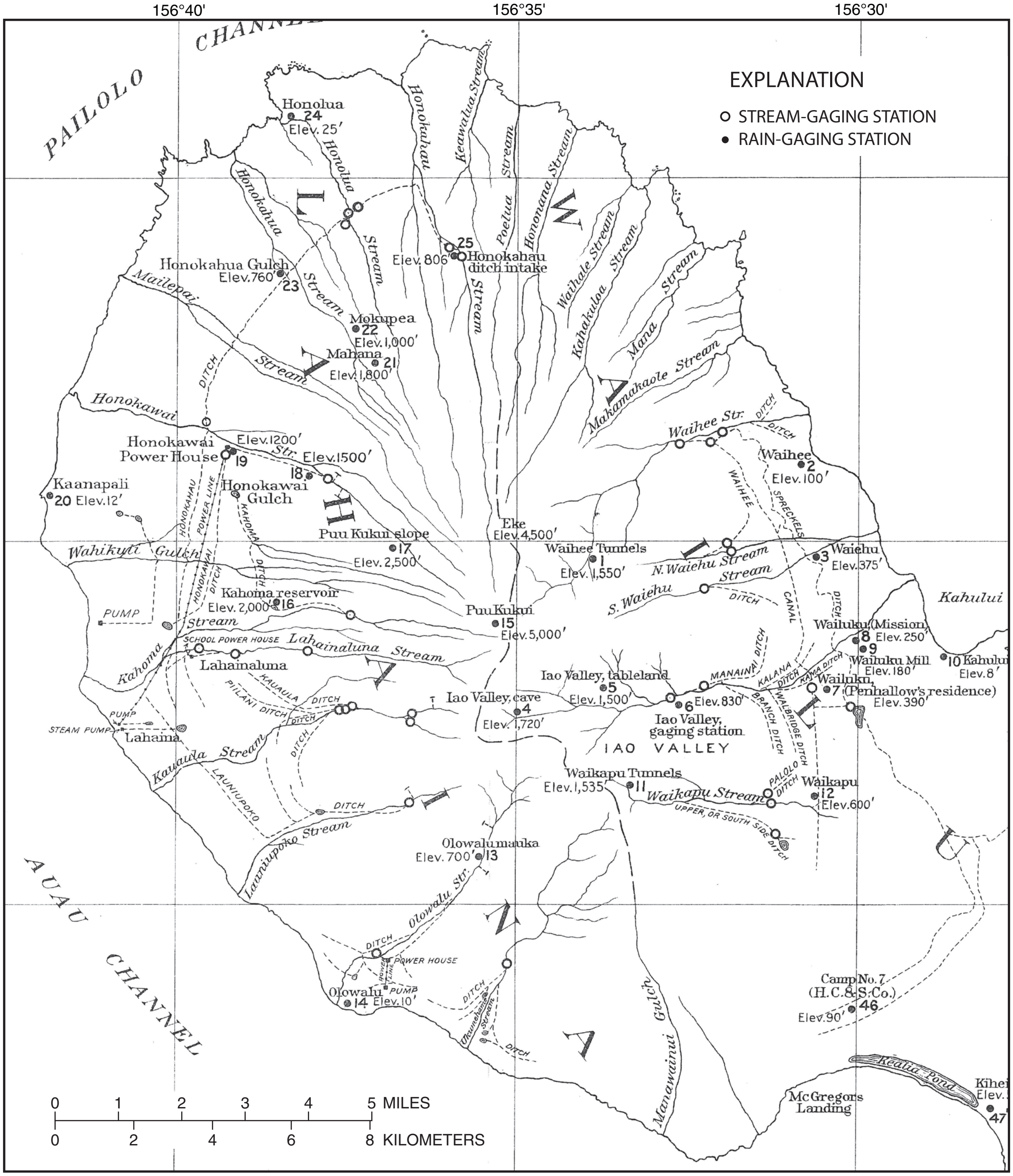


Figure A1. Historical ditch systems, West Maui, Hawaiʻi (modified from Martin and Pierce, 1913). Map projection and datum not specified on source.

is owned and maintained by WWC. Water in North Waiehu Stream is diverted into North Waiehu Ditch, located on the left (north) side of the stream, by a 5-ft-thick dam formed by boulders placed across the entire low-flow channel of the stream (fig. A6). The dam is about 2 ft high and 20 ft wide, forming an extension of the downstream wall of the ditch. A downstream control gate is set to limit flow in the North Waiehu Ditch to about 1.5 Mgal/d (Suzuki, 2007).

Three known diversions currently exist on South Waiehu Stream: two ʻauwai (ditches) for private use, with intakes near altitudes of 620 ft (north side of stream) and 570 ft (south side of stream) (fig. A7), and the Spreckels Ditch, with an intake near an altitude of 270 ft (fig. A8). The Spreckels Ditch intake near an altitude of 270 ft is owned and maintained by HC&S and consists of an intake grate near the right (south) edge of the channel. The intake grate is about

Figure A2. Photographs of Waiheʻe Ditch diversion intake near an altitude of 600 feet, Waiheʻe River, Maui, Hawaiʻi. *A*, South (right branch) intake (July 18, 2006). *B*, North (left branch) intake (July 18, 2006).

Figure A3. Photographs of Spreckels Ditch diversion intake on the south side of Waiheʻe River near an altitude of 400 feet, Maui, Hawaiʻi. *A*, Upstream side of intake gate (June 8, 2006). *B*, Downstream side of intake gate (far background) with view of Spreckels Ditch in foreground (July 18, 2006).

4.5 ft wide and about 13 ft long (in the general direction of flow). The grate has 13 openings (about 0.25 ft wide) between parallel steel bars and at the grate edges. The capacities of the diversions on South Waiehu Stream are not known. Limited measurements indicate that (1) flow in each of the two ʻauwai is less than 0.5 Mgal/d and (2) the Spreckels Ditch intake is capable of diverting all of the low flow of South Waiehu Stream up to at least 1 Mgal/d.

ʻĪao Stream

A map from 1878 of the Wailuku area (Bailey, 1878) shows three ditches originating in ʻĪao Stream: Kalani Ditch (shown as "Kalamauwai" on map) on the north side, Kama Ditch on the south side, and an unnamed ditch on the south side that leads to a sugar mill (likely the Mill Stream or Mill Ditch). Silva (1962, p. 19) also lists these three ditches that diverted water from ʻĪao Stream during 1881. Kalani and Kama Ditches likely were originally constructed for the purpose of irrigating taro on the plains to the north and south of ʻĪao Stream (Sterling, 1998, p. 86). Sterling (1998) indicated that several smaller ditches also diverted water from ʻĪao Stream at sites farther downstream. A map from 1882 of the Wailuku area (Monsarrat, 1882) shows two unnamed ditches on the north side of ʻĪao Stream and three ditches on the south side. One of the two ditches on the north side likely is the Kalani Ditch, and the other terminates at a reservoir a relatively short distance from ʻĪao Stream. The three ditches shown on the south side of ʻĪao Stream (Monsarrat, 1882) are (1) the Mission Ditch (likely the same as the Kama Ditch), which originates near an altitude of about 430 ft, (2) an unnamed ditch originating near an altitude of about 360 ft that leads to a sugar mill (likely Mill Stream), and (3) Kalua Ditch, which has an uncertain point of origin. Martin and Pierce (1913) show locations of Māniania (shown as "Manainai" on map, fig. A1) and Kalani (shown as "Kalana" on map, fig. A1) Ditches on the north side and Branch, Walbridge, and Kama Ditches on the south side of ʻĪao Stream (fig. A1). Concrete remnants that may be related to the intake for the Kama Ditch are still visible in the

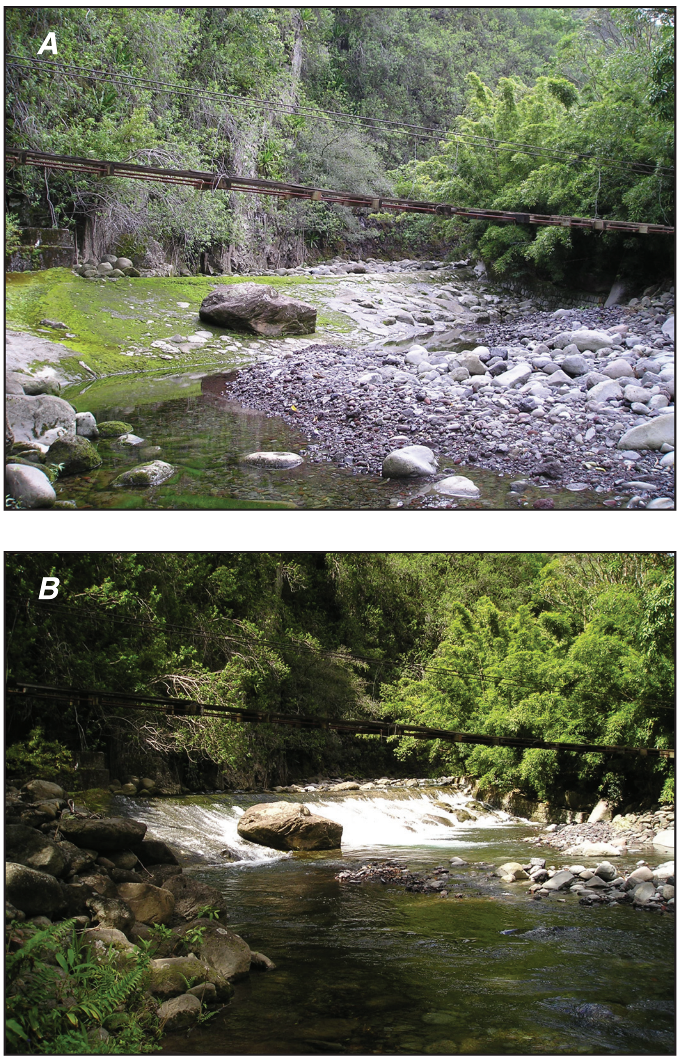


Figure A4. Photographs of dam structure for Spreckels Ditch diversion intake near an altitude of 400 feet, Waiheʻe River, Maui, Hawaiʻi. *A*, Typical dry weather diverted condition (August 7, 2006). *B*, During ditch maintenance period when water was temporarily restored to Waiheʻe River (June 8, 2006).

Figure A5. Photograph of Field 1 diversion intake (viewed from upstream side) near an altitude of 260 feet, Waiheʻe River, Maui, Hawaiʻi (June 8, 2006).

stream channel (fig. A9). Martin and Pierce (1913, p. 257) also indicate that "Third ditch" diverted water to the north side of ʻĪao Stream, although the location of this ditch was not identified.

Currently, the main diversions from ʻĪao Stream are the ʻĪao-Waikapū and ʻĪao-Māniania Ditches, which share a common intake near an altitude of 780 ft, and the Spreckels Ditch, with an intake near an altitude of 250 ft (fig. 7). A small private intake exists near an altitude of 650 ft and diverts water through a 6-in pipe for use on the south side of ʻĪao Stream.

The intake grate for the ʻĪao-Waikapū and ʻĪao-Māniania Ditches is owned and maintained by WWC and is located immediately downstream of the crest of a dam with a downstream face that is veneered by concrete (fig. A10). The intake grate stretches about 33 ft across the entire low-flow channel of ʻĪao Stream and is about 4 ft long (in the direction of flow). The grate has 222 openings (about 0.07 ft wide) between parallel steel bars and at the grate edges. Water that enters the intake grate drains into a collection sump and flows by gravity into the ditch system. The intake

Figure A6. Photographs of North Waiehu Ditch diversion intake near an altitude of 880 feet, North Waiehu Stream, Maui, Hawaiʻi. *A*, Upstream end of North Waiehu Ditch on the north side of North Waiehu Stream (June 29, 2006). *B*, Boulder and cobble dam that diverts most of flow in North Waiehu Stream (June 29, 2006). Arrows indicate general direction of flow.

Figure A7. Photographs of diversion intakes for private ʻauwai (ditches), South Waiehu Stream, Maui, Hawaiʻi. *A*, Intake on north side of stream near an altitude of 620 feet (July 17, 2006). *B*, Intake on south side of stream near an altitude of 570 feet (July 17, 2006). Arrows indicate general direction of flow.

in ʻĪao Stream has a design capacity of 60 Mgal/d, although a downstream control gate limits combined flow in the ʻĪao-Waikapū and ʻĪao-Māniania Ditches to about 20 Mgal/d (18 Mgal/d to the ʻĪao-Waikapū Ditch and 2 Mgal/d to the ʻĪao-Māniania Ditch) (Suzuki, 2007).

The intake grate in ʻĪao Stream for the Spreckels Ditch is owned and maintained by HC&S and is located near the right (south) edge of a concrete-lined flood-control channel and immediately upstream of a chute in the channel (fig. A11). Upstream of the Spreckels Ditch intake, the low flow of ʻĪao Stream occurs near the right edge of the channel. The intake grate consists of three separate parts. The downstream intake grate is about 27 ft wide and 3 ft long (in the direction

Figure A8. Photograph of Spreckels Ditch diversion intake on the south side of South Waiehu Stream near an altitude of 270 feet, Maui, Hawaiʻi (July 27, 2006).

Figure A9. Photograph of concrete remnants related to the diversion intake for the Kama Ditch near an altitude of 430 feet, ʻĪao Stream, Maui, Hawaiʻi (June 9, 2006).

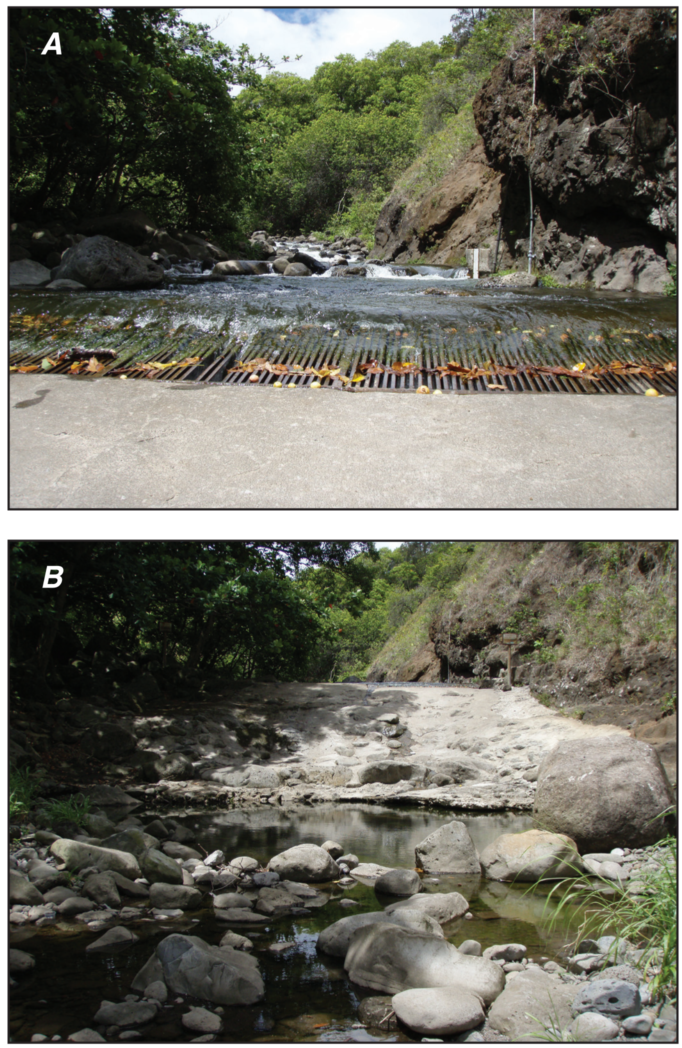


Figure A10. Photographs of diversion intake common to the ʻĪao-Māniania and ʻĪao-Waikapū Ditches near an altitude of 780 feet, ʻĪao Stream, Maui, Hawaiʻi. *A*, Intake grate (August 30, 2007). *B*, Diversion dam viewed from downstream (August, 30, 2007).

of flow) and has 206 openings that are about 0.1 ft wide between parallel steel bars and at the grate edges. The upstream intake grate nearest the right edge of the channel slopes upward in a downstream direction, is about 3 ft wide and 20 ft long (in the direction of flow), and has 17 openings that are about 0.1 ft wide between parallel steel bars and at the grate edges. The adjacent upstream intake grate itself has three parts: (1) an upstream sloping grate about 4 ft wide and 12 ft long with 8 openings that are about 0.1 to 0.3 ft wide; (2) a downstream grate about 3 ft wide and 3 ft long with grid openings that are about 0.3 ft wide and 0.1 ft long; and (3) a vertical grate at the left edge of the upstream sloping part of the intake, with openings that are about 0.15 ft wide and up to 1.5 ft high at the downstream end. The capacity of the intake for Spreckels Ditch is unknown, although it likely exceeds 10 Mgal/d, judging from available discharge measurements and observations.

Figure A11. Photographs of Spreckels Ditch diversion intake on the south side of ʻĪao Stream near an altitude of 250 feet, Maui, Hawaiʻi. *A*, Diversion intake just upstream of concrete chute (June 6, 2006). *B*, Closeup of parts of intake grate (June 6, 2006).

Waikapū Stream

A map from 1894 of Waikapū Stream shows three unnamed ditches on the north side and one unnamed ditch on the south side of Waikapū Stream (Monsarrat, 1894). The uppermost ditch on the north side of Waikapū Stream appears to correspond to the Everett Ditch (also referred to as Palolo Ditch), which originates near an altitude of 900 ft. The remaining two unnamed ditches on the north side originate near altitudes of 710 and 560 ft, whereas the unnamed ditch on the south side originates near an altitude of 580 ft.

Martin and Pierce (1913) indicate that water was diverted from Waikapū Stream through several ditches at various altitudes, and the South Side (Upper), Everett (Palolo), and Waiheʻe Ditches were shown (fig. A1). Martin and Pierce (1913, p. 257) also measured discharge in "Palama Ditch," although the location of that ditch was not identified. Currently (2009), five known diversion intakes exist on Waikapū Stream: (1) the South Side Ditch (also referred to as South Waikapū Ditch) is the most upstream diversion, with an intake near an altitude of 1,120 ft (fig. A12); (2) the Everett Ditch intake is near an altitude of 900 ft (fig. A13); (3) a private, community ʻauwai diverts water near an altitude of 560 ft (fig. A14); (4) the Waiheʻe Ditch intake is near an altitude of 440 ft (fig. A15); and (5) the Reservoir 6 intake is near an altitude of 410 ft (fig. A16).

The intake for the South Side Ditch is owned and maintained by WWC and is located near the right (south) edge of Waikapū Stream on the upstream side of a 55-ft-long dam that stretches across the entire low-flow channel (fig. A12). The vertical intake for the South Side Ditch is 4.5 ft wide and 2.3 ft high and has a design capacity of about 5 Mgal/d (Suzuki, 2007), although a control gate is set to limit flow in the South Side Ditch to about 3 Mgal/d (Suzuki, 2007).

The Everett Ditch intake was replaced in 1933, and that ditch was later abandoned when a landslide filled the intake and tunnel (Wilcox, 1996, p. 125). Sometime before June 2006, the Everett Ditch intake was cleared, and water has since been flowing in the ditch for a distance of about 900 feet before returning to Waikapū Stream near an altitude of about 850 feet. The intake for the Everett Ditch is located near the left (north) edge of the stream and consists of a steel intake grate that is about 2 ft wide and 4 ft long (in the direction of flow) (fig. A13). The intake has 10 openings that are about 0.07 to 0.2 ft wide between parallel steel bars and at the grate edges, and water that enters the intake grate drains into a collection sump and flows by gravity into the ditch. Remnants of an abandoned intake grate that stretched across the stream are adjacent to the existing intake. The capacity of the Everett Ditch intake is unknown but is less than the typical low flow of Waikapū Stream. During April 29 and April 30, 2008, discharges in the Everett Ditch near gaging station 16649000 (fig. 7) were 0.36 and 0.14 Mgal/d (0.56 and 0.21 ft^3/s), respectively. Measured discharges in Waikapū Stream, about 600 ft upstream of the Everett Ditch intake, were 3.19 and 1.29 Mgal/d (4.93 and 1.99 ft^3/s), respectively, on April 29 and April 30, 2008.

The intake for the Waiheʻe Ditch in Waikapū Stream is on the left (north) side of the stream (fig. A15). The main intake grate is about 10 ft wide and 2.5 ft long (in the direction of flow) with 51 openings that are about 0.08 ft wide between parallel steel bars and at the grate edges. A smaller intake grate (1.6 ft wide and 1.9 ft long with 17 openings that are 0.05 ft wide) is located at the left edge of the main intake. The Waikapū Stream intake for Reservoir 6 is about 15 ft wide and 3 ft long (in the direction of flow) with 53 openings that are about 0.2 ft wide and 35 openings (near the right edge of the channel) that are about 0.06 ft wide between parallel steel bars and at the grate edges (fig. A16). The capacities of the Waiheʻe Ditch and Reservoir 6 intakes each exceed 1 Mgal/d but are otherwise unknown.

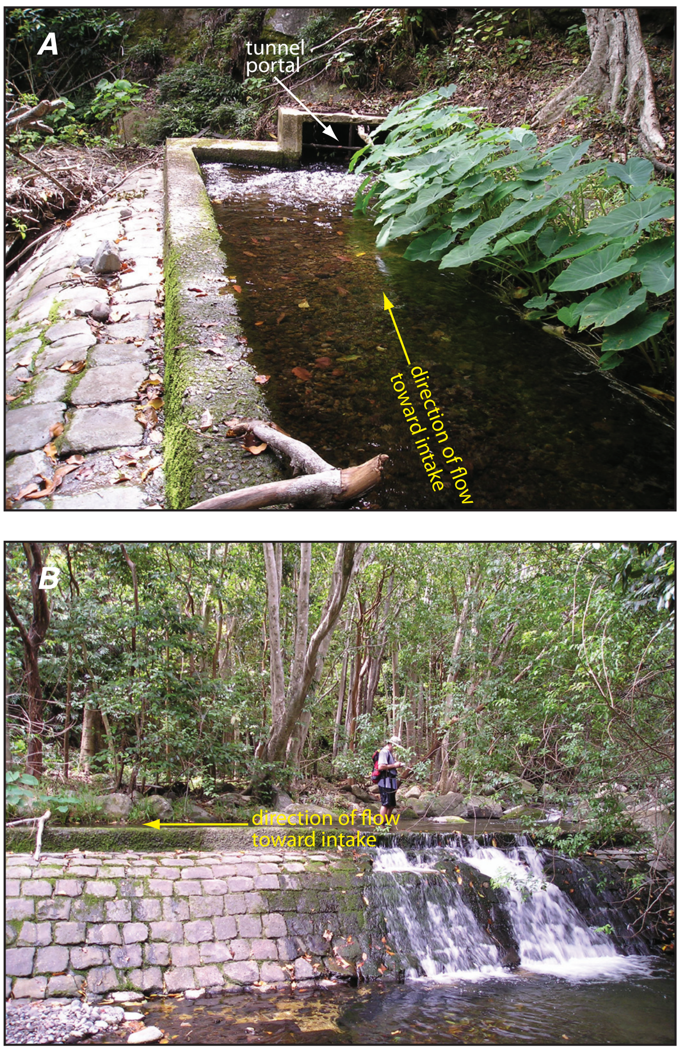


Figure A12. Photographs of South Side Ditch diversion intake on the south side of Waikapū Stream near an altitude of 1,120 feet, Maui, Hawaiʻi. *A*, Diversion intake that leads into a tunnel (June 7, 2006). *B*, Diversion dam viewed from downstream (June 7, 2006).

Figure A13. Photographs of Everett Ditch diversion intake near an altitude of 900 feet, Waikapū Stream, Maui, Hawaiʻi (August 23, 2006). *A*, Diversion intake near the left side (viewed downstream) of the channel being cleared of debris. *B*, Intake grate cleared of debris.

Figure A14. Photograph of diversion intake for private ‘auwai (ditch) on the north side of Waikapū Stream near an altitude of 560 feet, Maui, Hawai‘i (June 9, 2006).

Figure A15. Photograph of diversion intake for Waihe‘e Ditch near an altitude of 440 feet, Waikapū Stream, Maui, Hawai‘i (October 22, 2008).

Figure A16. Photograph of diversion intake for the Reservoir 6 Ditch near an altitude of 410 feet, Waikapū Stream, Maui, Hawai‘i (March 17, 2005).

Appendix B. Miscellaneous Discharge Measurements During 2004–2009, Nā Wai ʻEhā, Maui, Hawaiʻi

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ʻEhā stream and from upstream to downstream, Maui, Hawaiʻi.

[Dt, ditch; Str, stream; Trib, tributary; alt, altitude; ft, feet; nr, near; DS, downstream; US, upstream; LB, left bank (viewed downstream); RB, right bank (viewed downstream); <, less than; ~, about; —, no data]

				Discharge	
Site ID	Station name	Date	Time	Cubic feet per second	Million gallons per day
	Waiheʻe River				
205610156324701	Waihee Riv at Waihee Ditch intake right, Maui, HI	06/16/2004	1221	0.36	0.23
205610156324702	Waihee Riv at Waihee Ditch intake left, Maui, HI	06/16/2004	1303	0.16	0.10
205613156323901	Unnamed Trib to Waihee Riv at Waihee Dt DS Maui, HI	06/16/2004	—	0.12	0.078
205613156323901	Unnamed Trib to Waihee Riv at Waihee Dt DS Maui, HI	10/12/2006	1415	0.18	0.12
205613156324401	Waihee River near alt 580 ft, Maui, HI	10/12/2006	1050	0.066	0.043
205613156324401	Waihee River near alt 580 ft, Maui, HI	12/11/2006	1328	1.18	0.763
205613156324401	Waihee River near alt 580 ft, Maui, HI	01/17/2007	1325	0.16	0.10
205613156324401	Waihee River near alt 580 ft, Maui, HI	02/08/2007	1600	0.1	0.06
205613156324401	Waihee River near alt 580 ft, Maui, HI	03/05/2007	1504	0.05	0.03
205613156324401	Waihee River near alt 580 ft, Maui, HI	04/03/2007	1442	0.03-0.04	0.02-0.03
205613156324401	Waihee River near alt 580 ft, Maui, HI	08/27/2007	1614	0.045	0.029
205613156324401	Waihee River near alt 580 ft, Maui, HI	10/16/2007	1725	0.051	0.033
205613156324401	Waihee River near alt 580 ft, Maui, HI	11/13/2007	1432	0.030	0.019
205613156324401	Waihee River near alt 580 ft, Maui, HI	12/17/2007	1559	0.59	0.38
205615156324301	RB inflow to Waihee River nr alt 560 ft, Maui, HI	10/12/2006	1324	1.70	1.10
205615156324301	RB inflow to Waihee River nr alt 560 ft, Maui, HI	12/11/2006	1223	0.18	0.12
205615156324301	RB inflow to Waihee River nr alt 560 ft, Maui, HI	01/17/2007	1223	0.63	0.41
205615156324201	Waihee River near altitude 560 feet, Maui, HI	04/03/2007	1349	0.91	0.59
205618156323901	Waihee River near altitude 530 ft, Maui, HI	02/27/2008	0932	40.7	26.3
205618156323901	Waihee River near altitude 530 ft, Maui, HI	02/28/2008	1007	40.4	26.1
205621156323601	RB inflow to Waihee River nr alt 510 ft, Maui, HI	10/12/2006	1442	0.022	0.014
205621156323601	RB inflow to Waihee River nr alt 510 ft, Maui, HI	12/11/2006	1435	0.082	0.053
205621156323601	RB inflow to Waihee River nr alt 510 ft, Maui, HI	01/17/2007	1503	0.057	0.037
205621156323601	RB inflow to Waihee River nr alt 510 ft, Maui, HI	02/26/2008	1526	0.026	0.017
205621156323601	RB inflow to Waihee River nr alt 510 ft, Maui, HI	02/28/2008	0952	0.018	0.012
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	06/16/2004	1112	0.60	0.39
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	10/12/2006	1541	0.12	0.078
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	12/11/2006	1526	0.78	0.50
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	01/17/2007	1409	0.55	0.36
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	08/27/2007	1719	0.18	0.12
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	02/26/2008	1450	0.13	0.084
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	02/28/2008	0929	0.12	0.078
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	05/30/2008	1116	0.051	0.033
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	10/20/2008	1048	0.080	0.052
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	11/18/2008	1509	0.47	0.30
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	12/05/2008	0959	0.083	0.054
205627156323401	Huluhulupueo Stream at Waihee River, Maui, HI	12/19/2008	1238	0.11	0.071
205633156322401	Waihee River near altitude 445 ft, Maui, HI	02/28/2008	1600	41.2	26.6
205632156322001	Waihee River near alt 400 ft, Maui, HI	10/12/2006	0849	1.57	1.01
205632156322001	Waihee River near alt 400 ft, Maui, HI	12/11/2006	1639	2.94	1.90
205632156322001	Waihee River near alt 400 ft, Maui, HI	01/17/2007	1523	1.45	0.937
205632156322001	Waihee River near alt 400 ft, Maui, HI	07/09/2007	1557	2.26	1.46
205632156322001	Waihee River near alt 400 ft, Maui, HI	08/28/2007	0958	1.78	1.15
205632156322001	Waihee River near alt 400 ft, Maui, HI	09/18/2007	1328	19.3	12.5
205632156322001	Waihee River near alt 400 ft, Maui, HI	10/16/2007	1434	2.28	1.47
205632156322001	Waihee River near alt 400 ft, Maui, HI	11/13/2007	1633	1.98	1.28
205632156322001	Waihee River near alt 400 ft, Maui, HI	12/18/2007	1204	7.82	5.05
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	06/16/2004	1050	2.17	1.40
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	02/26/2008	1305	8.61	5.57
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	02/27/2008	1138	9.18	5.93
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	02/28/2008	0806	9.20	5.95
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	03/24/2008	1202	1.04	0.672
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	04/11/2008	1217	1.44	0.931
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	05/01/2008	1004	1.32	0.853
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	05/30/2008	0929	1.14	0.737
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	07/02/2008	0831	1.59	1.03
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	07/30/2008	1118	1.20	0.776
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	09/24/2008	0859	1.81	1.17
16615000	SPRECKELS DITCH NR WAIHEE, MAUI, HI	10/20/2008	0947	1.92	1.24
205634156321801	Waihee River near alt 390 ft, Maui, HI	08/28/2007	1531	0.014	0.0090
205634156321801	Waihee River near alt 390 ft, Maui, HI	10/16/2007	1319	0.005	0.003

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ‘Ehā stream and from upstream to downstream, Maui, Hawai‘i—Continued.

Site ID	Station name	Date	Time	Discharge	
				Cubic feet per second	Million gallons per day
205634156321801	Waihee River near alt 390 ft, Maui, HI	11/13/2007	1538	0.001	0.001
205634156321801	Waihee River near alt 390 ft, Maui, HI	12/18/2007	0912	1.33	0.860
205634156321801	Waihee River near alt 390 ft, Maui, HI	02/26/2008	1126	31.4	20.3
205634156321801	Waihee River near alt 390 ft, Maui, HI	02/27/2008	1302	31.0	20.0
205634156321801	Waihee River near alt 390 ft, Maui, HI	02/28/2008	1256	30.4	19.6
205634156321801	Waihee River near alt 390 ft, Maui, HI	02/29/2008	1154	31.0	20.0
205634156321801	Waihee River near alt 390 ft, Maui, HI	04/11/2008	1100	<0.01	<0.006
205634156321801	Waihee River near alt 390 ft, Maui, HI	05/01/2008	1200	<0.001	<0.0006
205634156321801	Waihee River near alt 390 ft, Maui, HI	05/30/2008	1140	<0.001	<0.0006
205634156321801	Waihee River near alt 390 ft, Maui, HI	06/30/2008	1818	<0.001	<0.0006
205634156321801	Waihee River near alt 390 ft, Maui, HI	07/02/2008	0845	<0.001	<0.0006
205634156321801	Waihee River near alt 390 ft, Maui, HI	07/30/2008	1145	<0.001	<0.0006
205634156321801	Waihee River near alt 390 ft, Maui, HI	09/23/2008	1020	~0.001	~0.0006
205634156321801	Waihee River near alt 390 ft, Maui, HI	10/20/2008	1217	0.001	0.001
205633156321901	Spreckels Ditch overflow to Waihee River, Maui, HI	06/16/2004	1139	0.10	0.065
205633156321901	Spreckels Ditch overflow to Waihee River, Maui, HI	02/26/2008	—	0.1	0.06
205633156321901	Spreckels Ditch overflow to Waihee River, Maui, HI	02/27/2008	0900	0.1	0.06
205633156321901	Spreckels Ditch overflow to Waihee River, Maui, HI	02/28/2008	0800	0.1	0.06
205633156321901	Spreckels Ditch overflow to Waihee River, Maui, HI	02/29/2008	1345	0.1	0.06
205634156321101	Waihee River near altitude 360 ft, Maui, HI	02/29/2008	1243	32.5	21.0
205634156321101	Waihee River near altitude 360 ft, Maui, HI	12/01/2008	1146	8.49	5.49
205634156321101	Waihee River near altitude 360 ft, Maui, HI	12/02/2008	0840	8.61	5.57
205634156320601	Waihee River near altitude 320 ft, Maui, HI	12/01/2008	1437	7.79	5.04
205634156320601	Waihee River near altitude 320 ft, Maui, HI	12/02/2008	0930	7.89	5.10
205633156315801	Waihee River near altitude 310 ft, Maui, HI	02/29/2008	0937	32.2	20.8
205633156315801	Waihee River near altitude 310 ft, Maui, HI	11/19/2008	1624	10.8	6.98
205633156315801	Waihee River near altitude 310 ft, Maui, HI	11/20/2008	1020	9.20	5.95
205633156315801	Waihee River near altitude 310 ft, Maui, HI	11/21/2008	0958	9.89	6.39
205633156315801	Waihee River near altitude 310 ft, Maui, HI	12/02/2008	1036	9.72	6.28
205634156315001	Waihee River near altitude 290 ft, Maui, HI	02/29/2008	0929	32.0	20.7
205634156315001	Waihee River near altitude 290 ft, Maui, HI	11/20/2008	1206	8.74	5.65
205634156314701	Waihee River near altitude 285 ft, Maui, HI	02/26/2008	0935	35.0	22.6
205634156314701	Waihee River near altitude 285 ft, Maui, HI	02/26/2008	1620	33.9	21.9
205634156314701	Waihee River near altitude 285 ft, Maui, HI	02/27/2008	1431	34.1	22.0
205634156314701	Waihee River near altitude 285 ft, Maui, HI	02/28/2008	0903	35.0	22.6
205634156314701	Waihee River near altitude 285 ft, Maui, HI	02/29/2008	0932	33.6	21.7
205634156314201	Waihee River upstream of Field 1 intake, Maui, HI	06/16/2004	1304	0.01	0.01
205634156314201	Waihee River upstream of Field 1 intake, Maui, HI	11/19/2008	1450	11.5	7.43
205634156314201	Waihee River upstream of Field 1 intake, Maui, HI	11/20/2008	0900	8.69	5.62
205634156314201	Waihee River upstream of Field 1 intake, Maui, HI	11/21/2008	0848	9.19	5.94
205634156314201	Waihee River upstream of Field 1 intake, Maui, HI	12/02/2008	1201	9.29	6.00
205634156313801	Waihee Riv downstream of Field 1 intake, Maui, HI	06/16/2004	1328	0.036	0.023
205639156305801	Waihee River near altitude 100 ft, Maui, HI	02/27/2008	1609	35.0	22.6
205639156305801	Waihee River near altitude 100 ft, Maui, HI	02/28/2008	1105	34.7	22.4
205639156305801	Waihee River near altitude 100 ft, Maui, HI	11/20/2008	1540	11.8	7.63
205639156305801	Waihee River near altitude 100 ft, Maui, HI	11/21/2008	1124	9.57	6.19
205639156305801	Waihee River near altitude 100 ft, Maui, HI	12/02/2008	1357	13.1	8.47
205639156305801	Waihee River near altitude 100 ft, Maui, HI	12/04/2008	1646	11.6	7.50
205639156305401	RB inflow to Waihee River nr alt 80 ft, Maui, HI	02/28/2008	1438	0.11	0.071
205639156305401	RB inflow to Waihee River nr alt 80 ft, Maui, HI	11/21/2008	1200	0	0
205639156305401	RB inflow to Waihee River nr alt 80 ft, Maui, HI	12/02/2008	1454	0.045	0.029
205639156305401	RB inflow to Waihee River nr alt 80 ft, Maui, HI	12/04/2008	1600	0.05	0.03
205640156305201	Waihee River near alt 75 ft, Maui, HI	12/12/2006	1140	2.49	1.61
205644156304401	Waihee River near alt 45 ft, Maui, HI	12/12/2006	0937	2.23	1.44
205644156304401	Waihee River near alt 45 ft, Maui, HI	01/17/2007	0930	1.97	1.27
205644156304401	Waihee River near alt 45 ft, Maui, HI	02/05/2007	1506	2.05	1.33
205644156304401	Waihee River near alt 45 ft, Maui, HI	02/07/2007	1456	2.00	1.29
205644156304401	Waihee River near alt 45 ft, Maui, HI	03/05/2007	1051	2.34	1.51
205644156304401	Waihee River near alt 45 ft, Maui, HI	04/30/2007	1019	3.61	2.33
205644156304401	Waihee River near alt 45 ft, Maui, HI	08/27/2007	1254	1.92	1.24
205644156304401	Waihee River near alt 45 ft, Maui, HI	10/16/2007	1019	2.72	1.76
205644156304401	Waihee River near alt 45 ft, Maui, HI	11/13/2007	1057	2.66	1.72

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ‘Ehā stream and from upstream to downstream, Maui, Hawai‘i—Continued.

Site ID	Station name	Date	Time	Discharge: Cubic feet per second	Discharge: Million gallons per day
205644156304401	Waihee River near alt 45 ft, Maui, HI	12/17/2007	1100	3.78	2.44
205644156304401	Waihee River near alt 45 ft, Maui, HI	02/26/2008	1645	34.4	22.2
205644156304401	Waihee River near alt 45 ft, Maui, HI	02/27/2008	1724	33.9	21.9
205644156304401	Waihee River near alt 45 ft, Maui, HI	02/28/2008	1306	34.8	22.5
205644156304401	Waihee River near alt 45 ft, Maui, HI	04/11/2008	0918	2.86	1.85
205644156304401	Waihee River near alt 45 ft, Maui, HI	04/30/2008	1658	2.36	1.53
205644156304401	Waihee River near alt 45 ft, Maui, HI	07/02/2008	1205	3.30	2.13
205644156304401	Waihee River near alt 45 ft, Maui, HI	07/30/2008	1322	3.06	1.98
205644156304401	Waihee River near alt 45 ft, Maui, HI	08/26/2008	1110	2.13	1.38
205644156304401	Waihee River near alt 45 ft, Maui, HI	09/23/2008	1128	2.56	1.65
205644156304401	Waihee River near alt 45 ft, Maui, HI	10/20/2008	1340	2.15	1.39
205644156304401	Waihee River near alt 45 ft, Maui, HI	11/20/2008	1357	8.48	5.48
205644156304401	Waihee River near alt 45 ft, Maui, HI	11/21/2008	1230	9.13	5.90
205644156304401	Waihee River near alt 45 ft, Maui, HI	12/02/2008	1544	12.8	8.27
205644156304401	Waihee River near alt 45 ft, Maui, HI	12/04/2008	1523	11.7	7.56
205648156304301	Waihee River near alt 35 ft, Maui, HI	08/24/2006	1216	1.79	1.16
205648156304301	Waihee River near alt 35 ft, Maui, HI	10/13/2006	1004	2.20	1.42
205651156303901	Waihee River near mouth, Maui, HI	06/16/2004	1507	1.41	0.911
	North Waiehu Stream				
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	10/10/2006	1350	3.52	2.28
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	03/07/2007	1000	3.42	2.21
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	07/11/2007	1258	4.63	2.99
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	09/19/2007	1458	3.23	2.09
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	10/19/2007	0927	2.89	1.87
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	11/14/2007	0937	2.62	1.69
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	12/19/2007	0930	3.14	2.03
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	03/10/2008	1100	3.62	2.34
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	03/11/2008	0948	3.40	2.20
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	03/11/2008	1123	3.37	2.18
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	03/12/2008	0906	3.65	2.36
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	03/13/2008	0911	3.62	2.34
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	05/29/2008	0943	3.25	2.10
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	07/01/2008	1035	3.22	2.08
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	07/28/2008	1122	3.55	2.29
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	08/25/2008	1021	2.92	1.89
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	10/21/2008	1005	2.74	1.77
205434156315701	North Waiehu Stream near alt 920 ft, Maui, HI	11/19/2008	0929	4.19	2.71
205434156315501	North Waiehu Stream near alt 900 ft, Maui, HI	07/25/2006	1453	4.10	2.65
205435156315201	N Waiehu Str US of N Waiehu Ditch intake, Maui, HI	08/17/2005	1054	3.29	2.13
205435156315001	N. Waiehu Ditch intake, N. Waiehu Stream, Maui, HI	08/17/2005	1148	3.00	1.94
205437156312301	North Waiehu ditch near alt 840 ft, Maui, HI	07/25/2006	1707	3.76	2.43
205437156312301	North Waiehu ditch near alt 840 ft, Maui, HI	10/10/2006	1124	3.11	2.01
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	10/10/2006	1631	0.61	0.39
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	07/11/2007	1011	0.37	0.24
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	09/19/2007	1725	0.33	0.21
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	10/19/2007	1136	0.48	0.31
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	11/14/2007	1115	0.32	0.21
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	11/14/2007	1136	0.37	0.24
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	12/19/2007	1110	0.81	0.52
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	05/29/2008	1148	0.60	0.39
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	07/01/2008	1244	1.55	1.00
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	07/28/2008	1237	0.71	0.46
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	08/25/2008	1549	0.50	0.32
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	10/21/2008	1120	0.38	0.25
205435156314701	North Waiehu Stream near alt 820 ft, Maui, HI	11/19/2008	1103	1.57	1.01
205432156312801	N Waiehu Stream near altitude 625 ft, Maui, HI	03/06/2007	1724	2.60	1.68
205432156312801	N Waiehu Stream near altitude 625 ft, Maui, HI	03/07/2007	1142	2.43	1.57
205432156312701	N Waiehu Str US of Waihee Ditch flume, Maui, HI	08/17/2005	0930	0	0
205432156312701	N Waiehu Str US of Waihee Ditch flume, Maui, HI	10/10/2006	1730	0	0
205432156310401	N Waiehu Stream near altitude 475 feet, Maui, HI	03/06/2007	0835	2.03	1.31
205432156310401	N Waiehu Stream near altitude 475 feet, Maui, HI	03/07/2007	1309	2.01	1.30
205432156310401	N Waiehu Stream near altitude 475 feet, Maui, HI	03/10/2008	1438	1.80	1.16

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ʻEhā stream and from upstream to downstream, Maui, Hawaiʻi—Continued.

Site ID	Station name	Date	Time	Discharge: Cubic feet per second	Discharge: Million gallons per day
205432156310401	N Waiehu Stream near altitude 475 feet, Maui, HI	03/11/2008	1334	1.76	1.14
205432156310401	N Waiehu Stream near altitude 475 feet, Maui, HI	03/12/2008	1109	1.76	1.14
205432156310401	N Waiehu Stream near altitude 475 feet, Maui, HI	03/13/2008	1110	1.81	1.17
205432156310401	N Waiehu Stream near altitude 475 feet, Maui, HI	03/14/2008	0842	1.78	1.15
205433156310101	N Waiehu Stream at Malaihi Road, Maui, HI	08/17/2005	1200	0	0
205435156305801	N Waiehu Stream near altitude 450 feet, Maui, HI	10/10/2006	1800	0	0
205435156305801	N Waiehu Stream near altitude 450 feet, Maui, HI	12/19/2007	—	0	0
205450156303601	N Waiehu Stream near altitude 280 feet, Maui, HI	03/06/2007	1158	1.48	0.957
205450156303601	N Waiehu Stream near altitude 280 feet, Maui, HI	03/07/2007	1418	1.46	0.944
205450156303601	N Waiehu Stream near altitude 280 feet, Maui, HI	03/10/2008	1625	0.89	0.58
205450156303601	N Waiehu Stream near altitude 280 feet, Maui, HI	03/11/2008	1440	1.10	0.711
205450156303601	N Waiehu Stream near altitude 280 feet, Maui, HI	03/12/2008	1219	1.08	0.698
205450156303601	N Waiehu Stream near altitude 280 feet, Maui, HI	03/13/2008	1112	1.15	0.743
205450156303601	N Waiehu Stream near altitude 280 feet, Maui, HI	03/14/2008	0839	1.27	0.821
205451156303401	North Waiehu Stream near alt 260 ft, Maui, HI	07/27/2006	1810	0.10	0.065
205452156303401	RB inflow to N. Waiehu Str nr alt 260 ft, Maui, HI	03/07/2007	1450	0.2	0.1
205450156303201	N Waiehu Stream near altitude 240 feet, Maui, HI	03/06/2007	1011	1.45	0.937
205449156302801	N Waiehu Stream upstream of fork, Maui, HI	08/17/2005	1502	0.28	0.18
205449156302801	N Waiehu Stream upstream of fork, Maui, HI	07/27/2006	1741	0.14	0.090
	South Waiehu Stream				
16610000	SOUTH WAIEHU STREAM NR WAILUKU, MAUI, HI	11/17/2008	1243	2.10	1.36
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	08/29/2007	1304	2.33	1.51
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	11/16/2007	1017	2.06	1.33
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	12/20/2007	1515	2.35	1.52
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	03/13/2008	1448	2.47	1.60
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	05/29/2008	1421	2.40	1.55
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	07/30/2008	1500	2.44	1.58
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	08/29/2008	0852	2.27	1.47
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	09/23/2008	1354	2.46	1.59
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	10/21/2008	1404	2.22	1.43
205426156313601	South Waiehu Stream near alt 670 ft, Maui, HI	11/17/2008	1024	2.05	1.33
205427156313101	South Waiehu Stream near alt 635 ft, Maui, HI	07/26/2006	1050	3.70	2.39
205427156313101	South Waiehu Stream near alt 635 ft, Maui, HI	01/18/2007	1615	3.42	2.21
205427156313101	South Waiehu Stream near alt 635 ft, Maui, HI	05/04/2007	1048	2.69	1.74
205421156310301	Kuleana Ditch nr alt 600ft,LB S Waiehu Str, Maui, HI	07/26/2006	1734	0.43	0.28
205423156311501	Ditch return to S Waiehu Str nr alt 550 ft, Maui, HI	07/26/2006	—	<0.005	<0.003
205420156311301	S Waiehu Str DS of Waihee Ditch flume, Maui, HI	08/17/2005	1124	3.20	2.07
205420156311301	S Waiehu Str DS of Waihee Ditch flume, Maui, HI	08/29/2007	1619	1.68	1.09
205420156311302	Kuleana Ditch nr 540 ft, RB S Waiehu Str, Maui, HI	07/26/2006	1311	0.26	0.17
205420156311302	Kuleana Ditch nr 540 ft, RB S Waiehu Str, Maui, HI	08/29/2007	1655	0.57	0.37
205415156310001	South Waiehu Stream near alt 460 ft, Maui, HI	07/26/2006	1615	2.33	1.51
205422156305401	South Waiehu Stream near alt 405 ft, Maui, HI	07/26/2006	1434	2.24	1.45
205422156305401	South Waiehu Stream near alt 405 ft, Maui, HI	07/27/2006	0949	2.78	1.80
205439156303401	S Waiehu Str US of Spreckels Dt intake, Maui, HI	08/17/2005	1500	3.67	2.37
205439156303401	S Waiehu Str US of Spreckels Dt intake, Maui, HI	07/27/2006	1228	2.24	1.45
205439156303401	S Waiehu Str US of Spreckels Dt intake, Maui, HI	07/12/2007	1303	1.99	1.29
205439156303401	S Waiehu Str US of Spreckels Dt intake, Maui, HI	08/03/2007	0900	2.00	1.29
205439156303401	S Waiehu Str US of Spreckels Dt intake, Maui, HI	08/03/2007	1140	1.74	1.12
205439156303401	S Waiehu Str US of Spreckels Dt intake, Maui, HI	11/14/2007	1419	1.56	1.01
205448156302801	S Waiehu Stream upstream of fork, Maui, HI	08/17/2005	1627	0.020	0.013
205448156302801	S Waiehu Stream upstream of fork, Maui, HI	03/06/2007	1230	0.5	0.3
205448156302801	S Waiehu Stream upstream of fork, Maui, HI	03/07/2007	1500	0.5	0.3
	Waiehu Stream				
205451156302401	Waiehu Stream near alt 210 ft, Maui, HI	07/27/2006	1709	0.21	0.14
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	03/06/2007	1402	1.91	1.23
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	03/07/2007	1515	2.24	1.45
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	03/08/2007	1456	1.75	1.13
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	04/02/2007	1120	0.48	0.31
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	09/21/2007	1408	0.40	0.26
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	11/14/2007	1622	0.21	0.14
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	12/19/2007	1415	0.89	0.58

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ʻEhā stream and from upstream to downstream, Maui, Hawaiʻi—Continued.

Site ID	Station name	Date	Time	Discharge	
				Cubic feet per second	Million gallons per day
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	03/11/2008	1509	1.32	0.853
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	03/12/2008	1403	1.53	0.989
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	03/13/2008	1218	1.40	0.905
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	03/14/2008	0940	1.44	0.931
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	05/01/2008	1314	0.36	0.23
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	07/02/2008	1336	0.29	0.19
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	08/29/2008	1004	0.39	0.25
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	09/24/2008	1318	0.37	0.24
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	10/21/2008	1547	0.45	0.29
205455156302301	Waiehu Stream near alt 190 ft, Maui, HI	12/03/2008	1700	0.42	0.27
205504156295101	Waiehu Stream at Kahekili Highway, Maui, HI	08/17/2005	1657	0.46	0.30
205506156294501	Waiehu Stream near altitude 50 feet, Maui, HI	03/06/2007	1533	1.31	0.847
205506156294501	Waiehu Stream near altitude 50 feet, Maui, HI	03/07/2007	1612	1.59	1.03
205506156293501	Waiehu Stream near mouth, Maui, HI	08/17/2005	1619	0.19	0.12
205506156293501	Waiehu Stream near mouth, Maui, HI	03/12/2008	1557	0.95	0.61
205506156293501	Waiehu Stream near mouth, Maui, HI	03/13/2008	1213	0.89	0.58
205506156293501	Waiehu Stream near mouth, Maui, HI	03/14/2008	0942	1.27	0.821
	ʻĪao Stream				
205254156322301	Right branch of Iao Str nr alt 800 ft, Maui, HI	08/28/2008	1303	3.83	2.48
205257156322001	Iao Stream DS of Maniania Ditch, Maui, HI	09/21/2004	0855	0.08	0.05
205257156321901	Iao Stream near alt 755 ft, Maui, HI	07/24/2006	1347	0.008	0.01
205256156321801	Iao Stream near alt 750 ft, Maui, HI	10/11/2006	1235	0.047	0.030
205256156321801	Iao Stream near alt 750 ft, Maui, HI	08/30/2007	1120	0.094	0.061
205256156321801	Iao Stream near alt 750 ft, Maui, HI	09/21/2007	1032	0.062	0.040
205256156321701	Iao Stream near alt 745 ft, Maui, HI	01/16/2007	1540	0.30	0.19
205256156321601	Iao Stream near alt 740 ft, Maui, HI	08/30/2007	1042	0.24	0.16
205256156321601	Iao Stream near alt 740 ft, Maui, HI	09/21/2007	1050	0.23	0.15
205256156321601	Iao Stream near alt 740 ft, Maui, HI	11/15/2007	1736	0.23	0.15
205256156321301	RB return flow to Iao Str nr alt 732 ft, Maui, HI	01/16/2007	1751	0.04	0.03
205256156321302	RB return flow to Iao Str nr alt 730 ft, Maui, HI	10/11/2006	1126	0.011	0.0071
205256156321302	RB return flow to Iao Str nr alt 730 ft, Maui, HI	01/16/2007	1745	0.040	0.026
205256156321303	Iao Stream near alt 725 ft, Maui, HI	07/24/2006	1110	0.49	0.32
205256156321303	Iao Stream near alt 725 ft, Maui, HI	10/11/2006	1138	0.40	0.26
205256156321303	Iao Stream near alt 725 ft, Maui, HI	01/16/2007	1647	0.87	0.56
205257156321001	Iao Stream at Kepaniwai Park, Maui, HI	09/21/2004	1005	0.48	0.31
205300156321401	Maniania Ditch Leakage to Iao Stream, Maui, HI	09/21/2004	0930	0.010	0.0065
205257156321101	LB return flow to Iao Str near alt 715 ft, Maui, HI	07/24/2006	1049	0.026	0.017
205257156321101	LB return flow to Iao Str near alt 715 ft, Maui, HI	10/11/2006	1031	0.018	0.012
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	09/21/2004	0945	0.17	0.11
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	07/24/2006	1200	0.087	0.056
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	10/11/2006	1321	0.094	0.061
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	08/30/2007	1205	0.062	0.040
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	11/16/2007	1309	0.051	0.033
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	05/30/2008	1409	0.051	0.033
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	09/24/2008	1510	0.045	0.029
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	10/23/2008	0839	0.057	0.037
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	11/21/2008	1335	0.051	0.033
205257156321002	Trib to Iao Stream at Kepaniwai Park, Maui, HI	12/03/2008	1352	0.051	0.033
205258156320201	LB return flow to Iao Stream nr alt 670 ft, Maui, HI	07/24/2006	1215	0.11	0.071
205258156320201	LB return flow to Iao Stream nr alt 670 ft, Maui, HI	10/11/2006	1345	0.12	0.078
205300156320001	Iao Stream near alt 660 ft, Maui, HI	07/24/2006	1515	0.37	0.24
205300156320002	Iao Stream near alt 655 ft, Maui, HI	07/24/2006	1530	0.19	0.12
205300156320002	Iao Stream near alt 655 ft, Maui, HI	10/11/2006	1543	0.10	0.065
205301156315901	Iao Stream near alt 650 ft, Maui, HI	07/24/2006	1600	0.087	0.056
205301156315901	Iao Stream near alt 650 ft, Maui, HI	10/11/2006	1500	0	0
205303156315201	Duey diversion from Iao Stream, Maui, HI	09/21/2004	1125	0.14	0.090
205303156315201	Duey diversion from Iao Stream, Maui, HI	07/24/2006	1620	0.083	0.054
205303156315101	Iao Stream downstream of Duey diversion, Maui, HI	09/21/2004	1156	0.29	0.19
205303156314701	Iao Stream near alt 595 ft, Maui, HI	12/14/2006	1220	22.8	14.7
205303156314701	Iao Stream near alt 595 ft, Maui, HI	07/13/2007	0812	2.90	1.87
205303156314701	Iao Stream near alt 595 ft, Maui, HI	09/18/2007	1730	38.7	25.0
205303156314701	Iao Stream near alt 595 ft, Maui, HI	09/19/2007	1009	34.4	22.2

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ʻEhā stream and from upstream to downstream, Maui, Hawaiʻi—Continued.

Site ID	Station name	Date	Time	Discharge: Cubic feet per second	Discharge: Million gallons per day
205303156314701	Iao Stream near alt 595 ft, Maui, HI	09/19/2007	1150	28.2	18.2
205303156314701	Iao Stream near alt 595 ft, Maui, HI	11/15/2007	1632	0.25	0.16
205303156314701	Iao Stream near alt 595 ft, Maui, HI	12/18/2007	1653	16.8	10.9
205303156314701	Iao Stream near alt 595 ft, Maui, HI	01/14/2008	1212	29.6	19.1
205303156314701	Iao Stream near alt 595 ft, Maui, HI	01/15/2008	1635	35.7	23.1
205303156314701	Iao Stream near alt 595 ft, Maui, HI	01/16/2008	1055	31.2	20.2
205303156314701	Iao Stream near alt 595 ft, Maui, HI	01/17/2008	0933	28.3	18.3
205303156314701	Iao Stream near alt 595 ft, Maui, HI	01/18/2008	0927	27.0	17.5
205303156314701	Iao Stream near alt 595 ft, Maui, HI	02/11/2008	1253	45.0	29.1
205303156314701	Iao Stream near alt 595 ft, Maui, HI	02/12/2008	0839	40.4	26.1
205303156314701	Iao Stream near alt 595 ft, Maui, HI	02/13/2008	1313	35.6	23.0
205303156314701	Iao Stream near alt 595 ft, Maui, HI	02/14/2008	1225	34.4	22.2
205303156314701	Iao Stream near alt 595 ft, Maui, HI	02/15/2008	0901	31.8	20.6
205303156314701	Iao Stream near alt 595 ft, Maui, HI	02/15/2008	1125	31.7	20.5
205303156314701	Iao Stream near alt 595 ft, Maui, HI	03/12/2008	1718	0.5	0.3
205303156314701	Iao Stream near alt 595 ft, Maui, HI	04/10/2008	1110	23.0	14.9
205303156314701	Iao Stream near alt 595 ft, Maui, HI	05/30/2008	1329	0.24	0.16
205303156314701	Iao Stream near alt 595 ft, Maui, HI	07/02/2008	1511	0.28	0.18
205303156314701	Iao Stream near alt 595 ft, Maui, HI	08/27/2008	1408	0.99	0.64
205303156314701	Iao Stream near alt 595 ft, Maui, HI	10/20/2008	1548	0.35	0.23
205303156314701	Iao Stream near alt 595 ft, Maui, HI	12/03/2008	1447	0.40	0.26
205303156314001	Duey return at Iao Stream, Maui, HI	09/21/2004	1355	0.030	0.019
205303156314001	Duey return at Iao Stream, Maui, HI	09/22/2004	1300	0.070	0.045
205303156314001	Duey return at Iao Stream, Maui, HI	12/14/2006	1018	0.01	0.01
205303156314001	Duey return at Iao Stream, Maui, HI	01/14/2008	1340	0.05-0.1	0.03-0.06
205303156314001	Duey return at Iao Stream, Maui, HI	01/16/2008	1205	0.4-0.5	0.3
205303156314001	Duey return at Iao Stream, Maui, HI	01/17/2008	1050	0.4-0.5	0.3
205303156314001	Duey return at Iao Stream, Maui, HI	01/18/2008	1100	0.4-0.5	0.3
205303156314001	Duey return at Iao Stream, Maui, HI	02/11/2008	1435	0.005	0.003
205303156314001	Duey return at Iao Stream, Maui, HI	02/12/2008	1630	0.001	0.001
205303156314001	Duey return at Iao Stream, Maui, HI	02/13/2008	1445	0.3	0.2
205303156314001	Duey return at Iao Stream, Maui, HI	02/14/2008	1415	0.3	0.2
205303156314001	Duey return at Iao Stream, Maui, HI	02/15/2008	1055	0.3	0.2
205303156314002	Iao Stream downstream of Duey return, Maui, HI	09/21/2004	1450	0.32	0.21
205301156310501	Iao Stream at Kama Ditch intake, Maui, HI	09/21/2004	1530	0	0
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	01/16/2008	1225	0.1-0.2	0.06-0.1
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	01/17/2008	0915	0.1-0.2	0.06-0.1
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	01/18/2008	0905	0.1-0.2	0.06-0.1
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	02/11/2008	1440	0.005	0.003
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	02/12/2008	1640	0.005	0.003
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	02/13/2008	1600	0.01	0.01
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	02/14/2008	1430	0.01	0.01
205300156305501	RB swale, Iao Str near altitude 400 feet, Maui, HI	02/15/2008	1105	0.01	0.01
205302156305601	Iao Stream near alt 395 ft, Maui, HI	12/14/2006	1631	18.6	12.0
205302156305601	Iao Stream near alt 395 ft, Maui, HI	01/16/2008	0914	28.7	18.6
205302156305601	Iao Stream near alt 395 ft, Maui, HI	01/16/2008	1235	26.8	17.3
205302156305601	Iao Stream near alt 395 ft, Maui, HI	01/17/2008	0812	24.2	15.6
205302156305601	Iao Stream near alt 395 ft, Maui, HI	01/17/2008	1300	23.7	15.3
205302156305601	Iao Stream near alt 395 ft, Maui, HI	01/18/2008	0755	23.0	14.9
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/11/2008	1230	41.5	26.8
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/12/2008	1639	36.1	23.3
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/13/2008	1250	33.7	21.8
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/13/2008	1440	33.6	21.7
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/14/2008	1139	31.0	20.0
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/14/2008	1336	30.4	19.6
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/15/2008	0747	30.7	19.8
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/15/2008	0930	30.2	19.5
205302156305601	Iao Stream near alt 395 ft, Maui, HI	02/15/2008	1125	29.7	19.2
205308156304401	Iao Stream near alt 340 ft, Maui, HI	07/25/2006	1046	0.068	0.044
205312156304701	Spring at Iao Stream debris basin wall, Maui, HI	09/21/2004	1618	0.48	0.31
205312156304701	Spring at Iao Stream debris basin wall, Maui, HI	08/29/2008	1206	0.89	0.58
205312156304701	Spring at Iao Stream debris basin wall, Maui, HI	09/25/2008	1548	0.65	0.42

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ʻEhā stream and from upstream to downstream, Maui, Hawaiʻi—Continued.

Site ID	Station name	Date	Time	Discharge: Cubic feet per second	Discharge: Million gallons per day
205312156304701	Spring at Iao Stream debris basin wall, Maui, HI	10/23/2008	0954	0.34	0.22
205312156304701	Spring at Iao Stream debris basin wall, Maui, HI	11/18/2008	1646	1.09	0.705
205312156304701	Spring at Iao Stream debris basin wall, Maui, HI	12/05/2008	1212	0.38	0.25
205312156304701	Spring at Iao Stream debris basin wall, Maui, HI	12/19/2008	1058	1.47	0.950
205315156304001	LB spring inflow to Iao Str nr alt 320 ft, Maui, HI	07/25/2006	1009	0.19	0.12
16607000	Iao Stream at Wailuku, Maui, HI	09/21/2004	1658	0.76	0.49
205333156300901	Iao Stream near alt 220 ft, Maui, HI	01/18/2007	0949	18.5	12.0
205333156300901	Iao Stream near alt 220 ft, Maui, HI	02/13/2008	0804	13.2	8.53
205333156300901	Iao Stream near alt 220 ft, Maui, HI	02/13/2008	1101	12.8	8.27
205333156300901	Iao Stream near alt 220 ft, Maui, HI	02/14/2008	0751	9.75	6.30
205333156300901	Iao Stream near alt 220 ft, Maui, HI	02/14/2008	1041	9.50	6.14
205423156292101	Iao Stream near alt 35 ft, Maui, HI	01/18/2007	1227	15.3	9.89
205423156292101	Iao Stream near alt 35 ft, Maui, HI	02/13/2008	0940	10.5	6.79
205423156292101	Iao Stream near alt 35 ft, Maui, HI	02/14/2008	0920	6.52	4.21
205425156291701	Iao Stream near alt 20 ft, Maui, HI	11/15/2006	1126	0.80	0.52
	Waikapū Stream				
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	08/23/2006	1107	4.08	2.64
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	09/06/2006	1307	3.49	2.26
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	11/13/2006	1141	3.54	2.29
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	12/13/2006	1458	3.73	2.41
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	05/02/2007	1346	3.37	2.18
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	05/03/2007	1308	3.19	2.06
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	07/31/2007	1316	7.73	5.00
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	08/01/2007	1425	3.94	2.55
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	08/02/2007	1337	3.62	2.34
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	09/20/2007	0925	3.31	2.14
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	10/18/2007	0907	4.24	2.74
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	11/15/2007	0933	2.76	1.78
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	12/20/2007	0846	6.00	3.88
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	04/28/2008	1133	3.14	2.03
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	04/29/2008	0947	3.37	2.18
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	04/30/2008	0844	3.36	2.17
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	07/03/2008	0839	2.99	1.93
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	07/29/2008	0930	18.6	12.0
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	08/27/2008	0946	4.41	2.85
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	09/25/2008	1058	2.98	1.93
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	10/22/2008	1032	2.95	1.91
205121156321501	Waikapu Stream near alt 1,160 ft, Maui, HI	12/03/2008	1008	3.08	1.99
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	10/28/2004	1235	2.79	1.80
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	08/23/2006	1212	2.48	1.60
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	11/13/2006	1257	2.47	1.60
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	12/13/2006	1425	2.28	1.47
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	05/03/2007	1247	3.12	2.02
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	08/01/2007	1432	3.31	2.14
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	08/02/2007	1344	3.02	1.95
205121156320901	Waikapu Str, South Waikapu Ditch intake, Maui, HI	11/15/2007	1016	2.43	1.57
205122156320901	Waikapu Str, DS of South Waikapu Ditch, Maui, HI	10/28/2004	1141	0.78	0.50
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	08/23/2006	1354	1.17	0.756
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	11/13/2006	1346	0.82	0.53
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	12/13/2006	1349	1.06	0.685
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	12/13/2006	1521	1.54	1.00
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	05/03/2007	1209	0.27	0.17
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	07/31/2007	1220	3.44	2.22
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	08/01/2007	1340	0.99	0.64
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	08/02/2007	1010	0.90	0.58
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	09/20/2007	1121	0.48	0.31
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	10/18/2007	0901	1.23	0.795
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	11/15/2007	1028	0.51	0.33
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	12/20/2007	0940	2.50	1.62
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	04/28/2008	1318	0.61	0.39
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	04/30/2008	0940	0.12	0.078
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	07/03/2008	0947	0.092	0.059

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ‘Ehā stream and from upstream to downstream, Maui, Hawai‘i—Continued.

Site ID	Station name	Date	Time	Discharge	
				Cubic feet per second	Million gallons per day
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	07/29/2008	1135	9.40	6.08
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	08/27/2008	1042	0.55	0.36
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	09/25/2008	0950	0.095	0.061
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	10/22/2008	0910	0.15	0.10
205123156320501	Waikapu Stream near alt 1,080 ft, Maui, HI	12/03/2008	0904	0.13	0.084
205122156320601	Waikapu Str, South Waikapu Dt overflow, Maui, HI	10/28/2004	1345	0.07	0.05
205124156320301	RB inflow to Waikapu Str nr alt 1,070 ft, Maui, HI	08/23/2006	1437	0.02	0.01
205124156320301	RB inflow to Waikapu Str nr alt 1,070 ft, Maui, HI	05/03/2007	1415	0.05-0.1	0.03-0.06
205124156320301	RB inflow to Waikapu Str nr alt 1,070 ft, Maui, HI	07/31/2007	—	0.005-0.01	0.003-0.006
205124156320301	RB inflow to Waikapu Str nr alt 1,070 ft, Maui, HI	08/01/2007	1330	0.005-0.01	0.003-0.006
205124156320301	RB inflow to Waikapu Str nr alt 1,070 ft, Maui, HI	11/15/2007	1122	0.1-0.15	0.06-0.1
205124156320301	RB inflow to Waikapu Str nr alt 1,070 ft, Maui, HI	04/30/2008	1008	0.1-0.2	0.06-0.1
205124156320301	RB inflow to Waikapu Str nr alt 1,070 ft, Maui, HI	07/03/2008	1050	0.1	0.06
205125156320101	Waikapu Str US unnamed trib at 1,060 ft, Maui, HI	10/28/2004	1450	0.62	0.40
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	10/28/2004	1408	2.27	1.47
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	05/03/2007	1538	1.80	1.16
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	08/01/2007	1536	1.68	1.09
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	08/02/2007	1459	1.64	1.06
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	09/20/2007	1230	1.58	1.02
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	11/15/2007	1134	1.53	0.989
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	04/29/2008	0940	2.02	1.31
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	04/30/2008	0835	1.98	1.28
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	07/29/2008	1332	1.82	1.18
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	08/27/2008	1138	1.76	1.14
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	09/25/2008	1246	1.85	1.20
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	10/22/2008	1138	1.65	1.07
205122156320101	Unnamed Trib to Waikapu Str at 1,060 ft, Maui, HI	12/03/2008	1118	1.76	1.14
205126156315501	Waikapu Stream near alt 1,020 ft, Maui, HI	08/23/2006	1546	3.25	2.10
205126156315501	Waikapu Stream near alt 1,020 ft, Maui, HI	12/13/2006	1223	3.42	2.21
205126156315501	Waikapu Stream near alt 1,020 ft, Maui, HI	12/13/2006	1608	3.96	2.56
205126156315501	Waikapu Stream near alt 1,020 ft, Maui, HI	05/03/2007	1141	2.09	1.35
205126156315501	Waikapu Stream near alt 1,020 ft, Maui, HI	08/01/2007	1318	3.10	2.00
205126156315501	Waikapu Stream near alt 1,020 ft, Maui, HI	11/15/2007	1150	2.19	1.42
205122156314701	Waikapu Stream near alt 950 ft, Maui, HI	12/13/2006	1126	3.16	2.04
205122156314701	Waikapu Stream near alt 950 ft, Maui, HI	12/13/2006	1621	3.41	2.20
205122156314701	Waikapu Stream near alt 950 ft, Maui, HI	05/03/2007	1037	2.27	1.47
205122156314701	Waikapu Stream near alt 950 ft, Maui, HI	08/01/2007	1249	2.56	1.65
205122156314701	Waikapu Stream near alt 950 ft, Maui, HI	11/15/2007	1252	1.68	1.09
205122156314701	Waikapu Stream near alt 950 ft, Maui, HI	04/29/2008	1102	4.93	3.19
205122156314701	Waikapu Stream near alt 950 ft, Maui, HI	04/30/2008	0955	1.99	1.29
205124156314301	RB inflow to Waikapu Str nr alt 925 ft, Maui, HI	11/15/2007	1340	0.1-0.15	0.06-0.1
205124156314301	RB inflow to Waikapu Str nr alt 925 ft, Maui, HI	04/30/2008	1020	0.1	0.06
16649000	PALOLO DITCH NEAR WAIKAPU,MAUI,HI	04/29/2008	1204	0.56	0.36
16649000	PALOLO DITCH NEAR WAIKAPU,MAUI,HI	04/30/2008	1114	0.21	0.14
16650000	WAIKAPU STREAM NEAR WAIKAPU,MAUI,HI	10/28/2004	1535	3.11	2.01
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	09/06/2006	1522	2.38	1.54
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	05/02/2007	0849	4.06	2.62
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	05/03/2007	1039	3.83	2.48
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	08/01/2007	0846	2.96	1.91
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	09/20/2007	1350	2.13	1.38
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	10/18/2007	1136	2.62	1.69
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	11/15/2007	1240	1.78	1.15
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	12/20/2007	1110	3.96	2.56
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	04/28/2008	1452	3.02	1.95
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	04/29/2008	1210	4.76	3.08
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	04/30/2008	1041	1.95	1.26
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	07/29/2008	1426	8.09	5.23
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	07/30/2008	0821	3.01	1.95
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	08/27/2008	0831	2.90	1.87
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	09/25/2008	1402	1.95	1.26
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	09/26/2008	0804	1.82	1.18
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	10/22/2008	1312	1.84	1.19

Table 12. U.S. Geological Survey miscellaneous discharge measurements during 2004–2009, sorted by Nā Wai ʻEhā stream and from upstream to downstream, Maui, Hawaiʻi—Continued.

Site ID	Station name	Date	Time	Discharge	
				Cubic feet per second	Million gallons per day
205120156312801	Waikapu Stream near alt 820 ft, Maui, HI	12/03/2008	1200	1.72	1.11
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	10/28/2004	1200	2.92	1.89
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	09/06/2006	1000	2.06	1.33
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	12/13/2006	0858	3.09	2.00
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	05/03/2007	0859	3.60	2.33
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	08/01/2007	1711	2.27	1.47
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	04/28/2008	1706	2.52	1.63
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	04/29/2008	1355	4.29	2.77
205125156304801	Waikapu Str, US of left bank taro intake, Maui, HI	04/30/2008	1226	1.35	0.873
205124156304401	Waikapu Str, left bank taro diversion, Maui, HI	10/28/2004	1310	1.02	0.659
205123156304201	Waikapu Str, left bank taro div overflow, Maui, HI	10/28/2004	1406	0.46	0.30
205121156304001	Waikapu Str, left bank taro return, Maui, HI	10/28/2004	1008	0.19	0.12
205118156302901	Waikapu Str, right bank inflow, Maui, HI	10/28/2004	1531	0.20	0.13
205116156302601	Waikapu Str US of Waihee Ditch intake, Maui, HI	10/28/2004	1602	2.77	1.79
205114156302301	Waikapu Str DS of Waihee Ditch, Maui, HI	10/28/2004	1711	0.60	0.39
205112156301601	Waikapu Str US of Reservoir 6 intake, Maui, HI	10/28/2004	1650	1.10	0.711
205112156301201	Waikapu Stream near alt 400 ft, Maui, HI	08/22/2006	0850	4.03	2.60
205112156301201	Waikapu Stream near alt 400 ft, Maui, HI	04/02/2007	1742	7.40	4.78
205112156301201	Waikapu Stream near alt 400 ft, Maui, HI	01/29/2009	1144	25.0	16.2
205112156301202	Waikapu Stream near alt 400 ft, Maui, HI	03/13/2009	1120	14.2	9.18
16650200	Waikapu Stream at Waikapu, Maui, HI	03/18/2004	1101	16.3	10.5
205040156292801	Waikapu Stream near alt 225 ft, Maui, HI	08/22/2006	1000	0	0
205024156292301	Waikapu Stream at Route 380 bridge, Maui, HI	10/28/2004	1730	0	0
205024156292301	Waikapu Stream at Route 380 bridge, Maui, HI	08/21/2006	1458	0.24	0.16
205024156292301	Waikapu Stream at Route 380 bridge, Maui, HI	04/02/2007	1650	5.63	3.64
204850156284901	Waikapu Str at lower Maalaea Rd nr Maalaea,Maui,HI	03/18/2004	0955	7.10	4.59
204850156284901	Waikapu Str at lower Maalaea Rd nr Maalaea,Maui,HI	01/29/2009	1008	18.2	11.8
204850156284901	Waikapu Str at lower Maalaea Rd nr Maalaea,Maui,HI	01/29/2009	1249	13.9	8.98
204850156284901	Waikapu Str at lower Maalaea Rd nr Maalaea,Maui,HI	03/13/2009	0938	8.27	5.35
204850156284901	Waikapu Str at lower Maalaea Rd nr Maalaea,Maui,HI	03/13/2009	1240	6.92	4.47
204827156283601	Waikapu Stream at alt. 30 ft near Kihei, Maui, HI	03/18/2004	1054	5.74	3.71

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication, January 6, 2010
Text edited by Peter H. Stauffer
Layout and design by Stephen L. Scott

Oki and others—Effects of Surface-Water Diversion on Streamflow, Recharge, Physical Habitat, and Temperature, Nā Wai ʻEhā, Maui—Scientific Investigations Report 2010–5011