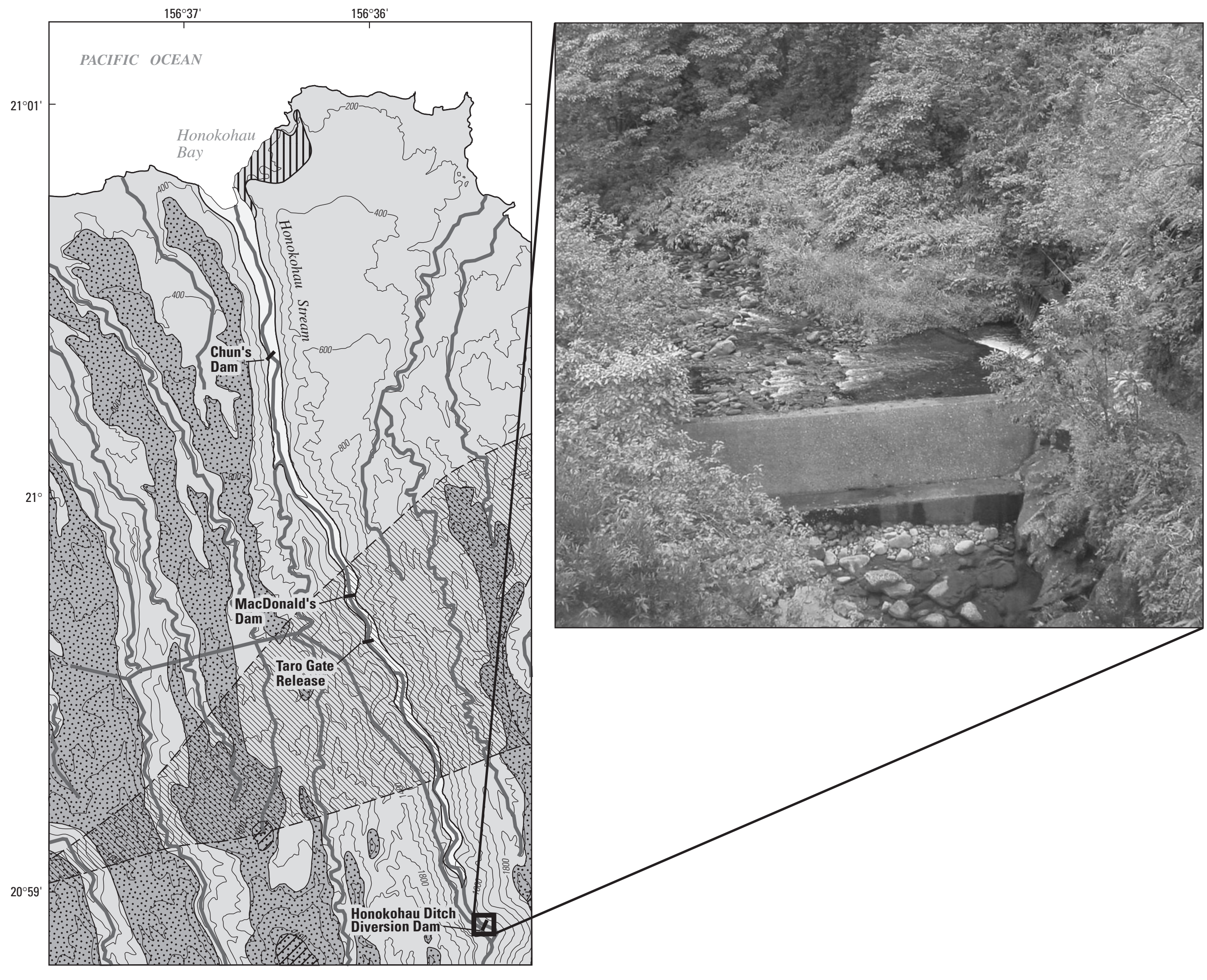
Availability and Distribution of Base Flow in Lower Honokohau Stream, Island of Maui

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

Water-Resources Investigations Report 03-4060



Prepared in cooperation with the
STATE OF HAWAII OFFICE OF HAWAIIAN AFFAIRS

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Honolulu, Hawaii
2003

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND DATUMS

Multiply	By	To obtain
inch (in)	2.54	centimeter
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1895	meter per kilometer
mile (mi)	1.609	kilometer
acres	4,047	square meter
square mile (mi^2)	2.590	square kilometer
square mile (mi^2)	640	acre
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Datums

Vertical coordinate information is referenced relative to mean sea level.
Horizontal coordinate information is referenced to the Northern American Datum of 1983 (NAD 83).

Availability and Distribution of Base Flow in Lower Honokohau Stream, Island of Maui, Hawaii

By **Richard A. Fontaine**

Abstract

Honokohau Stream is one of the few perennial streams in the Lahaina District of West Maui. Current Honokohau water-use practices often lead to conflicts among water users, which are most evident during periods of base flow. To better manage the resource, data are needed that describe the availability and distribution of base flow in lower Honokohau Stream and how base flow is affected by streamflow diversion and return-flow practices.

Flow-duration discharges for percentiles ranging from 50 to 95 percent were estimated at 13 locations on lower Honokohau Stream using data from a variety of sources. These sources included (1) available U.S. Geological Survey discharge data, (2) published summaries of Maui Land & Pineapple Company, Inc. diversion and water development-tunnel data, (3) seepage run and low-flow partial-record discharge measurements made for this study, and (4) current (2003) water diversion and return-flow practices. These flow-duration estimates provide a detailed characterization of the distribution and availability of base flow in lower Honokohau Stream.

Estimates of base-flow statistics indicate the significant effect of Honokohau Ditch diversions on flow in the stream. Eighty-six percent of the total flow upstream from the ditch is diverted from the stream. Immediately downstream from the diversion dam there is no flow in the stream 91.2 percent of the time, except for minor leakage through the dam. Flow releases at the Taro Gate, from Honokohau Ditch back into the stream, are inconsistent and were found to be less than the target release of 1.55 cubic feet per second on 9 of the 10 days on which measurements were made. Previous estimates of base-flow availability downstream from the Taro Gate release range from 2.32 to 4.6 cubic feet per second (1.5 to 3.0 million gallons per day). At the two principal sites where water is currently being diverted for agricultural use in the valley (MacDonald’s and Chun’s Dams), base flows of 2.32 cubic feet per second (1.5 million gallons per day) are available more than 95 percent of the time at MacDonald’s Dam and 80 percent of the time at Chun’s Dam. Base flows of 4.6 cubic feet per second (3.0 million gallons per day) are available 65 and 56 percent of the time, respectively.

A base-flow water-accounting model was developed to estimate how flow-duration discharges for 13 sites on Honokohau Stream would change in response to a variety of flow release and diversion practices. A sample application of the model indicates that there is a 1 to 1 relation between changes in flow release rates at the Taro Gate and base flow upstream from MacDonald’s Dam. At Chun’s Dam the relation between Taro Gate releases and base flow varies with flow-duration percentiles. At the 95th and 60th percentiles, differences in base flow at Chun’s Dam would equal about 50 and 90 percent of the change at the Taro Gate.

INTRODUCTION

Honokohau Stream is one of only three streams in the Lahaina District (fig. 1) that flows perennially to the sea (Hawaii Commission on Water Resource Management, 1990, p. 23). The perennial nature of Honokohau streamflow makes it a valuable resource for meeting the often conflicting needs of in-stream, near-stream, and off-stream water users in the area. These conflicts are most evident during periods of minimal streamflow, or base flow, when water in the stream is derived primarily from ground-water sources.

Starting in June 1904, with the completion of the Honokohau Ditch (also known as the Honolua Ditch), most of the flow in Honokohau Stream at an altitude of 700 ft (the ditch intake was relocated upstream to an altitude of 825 ft in November 1913) was diverted for off-stream uses. During periods of base flow, the stream reach between the ditch intake and the springs, located at an altitude of 600 ft, is considered dry (Hawaii Department of Land and Natural Resources, 1977, p. 30; and Mink, 1990). The stream reach between the springs and the ocean is considered perennial. Previous estimates indicated that at least 2.32 ft^3/s (1.5 Mgal/d) of base flow [0.77 ft^3/s (0.5 Mgal/d) from the spring at an altitude of 600 ft and 1.55 ft^3/s (1.0 Mgal/d) released from Honokohau Ditch] were available to meet the water needs in lower Honokohau Stream (Hawaii Department of Land and Natural Resources, 1977, p. iv).

The U.S. Geological Survey (USGS) operates a streamflow-gaging station, upstream of the Honokohau Ditch intake, at an altitude of 870 ft on Honokohau Stream. As of October 1, 2000, a total of 82 water years of streamflow data were available to describe hydrologic conditions at the gage. Only limited data were available to assess base flow and the effects of streamflow diversions downstream from the gage.

In cooperation with the Office of Hawaiian Affairs (OHA), the USGS investigated how base flow in lower Honokohau Stream varies both with time and location along the stream. Historic and new data were collected and analyzed to evaluate the effects associated with human manipulations of streamflow as well as natural variability. These data are needed to better manage the limited resource.

PURPOSE AND SCOPE

The purpose of this report is to (1) quantify the amount of water available in lower Honokohau Stream during periods of base flow, (2) describe how the base flow varies both with time and location along the stream, and (3) quantify the effects that streamflow diversions and return flows have on base-flow availability.

To achieve the purposes of this report, both historic and new streamflow data and field observations were analyzed. Historic data included (1) 82 years of streamflow data collected by the USGS at streamflow-gaging station 16620000 on Honokohau Stream at altitude 870 ft, (2) published summaries of Maui Land & Pineapple Company, Inc. flow data for the Honokohau ditch diversion and development tunnels T-21 and T-22 upstream from the diversion (fig. 4), (3) estimates of Honokohau ditch diversion capacity and ditch-flow release practices from Maui Land & Pineapple Company, Inc., and (4) historic discharge measurements made by the USGS along Honokohau Stream. New streamflow data and field observations included (1) three seepage runs made on the lower reach of Honokohau Stream (from station 16620000 downstream to the ocean), (2) a minimum of 10 discharge measurements at each of three low-flow partial-record stations on the lower reach of Honokohau Stream, and (3) field observations of streamflow (or lack of it) and diversion and return-flow practices.

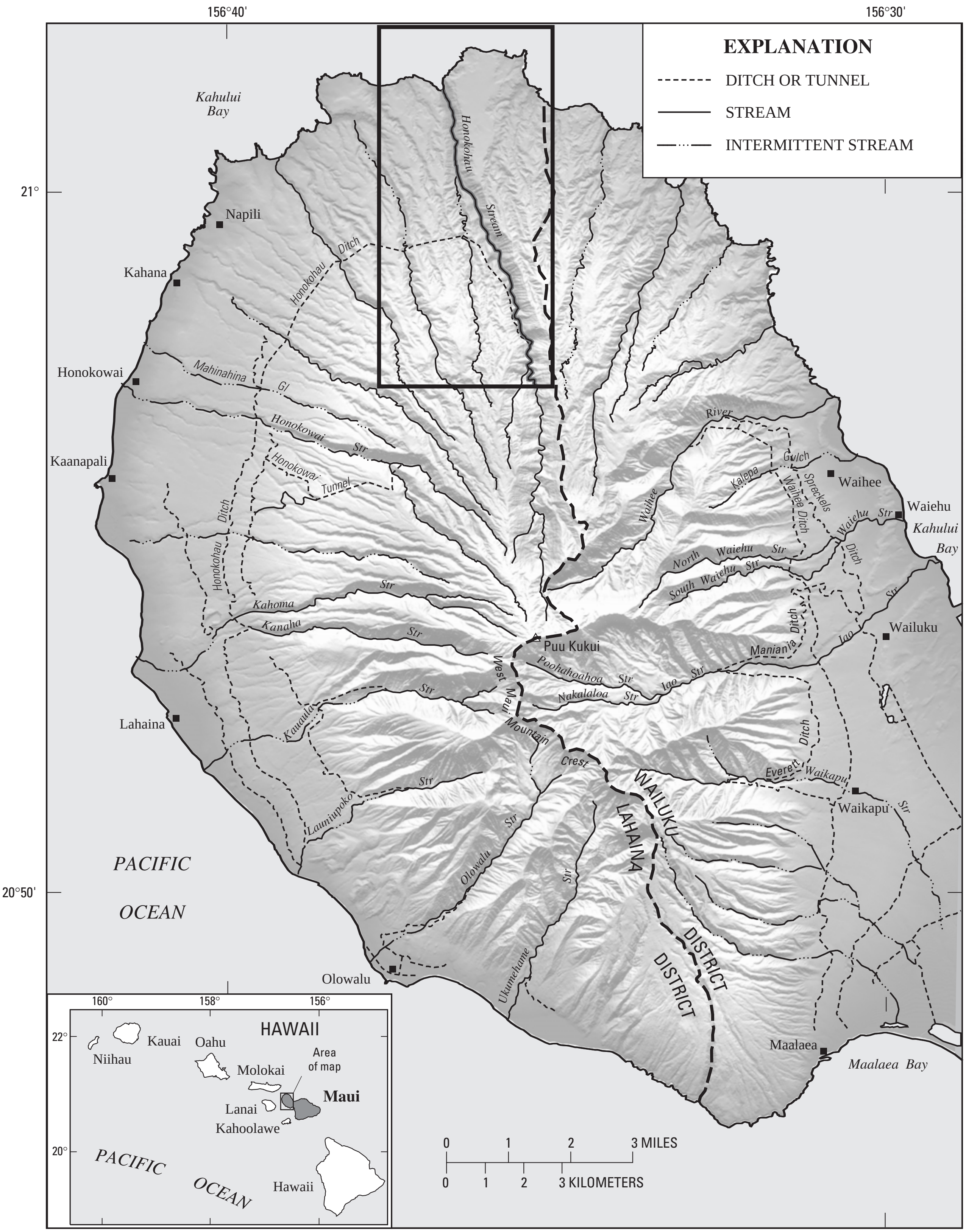
ACKNOWLEDGMENTS

Mr. Wesley Nohara and other Maui Land & Pineapple Company, Inc. (ML&P) employees were most generous with their time and detailed knowledge of the study area. In addition they allowed USGS personnel access to ML&P's properties in Honokohau Valley to collect new data. We also appreciate the information and access to privately owned lands provided by numerous residents of Honokohau Valley and members of the Honokohau Valley Association.

DESCRIPTION OF STUDY AREA

Physical Setting

The island of Maui is formed by two volcanoes (fig. 1). The Honokohau Stream watershed lies on the northwest side of the western volcano and has a total drainage area estimated to be 8.12 square miles (mi^2) at its mouth (Chiu Yeung, U.S. Geological Survey, Honolulu, Hawaii, oral commun., 2002). The total drainage area of the Honokohau Stream watershed upstream from station 16620000 (fig. 4) is 4.11 mi^2 (Taogoshi and others, 2001, p. 206). Honokohau is the longest stream in West Maui, traversing a nearly straight line



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 1. The Hawaiian islands, island of Maui, and the Honokohau Stream study area, Hawaii.

about 9.5 mi long from its headwaters at Puu Kukui to the ocean (Hawaii Department of Land and Natural Resources, 1977, p. 29). Starting from the summit of Puu Kukui (altitude of 5,788 ft) Honokohau Stream descends about 900 ft over its first 1.2 mi or an average slope of about 720 feet per mile (ft/mi). At Honokohau Falls the stream cuts down through the Wailuku Basalt about 2,300 ft, forming an impressive amphitheatre-shaped valley (Stearns and Macdonald, 1942, pl. 28). Over the remaining 8.3 mi of its course to the ocean, Honokohau Stream flows through a relatively wide valley and has a fairly uniform slope that averages about 310 ft/mi.

The Honokohau Stream watershed drains an area that has a steep rainfall gradient (fig. 2) (Giambelluca and others, 1986, p. 112). The mean annual rainfall at the head of the watershed (Puu Kukui) is greater than 355 in. (9,000 millimeters), which is the second highest total in Hawaii (Meyer and Presley, 2001, p. 8). Mean annual rainfall near the mouth of Honokohau Stream is about 40 in. (1,000 millimeters). The weighted-average mean annual rainfall for the part of the Honokohau watershed upstream from station 16620000 was estimated to be about 241 in. (Hawaii Department of Land and Natural Resources, 1977, p. 19).

The headwaters of Honokohau watershed are primarily forest covered. Downstream, the first evidence of artificial alterations in the Honokohau watershed are water development tunnels T-21 and T-22, which are located at altitudes of 880 and 900 ft (fig. 4). Just downstream at an altitude of 825 ft is the diversion dam and intake which marks the start of the Honokohau Ditch (fig. 4). Currently all residential housing in the valley is downstream from MacDonald's Dam, which is located at an altitude of about 340 ft (fig. 4). Historically taro cultivation was estimated to encompass in excess of 10 acres in Honokohau Valley (Hawaii Commission on Water Resource Management, 1990, p. 214). Field evidence indicated that this cultivation took place at stream altitudes up to about 600 ft. As of March 1992, 3.13 acres of taro was under cultivation with an additional 8.07 acres planned for future production (Bill Rozeboom, Hawaii Commission on Water Resource Management, written commun., 1992). Most of the existing taro cultivation takes place downstream from Chun's Dam (fig. 4), which is at an altitude of about 90 ft. Most of the taro cultivation planned for the future is downstream from MacDonald's Dam (fig. 4), however two parcels are near the Taro Gate release (fig. 4) at an altitude of about 405 ft. In addition to taro cultivation, a variety of other small-scale agricultural activities take place in the valley below the diversion at MacDonald's Dam (fig. 4).

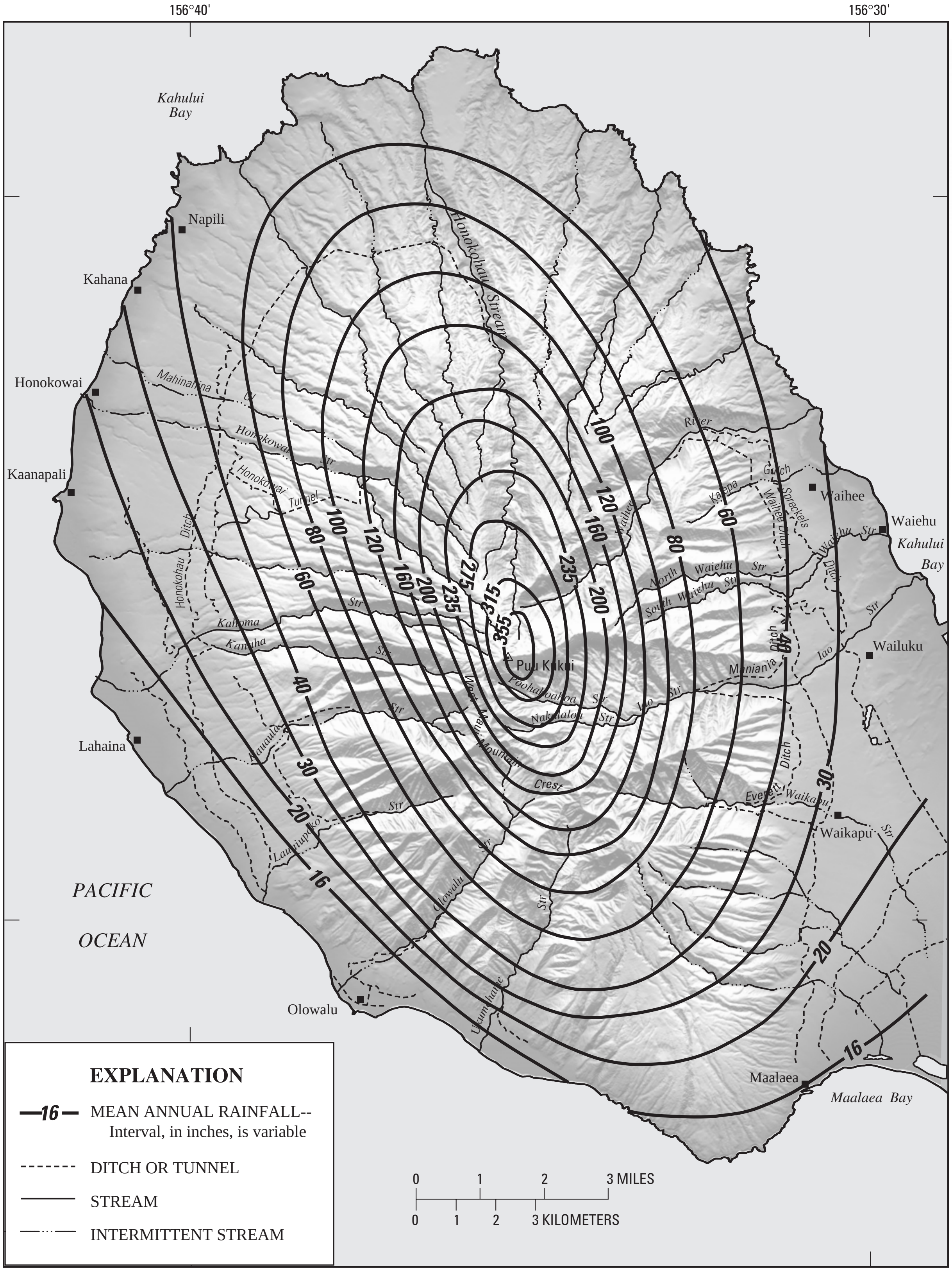
Geologic Setting

The volcano that forms west Maui differs from most Hawaiian volcanoes in that it is nearly circular (Stearns and Macdonald, 1942, p. 156). This near circular shape is attributed to the radial pattern of dikes from the volcano summit. The structure of the volcano is characterized by its central caldera and two principal rift zones, which trend to the northwest and southeast (fig. 3). Two less pronounced rift zones trend to the northeast and southwest (Macdonald and others, 1983, p. 381).

West Maui's volcano is composed of three principal units: the Wailuku Basalt, the Honolua Volcanics, and the Lahaina Volcanics (Stearns and Macdonald, 1942; and Langenheim and Clague, 1987). The Wailuku Basalt is the oldest of the three units and contains mostly thin pahoehoe and aa lava flows that built the shield volcano. Following the completion of the shield-building stage, a veneer estimated to range from 50 to 500 ft thick was deposited over most of the basaltic dome. These post-shield building deposits were classified as the Honolua Volcanics. Subsequent to the eruption of the Honolua Volcanics there was an extended erosional period. During this time canyons up to 2,000 to 4,000 ft deep were cut. The Lahaina Volcanics were the result of eruptions that took place after this period. These eruptions were minor and were confined to the western slopes of the volcano.

The northwest trending rift zone of the West Maui Volcano runs roughly parallel to the linear Honokohau Stream Valley. Dikes have been identified along most of Honokohau Stream (fig. 3) with the majority of them having strikes that are approximately parallel to the direction of the stream. Dikes in the Wailuku Basalt have widths that average about 1.5 ft and range from a few inches to 10 ft in width (Stearns and Macdonald, 1942, p. 163).

In the vicinity of Honokohau Valley the principal volcanic unit is the Wailuku Basalt. The limited areas of Honolua Volcanics found in the valley are located along the boundaries with adjacent watersheds. The Wailuku Basalt is one of the most permeable volcanic units on Maui. Dikes complexes in the Wailuku Basalt would be



Base modified from U.S. Geological Survey digital data, 1:24,000, 1983, Albers equal area projection, standard parallels 20°35' and 21°00', central meridian 156°20'

Figure 2. Mean annual rainfall in west Maui, Hawaii (modified from Giambelluca and others, 1986).

Figure 3. Geology of the West Maui Volcano, Hawaii (modified from Stearns and Macdonald, 1942, and Langenheim and Clague, 1987).

EXPLANATION

SEDIMENTARY DEPOSITS

- Unconsolidated deposits, chiefly younger alluvium
- Calcareous sand dunes
- Consolidated earthy deposits, chiefly older alluvium

VOLCANIC ROCKS

- Lahaina Volcanics
- Honolua Volcanics
- Kula Volcanics
- Wailuku Basalt

CONES, VENTS, DOMES, CRATERS, BOSSES, AND DIKES

- Cone or vent of Lahaina Volcanics
- Cones or domes of Honolua Volcanics
- Cones or vents of Wailuku Basalt
- Pit craters
- Bosses of Wailuku Basalt
- Dikes of either Wailuku Basalt or Honolua Volcanics
- Dikes, where too numerous to show individually
- Axis of main rift zones (from Macdonald and others, 1983)
- Caldera boundary, dotted where concealed, dashed where inferred

expected to contain significant quantities of high-level ground water. Streams cutting through these dike complexes would encounter perennial sources of water. The Honolua Volcanics has significantly lower permeabilities and would not be expected to carry significant volumes of water (Stearns and Macdonald, 1942, p. 157).

In Honokohau Valley unconsolidated alluvial deposits have been mapped along the stream channel at altitudes as high as about 800 ft (fig. 4). These alluvial materials are chiefly poorly-sorted lava-rock gravels that were deposited during periods when sea levels rose significantly higher than current levels. These unconsolidated deposits can be expected to contain water derived from perennial stream reaches. Consolidated deposits that consist chiefly of older alluvium underlie most of the unconsolidated deposits in west Maui (Stearns and Macdonald, 1942, p. 182).

Hydrologic Setting and Water Diversions

Ground water in the Honokohau watershed occurs primarily as a freshwater lens or dike-impounded, high-level water. The freshwater lens is ground water that floats on the denser, underlying saltwater. Dike-impounded, high-level ground water is in direct contact with the freshwater lens but is distinguished from it primarily because it is found at higher altitudes. Honokohau Valley lacks a significant zone of low permeability material (or caprock) that would impede the discharge of ground water at the ocean. As a result the surface of the freshwater lens stands about 1 foot above sea level near the coast. The freshwater lens rises about 1.5 to 2.5 ft/mi inland for about 2 to 3 mi (Stearns and Macdonald, 1942, p. 189) where there is a transition from the freshwater lens to high-level water.

In Honokohau Valley the location of the transitional area from the freshwater lens to high-level ground water is poorly defined. Yamanaga and Huxel (1969, p. 14) infer that the transitional zone is located along the edge of the dike zone. In Honokohau Valley this zone was shown to be located between 2.2 and 3.5 mi upstream from the mouth (fig. 4). In the transitional area, ground-water levels can be a few tens of feet above sea level (Yamanaga and Huxel, 1969, p. 16).

In Honokohau Valley, high-level ground water is confined in compartments of permeable Wailuku Basalt by numerous intersecting dikes. The radial pattern of dikes in the West Maui Volcano results in an oval-shaped area of high-level water that underlies most of the volcano. The surface of the dike-impounded high-level ground water rises from about 700 to 1,200 ft, near the inland edge of the transitional area, up to 3,500 ft, or more, inland (Stearns and Macdonald, 1942, p. 195). Heavy rainfall over the West Maui Volcano (fig. 2) provides an abundant source of recharge to these high-level water bodies.

Honokohau Stream has eroded a deep canyon, cutting down through the Wailuku Basalt and the confining dikes as much as 2,300 ft at Honokohau Falls (Stearns and Macdonald, 1942, pl. 28). This erosional activity, and to a lesser degree seepage through the confining dikes, allows Honokohau Stream to tap the significant volumes of water stored as high-level ground water. The result is that Honokohau Stream flows perennially in the zone of high-level ground water. The sustained perennial nature of this streamflow is apparent when analyzing flow records collected by the USGS at gaging station 16620000 on Honokohau Stream at an altitude of 870 ft. The minimum flow recorded during 82 years of data collected between 1913 and 2000 was 8.4 ft^3/s (5.4 Mgal/d) (Taogoshi and others, 2001, p. 206).

Large springs are located just downstream from station 16620000 and upstream from the Honokohau Ditch intake. Water development tunnels T-21 and T-22 (fig. 4) were constructed starting in 1913 (they were later extended in the 1920's), in an attempt to enhance the flow of the springs. However it is considered unlikely that perennial flow, in addition to that already being discharged naturally, was developed by the tunnels (Hawaii Department of Land and Natural Resources, 1977, p. 31). Tunnel T-21 is located on the west side of Honokohau Stream about 700 ft downstream from the USGS gage. The tunnel is about 850 ft long and cuts through 8 dikes (Mink, 1990). Tunnel T-22 is located on the east side of Honokohau Stream about 300 ft downstream from the USGS gage. The tunnel is 990 ft long and cuts through 10 dikes (Mink, 1990). Tunnels T-21 and T-22 in combination contributed an average flow of about 6.2 ft^3/s (4.0 Mgal/d) to Honokohau Stream over the period 1926–41 (Yamanaga and Huxel, 1969, p. 30). This flow enters the stream in the reach between station 16620000, at an altitude of 870 ft, and the current location of the Honokohau Ditch intake, at an altitude of 825 ft.

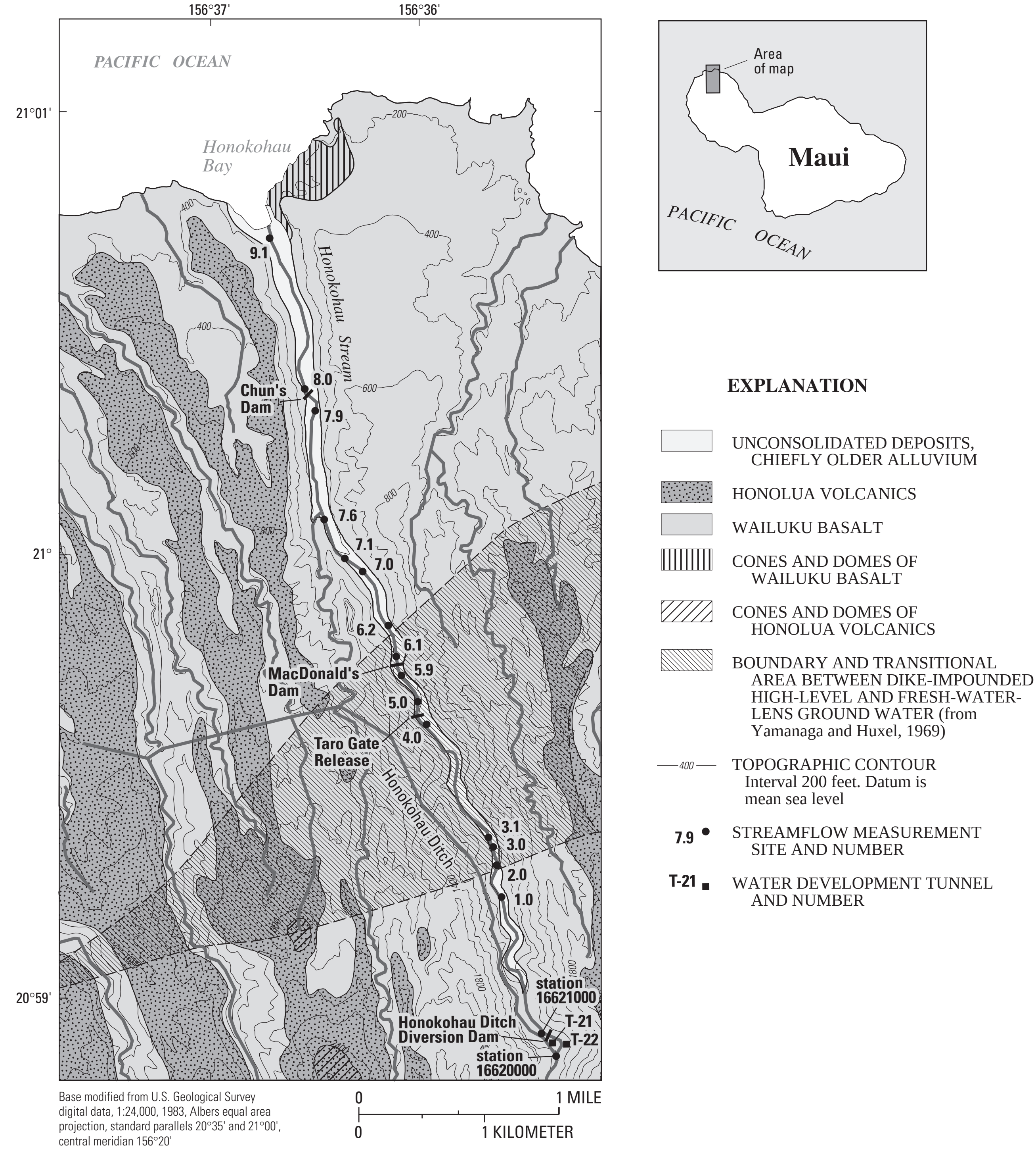


Figure 4. Streamflow measurement sites in, and geology of, lower Honokohau Valley, island of Maui (geology from Stearns and Macdonald, 1942, and Langenheim and Clague, 1987).

Starting in June 1904 with the completion of the first Honokohau Ditch (also known as the Honolua Ditch), most of the flow in Honokohau Stream at an altitude of 700 ft was diverted for off-stream uses. Honokohau Ditch was built twice and extensively renovated once during its first 20 years of operation (Wilcox, 1996, p. 126). As a result of these changes the ditch intake was relocated upstream, from the initial altitude of 700 ft to the current location, at an altitude of 825 ft. Updates to the ditch also significantly increased the capacity, at the Honokohau Stream intakes, from the original range of 30 to 39 Mgal/d (Wilcox, 1996, p. 127) to the current range of 60 to 65 Mgal/d (Wesley Nohara, Maui Land and Pineapple Company, Inc., oral commun., 2002). The average flow diverted from Honokohau Stream has been estimated to be 37.2 ft^3/s (24 Mgal/d) although it is not clear over which time period this average flow was computed (Hawaii Commission on Water Resource Management, 1992, p. D7).

During periods of base flow, Honokohau Ditch diverts all the flow in Honokohau Stream at the ditch intake. The stream reach extending about 1 mi downstream from the ditch intake to some springs, which start at an altitude of 600 ft (site 2.0 in figure 4), is dry during these periods (Hawaii Department of Land and Natural Resources, 1977; and Mink, 1990). The springs discharge into the stream along a reach that extends between altitudes of about 600 to 550 ft. This discharge is overflow from a dike compartment (Hawaii Department of Land and Natural Resources, 1977, p. 30). A variety of estimates have been given for the sustained discharge from the springs, ranging from about 0.77 ft^3/s (0.5 Mgal/d) (Hawaii Department of Land and Natural Resources, 1977, p. iv) to about 3.1 ft^3/s (2.0 Mgal/d) (Wesley Nohara, Maui Land and Pineapple Company, Inc., written commun., 1993). Flow estimates for the springs have been based on only limited historic data. The stream reach between the springs, which start at an altitude of 600 ft, and the ocean is perennial.

At a stream altitude of about 405 ft, ML&P returns some Honokohau Ditch water back into the stream. This water is released at a location commonly known as the Taro Gate to help support downstream taro farmers. ML&P has historically sought to maintain a flow release of 1.55 ft^3/s (1.0 Mgal/d) at this location (Wesley Nohara, Maui Land and Pineapple Company, Inc., oral commun., 2003). Three water pipes connected to Honokohau Ditch extend along Honokohau Stream downstream from the Taro Gate. One pipe transports water out of the Honokohau watershed for irrigation of pineapple fields. A second pipe historically provided an average of about 0.31 ft^3/s (0.2 Mgal/d) of water to a Maui Department of Water Supply (Maui DWS) water tank in the valley. This water tank in turn provided the drinking water supply for residents in the valley. Currently (2002) this second pipe is not in use and the Maui DWS pumps water from tanker trucks to replenish the storage tank. A third pipe provides an average of 0.46 ft^3/s (0.3 Mgal/d) of water to a small-scale hydropower generator located at MacDonald's Dam at an altitude of 340 ft (fig. 4). The 0.46 ft^3/s (0.3 Mgal/d) from the hydropower plant is subsequently released back into Honokohau Stream via the water diversion ditch that originates at MacDonald's Dam.

Downstream from the Taro Gate release two diversion dams are in place, MacDonald's Dam (altitude of 340 ft) and Chun's Dam (altitude of 90 ft). Both of these dams divert varying amounts of water into ditches that provide irrigation water in the valley. Excess water from these ditches is returned to Honokohau Stream, although the locations of the return flows are commonly widely dispersed. Numerous, smaller scale diversions, which usually involve small pipes set in the stream, can also be found in operation at various locations downstream between MacDonald's Dam and the ocean.

DATA COLLECTION AND ANALYSIS

In this section of the report, site-specific streamflow data that have historically been collected by the USGS or that have been collected specifically for this study in the Honokohau watershed will be summarized. Included are data for two streamflow-gaging stations, three low-flow partial-record stations, and several miscellaneous discharge measurements.

Streamflow-Gaging Stations

The USGS operated streamflow-gaging station 16621000 from March 1906 through August 1913. This station was located at the intake to the Honokohau Ditch and measured diversions from Honokohau Stream by the ditch. During this period, the original ditch, at the downstream location, was in operation and as a result these data have little applicability to present day conditions in the valley. It is interesting to note, however, that the maximum daily discharge recorded during this period was 48 ft^3/s (31 Mgal/d) and this value agrees

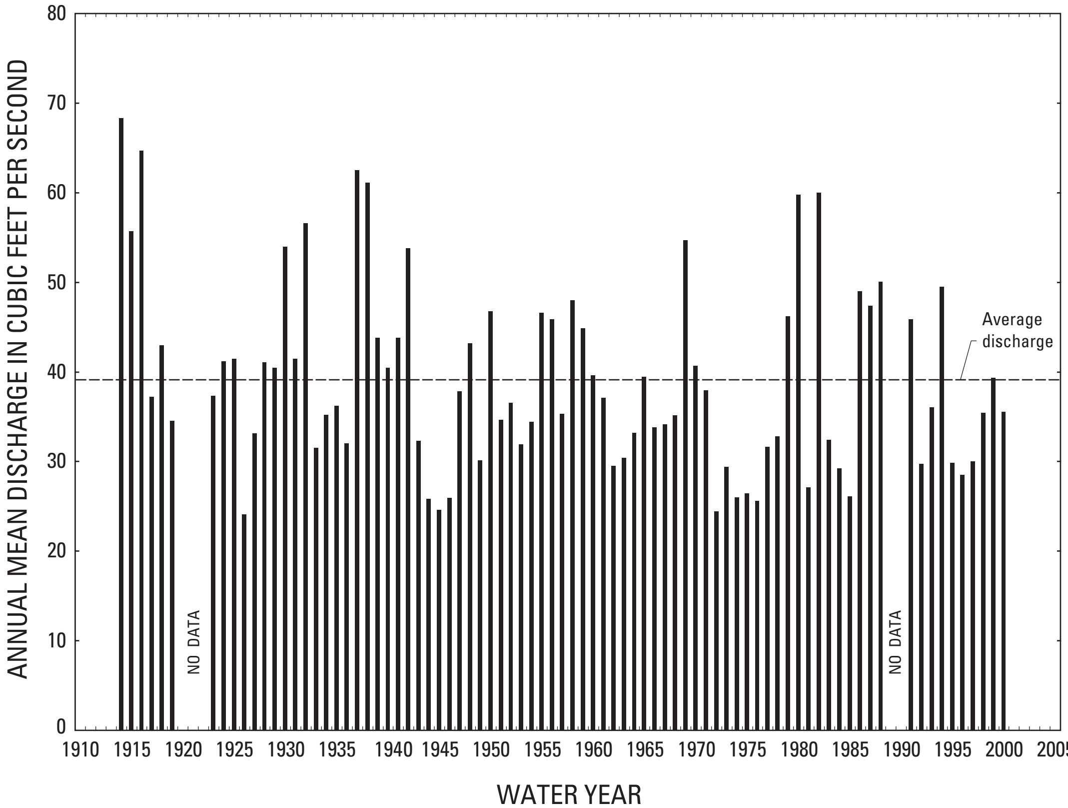


Figure 5. Annual mean and average discharge at streamflow-gaging station 16620000 on Honokohau Stream, Maui, water years 1914–2000.

with the stated capacity of the ditch during this period of 30 to 39 Mgal/d. The average discharge at the ditch intake during the period when station 16621000 was in operation was 34.4 ft^3/s.

The USGS has operated streamflow-gaging station 16620000 on Honokohau Stream for all or parts of the years 1913–1920, 1922–1988, and 1990 through the present (2003). This gaging station is part of the long-term-trend surface-water data network in Hawaii (Fontaine, 1996, p. 35) and will continue in operation for as long as possible. The station is located at an altitude of 870 ft, upstream from water development tunnels T-21 and T-22 and the diversion dam at the start of the Honokohau Ditch (fig. 4). Through the end of 2000, 82 complete water years of streamflow data have been collected at the gaging station. Water years extend from October 1 through September 30 of the following year and are designated by the calendar year in which it ends. Therefore the water year ending September 30, 1999 is called the “1999 water year.” The long-term streamflow data from the Honokohau Stream gaging station represents the only extended data set of its kind in the Honokohau watershed and therefore represents the index or base gaging station that will be used to estimate base-flow conditions at other locations.

There are a number of ways 82 water years of streamflow data for Honokohau gaging station 16620000 can be summarized. The following are some of the more common. All data summaries are for data collected through the end of water year 2000. Through water year 2000 the average discharge was 39.1 ft^3/s (25.3 Mgal/d). The maximum discharge recorded at any time was 7,260 ft^3/s (4,690 Mgal/d) and the minimum was 8.4 ft^3/s (5.4 Mgal/d). Annual mean discharge for all complete water years of record are shown in figure 5. The highest annual mean discharge was 68.3 ft^3/s (44.1 Mgal/d) in 1914 and the lowest annual mean discharge was 24.1 ft^3/s (15.6 Mgal/d) in 1926. There is no significant trend in the annual mean discharge data although there were several periods when streamflow was below normal for extended periods including

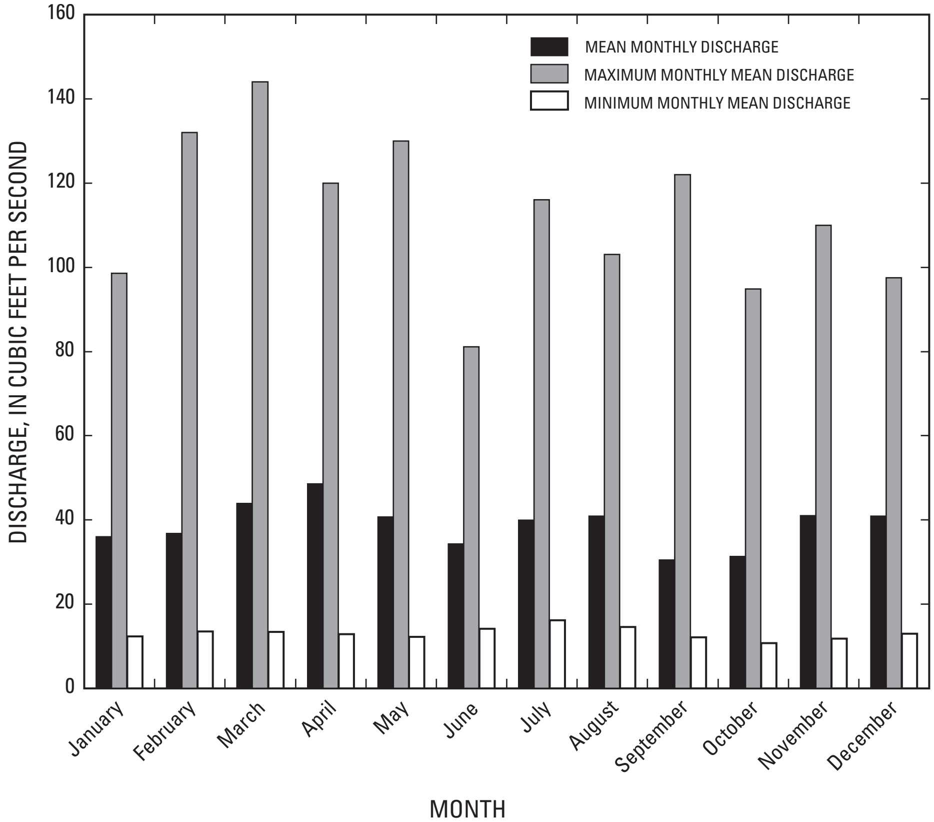


Figure 6. Mean monthly and maximum and minimum monthly mean discharges at streamflow-gaging station 16620000 on Honokohau Stream, Maui, water years 1914–2000.

1943–47, 1971–1978, 1983–85, and 1995–98. The differences in streamflow that take place over various, short-duration periods of time, such as those noted above, illustrate why it is important to have long-term data to provide accurate estimates of streamflow characteristics. Mean monthly discharges along with maximum and minimum values for each month are shown in figure 6. There is no distinctive seasonal pattern in monthly streamflow data evident and the maximum and minimum mean discharges for any month range from 144 ft^3/s (93.0 Mgal/d) (March 1942) to 10.8 ft^3/s (7.0 Mgal/d) (October 1985). The minimum monthly mean discharges are quite uniform throughout the year, indicating that extended periods of minimum base-flows can take place during any month in the year.

In this report the primary focus is on low, or base-flow, conditions. One of the most straightforward and useful ways to summarize streamflow data is through the use of flow-duration curves (Vogel and Fennessey, 1995). A flow-duration curve is simply a cumulative frequency curve, which shows the percentage of time that specified discharges were equaled or exceeded during a given period of record (Searcy, 1959). For example, one of the most frequently used points on a flow-duration curve is the 50th percentile, or median discharge. This is the discharge that is equaled or exceeded 50 percent of the time. A flow-duration curve based on daily mean discharges for 82 water years with complete record from 1913 through 2000, for Honokohau Stream gaging station 16620000, is shown in figure 7. The smooth flow-duration curve for total flow indicates that there are no flow manipulations of significance affecting the discharge recorded at the gage (Ries, 1993, p. 23). Another prominent feature of the total flow curve is the way it nearly levels out at the higher percentiles, which is indicative of a significant, sustained source of base flow (Searcy, 1959, p. 22). The long-term average discharge at the gage, 39.1 ft^3/s (25.3 Mgal/d), represents a flow rate that is equaled or exceeded about 26 percent of the time, indicating that average flow is not a representative measure of typical flow conditions in the

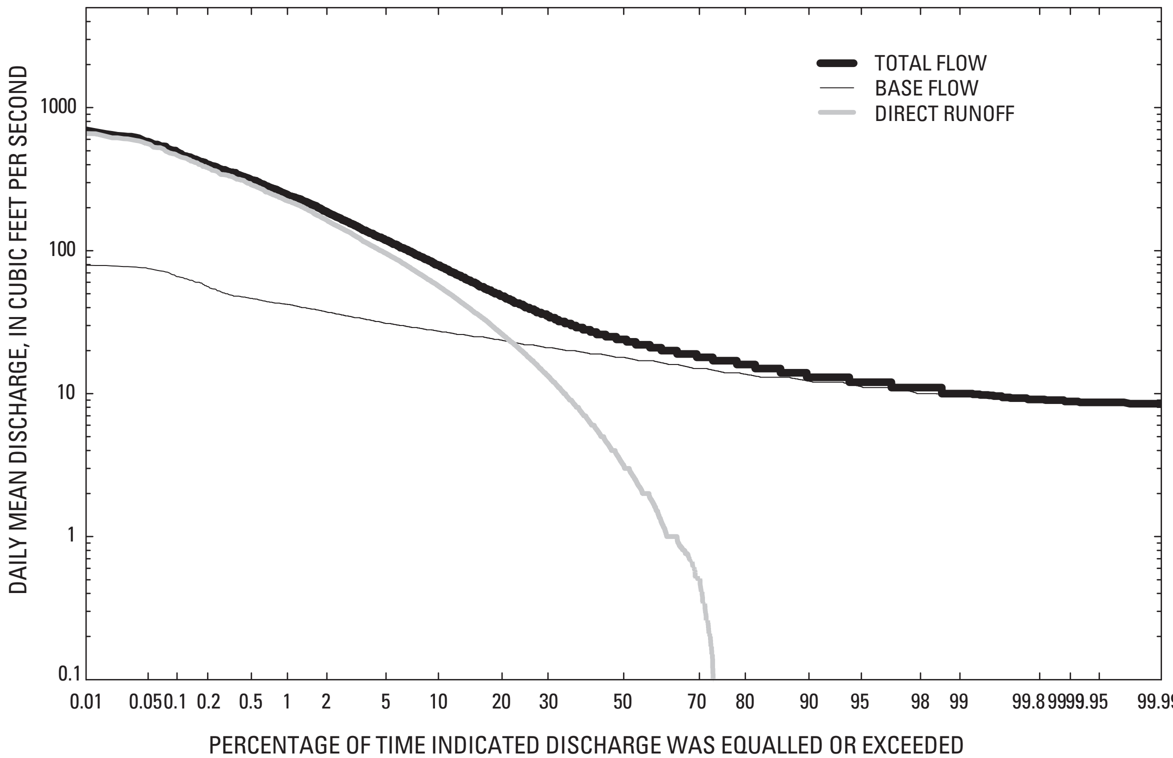


Figure 7. Flow-duration curves for total flow, base flow, and direct runoff at streamflow-gaging station 16620000 on Honokohau Stream, Maui, for 82 water years with complete record during 1913–2000.

stream. The median discharge for total flow of 24 ft^3/s (15.5 Mgal/d) would therefore be a preferred measure of typical flow conditions.

Streamflow at a gaging station is frequently divided into two basic components: base flow and direct runoff (Maidment, 1992). Base flow is that part of streamflow derived from ground water. Direct runoff is that part of streamflow derived from surface and rapid subsurface flow, which occurs in response to excess rainfall. The base-flow component of Honokohau streamflow at gaging station 16620000 was estimated using an automated hydrograph separation method developed by Wahl and Wahl (1995). In the method, two variables must be input: N (number of days) and f (turning-point test factor). The separation method divides the daily streamflow data into non-overlapping periods, each N-days long, and determines the minimum flow in each period. If the minimum flow within a period is less than f times the minimums for the adjacent periods, then the central period minimum is made a pivot (or turning point) on the base-flow hydrograph. Conceptually, the variable N represents the number of days following a storm before direct runoff generally ceases. Straight lines drawn on semilogarithmic paper between the turning points define the base-flow hydrograph. In this application N was determined to be 4 days and f was set at the 0.9 value recommend by Wahl and Wahl (1995). The direct runoff component of the total streamflow was computed as the total flow minus the base flow computed with the hydrograph separation method.

Flow-duration curves for the base-flow and direct-runoff components of streamflow at gaging station 16620000 on Honokohau Stream are shown in figure 7 and summarized in table 1. A striking feature of the curves in figure 7 is that direct runoff contributes to total flow only slightly more than 70 percent of the time. This also indicates the importance of the ground-water contribution to streamflow during periods of low flows and the interaction between ground water and surface water (Winter and others, 1998). The base-flow curve is much flatter than both the total-flow and direct-runoff curves, which indicates that base flow is not as variable at this gage. Of the total streamflow at gaging station

Table 1. Selected flow-duration discharges for total flow, base flow, and direct runoff at streamflow-gaging station 16620000 on Honokohau Stream, Maui, water years 1913–2000
[ft^3/s, cubic feet per second]

Percentage of time indicated flow equaled or exceeded	Total flow (ft^3/s)	Base flow (ft^3/s)	Direct runoff (ft^3/s)
99	10	9.7	0
95	12	11	0
90	13	12	0
80	16	14	0
70	18	15	0.5
60	21	17	1.3
50	24	18	3.2
40	28	19	6.7
30	35	21	13
20	48	24	26
10	79	27	57
5	118	31	96
1	246	42	223

16620000, 49 percent is derived from base flow and 51 percent is derived from direct runoff. The relative contributions of direct runoff and base flow to streamflow at gaging station 16620000 by water year are shown in figure 8.

Low-Flow Partial-Record Stations

If long-term streamflow data were available at multiple locations along Honokohau Stream it would be a relatively simple matter to describe the availability and distribution of base flow along the stream. However, operation of gaging stations to collect the required data is costly and requires long periods of time. For Honokohau Stream only one long-term gaging station is available (USGS station 16620000) so alternative techniques that are both inexpensive and timely are required. Operation of low-flow partial-record stations for use in estimating base flows at sites without long-term gaging stations has been demonstrated to be a viable alternative in Hawaii (Fontaine and others, 1992).

At low-flow partial-record stations, a minimum of 10 discharge measurements (Rantz and others, 1982) are made during periods of base flow. These measurements should be made over a variety of base-flow conditions and during independent recessions following periods of direct runoff. The discharge measurements are then correlated with the concurrent daily discharges recorded at an index station. The index station is a nearby gaging station where long-term data are available that can be used to accurately estimate streamflow statistics. In this case the index station is station 16620000 on Honokohau Stream. The type of correlation and the data analysis technique to be used is based on the shape of the log-log plot of discharge measurements at the low-flow partial-record station compared with daily mean discharges at the index station (Ries, 1993, p. 24). When the plot indicates curvature, then the graphical correlation technique would be used (Searcy, 1959, p. 17). When the plot indicates little or no curvature, then the Maintenance Of Variance Extension, Type I (MOVE.1) technique would be used (Hirsch, 1982). Using the established correlation, between the discharges at the stations, base-flow statistics from the index station can then be used to provide estimates of the same statistic at the low-flow partial-record stations.

In this study low-flow partial-record stations were established at sites 4.0, 5.9, and 9.1 (table 2 and fig. 4). Site 4.0 is just upstream from the Taro Gate release and data there would be indicative of gains in base flow associated with the springs which start at an altitude of 600 ft and any additional gains in the stream reach prior to the inflow of water released from Honokohau Ditch at the Taro Gate. Site 5.9 is located just upstream from MacDonald's Dam and data there would be indicative of total base flow available to meet the in-stream and near-stream water needs in lower Honokohau Stream.

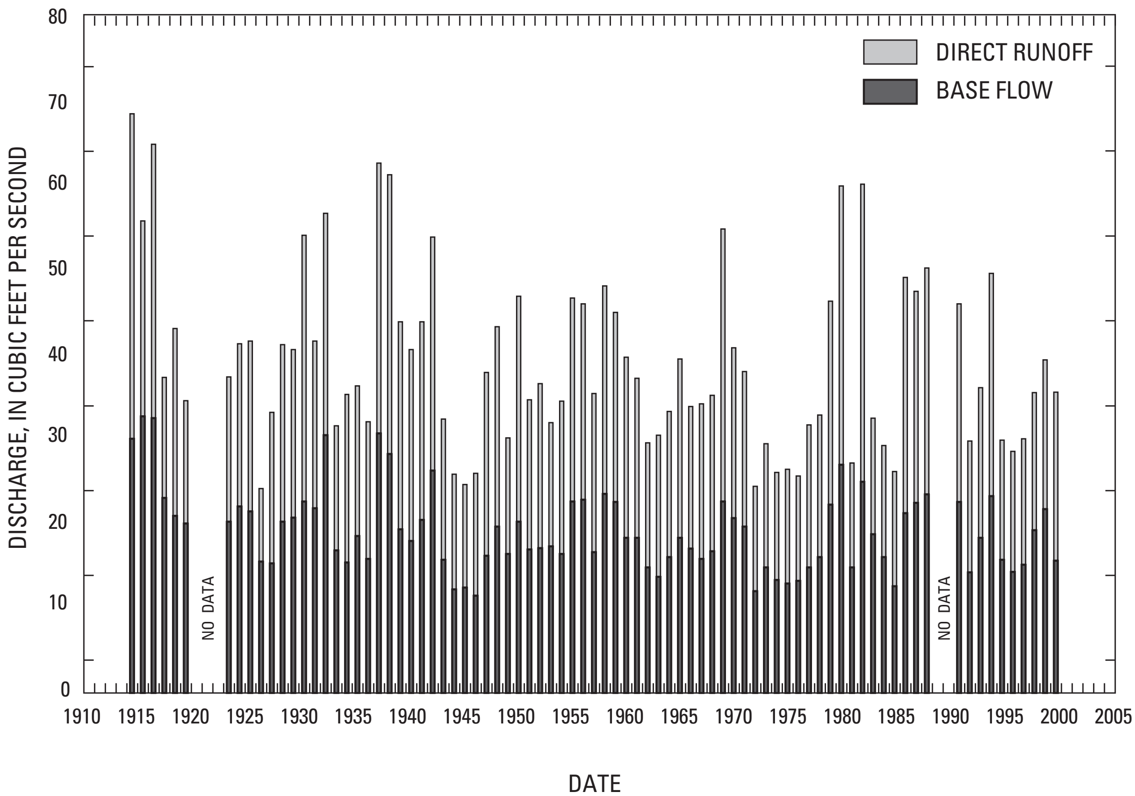


Figure 8. Relative contributions of direct runoff and base flow to annual mean streamflow at gaging station 16620000 on Honokohau Stream, Maui.

Table 2. Long-term and partial-record data-collection stations and miscellaneous sites on Honokohau Stream, Maui
[n.a., not applicable]

Site number (fig. 4)	USGS station number	Altitude (feet)	Distance upstream from mouth (feet)	Remarks
16620000	16620000	870	25,150	long-term streamflow-gaging station
0.2[a]	n.a.	830	23,950	upstream from Honokohau ditch intake
n.a.	n.a.	825	23,900	Honokohau ditch intake
0.4[a]	n.a.	820	23,850	downstream from Honokohau ditch intake
1.0	205830156353801	625	19,950	
2.0	n.a.	600	18,950	upstream end of springs
3.0	205843156354101	560	18,650	
3.1	205845156354201	540	18,150	
4.0	205915156360001	410	14,300	low-flow partial-record station
n.a.	n.a.	405	14,100	Taro Gate release
5.0	205922156360101	380	13,600	
5.9	205928156360601	350	12,950	low-flow partial-record station
n.a.	n.a.	340	12,600	McDonald’s Dam
6.1	205933156360801	330	12,400	
6.2	205940156360901	310	11,600	
7.0	205958156361701	235	9,980	
7.1	210001156362101	200	9,120	
7.6	210012156362801	180	7,800	
n.a.	n.a.	105	5,400	concrete road ford
7.9	210041156363001	100	5,050	
n.a.	n.a.	90	4,520	Chun’s Dam
8.0	210045156363301	80	4,500	
9.1	210128156364201	5	40	low-flow partial-record station

[a] Not shown in figure 4. See remarks for location.

Table 3. Discharge measurements at low-flow partial-record stations and concurrent daily mean discharges at gaging station 16620000, Honokohau Stream, Maui
[ft^3/s, cubic feet per second; --, no data available]

Date	Discharge (ft^3/s)			
	16620000[a]	Site 4.0[a]	Site 5.9[a]	Site 9.1[a]
01/22/76	11	0.69[b]	--	--
09/14/95	16	1.53	3.76	1.63
08/12/97	19	1.64	3.54	1.75
10/23/97	17	1.89	3.61	1.81
06/29/99	20	2.74	3.92	2.47
10/27/99	18	2.92	4.52	3.49
02/09/00	17	--	--	1.73
03/17/00	17	1.22	3.01	1.98
05/24/00	14	1.55	2.92	1.59
07/11/00	20	2.16	3.15	2.98
08/25/00	21	2.29	3.01	3.92
12/19/00	16	1.18	1.85	1.13

[a] Site numbers correspond to sites listed in table 2 and shown in figure 4
[b] Historic discharge measurement made by USGS personnel prior to study

Site 9.1 is located just upstream from the mouth of the stream and data there would be indicative of base-flow discharges to the ocean. Discharge measurements made at the low-flow partial-record stations and concurrent daily mean discharges at the index station (station 16620000) are listed in table 3. All of these data have been published in the series of USGS annual data reports and the data are stored in USGS electronic data bases.

Logarithmic plots of the discharge measurements for the three low-flow partial-record stations compared with daily mean discharges at the index station indicated linear relationships and therefore the MOVE.1 technique was used to make estimates of low-flow discharges for selected flow-duration percentiles. Correlation coefficients, which provide a measure of the strength of the linear relationship between the index and partial-record stations, are 0.826 for site 4.0, 0.305 for site 5.9, and 0.738 for site 9.1. The correlation coefficient for site 5.9 indicates that only a very weak relationship exists between discharge measurements there and daily mean discharges at gaging station 16620000 and therefore MOVE.1 analysis was not conducted using the site 5.9 data.

In the MOVE.1 analysis technique the discharge measurements at the partial-record stations and the concurrent daily mean discharges at the index station are transformed to log base 10 values. The means and standard deviations for the transformed discharge data at the two sites are then calculated. Estimates of discharges corresponding to selected base-flow durations at the partial-record station are obtained by entering the logarithms of known base-flow duration discharges at the index station (X_i) and the computed means and standard deviations into the MOVE.1 formula:

$$Y_i = \overline{Y} + s_y/s_x \, (X_i - \overline{X}), \qquad (1)$$

where:

Y_i is the logarithm of the estimated base-flow duration discharge at the partial-record station,

X_i is the logarithm of the computed base-flow duration discharge at the index station,

$\overline{Y}$ is the mean of the logarithms of the discharge measurements at the partial-record station,

$\overline{X}$ is the mean of the logarithms of the concurrent daily mean discharges at the index station,

s_y is the standard deviation of the logarithms of the discharge measurements at the partial-record station,

s_x is the standard deviation of the logarithms of the concurrent daily mean discharges at the index station,

Estimates of discharges corresponding to selected base-flow durations for the partial-record stations are then converted back into their original units of measurement in cubic feet per second.

Computed statistics for the MOVE.1 analyses at low-flow partial-record sites 4.0 and 9.1 and index station 16620000 are summarized in table 4. In table 4, two sets of statistics are provided for the index station

Table 4. Computed statistics for concurrent daily mean discharges at index station 16620000 and discharge measurements at low-flow partial-record stations, Honokohau Stream, Maui

Station	Mean	Standard deviation
16620000	1.229[a]	0.081
Site 4.0	0.224	0.182
16620000	1.246[b]	0.052[b]
Site 9.1	0.319	0.164

[a] Based on concurrent daily mean discharges associated with discharge measurements made at site 4.0

[b] Based on concurrent daily mean discharges associated with discharge measurements made at site 9.1

Table 5. Estimated flow-duration discharges for low-flow partial-record stations, Honokohau Stream, Maui

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

Percentage of time indicated flow equaled or exceeded	Site 4.0[a] (ft^3/s)	Site 9.1[a] (ft^3/s)
95	0.77	0.63
90	0.92	0.80
80	1.5	1.5
70	1.9	2.2
60	2.7	3.6
50	3.7	5.5

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

16620000 because discharge measurements were not made on the exact same days at the two partial-record sites. The statistics from table 4 along with the logarithms of selected flow-duration discharges for total flow at the index station 16620000 (table 1) were substituted into equation 1 to compute estimates for selected flow-duration discharges at the two partial record sites (table 5). Estimates were not provided for flow-duration percentiles less than 50 percent because in that flow range, surface runoff, or total flow minus base flow, starts becoming a significant part of the total flow (fig. 7 and table 1). Estimates were not provided for flow-duration percentiles greater than 95 percent because those estimates would fall too far beyond the range of the discharge measurements made during the study.

Historic Discharge Measurements at Miscellaneous Sites

The USGS surface-water data-collection program in Hawaii officially began in 1909 (Fontaine, 1996, p. 7). Over the years, numerous discharge measurements have been made at miscellaneous sites where no continuous-record gaging stations were in operation. These data provide valuable information that can be used to supplement current analyses. Historic discharge measurements made by the USGS on Honokohau Stream are summarized in table 6. Particularly noteworthy are the measurements made on January 24, 1924, which documented the combined discharge from development tunnels T-21 and T-22 as 5.9 ft^3/s. At the time of these measurements the daily mean discharge at station 16620000 was 20 ft^3/s or about a 65 percentile flow (table 1). On January 22, 1976 a discharge of 0.69 ft^3/s was measured near the location of present day partial-record station 4.0 and it was included in the MOVE.1 analysis of the measurements at that site (table 3). This discharge measurement was significant because it was the lowest made at site 4.0. The concurrent, daily mean discharge at station 16620000 was 11 ft^3/s or about a 97 percentile flow (table 1). On June 22–23, 1994, a seepage run was attempted but it is now known that these measurements were made during a period when direct runoff was taking place. This was determined by observing that rapid changes in discharge, which are indicative of periods of direct runoff, took place during this period at index station 16620000 on Honokohau Stream. Therefore, these measurements should not be used to indicate how base-flow conditions vary along the perennial reach of Honokohau Stream downstream from the springs at an altitude of 600 ft.

Table 6. Historic discharge measurements made by the U.S. Geological Survey at miscellaneous sites on Honokohau Stream, Maui
[ft^3/s, cubic feet per second; n.a., not applicable; --, no data available]

Date	Discharge (ft^3/s)	Altitude (feet)	Base-flow conditions	Remarks
10/20/21	11.3	870	yes	at gaging station 16620000 during a period when it was not in operation
	12.4	870	yes	at gaging station 16620000 during a period when it was not in operation
01/24/24	2.1	n.a.	yes	discharge from development tunnel T-21
	3.8	n.a.	yes	discharge from development tunnel T-22
08/29/68	2.78	580	yes	
	2.82	480	yes	
	2.95	300	yes	
09/23/75	0.97	580	yes	
01/22/76	0.76	580	yes	
	0.69	440	yes	included in analysis of base-flow measurements at partial-record site 4.0
06/22/94	0.26	600	no	
	4.34	540	no	
	3.86	410	no	
	5.36	380	no	
06/23/94	3.81	--	no	site is downstream from McDonald's Dam but exact location is unknown
	3.04	20	no	

BASE-FLOW AVAILABILITY AND DISTRIBUTION

In this section of the report, the distribution of base flow in lower Honokohau Stream and how it is affected by streamflow diversions and return flows are evaluated. For the purposes of this report, lower Honokohau Stream has been defined as the stream reach extending from gaging station 16620000, at an altitude of 870 ft, to the ocean. Data evaluated in this analysis included that summarized in the previous section of the report (Data Collection and Analysis) as well as results from three seepage runs conducted as part of this study. In addition, published summaries of ML&P data, their estimates of Honokohau Ditch diversion practices, and policies for returning flow from the ditch to Honokohau Stream are utilized.

Seepage Runs

Streams reaches can be classified as gaining, losing, or both (Winter and others, 1998, p. 10). Gaining stream reaches are lengths of stream where base flows increase due to inflows of ground water. Losing stream reaches are lengths of stream where base flows decrease due to outflows through the streambed to the underlying ground-water body. In some stream reaches both gaining and losing segments exist. In gaining stream reaches, water in the stream is directly (hydraulically) connected to the ground-water system. In losing stream reaches, there is an unsaturated zone between water in the stream and the underlying ground-water system. The above concepts become difficult to analyze in systems such as Honokohau Stream, where water is diverted from and returned to the stream.

In this study three seepage runs were conducted in an attempt to identify gaining and losing stream reaches and to determine how diversion and return-flow practices affect base flow. A seepage run is an intensive data-collection effort in which discharge measurements (Rantz and others, 1982) are made at several locations along a stream reach. These measurements are made during periods of base flow when flow rates at any given location in the stream are relatively constant. The time between the first and last measurement in a seepage run is minimized to further reduce the effect that any variability with time might introduce. During the seepage runs, measurements of water temperature and specific conductance also were made. In addition to the physical measurements, observations were made regarding a variety of factors including water diversion and return-flow practices, and streambed characteristics.

Discharge measurements made during seepage runs conducted on September 14, 1995, August 13, 1997, and October 23, 1997 are summarized in table 7. A graphical summary of the discharge measurements compared with stream altitude is shown in figure 9. At the time of the seepage runs, daily-mean discharges at gaging station 16620000 corresponded to flow-duration percentiles of 80 percent, 66 percent, and 75 percent, respectively. Analysis of the continuous streamflow record at gaging station 16620000 indicates that each of the seepage runs was made during periods of base flow when the flows remained relatively constant.

A visual inspection of the data in table 7 and figure 9 indicates that the pattern of streamflow in lower Honokohau Stream was similar during the three seepage runs. Streamflows in the reach upstream from the Honokohau Ditch diversion dam, at 825 ft, were several times greater than those measured at any location downstream from the diversion. The results from these seepage runs also confirm that during base-flow conditions, most of the reach is dry between the diversion dam at 825 ft and the springs, which start at an altitude of about 600 ft. Downstream from the springs flow is continuous in the stream. These results confirm earlier statements regarding the general nature of base flow in lower Honokohau Stream (Hawaii Department of Land and Natural Resources, 1977, p. 30; and Mink, 1990).

Discharge measurements and observations made during the seepage runs were used to provide the following information. A significant gain in base flow between gaging station 16620000 and the diversion dam at 825 ft was attributed primarily to discharge from development tunnels T-21 and T-22. During the seepage runs this gain was not measured directly. Discharge upstream from the diversion dam was computed as the flow rate at the gage plus estimated tunnel discharges. The method of estimation is discussed in greater detail in the following section of the report (Effect of Honokohau Ditch Diversion). During the seepage runs all the flow was diverted at the dam except for a minor amount of leakage, which was estimated to be about 0.1 ft^3/s. No suitable location was found to measure this small discharge directly. This minor flow persisted in a reach of the stream that is about 1,500 ft in length, ending at a location which corresponds with the upstream terminus of the unconsolidated alluvium in the channel (fig. 4). In this area the permeability of the streambed increases, allowing the minor flow to seep into the ground. Downstream from this location the channel remained dry in a reach that is several hundred feet in length, until it reached the start of the springs, at an altitude of 600 ft. These springs discharge into the stream over a reach of several tens of feet and discharge measurements were made downstream from this reach to insure that the total gain in flow was measured.

During all three seepage runs, discharge measurements were made on Honokohau Stream at sites 4.0 and 5.0, just upstream and downstream of the inflow from the Taro Gate release (fig. 4). The difference between these measurements can be used to quantify how much water was being released into Honokohau Stream. During the three runs, computed Taro Gate releases were 1.67, 1.42, and 1.30 ft^3/s, respectively, and averaged 1.46 ft^3/s. In only one instance was the computed release equal to or greater than the targeted release of 1.55 ft^3/s (1.0 Mgal/d). Flow releases at the Taro Gate are discussed in greater detail in a subsequent section of the report (Taro Gate Releases). During all three seepage runs, the stream reach extending from downstream of the Taro Gate (site 5.0) to just upstream of MacDonald's Dam (site 5.9) gained water (table 7). The magnitude of the gain ranged from 0.42 to 0.56 ft^3/s and averaged 0.49 ft^3/s. No flow is released in the reach of channel between sites 5.0 and 5.9 and the gains in flow are ground-water discharges into the stream. This is contrary to prior findings, which indicate that no natural increases in streamflow took place downstream from the springs near 600 ft (Hawaii Department of Land and Natural Resources, 1977, p. v).

During the two seepage runs made in 1997, discharge measurements were made at sites 5.9 and 6.1 just upstream and downstream of MacDonald's Dam (fig. 4). Using these measurements the diversion at the dam was computed to be 0.89 and 1.00 ft^3/s during the seepage runs. During all three seepage runs the hydropower diversion at MacDonald's Dam appeared to be operating at its maximum capacity, releasing 0.46 ft^3/s (0.3 Mgal/d) into the diversion ditch just downstream from the dam. Downstream from MacDonald's Dam through site 6.2 (altitude 310 ft) several return flows were noted, however they were not sufficient to account for all the water diverted at the dam plus the hydropower plant flow release. The returns of diverted water in this section of stream were diffuse and could not be accurately measured. The stream reach between sites 6.2 and 7.1 contained no identified return flows or diversions. During the August 13, 1997 seepage run, a loss of base flow totaling 0.20 ft^3/s was measured in this 2,480-ft reach.

Table 7. Discharge during seepage runs on Honokohau Stream, Maui
[ft³/s, cubic feet per second; --, no data available]

Site number[a]	Altitude (feet)	Distance upstream from mouth (feet)	Discharge (ft^3/s) 09/14/95	08/13/97	10/23/97
16620000	870	25,150	16[b]	19[b]	17[b]
0.2	830	23,950	21[c]	25[c]	21[c]
0.4	820	23,850	0.1[d]	0.1[d]	0.1[d]
1.0	625	19,950	0	0	0
2.0	600	18,950	0	0	0
3.0	560	18,650	1.29	--	--
3.1	540	18,150	--	1.95	--
4.0	410	14,300	1.53	1.64	1.89
5.0	380	13,600	3.20	3.06	3.19
5.9	350	12,950	3.76	3.54	3.61
6.1	330	12,400	--	2.65	2.61
6.2	310	11,600	--	3.26	3.04
7.0	235	9,980	3.96	--	--
7.1	200	9,120	--	3.06	--
7.6	180	7,800	--	3.70	3.12
7.9	100	5,050	--	2.76	2.50
8.0	80	4,500	1.05	1.25	1.81
9.1	5	40	1.63	1.75	1.81

[a] Site numbers correspond to sites listed in table 2 and shown in figure 4 (sites 0.2 and 0.4 not shown in figure 4; see remarks in table 2 for locations)
[b] Daily mean discharge at gaging station 16620000 on day of seepage run
[c] Data based on daily mean discharge at station 16620000 and estimated discharge from development tunnels T-21 and T-22
[d] Estimated leakage through the Honokohau Ditch diversion dam

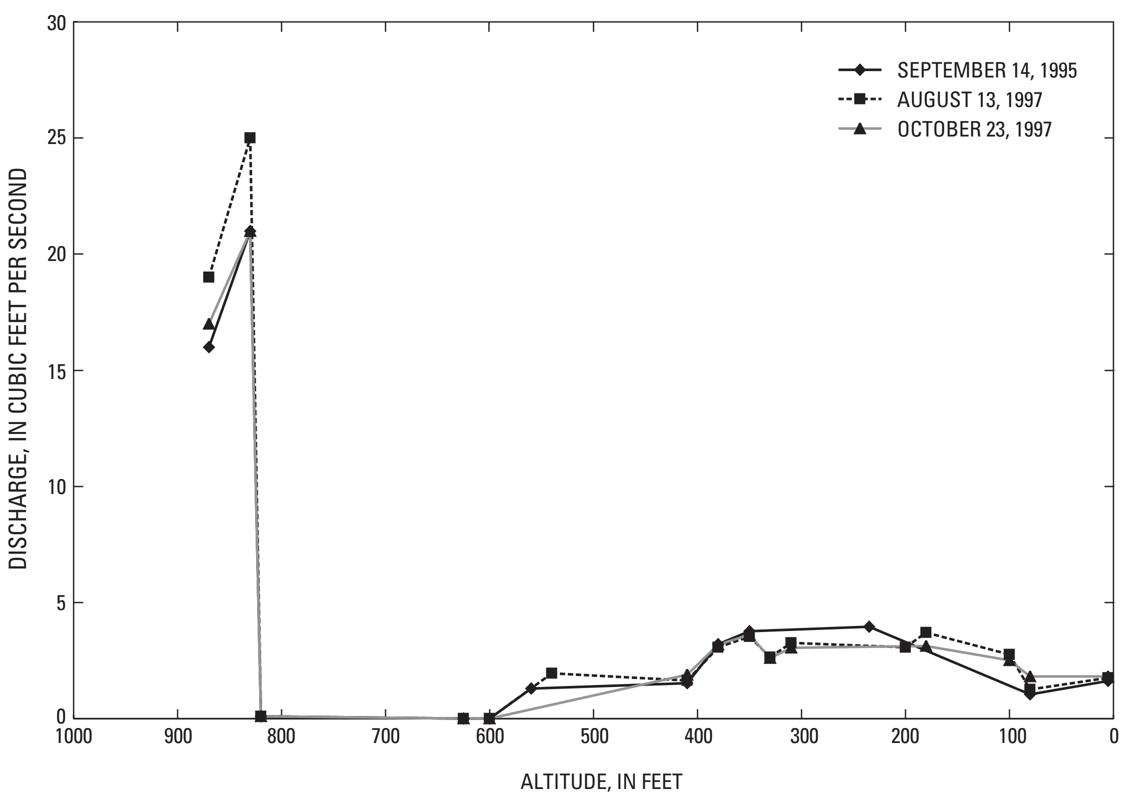


Figure 9. Discharge on Honokohau Stream, Maui, during three seepage runs.

During the same seepage run, a loss of base flow totaling 0.94 ft^3/s was measured in the 2,750-ft reach between sites 7.6 and 7.9, another reach where no return flows or diversions were identified. This loss rate is greater than that measured upstream although no reasons to directly account for it, such as differences in streambed material, were identified. These data provide a range of possible rates at which base flow infiltrates through the bed of Honokohau Stream to the underlying ground-water body in losing reaches, downstream from MacDonald's Dam.

During the two seepage runs made in 1997, discharge measurements were made at sites 7.9 and 8.0 just upstream and downstream of Chun's Dam (fig. 4). Using these measurements, the diversion at the dam was computed to be 1.51 and 0.69 ft^3/s during the seepage runs. Diversions at Chun's Dam are not as consistent as those upstream at MacDonald's Dam because of the variable nature of losses both through and over the dam. In the reach downstream from the dam several return flows were noted, however they were not sufficient to account for all the water diverted at Chun's Dam.

During the three seepage runs, the stream reach between MacDonald's Dam and the ocean loses water, although these losses are not of a magnitude that is sufficient to totally dry the stream. Total loss in streamflow can be computed as the discharge at site 5.9, plus the hydropower plant discharge of 0.46 ft^3/s, minus the discharge at site 9.1. Computed losses during the seepage runs were 2.59 ft^3/s (September 14, 1995), 2.25 ft^3/s (August 13, 1997), and 2.26 ft^3/s (October 23, 1997) and the average loss was 2.37 ft^3/s. Base-flow losses in Honokohau Stream can be attributed primarily to infiltration through the streambed. Although losses due to consumptive use of water that was diverted at MacDonald's Dam and Chun's Dam could not be measured directly, they can be assumed to be secondary. Penn (1997, p. 83–86) indicated that consumptive use of water in Hawaiian taro fields ranged from 0.06 to 0.19 ft^3/s per acre (0.04 to 0.12 Mgal/d per acre). Using the value of 3.13 acres as the amount of taro being irrigated in lower Honokohau Valley (Bill Rozeboom, Hawaii Commission on Water Resource Management, written commun., 1992), a range of possible consumptive water use can be estimated as 0.20 to 0.59 ft^3/s (0.13 to 0.38 Mgal/d). The range of possible consumptive water use would therefore equal 8 to 25 percent of the average loss of 2.37 ft^3/s measured during the three seepage runs.

Water-temperature and specific-conductance measurements were made during the three seepage runs (tables 8 and 9). Variations in water-temperature and specific-conductance data for the August 13, 1997 seepage run are shown graphically in figures 10 and 11. Water temperatures at site 16620000 and site 3.1 are lower than temperatures at other locations along the stream reach, indicating the water originates from a colder source such as ground-water inflow. A previous measure of water temperature at the springs at 600 ft (Hawaii Department of Land and Natural Resources, 1977, p. 30) was 18.9°C (66°F) and this agrees with results from this study. Water temperatures gradually increase as water flows downstream from the springs at 600 ft. This gradual increase indicates that little or no colder ground-water inflow is taking place along this reach of stream.

Specific-conductance values drop sharply between sites 4.0 and 5.0 (fig. 4). This drop is in response to the dilution effect associated with the inflow of lower conductivity water from the Taro Gate release between these sites. Water released from the Taro Gate would have characteristics similar to the water at gaging station 16620000. There is also a small drop in specific-conductance values downstream from MacDonald's Dam. This would be attributed to the dilution effect associated with the release of water from the hydropower plant. Hydropower plant releases come from the Honokohau Ditch and would also have characteristics similar to water at gaging station 16620000. Specific-conductance values increase slightly near the coast and this would most likely be the result of saltwater sprays affecting conductivity readings at site 9.1, which is a short distance upstream from the ocean.

Effect of Honokohau Ditch Diversion

The intake of Honokohau Ditch is located at an altitude of 825 ft and was constructed to divert essentially all of the base flow in Honokohau Stream. While the capacity of the ditch and intake has varied over the years (Wilcox, 1996), the current capacity at the intake on Honokohau Stream is estimated to be about 93 to 101 ft^3/s (60 to 65 Mgal/d) (Wesley Nohara, Maui Land and Pineapple Company, Inc., oral commun., 2002). To evaluate the effect of the Honokohau Ditch diversion on

Table 8. Stream temperature during seepage runs on Honokohau Stream, Maui
[--, no data available]

Site number[a]	Altitude (feet)	Distance upstream from mouth (feet)	Stream temperature (degrees Celsius)		
			09/14/95	08/13/97	10/23/97
16620000	870	25,150	--	19.5	--
0.2	830	23,950	--	--	--
0.4	820	23,850	--	--	--
1.0	625	19,950	--	--	--
2.0	600	18,950	--	--	--
3.0	560	18,650	19.0	--	--
3.1	540	18,150	--	19.5	--
4.0	410	14,300	20.0	21.0	20.5
5.0	380	13,600	20.5	21.0	20.5
5.9	350	12,950	21.5	21.0	21.5
6.1	330	12,400	--	21.5	21.5
6.2	310	11,600	--	21.5	22.0
7.0	235	9,980	21.0	--	--
7.1	200	9,120	--	22.0	--
7.6	180	7,800	--	22.0	22.0
7.9	100	5,050	--	22.5	22.5
8.0	80	4,500	--	22.0	23.0
9.1	5	40	25.0	24.5	24.5

[a] Site numbers correspond to sites listed in table 2 and shown in figure 4 (sites 0.2 and 0.4 not shown in figure 4; see remarks in table 2 for locations)

Table 9. Specific conductance during seepage runs on Honokohau Stream, Maui
[--, no data available]

Site number[a]	Altitude (feet)	Distance upstream from mouth (feet)	Specific conductance (microsiemens per centimeter)		
			09/14/95	08/13/97	10/23/97
16620000	870	25,150	--	68	--
0.2	830	23,950	--	--	--
0.4	820	23,850	--	--	--
1.0	625	19,950	--	--	--
2.0	600	18,950	--	--	--
3.0	560	18,650	--	--	--
3.1	540	18,150	--	111	--
4.0	410	14,300	--	114	120
5.0	380	13,600	--	88	95
5.9	350	12,950	--	92	95
6.1	330	12,400	--	92	95
6.2	310	11,600	--	90	92
7.0	235	9,980	--	--	--
7.1	200	9,120	--	90	--
7.6	180	7,800	--	90	94
7.9	100	5,050	--	90	94
8.0	80	4,500	--	92	95
9.1	5	40	--	101	111

[a] Site numbers correspond to sites listed in table 2 and shown in figure 4 (sites 0.2 and 0.4 not shown in figure 4; see remarks in table 2 for locations)

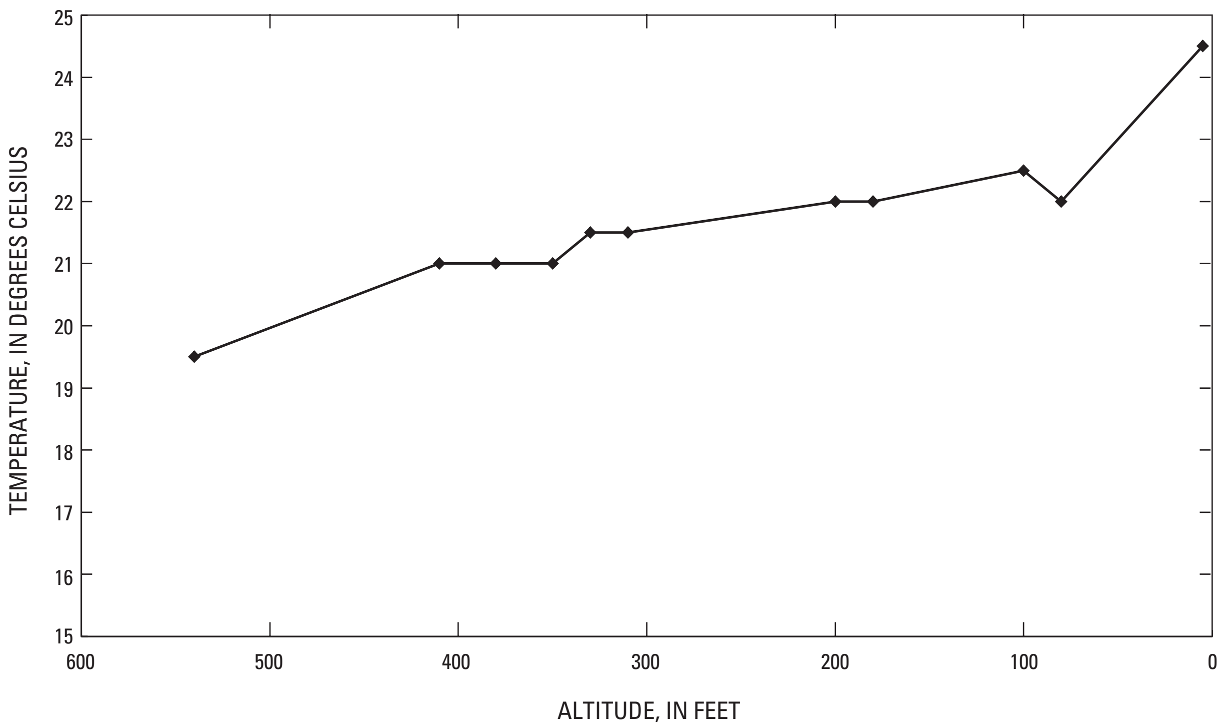


Figure 10. Stream temperature on Honokohau Stream, Maui, during August 13, 1997 seepage run.

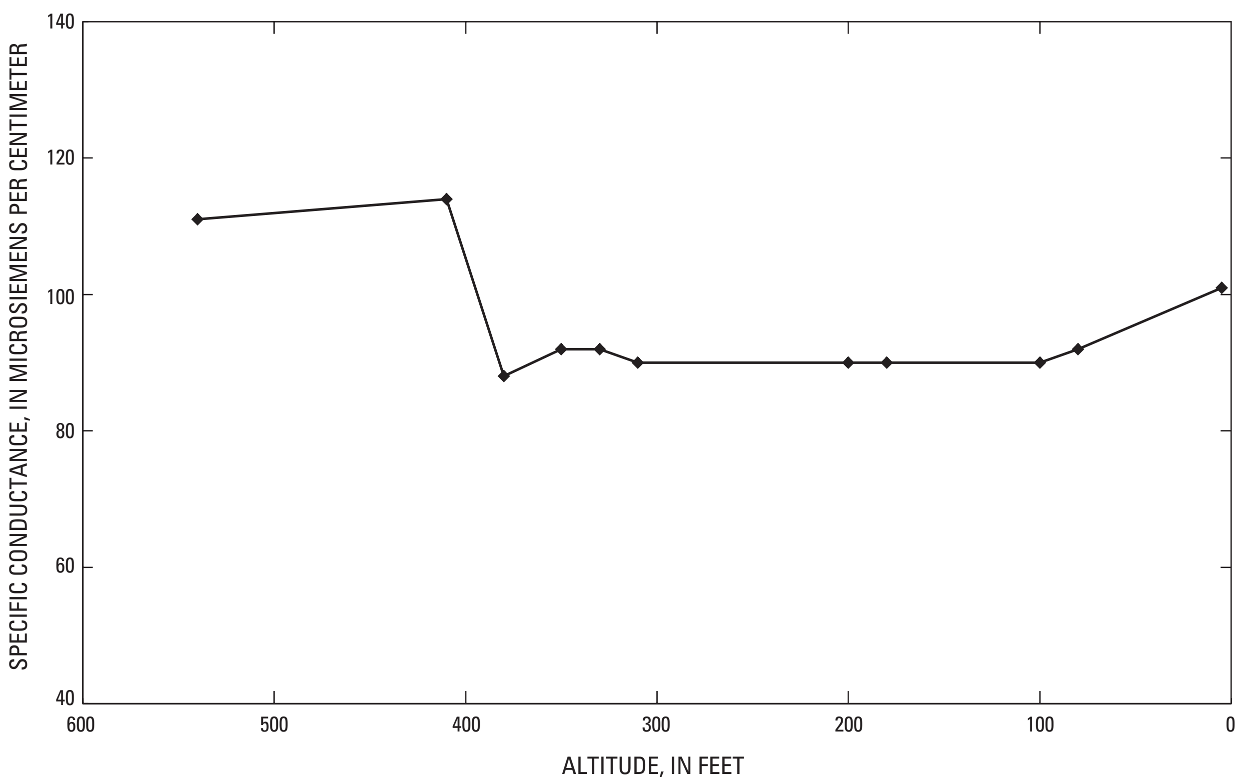


Figure 11. Specific conductance on Honokohau Stream, Maui, during August 13, 1997 seepage run.

Honokohau Stream, estimates of long-term streamflow data upstream and downstream of the diversion intake are needed. In the stream reach between station 16620000 and the diversion dam, significant inflow from development tunnels T-21 and T-22 enters Honokohau Stream. Inflow from the tunnels needs to be computed to provide estimates of long-term streamflow data upstream from the diversion.

ML&P gaged the outflow from development tunnels T-21 and T-22 for several years. However, the data have not been published, are of unknown accuracy, and are not stored in electronic format. Yamanaga and Huxel (1969, p. 30) indicated that for the period 1926–41 the combined daily flow from development tunnels T-21 (1.81 Mgal/d) and T-22 (2.25 Mgal/d) was 6.28 ft^3/s (4.06 Mgal/d) based on ML&P data. Mink (1990) used data for the tunnels, which was assumed to be from ML&P, for the period 1926–54 to compute an average discharge of 2.82 ft^3/s (1.82 Mgal/d) for tunnel T-21. Although ranges for minimum and maximum discharges for tunnel T-22 are computed by Mink (1990), no average discharge was given. The data given in Yamanaga and Huxel (1969, p. 30) are inconsistent with other sources (Mink, 1990; Stearns and Macdonald, 1942) and appear to have the relative contributions of tunnels T-21 and T-22 reversed (results given above are revised to account for this assumed error). This assumption appears to be correct as the average discharges, cited above for tunnel T-21, are now essentially the same. Stearns and Macdonald (1942, p. 213) indicated that the combined discharge from the two tunnels was 5.9 ft^3/s (3.75 Mgal/d) although this estimate was based on a single set of discharge measurements made by the USGS on January 24, 1924 (table 6).

The analyses summarized in the previous paragraph provide valuable background information; however, they are not directly compatible with data analyzed as part of this report. The available data are not in electronic format as a time series of daily discharges and are available for a much shorter period of time than data from gaging station 16620000. The importance of using long-term data is highlighted by the fact that average discharge for the period 1926–41, the period used by Yamanaga and Huxel (1969) in their analysis, at station 16620000 was 42.6 ft^3/s. This value is 9.0 percent greater than the average discharge computed for 82 water years between 1913–2000 of 39.1 ft^3/s.

To account for limitations in available data it was decided to estimate a time series of daily discharge representing the combined discharge of development tunnels T-21 and T-22 into Honokohau Stream. In an earlier section of this report, estimates of the base-flow component of the total discharge at station 16620000 were summarized (fig. 7 and table 1). Base flow at the gaging station comes primarily from high-level dike-impounded ground water in the Wailuku Basalt. Discharge from the development tunnels is also primarily base flow from a comparable source. It is therefore reasonable to assume that some direct correlation between base flows at station 16620000 and development tunnels T-21 and T-22 exists. The only USGS data available to assess this correlation are discharge measurements of tunnel discharge made on January 24, 1924 (table 6). On January 24, 1924, the daily mean discharge at station 16620000 was 20 ft^3/s, and all of this discharge was estimated to be base flow. The ratio of measured discharge from the tunnels to base flow at station 16620000 on January 24, 1924 was multiplied by the time series of daily base flows at station 16620000 to generate a time series of tunnel discharges for the period of available data from 1913–2000.

Comparisons with previously published tunnel discharge data were made to test the reasonableness of the estimated time series. As noted above, Yamanaga and Huxel (1969, p. 30) reported an average discharge from the tunnels for the period 1926–41 as 6.28 ft^3/s. Using the time series estimated for the current study, an average discharge for the same period was computed to be 6.01 ft^3/s, a value that is within 4.4 percent of 6.28 ft^3/s. Data presented by Mink (1990) indicate that the minimum discharge for the period 1926–54, from the two tunnels combined, was about 3.2 ft^3/s. Using the time series estimated for this study, a minimum discharge for the same time period was computed to be 2.8 ft^3/s. Although the time series computed for combined development-tunnel discharges can only be considered an estimate with unknown accuracy, the above comparisons indicate that the estimates are reasonable.

The estimated time series of tunnel discharges were then combined with the daily-discharge time series from station 16620000 to provide estimates of daily discharges for the period 1913–2000 upstream from the Honokohau Ditch intake. Flow-duration data for estimated development tunnel discharges and total discharge of Honokohau Stream, upstream from the diversion, are presented in table 10 and figure 12. Discharges from the development tunnels provide a significant portion of total base-flow discharge of Honokohau Stream, upstream from the diversion. For example, addition of development tunnel inflow increases the median, or 50th percentile, discharge of Honokohau Stream from 24 ft^3/s at gaging station 16620000 to 30 ft^3/s upstream from the diversion (table 10), an increase of 25 percent. When viewing flow-duration data, such as that presented in table 10, it is important to understand that results for a given flow-duration percentile at two sites cannot be directly combined. To compute the flow-duration curve for total discharge upstream from the diversion, first, flow data must be combined from station 16620000 and the development tunnels for each individual day, and then, a flow-duration curve is computed based on the new time series. This is why direct combination of individual flow-duration discharges for station 16620000 and the development tunnels do not always exactly equal those presented for total discharge upstream from the diversion in table 10.

To determine the effect of Honokohau Ditch diversions on streamflow, a maximum capacity of the intake on Honokohau Stream (at an altitude of 825 ft) of 93 ft^3/s (60 Mgal/d) was used. Although this value is at the low end of the estimated range provided by ML&P it was deemed to be the most reasonable value. Actual diversions tend to be lower than computed ditch capacities because of factors such as accumulation of debris on intake trash racks and deposits of sediment and aquatic growth in the ditch itself. These and other naturally occurring processes all tend to reduce magnitudes of streamflow diversions. Estimated daily discharges for the period 1913–2000, upstream from the diversion, were all reduced by a value equal to the lesser of the daily discharge upstream from the diversion and the assumed ditch capacity of 93 ft^3/s (60 Mgal/d). For all days a minimum leakage through the dam of 0.1 ft^3/s, based on leakage observed during the seepage runs (table 7), was assumed. The result of this analysis is a time series of estimated daily discharges for Honokohau Stream downstream from the diversion at an altitude of 825 ft. A time series for the period 1913–2000 of estimated daily discharges for Honokohau Ditch just downstream from the intake on Honokohau Stream, was estimated as the daily discharge upstream from the diversion less the daily discharge downstream from the diversion. This is an estimate of what the time series would have been if a consistent pattern of ditch capacity and diversion dam leakage, as assumed in the analysis, existed over the entire period of time.

To test the accuracy of the method used to assess the effect of ditch diversions, the average discharge, based on the estimated time series of discharge diverted by the ditch, was computed. Average ditch discharge was found to be 38.3 ft^3/s (24.7 Mgal/d) (table 11). This result compares favorably (within 2.9 percent) with the published value given for average ditch discharge of 37.2 ft^3/s (24 Mgal/d) (Hawaii Commission on Water Resource Management, 1990, 1992). Average ditch discharge computed from the estimated time series was not expected to exactly replicate the value cited in the literature because the two values were not based on the same period of record and the published value is rounded off to the nearest million gallons. Also, no basis for the value of average ditch discharge cited in the literature is provided. Therefore it is assumed that the method used to estimate ditch diversions and Honokohau Stream discharges downstream from the diversion provides data values that are reasonable. The estimated time series of ditch flow data can be also used to compute the median flow in the ditch, which is 29.4 ft^3/s (19.0 Mgal/d). In most cases median flow is a more representative measure of typical flow magnitudes than average flow.

A flow-duration curve for Honokohau Stream, downstream from the ditch diversion, based on the estimated time series of daily discharges for the period 1913–2000 was computed and is summarized in table 10 and figure 12. Although average discharge for Honokohau Stream downstream from the ditch diversion is computed to be 6.3 ft^3/s, this number does not accurately describe the situation there. The flow-duration curve (fig. 12) provides a simple method for quantifying the hydrologic effect of the ditch diversion. Using this analysis it can be estimated that for 91.2 percent of the days, flow in Honokohau Stream immediately downstream from the diversion is limited to the minor amount of leakage which takes place through the dam. In this analysis the volume of leakage was assumed to equal 0.1 ft^3/s based on observations made during three seepage runs (table 7). Streamflow of consequence exists downstream from the diversion dam only during 8.8 percent of all days and then only when significant surface-runoff events are ongoing. An alternate way to evaluate the hydrologic effect of the ditch diversion is through computation of average and minimum daily discharges (table 11). Average discharge

Table 10. Selected flow-duration discharges at gaging station 16620000 and estimates of development tunnel discharge and discharges upstream and downstream from the Honokohau Ditch diversion at altitude 825 feet, water years 1913–2000, Honokohau Stream, Maui

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

Percentage of time indicated discharge equaled or exceeded	USGS station 16620000 discharge (ft^3/s)	Total discharge from development tunnels T-21 and T-22[a] (ft^3/s)	Total discharge upstream from diversion at site 0.2[b] (ft^3/s)	Total discharge downstream from diversion at site 0.4[c] (ft^3/s)
99	10	2.8	13	0.1
95	12	3.2	15	0.1
90	13	3.5	17	0.1
80	16	4.0	20	0.1
70	18	4.4	23	0.1
60	21	4.8	26	0.1
50	24	5.2	30	0.1
40	28	5.6	34	0.1
30	35	6.1	41	0.1
20	48	6.9	55	0.1
10	79	7.9	86	0.1
5	118	9.0	126	32.8
1	246	12	252	160

[a] Based on the estimated time series for 82 complete water years of record from 1913–2000; daily estimates based on ratio of development tunnel discharge measured by the USGS on January 24, 1924 (5.9 ft^3/s) to concurrent base flow at gage 16620000 (20 ft^3/s) multiplied by daily estimates of base flow at gage 16620000

[b] Based on the estimated time series for 82 complete water years of record from 1913–2000; daily estimates equal the sum of the daily discharge at gage 16620000 plus the estimated daily discharge for the two development tunnels T-21 and T-22

[c] Based on estimated time series for 82 complete water years of record from 1913–2000; daily estimates based on estimated daily discharges upstream from the diversion minus 93 ft^3/s (60 Mgal/d), the maximum diversion capacity of the ditch intake, plus an estimated 0.1 ft^3/s of leakage through the diversion dam

Table 11. Average, median, and minimum daily discharges for selected locations in the vicinity of the Honokohau Ditch diversion at altitude 825 feet, water years 1913–2000, Honokohau Stream, Maui

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

Site locations	Average discharge (ft^3/s)	Median discharge (ft^3/s)	Minimum daily discharge (ft^3/s)
USGS gaging station 16620000	39.1	24	8.4
Development tunnels T-21 and T-22[a] (total)	5.6	5.2	2.5
Upstream of diversion dam at site 0.2[a]	44.6	30	11
Downstream of diversion dam at site 0.4[a]	6.3	0.1	0.1
Honokohau Ditch just below intake[a]	38.3	29	11

[a] Based on estimated daily discharges for period 1913–2000 computed as part of study

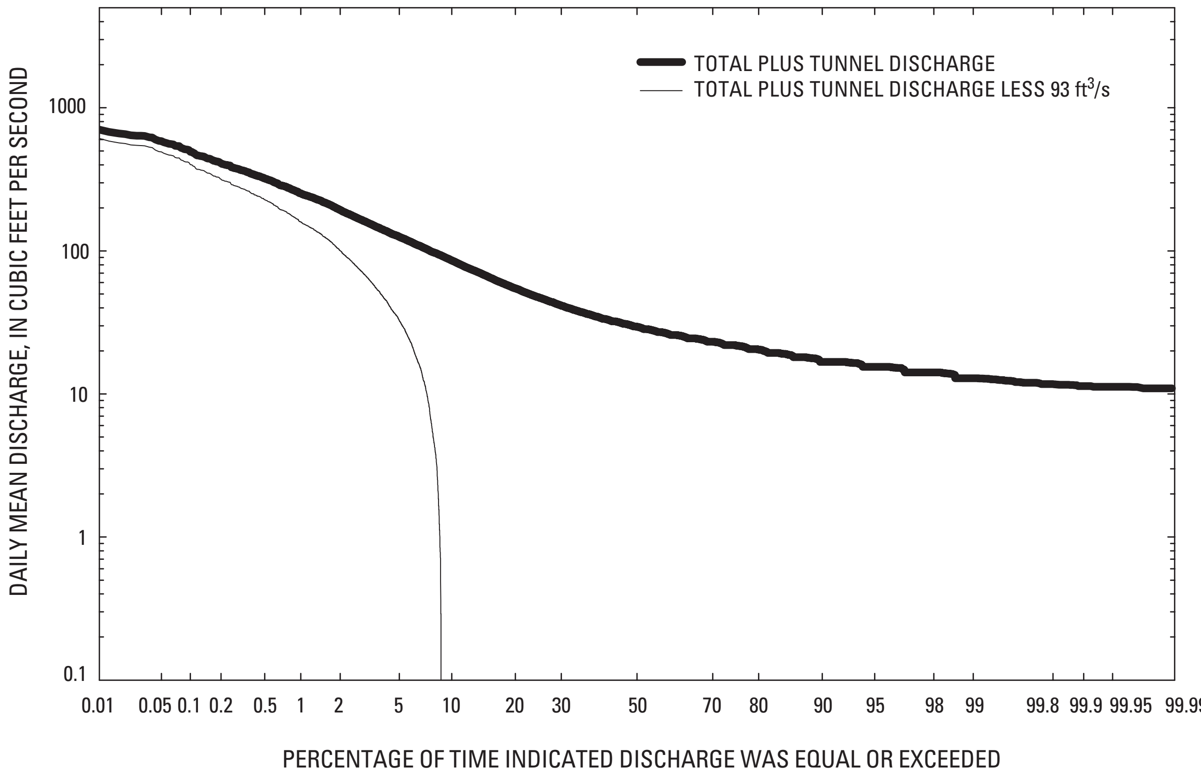


Figure 12. Flow-duration curves for estimates of daily discharges upstream and downstream of the Honokohau Ditch diversion at altitude 825 feet, water years 1913–2000, Honokohau Stream, Maui.

data can serve as a surrogate for total discharge and in this case average flow diverted in the Honokohau Ditch is 38.3 ft^3/s or 86 percent of the total flow of 44.6 ft^3/s upstream from the diversion. Minimum daily discharge in the diversion ditch is 11 ft^3/s and only 0.1 ft^3/s in the stream downstream from the diversion. Using most any measure, diversion of streamflow from Honokohau Stream at the ditch intake, located at an altitude of 825 ft, significantly alters the pattern of streamflow downstream from that location.

Taro Gate Releases

An important source of sustained base flow in lower reaches of Honokohau Stream, downstream from the springs at altitude 600 ft, are flow releases at the Taro Gate. During periods of base flow in the lower reaches of Honokohau Stream, flow releases at the Taro Gate are base flows, or ground-water-derived flows that were diverted from Honokohau Stream at an altitude of 825 ft by the Honokohau Ditch. ML&P currently targets a constant release of 1.55 ft^3/s (1.0 Mgal/d) from the Honokohau Ditch into the stream at an altitude of about 405 ft through the Taro Gate. For example, during the three seepage runs (table 7) Taro Gate releases increased the base flow downstream from site 4.0 by 69 to 109 percent. Flow releases from the Taro Gate during the three seepage runs were 1.67, 1.42, and 1.30 ft^3/s respectively, computed as the difference between measurements made at sites 4.0 and 5.0 (table 7). The availability of a constant release of 1.55 ft^3/s at the Taro Gate would have the greatest effect during periods of extreme low flows in Honokohau Stream. Using flow-duration data summarized for site 4.0 in table 5 it can be seen that at 95 and 90 percentile flow-duration discharges, constant inflow of 1.55 ft^3/s would increase base flow downstream from site 4.0 by 201 and 168 percent.

The availability of base flow in lower Honokohau Stream is therefore highly influenced and dependent on release of ditch water at the Taro Gate. As noted above, Taro Gate releases can be computed on the three days when seepage runs were conducted. During these seepage runs, discharge measurements were made just upstream and downstream of the flow release point. Flow releases from the Taro Gate can also be estimated at times when low-flow measurements at sites 4.0 and

5.9 (table 3) were made. To make these computations, estimates of discharge at site 5.0 are required for each day when discharge measurements were made at sites 4.0 and 5.9. As noted in the analysis of seepage runs, the reach between sites 5.0 and 5.9 gained an average of 0.49 ft^3/s from ground-water inflow during the three seepage runs. It can be expected that ground-water gains in this reach would be correlated to measured base flow at gaging station 16620000. To test this hypothesis, ratios of ground-water inflow between sites 5.0 and 5.9 during the seepage runs to concurrent base flow at gaging station 16620000 were computed. The resultant ratios were 0.035, 0.025, and 0.028 with an average of 0.029. The consistency of these ratios indicate that reasonable estimates of ground-water inflow for this reach can be made by multiplying the ratio 0.029 by the base flow at station 16620000. This computation was made for each day that low-flow partial-record measurements were made at sites 4.0 and 5.9. Estimates of discharge at site 5.0 on these days can be made by subtracting estimated ground-water inflow between sites 5.0 and 5.9 from measured discharge at site 5.9. Flow releases from the Taro Gate can be computed as estimated discharges at site 5.0 minus measured discharges at site 4.0. The accuracy of the proposed method was tested using data from the three seepage runs. Estimated Taro Gate releases were within +6.0, -4.9, and -1.5 percent of the results computed using measured discharges at site 5.0, indicating the suitability of the proposed method. The computations of Taro Gate releases are summarized in table 12 and a scatterplot of the computed Taro Gate flow releases compared with time are shown in figure 13.

The data in figure 13 and table 12 indicate that Taro Gate flow releases from Honokohau Ditch into Honokohau Stream are inconsistent and are frequently less than the targeted release of 1.55 ft^3/s. For the ten days when Taro Gate releases were computed, results ranged from a high of 1.67 ft^3/s to a low of 0.14 ft^3/s. The median flow release was 1.05 ft^3/s and computed releases were less than the targeted level on 9 of 10 days when measurements were made. ML&P attributes the problem of maintaining consistent flow releases to periodic blockage of the Taro Gate by leaves and debris (Wesley Nohara, Maui Land and Pineapple Company, Inc., written commun., 1993). Blockages at the Taro Gate are currently scheduled to be removed by ML&P personnel during their routine month-end visits to the site (Wesley Nohara, Maui Land and Pineapple Company, Inc., oral commun., 2003).

In an earlier section of the report (Low-Flow Partial-Record Stations) it was noted that no estimates of flow-duration statistics would be made at site 5.9 because the correlation coefficient between discharge measurements made there with daily mean discharges at station 16620000 was only 0.305. The variability of Taro Gate flow releases was likely the primary reason for this poor correlation.

Extrapolation of Base-Flow Characteristics

Flow-duration discharges have been computed and summarized for gaging station 16620000 (table 1), for low-flow partial-record sites 4.0 and 9.1 (table 5), and for sites 0.2 and 0.4 located upstream and downstream of the Honokohau Ditch diversion (table 10). The purpose of this section of the report is to summarize these computations of base-flow characteristics and to use these and other data, such as the seepage run measurements (table 7), to extrapolate the results to other locations along the lower section of Honokohau Stream.

Assuming current flow-diversion practices at Honokohau Ditch, at altitude 825 ft, (maximum of 93 ft^3/s) and measured median-return-flow practices at the Taro Gate release (1.05 ft^3/s) and hydropower plant release (0.46 ft^3/s) are consistently followed, extrapolations of base-flow computations can be made at sites 1.0, 2.0, 5.0, 5.9, 6.1, 7.6, 7.9, and 8.0 (table 2) using a variety of procedures. Flow-duration discharges for these sites as well as those for which results have been previously computed (tables 1, 5, and 10) are summarized in table 13.

During base-flow conditions observed in the field primarily during seepage runs (table 7), there was no flow observed at sites 1.0 and 2.0. It is reasonable to assume that no-flow conditions will exist at these sites over the range of flow-durations summarized in table 13. Flow-duration estimates can be made at site 5.0 by adding the measured median-flow release from the Taro Gate (1.05 ft^3/s) to site 4.0 flow-duration estimates. Flow-duration estimates for a single site can be manipulated directly when the adjustments made would be consistent (such as adding 1.05 ft^3/s of inflow) over the range of time and discharge being considered. Flow-duration estimates can be made at site 5.9 by adding estimates of ground-water inflow in the reach between sites 5.0 and 5.9 to flow-duration estimates made for site 5.0. As noted in an earlier section of the report (Taro Gate Releases) the inflow can be estimated by multiplying 0.029 times corresponding base flow at station 16620000.

Table 12. Computed Taro Gate flow releases from Honokohau Ditch into Honokohau Stream at altitude of 405 feet, Maui
[Values in cubic feet per second]

Date	Measured discharge			Estimated ground-water inflow between sites 5.0 and 5.9[a]	Computed Taro Gate release[b]
	Site 4.0	Site 5.0	Site 5.9		
09/14/95	1.53	3.20	3.76	0.46	1.67
08/13/97	1.64	3.06	3.54	0.55	1.42
10/23/97	1.89	3.19	3.61	0.44	1.30
06/29/99	2.74	3.43[c]	3.92	0.49	0.69
10/27/99	2.92	4.06[c]	4.52	0.46	1.14
03/17/00	1.22	2.57[c]	3.01	0.44	1.35
05/24/00	1.55	2.51[c]	2.92	0.41	0.96
07/11/00	2.16	2.77[c]	3.15	0.38	0.61
08/25/00	2.29	2.43[c]	3.01	0.58	0.14
12/19/00	1.18	1.39[c]	1.85	0.46	0.21

[a] Estimated ground-water inflow computed using the average ratio of measured ground-water inflow to base flow at station 16620000 determined for the first three pairs of measurements at sites 5.0 and 5.9 shown above; ground-water inflow equals 0.029 times base flow at station 16620000 for the day

[b] Taro Gate release determined as measured or estimated discharges at site 5.0 minus measured discharges at site 4.0

[c] Estimated discharge at site 5.0 computed as measured discharge at site 5.9 minus estimated ground-water inflow between sites 5.0 and 5.9

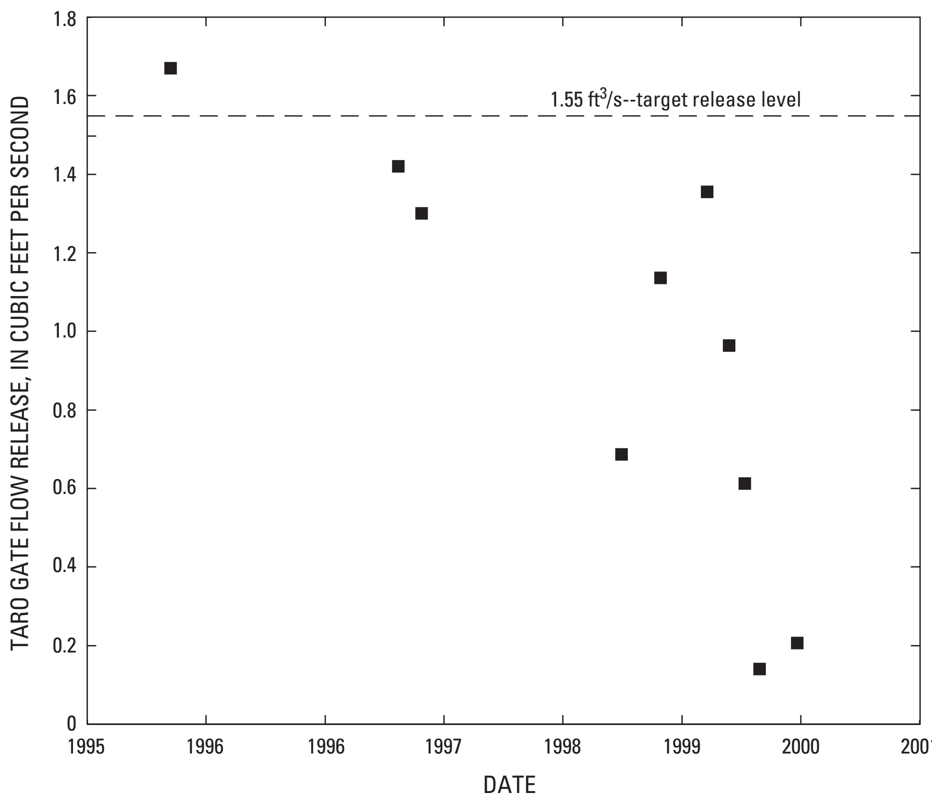


Figure 13. Scatterplot of computed Taro Gate flow releases from Honokohau Ditch into Honokohau Stream at altitude 405 feet, Maui.

Table 13. Computed flow-duration discharges for selected locations on lower Honokohau Stream, Maui, under current[a] diversion and return-flow practices

Site number[b]	Discharge equaled or exceeded indicated percentages of time (cubic feet per second)					
	95 percent	90 percent	80 percent	70 percent	60 percent	50 percent
16620000[c]	12	13	16	18	21	24
0.2[d]	15	17	20	23	26	30
0.4[d]	0.1	0.1	0.1	0.1	0.1	0.1
1.0[e]	0	0	0	0	0	0
2.0[e]	0	0	0	0	0	0
4.0[f]	0.77	0.92	1.5	1.9	2.7	3.7
5.0[g]	1.8	2.0	2.5	3.0	3.8	4.7
5.9[h]	2.1	2.3	2.9	3.4	4.3	5.2
6.1[i]	1.1	1.3	1.9	2.4	3.3	4.2
7.6[j]	2.0	2.2	2.9	3.4	4.4	5.6
7.9[j]	1.4	1.6	2.2	2.9	4.0	5.6
8.0[i]	0.34	0.39	0.74	1.3	2.5	4.1
9.1[f]	0.63	0.80	1.5	2.2	3.6	5.5

[a] Current practices include flow diversions up to 93 ft^3/s at the Honokohau Ditch, and return-flow releases of 1.05 ft^3/s at Taro Gate and 0.46 ft^3/s at hydropower plant

[b] Site numbers correspond to sites listed in table 2 and shown in figure 4 (sites 0.2 and 0.4 not shown in figure 4; see remarks in table 2 for locations)

[c] See table 1

[d] See table 10

[e] Discharge estimates based on field observations during seepage runs

[f] See table 5

[g] Discharge estimates based on site 4.0 data plus measured median-flow Taro Gate release of 1.05 ft^3/s

[h] Discharge estimates based on site 5.0 data plus estimated ground-water inflow in reach, see report section "Taro Gate Releases"

[i] Discharge estimates based on upstream site data minus maximum diversion observed during seepage runs of 1.00 ft^3/s at MacDonald's Dam and 1.51 ft^3/s at Chun's Dam plus a minimum leakage of 0.10 ft^3/s at MacDonald's Dam and 25 percent of discharge at Chun's Dam

[j] Discharge estimates based on average percentage of total loss between sites 5.9 and 9.1; percentages based on average for two 1997 seepage runs

Flow-duration estimates can be made at site 6.1, downstream from MacDonald's Dam, by subtracting the diversion at the dam from estimates for site 5.9. For the purposes of this work, diversion at the dam was assumed to be the maximum value of 1.00 ft^3/s observed during seepage runs (table 7). Flow-duration estimates at sites 7.6 and 7.9 were based on average percentages of flow losses between site 5.9 (plus the hydropower plant release of 0.46 ft^3/s) and the site (either site 7.6 or 7.9) to total flow losses in the losing reach of Honokohau Stream (site 5.9 to 9.1). The percentages were computed using data from the two 1997 seepage runs (table 7) which indicated that on average, 28 percent of total losses between sites 5.9 and 9.1, takes place between sites 5.9 and 7.6, and 62 percent of total losses takes place between sites 5.9 and 7.9. Flow-duration estimates can be made at site 8.0, downstream from Chun's Dam, by subtracting diversion at the dam from estimates for site 7.9. For purposes of this report, diversion at the dam was assumed to be the lesser of the flow-duration estimate at site 7.9 (upstream from Chun's Dam) less losses through and over the dam and the maximum diversion value of 1.51 ft^3/s observed during seepage runs (table 7). Losses through and over Chun's Dam are variable and not easily controlled; therefore, minimum losses at the dam were assumed to equal 25 percent of flow upstream from the dam at site 7.9.

Computations or estimates of flow-duration flows could not be made at a number of data sites used in this study (table 2). This was primarily attributed to variable ways by which flows diverted at MacDonald's and Chun's Dams were returned to the stream. Sites where flow-duration data could be computed provide a reasonable characterization of the distribution and availability of base flow in lower Honokohau Stream. In figure 14, flow-duration discharges for the 50th and 90th percentiles are plotted along with results from the August 13, 1997 seepage run to illustrate the extent to which base flows can be characterized in lower Honokohau Stream. The variation of 95th percentile flow-duration discharges are also shown on the map in figure 15. A previous estimate indicated that at least 2.32 ft^3/s

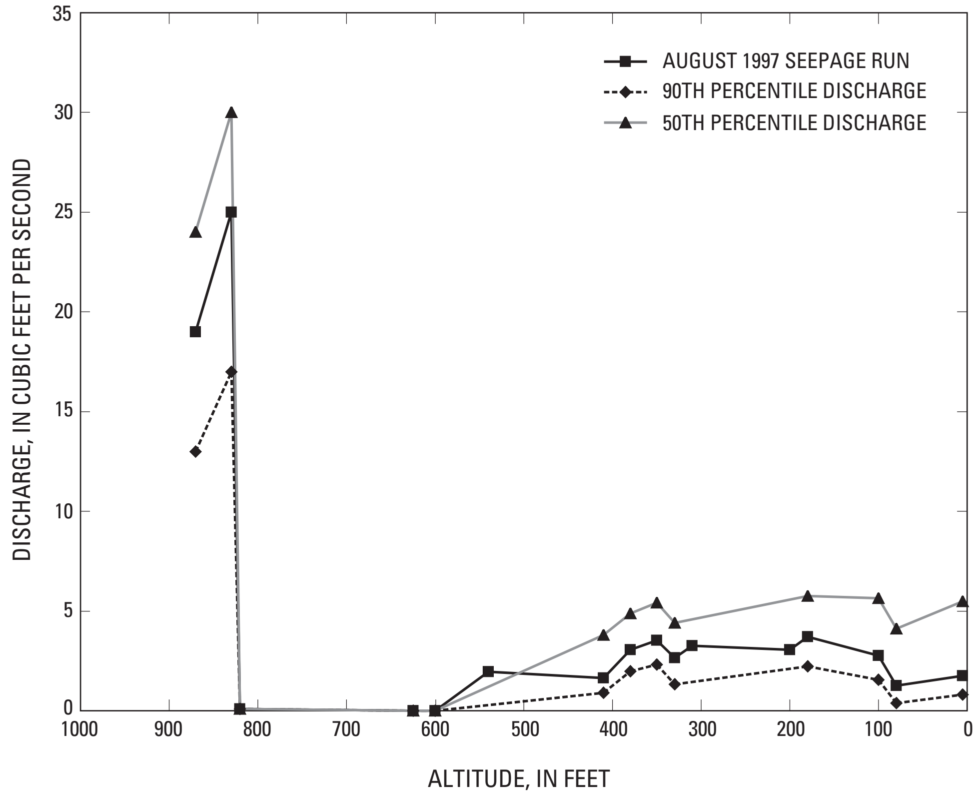


Figure 14. Discharge on Honokohau Stream, Maui, during August 13, 1997 seepage run and for selected flow-duration percentiles under current practices of 1.05 ft^3/s Taro Gate release and 0.46 ft^3/s hydropower plant release (ft^3/s, cubic feet per second).

(1.5 Mgal/d) of base flow was available to meet water needs in lower Honokohau Stream (Hawaii Department of Land and Natural Resources, 1977, p. iv). Estimates from ML&P (Wesley Nohara, Maui Land and Pineapple Company, Inc., written commun., 1993) indicate that available base flow is in excess of 4.6 ft^3/s (3.0 Mgal/d). Results in table 13 refine these estimates and indicate that base flows of 2.32 ft^3/s are available more than 95 percent of the time at MacDonald's Dam (site 5.9 plus the hydropower plant release) while flows in excess of 4.6 ft^3/s could be expected 65 percent of the time. Base flows of 2.32 and 4.6 ft^3/s are available 80 and 56 percent of the time, respectively, at Chun's Dam (site 7.9).

Reductions in base flow are summarized in table 14, both as absolute values and in terms of percentage for the entire losing reach of Honokohau Stream between MacDonald's Dam and the ocean. Reductions in base flow include the losses associated with consumptive uses and infiltration through the streambed to the ground-water system. Base-flow losses are reduced by the volumes of diverted flows that are returned to the stream. Base-flow losses decrease with increasing discharges both in terms of absolute values and percentages. For example, between the 95th and 50th percentile flows, the percentage of flow losses decreases from 77 to 4 percent. Some possible explanations for this process are (1) during higher flow conditions there is less need for irrigation water so that consumptive use of diverted water in the losing stream reach is lower, (2) during higher flow conditions, the freshwater lens is higher and as a result there is less seepage loss through the streambed, and (3) during higher flow conditions, contributions of flow from surface runoff start to become more significant. At gaging station 16620000 surface runoff starts becoming a factor at about the 70th percentile on the flow-duration curve (table 1 and fig. 7) and this is the percentile at which absolute base-flow losses in the losing reach start to drop (table 14).

It is instructive to summarize how much water would actually be available to support current taro cultivation practices in Honokohau Valley. In an earlier section of the report (Seepage Runs) it was noted that possible consumptive water use associated with current taro cultivation ranged from 0.20 to 0.59 ft^3/s. Given

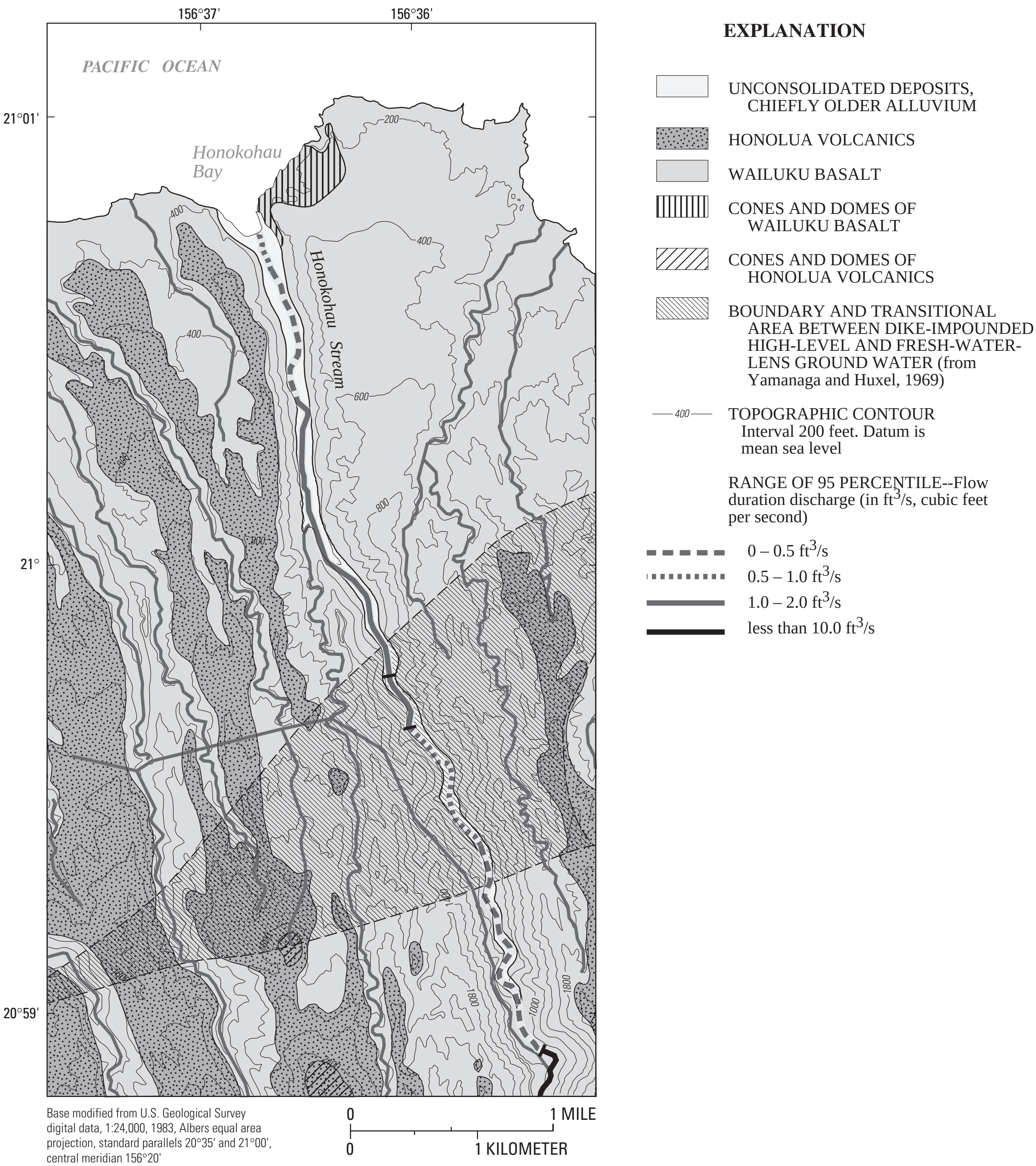


Figure 15. Discharge on Honokohau Stream, Maui, for the 95th percentile flow duration under current practices of 1.05 ft^3/s Taro Gate release and 0.46 ft^3/s hydropower plant release (geology from Stearns and Macdonald, 1942, and Langenheim and Clague, 1987).

Table 14. Reductions in base flow for selected flow-duration discharges in the losing reach of Honokohau Stream, Maui, between MacDonald's Dam and the ocean
[ft^3/s, cubic feet per second]

Computation	Results for indicated flow-duration percentiles					
	95 percent	90 percent	80 percent	70 percent	60 percent	50 percent
Site 5.9[a] (ft^3/s)	2.1	2.3	2.9	3.4	4.3	5.2
Site 5.9 plus hydropower release[b] (ft^3/s)	2.6	2.8	3.4	3.9	4.7	5.7
Site 9.1[c] (ft^3/s)	0.63	0.80	1.5	2.2	3.6	5.5
Total base flow loss[d] (ft^3/s)	2.0	2.0	1.9	1.7	1.1	0.2
Total base flow loss[e] (percent)	77	71	56	44	23	4

[a] Data from table 13
[b] Site 5.9 data plus targeted release of 0.46 ft^3/s from hydropower plant
[c] Data from table 13
[d] Computed as site 5.9 flow plus hydropower release flow minus site 9.1 flow
[e] Computed as ratio of total base flow loss to site 5.9 flow plus hydropower release flow in percent

that most of this cultivation is supported by Chun's Dam, it is useful to see how much water is currently available for diversion at that location. The difference in flow-duration discharges between site 7.9 and 8.0 in table 13 is a measure of the volume of water that can reasonably be diverted at Chun's Dam. These values range from about 1.1 ft^3/s at the 95th percentile discharge to the assumed maximum diversion capacity of 1.5 ft^3/s for all percentiles of 70 percent and lower. These data indicate that currently available discharges for all flow-duration percentiles of 95 percent or less at site 7.9 would be sufficient to meet the estimates of consumptive use using water diverted at Chun's Dam. Water diversions in excess of the volume of consumptive use are required to support taro cultivation; however, little or no consensus seems to exist as to what amounts of diversion, and therefore inflows, to taro fields are adequate. The Hawaii Commission on Water Resource Management, in its Waiahole decision (2001, p. 61), indicated that inflow rates in excess of 1.55 ft^3/s (1 Mgal/d) per acre of taro cultivation have been documented, but that in Waiahole Valley, a maximum rate of 0.06 ft^3/s (0.04 Mgal/d) per acre was established as sufficient. Current base-flow discharges in lower Honokohau Valley would be sufficient to meet the inflow requirements set in the Waiahole decision, but would not be sufficient to meet the upper range of documented inflow requirements for significant percentages of the time.

Base-Flow Water-Accounting Model

The results describing the availability and distribution of base flow in lower Honokohau Stream (primarily summarized in table 13) are based on continuation of current diversion and return-flow practices which include (1) diversions of flows up to 93 ft^3/s at the Honokohau Ditch at 825 ft, (2) median-flow releases of 1.05 ft^3/s from the Taro Gate at an altitude of 405 ft, (3) flow releases of 0.46 ft^3/s from the hydropower plant near MacDonald's Dam, (4) continued operation of MacDonald's and Chun's Dams in a manner that is consistent with that observed during the seepage runs, and (5) no major changes in the patterns of near-stream consumptive use of water in lower Honokohau Valley. Using the data collected as part of this study, a base-flow water-accounting model was developed using a spreadsheet to compute flow-duration discharges for the percentiles and sites summarized in table 13 in response to changes in several factors including flow releases at the Taro Gate and the hydropower plant and diversion practices at MacDonald's and Chun's Dams. When the established diversion and return-flow practices are changed in the spreadsheet then results shown in table 13 are automatically recomputed.

To demonstrate the utility of the base-flow water-accounting spreadsheet, changes in flow-duration discharges at MacDonald's and Chun's Dams were

Table 15. Variation in computed flow-duration discharges upstream from Chun's Dam on Honokohau Stream, Maui, associated with variable flow-release rates at the Taro Gate
[ft^3/s, cubic feet per second]

Taro Gate release rate (ft^3/s)	Discharge equaled or exceeded indicated percentages of time (ft^3/s)					
	95 percent	90 percent	80 percent	70 percent	60 percent	50 percent
0.0	0.82	0.97	1.5	2.1	3.1	4.5
0.25	0.95	1.1	1.7	2.3	3.3	4.8
0.5	1.1	1.2	1.9	2.4	3.6	5.0
0.75	1.2	1.4	2.0	2.6	3.8	5.3
1.00	1.3	1.5	2.2	2.8	4.0	5.5
1.05[a]	1.4	1.6	2.2	2.9	4.0	5.6
1.25	1.5	1.7	2.4	3.0	4.2	5.7
1.50	1.6	1.8	2.5	3.2	4.4	6.0
1.75	1.7	1.9	2.7	3.4	4.6	6.2
2.00	1.9	2.1	2.9	3.5	4.8	6.5
3.00	2.4	2.6	3.5	4.3	5.7	7.5

[a] 1.05 ft^3/s is the measured median-flow release rate and flow-duration discharges for this release rate are from table 13 site number 7.9

computed in response to a variety of flow-release rates from the Taro Gate. Honokohau Stream, between the Taro Gate release and MacDonald's Dam, was shown to be a gaining reach (described in section Seepage Runs). As a result there will be a 1 to 1 relation between changes in release rates at the Taro Gate and base flow upstream from MacDonald's Dam. For example, at site 5.9 (upstream from MacDonald's Dam) the 95 percent flow-duration discharge is 2.1 ft^3/s under the current release practice at the Taro Gate (1.05 ft^3/s). If the flow release at the Taro Gate was decreased or increased by 0.5 ft^3/s, the 95 percent flow-duration discharge would change to 1.6 or 2.6 ft^3/s, respectively. A similar 1 to 1 relation would be expected for other changes in release rates and for other flow-duration percentiles. These results were correctly reproduced by the model.

The response of flow-duration discharges upstream from Chun's Dam (site 7.9) to changes in Taro Gate release rates is more complicated and therefore the model results are summarized in table 15. Downstream from MacDonald's Dam, the stream loses base flow and therefore a 1 to 1 relation does not exist between variations in Taro Gate releases and base flow at site 7.9. As noted in table 14, rates of base-flow loss decrease from lower discharges to higher discharges and a similar pattern is evident in the variation of base-flow discharges with changes in flow-release rates at the Taro Gate. For example, if the release rate at the Taro Gate were to decrease from 1.00 to 0.0 ft^3/s, the 95th percentile discharge would decrease by 0.5 ft^3/s (50 percent of the change at the Taro Gate) while the 60th percentile discharge would decrease by 0.9 ft^3/s (90 percent of the change at the Taro Gate) (table 15). The reverse case also holds true in that release-rate increases of 1.00 ft^3/s at the Taro Gate results in flow increases at Chun's Dam that are variable with flow-duration percentile and less than 1.00 ft^3/s.

ACCURACY OF DATA AND BASE-FLOW ESTIMATES

Users of this report should be aware of the accuracy, and therefore possible limitations, associated with the data and base-flow estimates provided. Primary data and computations summarized in this report are discharge measurements, daily mean streamflow and selected summary statistics (at one continuous record station), flow-duration estimates (at two low-flow partial-record stations), computations of diversions and flow releases, and extrapolation of base-flow estimates to additional locations. The purpose of this section of the report is to provide, where possible, statistical measures of the accuracy associated with the data mentioned above.

Individual discharge measurements are summarized in this report for low-flow partial-record stations (table 3), historic miscellaneous sites (table 6) and seepage runs (table 7). Sauer and Meyer (1992) and Rantz and others (1982) provide a summary of the wide variety of factors that can influence the accuracy of individual discharge measurements. On the basis of findings summarized in those studies, USGS personnel assign accuracy ratings to each discharge measurement made. Measurements made as part of this study were primarily rated either good or fair. Good and fair measurements are considered to be within 5 and 8 percent of the actual "true" discharge (Sauer and Meyer, 1992, p. 2).

Daily mean discharge data from long-term streamflow-gaging station 16620000 on Honokohau Stream and statistical summaries of the data are provided in tables 1 and 13 (flow-duration curve), table 3 (daily mean discharges for selected days), table 11 (average, median, and minimum daily discharges), figure 5 (annual means), and figure 6 (monthly flow statistics). Daily mean discharge data published by the USGS are divided into one of four accuracy classifications (Novak, 1985, p. 65). These accuracy classifications take into account a broad variety of factors but depend primarily on the stability of the stage-discharge rating and the frequency and accuracy of stage and discharge measurements at the station. The majority of the daily mean discharge data for station 16620000 are rated good, which means that 95 percent of the daily mean discharges are within 10 percent of the actual "true" discharge (Novak, 1985, p. 65). Development of flow-duration curves and computations of average, median, and minimum daily discharges for selected periods of record do not introduce additional sources of error beyond those inherent in the daily mean discharges data used to make the computations.

The computed daily flow statistics are accurate measures for the period of record over which they have been computed. The question is how accurately does the period of record represent long-term conditions and future hydrologic conditions for the watershed. In this case 82 water years of streamflow data were available for Honokohau Stream gaging station 16620000. These data can be considered an excellent representation of long-term conditions given the length of record, the good rating for the majority of the daily mean discharge data, and the fact that no significant trends were evident in the data. Care must be used when extrapolating computed streamflow characteristics into the future, as there is no assurance that the relative stability of hydrologic conditions observed over the past 82 water years will continue.

Selected base-flow flow-duration discharges were computed for low-flow partial-record stations at sites 4.0 and 9.1 and summarized in tables 5 and 13. Unlike the flow-duration discharges computed for station 16620000, these statistics were not based on long-term daily discharge data and will therefore have additional errors associated with them. These errors are a function of a variety of factors, the two most important being the strength of the correlation between the discharge measurements at the low-flow partial-record stations and the daily mean discharges at the index station and the number of discharge measurements made. Using methods first developed by Hardison and Moss (1972) and later refined by Ries and Friesz (2000, p. 12) the total variance associated with the computations of each of the flow-duration discharges can be computed. Standard errors in percent were then computed based on the total variance using equations developed by Stedinger and Thomas (1985, p. 18). Standard errors at a low-flow partial-record station will differ slightly with the flow-duration statistic being computed. In this report, average standard errors for the computed flow-duration discharges were determined to be 21 and 34 percent for sites 4.0 and 9.1. These errors should be considered minimum errors as the methods used to compute them do not take into account the potential errors inherent in the discharge measurements made at the low-flow partial-record sites or the daily mean discharges at the index station.

Computations of flow-duration discharges and flow statistics upstream and downstream of Honokohau Ditch are provided in tables 10 and 11, flow releases from the Taro Gate are summarized in table 12, and flow-duration discharges that are extrapolated to additional locations are summarized in tables 13 and 15. Methods to estimate the errors associated with these computations are not available. Where possible, surrogate measures of accuracy were included in the report to provide some estimate of possible errors. For example, the computed discharge from development tunnels T-21 and T-22 (tables 10 and 11) was compared to estimates provided by Yamanaga and Huxel (1969) and Mink (1990) and computed diversion in the Honokohau Ditch was compared to estimates summarized by the Hawaii Commission on Water Resource Management (1990, 1992). The extrapolated flow-duration discharges were based on less data than were available to compute comparable discharges at low-flow partial-record site 4.0 and 9.1. Standard errors associated with the extrapolations would, as a minimum, be greater than the 34 percent value computed for site 9.1.

SUMMARY AND CONCLUSIONS

Results summarized in this report provide a detailed evaluation of the availability and distribution of base flow in lower Honokohau Stream and quantify how the base flow is affected by streamflow diversions and return flows located in the valley. The geology of Honokohau Valley plays a significant role because most of the naturally occurring base flow in the stream is derived from high-level water impounded by dikes in the Wailuku Basalt. At the only long-term USGS streamflow-gaging station in the valley (station 16620000), a flow-duration analysis indicated that a sustained and stable base flow, which equals or exceeds 10 ft^3/s is available at least 99 percent of the time.

Significant volumes of base flow, several times greater than those found downstream from Honokohau Ditch, are found upstream from the ditch. During base flow conditions, most of the stream, between the ditch diversion and the springs at an altitude of 600 feet, is dry. Starting with the springs and as far downstream as MacDonald's Dam, at an altitude of 340 feet, the stream gains from ground-water discharges. Downstream from MacDonald's Dam to the ocean the stream loses water as infiltration through the streambed.

The Honokohau Ditch diversion has a significant effect on the flow in Honokohau Stream. The average flow diverted from Honokohau Stream into the ditch is 38.3 ft^3/s or 86 percent of the total flow upstream from the ditch intake. Downstream from the diversion dam there is no flow in the stream 91.2 percent of the time, except for the minor amount of leakage taking place through the dam. At the Taro Gate, flow is returned from Honokohau Ditch into Honokohau Stream at an altitude of 405 feet. The flow release at this location is targeted to be 1.55 ft^3/s. The magnitude of the actual flow release was computed on ten separate occasions and the median value was determined to be 1.05 ft^3/s. Flow releases at the Taro Gate were found to be inconsistent and computed releases were less than the targeted level on 9 of the 10 days on which measurements were made.

Using current diversion and return-flow practices which include (1) diversion of up to 93 ft^3/s at Honokohau Ditch, (2) combined flow releases of 1.51 ft^3/s at the Taro Gate and the hydropower plant, and (3) continued operation of flow diversions at MacDonald's and Chun's Dams, flow-duration discharges for percentiles ranging from 50 to 95 percent were made at 13 locations between altitudes of 870 and 5 feet on Honokohau Stream. These flow-duration data provide detailed characterization of the distribution and availability of base flow in lower Honokohau Stream. Previous estimates indicated that base flows ranging from 2.32 to 4.6 ft^3/s were available to meet the water needs in lower Honokohau Stream. At the two principal water diversion sites in the lower valley (MacDonald's and Chun's Dams) data from this study indicate that base flows of 2.32 ft^3/s are available more than 95 percent of the time at MacDonald's Dam and 80 percent of the time at Chun's Dam. Base flows of 4.6 ft^3/s are available only 65 percent of the time at MacDonald's Dam and only 56 percent of the time at Chun's Dam.

A base-flow water-accounting model was developed to determine how flow-duration discharges computed for the 13 sites, using current diversion and return-flow practices, would change in response to a variety of flow-release practices at the Taro Gate and hydropower plant and diversion practices at MacDonald's and Chun's Dams. Use of the model indicates that there is a 1 to 1 relation between changes in release rates at the Taro Gate and base flow upstream from MacDonald's Dam. At Chun's Dam the relation varies with flow-duration percentiles. At the 95th percentile, differences in flow at Chun's Dam would equal 50 percent of the change at the Taro Gate. At the 60th percentile, differences in flow at Chun's Dam would equal 90 percent of the change at the Taro Gate.

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