Prepared in cooperation with the State of Hawai‘i Office of Hawaiian Affairs

Low-Flow Characteristics of Streams Under Natural and Diversion Conditions, Waipi‘o Valley, Island of Hawai‘i, Hawai‘i

Scientific Investigations Report 2011–5118

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

COVER
Alakahi Stream in Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi. (Photograph by Kolja Rotzoll, University of Hawaiʻi at Mānoa, Water Resources Research Center).

Low-Flow Characteristics of Streams Under Natural and Diversion Conditions, Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi

By Richard A. Fontaine

Prepared in cooperation with the State of Hawaiʻi Office of Hawaiian Affairs

Scientific Investigations Report 2011–5118

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 2012

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:
Fontaine, R.A., 2012, Low-flow characteristics of streams under natural and diversion conditions, Waipi‘o Valley, Island of Hawai‘i, Hawai‘i: U.S. Geological Survey Scientific Investigations Report 2011–5118, 80 p.

Contents

Figures

Tables

Conversion Factors, Abbreviations, and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	0.64599	million gallons per day (Mgal/d)

Vertical coordinate information is referenced to local mean sea level.

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

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

This page intentionally left blank.

Low-Flow Characteristics of Streams Under Natural and Diversion Conditions, Waipi‘o Valley, Island of Hawai‘i, Hawai‘i

By Richard A. Fontaine

Abstract

Over the past 100 years, natural streamflow in Waipi‘o Valley has been reduced by the transfer of water out of the valley by Upper and Lower Hāmākua Ditches. The physical condition and diversion practices along the two ditch systems have varied widely over the years, and as a result, so have their effects on natural streamflow in Waipi‘o Valley. Recent renovation and improvements to Lower Hāmākua Ditch system, along with proposals for its future operation and water-diversion strategies, have unknown implications. The purpose of this report is to quantify the availability of streamflow and to determine the effects of current and proposed diversion strategies on the low-flow hydrology in Waipi‘o Valley.

In this report, the low-flow hydrology of Waipi‘o Valley is described in terms of flow-duration statistics. Flow-duration statistics were computed for three locations in the Waipi‘o Valley study area where long-term surface-water gaging stations have been operated. Using a variety of streamflow record-extension techniques, flow-duration statistics were estimated at an additional 13 locations where only few historical data are available or where discharge measurements were made as part of this study. Flow-duration statistics were computed to reflect natural conditions, current (2000–2005) diversion conditions, and proposed future diversion conditions at the 16 locations. At the downstream limit of the study area, on Wailoa Stream at an altitude of 190 feet, a baseline for evaluating the availability of streamflow is provided by computed flow-duration statistics that are representative of natural, no-diversion conditions. At the Wailoa gaging station, 95- and 50-percentile discharges under natural conditions were determined to be 86 and 112 cubic feet per second, respectively. Under 1965–1969 diversion conditions, natural 95- and 50-percentile discharges were reduced by 52 and 53 percent, to 41 and 53 cubic feet per second, respectively. Under current (2000–2005) diversion conditions, natural 95- and 50-percentile discharges were reduced by 21 and 24 percent, to 68 and 85 cubic feet per second, respectively. Under proposed future diversion conditions, natural 95- and 50-percentile discharges would be reduced by 33 and 24 percent, to 58 and 85 cubic feet per second, respectively. Compared to discharges that reflect current (2000–2005) diversion conditions, proposed future diversion conditions would reduce 95-percentile discharges, which are representative of moderate drought levels in the stream, by 15 percent. No change would be expected in 50-percentile discharges, which are representative of normal conditions. The effects of current (2000–2005) and proposed future diversion conditions on the natural flow of streams in the Waipi‘o Valley study area differ, depending on the location. Under current (2000–2005) diversion conditions, reductions in natural 95- or 50-percentile discharges of greater than 30 percent were found in Kawainui Stream downstream from Upper Hāmākua Ditch to an altitude of about 1,435 feet and in the reach of Waimā Stream between Upper and Lower Hāmākua Ditches. Under proposed future diversion conditions, reductions in natural 95- or 50-percentile discharges of greater than 30 percent were found in Kawainui Stream downstream from Upper Hāmākua Ditch to an altitude of about 1,435 feet, in the reach of Waimā Stream between Upper and Lower Hāmākua Ditches, and along most stream reaches downstream from Lower Hāmākua Ditch, except for Waimā Stream.

Introduction

Waipi‘o Valley is a location of great cultural and historical significance to the Hawaiian people. In ancient times, Waipi‘o Valley was a noted royal and religious center with a large population (Department of Urban and Regional Planning, 1999). To support this population, several hundred acres of taro were cultivated, and the cultivation of taro, which requires large quantities of freshwater (Penn, 1997), continues today on approximately 100 acres of land. The importance of streams in Waipi‘o Valley was highlighted by the Hawai‘i Stream Assessment (Hawai‘i Commission on Water Resource Management, 1990), which identified the streams as candidates for protection because of their aquatic, riparian, cultural, and recreational resources.

Wailoa Stream and its major tributaries Kawainui, Alakahi, Ko‘iawe, Waimā, and Waipi‘o Streams historically provided an ample supply of freshwater needed to support taro cultivation and stream biota in Waipi‘o Valley. Over the past

100 years, the natural flow of Wailoa Stream has been reduced considerably by diversion systems that transfer water out of Waipiʻo Valley. Construction of the Upper Hāmākua Ditch was completed in 1907 (Wilcox, 1996). This ditch system diverts streamflow, from headwater tributaries that flow into Waipiʻo Valley, at altitudes ranging from 4,042 feet down to 3,044 feet. Water diverted by the Upper Hāmākua Ditch is transported away from Waipiʻo Valley, primarily for use in the Waimea area. Construction of the Lower Hāmākua Ditch was completed in 1910 (Wilcox, 1996). This system diverts streamflow and captured groundwater resources from within Waipiʻo Valley at altitudes ranging from 1,037 feet down to 985 feet. Water diverted by the Lower Hāmākua Ditch is transported out of Waipiʻo Valley, primarily for use along the Hāmākua coastal area between Kukuihaele and Paʻauilo.

The physical condition and diversion practices of the Upper and Lower Hāmākua Ditch systems have varied widely over the years, and as a result, so have their effects on natural streamflow in Waipiʻo Valley. When initially constructed, Upper Hāmākua Ditch had the capacity to divert an average flow of about 23 ft^3/s (cubic feet per second), or 15 Mgal/d (million gallons per day) (Wilcox, 1996). Streamflow data collected by the U. S. Geological Survey (USGS) at gaging station 16726000 on the Upper Hāmākua Ditch at 3,020 feet elevation indicates that flow diverted from the headwaters of Waipiʻo Valley averaged 9.4 ft^3/s (6.1 Mgal/d) over the 20-year period 1975–2004. When initially constructed, Lower Hāmākua Ditch had the capacity to divert an average flow of about 62 ft^3/s (40 Mgal/d) (Wilcox, 1996). The capacity of Lower Hāmākua Ditch has decreased significantly over the years. In 2003, USGS streamflow data collected at gaging station 16732800 on the Lower Hāmākua Ditch, upstream from the main weir, indicated that the average flow being diverted out of Waipiʻo Valley was 10.1 ft^3/s (6.5 Mgal/d).

Historically, flow diverted by Lower Hāmākua Ditch was used primarily by sugar plantations along the Hāmākua Coast. However, since the 1993 declaration of bankruptcy by Hāmākua Sugar Company (U.S. Department of Agriculture, 1999) and the subsequent demise of sugar plantations along the Hāmākua Coast, a wide variety of users compete for this resource. Future diversion plans for the Lower Hāmākua Ditch system, now being operated by the Hawaiʻi Department of Agriculture (DOA), were proposed in an environmental impact statement completed in 1999 (U.S. Department of Agriculture, 1999). As outlined in the proposed plan of operation for Lower Hāmākua Ditch, average rates of flow diversion out of Waipiʻo Valley would decrease from the 48 ft^3/s (31 Mgal/d) diverted during periods when sugar plantations were in operation to 11 ft^3/s (7 Mgal/d). During any future drought conditions, diversions would decrease from 28 ft^3/s (18 Mgal/d) that were typically diverted during past droughts to 20 ft^3/s (13 Mgal/d) (U.S. Department of Agriculture, 1999, p. 144).

The availability of streamflow in Waipiʻo Valley to support the new diversion strategies proposed for Lower Hāmākua Ditch, and the implications for instream flows downstream from points of diversion, were based primarily on results of a study completed in 1984 (Mink, 1984). Although the study by Mink utilized the best data available at that time, its results were based on limited streamflow data from within Waipiʻo Valley. The USGS has historically published data for numerous streamflow stations in Waipiʻo Valley, but most were operated for only short periods in 1901 and 1902 and none of those stations are currently being operated. The USGS operated gaging station 16732200 on Wailoa Stream between 1964 and 1969 (Fontaine, 1996). The Wailoa Stream gaging station, which was located in Waipiʻo Valley at an altitude of about 190 feet, provided the longest and most current streamflow dataset utilized in the Mink study (Mink, 1984).

In cooperation with the State of Hawaiʻi Office of Hawaiian Affairs (OHA), the USGS undertook this investigation to quantify availability of low flows in streams in Waipiʻo Valley and to investigate how these flows vary with time and location along the streams. Historical information, along with data collected as part of this study, were analyzed to develop current estimates of low-flow characteristics that would be representative of long-term conditions and to evaluate the effects of current and proposed flow diversions on natural low-flow characteristics.

Purpose and Scope

The purposes of this report are to (1) quantify current and natural low-flow characteristics along stream reaches both upstream and downstream from the Lower Hāmākua Ditch diversion intakes, (2) evaluate implications of proposed diversion strategies on low-flow characteristics at points downstream from diversion intakes, and (3) quantify current and natural low-flow characteristics of Wailoa Stream as it enters the lower part of Waipiʻo Valley, where diversions to support taro production commence.

The study focuses on principal tributary streams that contribute flow to the upper reaches of Waipiʻo Valley, including Kawainui, Kawaiki, Alakahi, Koʻiawe, and Waimā Streams. The study area heads on the subject tributary streams, at locations just upstream from Upper Hāmākua Ditch intakes, and continues downstream into Waipiʻo Valley, terminating at an altitude of about 190 feet on Wailoa Stream. This location is just upstream from the point where initial diversions of taro irrigation water from Wailoa Stream take place.

To achieve the purposes of this report, both historical and new streamflow data and field observations were analyzed. Historical data include records of streamflow and discharge measurements collected by the USGS at former and current streamflow-gaging stations, as well as data available from other agencies. New streamflow data and field observations include (1) discharge measurements made at five low-flow partial-record stations; (2) seepage runs—a series of concurrent discharge measurements—made along Lower Hāmākua Ditch from Kawainui intake downstream to the main weir; and (3) seepage runs conducted along Wailoa Stream between points on tributary streams, just upstream from the intakes of

Lower Hāmākua Ditch, and downstream to the terminus of the study area, on Wailoa Stream at an altitude of about 190 feet.

Description of Study Area

The Waipiʻo Valley study area is on the northeastern flank of Kohala Volcano, which forms most of the extreme northern part of the Island of Hawaiʻi (fig. 1). The study area encompasses about 14.3 square miles and extends from the headwaters of Kawainui, Kawaiki, Alakahi, Koʻiawe, and Waimā Streams in the Kohala mountains, downstream through Waipiʻo Valley, to the location of former USGS gaging station 16732200 on Wailoa Stream at an altitude of 190 feet. The downstream terminus of the study area is just upstream from the point where initial diversions of taro irrigation water from Wailoa Stream take place. The maximum altitude in the study area is about 5,260 feet, on the summit of Puʻu o ʻUmi in the headwaters of Kawainui Stream.

The present-day Island of Hawaiʻi consists of five volcanic mountains, of which Kohala is the oldest (Macdonald and others, 1983, p. 345). The materials that make up Kohala volcano have been divided into two groups, the Pololū Basalt and Hāwī Volcanics (Langenheim and Clague, 1987). The Pololū Basalt consists primarily of numerous basaltic flows that range in thickness from a few feet to as much as 50 feet. Pololū basalts extend from the surface, along the flanks of Waipiʻo Valley, to below sea level and are exposed throughout the walls and interior of Waipiʻo Valley. Pololū basalts are considered to be very permeable and, where confined by dikes, are able to store large quantities of high-level water (Stearns and Macdonald, 1946, p. 228). The younger Hāwī Volcanics, which in some locations cap the Pololū Basalt, are separated from the Pololū basalts by an eroded surface. The existence of this surface indicates that Kohala Volcano was likely dormant for an extended period after the Pololū flows took place. During this dormant period, weathering formed the eroded surface and, especially on the wetter northeastern side of Kohala Volcano, deep valleys such as Waipiʻo. Flows of the Hāwī Volcanics cap Pololū basalts in the headwaters of the study area and extend primarily northwesterly and southeasterly from Kohala Volcano. As a result, the deeply eroded Waipiʻo Valley was only partly filled by Hāwī flows. In general, the Hāwī Volcanics store lesser quantities of water than the Pololū Basalt, and vertical movement of this water is commonly restricted by intervening layers of dense basaltic flows and weathered soil. Alluvium covers most of the stream beds in Waipiʻo Valley and is evident at altitudes as high as 1,200 feet, especially in Kawainui, Alakahi, Waipiʻo, and Wailoa Streams (Stearns and Macdonald, 1946; p. 171). All but the most recent, unconsolidated alluvium in Waipiʻo Valley is classified as poorly permeable (Stearns and Macdonald, 1946, p. 172). Thick deposits of this alluvium form the broad flat valley near the downstream terminus of Waipiʻo Valley.

Although geology played a primary role in the evolution of deeply eroded Waipiʻo Valley, plentiful rainfall in the area was also an important factor. The highest annual rainfall totals in the study area are found in the headwaters of Kawainui Stream. In general, annual rainfall totals decrease as one travels from Kawainui Stream eastward towards Waimā Stream and then northeast down the valley towards the ocean (fig. 1). In most of Kawainui Stream watershed upstream from Lower Hāmākua Ditch, mean annual rainfall exceeds 160 inches (Giambelluca and others, 1986). In Alakahi Stream watershed, upstream from its confluence with Kawainui Stream, mean annual rainfall is between 120 and 160 inches (Giambelluca and others, 1986). Upstream from the mouth of Koʻiawe and Waimā Streams, mean annual rainfall is between 80 and 120 inches. In Wailoa Stream watershed, in the lower reaches of the study area, mean annual rainfall is about 100 inches. This abundant rainfall provides large volumes of groundwater recharge that ultimately supports low flows in Waipiʻo Valley streams.

Most of the study area is undeveloped and covered by thick vegetation. Upstream from Upper Hāmākua Ditch, the terrain is fairly gentle and is covered with thick, low-level shrubs, brush, and small trees. Downstream from Upper Hāmākua Ditch, the land surface drops off sharply into Waipiʻo Valley. In the valley, terrain is much steeper and vegetation consists of larger trees, except along sheer valley walls, where vegetation is sparser. Kawainui, Alakahi, Koʻiawe, and Waimā Streams flow into Waipiʻo Valley over waterfalls that in total are about 1,000, 1,900, 1,760, and 1,640 feet high, respectively. Deeply eroded Waipiʻo Valley cuts through numerous, closely spaced dikes and intercepts significant volumes of dike-impounded groundwater (Stearns and Macdonald, 1946; p. 175).

From the ocean, Waipiʻo Valley extends inland in a roughly southwesterly direction. Near the confluence of Alakahi and Kawainui Streams, the valley makes an abrupt, almost ninety-degree bend toward the northwest and up Kawainui Stream. This unusual shape is indicative of a geomorphic process commonly referred to as pirating, or capturing of stream reaches. According to Macdonald and others (1983, p. 360) it is probable that upper reaches of Kawainui Stream once flowed through a notch known as Waimanu Gap and formed the headwaters of Waimanu Stream. Because of more rapid rates of erosion in Waipiʻo Valley, however, Kawainui Stream was eventually intersected and therefore forced to flow into Waipiʻo Valley. Thus Waipiʻo Valley drains water that would otherwise have flowed in Waimanu Stream had erosional processes not altered the drainage pattern.

An important aspect of the study area is the water diversion systems located and operated there. The availability of abundant, high-level water in Waipiʻo Valley has long been valued (Herschler and Randolph Consulting Engineers, 1961). The existence and operation of two major water-diversion systems, Upper and Lower Hāmākua Ditches, is a testament to that fact.

Upper Hāmākua Ditch, which roughly follows the southern rim of Waipiʻo Valley, diverts water from Kawainui Stream (at altitude 4,042 feet), Kawaiki Stream (at altitude

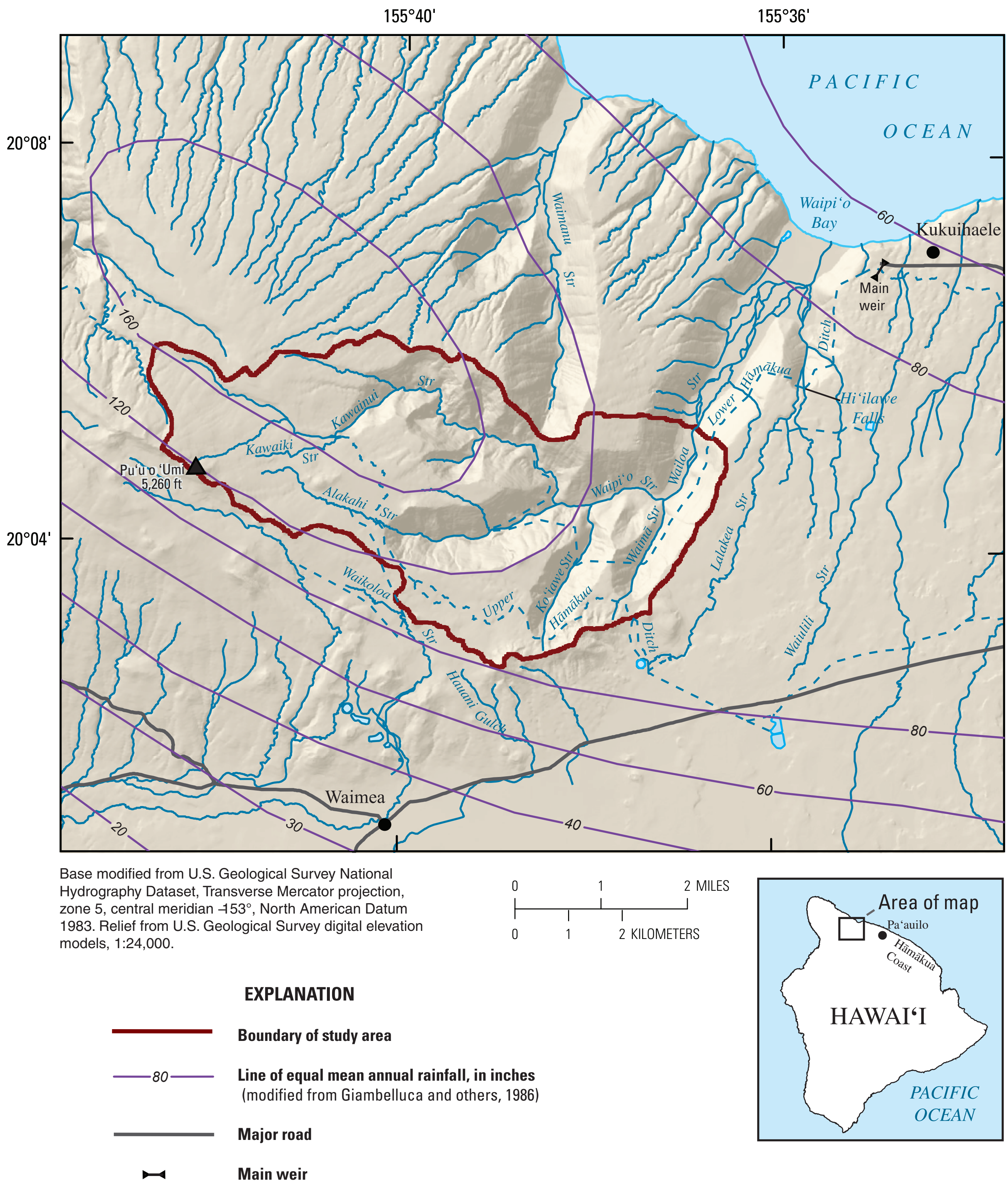


Figure 1. Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

4,026 feet), Alakahi Stream (at altitude 3,874 feet), Ko‘iawe Stream (at altitude 3,355 feet), and Waimā Stream (at altitude 3,044 feet) at locations just upstream of where they descend into Waipi‘o Valley (Hawaii Division of Water and Land Development, 1963). Diversion intakes along Upper Hāmākua Ditch were designed to capture all the water in the stream until the rate of flow almost exceeded the capacity of the intake structures. At this point, the water in the streams will start to top intake diversion dams and flow downstream into Waipi‘o Valley. Upper Hāmākua Ditch, between the uppermost intake at Kawainui Stream and the lowermost intake at Waimā Stream, is about 5.8 miles long and comprises a complex combination of open ditches, tunnels, flumes, and segments where water is channeled into existing stream reaches. Beyond Waimā intake, water is channeled to the southeast and away from Waipi‘o Valley watershed. Historically, the Parker Ranch diverted water from Alakahi Stream, well upstream from the Upper Hāmākua Ditch intake, through a 4-inch diameter pipeline. This pipeline was no longer in use at the time of this study (2000-2005). Hawai‘i County Department of Water Supply also diverted water, through an emergency pipeline, from a spring source located on top of the north rim of Alakahi Canyon. This emergency pipeline was also no longer in use at the time of this study.

Lower Hāmākua Ditch diverts water from Kawainui Stream (at altitude 1,037 feet), Alakahi Stream (at altitude 1,030 feet), and Ko‘iawe Stream (at altitude 1,000 feet) (U.S. Department of Agriculture, 1999, Mink, 1984). Diversion intakes along Lower Hāmākua Ditch also were designed to capture most of the water in the stream, until the rate of flow almost exceeded the intake capacity. Proposed modification of intakes would allow controlled diversion of water and maintenance of some flow past the diversion points at all times (U.S. Department of Agriculture, 1999). Starting in 1966, pumps raised water from lower reaches of Waimā Stream 380 feet up into Lower Hāmākua Ditch (Wilcox, 1996, p. 153). These pumps, which were operated only during periods of drought and originally had a capacity of about 9.3 ft^3/s (6 Mgal/d), were not operational during the period of this study. Lower Hāmākua Ditch intakes are connected by a series of tunnels, cut into valley walls, that are about 8.9 miles in length (Wilcox, 1996). The tunnels exit Waipi‘o Valley at a location known as the main weir (fig. 1). Water is then transported beyond the main weir, away from Waipi‘o Valley, to users along the Hāmākua coast as far away as the town of Pa‘auilo. In addition to carrying the water diverted at three stream intakes, the tunnels of Lower Hāmākua Ditch also intersect and capture dike-impounded groundwater within the walls of Waipi‘o Valley.

Acknowledgments

The list of individuals and organizations that provided support and help needed to conduct this study is extensive. At the risk of neglecting to mention several of these important contributors, the author would like to specifically acknowledge the following people: Former and current maintenance supervisors for the Lower Hāmākua Ditch, Kelly Loo and Ernest Alfonso, shared their knowledge of Waipi‘o Valley and how to access its remote interior. Kia Fronda and other Waipi‘o Valley landowners graciously allowed access across their properties. David Young of Wai Engineering provided up to date information on maintenance and construction activities along Lower Hāmākua Ditch. Todd Presley and numerous other USGS employees participated in many challenging field trips to remote reaches of Waipi‘o Valley. Finally, John Engott and Chiu Yeung assisted with preparation of several illustrations in this report.

Data and Methods Used to Estimate Low-Flow Statistics

In this report, the low-flow hydrology of the streams in Waipi‘o Valley will be described in terms of flow-duration curves and their related statistics (Searcy, 1959). Flow-duration curves offer an extremely useful way to summarize streamflow data (Vogel and Fennessey, 1995). A flow-duration curve is a cumulative frequency curve that shows the percentage of time that specified discharges in a stream were equaled or exceeded during a given period of record. Daily mean discharge will be the basis for flow-duration curves developed for this report, but curves can be developed using alternative time steps for discharge, such as weekly, monthly, or annual. Flow-duration curves are constructed by ranking streamflow data collected at a location for a specified period of time, in descending order, with the largest flow value first and the smallest value last (Ries, 1993, p, 20). The plotting position, or exceedance probability, for each streamflow value can then be calculated by using the Weibull formula (Helsel and Hirsch, 2002; Langbein, 1960):

$$P_k = k/(n+1), \qquad (1)$$

where: P_k is the plotting position or exceedance probability for the streamflow value with rank k,
k is the rank of the given streamflow value, and
n is the total number of streamflow values for the specified period.

For example, assume that during a 5-day period we had the following sequence of daily mean discharge values: 300, 39, 3, 2, and 1 ft^3/s, and we wanted to compute the exceedance probability for 3 ft^3/s on the basis of these data. The data are already ranked in descending order, and the value 3 ft^3/s has a rank k of 3 (the third largest value). There are a total of 5 values, so n equals 5. Applying formula (1):

$P_k = 3/(5 + 1) = 0.50$, and converting to a percentage,or flow-duration percentile,

$P_k = 0.50 \times 100 = 50$ percent

For this simplified data set, we have determined that a daily mean discharge value of 3 ft^3/s was equaled or exceeded 50 percent of the time during this 5-day period. In this report, significantly longer periods of time will be used to compute flow-duration statistics, and flow-duration exceedance probabilities will be discussed primarily in terms of percentages or flow-duration percentiles.

An example of a flow-duration curve based on daily mean discharges for the period 1965–2004 at streamflow-gaging station 16720000 on Kawainui Stream is shown in figure 2. This gaging station is upstream from Upper Hāmākua Ditch. One of the most frequently referred to points on a flow-duration curve is the 50th percentile, or median discharge (abbreviated as Q_{50}). This is the discharge that is equaled or exceeded 50 percent of the time. In figure 2, the indicated median discharge is 4.5 ft^3/s. In contrast, average discharge for the period 1965-2004 at station 16720000 is 14.9 ft^3/s. On the flow-duration curve, it can be determined that the average discharge of 14.9 ft^3/s is equaled or exceeded only about 28 percent of the time. In this instance, and for most Hawaiian streams, median discharge provides a more representative measure of typical flow conditions than does average discharge. Flow-duration percentiles of 50 and higher (for example, the 95th percentile) are typically used to describe low-flow characteristics of streams. A tabular listing of selected discharges used to construct the flow-duration curve shown in figure 2 is provided in a subsequent section of the report, in table 7.

Another interesting value can be determined from flow-duration curve percentiles. A flow-duration percentile represents the percent of time that a specified discharge is equaled or exceeded. The opposite of this value is the percent of time that the discharge is less than the specified value. Following the example from above, the 50th percentile discharge is 4.5 ft^3/s (fig. 2). Again, this is the discharge that is equaled or exceeded 50 percent of the time. By subtracting the flow duration percentile from 100 percent (in this case 100-50 = 50 percent), we determine the percent of time that the discharge is less than 4.5 ft^3/s. Also from figure 2, the discharge that is equaled or exceeded 95 percent of the time (the 95th percentile) is only 0.29 ft^3/s; this means that 5 percent of the time (100-95 = 5 percent), discharge in the stream is less than 0.29 ft^3/s. If you are a taro farmer with fields adjacent to streamflow-gaging station 16720000 on Kawainui Stream that need a minimum of 0.29 ft^3/s of irrigation water to sustain your crop, it is important to understand that for 5 percent of the time this level of discharge will not be available in the stream for your use.

The shape of a flow-duration curve is indicative of the type of streamflow conditions that can be expected at a particular location. Smooth curves indicate unregulated or natural flow. Flow-duration curves that “flatten out” and show only minor reductions in lower discharges are indicative of sustained inflow to the stream, most likely as the discharge of groundwater to the channel. The flow-duration curve for Kawainui Stream (fig. 2) is smooth and does not flatten out at low discharges, indicating that flow at this location is representative of natural conditions, but also that it is not sustained by large volumes of groundwater inflow. The flow-duration curve for Kawainui Stream does not decline to zero, however, which indicates that streamflow at this location is perennial.

Streamflow Data

To describe the low-flow hydrology of Waipi‘o Valley, a combination of historical and new streamflow data, the latter collected as part of this study, was used to develop flow-duration curves. Historical data include records of streamflow and discharge measurements collected by the USGS at former and current streamflow-gaging stations, as well as those available from other agencies. New data include miscellaneous discharge measurements made at 27 locations in Waipi‘o Valley and along the Lower Hāmākua Ditch.

Historical Data

The value of water resources in Waipi‘o Valley has been long recognized (Herschler and Randolph Consulting Engineers, 1961). As a result, an abundance of data, in the form of systematic records of daily discharge and miscellaneous discharge measurements, has been collected along streams and ditches that feed into and drain Waipi‘o Valley (Fontaine, 1996). To the extent possible, these data are utilized in this report to aid in describing the low-flow hydrology of Waipi‘o Valley.

In a report that focused primarily on availability of water for diversion through Lower Hāmākua Ditch, Mink (1984) provided an excellent summary of the data that have been collected in the area. According to Mink (1984, p. 7), the first streamflow measurements in the Waipi‘o drainage basin were made by J.M. Lydgate, over a 10-month period in 1889 and 1890. Records of these measurements were thought to exist at the Bernice Pauahi Bishop Museum (Honolulu) but were not recovered or used by Mink (1984) and will not be used in this study. Records for most locations where systematic daily discharge data have been collected in the area, however, have been published in USGS reports (for example, see Martin and Pierce, 1913). The locations of these stream and ditch gaging stations are shown in figure 3, and the availability of data for the stations is summarized in table 1.

At 12 of the surface-water gaging stations listed in table 1, the only data collected were those obtained by Arthur Tuttle, for Bishop Estate, during the period August 1901 through January 1902 (Martin and Pierce, 1913, p. 397). Tuttle also collected data at a 13th station, on Wailoa Stream at an altitude of 190 feet, a site that later became USGS gaging station 16732200 (tables 1 and 2).

Data collected at these 13 gaging stations provide useful information to quantify variations in flow along stream reaches in Waipi‘o Valley under natural, undiverted flow conditions that existed before the construction of Upper and Lower Hāmākua Ditches. The data collected throughout Waipi‘o

Valley by Tuttle were used to justify construction of Lower Hāmākua Ditch (Mink, 1984, p. 8). The Hawaiian Irrigation Company (HIC) collected flow records for Upper Hāmākua Ditch (Hawaii Division of Water and Land Development, 1963) and Lower Hāmākua Ditch (Mink, 1984) at numerous locations. Some of these data, for gaging stations 16732600 (1910–1913) and 16732900 (1910–1920), were published by the USGS (table 1). These data provide historical documentation of how the ditches were formerly operated but are of limited use in describing current operational practices and capacities of Upper and Lower Hāmākua Ditch systems.

The USGS has collected data at gaging stations on and upstream from Upper Hāmākua Ditch and at three surface-water gaging stations in adjacent watersheds that are useful for describing the low-flow hydrology of the Waipi‘o Valley study area (table 1). Three of these stations, Kawainui Stream at 4,060 feet (16720000), Alakahi Stream at 3,900 feet (16725000), and Waikoloa Stream at 3,460 feet (16758000), are still being operated (2009). These three stations currently in operation, as well as that on Hauani Gulch at 3,117 feet (16759000), which was discontinued in 2004, are all long-term stations that have been in operation for 41 to 58 years. The USGS has operated only one gaging station within the main part of the Waipi‘o Valley for any extended period, Wailoa Stream at 190 feet (16732200). Data from this station will be used to help define low-flow characteristics at the downstream limit of the study area.

Individual discharge measurements, or series of near-concurrent measurements (seepage runs), have been made at various locations and times throughout the Waipi‘o Valley study area. A number of these measurements were made to define specific low-flow characteristics in Waipi‘o Valley, and those will be of significance in this report. Stearns and Macdonald (1946, p. 230-239) summarized discharge measurements that were made to document gains and losses in Lower Hāmākua Ditch on January 28, 1912; low flow of the main tributaries of Waipi‘o Stream during dry weather in December 1944; spring flow along Kawainui Stream upstream from Lower Hāmākua Ditch on December 6, 1943; and gains in the main tributaries of Waipi‘o Stream in reaches 100 feet downstream from

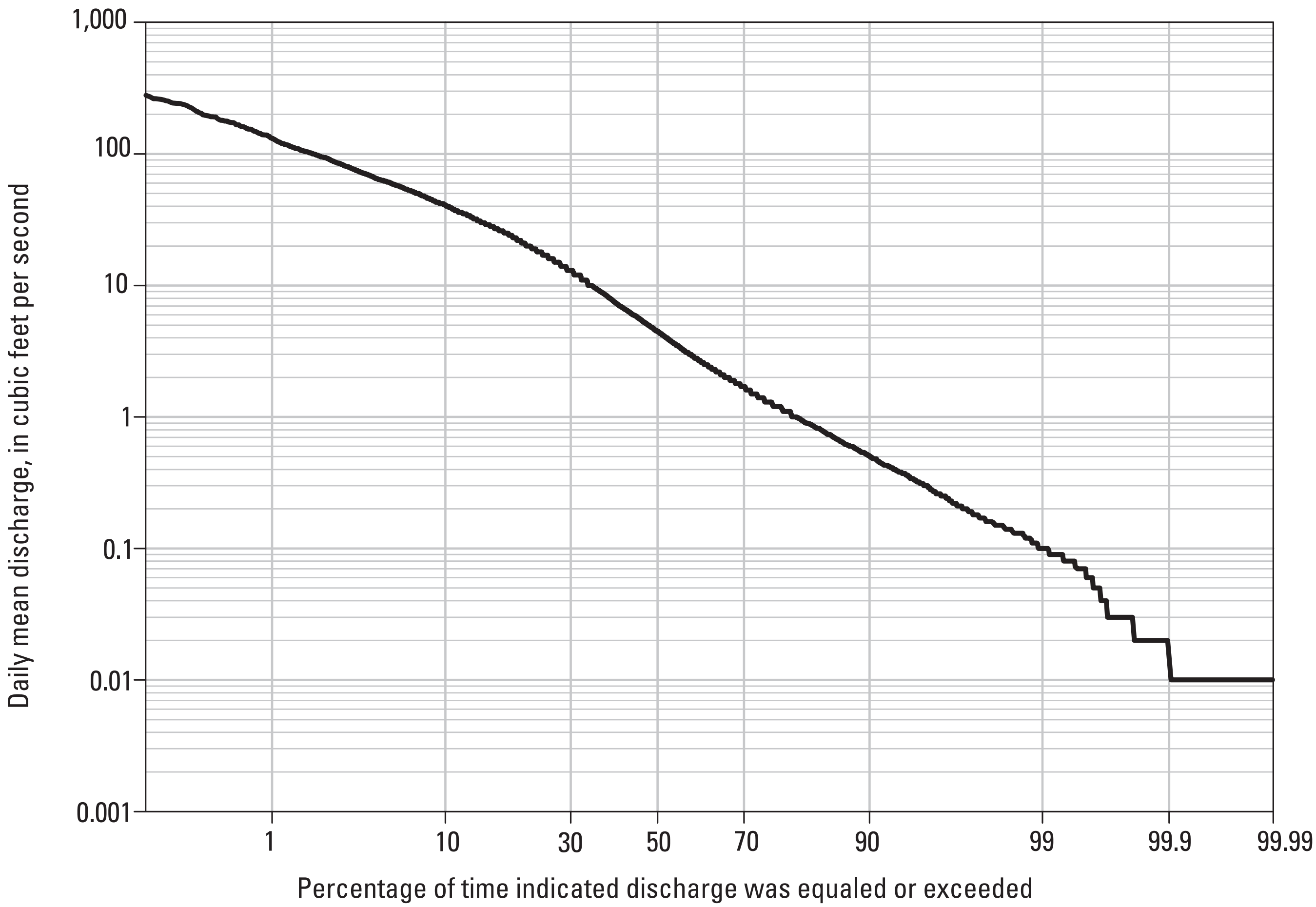


Figure 2. Flow-duration curve for streamflow gaging station 16720000 on Kawainui Stream, Island of Hawai‘i, for water years 1965–2004.

Table 1. Surface-water gaging stations operated in and adjacent to the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

[P, in operation 2006 water year]

Gaging-station number	Station location	Period of record	Remarks
Gaging stations on and upstream from Upper Hāmākua Ditch and adjacent to the Waipiʻo Valley study area			
16720000	Kawainui Stream at 4,060 feet	1965-P	Used as index station
16720300	Kawaiki Stream at 4,090 feet	1969-1999	
16720500	Upper Hāmākua Ditch at 4,020 feet	1964-2002	Ditch gaging station
16724800	Upper Hāmākua Ditch at 3,890 feet	1968-2000	Ditch gaging station
16725000	Alakahi Stream at 3,900 feet	1965-P	Used as index station
16726000	Upper Hāmākua Ditch at 3,020 feet	1974-2004	Ditch gaging station
16757000	Waikoloa Stream at 3,570 feet	1947-1971	
16758000	Waikoloa Stream at 3,460 feet	1948-P	Used as index station
16759000	Hauani Gulch at 3,117 feet	1957-2004	Used as index station
Gaging stations downstream from Upper Hāmākua Ditch and upstream from Lower Hāmākua Ditch			
16721000	Kawainui Stream at 2,120 feet	1901-1902	51 days of data
16721500	Kawainui Stream Branch 3 at 1,700 feet	1901-1902	94 days of data
16722000	Kawainui Stream at 1,435 feet	1901-1902	77 days of data
16722300	Kawainui Stream Branch 2 at 1,405 feet	1901-1902	106 days of data
16722600	Kawainui Stream Branch 1 at 1,380 feet	1901-1902	106 days of data
16723000	Kawainui Stream at 1,040 feet	1911	1 discharge measurement
16728000	Alakahi Stream at 1,200 feet	1901-1902	71 days of data
16730000	Koʻiawe Stream at 1,120 feet	1901-1902	68 days of data
Gaging stations on and downstream from Lower Hāmākua Ditch			
16724000	Kawainui Stream at 775 feet	1901-1902	115 days of data
16729000	Alakahi Stream at 730 feet	1901-1902	126 days of data
16731000	Koʻiawe Stream at 610 feet	1901-1902	132 days of data
16732000	Waipiʻo Stream at 580 feet	1911	1 discharge measurement
16732100	Waimā Stream at 790 feet	1901-1902	132 days of data
16732150	Waimā Stream at 385 feet	1901-1902	127 days of data
16732200	Wailoa Stream at 190 feet	1901-1902, 1911, 1964-1969	Downstream end of study area
16732600	Lower Hāmākua Ditch at 1,000 feet	1910-1913	Ditch gaging station
16732800	Lower Hāmākua Ditch upstream from main weir	2002-2004	Ditch gaging station
16732900	Lower Hāmākua Ditch at main weir	1910-1920	Ditch gaging station
16733000	Lower Hāmākua Ditch wasteway	1964-1973	Releases of water at main weir
16733100	Lower Hāmākua Ditch downstream from main weir	1964-1973	Ditch gaging station

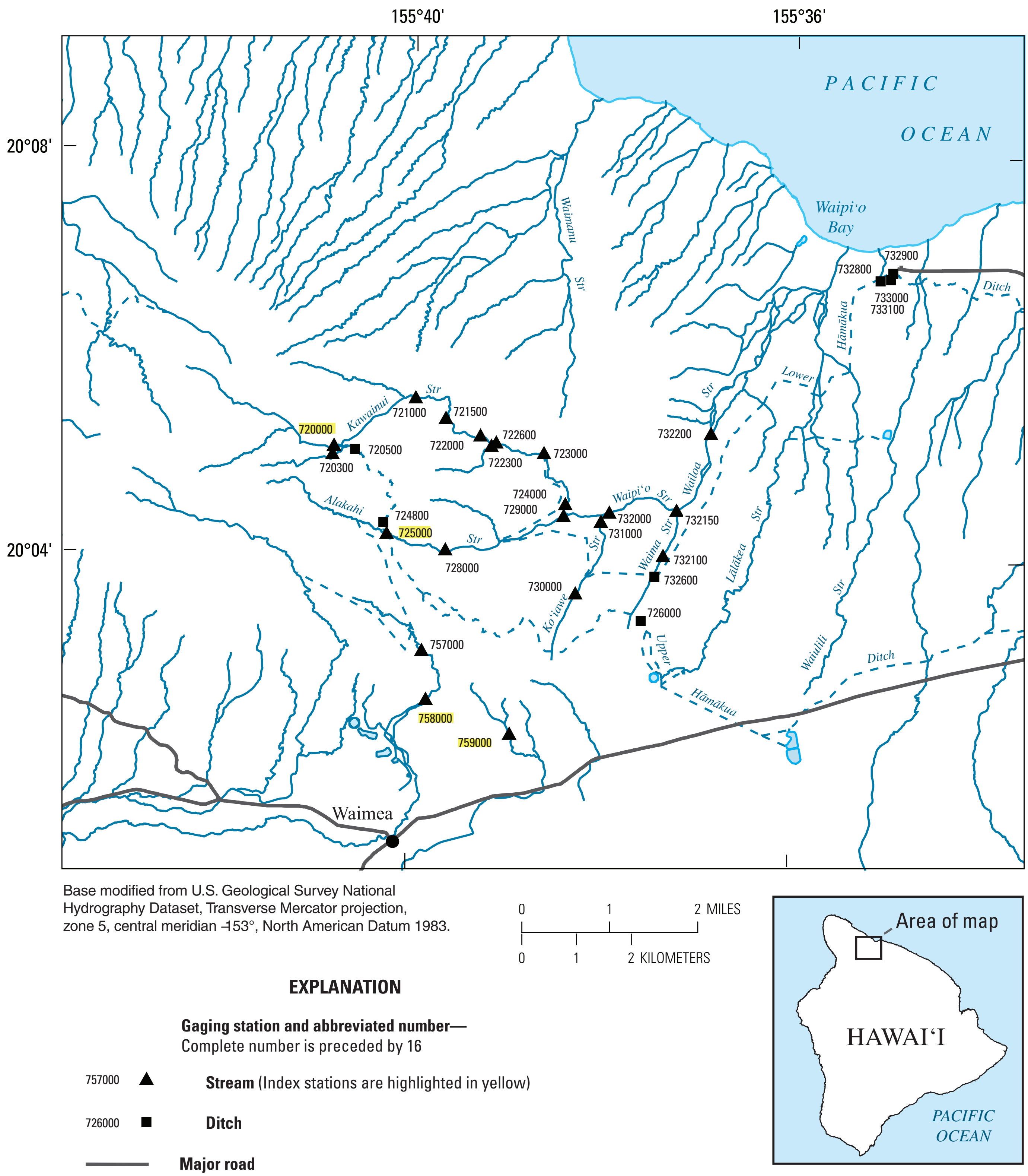


Figure 3. Location of stream and ditch surface-water gaging stations operated in and adjacent to the Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

Lower Hāmākua Ditch on January 28, 1912. During a severe drought in 1962-63 (Giambelluca and others, 1991, p. 35), the USGS made numerous discharge measurements along streams and ditches in the Waipiʻo Valley study area. These measurements are summarized by Davis and Yamanaga (1963) and in the USGS annual data report for 1963 (U.S. Geological Survey, 1963). During the period October to December 1963, the USGS made three sets of discharge measurements along Upper Hāmākua Ditch and its tributary streams (U.S. Geological Survey, 1964). In 1965 and 1966, the USGS made several series of discharge measurements along Waimā Stream, although not all measurements were made on the same day in each year (U.S. Geological Survey, 1967). On March 9, 1983, the USGS made discharge measurements on Waipiʻo Stream upstream from the mouth of Waimā Stream and on Wailoa Stream at the site of former gaging station 16732200 (fig. 3) (Chinn and others, 1984).

Data Collected for This Study

To meet the objectives of this study, additional data beyond the historical data already available were required. Additional discharge measurements were made at 27 locations in Waipiʻo Valley and along Lower Hāmākua Ditch (table 2 and fig. 4) in order to (1) describe low flow in Waipiʻo Valley upstream from Lower Hāmākua Ditch intakes, (2) describe variability of low flows along Lower Hāmākua Ditch, and (3) describe variability of low flows along stream reaches downstream from Lower Hāmākua Ditch.

The locations at which additional discharge measurements were made fall into two distinct categories—low-flow partial-record stations and seepage-run sites. Multiple discharge measurements are made at each low-flow partial-record station, covering a wide variety of low-flow conditions. The measurements are timed such that each is made during an independent recession in streamflow following periods of direct runoff at the station (Fontaine, 2003). Discharge measurements were made at five low-flow partial-record stations. The stations are at sites 1, 6, 15, 18, and 24 (fig. 4), which are upstream from the intakes of Lower Hāmākua Ditch on Kawainui, Alakahi, Koʻiawe, and Waimā Streams and at the site of former USGS gaging station 16732200 on Wailoa Stream, respectively. The Lower Hāmākua Ditch does not actively divert water at Waimā intake. The discharge measurements made at these five low-flow partial-record stations are listed in table 3.

During a seepage run, discharge measurements are made within a short period of time at several locations along a stream reach or ditch. The measurements usually are made during periods of low flow, when conditions within a given reach of the stream or ditch are relatively steady (Fontaine, 2003). Seepage runs were made on streams in Waipiʻo Valley on September 20–21, 2000, and on September 26, 2001. During these seepage runs, measurements were made at as many as 27 sites (the low-flow partial-record stations are included in the seepage-run sites); these data are listed in table 4.

Selection of Base Period

Flow-duration curves show the percent of time that specific discharges were equaled or exceeded, but they are applicable only to the time period for which they were computed. When selecting a base period for analysis, a reasonable goal is to select a period that is long enough to be representative of long-term streamflow conditions in the study area of interest or concern. If this goal can be met, then flow-duration curves computed for the selected base period can also be considered representative of future streamflow conditions. In comparing flow-duration values computed for a variety of locations, as will be done as part of this report, care must be taken to ensure that the values represent the same base period at all locations. If this is not done, one might end up comparing flow data collected during a period when streamflow was above normal (for example, at station A) to flow data collected during a drought, when streamflow was below normal (for example, at station B). Such comparisons would be misleading.

In this study of streamflow conditions in the Waipiʻo Valley, the period extending from water year 1965 through water year 2004 was selected as the base period. This 40-year period was assumed to be long enough to adequately reflect long-term streamflow conditions in Waipiʻo Valley. In addition, a continuous record of flow for this entire period is available for at least four USGS surface-water gaging stations either within or adjacent to the Waipiʻo Valley study area (table 1). Flow-duration curves computed for the entire base period at these four stations, which also are referred to as index stations (see later section “Selection of Index Stations and Application of Data”), can be used to extend (in time) the data collected at other locations so that they also are representative of the 1965–2004 base period and thus of long-term flow conditions. Extending the base period before 1965 is counterproductive because it would eliminate use of two index stations for which 1965 was the first year of operation. Similarly, extending the base period after 2004 would eliminate use of one index station because 2004 was the last year it was operated.

As noted in the previous paragraph, the 40-year base period, water years 1965–2004, was assumed to be representative of long-term streamflow conditions in the study area. To test this assumption, selected flow-duration discharges were computed for the entire period of record and for the 40-year base period at gaging stations 16758000 on Waikoloa Stream, which drains a valley just to the south of Waipiʻo Valley (fig. 1 and table 5) and 16010000 on Kawaikōī Stream on the Island of Kauaʻi (table 6). In these flow-duration analyses and those based on gaging-station records throughout the report, only water years with complete records were considered. The gaging station on Waikoloa Stream is currently (2006) in operation and has records that extend back to 1948, making it the station with the longest streamflow record on the Island of Hawaiʻi that is not affected by regulation (Fontaine, 1996). The gaging station on Kawaikōī Stream has the longest complete streamflow record in the entire State of Hawaiʻi, extending back to 1912. In both cases, flow-duration discharges computed for the base period were virtually the same as those

Table 2. Locations where discharge measurements were made in the Waipi‘o Valley study area during the period 2000–2005, Island of Hawai‘i, Hawai‘i.

[LHD, Lower Hāmākua Ditch; us, upstream; ds, downstream; LFPR, low-flow partial-record station]

Site number (fig. 4)	Gaging-station number	Station location	Remarks
1	200505155383801	Kawainui Stream us from LHD	LFPR, seepage-run site
2	16723000	Kawainui Stream ds from LHD	Seepage-run site
3	200502155383601	LHD ds from Kawainui Stream intake	Seepage-run site
4	200415155390001	LHD us from Alakahi Stream intake	Seepage-run site
5	200414155385901	Alakahi Stream ds from LHD	Seepage-run site
6	200413155390301	Alakahi Stream us from LHD	LFPR, seepage-run site
7	200413155385901	LHD ds from Alakahi Stream intake	Seepage-run site
8	16724000	Kawainui Stream at mouth	Seepage-run site
9	16729000	Alakahi Stream at mouth	Seepage-run site
10	200430155381801	Waipi‘o Stream ds from confluence of Kawainui and Alakahi Streams	Seepage-run site
11	200429155380001	Waipi‘o Stream us from mouth of Ko‘iawe Stream	Seepage-run site
12	16732000	Waipi‘o Stream ds from mouth of Ko‘iawe Stream	Seepage-run site
13	16731000	Ko‘iawe Stream at mouth	Seepage-run site
14	200354155380801	LHD us from Ko‘iawe Stream intake	Seepage-run site
15	200351155380901	Ko‘iawe Stream us from LHD	LFPR, seepage-run site
16	200354155380701	Ko‘iawe Stream ds from LHD	Seepage-run site
17	200353155380801	LHD ds from Ko‘iawe Stream intake	Seepage-run site
18	200351155372801	Waimā Stream us from LHD	LFPR, seepage-run site
19	200354155372601	Waimā Stream ds from LHD	Seepage-run site
20	16732600	LHD at Waimā Stream	Seepage-run site
21	200424155370301	LHD ds from pump inflow	Seepage-run site
22	200434155372001	Waipi‘o Stream us from mouth of Waimā Stream	Seepage-run site
23	16732150	Waimā Stream at mouth	Seepage-run site
24	16732200	Wailoa Stream at 190 feet	LFPR, seepage-run site
25	200542155354501	LHD at Hi‘ilawe Falls	Seepage-run site
26	200542155354101	LHD at Hakalaoa Falls	Seepage-run site
27	16732800	LHD upstream from main weir	Seepage-run site

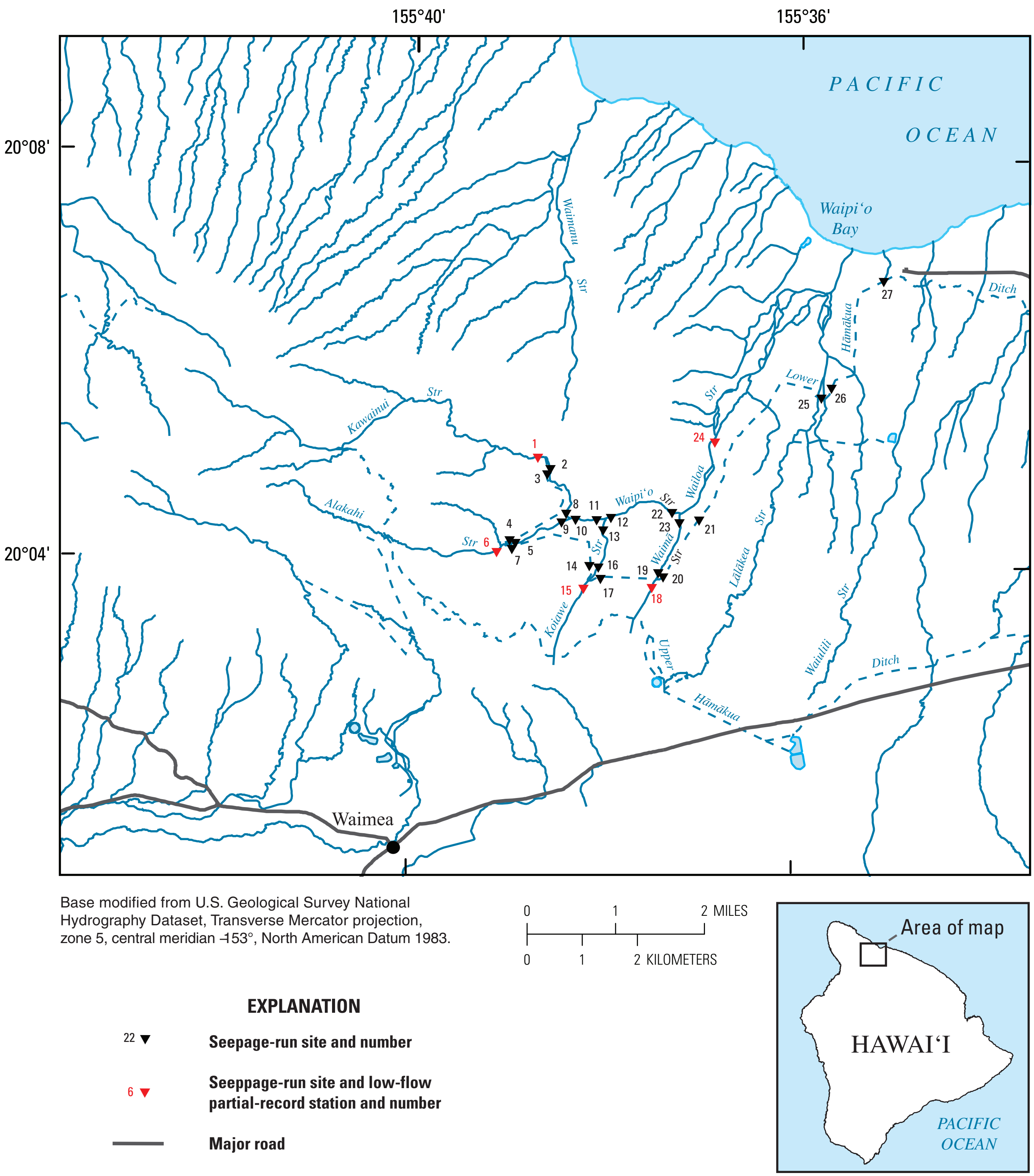


Figure 4. Locations where discharge measurements were made in Waipi‘o Valley study area during the period 2000–2005, Island of Hawai‘i, Hawai‘i.

Table 3. Discharge measurements at low-flow partial-record stations in Waipi‘o Valley during the period 2000–2005, Island of Hawai‘i, Hawai‘i.

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

Date	Discharge (ft^3/s)				
	Kawainui Stream Site 1[a]	Alakahi Stream Site 6[a]	Ko‘iawe Stream Site 15[a]	Waimā Stream Site 18[a]	Wailoa Stream Site 24[a]
08/08/00	---	---	7.02	0.62	---
09/20/00	---	17.4[b]	---	0.61	---
09/21/00	26.5	---	7.53	---	78.3
01/10/01	18.6	14.1	---	---	68.8
01/11/01	---	---	7.28	0.69	---
03/08/01	59.1	25.7	---	---	---
03/09/01	---	---	8.28	0.60	76.5
05/30/01	21.7	14.2	---	---	73.3
05/31/01	---	---	7.18	0.53	---
09/26/01	41.5	---	10.5	0.86	103
06/26/03	35.0	17.2	---	---	---
06/27/03	---	---	8.30	0.67	82.9
09/25/03	22.6	14.3	---	---	84.6
09/26/03	---	---	7.52	0.67	---
10/06/04	16.2	12.5	---	---	69.4
10/07/04	---	---	7.32	0.72	---
02/25/05	11.4	11.4	---	---	---
04/27/05	---	---	7.38	---	---
08/23/05	---	---	---	0.93	95.7
08/24/05	28.6	13.6	---	---	---

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

[b] Computed by mass balance as Site 6 = Site 5 + (Site 7 - Site 4), data from table 4.

for the entire period of record, thereby supporting the assumption that the 1965–2004 base period selected for this study is representative of long-term streamflow conditions. In an analysis of streamflow throughout the State of Hawai‘i (Fontaine and others, 1992, p. 13), median streamflow was computed for several 40-year periods at gaging station 16587000 on Honopou Stream on the Island of Maui. The standard error for the various 40-year median streamflow estimates, when compared to long-term median streamflow for the 75-year period 1912–1986, was only 7.8 percent, again supporting use of a 40-year base period in this current study as representative of long-term streamflow conditions.

Another important factor to consider in the selection of a base period and subsequent flow-duration analyses is the presence of any trends in the streamflow data being used. Oki (2004) conducted an analysis to test for the presence (or absence) of trends in streamflow characteristics at long-term gaging stations in Hawai‘i. Included in the analysis was the gaging station on Waikoloa Stream (16758000), which is used as an index station in this report (table 1). In his analysis, Oki tested for trends in annual mean discharges and in 10-, 25-, 50-, 75-, and 90-percentile flow-duration discharges. No significant trends were detected in any of the flow characteristics tested (Oki, 2004, p. 32). These results can reasonably be assumed to apply to other index stations being used in this report.

Record-Extension Techniques

Except for the gaging stations referred to above as index stations, streamflow data for most of the gaging

Table 4. Discharge measurements at seepage-run sites in Waipi‘o Valley during the period 2000–2001, Island of Hawai‘i, Hawai‘i.

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

Site number[a]	Stream or ditch	Altitude (feet)	Discharge (ft^3/s)	
			Sept. 20-21, 2000	Sept. 26, 2001
1	Kawainui Stream	1,070	26.5	41.5
2	Kawainui Stream	1,037	4.7[b]	26.1[b]
8	Kawainui Stream	775	11.8	---
6	Alakahi Stream	1,030	17.4[c]	---
5	Alakahi Stream	1,000	19.1	---
9	Alakahi Stream	730	19.7[d]	---
10	Waipi‘o Stream	720	31.5	---
11	Waipi‘o Stream	595	34.8	---
12	Waipi‘o Stream	580	41.2[e]	---
22	Waipi‘o Stream	400	43.3	---
15	Ko‘iawe Stream	1,020	7.53	10.5
16	Ko‘iawe Stream	980	2.2[f]	1.8[f]
13	Ko‘iawe Stream	610	6.44	---
18	Waimā Stream	1,040	0.61	0.86
19	Waimā Stream	970	0.6[g]	0.9[g]
23	Waimā Stream	385	35.0	---
24	Wailoa Stream	190	78.3	103
3	Lower Hāmākua Ditch	1,037	21.8	15.4
4	Lower Hāmākua Ditch	1,030	19.8	13.0
7	Lower Hāmākua Ditch	1,030	18.1	11.0
14	Lower Hāmākua Ditch	1,000	18.1	11.9
17	Lower Hāmākua Ditch	1,000	23.4	20.6
20	Lower Hāmākua Ditch	980	23.4	22.1
21	Lower Hāmākua Ditch	975	25.5	20.0
25	Lower Hāmākua Ditch	970	26.8	22.2
26	Lower Hāmākua Ditch	970	21.8[h]	20.4
27	Lower Hāmākua Ditch	965	22.4	22.2

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

[b] Computed by mass balance as Site 2 = Site 1 - Site 3.

[c] Computed by mass balance as Site 6 = Site 5 + (Site 7 - Site 4).

[d] Computed by mass balance as Site 9 = Site 10 - Site 8.

[e] Computed by mass balance as Site 12 = Site 11 + Site 13.

[f] Computed by mass balance as Site 16 = Site 15 - (Site 17 - Site 14).

[g] Estimated as about the same as Site 18, no diversion of water at the ditch intake.

[h] Average of two discharge measurements made at the site.

Table 5. Selected flow-duration discharges for the period of record and the base period at gaging station 16758000 on Waikoloa Stream, Island of Hawai‘i, Hawai‘i.

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

Percentage of time indicated discharge equaled or exceeded	Period of record 1948-2005 (ft^3/s)	Base period 1965-2004 (ft^3/s)	Difference in percent
99	1.0	0.99	-1.0
95	1.5	1.5	0.0
90	1.8	1.7	-5.6
80	2.3	2.3	0.0
70	2.8	2.8	0.0
60	3.5	3.4	-2.9
50	4.4	4.3	-2.3
40	5.8	5.8	0.0

Table 6. Selected flow-duration discharges for the period of record and the base period at gaging station 16010000 on Kawaikōī Stream, Island of Kaua‘i, Hawai‘i.

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

Percentage of time indicated discharge equaled or exceeded	Period of record 1912-2005 (ft^3/s)	Base period 1965-2004 (ft^3/s)	Difference in percent
99	2.3	2.3	0.0
95	3.5	3.6	2.9
90	4.4	4.5	2.3
80	6.0	6.0	0.0
70	7.8	7.7	-1.3
60	10	9.7	-3.0
50	13	13	0.0
40	17	17	0.0

stations in Waipi‘o Valley, as well as for locations where multiple discharge measurements were made, are available only for parts of the selected base period, 1965–2004. For these latter stations and the measurement locations, record-extension techniques were used to estimate flow-duration data for the base period on the basis of available short-term records and discharge data. A basic assumption of record-extension techniques is that relations between concurrent streamflow data and statistics based on them, at the station with short-term record and the index station with complete record, are the same for the short-term and extended periods of time (Ries, 1993). Although similar in concept, the procedures for extending records at surface-water gaging stations differ slightly depending on whether the available short-term data are for continuous-record stations or for low-flow, partial-record stations, where only discharge measurements were made.

Continuous-Record Gaging Stations

The steps used in this study when extending records at continuous-record gaging stations are as follows:

1. Low-flow duration discharges for 99-, 98-, 97-, 95-, 90-, 85-, 80-, 75-, 70-, 65-, 60-, 55-, 50-, and 40-percentiles are computed for the entire period of concurrent record at the short-term station and at each of the four index stations being used in this study.

2. The correlation coefficient between discharges at selected flow-duration percentiles at the short-term station and each of the four index stations is determined. Only index stations with correlation coefficients greater than 0.80 will be used for record extension.

3. Concurrent flow-duration discharges for the short-term station and for each of the index stations selected in step 2 are then plotted, both in linear and log space (base 10 logarithms were used throughout this study), to determine which index station provided the best relation. In general, plots in log space provided the best results. If one index station had a significantly higher correlation coefficient and clearly provided the best relation with the short-term station, then it was selected for use in record extension. If correlation coefficients and relations with several index stations are similar, then each was used for record extension.

4. Plots that reflect the best relation between the short-term station and each index station selected in step 3 were evaluated to determine if the best fit relation was linear or curvilinear. If the relation was linear, then the Maintenance Of Variance Extension, Type 1 (MOVE.1) technique (Hirsch, 1982) was used for record extension. If the relation was curvilinear, a graphical-correlation method (Searcy, 1959, p. 14) was used for record extension.

In the application of the MOVE.1 technique, the data format (linear or log) that provided the strongest correlation and relation is used. When applying the MOVE.1 technique to extend records at short-term stations, the analysis can be based on use of either concurrent flow-duration discharges or concurrent daily mean discharges at the stations. In this study, concurrent flow-duration discharges were consistently used for analyses. The mean and standard deviation of the selected flow-duration discharges at both the short-term and index stations are then computed. If a logarithmic relation is used, the discharges are transformed to log base 10 values before computation of means and standard deviations (Fontaine, 2003, p. 16). Estimates of base period (1965–2004) flow-duration discharges at the short-term surface-water gaging station are then computed by using the MOVE.1 formula as follows:

$$Y_i = Y_m + s_y/s_x\,(X_i - X_m)\,, \qquad (2)$$

where:

Y_i is the estimated flow-duration discharge for the base period at the short-term station,

X_i is the flow-duration discharge for the base period at the index station,

Y_m is the mean of the concurrent flow-duration discharges at the short-term station,

X_m is the mean of the concurrent flow-duration discharges at the index station,

s_y is the standard deviation of the concurrent flow-duration discharges at the short-term station, and

s_x is the standard deviation of the concurrent flow-duration discharges at the index station.

Estimated flow-duration discharges for the base period at the short-term stations, which are based on use of data in logarithmic form, are converted back to their original units of measurement (cubic feet per second) subsequent to the application of equation 2.

In the application of the graphical-correlation method, the data format (linear or log) that provided the strongest correlation and relation is used and a smooth curve connecting concurrent flow-duration discharges for the short-term and index stations is developed. This curve defines the relation between flow-duration discharges at the stations and becomes the basis for estimating base period flow-duration discharges at the short-term station. Finally, using flow-duration discharges for the base period at the index station, corresponding base-period flow-duration discharges at the short-term station are read from the smoothed relation curve.

As noted in step 3 above, if correlation coefficients and the relation with several of the index stations are both significant and similar, then each was used for record extension. In such cases, more than one independent estimate of base period flow-duration discharges for the short-term station will be computed. Tasker (1975) noted that when multiple independent estimates are available, an improved estimate can be obtained by computing an average of the multiple estimates. Therefore, in this report, variance-weighted averages are computed in all cases in which multiple index stations were used for record extension. Variance is a measure of how accurately the line of relation developed between data for the short-term and index stations match the data used to develop it—the better the relation, the smaller the variance. A detailed explanation of how to compute variance for each independent estimate and the variance-weighted average estimates is given by Ries and Friesz (2000, p. 11-13) and will not be replicated here.

Values of variance associated with independent and weighted estimates of base period flow-duration discharges can be used to compute standard errors for results computed using record-extension techniques. These standard errors are primarily a reflection of the strength of correlation between short-term and index stations and do not account for errors associated with discharge measurements and daily mean discharge data used in the analyses. As a result, computed standard errors summarized in this report will underestimate true errors. The reader is again referred to Ries and Friesz (2000, p. 11-13) for a more detailed explanation of how standard errors are computed.

Low-Flow Partial-Record Stations

At low-flow partial-record stations, the data available for analysis are multiple discharge measurements, each made during independent streamflow recessions. To estimate base-period flow-duration statistics at these stations, the same procedures outlined above for short-term surface-water gaging stations are used with one minor difference. Estimates for short-term gaging stations are based on relations developed from flow-duration discharges computed from concurrent periods of record at the short-term and index stations. At low-flow partial-record stations, estimates are based on relations developed between discharge measurements at the partial-record stations and concurrent daily mean discharges at the index stations. On days with variable flow at the index stations, mean discharges computed for base-flow parts of the day were used in the analysis. Relations developed with each of the four index stations are evaluated in terms of their correlation coefficients to determine which are most appropriate for use. Based on the nature of relations identified, either the MOVE.1 technique (linear) or graphical-correlation method (curvilinear) is used for record extension. If multiple index stations are used in the analysis, then each of the independent results is averaged using variance-weighting techniques.

Selection of Index Stations and Application of Data

Four surface-water gaging stations with a complete record of flow for the entire 1965–2004 base period are identified in table 1. Flow-duration discharges representative of the base period can be computed directly from the data available at each of these stations; they do not have to be estimated by record-extension techniques. The availability of a complete record and directly computed flow-duration discharges means that these four stations can be used as index stations to help extend the records of short-term gaging stations and low-flow partial-record stations in the Waipiʻo Valley study area.

Flow-duration discharges for the 1965–2004 base period at the four index stations have been computed and are summarized in table 7. The values in table 7 have no standard errors associated with them because they were not estimated by record-extension techniques. Flow-duration discharges summarized in table 7 assume use of current (2000–2005) diversion practices during the entire base period. However, because none of the four index stations are affected by diversions from either the Upper or Lower Hāmākua Ditches, the computed-flow duration discharges also reflect natural, undiverted conditions. Although complete flow-duration curves have been computed for each of the four index stations, only the higher percentile duration discharges are shown, in keeping with the focus of this report on low-flow hydrology of Waipiʻo Valley. Expanded flow-duration discharges are shown for the four index stations because these data will be used for record-extension techniques at short-term surface-water gaging stations.

The index stations on Kawainui Stream at 4,060 feet (16720000) and on Alakahi Stream at 3,900 feet (16725000) are located just upstream from Upper Hāmākua Ditch on tributary streams to Waipiʻo Valley (fig. 3). Thus they can be used to directly define low-flow hydrology within the study area in addition to being used as index stations to extend records. The index stations on Waikoloa Stream at 3,460 feet (16758000) and on Hauani Gulch at 3,117 feet (16759000) , which are in watersheds outside the study area, are actually closer to the downstream reaches of Waipiʻo Valley than the index stations on Kawainui and Alakahi Streams (fig. 3). Because of the location of these latter two stations, they cannot be used to directly define low-flow hydrology within the study area, but they still serve as valuable index stations for extending records at data-collection sites on reaches farther downstream in Waipiʻo Valley.

Computation of Low-Flow Statistics at Sites with Historical Data

In the Waipiʻo Valley study area, historical data, in addition to that at index, short-term, and low-flow partial-record stations that were described in previous sections of this report, are available for analysis. Historical data can be divided into two basic types: data for stations where daily discharge data were collected between August 1901 and January 1902, and data for stations where only miscellaneous discharge measurements were made. The analysis of data from the short-term daily discharge stations and its application to the 1965–2004 base period, as well as the miscellaneous discharge measurements and their value in the verification of discharge statistics computed by other methods, are described in detail in appendix 1.

Table 7. Selected natural flow-duration discharges for the 1965–2004 base period at index gaging-stations operated in the Waipi‘o Valley area, Island of Hawai‘i, Hawai‘i.[1]

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

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)			
	Kawainui Stream 16720000	Alakahi Stream 16725000	Waikoloa Stream 16758000	Hauani Gulch 16759000
99	0.10	0.15	0.99	0.00
98	0.15	0.23	1.2	0.03
97	0.19	0.29	1.3	0.04
95	0.29	0.38	1.5	0.06
90	0.51	0.59	1.7	0.11
85	0.74	0.80	2.0	0.15
80	1.0	1.0	2.3	0.20
75	1.3	1.2	2.5	0.25
70	1.7	1.5	2.8	0.29
65	2.1	1.8	3.0	0.34
60	2.7	2.2	3.4	0.40
55	3.5	2.6	3.8	0.47
50	4.5	3.1	4.3	0.55
40	7.4	4.5	5.8	0.77

[1] Discharge values shown on this table also represent discharge at the index stations under current (2000-2005) diversion practices, even though those diversions do not affect flow at the stations.

Computation of Low-Flow Statistics for Ungaged Sites

Streamflow data and associated low-flow statistics are not available at all locations in Waipi‘o Valley where they might be required, primarily because the collection of data is both time consuming and expensive. As a result, it is important to consider alternative methods that could be applied to extrapolate hydrologic information collected at gaged sites to ungaged sites, where no data are available. Methods that could be used to extrapolate data to ungaged sites range from simple techniques, such as linear interpolation between gaged sites, to complex techniques, such as rainfall-runoff modeling and multivariate regional-regression analyses. Descriptions and applications of some of the simpler techniques are included in appendix 2.

Low-Flow Statistics Under Current (2000–2005) Diversion Practices

Streamflow statistics used in this report to describe low-flow characteristics are based on flow-duration curves and their associated discharges. All flow-duration discharges summarized in this section of the report were computed or extended to reflect long-term conditions, assuming that current diversion practices in the Upper and Lower Hāmākua Ditches were actually followed during the entire 40-year base period 1965–2004. Current diversion conditions, for the purposes of this report, are defined as those in effect during the period 2000–2005, when additional data required for this study were collected. During the period March to November 2003, average diversion from Waipi‘o Valley by Upper Hāmākua Ditch, as measured at surface-water gaging station 16726000 at 3,020 feet, was 6.75 ft^3/s, and diversion by Lower Hāmākua Ditch, as measured at surface-water gaging station 16732800 upstream from the main weir, was 16.7 ft^3/s. March to November 2003 is the longest period of consecutive months during the years 2000–2005 when both gaging stations 16726000 and 16732800 and both ditches were operational.

Flow-duration discharges were computed for the four index stations (see table 7 and the footnote there), two short-term gaging stations, and five low-flow partial-record stations. Flow data are available for the entire base period for the index stations, but for only parts of the base period at the short-term stations. Data for multiple discharge measurements, but no continuous records of flow, are available for the low-flow partial record stations.

Short-Term Gaging Stations

Two gaging stations in the Waipiʻo Valley study area—Kawaiki Stream at 4,090 feet (16720300) and Wailoa Stream at 190 feet (16732200) (fig. 3)—have short-term records during some part of the 1965–2004 base period (table 1). The availability of concurrent periods of record with one or more of the four index stations means that the records at these gaging stations can be extended to be representative of the entire base period.

The Kawaiki Stream short-term station (16720300), just upstream from the Upper Hāmākua Ditch, has continuous streamflow records for the period 1969–1999; these data reflect natural, undiverted, streamflow conditions. Kawaiki Stream joins Kawainui Stream a short distance downstream from Upper Hāmākua Ditch. The index station on Kawainui Stream (16720000) was used to extend short-term records for Kawaiki Stream because of its proximity and the strength of the correlation between the stations. Selected flow-duration discharges for the concurrent period of record (1969–1999) at the two stations are shown in table 8. Plots of concurrent flow-duration discharges indicate a strong linear relation (correlation coefficient of 0.99) between the low flow-duration discharges at the Kawaiki and Kawainui stations. Normally, this would indicate that the MOVE.1 technique should be used to extend records. In this case, however, the graphical-correlation method was used because an analysis of the correlation plots indicated downward curvature for discharges between the 99- and 95-percentile durations. Estimated 1965–2004 base period flow-duration discharges for the short-term station on Kawaiki Stream (16720300), based on graphical-correlation record extension, also are shown in table 8. Standard errors were not computed for the estimated 1965–2004 base period, flow-duration discharges shown in table 8 because the estimates were made by interpolation along a smooth curve fit to concurrent flow-duration discharges. Standard errors would be expected to be relatively small because the Kawaiki short-term station (16720300) had complete streamflow data for 31 years out of the 40-year base period.

The Wailoa Stream short-term station (16732200) is at the downstream terminus of the Waipiʻo Valley study area. This station has continuous record for the period 1964–1969, and a low-flow partial-record station was operated at this site during the period 2000–2005. Streamflow data were not available for all of 1964, so only those data for the period 1965–1969 were used in this analysis. During the period 1965–1969, however, upstream diversions were significantly higher than they were under current (2000–2005) conditions. Average diversion from Waipiʻo Valley by Lower Hāmākua Ditch, as measured at the main weir (combined flow for stations 16733000 and 16733100), was 48 ft^3/s during the period 1965–1969 versus 10.0 ft^3/s during 2003 (station 16732800). Estimates of base period flow-duration discharges using the period of continuous streamflow record 1965–1969 will therefore reflect these higher diversion rates and not current diversion (2000–2005) conditions. Estimates reflective of the current diversion conditions will be described in the next section, where analyses using low-flow partial-record data collected during the period 2000–2005 are summarized.

The index station that had the strongest correlation with Wailoa Stream short-term station (16732200) was Waikoloa Stream at 3,460 feet (16758000). Selected flow-duration discharges for the concurrent period of record (1965–1969) at the two stations are shown in table 9. Plots of concurrent flow-duration discharges indicate a strong linear relation (correlation coefficient of 0.99) between the low flow-duration discharges at the Wailoa and Waikoloa gaging stations. As in the analyses of data for the Kawaiki and Kawainui Streams described above, a graphical correlation method was used to extend the record of the station on Wailoa Stream, and the estimated 1965–2004 base period flow-duration discharges are shown in table 9. Standard errors in the estimates were not computed but would be expected to be relatively small because of the strong correlation between low-flow discharges at the short-term and index stations.

Low-Flow Partial-Record Stations

Discharge measurements were made at five low-flow partial-record stations in the Waipiʻo Valley study area during the period 2000–2005 (table 3). These stations are located at sites 1, 6, 15, 18, and 24 (fig. 4), upstream from intakes of Lower Hāmākua Ditch, on Kawainui, Alakahi, Koʻiawe, and Waimā Streams, and at the site of former USGS gaging station 16732200 on Wailoa Stream, respectively. Estimates of base period (1965–2004) flow-duration discharges made on the basis of these discharge measurements will reflect current (2000–2005) diversion conditions.

Log base 10 linear correlations were found to exist between each of the five low-flow partial-record stations and at least one index station. In all cases, estimates of flow-duration discharges for the five low-flow partial-record stations were computed using the MOVE.1 technique with log base 10 transformed data. Daily mean and flow-duration discharge data for all index stations were increased by 1.0 ft^3/s before analysis to avoid complications associated with attempting log transformations of discharge values of 0.0 ft^3/s. The index station or stations that were used in the MOVE.1 computations for each low-flow partial-record station, along with the mean, standard deviation, and correlation coefficient statistics for concurrent discharge measurements and daily mean discharges, are given in table 10.

In the section of the report that described record-extension techniques, it was stated that only those index stations with correlation coefficients greater than 0.80 would be used in the analyses made in this study. Kawainui Stream at 4,060 feet (16720000) was used as an index station for the Koʻiawe Stream low-flow partial-record station (Site 15), even though the correlation coefficient between concurrent discharge values at the two sites was 0.791. This was considered a reasonable exception because the correlation coefficient was so close to the cutoff value and also because final MOVE.1 computations

Table 8. Selected natural flow-duration discharges for the 1969–1999 concurrent period of record at gaging stations 16720300 on Kawaiki Stream and 16720000 on Kawainui Stream and estimated 1965–2004 base period natural flow-duration discharges at gaging station 16720300 on Kawaiki Stream.

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

Percentage of time indicated discharge equaled or exceeded	Concurrent period of record 1969-1999		Base period 1965-2004
	Kawainui Stream 16720000 (ft^3/s)	Kawaiki Stream 16720300 (ft^3/s)	Kawaiki Stream 16720300 (ft^3/s)
99	0.09	0.02	0.02
98	0.14	0.04	0.05
97	0.18	0.06	0.07
95	0.26	0.10	0.11
90	0.50	0.16	0.16
85	0.75	0.23	0.23
80	1.0	0.29	0.29
75	1.4	0.38	0.36
70	1.8	0.48	0.46
65	2.2	0.60	0.57
60	2.8	0.77	0.74
55	3.6	0.98	0.95
50	4.6	1.3	1.3
40	7.7	2.1	2.0

were weighted with a second index station, on Hauani Gulch (16759000), which has a correlation coefficient (0.874) greater than the cutoff value. The station on Hauani Gulch was used as an index station for Waimā Stream low-flow partial-record station (Site 18), even though the correlation coefficient was only 0.539. In this case, MOVE.1 computations were run for Waimā Stream (Site 18) independently, using each of the four potential index stations. Estimated flow-duration discharges based on the four independent analyses were virtually identical. In this instance the consistency of results supports use of an index station having a correlation coefficient well below the cutoff value.

All MOVE.1 computations were made using log base 10 transformed data. Final estimates of base period, flow-duration discharges for the five low-flow partial-record stations were converted back into their original units of measurement (cubic feet per second). Estimated discharges for 99-, 95-, 90-, 80-, 70-, 60-, and 50-percentile durations and average standard errors are shown in table 11. In the process of computing standard errors for the estimated discharges throughout the report, it was assumed that the flow statistics at the index gaging stations have no standard errors associated with them because they were not estimated using record-extension techniques. Flow-duration discharges summarized in tables 7–9 were shown for an expanded number of percentiles because the extra data were required for the application of record-extension techniques at short-term stream-gaging stations.

Low-Flow Statistics Representative of Natural Conditions

Natural streamflow conditions are those in which flow at a given location has not been modified or regulated in some way by humans. To be representative of natural conditions, computed flow-duration discharges at most locations in the Waipiʻo Valley study area had to account for diversion of water by Upper and Lower Hāmākua Ditches. Natural flow-duration discharges were computed for two index stations, one short-term surface-water gaging station, and five low-flow partial-record stations in the Waipiʻo Valley study area.

Index and Short-Term Gaging Stations

Two index stations in the Waipiʻo Valley study area have a complete record for the entire 40-year base period, 1965–2004. These stations, on Kawainui Stream at 4,060 feet

Table 9. Selected flow-duration discharges for the 1965–1969 concurrent period of record at gaging stations 16732200 on Wailoa Stream and 16758000 on Waikoloa Stream and estimated 1965–2004 base period regulated flow-duration discharges at the gaging station on Wailoa Stream.

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

Percentage of time indicated discharge equaled or exceeded	Concurrent period of record 1965-1969		Base period 1965-2004
	Waikoloa Stream 16758000 (ft^3/s)	Wailoa Stream[a] 16732200 (ft^3/s)	Wailoa Stream[a] 16732200 (ft^3/s)
99	0.79	39	39
98	1.0	39	40
97	1.2	40	40
95	1.3	40	41
90	1.6	42	43
85	1.8	43	43
80	2.0	43	44
75	2.2	45	46
70	2.4	46	47
65	2.6	46	47
60	2.9	47	49
55	3.2	48	51
50	3.6	50	53
40	4.6	54	57

[a] Flow-duration discharges for Wailoa Stream during both the concurrent period of record and the base period are reflective of regulated conditions when the average diversion (1965–1969) by the Upper Hāmākua Ditch at station 16720500 below Kawaiki Stream was 9.3 ft^3/s and the combined diversion by the Lower Hāmākua Ditch at Stations 16733000 and 16733100 at the main weir was 48 ft^3/s.

(16720000) and Alakahi Stream at 3,900 feet (16725000), are just upstream from Upper Hāmākua Ditch (fig. 3). Thus the flows at these stations are not affected by diversions at either the Upper or Lower Hāmākua Ditches, and flow-duration discharges representative of natural conditions for the base period can be computed directly from the data available for the stations. Natural flow-duration discharges for the 1965–2004 base period at the two index stations have been computed and are summarized in table 7.

Two gaging stations in the Waipi‘o Valley study area—Kawaiki Stream at 4,090 feet and Wailoa Stream at 190 feet—have short-term records during some part of the base period (table 1). The Kawaiki Stream station (16720300) is upstream from Upper Hāmākua Ditch on a tributary stream to Kawainui Stream and Waipi‘o Valley (fig. 3). Thus the flows at the Kawaiki station are not affected by diversion associated with Upper or Lower Hāmākua Ditches, and flow-duration discharges representative of natural conditions for the base period can be computed by extending the data available for the station. Estimation of natural flow-duration discharges for the 1965–2004 base period for the Kawaiki Stream station was discussed in a previous section of this report (Low-Flow Statistics Under Current (2000–2005) Diversion Practices) and the estimates are summarized in table 8.

The short-term station on Wailoa Stream (16732200) is downstream from both Upper and Lower Hāmākua Ditches. Streamflow data collected during the period 1964–1969 at this station were directly affected by diversions into both ditch systems. To compute flow-duration discharges representative of natural conditions, the 1964–1969 data would first have to be adjusted to account for the effects of these diversions. However, daily data that document the total amount of water diverted from Waipi‘o Valley by Upper and Lower Hāmākua Ditches upstream from Wailoa Stream are not available for the period 1964–1969. As a consequence, natural flow-duration discharges for the 1965–2004 base period were not computed using the Wailoa Stream short-term gaging station data from 1964–1969.

Low-Flow Partial-Record Stations

Discharge measurements were made at five low-flow partial-record stations in the Waipi‘o Valley study area during the period 2000–2005 (fig. 4 and table 3). The stations at sites 1, 6, 15, and 18 are upstream from intakes of Lower Hāmākua Ditch on Kawainui, Alakahi, Ko‘iawe, and Waimā Streams, respectively. The station at site 24 is on Wailoa Stream,

Table 10. Computed statistics for concurrent discharge measurements at low-flow partial-record stations and daily mean discharges at index stations in Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

[n.a., not applicable]

Low-flow partial-record station[a]	Index station[b]	Mean[c]	Standard deviation[c]	Correlation coefficient
Site 1 Kawainui Stream		1.4040	0.2074	n.a.
	16720000 Kawaini Stream	0.4926	0.4201	0.926
	16725000 Alakahi Stream	0.4501	0.3142	0.944
Site 6 Alakahi Stream		1.1811	0.1038	n.a.
	16720000 Kawaini Stream	0.4581	0.4122	0.896
	16725000 Alakahi Stream	0.4268	0.3149	0.938
Site 15 Koʻiawe Stream		0.8908	0.0518	n.a.
	16720000 Kawaini Stream	0.4300	0.3113	0.791
	16759000 Hauani Gulch	0.1459	0.0936	0.874
Site 18 Waimā Stream		-0.1669	0.0731	n.a.
	16759000 Hauani Gulch	0.1544	0.0969	0.539
Site 24 Wailoa Stream		1.9068	0.0600	n.a.
	16759000 Hauani Gulch	0.1552	0.1018	0.928

[a] Site numbers correspond to gaging stations listed in table 2 and shown in figure 4.

[b] Station numbers correspond to gaging stations listed in table 1 and shown in figure 3.

[c] Statistics are based on log base 10 values. Daily mean discharge values for index stations were all increased by 1.0 prior to transformation to log base 10 values and the subsequent computation of statistics.

downstream from both Upper and Lower Hāmākua Ditches, at the location of the former short-term gaging station 16732200. Discharges measured at sites 1, 6, 15, and 18 were modified by flow diversions, return flows, and ditch losses that took place upstream along Upper Hāmākua Ditch. Discharges measured at site 24 were modified by flow diversions, return flows, and ditch losses that took place upstream along both of the ditch systems. To compute flow-duration discharges representative of natural conditions, the discharge measurements at these five low-flow partial-record stations have to be adjusted to account for the effects of these diversions.

A basic assumption made in this analysis was that streamflow at low-flow partial-record stations downstream from Upper and Lower Hāmākua Ditches would be changed by virtually the same amount that was being removed or released by the ditches upstream. Following this logic, measured or estimated diversion totals could be combined directly with the discharge measured at the stations so that the computed flow would reflect natural conditions (conditions that would be in place if no upstream manipulation of flow by diversion ditches was taking place). The validity of this assumption is supported by geologic factors and historical streamflow data in the study area. Upper Hāmākua Ditch runs along the rim of Waipiʻo Valley. A short distance downgradient of the ditch, the deeply eroded Waipiʻo Valley cuts through numerous closely spaced dikes that intercept large volumes of dike-impounded ground water (Stearns and Macdonald, 1946, p. 175). As a result, tributary streams entering Waipiʻo Valley could be expected to be gaining flow and to flow year round. The gaining and perennial nature of Waipiʻo Valley streams is supported by historical streamflow data such as that summarized by Mink (1984) and Martin and Pierce (1913). In such settings, there would be no natural reductions in streamflow to account for, but only the changes caused by the diversions.

Natural Low-Flow Statistics

To compute natural low-flow statistics for the five low-flow partial-record stations in Waipiʻo Valley, discharge measurements made during 2000–2005 first had to be adjusted to remove the effects of upstream diversions. These adjustments, which are described in detail in appendix 3 and summarized in tables 3–B through 3–F in the appendix, allow the computation of what would have been the natural discharge at each of the stations when the measurements were made. Estimates of flow-duration discharges made on the basis of these adjusted discharge measurements represent what natural conditions would have been over the 1965–2004 base period.

Table 11. Estimated regulated flow-duration discharges for the 1965–2004 base period that reflect diversion practices during the study period (2000–2005) at low-flow partial-record stations in Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi.

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

Percentage of time indicated discharge equaled or exceeded	Discharge[a] (ft^3/s)				
	Kawainui Stream Site 1[b]	Alakahi Stream Site 6[b]	Koʻiawe Stream Site 15[b]	Waimā Stream Site 18[b]	Wailoa Stream Site 24[b]
99	15	12	6.6	0.52	65
95	16	12	6.8	0.54	68
90	18	13	6.9	0.56	70
80	20	14	7.3	0.60	73
70	24	15	7.6	0.63	76
60	28	16	7.9	0.67	80
50	33	18	8.4	0.72	85
Average standard error (percent)	5.1	3.0	2.2	7.8	2.6

[a] All estimated flow-duration discharges reflect diversion conditions at Upper and Lower Hāmākua Ditches in effect during the study period 2000–2005. During the period March to November 2003 average diversion from Waipiʻo Valley by Upper Hāmākua Ditch, as measured at surface-water gaging station 16726000 at 3,020 feet, was 6.75 ft^3/s and by Lower Hāmākua Ditch, as measured at surface-water gaging station 16732800 upstream from the main weir, was 16.7 ft^3/s. March to November 2003 is the longest period of consecutive months during 2000–2005 when both gaging stations 16726000 and 16732800 and both ditches were operational.

[b] Site numbers correspond to gaging stations listed in table 2 and shown in figure 4.

Linear correlations were found to exist between each of the five low-flow partial-record stations and at least one index station. In all cases, estimates of flow-duration discharges for the low-flow partial-record stations were computed using the MOVE.1 technique (see earlier section "Record-Extension Techinques"). MOVE.1 computations were based on log base 10 transformed data for Kawainui (site 1) and Wailoa (site 24) Streams and on untransformed data at Alakahi (site 6), Koʻiawe (site 15), and Waimā (site 18) Streams. Daily mean and flow-duration discharge data for all index stations were increased by 1.0 ft^3/s before analysis for sites 1 and 24 to avoid complications associated with attempting log transformations of discharge values of 0.0 ft^3/s. The index station or stations that were used in MOVE.1 computations for each low-flow partial-record station, along with the mean, standard deviation, and correlation coefficient statistics for concurrent discharge measurements and daily mean discharges, are given in table 12.

MOVE.1 estimates of base period, natural flow-duration discharges for the five low-flow partial-record stations were either computed in or converted back into their original units of measurement (cubic feet per second), and estimated discharges for 99-, 95-, 90-, 80-, 70-, 60-, and 50-percentile durations and average standard errors are shown in table 13. Flow-duration discharges, summarized in tables 7–9, were shown for an expanded number of percentiles because the extra data were required for the record-extension techniques at short-term stream-gaging stations.

Effects of Diversion Practices on Low-Flow Statistics

Up to this point in the report, the focus has been on the data and methods used to derive low-flow statistics at selected locations within the Waipiʻo Valley study area. The focus will now shift to an evaluation of the effects that various diversion practices have on the low-flow hydrology in Waipiʻo Valley study area. First, a comparison will be made between low-flow hydrology under natural conditions and under 2000–2005 diversion practices. Second, a comparison will be made between low-flow hydrology under proposed future diversion practices and low-flow hydrology under 2000–2005 diversion practices and under natural conditions. Finally, the effects of historical (1965–1969) diversion practices, current (2000–2005) practices, and proposed future practices on natural low-flow hydrology at the downstream limit of the study area will

Table 12. Computed statistics for concurrent discharge measurements adjusted to represent natural conditions at low-flow partial-record stations and daily mean discharges at index stations in Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

[n.a., not applicable]

Low-flow partial-record station[a]	Index station[b]	Mean	Standard deviation	Correlation coefficient
Site 1 Kawainui Stream		1.3933[c]	0.1977[c]	n.a.
	16758000 Waikoloa Stream	0.5624[c]	0.2338[c]	0.964
Site 6 Alakahi Stream		15.7[d]	3.03[d]	n.a.
	16720000 Kawainui Stream	1.86[d]	2.12[d]	0.922
	16725000 Alakahi Stream	1.40[d]	1.09[d]	0.931
Site 15 Koʻiawe Stream		8.36[d]	0.89[d]	n.a.
	16758000 Waikoloa Stream	2.69[d]	1.18[d]	0.830
	16759000 Hauani Gulch	0.33[d]	0.18[d]	0.838
Site 18 Waimā Stream		0.97[d]	0.26[d]	n.a.
	16758000 Waikoloa Stream	2.47[d]	1.26[d]	0.938
	16759000 Hauani Gulch	0.34[d]	0.24[d]	0.933
Site 24 Wailoa Stream		2.0154[c]	0.0721[c]	n.a.
	16758000 Waikoloa Stream	0.5841[c]	0.1773[c]	0.939
	16759000 Hauani Gulch	0.1552[c]	0.1018[c]	0.953

[a] Site numbers correspond to gaging stations listed in table 2 and shown in figure 4.

[b] Station numbers correspond to gaging stations listed in table 1 and shown in figure 3.

[c] Statistics are based on log base 10 values. Daily mean discharge values for index stations were all increased by 1.0 prior to transformation to log base 10 values and the subsequent computation of statistics.

[d] Statistics are based on untransformed values.

Table 13. Estimated natural flow-duration discharges for the 1965–2004 base period at low-flow partial-record stations in Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi.

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

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)				
	Kawainui Stream Site 1[a]	Alakahi Stream Site 6[a]	Koʻiawe Stream Site 15[a]	Waimā Stream Site 18[a]	Wailoa Stream Site 24[a]
99	15	13	6.9	0.64	80
95	18	13	7.3	0.73	86
90	19	14	7.5	0.77	88
80	23	14	7.9	0.89	95
70	26	16	8.3	0.98	100
60	29	17	8.8	1.1	105
50	34	20	9.5	1.2	112
Average standard error (percent)	5.4	2.8	2.5	4.5	1.9

[a] Site numbers correspond to gaging stations listed in table 2 and shown in figure 4.

be summarized. The downstream limit of the study area is just upstream from the site of the current, most upstream diversions for taro production in Waipiʻo Valley.

Current (2000–2005) Diversion Practices

To evaluate the effects of diversion practices at Upper and Lower Hāmākua Ditch systems during the period 2000–2005 on low-flow hydrology in Waipiʻo Valley study area, the 95- and 50-percentile flow-duration discharges representative of natural conditions and conditions during that period will be compared. These two discharge statistics for the gaging stations and data-collection sites in the study area under natural conditions and under 2000–2005 diversion practices are summarized in tables 14 and 15. The reduction in discharge associated with 2000–2005 diversion practices is shown as a percent in both tables. The spatial pattern of discharge reduction for the 95- and 50-percentile discharges is shown in figures 5 and 6.

The 2000–2005 diversion practices of Upper and Lower Hāmākua Ditches have no effect on the 95- and 50-percentile discharges at gaging stations 16720000 on Kawaimui Stream, 16720300 on Kawaiki Stream, and 16725000 on Alakahi Stream, because these stations are upstream from both ditches. The most significant reductions in flow-duration discharge associated with the 2000–2005 diversion practices are shown to take place immediately downstream from Upper Hāmākua Ditch intakes on Kawainui and Kawaiki Streams, where 95-percentile discharge is reduced by 100 percent and 50-percentile discharge is reduced by 92 percent. Similar computations for locations directly downstream from Upper Hāmākua Ditch intakes on Alakahi, Koʻiawe, and Waimā Streams were not possible, but similar reduction in flow could be expected there.

Just downstream from Upper Hāmākua Ditch, tributary streams to Waipiʻo Valley drop sharply in altitude. As noted from analyses of 1901–1902 data (appendix 1) and during seepage runs (appendix 2), tributary streams consistently gain flow within Waipiʻo Valley. As a result , the effects of 2000–2005 diversion practices on natural discharge decrease in a downstream direction. At locations just upstream from Lower Hāmākua Ditch intakes, natural 50-percentile discharges have been reduced by 3, 5, 12, and 40 percent on Kawainui, Alakahi, Koʻiawe, and Waimā Streams, respectively. The reduction in discharge along Waimā Stream is inconsistent with those for the other tributary streams because the largest gains in discharge along Waimā Stream take place at much lower altitudes.

The percentages by which natural discharges are reduced by diversions in 2000–2005 increase sharply downstream from the intakes of Lower Hāmākua Ditch. At the mouths of Kawainui, Alakahi, Koʻiawe, and Waimā Streams, the 50-percentile discharges have been reduced by 29, 14, 20, and 7 percent, respectively. Once again Waimā Stream is inconsistent in that the percent reduction in natural low flows continues to decrease downstream from Lower Hāmākua Ditch.

Along Waipiʻo and Wailoa Streams, the percentages by which natural discharges have been reduced as a result of the combined 2000–2005 diversion practices of Upper and Lower Hāmākua Ditches is relatively consistent. During 95-percentile flow conditions, natural discharge reductions range between 18 and 22 percent. During 50-percentile flow conditions, natural discharge reductions range between 19 and 24 percent.

The ratio of 95-percentile to 50-percentile discharges can be used as an index of low-flow variability. Ratios close to zero are indicative of more variable and less sustained low flows. Ratios closer to one are indicative of less variable and more sustained low flows (Oki and others, 2006, p. 15). In most cases, the ratio of 95-percentile to 50-percentile discharges under 2000–2005 diversion practices is greater than that under natural conditions at the same gaging station. The average ratio of the two discharges for gaging stations in Waipiʻo Valley is 0.76 under regulated flow conditions and 0.73 under natural flow conditions (see tables 2-D and 2-E in appendix 2). This difference indicates that low flows of streams in Waipiʻo Valley are smaller and slightly less variable under 2000–2005 diversion practices than under natural conditions.

Proposed Future Diversion Practices for Lower Hāmākua Ditch

In an environmental impact statement related to future operation of Lower Hāmākua Ditch (U.S. Department of Agriculture, 1999, p. 144), diversion rates out of Waipiʻo Valley were projected to be 7 Mgal/d (10.8 ft^3/s) during average conditions and 13 Mgal/d (20.1 ft^3/s) during drought conditions. The effects of these proposed diversion rates are evaluated in this section of the report. Low-flow statistics were computed for gaging stations and data-collection sites located downstream from Lower Hāmākua Ditch. A detailed description of those computations and their analysis follows.

Computation of Low-Flow Statistics under Proposed Diversion Practices at Lower Hāmākua Ditch

Changes in diversion practices of Lower Hāmākua Ditch will not have an effect on the low-flow statistics for gaging stations and data-collection sites located upstream from it. Low-flow statistics for gaging stations and data-collection sites downstream from Lower Hāmākua Ditch, however, are modified by diversion practices of both Upper and Lower Hāmākua Ditches and therefore will be directly affected. To compute low-flow statistics for such downstream locations that reflect proposed future diversion practices, the first step is to determine the amount by which current diversion practices (2000–2005) affect natural discharges. Total diversion effects for downstream locations need to be partitioned between those associated with diversions by Upper and Lower Hāmākua Ditches.

Table 14. Comparison of 95-percentile flow-duration discharges under natural conditions and 2000–2005 diversion practices at gaging stations and data-collection sites in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

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

Gaging-station or site number[a]	Stream	95-percentile discharge (ft^3/s)		Difference in percent
		Natural conditions	2000-2005 diversion practices	
Upstream from Upper Hāmākua Ditch				
16720000	Kawainui	0.29	0.29	0
16720300	Kawaiki	0.11	0.11	0
16725000	Alakahi	0.38	0.38	0
Downstream from Upper Hāmākua Ditch				
16720000 + 16720300	Kawainui	0.40	0.00	-100
16721000	Kawainui	14	9.8	-30
16722000	Kawainui	17	13	-24
1	Kawainui	18	16	-11
16728000	Alakahi	12	10	-17
6	Alakahi	13	12	-8
16730000	Koʻiawe	7.5	6.5	-13
15	Koʻiawe	7.3	6.8	-7
18	Waimā	0.73	0.54	-26
Downstream from Lower Hāmākua Ditch				
16724000	Kawainui	28	21	-25
16729000	Alakahi	18	15	-17
10[b]	Waipiʻo	46	36	-22
11[c]	Waipiʻo	49	40	-18
16732000[b]	Waipiʻo	61	50	-18
22[d]	Waipiʻo	63	52	-18
16731000	Koʻiawe	12	10	-17
16732150	Waimā	26	24	-8
16732200	Wailoa	86	68	-21

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

[b] Site 10 data computed by adding flow-duration discharges for stations 16724000 and 16729000. Station 16732000 data computed by adding flow-duration discharges for site 11 and station 16731000.

[c] Translation of site 10 data downstream using seepage run adjustment factors of 1.06 for natural discharge and 1.10 for regulated discharge.

[d] Translation of station 16732000 data downstream using seepage run adjustment factors of 1.03 for natural discharge and 1.05 for regulated discharge.

Table 15. Comparison of 50-percentile flow-duration discharges under natural conditions and 2000–2005 diversion practices at gaging stations and data-collection sites in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

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

Gaging-station or site number[a]	Stream	50-percentile discharge (ft^3/s)		Difference in percent
		Natural conditions	2000-2005 diversion practices	
Upstream from Upper Hāmākua Ditch				
16720000	Kawainui	4.5	4.5	0
16720300	Kawaiki	1.3	1.3	0
16725000	Alakahi	3.1	3.1	0
Downstream from Upper Hāmākua Ditch				
16720000 + 16720300	Kawainui	6.0	0.46	-92
16721000	Kawainui	21	14	-33
16722000	Kawainui	24	17	-29
1	Kawainui	34	33	-3
16728000	Alakahi	15	12	-20
6	Alakahi	20	18	-5
16730000	Koʻiawe	9.0	7.4	-18
15	Koʻiawe	9.5	8.4	-12
18	Waimā	1.2	0.72	-40
Downstream from Lower Hāmākua Ditch				
16724000	Kawainui	38	27	-29
16729000	Alakahi	21	18	-14
10[b]	Waipiʻo	59	45	-24
11[c]	Waipiʻo	63	50	-21
16732000[b]	Waipiʻo	78	62	-20
22[d]	Waipiʻo	80	65	-19
16731000	Koʻiawe	15	12	-20
16732150	Waimā	44	41	-7
16732200	Wailoa	112	85	-24

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

[b] Site 10 data computed by adding flow-duration discharges for stations 16724000 and 16729000. Station 16732000 data computed by adding flow-duration discharges for site 11 and station 16731000.

[c] Translation of site 10 data downstream using seepage run adjustment factors of 1.06 for natural discharge and 1.10 for regulated discharge.

[d] Translation of station 16732000 data downstream using seepage run adjustment factors of 1.03 for natural discharge and 1.05 for regulated discharge.

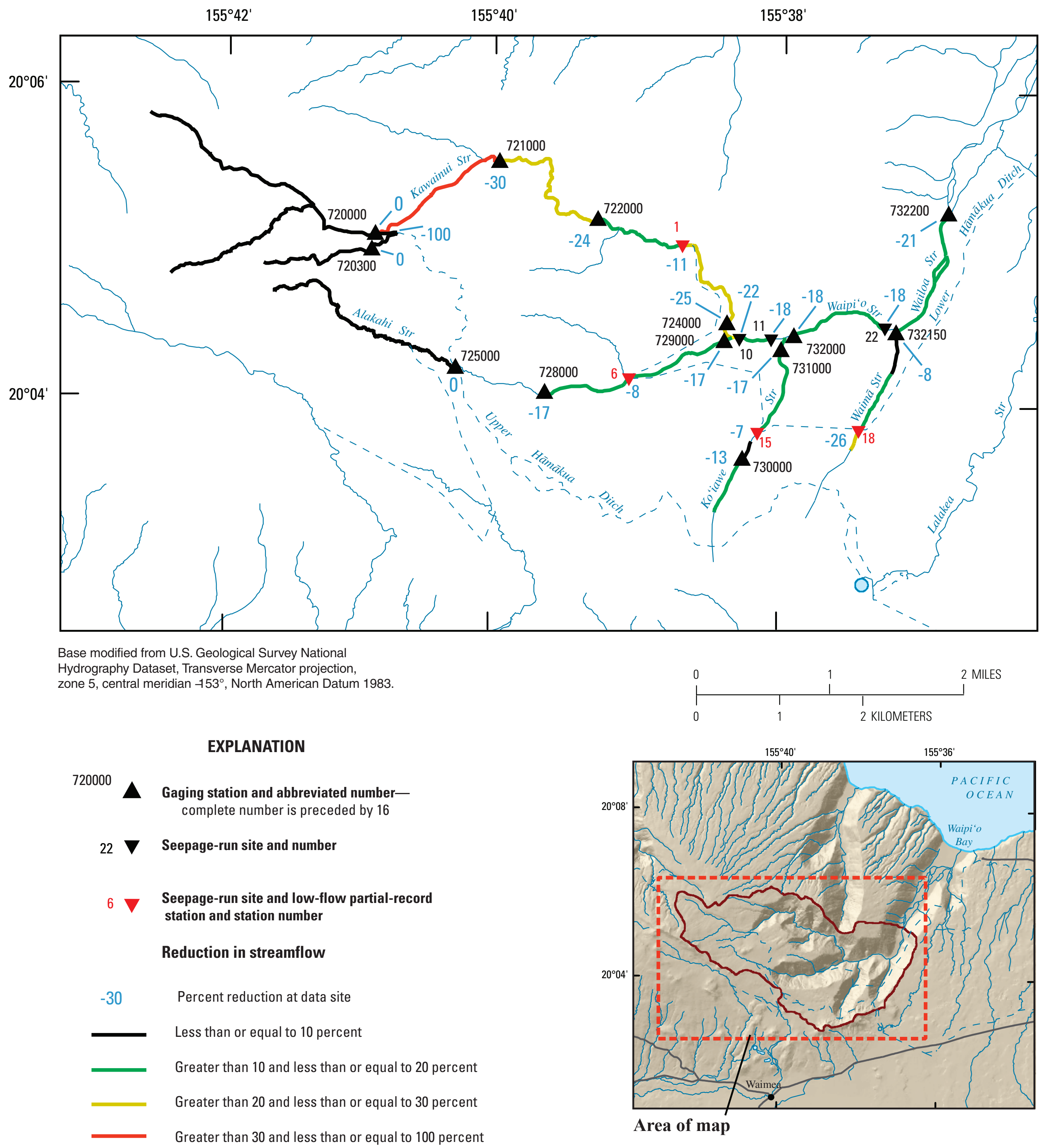


Figure 5. Percent reduction in natural 95-percentile discharge under 2000–2005 diversion practices, Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

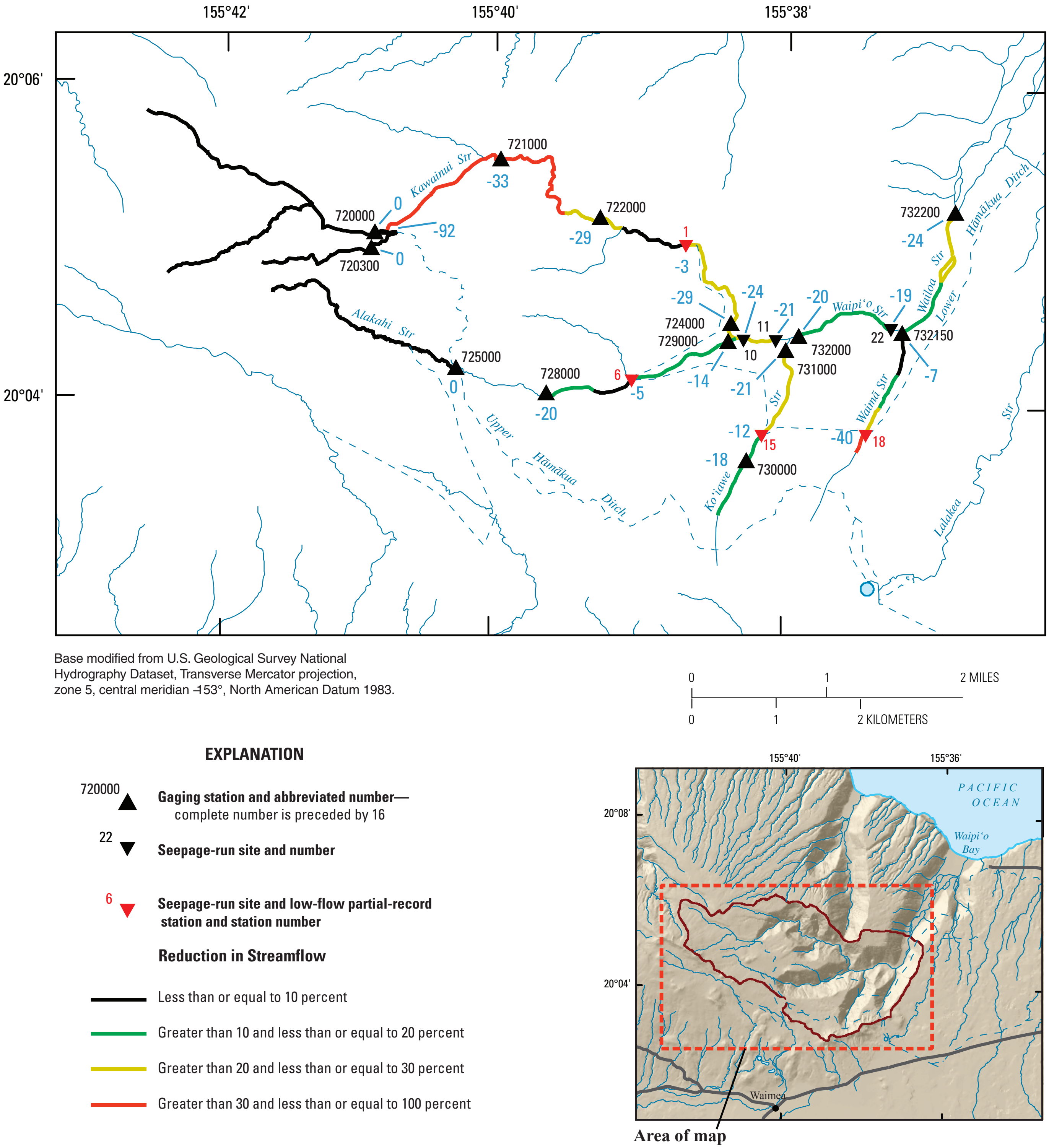


Figure 6. Percent reduction in natural 50-percentile discharge under 2000–2005 diversion practices, Waipi'o Valley study area, Island of Hawai'i, Hawai'i.

Diversion effects associated with current diversion practices (2000–2005) can be estimated by calculating the difference between natural and regulated low-flow statistics at the location of interest. Diversion effects will vary with location along streams because of the complex manner that Upper and Lower Hāmākua Ditches gain and lose water along their reaches, and they also will vary with the magnitude of low flow. Differences between natural flow and flow under 2000–2005 diversion practice were computed for 95- and 50-percentile discharges and are summarized in table 16. Differences were computed at locations just upstream from the intakes of Lower Hāmākua Ditch at sites 1, 6, 15, and 18 (fig. 4) to determine diversion effects associated with Upper Hāmākua Ditch before diversions by Lower Hāmākua Ditch. Differences were computed at the mouths of Kawainui, Alakahi, Koʻiawe, and Waimā Streams, at gaging stations 16724000, 16729000, 16731000, and 16732150, respectively (fig. 3)**,** to determine combined diversion effects associated with Upper and Lower Hāmākua Ditches at the downstream reaches of the tributary streams. Finally, differences were computed at gaging station 16732200 on Wailoa Stream to reflect total diversion effects at the downstream limit of the study area. For example, Upper Hāmākua Ditch reduced the 95-percentile discharge by 2 ft^3/s on Kawainui Stream at site 1. The combined diversions at Upper and Lower Hāmākua Ditches reduced 95-percentile discharge by 7 ft^3/s on Kawainui Stream at gaging station 16724000.

To partition discharge reductions in the four tributary streams—Kawainui, Alakahi, Koʻiawe, and Waimā—between Upper and Lower Hāmākua Ditches, a second computation was required. Using data from the example given above, it follows that of the 7 ft^3/s reduction in 95-percentile discharge estimated for Kawainui Stream downstream from Lower Hāmākua Ditch, 2 ft^3/s was associated with Upper Hāmākua Ditch. As a result, reduction in discharge associated with Lower Hāmākua Ditch can be computed as the difference, 7 minus 2, or 5 ft^3/s. Similar computations for 95- and 50-percentile discharges were made for Alakahi, Koʻiawe, and Waimā Streams, and the results are summarized in table 17. Total diversions from the four tributary streams for 95- and 50-percentile discharges, respectively, are 3.69 ft^3/s and 4.58 ft^3/s by Upper Hāmākua Ditch and 10.3 ft^3/s and 15.4 ft^3/s by Lower Hāmākua Ditch. As a result, combined totals for diversions by both ditches are 14 ft^3/s and 20 ft^3/s for 95- and 50-percentile discharges. These combined diversion totals are those reflected in discharges of the four tributary streams and will not equal diversion totals as noted at the downstream limit of the study area at gaging station 16732200 on Wailoa Stream. Diversion totals computed at gaging station 16732200 equal 18 ft^3/s and 27 ft^3/s for 95- and 50-percentile discharges (table 16). Differences in combined diversion totals between the four tributary streams and those at the downstream limit of the study area can be attributed, in part, to rounding criteria applied to each of the computed values. The primary reason for the differences, however, is that Lower Hāmākua Ditch gains water in several of its tunneled reaches within Waipiʻo Valley and these diversion effects are not fully reflected in computed low-flow discharges until the downstream limit of the study area at Wailoa Stream gaging station 16732200.

As noted previously, proposed future diversion rates out of Waipiʻo Valley by Lower Hāmākua Ditch were projected to be 7 Mgal/d (10.8 ft^3/s) during normal conditions and 13 Mgal/d (20.1 ft^3/s) during drought conditions (U.S. Department of Agriculture, 1999, p. 144). In the same report, diversions at each of the four tributary stream intakes were shown as 1, 5, 2, and 0 Mgal/d, respectively, at the Kawainui, Alakahi, Koʻiawe, and Waimā intakes during normal conditions. During drought conditions, diversion rates were shown as 6.6, 3.9, 1.8, and 0 Mgal/d, respectively, at the same intakes. When combined, diversion totals at the individual ditch intakes do not exactly equal proposed totals of 7 Mgal/d and 13 Mgal/d because of rounding and gains in Lower Hāmākua Ditch tunnels (U.S. Department of Agriculture, 1999, p. 144). In this report, these diversion values were converted to units of cubic feet per second and were rounded to the nearest unit as follows: 2, 8, 3, and 0 ft^3/s during normal conditons and 10, 6, 3, and 0 ft^3/s during drought conditions at the Kawainui, Alakahi, Koʻiawe, and Waimā intakes, respectively. These values were then used to replace computed diversions by Lower Hāmākua Ditch reflective of 2000–2005 conditions, shown in table 17, to compute new diversion totals reflective of proposed future diversion practices. These new diversion totals, for proposed future practices, are shown in table 18. It can be noted from the data in table 18 that no changes are being proposed for diversion practices by Upper Hāmākua Ditch, so those values remain the same. In addition, no changes are proposed for the operation of Waimā intake on the Lower Hāmākua Ditch, so the computed diversion totals from table 17 remain the same in table 18.

Resultant 95- and 50-percentile discharges under proposed future diversion practices for nine gaging stations and data-collection sites located downstream from Lower Hāmākua Ditch are shown in table 19. Natural flow-duration discharges for these locations are reduced by total proposed diversions for future conditions (table 18), for each of the individual streams, to determine resultant discharges. By applying the same principles discussed in the section "Combining Flow-Duration Curves" in appendix **2,** total proposed diversions can be determined for locations along Waipiʻo Stream downstream from the confluence of individual tributaries. For example, total proposed diversions for Kawainui Stream at gaging station 16724000 and Alakahi Stream at gaging station 16729000 are 12 ft^3/s and 7 ft^3/s. Total proposed diversion for Waipiʻo Stream at site 10, located just downstream from the confluence of Kawainui and Alakahi Streams, is therefore 12 + 7, or 19 ft^3/s. A slight modification to this process is required for the gaging station on Wailoa Stream (16732200) at the downstream limit of the study area because not all of Lower Hāmākua Ditch diversion effects are reflected in four upstream tributary streams (see discussion above). For example (using 95-percentile discharges), to compute total proposed diversion effects at the Wailoa Stream gage (16732200), total diversion

Table 16. Reductions in natural discharge associated with 2000–2005 diversion practices on streams in the Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

[ft^3/s, cubic feet per second; us, upstream; ds, downstream; LHD, Lower Hāmākua Ditch]

Stream and location	Gaging-station or site number[a]	Hydrologic condition	95-percentile discharge (ft^3/s)	50-percentile discharge (ft^3/s)
Kawainui us from LHD	1	Natural	18	34
		2000–2005[b]	16	33
Difference			2	1
Kawainui ds from LHD	16724000	Natural	28	38
		2000–2005[b]	21	27
Difference			7	11
Alakahi us from LHD	6	Natural	13	20
		2000–2005[b]	12	18
Difference			1	2
Alakahi ds from LHD	16729000	Natural	18	21
		2000–2005[b]	15	18
Difference			3	3
Ko‘iawe us from LHD	15	Natural	7.3	9.5
		2000–2005[b]	6.8	8.4
Difference			0.5	1.1
Ko‘iawe ds from LHD	16731000	Natural	12	15
		2000–2005[b]	10	12
Difference			2	3
Waimā us from LHD	18	Natural	0.73	1.2
		2000–2005[b]	0.54	0.72
Difference			0.19	0.48
Waimā ds from LHD	16732150	Natural	26	44
		2000–2005[b]	24	41
Difference			2	3
Wailoa	16732200	Natural	86	112
		2000–2005[b]	68	85
Difference			18	27

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

[b] Diversion conditions in effect during the 2000–2005 study period.

Table 17. Estimated diversions by Upper and Lower Hāmākua Ditches from 95- and 50-percentile flow-duration discharges under 2000–2005 diversion conditions on streams in the Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

[ft^3/s, cubic feet per second; Q_{95}, 95-percentile discharge; Q_{50}, 50-percentile discharge; UHD, Upper Hāmākua Ditch; LHD, Lower Hāmākua Ditch; us, upstream; ds, downstream]

Stream and location	Difference in Q_{95} discharges[a] (ft^3/s)	Diversion by UHD at Q_{95}[b] (ft^3/s)	Diversion by LHD at Q_{95}[c] (ft^3/s)	Difference in Q_{50}[d] discharges (ft^3/s)	Diversion by UHD at Q_{50}[b] (ft^3/s)	Diversion by LHD at Q_{50}[c] (ft^3/s)
Kawainui		2	5		1	10
us of LHD	2			1		
ds of LHD	7			11		
Alakahi		1	2		2	1
us of LHD	1			2		
ds of LHD	3			3		
Ko‘iawe		0.5	1.5		1.1	1.9
us of LHD	0.5			1.1		
ds of LHD	2			3		
Waimā		0.19	1.81		0.48	2.52
us of LHD	0.19			0.48		
ds of LHD	2			3		
Total		3.7	10.3		4.58	15.4
Combined totals			14			20

[a] Difference between Q_{95} discharges for natural and 2000–2005 diversion conditions.

[b] Difference between discharges upstream of Lower Hāmākua Ditch.

[c] Downstream differences in discharge minus upstream differences in discharge.

[d] Difference between Q_{50} discharges for natural and 2000–2005 diversion conditions.

Table 18. Estimated diversions by Upper and Lower Hāmākua Ditches from 95- and 50-percentile flow-duration discharges under proposed, future diversion practices on streams in the Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

[ft^3/s, cubic feet per second; Q_{95}, 95-percentile discharge; Q_{50}, 50-percentile discharge; UHD, Upper Hāmākua Ditch; LHD, Lower Hāmākua Ditch; us, upstream; ds, downstream]

Stream and location	Diversion by UHD at Q_{95}[a] (ft^3/s)	Diversion by LHD at Q_{95}[b] (ft^3/s)	Total diversion at Q_{95} (ft^3/s)	Diversion by UHD at Q_{50}[a] (ft^3/s)	Diversion by LHD at Q_{50}[b] (ft^3/s)	Total diversion at Q_{50} (ft^3/s)
Kawainui ds of LHD	2	10	12	1	2	3
Alakahi ds of LHD	1	6	7	2	8	10
Ko‘iawe ds of LHD	0.5	3	3.5	1.1	3	4.1
Waimā ds of LHD	0.19	1.81[c]	2[c]	0.48	2.52[c]	3[c]
Total	3.7	20.8	24.5	4.58	15.5	20.1

[a] Data from table 17.

[b] Proposed diversion data from U.S. Department of Agriculture (1999, p. 144).

[c] No change from 2000–2005 diversion practices proposed for future diversion conditions.

effects associated with 2000–2005 conditions at the gage of 18 ft^3/s (table 16) are adjusted to reflect the difference in total diversions from the four upstream tributary streams under proposed future diversion conditions (24.5 ft^3/s in table 18) and 2000–2005 diversion conditions (14 ft^3/s in table 17). The total proposed diversions effects are therefore computed as 18 + (24.5-14), or 28.5 ft^3/s, as shown in table 19.

Changes in Low Flow Relative to 2000–2005 Diversion Practices

To evaluate the effects that proposed future diversion practices for Lower Hāmākua Ditch will have on current low-flow hydrology in the Waipiʻo Valley study area, flow-duration statistics for the 95 and 50 percentiles under 2000–2005 diversion practices and under proposed future diversion practices were compared. The 95- and 50-percentile discharges under both 2000–2005 and proposed future diversion practices at nine gaging stations and data-collection sites downstream from Lower Hāmākua Ditch are summarized in table 20. The reduction in discharge associated with a change from current to proposed, future diversion practices is shown as a percent in the table.

Current (2000–2005) flow-duration discharges for locations upstream from Lower Hāmākua Ditch will not be altered by proposed future changes in diversion practices at the ditch. The proposed future diversion practices would, however, result in discharges downstream from Lower Hāmākua Ditch that are distinctly different from those under current diversion practices. At gaging stations and data-collection sites along Kawainui, Alakahi, and Waipiʻo Streams, current (2000–2005) 95-percentile discharges will be reduced between 21 and 27 percent. At gaging stations and data-collection sites along Koʻiawe and Wailoa Streams, the magnitude of the flow reduction will be only slightly smaller, at 15 percent. No changes in 95-percentile discharges will occur along Waimā Stream. The only changes in excess of 10 percent of current (2000–2005) 50-percentile discharges will be at gaging stations and data-collection sites along Kawainui and Alakahi Streams; discharges on Kawainui Stream will increase by 30 percent and discharges on Alakahi Stream will decrease by 39 percent.

Changes in Low Flow Relative to Natural Conditions

To evaluate the effects that proposed future diversion practices for Lower Hāmākua Ditch will have on natural low-flow hydrology in the Waipiʻo Valley study area, flow-duration statistics for the 95 and 50 percentiles under proposed, future diversion and natural conditions were compared. The 95- and 50-percentile discharges under both conditions at nine gaging stations and data-collection sites downstream from Lower Hāmākua Ditch are summarized in table 21. The reduction in discharge associated with a change from natural to proposed future diversion practices is shown as a percent in the table. The spatial patterns of discharge reduction for 95- and 50-percentile discharges are shown in figures 7 and 8.

Natural flow-duration discharges for locations upstream from Upper Hāmākua Ditch will not be altered by proposed future changes in diversion practices in Lower Hāmākua Ditch. Natural flow-duration discharges in stream reaches between Upper and Lower Hāmākua Ditches, however, will continue to be reduced in response to current (2000–2005) practices in effect. Proposed future changes in diversion practices in Lower Hāmākua Ditch will not alter these conditions. Changes in discharges in stream reaches between Upper and Lower Hāmākua Ditches are summarized in tables 14 and 15. The spatial pattern of discharge reduction for stream reaches upstream from Lower Hāmākua Ditch, shown in figures 7 and 8 for proposed future changes in diversion practices, reflect the above.

At gaging stations and data-collections sites downstream from Lower Hāmākua Ditch—along Kawainui, Alakahi, Waipiʻo, and Wailoa Streams—natural 95-percentile discharges will be reduced between 29 and 43 percent. At the stations and sites along Waimā Stream, natural 95-percentile discharges will be reduced by 8 percent. The changes in 50-percentile discharges will be slightly smaller but more variable than those for 95-percentile discharges. At gaging stations and data-collection sites along Waipiʻo, Koʻiawe, and Wailoa Streams, the natural 50-percentile discharges will be reduced between 21 and 27 percent. At gaging stations and data-collection sites along Kawainui and Waimā Streams, the natural 50-percentile discharges will be reduced by 7 to 8 percent. Changes will be greatest at gaging stations and data-collections sites along Alakahi Stream, where 50-percentile discharges will be reduced by 48 percent.

As noted previously, the ratio of 95-percentile to 50-percentile discharges can be used as an index of low-flow variability. In table 22, ratios of 95-percentile to 50-percentile discharges are summarized for nine gaging stations and data-collections sites downstream from Lower Hāmākua Ditch. Under proposed future diversion conditions, the average ratio is 0.66, which is markedly lower than those for natural conditions (0.76) and current (2000–2005) diversion conditions (0.78). These differences indicate that low flows under proposed future diversion conditions will be more variable.

Summary of Effects of Various Diversion Practices at the Downstream Limit of Study Area

One of the important aspects of this study was to determine the effects that diversion practices have on the low-flow hydrology of Wailoa Stream as it enters the lower part of Waipiʻo Valley. It is in the lower parts of the valley that water from Wailoa Stream is used to support taro production and therefore where the availability of this water is very important. During this study data were collected at gaging station

Table 19. Resultant 95- and 50-percentile flow-duration discharges under proposed, future diversion practices at gaging stations and data-collection sites downstream from Lower Hāmākua Ditch in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

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

Gaging-station or site number[a]	Stream	Discharge (ft^3/s)		
		Natural conditions[b]	Total proposed diversions	Resultant
		95-percentile		
16724000	Kawainui	28	12	16
16729000	Alakahi	18	7	11
10	Waipiʻo	46	19[c]	27
11	Waipiʻo	49	19[c]	30
16732000	Waipiʻo	61	22.5[d]	39
22	Waipiʻo	63	22.5[d]	41
16731000	Koʻiawe	12	3.5	8.5
16732150	Waimā	26	2	24
16732200	Wailoa	86	28.5[e]	58
		50-percentile		
16724000	Kawainui	38	3	35
16729000	Alakahi	21	10	11
10	Waipiʻo	59	13[c]	46
11	Waipiʻo	63	13[c]	50
16732000	Waipiʻo	78	17.1[d]	61
22	Waipiʻo	80	17.1[d]	63
16731000	Koʻiawe	15	4.1	11
16732150	Waimā	44	3	41
16732200	Wailoa	112	27.1[e]	85

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

[b] Data from tables 14 and 15.

[c] Combined diversions from Kawainui and Alakahi Streams.

[d] Combined diversions from Kawainui, Alakahi, and Koʻiawe Streams.

[e] Total diversion from upstream from gaging station.

Table 20. Comparison of 95- and 50-percentile flow-duration discharges under 2000–2005 and proposed, future diversion practices at gaging stations and data-collection sites downstream from Lower Hāmākua Ditch in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

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

Gaging-station or site number[a]	Stream	Discharge (ft^3/s) 2000–2005 diversion practices	Discharge (ft^3/s) Proposed future diversions	Difference in percent
		95-percentile		
16724000	Kawainui	21	16	-24
16729000	Alakahi	15	11	-27
10	Waipiʻo	36	27	-25
11	Waipiʻo	40	30	-25
16732000	Waipiʻo	50	39	-22
22	Waipiʻo	52	41	-21
16731000	Koʻiawe	10	8.5	-15
16732150	Waimā	24	24	0
16732200	Wailoa	68	58	-15
		50-percentile		
16724000	Kawainui	27	35	30
16729000	Alakahi	18	11	-39
10	Waipiʻo	45	46	2
11	Waipiʻo	50	50	0
16732000	Waipiʻo	62	61	-2
22	Waipiʻo	65	63	-3
16731000	Koʻiawe	12	11	-8
16732150	Waimā	41	41	0
16732200	Wailoa	85	85	0

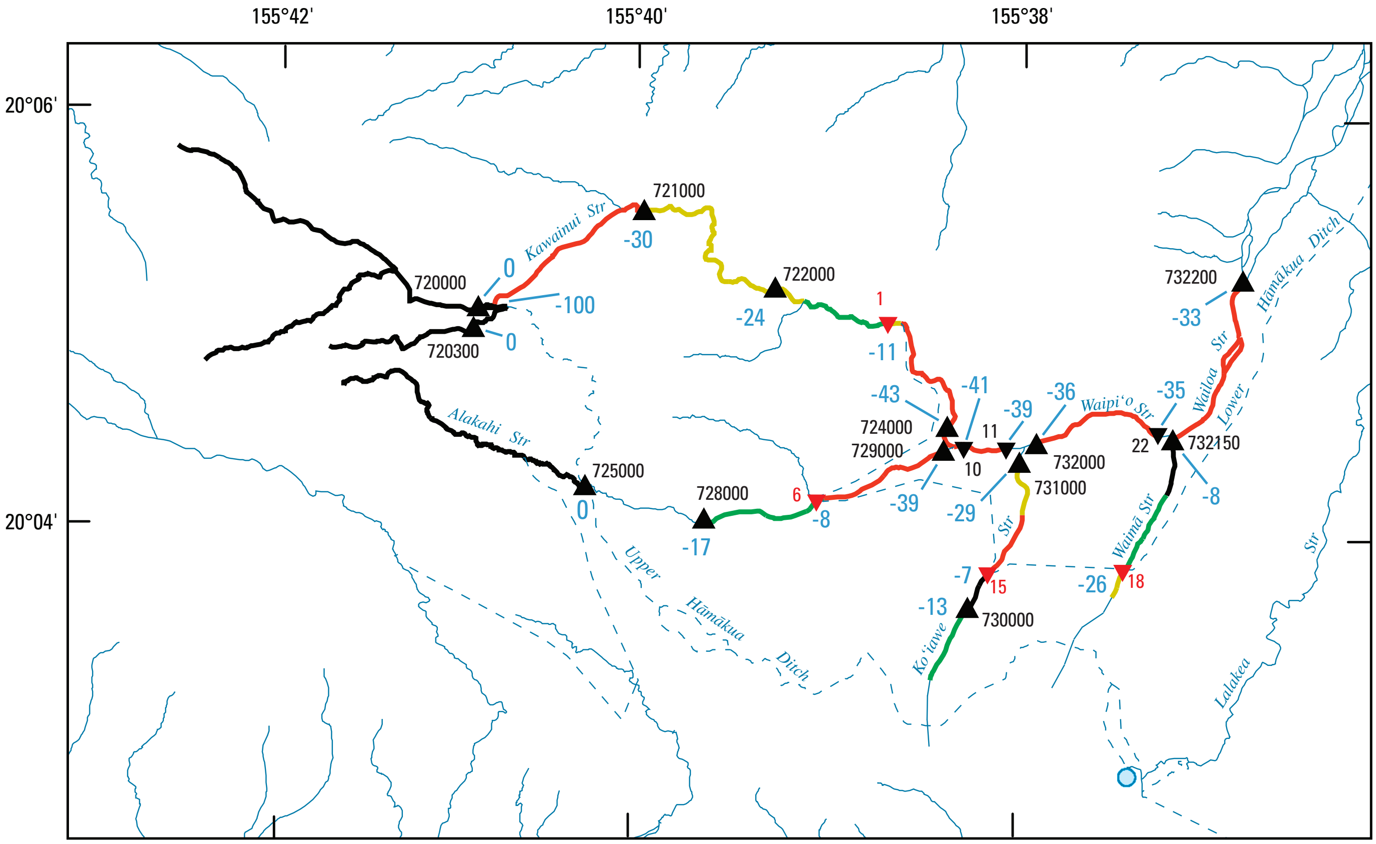
[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

Table 21. Comparison of 95- and 50-percentile flow-duration discharges under natural and proposed, future diversion practices at gaging stations and data-collection sites downstream from Lower Hāmākua Ditch in the Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

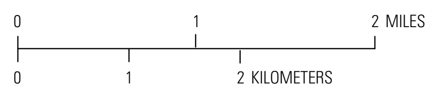
[ft^3/s, cubic feet per second]

Gaging-station or site number[a]	Stream	Discharge (ft^3/s) Natural conditions	Discharge (ft^3/s) Proposed future diversions	Difference in percent
		95-percentile		
16724000	Kawainui	28	16	-43
16729000	Alakahi	18	11	-39
10	Waipi‘o	46	27	-41
11	Waipi‘o	49	30	-39
16732000	Waipi‘o	61	39	-36
22	Waipi‘o	63	41	-35
16731000	Ko‘iawe	12	8.5	-29
16732150	Waimā	26	24	-8
16732200	Wailoa	86	58	-33
		50-percentile		
16724000	Kawainui	38	35	-8
16729000	Alakahi	21	11	-48
10	Waipi‘o	59	46	-22
11	Waipi‘o	63	50	-21
16732000	Waipi‘o	78	61	-22
22	Waipi‘o	80	63	-21
16731000	Ko‘iawe	15	11	-27
16732150	Waimā	44	41	-7
16732200	Wailoa	112	85	-24

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.



Base modified from U.S. Geological Survey National Hydrography Dataset, Transverse Mercator projection, zone 5, central meridian -153°, North American Datum 1983.



EXPLANATION

720000 ▲ **Gaging station and abbreviated number—** complete number is preceded by 16

22 ▼ **Seepage-run site and number**

6 ▼ **Seepage-run site and low-flow partial-record station and station number**

Reduction in streamflow

-30 Percent reduction at data site

Less than or equal to 10 percent

Greater than 10 and less than or equal to 20 percent

Greater than 20 and less than or equal to 30 percent

Greater than 30 and less than or equal to 100 percent

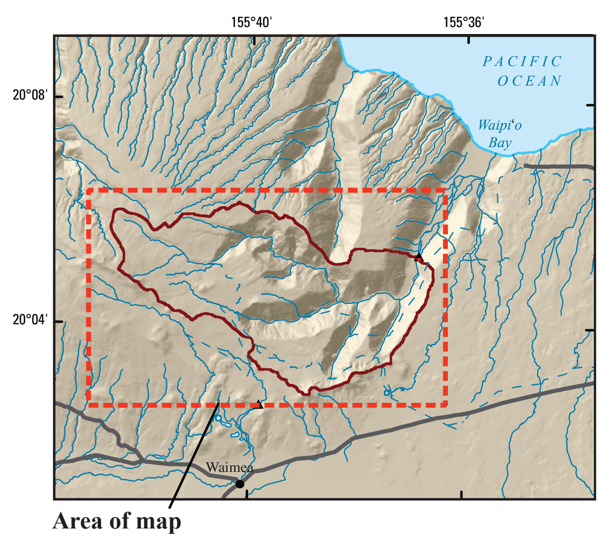


Figure 7. Percent reduction in natural 95-percentile discharge under proposed, future diversion practices, Waipi'o Valley study area, Island of Hawai'i, Hawai'i.

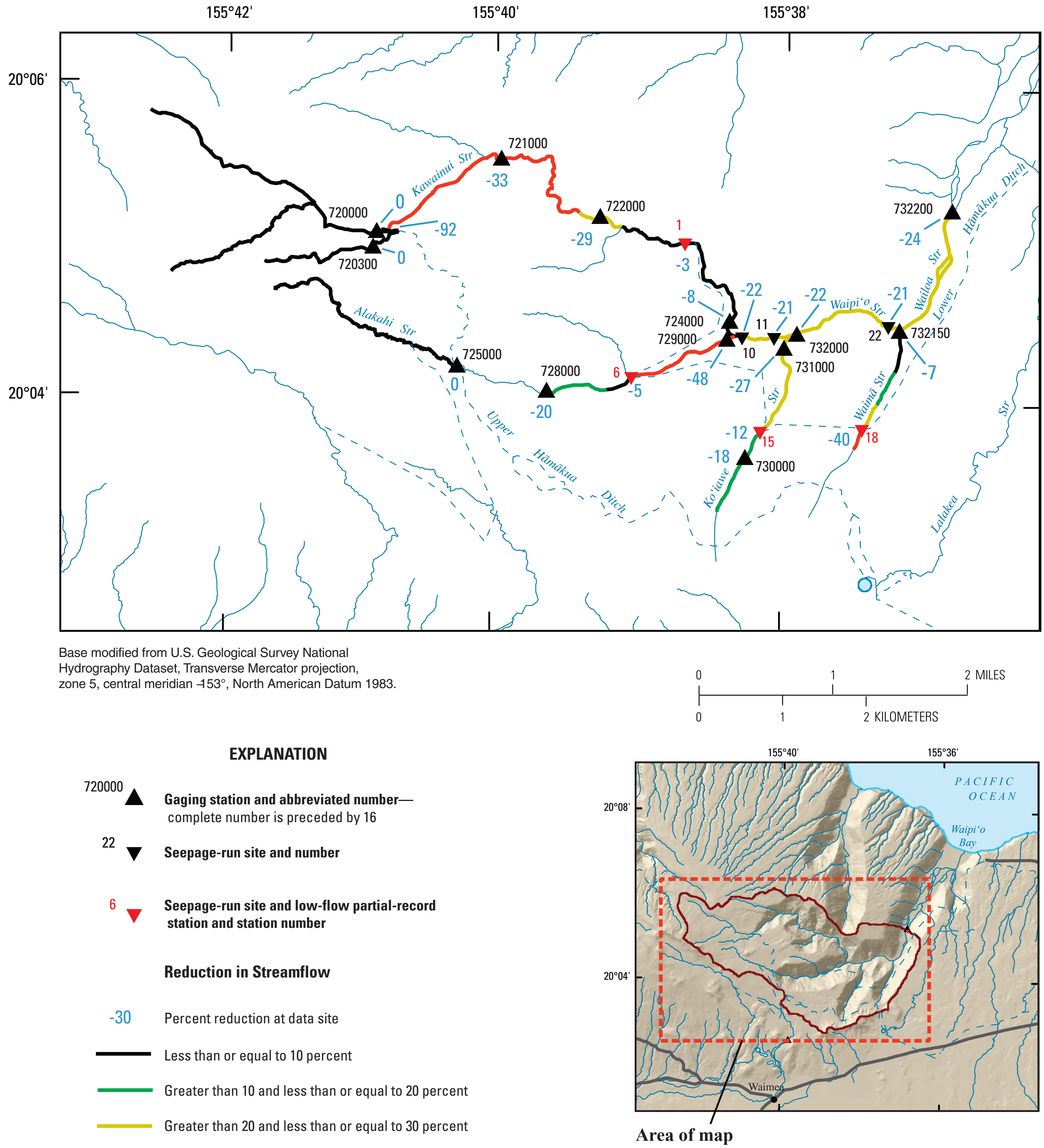


Figure 8. Percent reduction in natural 50-percentile discharge under proposed, future diversion practices, Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

Table 22. Relation between 95- and 50-percentile flow-duration discharges under natural, 2000–2005 diversion, and proposed, future diversion conditions at gaging stations and data-collection sites downstream from Lower Hāmākua Ditch in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; Q_{95}, 95-percentile discharge; Q_{50}, 50-percentile discharge]

Gaging-station or site number[a]	Stream	50-percentile discharge (ft^3/s)	95-percentile discharge (ft^3/s)	Ratio Q_{95}/Q_{50}
Natural conditions				
16724000	Kawainui	38	28	0.74
16729000	Alakahi	21	18	0.86
10	Waipiʻo	59	46	0.78
11	Waipiʻo	63	49	0.78
16732000	Waipiʻo	78	61	0.78
22	Waipiʻo	80	63	0.79
16731000	Koʻiawe	15	12	0.80
16732150	Waimā	44	26	0.59
16732200	Wailoa	112	86	0.77
Average				0.76
2000–2005 diversion conditions				
16724000	Kawainui	27	21	0.78
16729000	Alakahi	18	15	0.83
10	Waipiʻo	45	36	0.80
11	Waipiʻo	50	40	0.80
16732000	Waipiʻo	62	50	0.81
22	Waipiʻo	65	52	0.80
16731000	Koʻiawe	12	10	0.83
16732150	Waimā	41	24	0.59
16732200	Wailoa	85	68	0.80
Average				0.78
Proposed future diversion conditions				
16724000	Kawainui	35	16	0.46
16729000	Alakahi	11	11	1.0
10	Waipiʻo	46	27	0.59
11	Waipiʻo	50	30	0.60
16732000	Waipiʻo	61	39	0.64
22	Waipiʻo	63	41	0.65
16731000	Koʻiawe	11	8.5	0.77
16732150	Waimā	41	24	0.59
16732200	Wailoa	85	58	0.68
Average				0.66

[a] Site numbers correspond to those listed in table 2 and shown in figure 4.

16732200 on Wailoa Stream at an altitude of 190 feet (fig. 3), which is a short distance upstream from the site of the most upstream active (2005) taro diversion. In addition, a wide variety of current and historical data is available for the Wailoa gaging station (table 1); daily discharge records were collected at the site in 1901–1902, a discharge measurement was made there in 1911, continuous records of daily discharge were collected in 1964–1969, and discharge measurements were made between 2000 and 2005 as part of this study (table 3).

Analyses summarized in earlier sections of this report document the computation of flow-duration discharges at the location of the Wailoa Stream gaging station that are representative of natural conditions, 1965–1969 diversion conditions, 2000–2005 diversion conditions, and proposed, future diversion conditions. These data are summarized and compared in table 23. In all cases, computed values reflect what the discharges would have been had the indicated conditions been in effect over the entire 40-year (1965–2004) base period. Conversion to a common base period is required to allow direct comparison of various flow-duration discharges.

Diversion practices at the Upper and Lower Hāmākua Ditch systems have significant effects on the low-flow hydrology of Wailoa Stream at the downstream limit of the study area. In all cases, diversion practices reduced the magnitudes of low-flow discharges in Wailoa Stream. Under 1965–1969 diversion conditions, natural flow-duration discharges were reduced between 41 ft^3/s (at the 99-percentile discharge) and 59 ft^3/s (at the 50-percentile discharge). The percentage reduction in natural flow-duration discharges was reasonably constant and varied between 51 and 54 percent. Under 2000–2005 diversion conditions, natural flow-duration discharges were reduced between 15 ft^3/s (99-percentile) and 27 ft^3/s (50-percentile). The percent reduction in natural flow-duration discharges was reasonably constant and varied between 19 and 24 percent. Under proposed future diversion conditions, natural flow-duration discharges were reduced by 28 ft^3/s (95 percentile) and 27 ft^3/s (50 percentile). The percent reduction in natural flow-duration discharges were 33 and 24 percent, respectively.

The effects of the diversions have become less significant over the years as conditions in Upper and Lower Hāmākua Ditches have deteriorated and the magnitudes of diversion have been reduced. Proposed future diversion practices, relative to current (2000–2005) diversion practices, will result in increased diversion during periods of drought (represented by 95-percentile discharges) and virtually no change in diversion during normal conditions (represented by 50-percentile discharges). There is a close correspondence between total reduction in natural 50-percentile flow-duration discharges of Wailoa Stream at the downstream limit of the study area (at gaging station 16732200), and the combined average discharge of Upper Hāmākua Ditch (as measured at gaging station 16726000 above Waimea Reservoir) and Lower Hāmākua Ditch (as measured at gaging station 16732800 upstream from the main weir). For example, during the 2000–2005 study period, the combined average ditch discharge at stations 16726000 and 16732800 was about 24 ft^3/s (see footnote on table 11) and the reduction in natural 50-percentile discharge was 27 ft^3/s (table 23). Similar correspondence was noted for 1965–1969 diversion conditions, when the average combined ditch discharge upstream from Waimea Reservoir and the main weir was about 57 ft^3/s (see footnote on table 9) and the reduction in natural 50-percentile discharge was 59 ft^3/s (table 23). When they were first built, the average diversion capacities of Upper and Lower Hāmākua Ditches were 23 and 62 ft^3/s, respectively (Wilcox, 1966). At these maximum historical diversion rates, the combined average ditch discharge of 85 ft^3/s would have reduced the natural 50-percentile discharge of 112 ft^3/s at the downstream limit of the study area by about 76 percent.

Summary and Conclusions

Waipi‘o Valley is an area of great cultural and historical significance to the Hawaiian people. Streams in the valley have been identified by the Hawai‘i Commission on Water Resource Management as candidates for protection because of their importance to the cultivation of taro, a culturally significant agricultural product in Hawai’i. Approximately 100 acres of taro, which requires large quantities of water, are still cultivated in Waipi‘o Valley.

The availability of abundant, high-level water in Waipi‘o Valley has long been valued by Waipi‘o Valley residents as well as by agricultural interests in adjacent areas. As a result, two major water diversion systems, Upper and Lower Hāmākua Ditches, were constructed in the valley in the early 1900’s. Over the past 100 years, natural streamflow in Waipi‘o Valley has been reduced by operation of the two diversion systems, which transfer water out of the valley to other locations on the Island of Hawai‘i. The physical condition and diversion practices of Upper and Lower Hāmākua Ditches have varied widely over the years, and as a result, so have their effects on natural streamflow in Waipi‘o Valley. Recent change in ownership of Lower Hāmākua Ditch, subsequent renovation and improvements to the system, and proposals for its future operation and water diversion strategies provided the impetus for this study. Proposed diversions of water out of Waipi‘o Valley would be 7 Mgal/d (10.8 ft^3/s) under normal flow conditions and would increase to 13 Mgal/d (20.1 ft^3/s) during drought conditions. The availability of streamflow in Waipi‘o Valley to support the proposed new diversion strategies, and the effects of such diversions on streamflow, were the primary focal points for this report.

The availability of water for a variety of conflicting uses (for example, out-of-valley diversions, downstream taro cultivation, and support of instream biota) is of particular concern during dry periods, when streamflows are low. As a result, the primary focus of this report is the low-flow hydrology of Waipi‘o Valley. An important consideration in such an analysis

Table 23. Relation between selected flow-duration discharges under natural conditions and diversion conditions during 1965–1969, 2000–2005, and proposed for the future, extended to a common base period of 1965–2004, at the downstream limit of the Waipiʻo Valley study area at Wailoa Stream station 16732200, Island of Hawaiʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; ---, not computed]

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)	Difference from natural condition discharge (ft^3/s)	Difference from natural condition in percent
Natural conditions[a]			
99	80	---	---
95	86	---	---
90	88	---	---
80	95	---	---
70	100	---	---
60	105	---	---
50	112	---	---
1965–1969 diversion conditions[b]			
99	39	-41	-51
95	41	-45	-52
90	43	-45	-51
80	44	-51	-54
70	47	-53	-53
60	49	-56	-53
50	53	-59	-53
2000–2005 diversion conditions[c]			
99	65	-15	-19
95	68	-18	-21
90	70	-18	-20
80	73	-22	-23
70	76	-24	-24
60	80	-25	-24
50	85	-27	-24
Proposed future diversion conditions[d]			
99	---	---	---
95	58	-28	-33
90	---	---	---
80	---	---	---
70	---	---	---
60	---	---	---
50	85	-27	-24

[a] Discharge data from table 13.

[b] Discharge data from table 9.

[c] Discharge data from table 11.

[d] Discharge data from table 19.

is the fact that streamflow and the effects of various diversion practices are extremely variable over time and at various locations along streams in Waipiʻo Valley.

Low-flow hydrology was described in this report in terms of flow-duration statistics, which provide useful summaries of streamflow data. For example, at a location where a long-term surface-water gaging station has been operated, average streamflow data are available for each day that the station has been in operation. To compute flow-duration statistics, these data are ranked in descending order, with the largest daily streamflow value first and the smallest value last. Once this is done, one can readily determine which value of daily streamflow was equaled or exceeded 50 percent of the time; note that streamflow will also be less than this value 50 percent of the time. This single flow-duration statistic, which is referred to as the 50-percentile discharge, or the median discharge, is considered an indicator of normal flow conditions in a stream. This same process can be repeated for a variety of low streamflow values. For example, the 95-percentile discharge is the value of daily streamflow that is equaled or exceeded 95 percent of the time; streamflow will also be less than this value 5 percent of the time. The 95-percentile discharge is an indicator of moderate drought conditions in a stream.

Flow-duration statistics were computed directly from available data for three locations in the Waipiʻo Valley study area where long-term surface-water gaging stations have been operated. At an additional 13 locations where only limited historical data are available or where discharge measurements were made as part of this study, a variety of record-extension techniques were used to estimate flow-duration statistics. Flow-duration statistics were computed to reflect natural conditions, current (2000–2005) and historical (1965–1969) diversion conditions, and proposed future diversion conditions.

Results contained in this report can best be summarized by examining data collected at the gaging station on Wailoa Stream at 190 feet elevation. This station is at the downstream limit of the study area and a short distance upstream from the most upstream active (as of 2005) diversion for taro irrigation in Waipiʻo Valley. In addition, the Wailoa Stream station is downstream from all Upper and Lower Hāmākua Ditch diversion intakes and thus will reflect the full effects of diversions to the ditches.

Flow-duration statistics that are representative of natural, no-diversion conditions provide a base line for evaluating the availability of streamflow. At the Wailoa Stream gaging station, natural 95- and 50-percentile discharges were determined to be 86 and 112 ft^3/s, respectively. Under 1965–1969 diversion conditions, natural 95- and 50-percentile discharges were reduced by 52 and 53 percent, to 41 and 53 ft^3/s. Under current (2000–2005) diversion conditions, natural 95- and 50-percentile discharges were reduced by 21 and 24 percent to 68 and 85 ft^3/s. Under proposed future diversion conditions, natural 95- and 50-percentile discharges at the station would be reduced by 33 and 24 percent, to 58 and 85 ft^3/s. Compared to discharges that result from current (2000–2005) diversion practices, proposed future diversion conditions would reduce 95-percentile discharges, which are representative of moderate drought levels in the stream, by 15 percent. No change, however, would be expected in 50-percentile discharges, which are representative of normal conditions.

The effects of current (2000–2005) diversion practices on natural 95- and 50-percentile discharges differ along the several streams in Waipiʻo Vallely. Reductions in natural 95-percentile discharges of greater than 30 percent were found in Kawainui Stream in the reach downstream from Upper Hāmākua Ditch to an altitude of about 2,120 feet. Reductions in natural 95-percentile discharges along other streams in their reaches downstream from Upper Hāmākua Ditch were mostly between 10 and 30 percent. Reductions in natural 50-percentile discharges of greater than 30 percent were found in Kawainui Stream in the reach downstream from Upper Hāmākua Ditch to an altitude of about 1,435 feet and in the reach of Waimā Stream between Upper and Lower Hāmākua Ditches. Reductions in natural 50-percentile discharges along other streams in their reaches downstream from Upper Hāmākua Ditch were mostly between 10 and 30 percent.

The potential effects of proposed future diversion practices on natural 95- and 50-percentile discharges of streams in Waipiʻo Valley also differ slightly from the effects of current practices. Reductions in natural 95-percentile discharges of greater than 30 percent were found in Kawainui Stream downstream from Upper Hāmākua Ditch to an altitude of about 2,120 feet, and along most stream reaches downstream from Lower Hāmākua Ditch, except for Waimā Stream. Reductions in natural 50-percentile discharges of greater than 30 percent were found in Kawainui Stream downstream from Upper Hāmākua Ditch to an altitude of about 1,.435 feet, along Alakahi Stream downstream from Lower Hāmākua Ditch, and in the reach of Waimā Stream between Upper and Lower Hāmākua Ditches. Reductions in natural 50-percentile discharges over the remainder of the stream reaches downstream from Lower Hāmākua Ditch were extremely variable, from 0 to 10 percent along Kawainui Stream and the lower reaches of Waimā Stream and from 20 to 30 percent along Waipiʻo and Wailoa Streams.

References Cited

Chinn, S.S., Tateishi, G.A., and Yee, J.J.S., 1984, Water resources data Hawaii and other Pacific Areas water year 1983, Volume 1, Hawaii: U.S. Geological Survey Water-Data Report HI–83–1, 243 p.

Davis, D.A., and Yamanaga, George, 1963, Preliminary report on the water resources of Kohala Mountain and Mauna Kea Hawaii: Hawaii Department of Land and Natural Resources Division of Water and Land Development Circular C14, 44 p.

Department of Urban and Regional Planning, 1999, Waipi‘o Valley; towards community planning and ahupua‘a management: Honolulu, University of Hawai‘i at Mānoa, 93 p., 5 app.

Fontaine, R.A., 1996, Evaluation of the surface-water quantity, surface-water quality, and rainfall data-collection programs in Hawaii, 1994: U.S. Geological Survey Water-Resources Investigations Report 95–4212, 125 p.

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, Iwao, 1992, Estimates of median streamflows at perennial stream sites in Hawaii: U.S. Geological Survey Water-Resources Investigations Report 92–4009, 37 p.

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

Giambelluca, T.W., Nullet, M.A., Ridgley, M.A., Eyre, P.R., Moncur, J.E.T., and Price, Saul, 1991, Drought in Hawai‘i: Hawaii Department of Land and Natural Resources Commission on Water Resource Management Report R88, 232 p.

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

Hawai‘i Commission on Water Resource Management, 1990, Hawaii stream assessment; a preliminary appraisal of Hawaii’s stream resources: Hawaii Department of Land and Natural Resources Report R–84, 294 p.

Hawaii Division of Water and Land Development, 1963, A brief description of the Upper Hamakua Ditch, Waimea, Island of Hawaii: Hawaii Department of Land and Natural Resources Circular C18, 13 p.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations Book 4 Chapter A3, 510 p.

Herschler and Randolph Consulting Engineers, 1961, The value of high level water—Waipio Valley, Island of Hawaii: Report to the Trustees, Bernice P. Bishop Museum, Honolulu, Hawaii, 146 p., 3 app.

Hirsch, R.M., 1982, A comparison of four streamflow record extension techniques: Water Resources Research, v. 18, no. 4, p. 1081–1088.

Langbein, W.B., 1960, Plotting positions in frequency analysis, *in* Dalrymple, T., Flood-frequency analysis: U.S. Geological Survey Water-Supply Paper 1543–A, p. 48–51.

Langenheim, V.A.M., and Clague, D.A., 1987, The Hawaiian-Emperor volcanic chain; 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.

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

Martin, W.F., and Pierce, C.H., 1913, Water resources of Hawaii 1909-1911: U.S. Geological Survey Water-Supply Paper 318, 552 p., 4 pl.

Mink, J.F., 1984, Water resources and development for Hamakua Sugar Company: Honolulu, Hawai‘i, 46 p., 5 app.

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

Penn, D.C., 1997, Water and energy flows in Hawaii taro pondfields: Honolulu, University of Hawaii, Ph.D. dissertation, 376 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.

Ries, K.G., III, and Friesz, P.J., 2000, Methods for estimating low-flow statistics for Massachusetts streams: U.S. Geological Survey Water-Resources Investigations Report 00–4135, 81 p.

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

Stearns, H.T., and Macdonald, G.A., 1946, Geology and ground-water resources of the Island of Hawaii: Hawaii Division of Hydrography Bulletin 9, 363 p., 3 pl.

Tasker, G.D., 1975, Combining estimates of low-flow characteristics of streams in Massachusetts and Rhode Island: Journal of Research of the U.S. Geological Survey, v. 3, no. 1, p. 107–112.

U.S. Department of Agriculture, 1999, Watershed plan and final environmental impact statement, Lower Hamakua Ditch watershed, Hawaii County, Hawaii: U.S. Department of Agriculture, Natural Resources Conservation Service (Lead Agency), 218 p., 5 app.

U.S. Geological Survey, 1963, Surface water records of Hawaii and other Pacific areas 1963: U.S. Geological Survey Water-Data Report HI–63, 189 p.

U.S. Geological Survey, 1967, Water resources data for Hawaii and other Pacific areas 1966: U.S. Geological Survey Water-Data Report HI–66, 261 p.

Vogel, R.M., and Fennessey, N.M., 1995, Flow duration curves II, A review of applications in water resources planning: Water Resources Bulletin, v. 31, p. 1029–1039.

Wilcox, Carol, 1996, Sugar water, Hawaii’s plantation ditches: Honolulu, University of Hawai‘i Press, 191 p.

Appendixes 1–3

Appendix 1. Computation of Low-Flow Statistics for Sites with Historical Data

Gaging Stations Operated between August 1901 and January 1902

Daily streamflow data were collected by Arthur Tuttle, for Bishop Estate, at 13 stations in Waipiʻo Valley during the period August 1901 to January 1902 (table 1-A). These data were published in a USGS report (Martin and Pierce, 1913, p. 397). The length of the records collected at these stations is variable, ranging from a minimum of 51 days to a maximum of 146 days. Because of the limited length of the records, the data cannot be used to compute directly the low-flow duration statistics representative of the base period (1965–2004) used in the current study. In spite of these limitations, however, the data are particularly significant; they were collected during a period of natural flow, before construction of Upper and Lower Hāmākua Ditch systems, which also is considered to have been unusually dry (Mink, 1984, p. 8).

A modified version of record-extension techniques, which were described in the main body of this report, was applied to the 1901–1902 data to estimate base period, low-flow statistics. In the "standard" application of record-extension techniques, a relation is established between concurrent flows at a station with limited or short-term data and flows at a station with complete data over the selected base period; the latter is typically designated an index station. In such a situation, low-flow statistics for the base period at the index station can be computed directly. These computed low-flow statistics can then be applied to the established relation, based on concurrent data at the short-term and index stations, to estimate base period low-flow statistics at the short-term stations.

Unfortunately, none of the 13 stations operated in 1901–1902 have data concurrent with data for any of the index stations that were used in this study (fig. 1-A and table 1-B). One of the 13 stations operated by Tuttle, Wailoa Stream at 190 feet, later became USGS gaging station 16732200, where data were subsequently collected for short periods—in 1911 and from 1964 to 1969—and discharge measurements were made between 2000 and 2005. The later of these subsequent periods of data collection were concurrent with data collected at the index stations used in the current study. Thus estimates of low-flow statistics for the base period used in the current study (1965–2004) could be computed for regulated and natural flow conditions at the Wailoa Stream station (site 24 on tables 1-C and 1-D). The results of these computations provided a basis for applying modified record-extension techniques to the 1901–1902 data because Wailoa Stream station 16732200 now has what is considered concurrent data with the 12 remaining stations operated by Tuttle, and it has low-flow statistics for the base period. A limitation of this analysis is that the computations of low-flow statistics for the base period at the gaging station on Wailoa Stream, which was then considered a "substitute" index station, are not based on a complete record of flow but are in fact estimates themselves. As a result, errors associated with the modified record-extension techniques will be unknown, and the resulting low-flow statistics must be treated as estimates with unknown levels of accuracy.

Regulated Low-Flow Statistics

During the period August 1901 to January 1902, Tuttle collected 146 days of streamflow data at the site on Wailoa Stream that became gaging station 16732200. Regulated low-flow statistics reflective of 1965–2004 base period and of diversion practices in place during the study period (2000–2005) have been computed for this station and are summarized in table 1-C (site 24). Data also were collected at an additional 12 stations during the period late 1901 to early 1902. Computations were not made for three of these stations because they were on small, upstream branches of Kawainui Stream, at altitudes ranging from 1,380 to 1,700 feet. The data for each of the other nine stations were screened, and only

Table 1–A. Surface-water gaging stations operated in the Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi, August 1901-January 1902.

Station number	Location	Days of record
16721000	Kawainui Stream at 2,120 feet	51
16721500	Kawainui Stream Branch 3 at 1,700 feet	94
16722000	Kawainui Stream at 1,435 feet	77
16722300	Kawainui Stream Branch 2 at 1,405 feet	106
16722600	Kawainui Stream Branch 1 at 1,380 feet	106
16728000	Alakahi Stream at 1,200 feet	71
16730000	Koʻiawe Stream at 1,120 feet	68
16724000	Kawainui Stream at 775 feet	115
16729000	Alakahi Stream at 730 feet	126
16731000	Koʻiawe Stream at 610 feet	132
16732100	Waimā Stream at 790 feet	132
16732150	Waimā Stream at 385 feet	127
16732200	Wailoa Stream at 190 feet	146[a]

[a] Data also collected at this station in 1911 and from 1964 to 1969 and discharge measurements were made between 2000 and 2005; designated a "substitute" index station in analysis of data for other stations listed above.

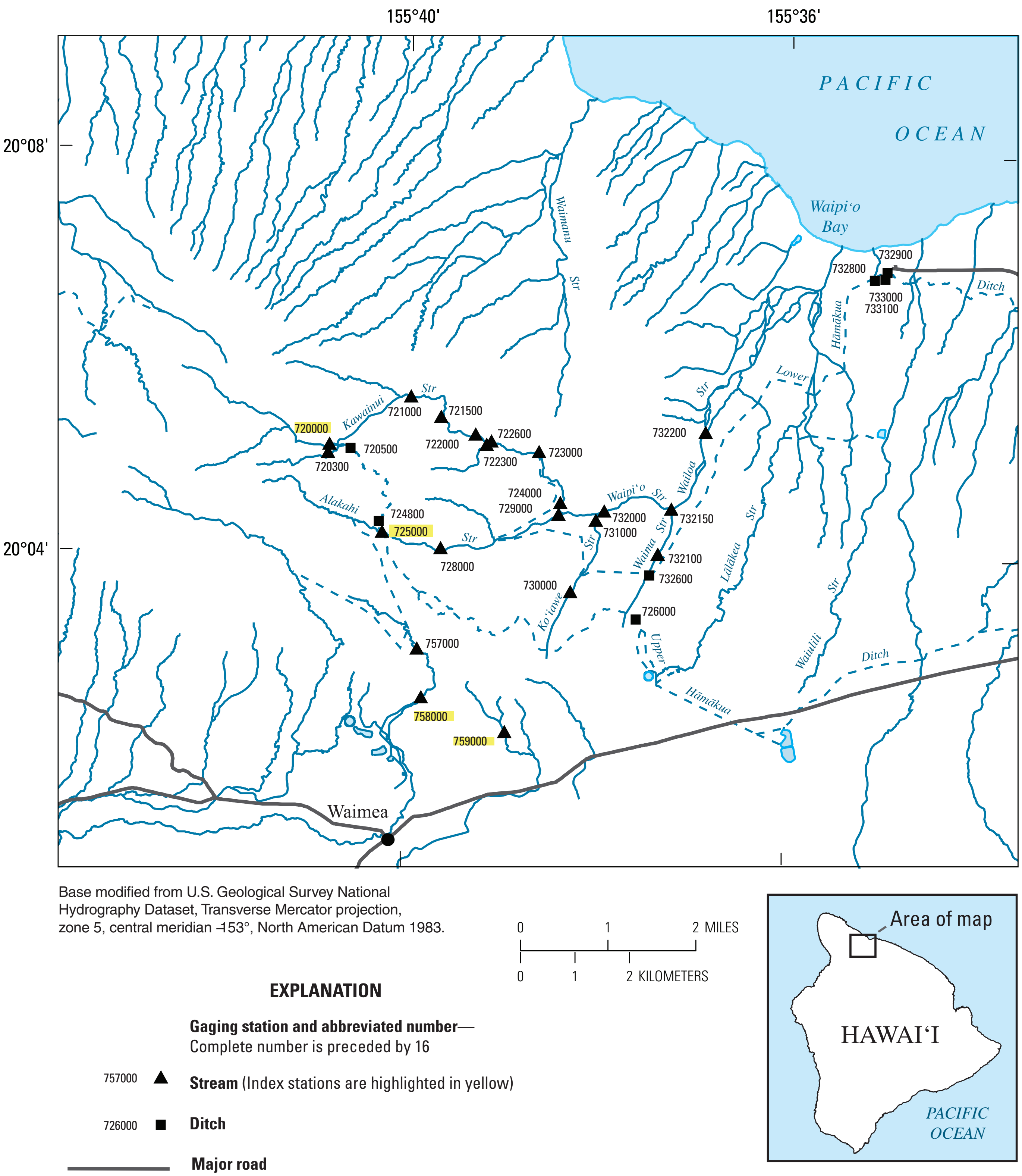


Figure 1–A. Location of stream and ditch surface-water gaging stations operated in and adjacent to the Waipi'o Valley study area, Island of Hawai'i, Hawai'i.

Table 1–B. Selected natural flow-duration discharges for the 1965–2004 base period at index gaging-stations operated in the Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

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

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)			
	Kawainui Stream 16720000[a]	Alakahi Stream 16725000[a]	Waikoloa Stream 16758000[a]	Hauani Gulch 16759000[a]
99	0.10	0.15	0.99	0.00
98	0.15	0.23	1.2	0.03
97	0.19	0.29	1.3	0.04
95	0.29	0.38	1.5	0.06
90	0.51	0.59	1.7	0.11
85	0.74	0.8	2.0	0.15
80	1.0	1.0	2.3	0.20
75	1.3	1.2	2.5	0.25
70	1.7	1.5	2.8	0.29
65	2.1	1.8	3.0	0.34
60	2.7	2.2	3.4	0.40
55	3.5	2.6	3.8	0.47
50	4.5	3.1	4.3	0.55
40	7.4	4.5	5.8	0.77

[a] Station numbers correspond to those shown on figure 1-A.

Table 1–C. Estimated regulated flow-duration discharges for the 1965–2004 base period that reflect diversion practices during the study period (2000–2005) at low-flow partial-record stations in Waipi‘o Valley, Island of Hawai‘i, Hawai‘i.

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

Percentage of time indicated discharge equaled or exceeded	Discharge[a] (ft^3/s)				
	Kawainui Stream Site 1[b]	Alakahi Stream Site 6[b]	Ko‘iawe Stream Site 15[b]	Waimā Stream Site 18[b]	Wailoa Stream Site 24[b]
99	15	12	6.6	0.52	65
95	16	12	6.8	0.54	68
90	18	13	6.9	0.56	70
80	20	14	7.3	0.60	73
70	24	15	7.6	0.63	76
60	28	16	7.9	0.67	80
50	33	18	8.4	0.72	85
Average standard error (percent)	5.1	3.0	2.2	7.8	2.6

[a] All estimated flow-duration discharges reflect diversion conditions at Upper and Lower Hāmākua Ditches in effect during the study period 2000–2005. During the period March to November 2003 average diversion from Waipi‘o Valley by Upper Hāmākua Ditch, as measured at surface-water gaging station 16726000 at 3,020 feet, was 6.75 ft^3/s and by Lower Hāmākua Ditch, as measured at surface-water gaging station 16732800 upstream from the main weir, was 16.7 ft^3/s. March to November 2003 is the longest period of consecutive months during 2000–2005 when both gaging stations 16726000 and 16732800 and both ditches were operational.

[b] Site numbers correspond to those shown on figures 1-B and 1-C.

Table 1–D. Estimated natural flow-duration discharges for the1965–2004 base period at low-flow partial-record stations in Waipi‘o Valley, Island of Hawai‘i, Hawai‘i.

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

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)				
	Kawainui Stream Site 1[a]	Alakahi Stream Site 6[a]	Ko‘iawe Stream Site 15[a]	Waimā Stream Site 18[a]	Wailoa Stream Site 24[a]
99	15	13	6.9	0.64	80
95	18	13	7.3	0.73	86
90	19	14	7.5	0.77	88
80	23	14	7.9	0.89	95
70	26	16	8.3	0.98	100
60	29	17	8.8	1.1	105
50	34	20	9.5	1.2	112
Average standard error (percent)	5.4	2.8	2.5	4.5	1.9

[a] Site numbers correspond to those shown on figures 1-B and 1-C.

the data for days when low-flow conditions existed and days for which concurrent data were available at the Wailoa index station (16732200) were selected for analysis. The results of the analyses of the data for the nine stations that met the above criteria are shown in table 1–E.

Linear correlations were found to exist between the substitute index station on Wailoa Stream (16732200) and seven of the nine remaining 1901–1902 stations. On the basis of these correlations, MOVE.1 techniques were applied to the untransformed data to compute flow-duration discharges at these 7 stations. The MOVE.1 computations were based on computed mean, standard deviation, and correlation coefficient data summarized in table 1-E and previously computed, regulated flow-duration statistics for the substitute index station (table 1-C). Estimates of regulated flow-duration discharges for the seven stations, reflective of the 1965–2004 base period and diversion practices in place during the study period (2000–2005), are summarized in table 1-F. As noted above, the accuracy of these results is unknown because they are based on estimated flow-duration statistics for the substitute index station.

Table 1–F includes estimated flow-duration discharges for stations on Alakahi Stream (16729000) and Ko‘iawe Stream (16730000 and 16731000), for which correlation coefficients are less than the recommended minimum of 0.80. At two of the stations (16729000 and 16731000), the correlation coefficients, 0.777 and 0.791 respectively, were close enough to the recommended minimum that results were deemed acceptable. At one of the stations, Ko‘iawe Stream (16730000), the correlation coefficient of 0.737 was well below the recommended minimum, but results for this station were included in table 1–F because they were consistent with those computed for low-flow partial-record site 15 (table 1-C), which is only a short distance downstream.

The application of MOVE.1 methods to compute flow-duration statistics shown in table 1–F was based on correlations established between flow at the substitute index station on Wailoa Stream and at seven of the nine remaining 1901–1902 stations. In this case, correlations are based on discharge data for a period of natural (unregulated) streamflow. It was assumed in this analysis that correlations established on the basis of natural discharge could also be used to estimate flow-duration discharges representative of regulated conditions. This is considered a reasonable assumption in that all seven 1901–1902 stations for which estimates were made, as well as the substitute index station, are downstream from the same diversion ditches and should be affected in a similar manner. To evaluate this assumption, estimates of regulated flow-duration statistics for the 1901–1902 stations, extrapolated to the 1965–2004 base period (table 1-F), are shown in figure 1–B along with comparable estimates made for selected additional stations in the Waipi‘o Valley study area. The data shown in figure 1–B indicate a smooth pattern of increasing magnitudes of flow-duration values when moving downstream along Waipi‘o Valley tributaries and streams. Estimates made for 1901–1902 stations fit seamlessly into this pattern, and the results are therefore considered to be reasonable.

No correlation coefficients greater than 0.80 were found between flow at the 1901–1902 stations on Waimā Stream (16732100 and 16732150) and flow at the substitute index station on Wailoa Stream (16732200). As a result, MOVE.1 estimates of flow-duration discharges were not made for these two stations. Over the 101 days with low-flow discharges, the mean value was 8.70 ft^3/s and the standard deviation was 0.75

Table 1–E. Computed statistics for concurrent daily discharges during periods of low-flow at gaging stations operated between August 1901 and January 1902 in Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi.

[n.a., not applicable]

Gaging station[a]	Index station[a]	Number of concurrent daily discharges	Mean[b]	Standard deviation[b]	Correlation coefficient
16721000 Kawainui Stream		49	9.20	4.58	n.a.
	16732200 Wailoa Stream		65.8	17.7	0.881
16722000 Kawainui Stream		67	14.5	5.97	n.a.
	16732200 Wailoa Stream		75.1	23.9	0.916
16724000 Kawainui Stream		98	24.9	10.1	n.a.
	16732200 Wailoa Stream		78.3	26.6	0.936
16728000 Alakahi Stream		67	11.2	2.45	n.a.
	16732200 Wailoa Stream		75.8	24.8	0.884
16729000 Alakahi Stream		105	16.6	2.90	n.a.
	16732200 Wailoa Stream		76.4	22.3	0.777
16730000 Koʻiawe Stream		61	6.76	1.18	n.a.
	16732200 Wailoa Stream		73.1	20.2	0.737
16731000 Koʻiawe Stream		116	11.7	2.53	n.a.
	16732200 Wailoa Stream		80.4	26.6	0.791
16732100 Waimā Stream		101	8.70	0.75	n.a.
	16732200 Wailoa Stream		77.4	24.9	0.137
16732150 Waimā Stream		118	18.8	1.14	n.a.
	16732200 Wailoa Stream		79.0	24.4	0.25

[a] Station numbers correspond to surface-water gaging stations listed in table 1-A and shown in figure 1-A.

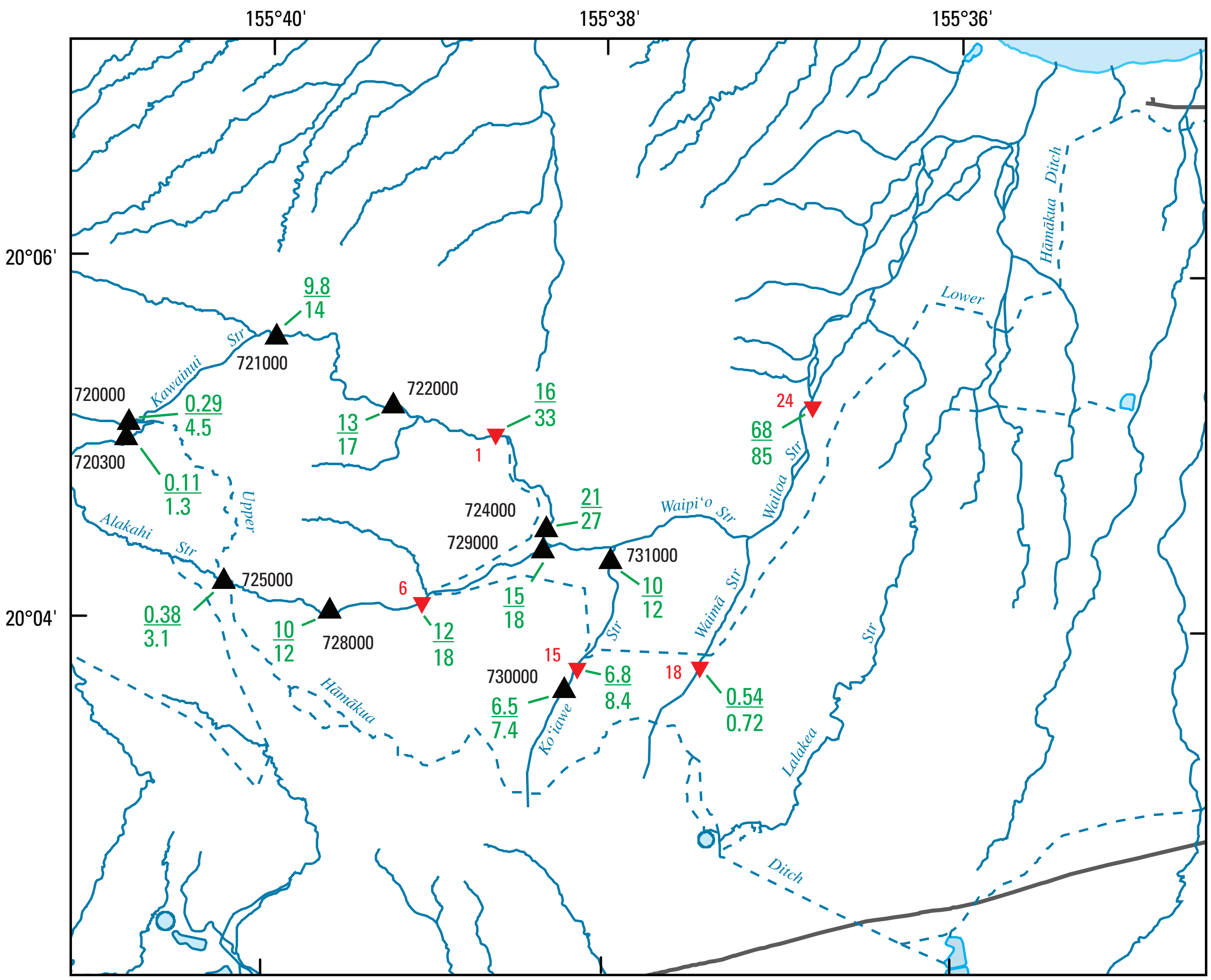
[b] Statistics are based on untransformed values in cubic feet per second.

Table 1–F. Estimated regulated flow-duration discharges for the 1965–2004 base period that reflect diversion practices during the study period (2000–2005) at gaging stations operated between August 1901 and January 1902 in Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi.

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

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)						
	Kawainui Stream 16721000[a]	Kawainui Stream 16722000[a]	Kawainui Stream 16724000[a]	Alakahi Stream 16728000[a]	Alakahi Stream 16729000[a]	Koʻiawe Stream 16730000[a]	Koʻiawe Stream 16731000[a]
99	9.0	12	20	10	15	6.3	10
95	9.8	13	21	10	15	6.5	10
90	10	13	22	11	16	6.6	11
80	11	14	23	11	16	6.8	11
70	12	15	24	11	17	6.9	11
60	13	16	26	12	17	7.2	12
50	14	17	27	12	18	7.4	12

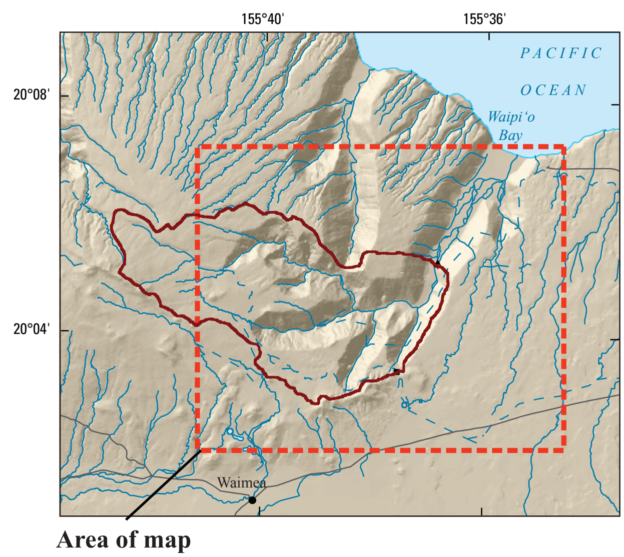
[a] Station numbers correspond to surface-water gaging stations listed in table 1-A and shown in figure 1-A.



Base modified from U.S. Geological Survey National Hydrography Dataset, Transverse Mercator projection, zone 5, central meridian -153°, North American Datum 1983.

0 1 2 MILES

0 1 2 KILOMETERS



EXPLANATION

720000 ▲ **Gaging station and abbreviated number**—complete number is preceded by 16

6 ▼ **Low-flow partial-record station and site number**

13 / 21 **Discharge, in cubic feet per second, equaled or exceeded 95 percent of the time** / **Discharge, in cubic feet per second, equaled or exceeded 50 percent of the time**

Figure 1–B. Low flow-duration discharges reflective of current (2000–2005) regulated conditions extended over the 1965–2004 base period at data collection stations in the Waipi'o Valley study area, Island of Hawai'i, Hawai'i.

ft^3/s for Waimā Stream at 790 feet (station 16732100). Over the 118 days with low-flow discharge data for Waimā Stream at 790 feet (station 16732100), the mean flow was 18.8 ft^3/s and the standard deviation was 1.14 ft^3/s. Low flows at both of the Waimā Stream stations are high relative to the size of their respective drainage areas (0.51 and 0.77 mi^2).

Natural Low-Flow Statistics

Natural low-flow statistics reflective of 1965–2004 base period also have been computed for the substitute index station on Wailoa Stream (table 1–D, site 24). On the basis of the linear correlations between flow at the substitute index station and at seven of the 1901–1902 stations (described in the preceding section) and the computed natural low-flow statistics (table 1-D, site 24), MOVE.1 methods were used to estimate natural flow-duration discharges for these seven stations (table 1–G). And as noted above, the accuracy of these discharge values is unknown because they are based on estimated flow-duration statistics for the substitute index station.

To qualitatively evaluate the reasonableness of the estimated natural flow-duration statistics for the 1901–1902 stations (table 1-G), they are shown in figure 1–C along with comparable estimates for selected additional gaging stations in the Waipiʻo Valley study area. The consistent downstream increase in magnitude of the natural flow-duration values (figure 1–C), similar to the pattern for regulated flow (figure 1–B), indicates the reasonableness of the computed natural flow values.

As noted previously, the period when Tuttle collected data, between August 1901 and January 1902, was said to have been unusually dry (Mink, 1984, p. 8). This statement can now be evaluated in terms of the computed low-flow statistics. For example, at the gaging station on Wailoa Stream (16732200), Tuttle collected a total of 146 days of data (Martin and Pierce, 1913, p. 397). The average discharge over the entire 146-day period was determined to be 97.8 ft^3/s; this value corresponds to a natural flow-duration percentile of about 75 percent (table 1–D). Perhaps even more dramatic is the fact that average discharge over 131 days when low-flow conditions existed was determined to be 82.1 ft^3/s; this value corresponds to a natural flow-duration percentile between 95 and 99 percent (table 1–D).

Sites with Miscellaneous Discharge Measurements

In addition to the streamflow data collected by Tuttle in the early 1900s, miscellaneous discharge measurements have been made at several times and locations throughout the Waipiʻo Valley study area. These were often just single measurements made during periods when diversion practices of Upper and Lower Hāmākua Ditches and pumping of water from the lower reaches of Waimā Stream were substantially different from those during the study period (2000–2005). In most cases, actual diversions and their effects on streamflow when the measurements were being made are unknown. These data were not used to estimate flow-duration statistics at additional locations, but they can be used to provide valuable, independent verifications of results already computed.

Stearns and Macdonald (1946, p, 230) noted, during a period of dry weather in December 1944, that Kawainui, Alakahi, and Koʻiawe Streams gained at total of 6.2, 5.4, and 6.2 ft^3/s, respectively, between Lower Hāmākua Ditch intakes and their mouths. These values compare well with differences in computed natural flow-duration statistics between stations located at the ditch intakes (table 1–D) and estimated natural flow-duration statistics at stations located near the mouths of the respective streams (table 1–G), at flow percentiles ranging from 60 to 80 percent.

Numerous discharge measurements were made throughout Waipiʻo Valley study area during a severe drought in 1962–1963 (U.S. Geological Survey, 1963). During this period, several measurements were made at the sites of future index gaging stations on Kawainui Stream (16720000) and Alakahi Stream (16725000). The lowest discharge measured during 1962 was 0.146 ft^3/s at Kawainui Stream and 0.135 ft^3/s at Alakahi Stream, on November 16, 1962. These measured discharge values correspond to 98 to 99 percentile flow-duration discharges at the Kawainui and Alakahi index stations (table 1–B). The lowest discharge measured during 1963 was 0.48 ft^3/s at Kawainui Stream and 0.43 ft^3/s at Alakahi Stream, on December 10, 1963. These measured discharges correspond to 90 to 95 percentile flow-duration discharges at the Kawainui and Alakahi index stations. On December 12, 1962, a discharge measurement of 0.226 ft^3/s at the site of future index gaging station on Alakahi Stream indicated a flow-duration percentile of about 98 percent. On December 11, 1962, discharge measurements at the mouths of Alakahi and Koʻiawe Streams indicated gains in streamflow between Lower Hāmākua Ditch intakes (assuming all flow was diverted at the intakes) and their mouths of 3.22 ft^3/s and 4.58 ft^3/s, respectively. These values compare well with differences in computed 99-percentile, natural flow-duration statistics, between stations located at the ditch intakes (table 1–D) and near their mouths (table 1–G), of 4 ft^3/s for Alakahi Stream and 5.1 ft^3/s for Koʻiawe Stream.

As noted earlier, no estimates of flow-duration statistics were made for the gaging station near the mouth of Waimā Stream (16732150). Tuttle's 1901–1902 data indicated that the mean flow at this station, over 118 days with low-flow discharges, was 18.8 ft^3/s. Mink (1984, p. 10), however, noted that Tuttle experienced difficulty making measurements at this location and indicated that the measurements underestimated true discharge. On December 11, 1962, when the flow-duration percentile at Alakahi Stream (16725000) was about 98 percent (see paragraph above), a discharge of 21.9 ft^3/s was measured near the mouth of Waimā Stream (U.S. Geological Survey, 1963). On March 9, 1983, when daily mean discharges at the index gaging stations on Kawainui Stream (16720000) and Alakahi Stream (16725000) of 0.08 ft^3/s and

Table 1–G. Estimated natural flow-duration discharges for the 1965–2004 base period at gaging stations operated between August 1901 and January 1902 in Waipi‘o Valley, Island of Hawai‘i, Hawai‘i.

[ft³/s, cubic feet per second]

Percentage of time indicated discharge equaled or exceeded	Discharge (ft³/s)						
	Kawainui Stream 16721000[a]	Kawainui Stream 16722000[a]	Kawainui Stream 16724000[a]	Alakahi Stream 16728000[a]	Alakahi Stream 16729000[a]	Ko‘iawe Stream 16730000[a]	Ko‘iawe Stream 16731000[a]
99	13	16	26	12	17	7.2	12
95	14	17	28	12	18	7.5	12
90	15	18	29	12	18	7.6	12
80	17	19	31	13	19	8.0	13
70	18	21	33	14	20	8.3	14
60	19	22	35	14	20	8.6	14
50	21	24	38	15	21	9.0	15

[a] Station numbers correspond to surface-water gaging stations listed in table 1-A and shown in figure 1-A.

0.13 ft³/s indicated flow-duration percentiles of greater than 99 percent (table 1–B), a discharge of 14.6 ft³/s at the mouth of Waimā Stream was computed (Chinn and others, 1984) (difference between discharge measurements made upstream and downstream from the mouth of Waimā Stream on Waipi‘o and Wailoa Streams, respectively). Factoring in upstream pumping of about 5 million gallons per day (7.7 ft³/s) from Waimā Stream that was taking place at this time (Wilcox, 1996, p. 153), total discharge at the mouth of Waimā Stream would be about 22.3 ft³/s (14.6 plus 7.7). The above data, from extremely dry periods in 1962 and 1983, indicate that even when flow-duration percentiles are in the range of 98 to 99 percent, discharge at the mouth of Waimā Stream is about 22 ft³/s. This value is significantly greater than the mean value of 18.8 ft³/s based on Tuttle's 1901-02 data and is also consistent with the statement that the 1901–1902 data underestimated true discharge (Mink, 1984).

In addition to the above historical data, discharge at the mouth of Waimā Stream was measured twice during the current study period (2000–2005). On September 21, 2000, at the time when a seepage run was conducted (see discussion of seepage runs in appendix 2), a discharge of 35 ft³/s was measured. On August 23, 2005, a discharge of 33 ft³/s was computed (difference between discharge measurements made upstream and downstream from the mouth of Waimā Stream on Waipi‘o and Wailoa Streams, respectively). At the upstream index stations on Kawainui Stream (16720000) and Alakahi Stream, (16725000), concurrent daily mean discharges indicated flow-duration percentiles of about 60 to 65 percent and 65 to 70 percent, respectively (table 1–B).

The four discharge measurements made near the mouth of Waimā Stream (gaging station 16732150) are summarized in table 1–H. Only the measurement made on March 9, 1983, was significantly affected by upstream diversions (pumping from Waimā Stream up to Lower Hāmākua Ditch was taking place at this time). Within Waimā watershed, only small amounts of water are diverted by Upper Hāmākua Ditch, no water is diverted by Lower Hāmākua Ditch, and moderate amounts of groundwater are intercepted by the tunnels of Lower Hāmākua Ditch within Waimā watershed, upstream from its mouth. The discharge measurement of 35.0 ft³/s, made on September 21, 2000, was part of a seepage run in Waipi‘o Valley on that day (see appendix 2). On the basis of the seepage-run data and concurrent gaging-station data, it was determined that natural discharge at the mouth of Waimā Stream at that time would have been 37.5 ft³/s. In other words, natural discharge was 7.1 percent greater than regulated discharge. Although diversion activity within Waimā watershed was probably not exactly the same when each of the four discharge measurements were made, it is reasonable to assume that overall differences were relatively minor. Therefore, use of 7.1 percent as an average adjustment factor to convert the four measurements from regulated to natural discharges should not lead to significant errors.

In the main body of this report and to this point in appendix 1, record-extension techniques have successfully been applied to low-flow partial-record stations, where the only data available were discharge measurements. In all cases, linear relations (using either untransformed or log transformed data) between discharge measurements and concurrent daily mean discharges at index stations were found to exist, and MOVE.1 record-extension methods were used. It is recommended that a minimum of 10 discharge measurements be used when applying the MOVE.1 methods for record extension, but only 4 discharge measurements are available near the mouth of Waimā Stream at station 16732150. In the "Record-Extension Techniques" section in the main text of this report, an alternative, graphical method for record extension was described.

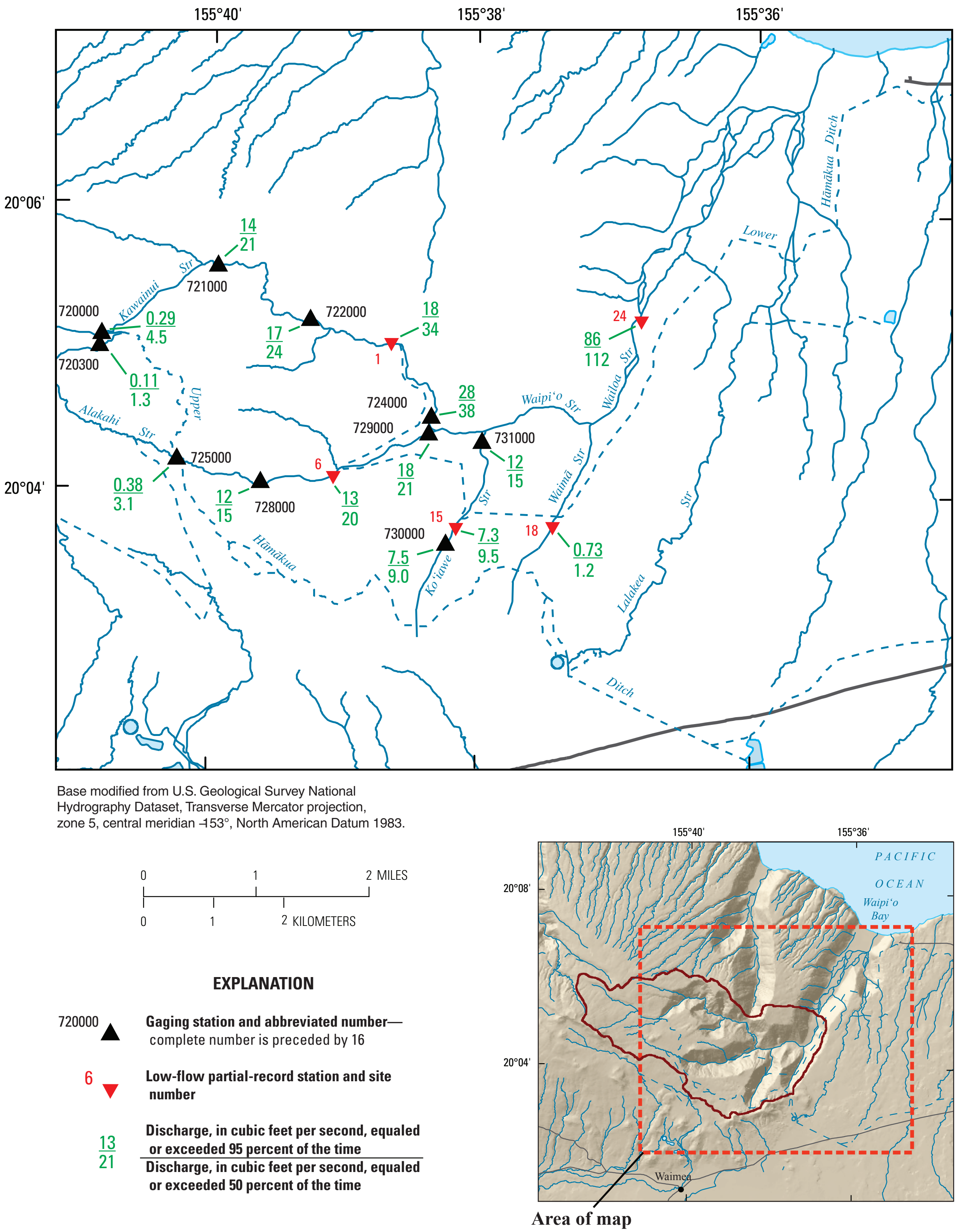


Figure 1–C. Low flow-duration discharges reflective of natural conditions extended over the 1965–2004 base period at data collection stations in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

Table 1–H. Regulated discharge measurements, concurrent daily mean discharges at long-term index stations, and estimated flow-duration discharges for the 1965–2004 base period at surface-water gaging station 16732150 on Waimā Stream, Waipi‘o Valley, Island of Hawai‘i, Hawai‘i.

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

Date	Measured discharge Waimā Stream 16732150 (ft^3/s)	Concurrent daily mean discharge (ft^3/s)			
		Kawainui Stream 16720000	Alakahi Stream 16725000	Wailoloa Stream 16758000	Hauani Gulch[a] 16759000
12/11/1962	21.9	0.23[c]	0.15[c]	0.74	1.00
3/9/1983	22.3[b]	0.08	0.13	1.1	1.03
9/21/2000	35.0	2.3	2.0	3.3	1.46
8/23/2005	33.0	1.8	1.5	3.9	1.67
Percentage of time indicated discharge equaled or exceeded	**Average regulated flow-duration discharge (ft^3/s)**	**Regulated flow-duration discharge at station 16732150 using indicated index station[d] (ft^3/s)**			
		Kawainui Stream 16720000	**Alakahi Stream 16725000**	**Waikoloa Stream 16758000**	**Hauani Gulch 16759000**
99	23	23	22	23	22
95	24	24	24	25	24
90	25	25	25	26	25
80	28	28	28	28	26
70	31	33	32	30	28
60	35	39	37	33	30
50	41	50	44	37	33
Percentage of time indicated discharge equaled or exceeded	**Average natural flow-duration discharge (ft^3/s)**	**Natural flow-duration discharge at station 16732150 using indicated index station[e] (ft^3/s)**			
		Kawainui Stream 16720000	**Alakahi Stream 16725000**	**Waikoloa Stream 16758000**	**Hauani Gulch 16759000**
99	24	24	24	24	24
95	26	26	26	27	25
90	27	27	27	28	26
80	30	30	30	30	28
70	33	35	34	32	30
60	37	42	40	35	32
50	44	54	47	39	35

[a] Concurrent daily mean discharges in Hauani Gulch were all increased by 1.0 ft^3/s.

[b] Increased by 5.0 million gallons per day (7.7 ft^3/s) to account for pumping effects.

[c] Discharge measurements.

[d] Estimated using graphical analysis.

[e] Estimated as regulated value increased by 7.1 percent to account for diversions.

Admittedly, record extension using graphical relations based on only four discharge measurements is less than ideal. In this instance, however, several factors make this a reasonable alternative to consider for the Waimā Stream station. As noted above, the four available discharge measurements were made at times when concurrent daily mean discharges at index stations in the Waipiʻo Valley study area were equal to flow-duration percentiles between 55 and 99 percent. These flow-duration percentiles effectively span the range of low-flow conditions of interest in this study. Experience with low-flow partial-record stations in Waipiʻo Valley indicate that it is reasonable to assume linear relations between discharge measurements on Waimā Stream (gaging station 16732150) and available index stations. Finally, straight lines closely fit all four discharge measurements when plotted against concurrent daily mean discharges at each of the four available index stations when untransformed data were used. Concurrent daily mean discharges for Hauani Gulch (16759000) were all increased by 1.0 ft^3/s before the analysis because the dischage for one of the days, December 11, 1962, was 0.0 ft^3/s and use of the adjustment provided a better fit to the Waimā Stream data. On the basis of these facts, graphical record-extension techniques were used to estimate flow-duration statistics of interest for Waimā Stream using data from each of the four index stations. As can be seen from the results, summarized in table 1–H, there is very close agreement among the four independent computations for each of the flow-duration percentiles, with the possible exception of those for the 50-percentile flow-duration discharges. These consistent results provide an extra measure of confidence in the estimates and indicate that use of an average of the four independent computations for each flow-duration percentile would be reasonable. To account for the effects of upstream diversions, regulated flow-duration discharges were multiplied by a factor of 1.071 (based on computed difference between regulated and natural discharge during the September 2000 seepage run) to estimate natural flow-duration discharges. It should be kept in mind, however, that the flow-duration discharges shown in table 1-H are based on the application of less than ideal methods and therefore should be treated as estimates with unknown levels of accuracy.

Appendix 2. Computation of Low-Flow Statistics for Ungaged Sites

Combining Flow-Duration Curves

At several locations in the Waipiʻo Valley study area where two streams join to form a third, larger stream, discharge data have been collected on only two of the three. An example of this situation is on Kawainui Stream, where gaging stations 16720000 on Kawainui Stream and 16720300 on Kawaiki Stream have been operated just upstream from their confluence, yet no data have been collected immediately downstream from the confluence. Flow-duration statistics can be computed directly for the two upstream gages using available data, but the question becomes how best to compute flow-duration statistics for the combined streams. In the case in which natural flow-duration statistics are desired, it is assumed that no diversion by Upper Hāmākua Ditch is taking place. The first step was to add the daily mean discharges for each day of concurrent record from the two upstream gaging stations. The next step was to compute natural flow-duration statistics on the basis of the combined daily mean discharges, which provides theoretically correct values (table 2–A) (see section in report titled “Data and Methods Used to Estimate Low-Flow Statistics”).

Determining flow-duration statistics for a point downstream from the confluence of Kawainui and Kawaiki Streams poses a complicating factor in that Upper Hāmākua Ditch originates in this area, and a significant amount of the flow of both streams is diverted by the ditch just above their confluence. To compute regulated flow-duration statistics for the combined flow of the two streams that reflects diversion by Upper Hāmākua Ditch, data from gaging station 16720500 (on the ditch) must be incorporated into the analysis. Gaging station 16720500 measures the total amount of flow diverted from Kawainui and Kawaiki Streams. In this situation, the first step was to add daily mean discharges for each day of concurrent record from the two upstream gaging stations (16720000 and 16720300) and then subtract the concurrent daily mean flow that was diverted, as measured at gaging station 16720500. As above, the next step was to compute regulated flow-duration statistics using the combined daily mean discharges. Regulated flow-duration discharges for a location on Kawainui Stream just downstream from the point where Kawainui and Kawaiki Streams join and where diversion by Upper Hāmākua Ditch takes place, based on combination of concurrent daily mean discharges, have been computed and are shown in table 2–B.

A more common situation at locations where streams join or where streams are subjected to diversions is that gaging stations both above and below the confluence and (or) the diversion point that have concurrent daily mean discharge data are unavailable. In such cases, an alternative technique for computing flow-duration statistics is to simply combine estimated flow-duration discharges of the two streams for the common percentiles of interest. An example of results based on combining flow-duration discharges directly for two streams is shown in table 2–A. In this example it was assumed that gaging station data were not available for either Kawainui Stream or Kawaiki Stream but that flow-duration discharges were available. This would be the case if, for example, low-flow partial-record stations had been operated at both locations. As can be seen from data summarized in table 2–A, flow-duration discharges based on direct combination of discharges for common percentiles gives results that are virtually the same as the theoretically correct results based on combination of concurrent daily mean discharges. Only for extreme low flows, such as the 99-percentile flow, are errors greater than 10 percent, and in this case the absolute error is only 0.04 ft^3/s. Direct addition of concurrent flow-duration discharges for streams that are hydrologically similar should produce statistics for the combined flow that have only minimal errors.

The combination of estimated, common flow-duration discharges at locations where streams and diversions interact is a more complex problem. Regulation associated with diversions often means that flow-duration conditions in effect on the stream might not be the same as those in effect at the same time on the diversion ditch; in other words, they are not hydrologically similar. For example, 50-percentile flow conditions might exist in the stream during a period when the ditch intakes are plugged, so that low-flow (99-percentile) conditions exist in the ditch. An example of results based on combining common flow-duration discharges directly for two streams and a ditch is shown in table 2–B. In this example, it was assumed that concurrent daily mean discharge data were not available for Kawainui or Kawaiki Streams and for Upper Hāmākua Ditch, although flow-duration discharges had been estimated. As can be seen from the data summarized in the table, flow-duration discharges based on direct combination of common percentiles gives results that often differ by large percentages and by large absolute amounts from the theoretically correct results—those based on combination of concurrent daily mean discharges. Direct addition of common flow-duration discharges for streams and ditches that are hydrologically different should be used with caution; results could have large errors.

Use of Seepage Run Data

In a seepage run, discharge measurements are made at several locations along a reach of stream and(or) ditch. Seepage runs are most commonly made during periods of low flow, when discharge conditions at any given location are relatively constant. The total elapsed time between the first and last discharge measurements in a seepage run is minimized to further reduce the effects of flow variability (Fontaine, 2003). Seepage-run results can be used to determine which stream or ditch reaches are gaining or losing water and where these

Table 2–A. Selected natural flow-duration discharges for the concurrent period of record 1970–1999 at surface-water gaging stations 16720000 on Kawainui Stream and 16720300 on Kawaiki Stream, Waipi‘o Valley area, Island of Hawai‘i, Hawai‘i.

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

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)				Percent error using combination of current percentiles
	Kawainui Stream 16720000	Kawaiki Stream 16720300	Based on combination of concurrent percentiles	Based on combination of concurrent daily flows	
99	0.09	0.02	0.11	0.15	-26.7
95	0.27	0.10	0.37	0.40	-7.5
90	0.51	0.17	0.68	0.71	-4.2
80	1.1	0.29	1.4	1.4	0.0
70	1.8	0.48	2.3	2.3	0.0
60	2.8	0.77	3.6	3.7	-2.7
50	4.6	1.3	5.9	6.0	-1.7
40	7.6	2.1	9.7	9.7	0.0
30	13	3.3	16	17	-5.9
20	23	5.3	28	28	0.0
10	42	9.5	52	51	2.0
5	63	15	78	78	0.0
1	138	32	170	169	0.6

Table 2–B. Selected regulated flow-duration discharges for the concurrent period of record 1970–1999 at gaging stations 16720000 on Kawainui Stream, 16720300 on Kawaiki Stream, and 16720500 on Upper Hāmākua Ditch, Waipi‘o Valley area, Island of Hawai‘i, Hawai‘i.

[ft^3/s, cubic feet per second; N.A., not applicable]

Percentage of time indicated discharge equaled or exceeded	Discharge (ft^3/s)					Percent error using combination of current percentiles
	Kawainui Stream 16720000	Kawaiki Stream 16720300	Upper Hāmākua Ditch 16720500	Based on combination of concurrent percentiles	Based on combination of concurrent daily flows	
99	0.09	0.02	0.00	0.11	0.00	N.A.
95	0.27	0.10	0.20	0.17	0.00	N.A.
90	0.51	0.17	0.56	0.12	0.00	N.A.
80	1.1	0.29	1.1	0.29	0.00	N.A.
70	1.8	0.48	1.9	0.38	0.00	N.A.
60	2.8	0.77	3.2	0.37	0.13	185
50	4.6	1.3	5.0	0.90	0.46	96.1
40	7.6	2.1	7.5	2.2	1.6	35.0
30	13	3.3	10	6.3	6.1	2.9
20	23	5.3	13	15	16	-6.2
10	42	9.5	15	36	37	-2.7
5	63	15	17	61	63	-3.2
1	138	32	25	145	155	-6.4

changes take place. Seepage runs also provide valuable insight into how low-flow and therefore low-flow duration discharges vary along stream reaches. Seepage runs along ditches provide insight into how diversion systems operate. On September 20–21, 2000, a seepage run was conducted along major streams in Waipiʻo Valley, starting upstream from Lower Hāmākua Ditch intakes and extending downstream to Wailoa Stream at 190 feet elevation. At the same time, a seepage run was conducted along Lower Hāmākua Ditch over its entire reach in Waipiʻo Valley. A second seepage run was begun on September 26, 2001, but rapidly increasing streamflow conditions in Waipiʻo Valley near the end of that day forced cancellation of data collection. Measured and computed discharges during the seepage runs along streams in Waipiʻo Valley and Lower Hāmākua Ditch represent regulated conditions; the results of the measurements are presented in table 2–C and shown in figures 2–A and 2–B.

During the September 20–21, 2000, seepage run along Lower Hāmākua Ditch, only Kawainui and Koʻiawe Stream intakes were actually withdrawing water. There was a net loss of water out of Lower Hāmākua Ditch at Alakahi Stream intake, and no diversion took place at the Waimā Stream intake. There was a net loss of water out of Lower Hāmākua Ditch in the reach between Kawainui and Alakahi Stream intakes and no changes in discharge in the reaches between Akakahi and Koʻiawe Stream intakes and between Koʻiawe and Waimā Stream intakes. Between Waimā Stream intake and the main weir (where the ditch exits Waipiʻo Valley), there was a net inflow of 4.0 ft^3/s of groundwater directly into the tunnels of Lower Hāmākua Ditch (most of Lower Hāmākua Ditch in Waipiʻo Valley consists of tunnels). During the September 21–21, 2000, seepage run, leakage of 5.0 ft^3/s from Lower Hāmākua Ditch was taking place, at Hakalaoa waterfall between sites 25 and 26 (see table 2–C); this leakage has since been repaired.

In the section "Low-Flow Statistics Representative of Natural Conditions" in the main body of this report, computations were made under the assumption that flow in downstream tributaries was changed by the same amount that was removed or released at upstream points of diversion. This assumpton was based, in part, on the fact that downstream tributaries were gaining flow. Review of the seepage run results shown in figure 2–A indicates that flow did in fact increase along stream reaches where ditch diversion intakes were not located. Techniques outlined in appendix 3, "Accounting for Effects of Diversions at Upper and Lower Hāmākua Ditches," and results from the seepage run along Lower Hāmākua Ditch were used to convert measured discharges along streams in Waipiʻo Valley to reflect what they would have been under natural conditions during the time of the September 20–21, 2000, seepage run. Adjustments associated with regulation by the Upper Hāmākua Ditch were based on average diversions for the 2-day period over which the seepage run was conducted. These estimated natural discharges are shown in figure 2–C.

During the September 20–21, 2000, seepage run, there were significant gains in natural discharges between locations where tributary streams first enter Waipiʻo Valley and Lower Hāmākua Ditch intakes. Waimā Stream was a notable exception to this pattern. In general, the rates at which tributary streams gained water decreased downstream from the intakes of Lower Hāmākua Ditch. However, Waimā Stream was again a notable exception, as natural discharge increased from 1.0 to 37.5 ft^3/s in the reach between Lower Hāmākua Ditch intake and the stream mouth. Estimated natural discharges at index and low-flow partial-record stations at the time of the seepage run were compared to computed flow-duration discharges for those stations (tables 7 and 13 in the main body of this report). On average, the natural discharges were between the 60 and 50 flow-duration percentiles. As described in appendix 1, discharge data were collected at 13 stations between August 1901 and January 1902, when no regulation or diversion of the streams was occurring (Martin and Pierce, 1913, p. 397). Concurrent discharge data at these 13 stations can be used to approximate additional seepage runs. On October 29, November 7, and December 6, 1901, streamflow conditions were similar to those during the September 20–21, 2000, seepage run. Concurrent discharge values for those three dates in 1901, along with regulated and natural discharges during the September 21–21, 2000, seepage run along the main streams in Waipiʻo Valley (Kawainui, Waipiʻo, and Wailoa Streams), were plotted against altitude of the location where the data were collected (figure 2–D). The data in figure 2–D highlight the significant differences between regulated and natural discharges and the close correspondence between natural discharge data in 1901 and estimated natural discharge data in 2000.

Seepage-run results can be used as an aid in extrapolating flow-duration discharges to locations where data are lacking. For example, during the September 20–21, 2000, seepage run, natural discharge was estimated to be 55.3 ft^3/s at site 10 and 58.6 ft^3/s at site 11 (fig. 2–C). In other words, discharge in this reach of Waipiʻo Stream increased by a factor of 1.06 (58.6/55.3). The 50-percentile discharge at site 10 is unknown, but using the technique of combining flow-duration curves (discussed above), 50-percentile discharges at station 16724000 (38 ft^3/s) and at station 16729000 (21 ft^3/s) can be combined to estimate a natural 50-percentile discharge of 59 ft^3/s at site 10. Multiplying the estimated 50-percentile discharge of 59 ft^3/s at site 10 by 1.06 (based on natural seepage run data) yields an estimated 50-percentile discharge of about 63 ft^3/s at site 11 (Waipiʻo Stream upstream from the mouth of Koʻiawe Stream). Use of seepage run results to extrapolate flow-duration discharges will yield the best results when adjustment factors are not significantly different from 1.0 and when they are applied to flow-duration discharges similar to those in existence at the time of the September 20–21, 2000, seepage run.

Regional Analysis

A commonly applied form of regional analysis is based on the concept that multivariate-regression equations can be developed to relate computed low-flow statistics to basin characteristics at gaged sites (Gingerich, 2005). At ungaged sites, these basin characteristics, such as drainage area, can be readily measured and then applied in the regression equations to estimate low-flow statistics. A complete regional

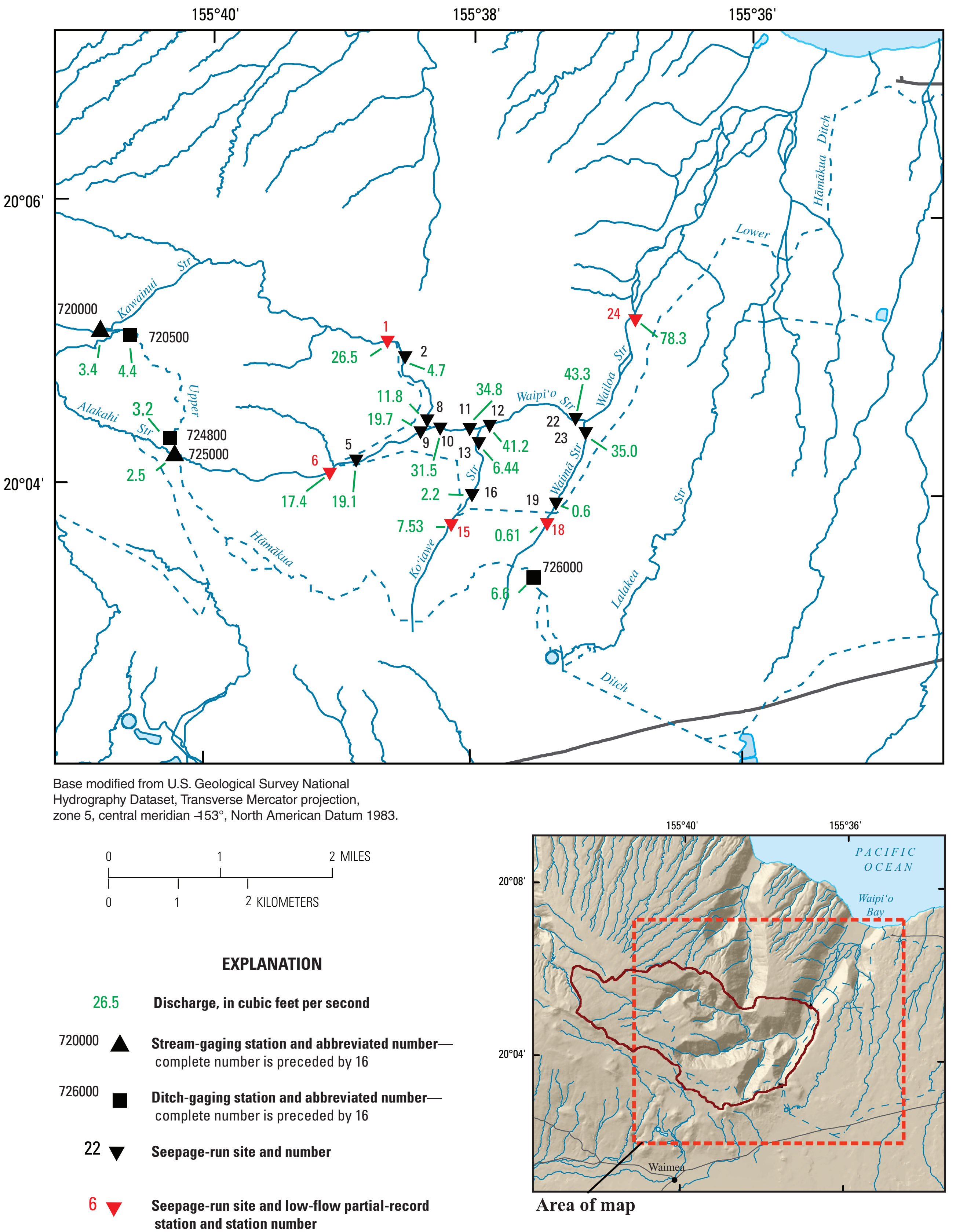


Figure 2–A. Measured and computed regulated discharges at the time of the September 20–21, 2000, seepage run along streams in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

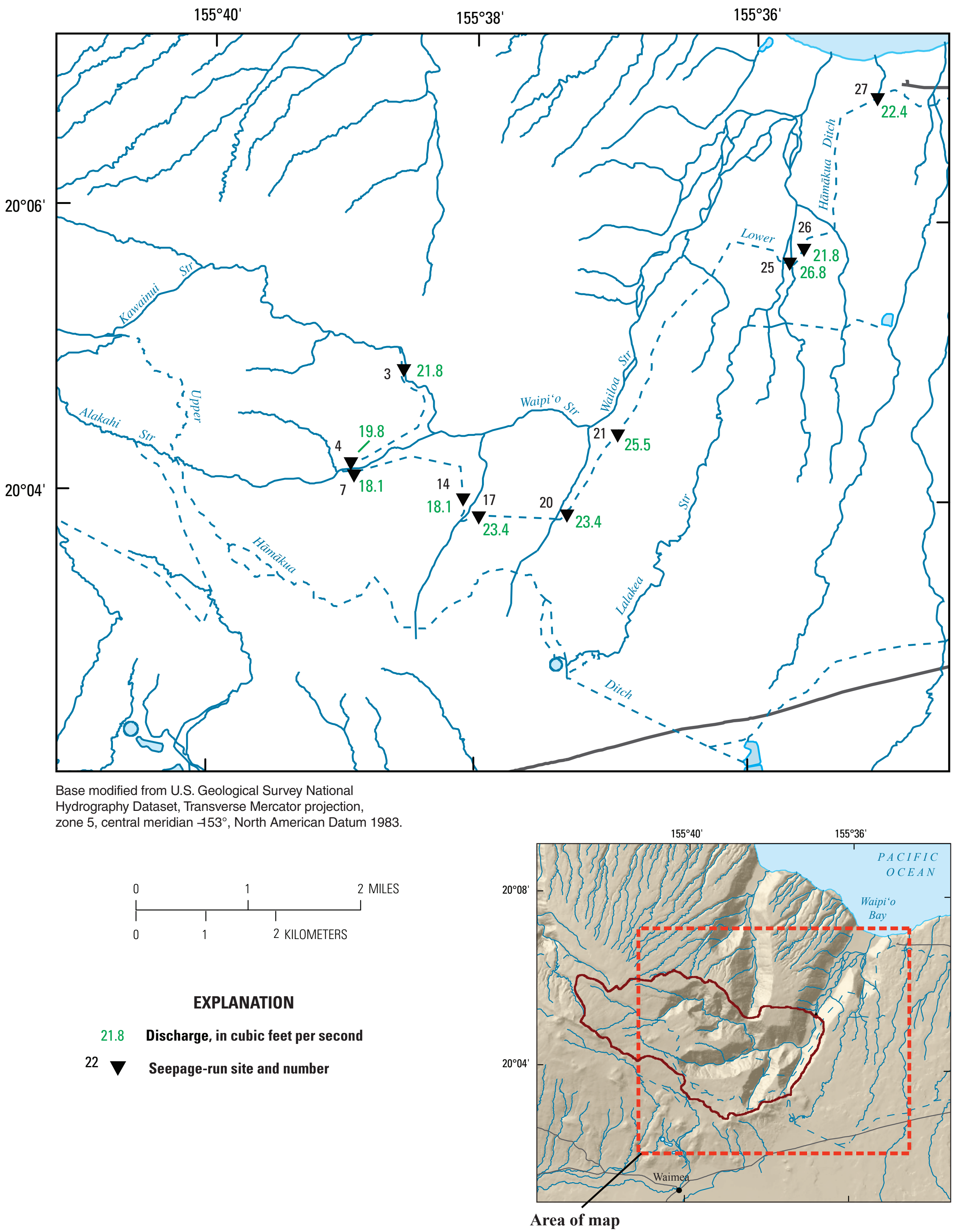


Figure 2–B. Measured and computed discharges at the time of the September 20–21, 2000, seepage run along Lower Hāmākua Ditch, Island of Hawai'i, Hawai'i.

Table 2–C. Discharge measurements at seepage-run sites in Waipi‘o Valley in September 2000 and September 2001, Island of Hawai‘i, Hawai‘i.

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

Site number[a]	Stream or ditch	Altitude (feet)	Discharge (ft^3/s)	
			Sept. 20-21, 2000	Sept. 26, 2001
1	Kawainui Stream	1,070	26.5	41.5
2	Kawainui Stream	1,037	4.7[b]	26.1[b]
8	Kawainui Stream	775	11.8	---
6	Alakahi Stream	1,030	17.4[c]	---
5	Alakahi Stream	1,000	19.1	---
9	Alakahi Stream	730	19.7[d]	---
10	Waipi‘o Stream	720	31.5	---
11	Waipi‘o Stream	595	34.8	---
12	Waipi‘o Stream	580	41.2[e]	---
22	Waipi‘o Stream	400	43.3	---
15	Ko‘iawe Stream	1,020	7.53	10.5
16	Ko‘iawe Stream	980	2.2[f]	1.8[f]
13	Ko‘iawe Stream	610	6.44	---
18	Waimā Stream	1,040	0.61	0.86
19	Waimā Stream	970	0.6[g]	0.9[g]
23	Waimā Stream	385	35.0	---
24	Wailoa Stream	190	78.3	103
3	Lower Hāmākua Ditch	1,037	21.8	15.4
4	Lower Hāmākua Ditch	1,030	19.8	13.0
7	Lower Hāmākua Ditch	1,030	18.1	11.0
14	Lower Hāmākua Ditch	1,000	18.1	11.9
17	Lower Hāmākua Ditch	1,000	23.4	20.6
20	Lower Hāmākua Ditch	980	23.4	22.1
21	Lower Hāmākua Ditch	975	25.5	20.0
25	Lower Hāmākua Ditch	970	26.8	22.2
26	Lower Hāmākua Ditch	970	21.8[h]	20.4
27	Lower Hāmākua Ditch	965	22.4	22.2

[a] Site numbers correspond to those listed in table 2 and shown in figure 4 in main body of report.

[b] Computed by mass balance as Site 2 = Site 1 - Site 3.

[c] Computed by mass balance as Site 6 = Site 5 + (Site 7 - Site 4).

[d] Computed by mass balance as Site 9 = Site 10 - Site 8.

[e] Computed by mass balance as Site 12 = Site 11 + Site 13.

[f] Computed by mass balance as Site 16 = Site 15 - (Site 17 - Site 14).

[g] Estimated as about the same as Site 18, no diversion of water at the ditch intake.

[h] Average of two discharge measurements made at the site.

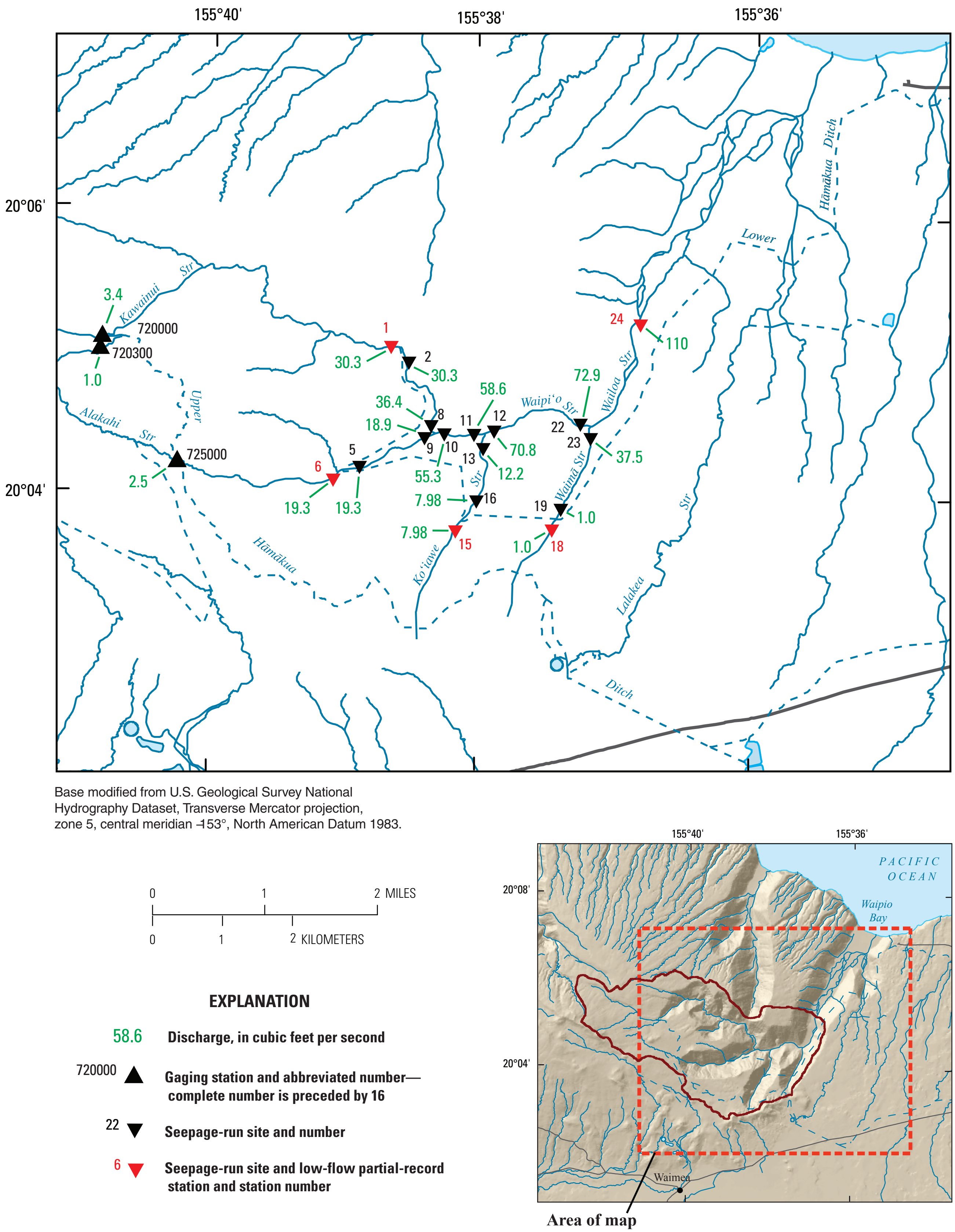


Figure 2–C. Computed natural discharges at the time of the September 20–21, 2000, seepage run along streams in the Waipi'o Valley study area, Island of Hawai'i, Hawai'i.

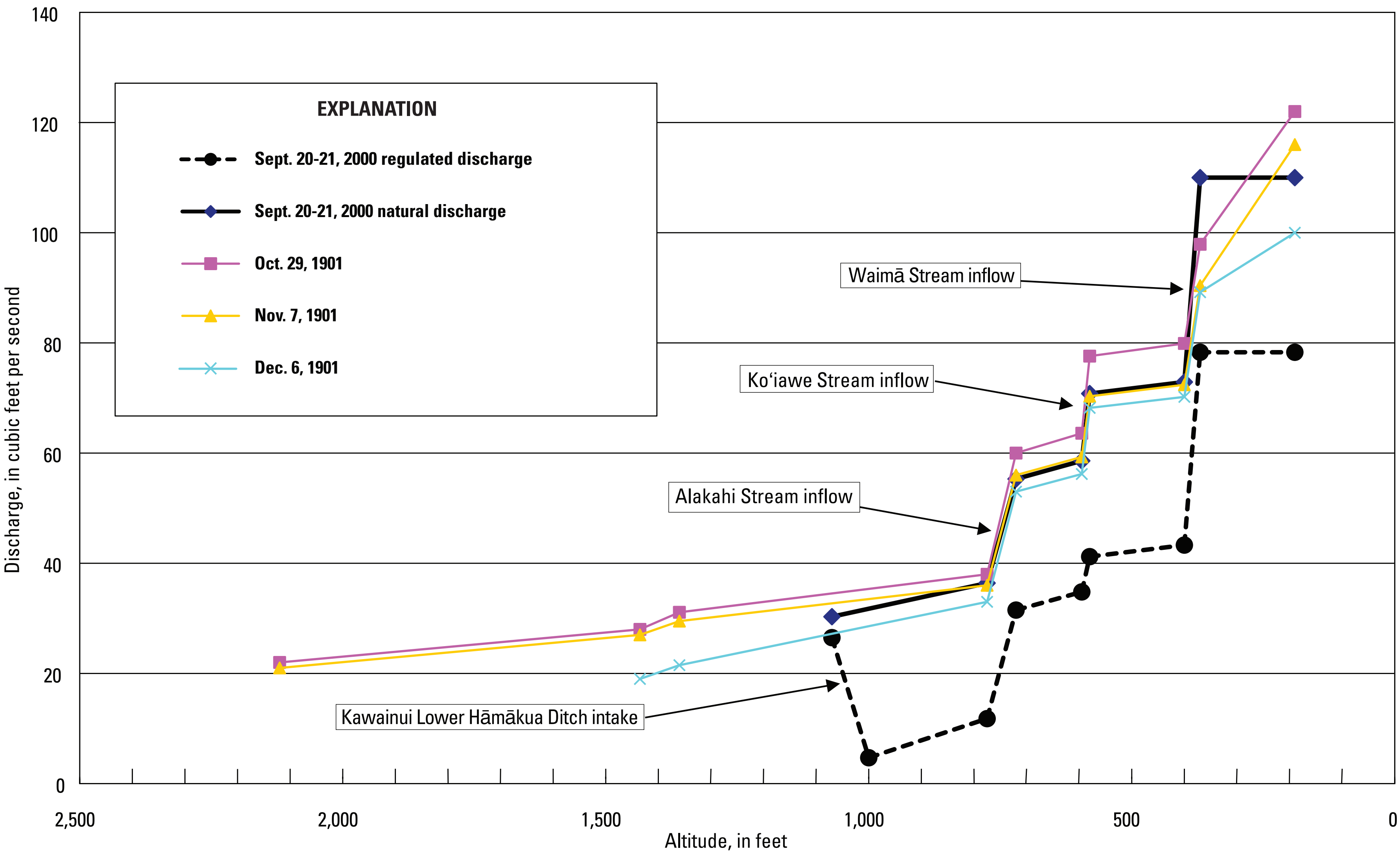


Figure 2–D. Discharge in Kawainui, Waipi‘o, and Wailoa Streams during the September 20–21, 2000, seepage run and on selected days in 1901 prior to the onset of flow diversions, Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

multivariate-regression analysis of low flow is well beyond the scope of this report. However, to demonstrate how such analyses can be applied, a simple regression analysis was conducted using only drainage area as a predictive basin characteristic.

Drainage area and natural 50- and 95-percentile flow-duration discharges for the 1965–2004 base period for all sites in Waipiʻo Valley study area where the data are available are shown in table 2-D; regulated flow-duration discharges are shown in table 2–E. Data in these two tables were used to quantify linear relations between natural and regulated 50-percentile flow-duration discharges and drainage area shown in figures 2–E and 2–F. It is important to note that data for gaging stations along the lower reaches of Waimā Stream, downstream from Lower Hāmākua Ditch, were not included in this analysis. Low-flow duration discharges (per unit of drainage area) of Waimā Stream, downstream from Lower Hāmākua Ditch, are significantly higher than those at other gaging stations in Waipiʻo Valley. The degree by which flow-duration discharges for Waimā Stream, at gaging station 16732150, differ hydrologically is clearly illustrated by the plotting position of estimated 50-percentile discharges for this gaging station in figures 2–E and 2–F. As a result, the simplified regional analysis based on drainage area, which was developed in this section, should not be applied to Waimā Stream downstream from Lower Hāmākua Ditch. The confluence of Waimā and Waipiʻo Streams is also a good example of a location where two streams are not hydrologically similar, and therefore combining flow-duration curves to determine low-flow statistics should be avoided. A detailed analysis of the accuracy of resultant regression equations based on drainage area shown in figures 2–E and 2–F is beyond the scope of this report. However, a similar drainage-area-based regression equation for 50-percentile flow-duration discharge developed for the islands of Oʻahu, Molokaʻi, and Hawaiʻi had a standard error of prediction of 41.4 percent (Fontaine and others, 1992).

Similar drainage-area based regression equations could be developed for other flow-duration discharges, such as the 95-percentile discharge data shown in tables 2–D and 2–E. In a detailed regional analysis of flow-duration discharges in northeast Maui, however, Gingerich (2005) showed that regression equations developed for lower flow-duration discharges, such as the 95-percentile, have substantially higher errors of prediction. An alternative approach is to compute ratios of flow-duration discharge of interest to the 50-percentile discharges. This ratio could be then used to adjust the computed 50-percentile discharge determined by using the regression equation to estimate the flow-duration discharge of interest. In tables 2–D and 2–E, ratios of natural and regulated 95-percentile to 50-percentile discharges are summarized.

Selection of the appropriate ratio to use when computing alternative flow-duration discharges, such as the 95-percentile value, can be based on the known ratio computed at the nearest hydrologically similar gaging station. An alternative method would be to use average values for the ratios shown in tables 2–D and 2–E. Ratios of 95-percentile to 50-percentile flow-duration discharges at gaging stations in the Waipiʻo Valley study area exhibit distinct patterns. Gaging stations upstream from Upper Hāmākua Ditch have average ratios for natural discharges (0.09; table 2–D) that are much smaller than those for gaging stations in Waipiʻo Valley, downstream from Upper Hāmākua Ditch (0.73).

The ratio of 95-percentile to 50-percentile flow-duration discharges also can be used as an index of low-flow variability (Oki and others, 2006, p. 15). Ratios closer to zero are indicative of more variable and less sustained low flows. Ratios closer to one are indicative of less variable and more sustained low flows. The relatively lower average ratios for gaging stations upstream from Upper Hāmākua Ditch reflect the fact that streams there are in contact with Hāwī Volcanics, which carry lesser quantities of water than the underlying Pololū Basalt. The higher average ratios for gaging stations in Waipiʻo Valley reflect the fact that streams there are in contact with the Pololū Basalt and have also eroded down into dike-impounded compartments that hold significant quantities of water.

In most cases, the ratios of 95-percentile to 50-percentile flow-duration discharges under 2000–2005 regulated conditions are greater than those associated with natural discharge conditions at the same gaging station. The average ratio for gaging stations in Waipiʻo Valley, under 2000–2005 regulated discharge conditions, is 0.76; under natural discharge conditions the ratio is 0.73. This difference indicates that 2000–2005 regulated low-flows, although they are smaller than natural flows, are slightly less variable at gaging stations in Waipiʻo Valley.

Application of the simplified regional analysis of low-flow characteristics outlined above can be demonstrated in a simple example. Assume that 50- and 95-percentile flow-duration discharges for natural conditions are desired for an ungaged site in Waipiʻo Valley. For the purposes of this example, assume that the drainage area at the ungaged site was determined to be 1.0 square mile. Natural 50-percentile flow-duration discharge can be computed using the formula shown in figure 2–E as 4.1578(drainage area)$^{1.3026}$, or 4.1578(1.0)$^{1.3026}$, which equals 4.2 ft^3/s. The average ratio of natural 95-percentile to 50-percentile flow-duration discharges in Waipiʻo Valley is 0.73 (table 2–D), and the 95-percentile flow-duration discharge can be computed as 0.73(4.2), or 3.1 ft^3/s. Note that if this ungaged site was upstream from Upper Hāmākua Ditch, the average ratio of natural 95-percentile to 50-percentile flow-duration discharges would be 0.09 and the 95-percentile flow-duration discharge would be computed as 0.09(4.2), or 0.38 ft^3/s.

When estimating flow-duration discharges at ungaged sites in Waipiʻo Valley study area, the most accurate results will be obtained at locations where direct combinations of computed flow-duration discharges from gaging stations are possible. Where ungaged sites of interest are only short distances from gaging stations, estimates based on extrapolations using linear interpolations or adjustments based on seepage-run data will provide results with slightly lower accuracies. The least accurate estimates will be those made using the simplified, one-parameter (drainage area) regional analysis method outlined above. If multivariate regression equations had been developed, the predictive accuracy of the regional methods would be improved.

Table 2–D. Drainage area and selected natural flow-duration discharges for the 1965–2004 base period at gaging stations and data-collection sites in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

[mi^2, square miles; ft^3/s, cubic feet per second; Q_{95}, 95-percentile discharge; Q_{50}, 50-percentile discharge]

Gaging-station or site number[a]	Drainage area (mi^2)	50-percentile discharge (ft^3/s)	95-percentile discharge (ft^3/s)	Ratio (Q_{95}/Q_{50})
Gaging stations or sites upstream from Upper Hāmākua Ditch				
16720000	1.58	4.5	0.29	0.06
16720300	0.45	1.3	0.11	0.08
16725000	0.87	3.1	0.38	0.12
Average				0.09
Gaging stations or sites downstream from Upper Hāmākua Ditch				
1	5.55	34	18	0.53
6	2.45	20	13	0.65
15	1.85	9.5	7.3	0.77
18	0.49	1.2	0.73	0.61
16721000	3.48	21	14	0.67
16722000	4.43	24	17	0.71
16724000	6.00	38	28	0.74
16728000	1.49	15	12	0.80
16729000	3.14	21	18	0.86
16730000	1.65	9.0	7.5	0.83
16731000	2.23	15	12	0.80
16732150	0.77	44	26	0.59[b]
16732200	14.3	112	86	0.77
Average				0.73

[a] Site numbers correspond to those listed in table 2 and shown in figure 4 in main body of report.

[b] Not used when computing average.

Table 2–E. Drainage area and selected regulated flow-duration discharges for the1965–2004 base period at gaging stations and data-collection sites in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

[mi^2, square miles; ft^3/s, cubic feet per second; Q_{95}, 95-percentile discharge; Q_{50}, 50-percentile discharge]

Gaging-station or site number[a]	Drainage area (mi^2)	50-percentile discharge[c] (ft^3/s)	95-percentile discharge[c] (ft^3/s)	Ratio (Q_{95}/Q_{50})
Gaging stations or sites downstream from Upper Hāmākua Ditch				
1	5.55	33	16	0.48
6	2.45	18	12	0.67
15	1.85	8.4	6.8	0.81
18	0.49	0.72	0.54	0.75
16721000	3.48	14	9.8	0.70
16722000	4.43	17	13	0.76
16724000	6.00	27	21	0.78
16728000	1.49	12	10	0.83
16729000	3.14	18	15	0.83
16730000	1.65	7.4	6.5	0.88
16731000	2.23	12	10	0.83
16732150	0.77	41	24	0.59[b]
16732200	14.30	85	68	0.80
Average				0.76

[a] Site numbers correspond to those listed in table 2 and shown in figure 4 in main body of report.

[b] Not used when computing average.

[c] Reflective of 2000–2005 diversion conditions.

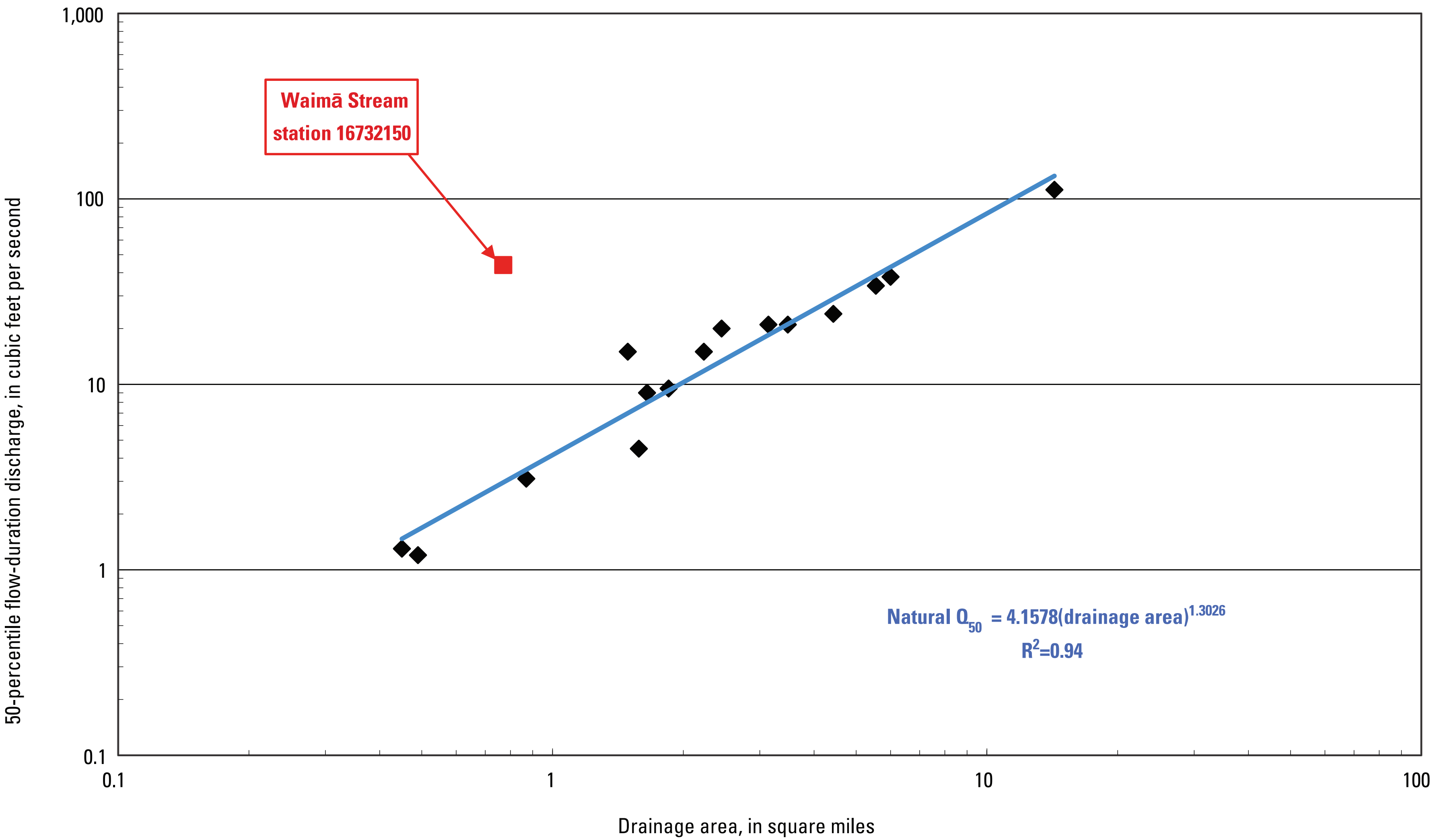


Figure 2–E. Natural 50-percentile flow-duration discharges, for the 1965–2004 base period, versus drainage area in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

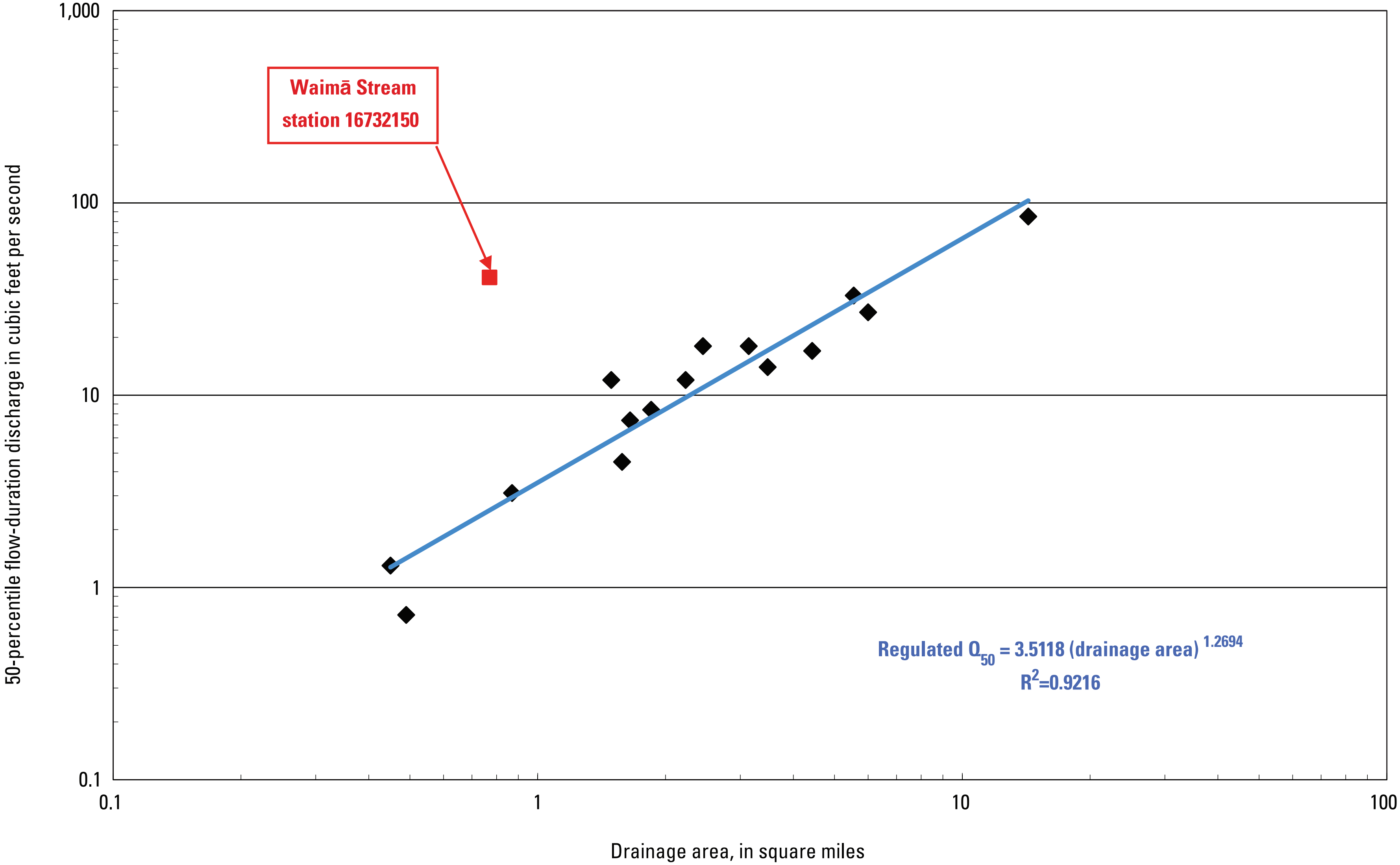


Figure 2–F. Regulated 50-percentile flow-duration discharges, for the 1965–2004 base period, versus drainage area in the Waipiʻo Valley study area, Island of Hawaiʻi, Hawaiʻi.

Appendix 3. Accounting for Effects of Diversions at Upper and Lower Hāmākua Ditches

Effects of Diversions at Upper Hāmākua Ditch

Upper Hāmākua Ditch, along the rim of Waipiʻo Valley, diverts water primarily through intakes on Kawainui Stream (altitude 4,042 feet), Kawaiki Stream (a tributary to Kawainui Stream, at altitude 4,026 feet), Alakahi Stream (altitude 3,874 feet), Koʻiawe Stream (altitude 3,355 feet), and Waimā Stream (altitude 3,044 feet) at locations just upstream of where they descend into Waipiʻo Valley (Hawaii Division of Water and Land Development, 1963). Diversion intakes along Upper Hāmākua Ditch were designed to capture all of the water in the stream until the rate of flow exceeded the capacity of the intake structures. At this point, water in streams will overtop the intake diversion dams and flow downstream into Waipiʻo Valley. Unfortunately, accounting for effects of diversions by Upper Hāmākua Ditch is not simply a matter of determining how much water is withdrawn at each intake.

Upper Hāmākua Ditch, like most diversion systems in Hawaiʻi, does not just withdraw water from streams at established intakes; it also gains and loses water at both diffuse and point locations along its entire reach. In addition to the stream intakes, Upper Hāmākua Ditch can intercept water along open sections where overland runoff and small seeps can flow directly into the ditch, as well as along tunneled sections of the ditch, where groundwater-saturated rocks are intersected. Upper Hāmākua Ditch discharges water at locations in addition to those of intended water users—back into streams at maintenance spillways and release gates where it is intentionally or unintentionally released, at points of overflow where the capacity of the ditch is exceeded (often due to blockages), and at diffuse locations along its reach where there are leakage or seepage losses. Water diverted or "lost" via seepage from Upper Hāmākua Ditch at diffuse and point locations does not always return to the same stream from which the water was originally diverted or lost, which further complicates water accounting.

Three gaging stations have been operated on tributaries upstream from intakes of Upper Hāmākua Ditch, and three stations have been operated along the ditch itself. These stations and the periods during which they have been in operation are summarized in table 3-A; their locations are shown in figure 3–A. Only two gaging stations, Kawainui Stream at 4,060 feet (station 16720000) and Alakahi Stream at 3,900 feet (station 16725000), were in operation during the entire 2000–2005 study period. As a result, a combination of actual gaging station data and estimates of discharge based on relations established using historical data will be needed to account for the effects of diversions by Upper Hāmākua Ditch. To be consistent and as relevant to study-period (2000–2005) conditions as possible, historical data from water year 1999 were used when estimated diversion relations were required. Water year 1999 was the most current 12-month period during which all three stream-gaging stations and three ditch-gaging stations, on or upstream from Upper Hāmākua Ditch, were in operation.

To account for effects of diversions by Upper Hāmākua Ditch, computations were run for each day that a discharge measurement was made at any of the five low-flow partial-record stations downstream from the ditch. At the upstream limit of Upper Hāmākua Ditch, intakes divert water from Kawainui Stream and its tributary Kawaiki Stream. The amount of water diverted by Upper Hāmākua Ditch from Kawainui Stream watershed (the combined total of water diverted at Kawainui and Kawaiki Stream ditch intakes) was measured at gaging station Upper Hāmākua Ditch at 4,020 feet (16720500) through 2002.

To estimate the amount of water diverted by Upper Hāmākua Ditch from Kawainui Stream watershed for the balance of the study period (2003–2005), the relation shown in figure 3-B was developed. In figure 3–B, discharge in Upper Hāmākua Ditch at 4,020 feet (station 16720500) is plotted against the combined discharge of Kawainui Stream at 4,060 feet (station 16720000) and Kawaiki Stream at 4,090 feet (station 16720300). The graph shows that discharge in Upper Hāmākua Ditch is greater than or equal to the combined discharge of Kawainui and Kawaiki Streams on most days in 1999 when the combined discharge of the streams is less than or equal to 9.5 ft^3/s. This indicates that at the intakes, Upper Hāmākua Ditch will divert all the water in Kawainui and Kawaiki Streams up to 9.5 ft^3/s. Conversely, the discharge in Upper Hāmākua Ditch is less than the combined discharge of Kawainui and Kawaiki Streams on all days in 1999 when the combined discharge of the streams is greater than 9.5 ft^3/s. This indicates that water will overflow Upper Hāmākua Ditch diversion dams at the intakes and flow downstream into Waipiʻo Valley (and Kawainui Stream) when the combined discharge of Kawainui and Kawaiki Streams is greater than 9.5 ft^3/s.

The amount of water diverted by Upper Hāmākua Ditch from Kawainui Stream watershed (the total diverted from Kawainui and Kawaiki Streams) on days when discharge measurements were made at low-flow partial-record stations in Waipiʻo Valley during the period 2000–2002 equals that measured at the gaging station Upper Hāmākua Ditch at 4,020 feet (16720500). The amount of water diverted by Upper Hāmākua Ditch during the period 2003-2005 was estimated to equal all the combined discharge of Kawainui and Kawaiki Streams up to 9.5 ft^3/s. Diversion totals were not estimated on days when the combined discharge of the two streams was greater than 9.5 ft^3/s. The amount of water available for diversion was measured during the entire 2003–2005 period at Kawainui Stream

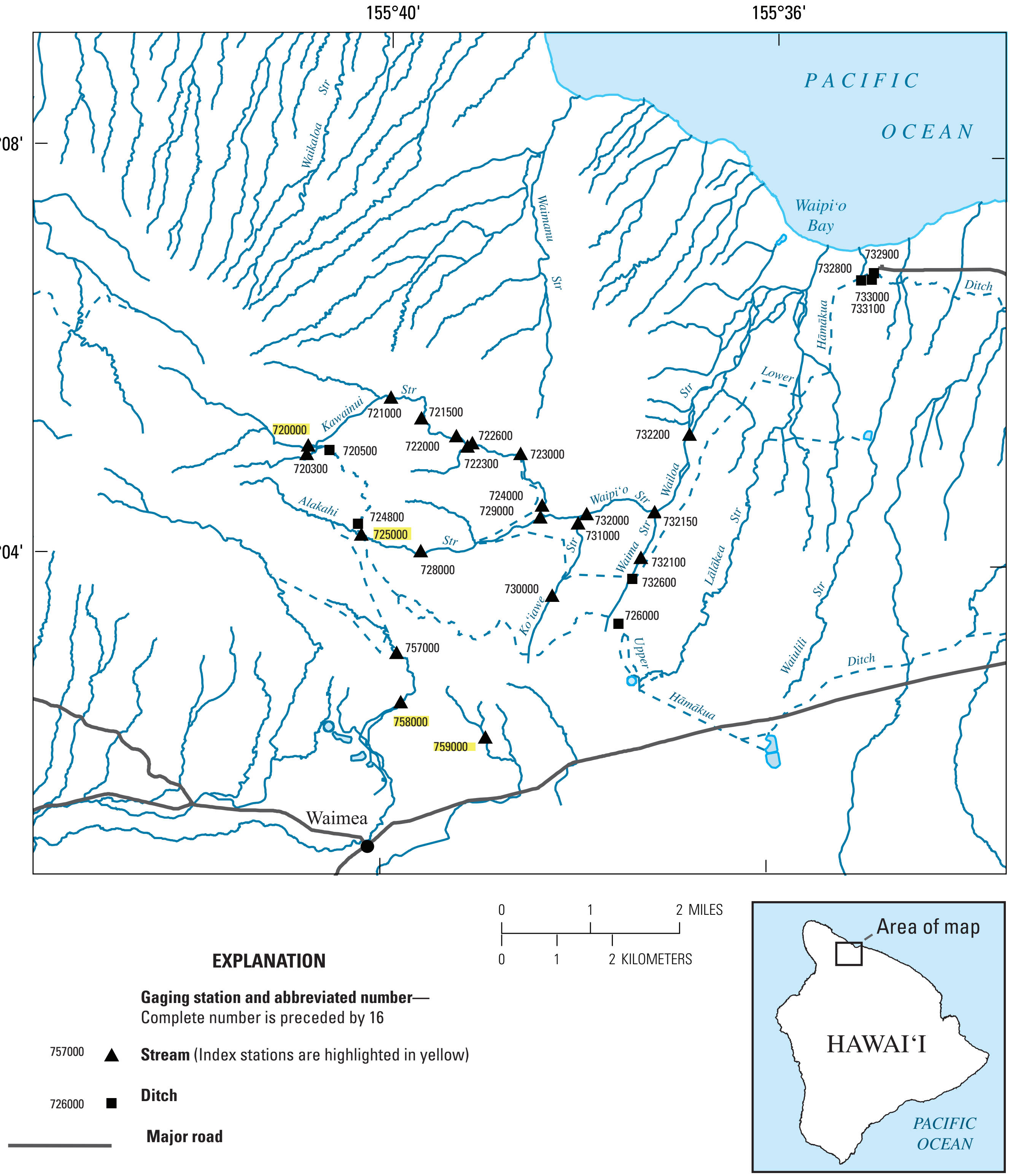


Figure 3–A. Location of stream and ditch surface-water gaging stations operated in and adjacent to the Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

Table 3–A. Gaging stations on and upstream from Upper Hāmākua Ditch, Waipi‘o Valley study area, Island of Hawai‘i, Hawai‘i.

[P, in operation during 2006 water year]

Station number	Location	Period of record	Remarks
16720000	Kawainui Stream at 4,060 feet	1965-P	Used as index station
16720300	Kawaiki Stream at 4,090 feet	1966-1999	
16720500	Upper Hāmākua Ditch at 4,020 feet	1964-2002	Ditch gaging station
16724800	Upper Hāmākua Ditch at 3,890 feet	1968-2000	Ditch gaging station
16725000	Alakahi Stream at 3,900 feet	1965-P	Used as index station
16726000	Upper Hāmākua Ditch at 3,020	1974-2004	Ditch gaging station

(station 16720000). The Kawaiki Stream (station 16720300) was discontinued in 1999; therefore concurrent streamflow data at that location needed to be estimated. This was done by establishing a simple linear regression model between daily mean streamflow data at Kawaiki Stream (station 16720300) and Kawainui Stream (station 16720000). Data for all days in water year 1999 when daily mean discharge of Kawainui Stream was less than or equal to 20 ft^3/s were used in the analysis. The model indicated that the flow of Kawaiki Stream could be estimated as 0.2437 x Kawainui Stream flow (in ft^3/s) + 0.0627. This model has a correlation coefficient of 0.976, which indicates a strong linear relation.

An analysis of discharge data for Upper Hāmākua Ditch at 4,020 feet (station 16720500) and at 3,890 feet (station 16724800) indicated a consistent pattern of diminishing discharge between Kawainui and Kawaiki Stream ditch intakes and a point just upstream from Alakahi Stream ditch intake. During 2000, when both gaging stations on Upper Hāmākua Ditch were in operation, the loss of discharge from the ditch could be computed by subtracting concurrent daily mean discharges at the stations. During the balance of the study period (2001–2005), this loss of discharge had to be estimated. This was done by establishing a simple linear regression model between the magnitude of loss of discharge from the ditch and discharge at the upstream gaging station on Upper Hāmākua Ditch at 4,020 feet (16720500). This model was developed for low-flow days during water year 1999, when the upstream discharge was 10 ft^3/s or less. The model indicated that loss of discharge from Upper Hāmākua Ditch between Kawainui and Kawaiki Stream intakes and Alakahi Stream intake could be estimated as -0.1868 x Flow in Upper Hāmākua Ditch at 4,020 feet (in ft^3/s) – 0.5396. This model has a correlation coefficient of 0.492, indicating that ditch losses are variable and at times poorly predicted by the linear regression model.

Measured and estimated losses of water from Upper Hāmākua Ditch between Kawainui and Kawaiki Stream intakes and Alakahi Stream intake during periods of low flow most likely are associated with diffuse leakage or seepage losses. Water lost from Upper Hāmākua Ditch is assumed to contribute to flow in downgradient streams. In this case, the reach of Upper Hāmākua Ditch between Kawainui and Kawaiki Stream intakes and the Alakahi Stream intake lies within parts of Kawainui and Alakahi Stream watersheds that are upstream from low-flow partial-record stations at sites 1 and 6 (fig. 3–C). It is not known exactly where along Upper Hāmākua Ditch that losses of water take place. For the pruposes of this study, it was estimated that the distribution of losses from Upper Hāmākua Ditch into Kawainui and Alakahi Stream watersheds was directly proportional to the length of Upper Hāmākua Ditch within each watershed. For the 9,636-foot reach of Upper Hāmākua Ditch between the Kawainui and Kawaiki intakes and the Alakahi intake (Hawaii Division of Water and Land Development, 1963), 57 percent of the ditch lies in Kawainui Stream watershed and 43 percent lies in Alakahi Stream watershed.

At the time that discharge measurements were made at the low-flow partial-record station at site 1 on Kawainui Stream (see table 3 in main body of this report), discharge had been reduced by the amount of water being diverted by Upper Hāmākua Ditch at the Kawainui and Kawaiki intakes and increased by losses from the section of the ditch upgradient in the watershed. The magnitudes of these diversions and losses were computed, as outlined above, and used to estimate what the discharge at site 1 would have been under natural conditions had Upper Hāmākua Ditch not been active in any way (table 3–B). To estimate natural flow at site 1, measured discharge at the site was increased by the amount of water diverted upstream by the Upper Hāmākua Ditch. However, the measured discharge at site 1 is enhanced by upstream losses from Upper Hāmākua Ditch that return to Kawainui Stream upstream of the site. Thus, to avoid double counting of water, the amount of upstream losses were subtracted from measured discharge at site 1. This same type of water accounting process was followed at the remaining low-flow partial-record stations in Waipi‘o Valley. On average, discharge at site 1 had been reduced by about 3.0 ft^3/s,

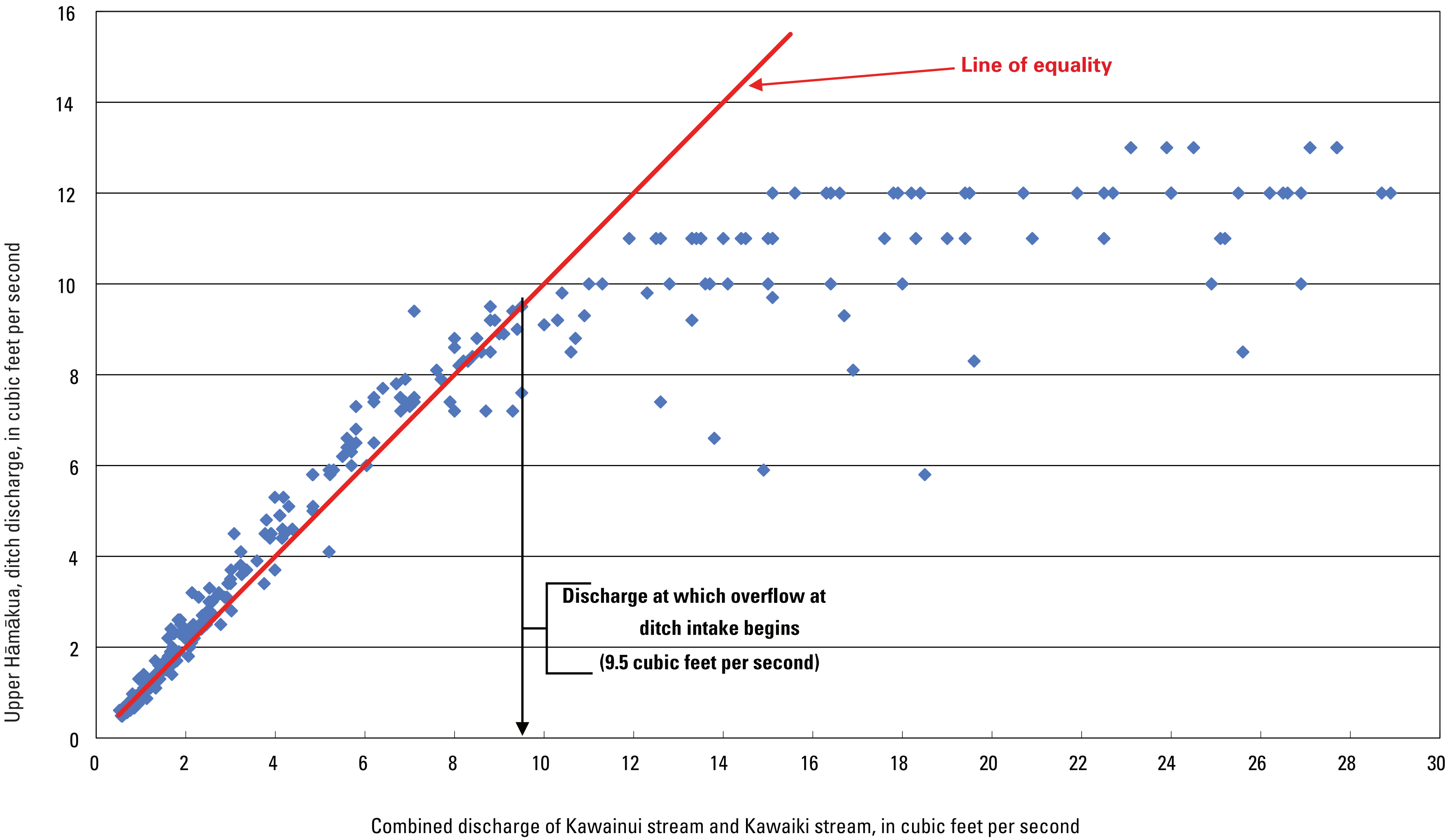


Figure 3–B. Relation between discharge at Upper Hāmākua Ditch (station 16720500) and combined discharge of Kawainui Stream (station 16720000) and Kawaiki Stream (station 16720300), Island of Hawai‘i, Hawai‘i, water year 1999.

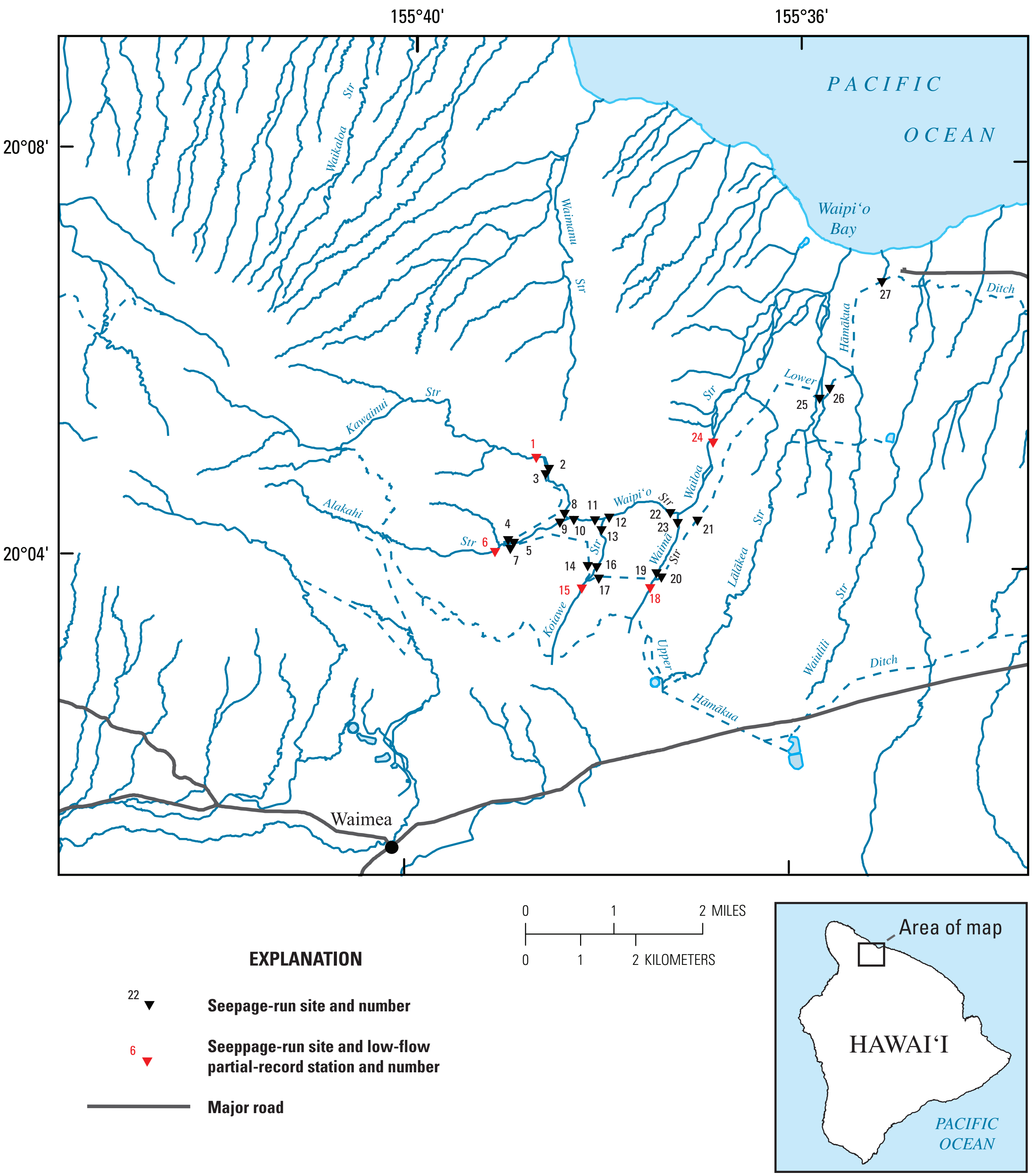


Figure 3–C. Locations where discharge measurements were made in Waipi‘o Valley study area during the period 2000–2005, Island of Hawai‘i, Hawai‘i.

Table 3–B. Effect of diversions by the Upper Hāmākua Ditch on discharge measurements made during the period 2000–2005 at Kawainui Stream low-flow partial-record site 1[a], Island of Hawai‘i, Hawai‘i.

[ft^3/s, cubic feet per second; UHD, Upper Hāmākua Ditch; --, not computed]

Date	Discharge measurement (ft^3/s)	Net effect of diversions by UHD (ft^3/s)	Estimated natural discharge (ft^3/s)	Change in natural discharge caused by UHD diversions (percent)
9/21/2000	26.5	-2.53	29.0	-8.7
1/10/2001	18.6	-0.12	18.7	-0.6
3/8/2001	59.1	-8.54	67.6	-12.6
5/30/2001	21.7	-1.12	22.8	-4.9
9/26/2001	41.5	-8.54	50.0	-17.1
6/26/2003	35.0	-5.97	41.0	-14.6
9/25/2003	22.6	-0.15	22.8	-0.7
10/6/2004	16.2	-0.46	16.7	-2.8
2/25/2005	11.4	-0.15	11.6	-1.3
8/24/2005	28.6	-2.64	31.2	-8.5
Average	--	-3.02	--	-7.2

[a] Site number corresponds to that shown in figure 3-C.

or 7.2 percent, from natural conditions on the 10 days when discharge measurements were made.

Total discharge in Upper Hāmākua Ditch at 3,890 feet was determined from data collected at the gaging station (16724800) in operation at that location through 2000. During the balance of the study period (2001–2005), discharge in Upper Hāmākua Ditch at 3,890 feet and upstream from Alakahi Stream was determined to be either the measured or estimated discharge in Upper Hāmākua Ditch at 4,020 feet (station 16720500) minus estimated loss of discharge in the reach of ditch between the two locations (see paragraphs above). Just downstream from the gaging station at 3,890 feet, Upper Hāmākua Ditch discharges into Alakahi Stream. This discharge point is just downstream from the streamflow-gaging station on Alakahi Stream at 3,900 feet (station 16725000) and just upstream from Upper Hāmākua Ditch Alakahi Stream intake at 3,874 feet. Total discharge in Alakahi Stream, just upstream from the ditch intake, can be computed by combining concurrent data measured or estimated in Upper Hāmākua Ditch at 3,890 feet (station 16724800) with measured data in Alakahi Stream at 3,900 feet (station 16725000). Discharge data for Alakahi Stream at 3,900 feet were available at gaging station 16725000 during the entire study period (2000–2005).

The amount of water diverted by Upper Hāmākua Ditch at Alakahi Stream intake has not been systematically measured. The next gaging station downstream along Upper Hāmākua Ditch is at 3,020 feet (station 16726000) (fig. 3–A), and flow at this location includes water diverted at Ko‘iawe and Waimā Stream intakes. To estimate the amount of water diverted by Upper Hāmākua Ditch at Alakahi Stream intake, the relation shown in figure 3–D was developed. In figure 3–D, discharge in Upper Hāmākua Ditch at 3,020 feet (station 16726000) is plotted against total discharge upstream from the Alakahi ditch intake. The graph shows that discharge in Upper Hāmākua Ditch at 3,020 feet is greater than total discharge upstream from Alakahi Stream intake on all but one day in 1999 when total Alakahi Stream discharge is less than or equal to about 11.0 ft^3/s. This indicates that Upper Hāmākua Ditch potentially has the capacity to divert all water at the Alakahi Stream intake up to 11.0 ft^3/s. This would be logical, given that Upper Hāmākua Ditch was estimated to be able to divert all water in Kawainui and Kawaiki Streams up to 9.5 ft^3/s (see paragraphs above), and ditch capacity typically increases in a downstream direction as more sources of potential contributing inflow are encountered.

Unfortunately, estimation of how much water will be diverted at Alakahi Stream intake is complicated by the additional intakes along Upper Hāmākua Ditch above the next downstream ditch-gaging station (16726000). The degree by which discharge in Upper Hāmākua Ditch at 3,020 feet exceeds total discharge upstream from Alakahi Stream intake is an indicator of potential increases in discharge at points downstream from the intake, assuming all discharge upstream from the intake is being diverted. Potential increases are

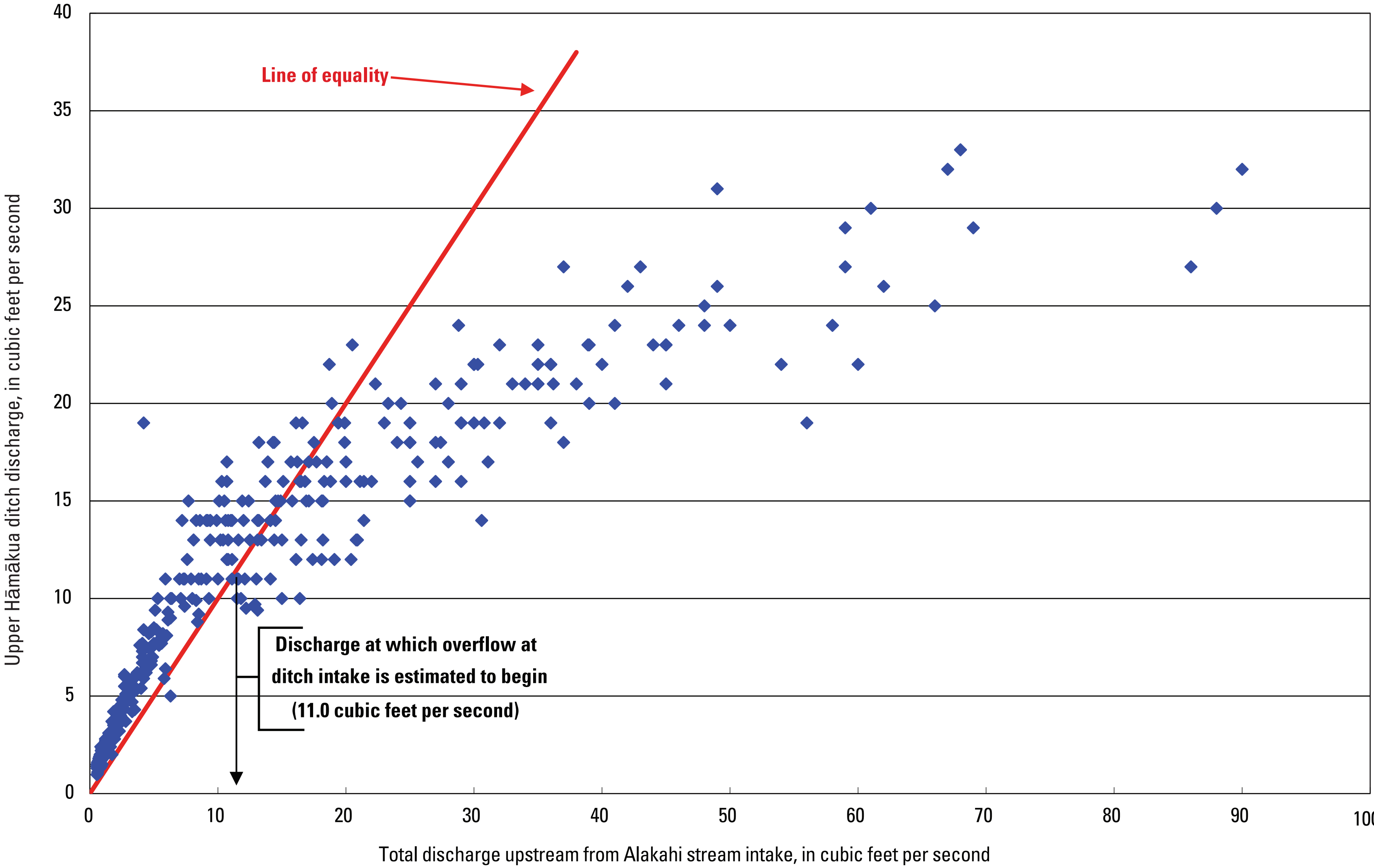


Figure 3–D. Relation between discharge at Upper Hāmākua Ditch (station 16726000) and the total discharge upstream from the Alakahi Stream Upper Hāmākua Ditch intake, Island of Hawai‘i, Hawai‘i, water year 1999.

represented by the degree to which concurrent discharge data points plot above the line of equality in figure 3–D. Potential increases follow a very distinct linear pattern up to a point at which total discharge upstream from Alakahi Stream intake equals about 8.0 ft^3/s; beyond that point, the data are quite variable. This distinct linear pattern is what would be expected when Upper Hāmākua Ditch diverts all the water available at Alakahi Stream intake and the intakes encountered before reaching ditch-gaging station 16726000 on Upper Hāmākua Ditch at 3,020 feet. Following this logic, it could reasonably be assumed that Upper Hāmākua Ditch diverts all the water upstream at Alakahi Stream intake up to 8.0 ft^3/s (assuming no ditch losses). In this study, diversion totals at the Alakahi ditch intake were not estimated for times when total discharge upstream from the intake exceeds 8.0 ft^3/s. This will not prove to be a significant limitation as there were only two days on which discharge measurements were made at downstream low-flow partial-record stations that discharge at Alakahi Stream intake exceeded this limit. On both of those days, discharge upstream from Alakahi Stream intake exceeded the maximum potential diversion capacity of 11.0 ft^3/s and was therefore beyond any reasonable range where diversion totals could be estimated.

There is a consistent pattern of increasing discharge in Upper Hāmākua Ditch between Alakahi Stream intake and the gaging station at 3,020 feet (16726000) (fig. 3–D). The magnitude of this increase can be computed by subtracting concurrent daily mean discharges at the two locations. Data upstream from Alakahi Stream intake were computed or estimated as discussed above. Data at Upper Hāmākua Ditch gaging station at 3,020 feet (16726000) are available through 2004. For the balance of the study period (2000–2005), a simple linear regression model was used to estimate the increase in discharge in the subject reach of the Upper Hāmākua Ditch. The regression was developed on the basis of data for 171 days in 1999 when the combined flow upstream from Alakahi Stream ditch intake was 8.0 ft^3/s or less, and it excluded data for four days when uncharacteristically large gains or losses in flow were indicated. The regression takes the form: increase in Upper Hāmākua Ditch discharge between Alakahi Stream intake and gaging station 16726000 at 3,020 feet = 1.6001 x discharge (in ft^3/s) at Alakahi Stream gaging station (16725000) – 0.1707. This model has a correlation coefficient of 0.869, which indicates a moderately strong linear relation.

Upper Hāmākua Ditch gaging station at 3,020 feet (16726000) is near the watershed divide between streams that drain to the north, into Waipiʻo Valley, and streams that drain to the southeast, away from Waipiʻo Valley. Increasing discharge in Upper Hāmākua Ditch between Alakahi Stream intake and the ditch-gaging station at 3,020 feet (16726000) can therefore be attributed to additional diversions from Alakahi, Koʻiawe, and Waimā watersheds, which are tributary to Waipiʻo Valley. The exact distribution of additional diversions from the three watersheds is unknown. In this study, it was estimated that the distribution of diversions was directly proportional to the percentage of Upper Hāmākua Ditch, for the reach in question, located in each of the three watersheds. For the 22,800-foot reach of Upper Hāmākua Ditch between Alakahi Stream intake and the ditch-gaging station at 3,020 feet (16726000) (Hawaii Division of Water and Land Development, 1963), 27 percent of the ditch lies in Alakahi watershed, 55 percent in Koʻiawe watershed, and 18 percent in Waimā watershed.

At the time that discharge measurements were made at the low-flow partial-record station at site 6 on Alakahi Stream (table 3–C), natural discharge had been (1) increased by the amount of losses from the section of Upper Hāmākua Ditch upgradient in the watershed and upstream from Alakahi Stream intake, (2) decreased by the amount of water originating from Alakahi Stream and being diverted by Upper Hāmākua Ditch at the Alakahi intake, and (3) decreased by the amount of diversion taking place along the part of Upper Hāmākua Ditch upgradient in the watershed and downstream from the Alakahi Stream intake. The magnitude of these diversions and losses were computed, as outlined above, and used to estimate what discharge at site 6 would have been under natural conditions had Upper Hāmākua Ditch not been active in any way (table 3–C). On average, discharge at site 6 was reduced by about 1.4 ft^3/s, or 7.9 percent, on eight days when measurements were made. Note that data were not computed for the March 8, 2001, discharge measurement because reasonable estimates of diversions at Alakahi Stream intake could not be made on that day (see discussion above regarding Alakahi ditch intake capacity).

At the time that discharge measurements were made at low-flow partial-record stations at sites 15 and 18 on Koʻiawe and Waimā Streams, natural discharge had been decreased by the amount of diversion taking place along the section of Upper Hāmākua Ditch located upgradient in the respective watersheds. As noted above, this diversion was estimated to be 55 percent of the gain in Upper Hāmākua Ditch discharge between Alakahi Stream intake and ditch-gaging station 16726000 at 3,020 feet (from Koʻiawe watershed) and 18 percent of the gain from Waimā watershed. The magnitudes of these diversions were computed and used to estimate what the discharge at sites 15 and 18 would have been under natural conditions had Upper Hāmākua Ditch not been active in any way (tables 3–D and 3–E). On average, discharge at sites 15 and 18 was reduced by about 0.8 and 0.2 ft^3/s, or 9.3 and 19.8 percent, respectively, on nine days when measurements were made. Note that data at both sites were not computed for the September 26, 2001, discharge measurement because reasonable estimates of diversions at Alakahi Stream intake could not be made on that day (see discussion above regarding Alakahi ditch intake capacity).

Effects of Diversions by Lower Hāmākua Ditch

Lower Hāmākua Ditch diverts water from Kawainui Stream (altitude 1,037 feet), Alakahi Stream (altitude 1,030 feet), and Koʻiawe Stream (altitude 1,000 feet) (U.S. Department of Agriculture, 1999, Mink, 1984). In addition to

Table 3–C. Effect of diversions by the Upper Hāmākua Ditch on discharge measurements made during the period 2000–2005 at Alakahi Stream low-flow partial-record site 6[a], Island of Hawaiʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; UHD, Upper Hāmākua Ditch; --, not computed]

Date	Discharge measurement (ft^3/s)	Net effect of diversions by UHD (ft^3/s)	Estimated natural discharge (ft^3/s)	Change in natural discharge caused by UHD diversions (percent)
9/20/2000	17.4	-2.36	19.8	-11.9
1/10/2001	14.1	-0.41	14.5	-2.8
3/8/2001	25.7	--	--	--
5/30/2001	14.2	-0.91	15.1	-6.0
6/26/2003	17.2	-3.16	20.4	-15.5
9/25/2003	14.3	-0.78	15.1	-5.2
10/6/2004	12.5	-0.72	13.2	-5.4
2/25/2005	11.4	-0.19	11.6	-1.6
8/24/2005	13.6	-2.32	15.9	-14.6
Average	--	-1.36	--	-7.9

[a] Site number corresponds to that shown in figure 3-C.

Table 3–D. Effect of diversions by the Upper Hāmākua Ditch on discharge measurements made during the period 2000–2005 at Koʻiawe Stream low-flow partial-record site 15[a], Island of Hawaiʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; UHD, Upper Hāmākua Ditch; --, not computed]

Date	Discharge measurement (ft^3/s)	Net effect of diversions by UHD (ft^3/s)	Estimated natural discharge (ft^3/s)	Change in natural discharge caused by UHD diversions (percent)
8/8/2000	7.02	-0.92	7.94	-11.6
9/21/2000	7.53	-1.05	8.58	-12.2
1/11/2001	7.28	-0.16	7.44	-2.2
3/9/2001	8.28	+0.11	8.17	+1.3
5/31/2001	7.18	-0.69	7.87	-8.8
9/26/2001	10.5	--	--	--
6/27/2003	8.30	-2.07	10.4	-20.0
9/26/2003	7.52	-0.59	8.11	-7.3
10/7/2004	7.32	-0.35	7.67	-4.6
4/27/2005	7.38	-1.67	9.05	-18.5
Average	--	-0.82	--	-9.3

[a] Site number corresponds to that shown in figure 3-C.

Table 3–E. Effect of diversions by the Upper Hāmākua Ditch on discharge measurements made during the period 2000–2005 at Waimā Stream low-flow partial-record site 18[a], Island of Hawai‘i, Hawai‘i.

[ft^3/s, cubic feet per second; UHD, Upper Hāmākua Ditch; --, not computed]

Date	Discharge measurement (ft^3/s)	Net effect of diversions by UHD (ft^3/s)	Estimated natural discharge (ft^3/s)	Change in natural discharge caused by UHD diversions (percent)
08/08/2000	0.62	-0.30	0.92	-32.6
09/20/2000	0.61	0.00	0.61	-0.0
01/11/2001	0.69	-0.05	0.74	-6.8
03/09/2001	0.60	+0.04	0.56	+7.1
05/31/2001	0.53	-0.23	0.76	-30.3
09/26/2001	0.86	--	--	--
06/27/2003	0.67	-0.68	1.35	-50.4
09/26/2003	0.67	-0.19	0.86	-22.1
10/07/2004	0.72	-0.11	0.83	-13.3
08/23/2005	0.93	-0.40	1.33	-30.1
Average	--	-0.21	--	-19.8

[a] Site number corresponds to that shown in figure 3-C.

diversions at the three intakes, Lower Hāmākua Ditch also diverts (gains) or loses water at various diffuse and point locations along its entire reach. The gaging station on Lower Hāmākua Ditch (16732800), upstream from the main weir, measures the net amount of water diverted by the ditch from tributaries to Wailoa Stream. Discharge measured at station 16732800 also reflects gains associated with the interception of groundwater by Lower Hāmākua Ditch and losses at Hi‘ilawe Falls that would discharge into Wailoa Stream at points downstream from site 24 (fig. 3–C). Visual observations during the time of the study (2000–2005) indicate that the magnitudes of gains and loses were comparable. For this analysis, it was assumed that these gains and losses would cancel each other out; therefore discharge measured at gaging station 16732800 during the study will account for the total effects of diversions by Lower Hāmākua Ditch on discharge measured at site 24.

Discharge measurements or gaging station data that documented net diversions were available at Lower Hāmākua Ditch gaging station 16732800 on five of the nine days that discharge measurements were made at low-flow partial-record station at site 24 (see table 3 in main body of this report). Discharge data that documented net diversions at gaging station 16732800 on the remaining four days was estimated by establishing a simple linear regression model. The model was based on estimated discharge data at Upper Hāmākua Ditch gaging station 16726000 and measured discharge data at Lower Hāmākua Ditch gaging station 16732800 on the four days for which data were available at both stations and discharge measurements were made at the low-flow partial-record station at site 24. The regression indicated that Lower Hāmākua Ditch discharge (ft^3/s) could be estimated as 2.313 x Upper Hāmākua Ditch discharge (in ft^3/s) + 8.776. This model has a correlation coefficient of 0.918, which indicates a moderately strong linear relation.

At the time that discharge measurements were made at the low-flow partial-record station at site 24 on Wailoa Stream, discharge was decreased by diversions to Upper and Lower Hāmākua Ditches at upgradient locations. The magnitudes of these diversions were computed, as outlined above, and used to estimate what discharge at site 24 would have been, under natural conditions, had Upper and Lower Hāmākua Ditches not been active in any way (table 3-F). On average, discharge at site 24 was reduced by diversions of 5.1 ft^3/s to Upper Hāmākua Ditch and 18.3 ft^3/s to Lower Hāmākua Ditch. On average, discharge in Wailoa Stream at site 24 (fig. 3–C) was reduced by a total of 21.9 percent on the nine days when discharge measurements were made.

Table 3–F. Effect of diversions by the Upper and Lower Hāmākua Ditches on discharge measurements made during the period 2000–2005 at Wailoa Stream low-flow partial-record site 24[a], Island of Hawaiʻi, Hawaiʻi.

[ft^3/s, cubic feet per second; UHD, Upper Hāmākua Ditch; LHD, Lower Hāmākua Ditch; --, not computed]

Date	Discharge measurement (ft^3/s)	Net effect of diversions by UHD (ft^3/s)	Net effect of diversions by LHD (ft^3/s)	Estimated natural discharge (ft^3/s)	Change in natural discharge caused by UHD and LHD diversions (percent)
09/21/2000	78.3	-6.00	-25.5	110	-28.7
01/10/2001	68.8	-0.75	-11.1	80.7	-14.7
03/09/2001	76.5	-7.40	-25.9	110	-30.3
05/30/2001	73.3	-2.50	-16.2	92.0	-20.3
09/26/2001	103	-14.0	-20.0	137	-24.8
06/27/2003	82.9	-6.90	-19.0	109	-23.8
09/25/2003	84.6	-1.80	-9.8	96.2	-12.1
10/06/2004	69.4	-1.70	-17.0	88.1	-21.2
08/23/2005	95.7	-5.06	-20.5	121	-21.1
Average	--	-5.12	-18.3	--	-21.9

[a] Site number corresponds to that shown in figure 3-C.

Menlo Park Publishing Service Center, California
Manuscript approved for publication, January 28, 2011
Edited by Peter H. Stauffer
Layout by Judy Weathers

Fontaine, R.A.—**Low-Flow Characteristics of Streams Under Natural and Diversion Conditions, Waipiʻo Valley, Island of Hawaiʻi, Hawaiʻi**—Scientific Investigations Report 2011–5118