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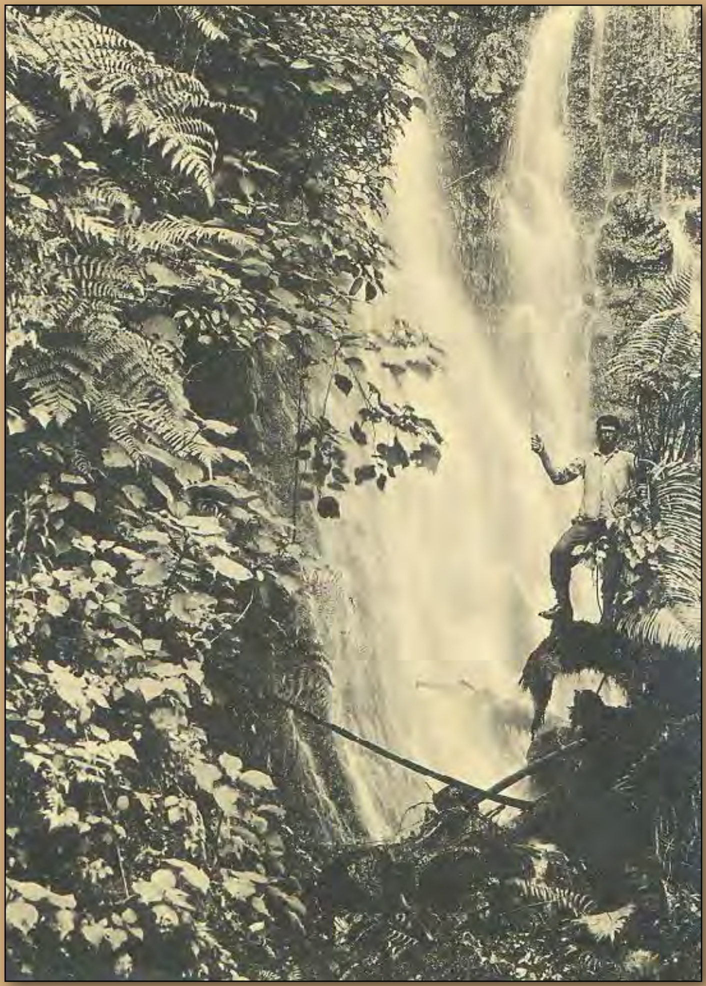
Natural and Diverted Low-Flow Duration Discharges for Streams Affected by the Waiāhole Ditch System, Windward O‘ahu, Hawai‘i



Scientific Investigations Report 2006–5285

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

COVER
Waterfall at one of the water sources of Waiāhole Stream, windward Oʻahu, Hawaiʻi.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the mean sea level.

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

Altitude, as used in this report, refers to distance above the mean sea level.

Natural and Diverted Low-Flow Duration Discharges for Streams Affected by the Waiāhole Ditch System, Windward O‘ahu, Hawai‘i

By Chiu W. Yeung and Richard A. Fontaine

Abstract

For nearly a century, the Waiāhole Ditch System has diverted an average of approximately 27 million gallons per day of water from the wet, northeastern part of windward O‘ahu, Hawai‘i, to the dry, central part of the island to meet irrigation needs. The system intercepts large amounts of dike-impounded ground water at high altitudes (above approximately 700 to 800 ft) that previously discharged to Waiāhole (and its tributaries Waianu and Uwao[1]), Waikāne, and Kahana Streams through seeps and springs. Diversion of this ground water has significantly diminished low flows in these streams. Estimates of natural and diverted flows are needed by water managers for (1) setting permanent instream flow standards to protect, enhance, and reestablish beneficial instream uses of water in the diverted streams and (2) allocating the diverted water for instream and offstream uses.

Data collected before construction of the Waiāhole Ditch System reflect natural (undiverted) flow conditions. Natural low-flow duration discharges for percentiles ranging from 50 to 99 percent were estimated for four sites at altitudes of 75 to 320 feet in Waiāhole Stream (and its tributaries Waianu and Uwao Streams), for six sites at altitudes of 10 to 220 feet in Waikāne Stream, and for three sites at altitudes of 30 to 80 feet in Kahana Stream. Among the available low-flow estimates along each affected stream, the highest natural Q_{50} (median) flows on Waiāhole (altitude 250 ft), Waianu (altitude 75 ft), Waikāne (altitude 75 ft), and Kahana Streams (altitude 30 ft) are 13, 7.0, 5.5, and 22 million gallons per day, respectively. Q_{50} (median) is just one of five duration percentiles presented in this report to quantify low-flow discharges. All flow-duration estimates were adjusted to a common period of 1960-2004 (called the base period). Natural flow-duration estimates compared favorably with limited pre-ditch streamflow data available for Waiāhole and Kahana Streams.

Data collected since construction of the ditch system reflect diverted flow conditions, which can be further divided into pre-release and post-release periods—several flow releases to Waiāhole, Waianu, and Waikāne Streams were initiated between December 1994 and October 2002. Comparison of pre-release to natural flows indicate that the effects of the Waiāhole Ditch System diversion are consistently greater at lower low-flow conditions (Q_{99} to Q_{90}) than at higher low-flow conditions (Q_{75} to Q_{50}). Results also indicate that the effects of the diversion become less significant as the streams gain additional ground water at lower altitudes. For Waiāhole Stream, pre-release flows range from 25 to 28 percent of natural flows at an altitude of 250 feet and from 19 to 20 percent at an altitude of 320 feet. For Waikāne Stream, pre-release flows range from 30 to 46 percent of natural flows at an altitude of 10 feet and from 7 to 19 percent at an altitude of 220 feet. For Kahana Stream, pre-release flows range from 65 to 72 percent of natural flows at an altitude of 30 feet and from 58 to 71 percent at an altitude of 80 feet.

Estimates of post-release flows were compared with estimates of natural flows to assess how closely current streamflows are to natural conditions. For Waianu Stream, post-release flows at an altitude of 75 feet are 41 to 46 percent lower than corresponding natural flows. For Waikāne Stream, post-release flows at an altitude of 75 feet are within 12 percent of the corresponding natural flows.

Comparisons of pre-release and post-release flows for Waikāne Stream at altitudes of 10 to 220 feet were used to assess downstream changes in flow along the stream reach where flow releases were made. For a particular stream altitude, proportions of pre-release to post-release flows associated with median flows are consistently greater than proportions associated with lower low flows because the relative effect of the flow release is smaller at higher low flows. Similarly, for a particular flow-duration percentile, proportions of pre-release to post-release flows associated with lower altitudes are consistently greater than proportions at higher altitudes because the relative effect of the flow release is smaller as the stream gains ground water at lower altitudes. Proportions of pre-release to post-release flows for selected flow-duration percentiles at an altitude of 10 feet range from 35 to 43 percent, whereas proportions at a higher altitude of 220 feet range from 5 to 11 percent.

[1] The name of this stream was formerly spelled Uwau, but the Hawai‘i Board on Geographic Names decided in 2000 that Uwao should be the correct spelling.

Introduction

In 1897, the Oahu Sugar Company established a large-scale sugar plantation on the dry, southwestern side of Oʻahu. Irrigation water for the sugar-cane plantation was initially pumped from the Pearl Harbor aquifer (Wilcox, 1996). Because of the high pumping cost, the Oahu Sugar Company constructed the Waiāhole Ditch System to transport, by gravity, surface water from the northeastern side of the Koʻolau Range (fig. 1). For nearly a century, the Waiāhole Ditch System diverted an average of about 27 million gallons per day (Mgal/d) (Hawaiʻi Commission on Water Resource Management, 2001, table 1 on p.143) of water from windward Oʻahu to central Oʻahu to meet irrigation needs. This diverted flow consists of ground water gained from the connecting tunnels, the four development tunnels, and the trans-Koʻolau tunnel and of surface water gained primarily from Kahana Valley.

The Waiāhole Ditch collection and delivery system was initially constructed during 1913-1916. The collection system, on the windward side of Oʻahu, consists of 4 development tunnels, 27 connecting tunnels, and 37 stream intakes, one at each gulch. The collection system was originally designed to divert the abundant surface water of windward Oʻahu streams. The 4.7 mi of connecting tunnels begins in Kahana Valley at about 790 ft altitude and extends south through the Waikāne and Waiāhole Valleys (fig. 1). At Waiāhole Valley, a 2.7-mi-long trans-Koʻolau tunnel was bored through the Koʻolau Range. The delivery part of the ditch system begins at Adit 8, where the main tunnel exits the Koʻolau Range, and terminates at Reservoir 155 at Honouliuli (Water Resource Associates, 2003). Reservoir 155 is located near the foot of the Waiʻanae Range at an altitude of about 600 ft (Wilcox, 1996).

The main tunnel through the Koʻolau Range was primarily designed as a transmission tunnel. The success of this tunnel in intercepting large amounts of dike-impounded ground water in the Koʻolau Range led to the construction of additional high-level ground-water development tunnels. Between 1925 and 1935, six tunnels with headings directed into the Koʻolau Range were added to the ditch system to develop ground water stored in dike compartments. Four development tunnels (Uwao, Waikāne 1, Waikāne 2, and Kahana) were considered successful (fig. 1, table 1). The Uwao tunnel was extended in 1963-64 beyond the topographic divide of the Koʻolau Range for about 228 ft (Takasaki and others, 1969, p.114), which increased production by about 2-3 Mgal/d (Takasaki and Mink, 1985, p.38). In 1992, a bulkhead was installed in the Kahana tunnel, which reduced production by an average of 1.5 Mgal/d (Hawaiʻi Commission on Water Resource Management, 2001, table 1 on p.143). Several major flow releases to windward Oʻahu streams from the Waiāhole Ditch System were initiated between December 1994 and October 2002. Construction timelines for the Waiāhole Ditch System and other events that affected flows in the windward Oʻahu streams are summarized in figure 2.

Waiāhole Ditch diversion of the dike-impounded ground water, which previously discharged to Waiāhole, Waikāne, and Kahana Streams through seeps and springs, has significantly diminished base flows in these streams. Base flows of streams are sustained by ground-water discharge and may continue even during dry-weather conditions. The effects of Waiāhole Ditch diversions received significant attention in 1993, when it became known that large amounts of diverted water were not being used for irrigation and instead were being released into streams on the leeward side of Oʻahu. This coincided with the Oahu Sugar Company announcement of the closure of its sugar-plantation operations. Releases of water into leeward streams initiated a legal proceeding (Waiāhole Ditch Contested Case) before the Hawaiʻi Commission on Water Resource Management (CWRM) over rights to the water. In December 1997, the CWRM released its initial decision,

Table 1. Average flows for Waiāhole Ditch System development tunnels.

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

Tunnel	Period	Number of years	Average flow (Mgal/d)	Standard deviation (Mgal/d)
Waikāne 1	1938-78[d]	41	4.6	0.97
	1989-1993[e]	5	4.2	--
	1999-2004[f]	5	4.3	1.16
Waikāne 2	1938-78[d]	41	1.1	0.16
	1989-1993[e]	5	1.1	--
	1999-2004[f]	5	1.1	0.16
Kahana[a]	1938-78[d]	41	3.6	0.73
	1989-1993[e]	5	2.6[g]	--
	1999-2004[f]	5	0.8[h]	0.02
Uwao[b]	1938-62[d]	25	10.2	2.01
	1967-78[d]	12	13.0	1.77
	1989-1993[e]	5	13.5	--
	1999-2004[f]	5	13.4	1.41
Main tunnel[c]	1938-78[d]	41	4.8	0.98
	1989-1993[e]	5	3.7	--
	1999-2004[f]	5	4.8	1.17

[a]Bulkhead installed in Kahana tunnel in 1992.

[b]Uwao tunnel was lengthened by 228 ft in 1963-64; Uwao was formerly spelled Uwau.

[c]Values represent ground-water gain between North Portal and Adit 8 stations.

[d]Values obtained from Takasaki and Mink (1985).

[e]Values obtained from Hawaiʻi Commission on Water Resource Management (2001, table 1 on p.143).

[f]Data provided by Agribusiness Development Corporation.

[g]Reflects flow reduction of 1.1 Mgal/d due to bulkhead.

[h]Average flow computed on the basis of estimated data.

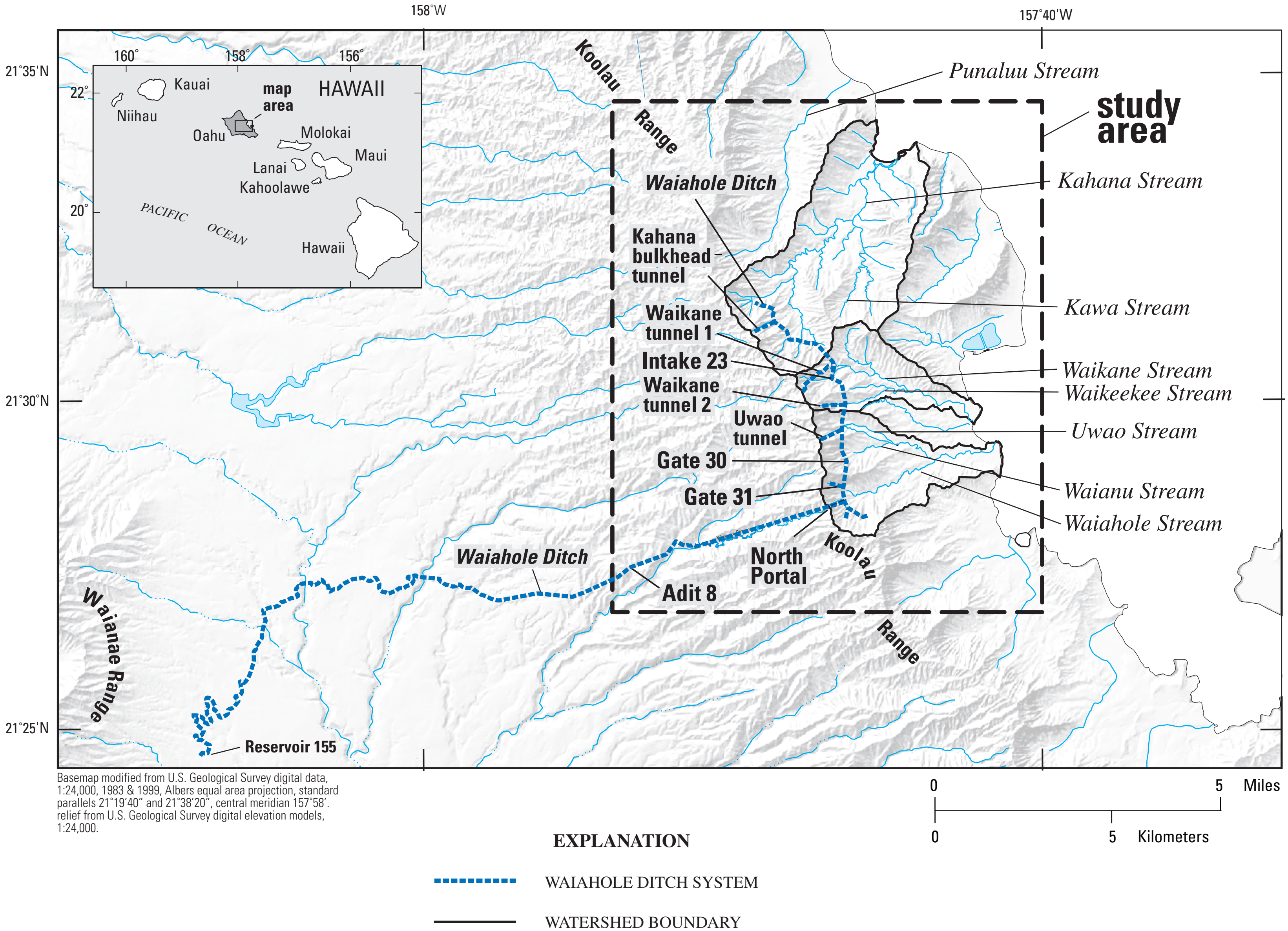


Figure 1. Waiāhole Ditch System and the location of the Kahana, Waikāne, Waiāhole Streams, windward O‘ahu, Hawai‘i. Uwao was formerly spelled Uwau.

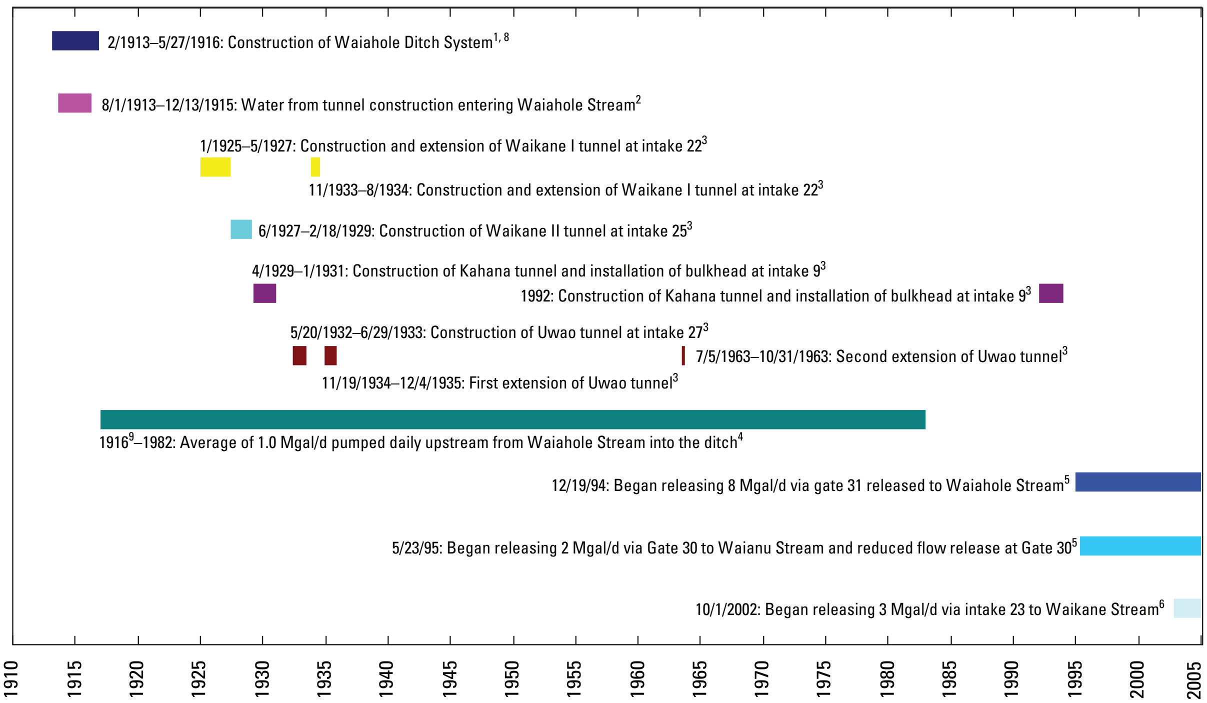


Figure 2. Timeline of major events affecting low flows in the study area, windward O‘ahu, Hawai‘i. Uwao was formerly spelled Uwau. [1]Kluegel, 1916; [2]Wilcox, 1996; [3]Stearns and Vaksvik, 1935; [4]table 22 in Takasaki and others, 1969; [5]Hawai‘i Commission on Water Resource Management, 2001; [6]assumes the pumping began after the opening of ditch system in 1916; [7]Takasaki and Mink, 1985; [8]unpublished USGS letter to Hawai‘i Commission on Water Resource Management, 1966; [9]Agribusiness Development Corporation, written commun., 2003.

which was appealed to the State Supreme Court. In August 2000, the Supreme Court vacated part of the initial decision and remanded several issues for additional findings. In December 2001, the CWRM revised the decision on remand, which was again appealed to the Supreme Court. In June 2004, the Supreme Court vacated part of the revised decision and remanded several issues for additional findings. As of February 2006, the Waiāhole Ditch Contested Case has yet to be fully resolved. As an interim resolution, the CWRM ordered the restoration of water back into windward streams to meet instream-flow needs. Waiāhole Ditch is currently maintained by the Agribusiness Development Corporation (ADC), a State agency. ADC began releasing water from the Waiāhole Ditch System into Waiāhole Stream at Gate 31 on December 19, 1994, into Waianu Stream at Gate 30 on May 23, 1995, and into Waikāne Stream at Intake 23 starting on October 1, 2002 (fig. 1).

In 2004, the U.S. Geological Survey (USGS), in cooperation with the CWRM, undertook a study to estimate low flows representative of natural undiverted conditions in Waiāhole, Waikāne, and Kahana Streams affected by the Waiāhole Ditch System. These estimates are needed by the CWRM for setting permanent instream flow standards to protect, enhance, and reestablish, where practicable, beneficial instream uses of water.

Purpose and Scope

This report (1) presents estimates of natural low-flow characteristics at selected locations in Waiāhole, Waikāne, and Kahana Streams, (2) quantifies the effects of diversions by the Waiāhole Ditch System on low flows, and (3) describes the effects of flow releases on flows in the streams. A combination of pre-ditch and post-ditch streamflow data and ditch-flow data were analyzed for this report. Data collected during the pre-ditch period reflect natural (undiverted) flow conditions before any effects from the construction of Waiāhole Ditch System. Data collected during the post-ditch period reflect diverted flow conditions, which can be further divided into pre-release and post-release periods for Waiāhole, Waianu, and Waikāne Streams where flow releases were made.

Pre-ditch streamflow data include data collected before any effects on streamflow from the construction of Waiāhole Ditch System at (1) continuous-record stations on Waiāhole and Kahana Streams and (2) miscellaneous sites along Waiāhole, Waikāne, and Kahana Streams. Post-ditch streamflow data include data collected at (1) continuous-record stations on Waiāhole (1914-16, 1950-69, 2000-present), Waikāne (1959-present), and Kahana (1958-present) Streams and (2) miscellaneous sites along Waiāhole, Waikāne, and Kahana Streams after the construction of the ditch system. Post-ditch streamflow data collected specifically for this study include (1) low-flow measurements representative of existing diversion conditions at 12 sites on Waianu, Uwao, Waikāne, and Kahana Streams in 2002-03, (2) two sets of discharge measurements made at multiple sites along the connecting tunnel of the Waiāhole Ditch System from Kahana Stream to the North Portal in 2002-03, and (3) two sets of discharge measurements made at multiple sites along Waikāne Stream in 2002-03. Ditch-flow data include (1) development-tunnel flows available in digital format for the period 1999–2004 provided by ADC and (2) ditch flows recorded at continuous-record stations for various periods along the connecting tunnel.

Acknowledgements

The authors would like to thank Agribusiness Development Corporation (ADC) personnel for sharing their detailed knowledge of the ditch and for flow data collected in the Waiāhole Ditch System. ADC also provided valuable cooperation and assistance in accessing the Waiāhole Ditch System. Personnel from the U.S. Marine Corps escorted U.S. Geological Survey (USGS) personnel in Waikāne Valley during seepage runs conducted as part of this study. The authors would also like to acknowledge Delwyn Oki from the USGS for his technical assistance during this study and the employees from the USGS Honolulu field office for conducting seepage runs and making low-flow measurements.

Description of Study Area

Physical Setting

The island of O‘ahu, with an area of 604 square miles (mi^2), is the third largest of the Hawaiian Islands. It is formed by the eroded remnants of two elongated shield volcanoes, the older Wai‘anae Volcano and the younger Ko‘olau Volcano (Visher and Mink, 1964). The Wai‘anae Range forms the western part of the island, and the Ko‘olau Range forms the eastern part. The study area, in the northeastern part of the island, lies on the eastern slope, or windward side, of the Ko‘olau Range. The study area encompasses the three watersheds (Waiāhole, Waikāne, and Kahana) that are affected by the Waiāhole Ditch System (fig. 1). The three watersheds have a combined drainage area of about 14.95 mi^2. The drainage areas of Waiāhole and Waikāne watersheds are 3.95 and 2.65 mi^2, respectively. Kahana Stream, which has a drainage area of 8.35 mi^2, is the largest drainage area and has the longest stream length in the study area. The land uses in the headwaters of the three watersheds are primarily classified as conservation undeveloped areas (Klasner and Mikami, 2003) (fig. 3). The ridge (topographic crest) of the Ko‘olau Range forms the southwest boundary of these three watersheds. The topographic relief in the study area ranges from mean sea level at the coast to 2,786 ft at the peak of the topographic divide of the Waiāhole watershed. Headwater areas above ditch altitudes are in amphitheater-headed valleys, with steep slopes of about 45° to nearly 80° (Takasaki and others, 1969). The stream gradients decrease abruptly to less than 5° in the lower parts of the watersheds, which have flat-bottomed valleys near the shore (Takasaki and others, 1969).

In general, Waiāhole, Waikāne, and Kahana Streams flow northeastward from the topographic crest of the Ko‘olau Range to the coast. Many small tributaries contribute flow to the main streams, particularly at high altitudes. Waiāhole Stream has one main tributary, Waianu Stream, on the north. Upper Waiāhole Stream is formed by Waihī Stream (north fork of Waiāhole Stream) and Hālona Stream (south fork of Waiāhole Stream) (fig. 4). Waikāne watershed lies north of Waiāhole watershed. Waike‘eke‘e Stream is the main tributary of Waikāne Stream. Kahana watershed lies south of Punalu‘u watershed and north of Waikāne watershed. Kāwā Stream, a major tributary to Kahana Stream, is not directly affected by the ditch system, because it originates below the ditch, mostly in the marginal dike zone.

Climate

The climate of O‘ahu is semitropical and is characterized by mild temperatures, persistent northeasterly winds, a wet season from October through April, and a dry season from May through September (Blumenstock and Price, 1967; Sanderson, 1993). The prevailing northeasterly trade winds throughout most of the year and the mountainous topography are the main controls of the climate on O‘ahu. Average annual air temperature on O‘ahu ranges from about 74° F near the northeast coast to about 68° F at higher altitudes of the Ko‘olau Range (Nullet and Sanderson, 1993).

The Ko‘olau Range extends along the northeastern side of the island and is oriented roughly perpendicular to the northeasterly trade winds. Orographic lifting of the moisture-laden air causes frequent and heavy rainfall on the windward side of the Ko‘olau Range relative to the less frequent and lighter showers on the leeward side. This orographic effect causes significant differences in rainfall over short distances. Within the study area, the mean annual rainfall varies from less than 40 in. along the coastal lowland areas to about 240 in. over the mountainous areas of the Kahana watershed (fig. 4).

Geology

The Ko‘olau Range has been significantly modified by erosion (Stearns and Vaksvik, 1935). Eruptions during the mountain-building (shield) stage from the central caldera and two principal rift zones fed lava flows that formed the bulk of the island (fig. 5). The two principal rift zones are oriented in northwestern and southeastern directions from the central caldera; the northwest rift zone crosses the study area. Within

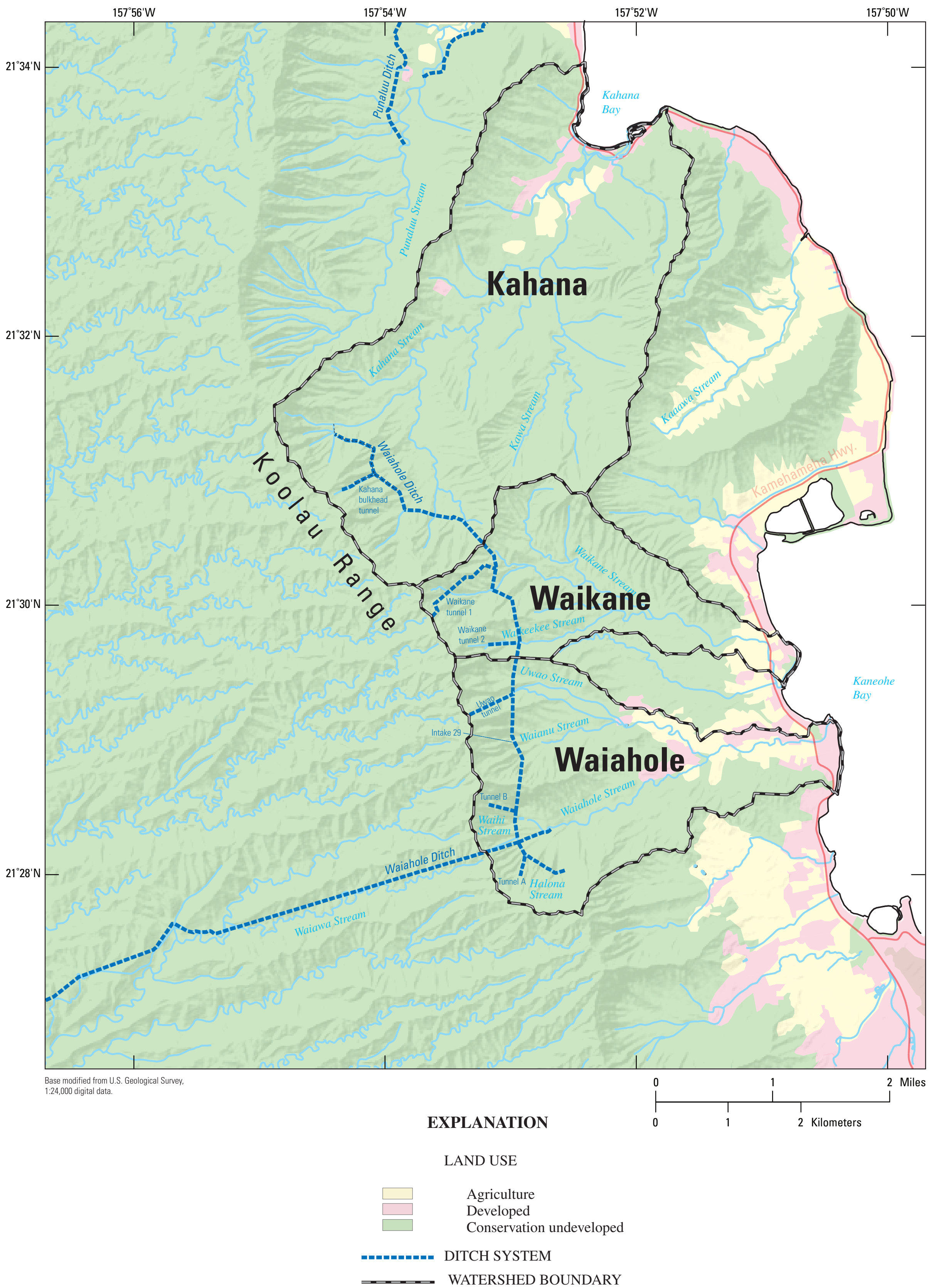


Figure 3. Land use and land cover in 1998 for the study area, windward O‘ahu, Hawai‘i (modified from Klasner and Mikami, 2003). Uwao was formerly spelled Uwau.

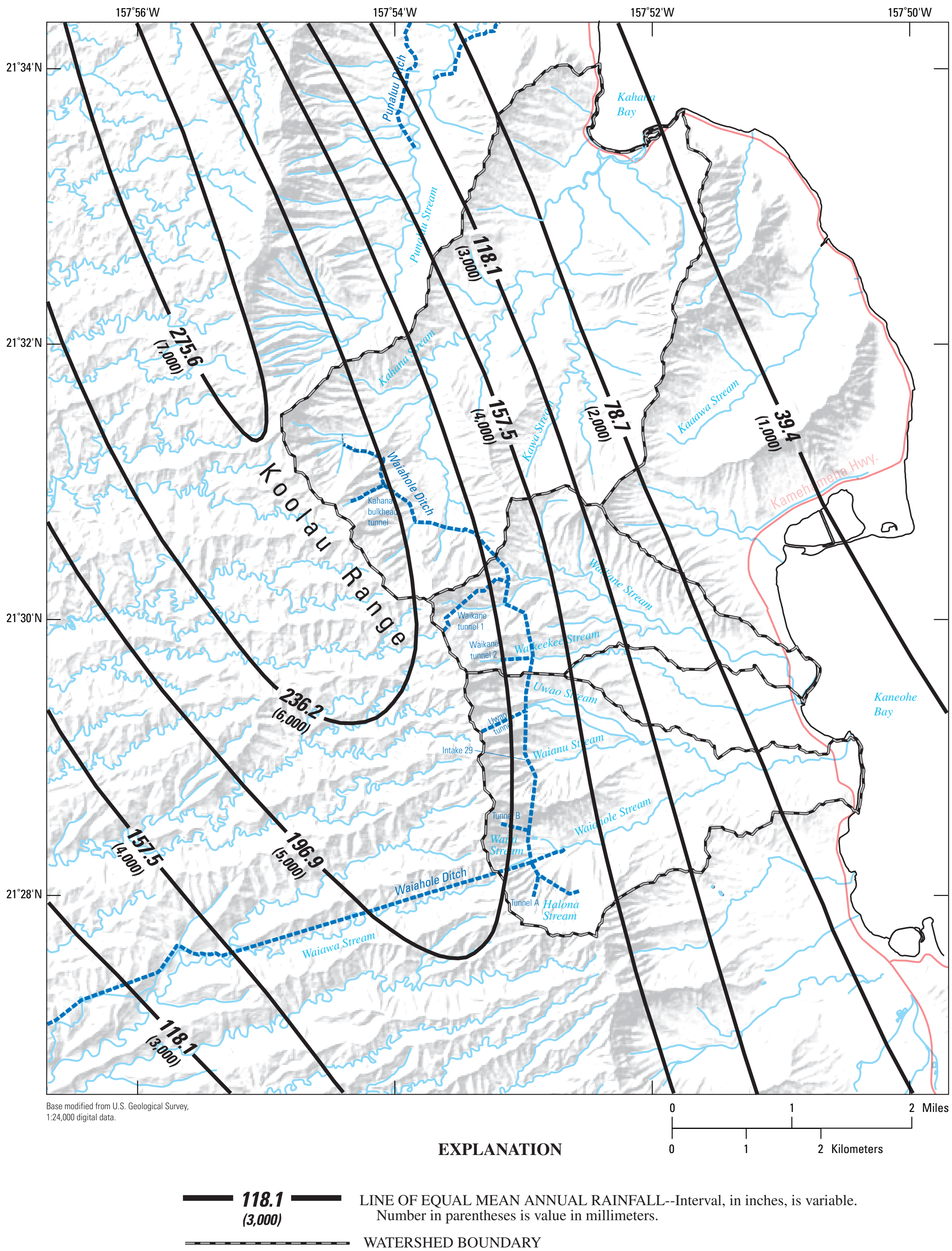


Figure 4. Mean annual rainfall for the study area, windward O‘ahu, Hawai‘i (modified from Giambelluca and others, 1986). Uwao was formerly spelled Uwau.

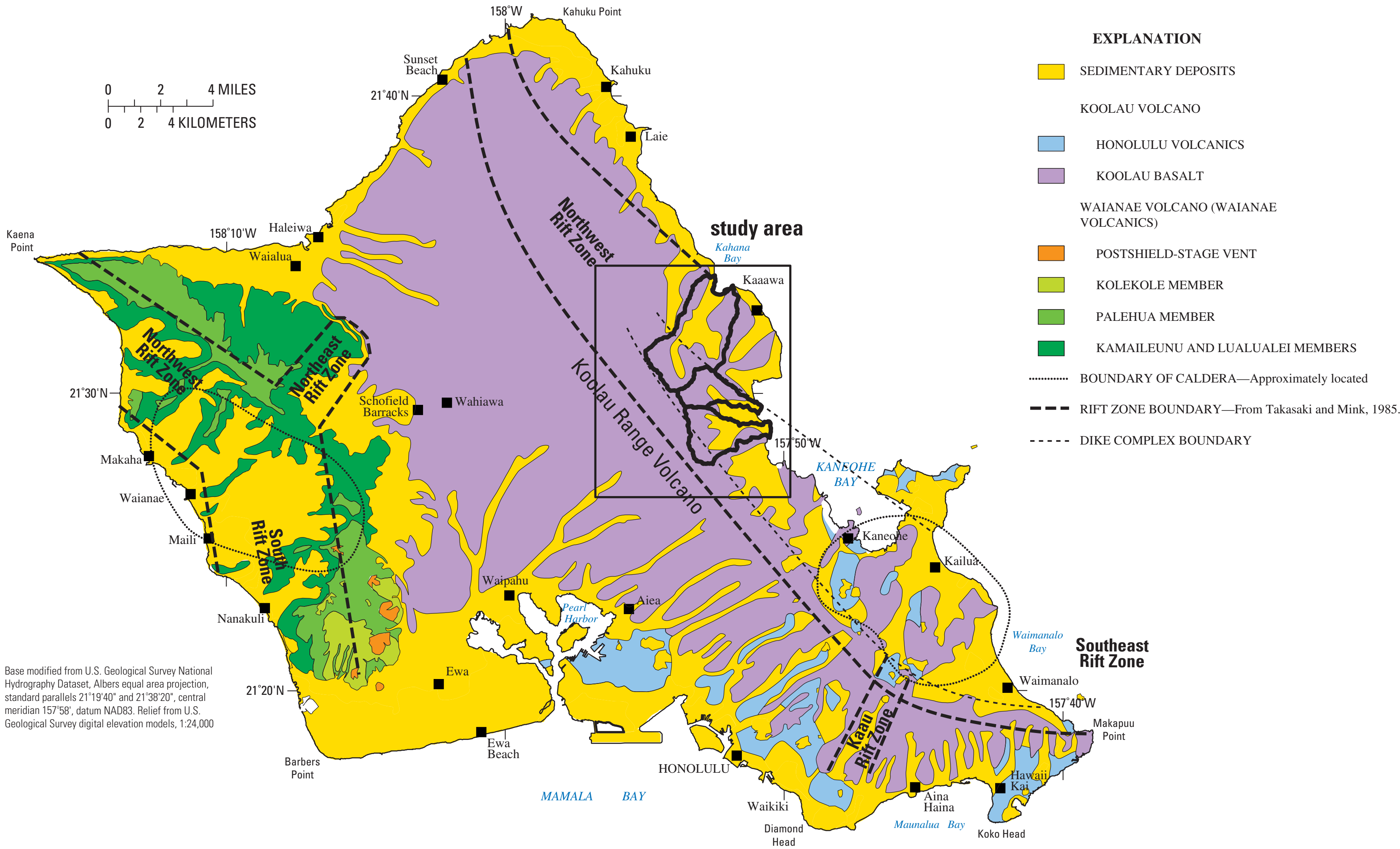


Figure 5. Generalized surficial geology, island of O'ahu, Hawai'i (modified from Stearns, 1939; Langenheim and Clague, 1987; and Presley and others, 1997).

the caldera and rift-zone areas, rising magma that cooled in the subsurface solidified to form dikes (Stearns and Vaksvik, 1935). The main period of eruptive activity was followed by a long period of extensive erosion, during which streams on the windward side removed more than a thousand feet of the original surface from the Koʻolau Volcano to form amphitheater-headed valleys (Stearns and Vaksvik, 1935). Following the period of extensive erosion, streams transported material to coastal areas and deposits of marine and terrestrial sediments formed the coastal plain (Oki and Brasher, 2003).

Exposed rocks of the Koʻolau Range are composed of three principal units: Koʻolau Basalt, Honolulu Volcanics, and sedimentary deposits (fig 5). Within the study area, sedimentary deposits at low altitudes overlie Koʻolau Basalt. Koʻolau Basalt is highly permeable where free of dikes. Sedimentary deposits near the coastal areas consist of older and younger alluvium. Older alluvium, moderately to well consolidated and weathered, is at an altitude of about 600 ft to below sea level in the lower reaches of valleys. At lower altitudes, in valleys and along the coastal plain, younger and generally poorly consolidated alluvium overlies the older alluvium (Takasaki and others, 1969).

Dike-Impounded System

Dikes in the rift zone are near-vertical, intrusive volcanic rocks that are hydrologically significant because of their low permeability and impounding effect on ground water. They are most abundant within the central area of the rift zone. Poorly permeable dikes tend to compartmentalize areas of permeable volcanic rocks and impede the flow of ground water. Dikes impound water to altitudes as much as 1,600 ft above sea level on Oʻahu (Gingerich and Oki, 2000). These high-level ground-water reservoirs accumulate and store rainfall recharge and discharge ground water to downgradient streams cutting into the dike-impounded reservoirs (Takasaki and Mink, 1985).

The headwater areas of the three study-area watersheds lie mostly within the northwest rift zone of the Koʻolau Volcano (fig. 5). This rift zone is divided into a central dike complex and marginal dike zone. Dikes associated with the rift zones of the Koʻolau Volcano generally are numerous and closely spaced in the dike complex and widely scattered in the marginal dike zone. The volcanic rocks are highly permeable where free of dikes, moderately permeable in the marginal dike zone, and generally poorly permeable in the dike complex (Takasaki and others, 1969). Headwaters of the three study-area watersheds at higher altitudes originate and are almost entirely in the dike complex. At lower altitudes, Kahana watershed lies in the marginal dike zone, whereas almost the entire area of Waikāne and Waiāhole watersheds are in the dike complex. In areas where dikes and the ground water they impound have been exposed by erosion in stream channels, ground water discharges directly to the stream. Ground water also may discharge through sedimentary deposits into streams.

Hydrologic Setting and Water Diversions

Recharge to dike compartments follows the path with the least resistance, discharging to downgradient water bodies and directly to streams through seeps and springs. Waiāhole, Waikāne, and Kahana Streams are naturally perennial throughout their entire courses because rainfall in the watersheds is persistent (fig. 4) and because these stream channels intersect high-level ground-water bodies in the interior, dike-intruded areas. Before the boring of the Waiāhole Ditch System development tunnels, ground water discharged to springs above the level of the ditch. Streams received ground-water discharge where stream channels cut through dikes impounding ground water. Ground-water withdrawals by the main tunnel and the development tunnels caused a decline in ground-water levels in the high-level dike compartments and created new ground-water discharge points and flow paths (Takasaki and others, 1969). The lowering of ground-water levels caused natural discharge at higher level springs and streams to decrease or cease (Hirashima, 1971). Base flows of streams therefore have been significantly reduced because ground water impounded by high-level dikes in the headwaters of the three diverted streams have been intercepted by the development tunnels and diverted by the ditch system. Although a significant source of ground water available for stream base flow was diverted, most of the lower reaches of the three diverted streams remained perennial because base flows in these streams are sustained by ground-water discharge from dike compartments at lower altitudes.

Historic and recent field observations indicate that tributaries of all the diverted streams upgradient of the ditch system at about 750 ft altitude, except for Kahana Stream, flow intermittently. Stearns and Vaksvik (1935, p. 408) noted that the Kahana development tunnel did not cause the upgradient streams in Kahana Valley to become completely dry. It dried up a spring yielding a million gallons daily about 2,000 ft to the south of the tunnel but did not affect springs to the north. During the period 1989 to 1993 an average of 2.1 Mgal/d was estimated to enter the Waiāhole Ditch System through surface-water intakes in Kahana Valley (Edwin Sakoda, CWRM, written commun., 2005). Currently (2006), the intakes in Kahana Valley are not maintained; inflows of surface water through these intakes are less than 2.1 Mgal/d, as indicated by ditch seepage runs in 2002-03. The surface-water intakes feeding the Waiāhole Ditch System were maintained until Oahu Sugar Company converted from furrow to drip irrigation during the mid-1980s. Surface water inflows contained higher levels of suspended sediments, which tended to clog drip-irrigation tubes—hence the shift to developing water primarily from ground-water sources.

According to field observations from a USGS reconnaissance survey on August 23, 2002, the channel of South Fork Waikāne Stream above an altitude of 260 ft was dry. However, no historical information was found on the effects of the two Waikāne tunnels (one near intake 22 and one near intake 25) on high-altitude springs in upper Waikāne Valley.

Tributaries of Waiāhole Stream upstream from the connecting tunnels are no longer perennial. Discharge measurements made during the 2002-03 ditch seepage run indicated insignificant surface-water flow coming from intakes in Waiāhole Valley. According to Stearns and Vaksvik (1935, p. 403), the boring of the main tunnel dried up two springs in the upper Waiāhole Valley. The two springs on Hālona Stream had an average flow during June-July, 1911, of 4.7 and 1.04 Mgal/d (Lippencott, 1911, p.10; Stearns and Vaksvik, 1935, p.403), which indicated that a combined spring flow of 5.7 Mgal/d was diverted by the main tunnel. The springs apparently dried up as the ground water was redirected to the main tunnel. It is commonly assumed that a portion of the ground water intercepted by the main tunnel leeward of the topographic crest of the Koʻolau Range naturally would have discharged to the windward side (Takasaki and others, 1969, p.74). The failure of tunnel A (735 ft south of the main tunnel) and tunnel B (1,400 ft north of the main tunnel) to develop ground water was attributed to their proximity to the main tunnel. Assuming Stearns and Vaksvik (1935, p.405) correctly interpreted the failure of these two tunnels, the main tunnel has completely drained the dike compartments to the level of the main tunnel for more than 2,000 ft on each side of the main tunnel.

In addition to the development tunnels, other water diversions to or from Waiāhole Ditch affected low flows in the Waiāhole watershed. Between 1916 and 1982, an average flow of 1 Mgal/d (Takasaki and Mink, 1985) and as much as 3 Mgal/d (an estimate obtained from USGS continuous-record station 16291000 documents) was pumped daily from Waiāhole Stream at 450 ft altitude into the Waiāhole Ditch. In addition, an average flow of 0.5 Mgal/d is delivered from the ditch to users in Waiāhole Valley through the McCandless Pipeline in compliance with water rights purchased from McCandless (Hawaiʻi Commission on Water Resource Management, 2001). This 0.5 Mgal/d is being diverted into Waianu Stream near 400 ft altitude, and supposedly the same quantity is diverted out of the stream at a slightly lower altitude into a pipeline system that supplies downstream users. According to Agribusiness Development Corporation personnel (Alfredo Lee, oral commun., 2005), flow being released from Waiāhole Ditch through the McCandless Pipeline is fairly steady.

Available Discharge Data

Available discharge data for natural and diverted flow conditions were compiled from (1) seepage runs, (2) continuous-record stations, (3) low-flow partial-record (LFPR) stations, and (4) miscellaneous measurement sites. Seepage runs consist of a series of discharge measurements made at multiple locations on a stream or ditch at approximately the same time during a period of steady base flow. Measurements are made at about the same time to minimize the effect that any variability with time might introduce (Fontaine, 2003). Data from continuous-record stations consist of a record of stage, individual measurements of discharge throughout a range of stages, and notations regarding factors that may affect relations between stage and discharge. Discharge for any particular instant or for selected periods of time are computed from the continuous record of stage and the relation between stage and discharge at the station. LFPR stations are typically nonrecording gages where systematic, instantaneous measurements of discharge and stream elevation are made during times of low flow. The discharge measurements are used to make estimates of selected low-flow statistics, such as median streamflow, at the stations. Miscellaneous measurement sites are locations where only random, instantaneous measurements of discharge are made.

Seepage Runs

Seepage runs have been conducted historically and specifically for this study to identify reaches where gains and losses of flow take place and to quantify these changes along Waiāhole, Waianu, Waikāne, and Kahana Streams and in the connecting Waiāhole tunnels (figs. 6-13). Seepage runs done specifically for this study were conducted to determine how the releases of Waiāhole ditch water into Waiāhole, Waianu, and Waikāne Streams affect downstream base flows. Seepage runs were also conducted in the Waiāhole tunnels to determine the amount of ground water intercepted by the development tunnels in Kahana, Waikāne, and Waiāhole watersheds. It should be noted that gaining reaches in the streams during diverted (post-ditch) conditions likely were gaining reaches during natural (pre-ditch) conditions; losing stream reaches during post-ditch conditions may or may not have been losing reaches during the pre-ditch period. The channel gains and losses in stream or ditch reaches reported in this study exclude flow releases or diversions and inflows from intakes, tributaries, and return flows. For example, tributary flow was not considered to be a gain in stream. The reported values therefore reflect natural gains and losses in stream or ditch reaches.

Waiāhole Ditch Tunnel

As part of this study, seepage runs along the connecting and main tunnels of the Waiāhole Ditch System were made on February 27, 2002 (wet season), and August 20, 2003 (dry season) (table 2). The seepage-run reach is 4.8 mi in length and extends from Intake 1 in Kahana Valley to the North Portal gage (fig. 6B). Flow records from the North Portal gage (USGS station number 16287000) indicated that the discharge measurements were made during a period of steady base flow in the tunnel. Both seepage runs indicate that a short reach between Waikāne tunnel 2 (site 10) and Uwao development tunnel (site 11) loses water (fig. 6). The 2002 seepage run, made at the beginning of the wet season, indicates that the reach from downstream of Intake 29 to North Portal gage loses water. However, the 2003 seepage run, made at the beginning of the dry season, indicates that the same reach gained rather than lost water. The two seepage runs indicate that the Waiāhole Ditch System intercepted an average of 1.45, 4.85, and 12.7 Mgal/d from the Kahana, Waikāne, and Waiāhole watersheds, respectively (fig. 6).

On September 2, 1959, a seepage run was made on a short reach of the Waiāhole Ditch connecting tunnel in Kahana Valley. Discharge measurements were made at three locations from just upstream of Kahana development tunnel (site 2) to downstream of Intake 19 (site 4A) (fig. 6A, table 3). During the 2002 and 2003 seepage runs, 0.15 and 0.16 Mgal/d, respectively, were measured just upstream of the Kahana development tunnel at site 2. In contrast, during the 1959 seepage run 0.61 Mgal/d was measured at site 2. The significant reduction (0.46 Mgal/d) in measured flow at site 2 can be attributed to the decreased role played by the surface water inflows to the Waiāhole Ditch System. Subsequent to the mid 1980's, a majority of the surface-water intakes have not been maintained (Edwin Sakoda, CWRM, written commun., 2005). During the 2002 and 2003 seepage runs, only minor surface water inflows were observed at the Kahana intakes upstream from site 2.

Table 2. Discharge measurements made during seepage runs in the connecting tunnels of the Waiāhole Ditch System, windward O‘ahu, Hawai‘i, 2002-03

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

Site number (fig. 6)	February 27, 2002	August 20, 2003	Site description
	Mgal/d	Mgal/d	
1	0.03	--	Downstream of Intake 1
2	0.15	0.16	Upstream of Kahana development tunnel
3	1.14	0.99	Downstream of Kahana development tunnel
4	1.59	1.13	Downstream of Intake 17
5	1.80	1.14	Kahana/Waikāne watershed divide
6	2.37	1.78	Intake 21 gage
7	5.05	4.20	Downstream of Waikāne development tunnel 1 at Intake 22
8	--	2.97[b]	Intake 23 release
9	6.44	1.49	Upstream of Waikāne development tunnel 2
10	7.37	2.26	Downstream of Waikāne development tunnel 2; Waikāne/Waiāhole divide
11	7.17	1.89	Upstream of Uwao[a] development tunnel
12	19.2	12.1	Downstream of Uwao[a] development tunnel
13	20.5	13.9	Gage 16285000; downstream of Intake 29
14	2.84	3.03[b]	Gate 30 release
15	16.0[b]	6.98[b]	Gate 31 release; Gage 16286000
16	1.20[b]	4.94[b]	North Portal gage 16287000

[a]Uwao was formerly spelled Uwau.

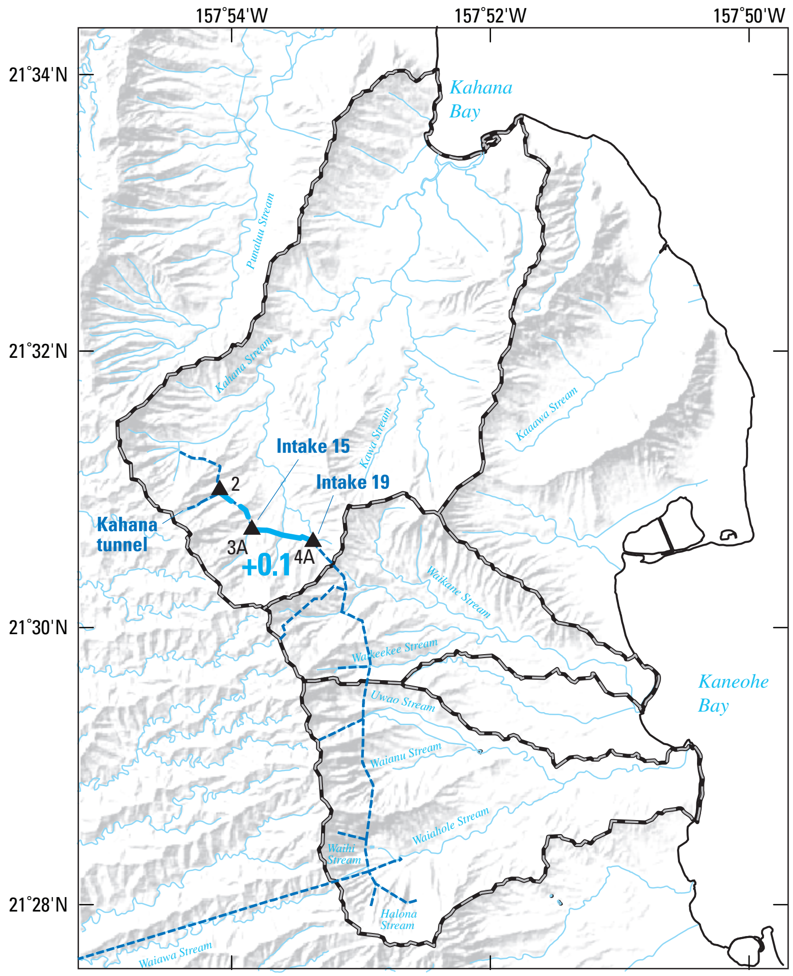
[b]Discharge from stage-discharge relationship.

Table 3. Discharge measurements made during seepage run in the connecting tunnels of the Waiāhole Ditch System, windward O‘ahu, Hawai‘i, 1959.

[These unpublished measurements are in the files of the USGS Pacific Islands Water Science Center; Mgal/d, million gallons per day]

Site number (fig. 6)	September 2, 1959	Site description
	Mgal/d	
2	0.61	Upstream of Kahana development tunnel
3A	4.01	Downstream of Intake 15
4A	4.11	Downstream of Intake 19

A



09/02/1959

EXPLANATION

DITCH SECTION–Number shows water gain or loss, in million gallons per day. Dashed where uncertain. Channel gains or losses in section excludes flow releases or diversions and inflows from intakes, tunnels, and tributaries, and return flows.

Losing section

+0.1 Gaining section

DITCH

WATERSHED BOUNDARY

4A ▲ MEASUREMENT SITE AND IDENTIFICATION NUMBER

+1.8 NET GAIN FROM WATERSHED, IN MILLION GALLONS PER DAY

0 1 2 Miles

0 1 2 Kilometers

Figure 6. Results of seepage runs on Waiāhole Ditch System, windward O‘ahu, Hawai‘i, 1959 (*A*) and 2002-03 (*B*). Uwao was formerly spelled Uwau.

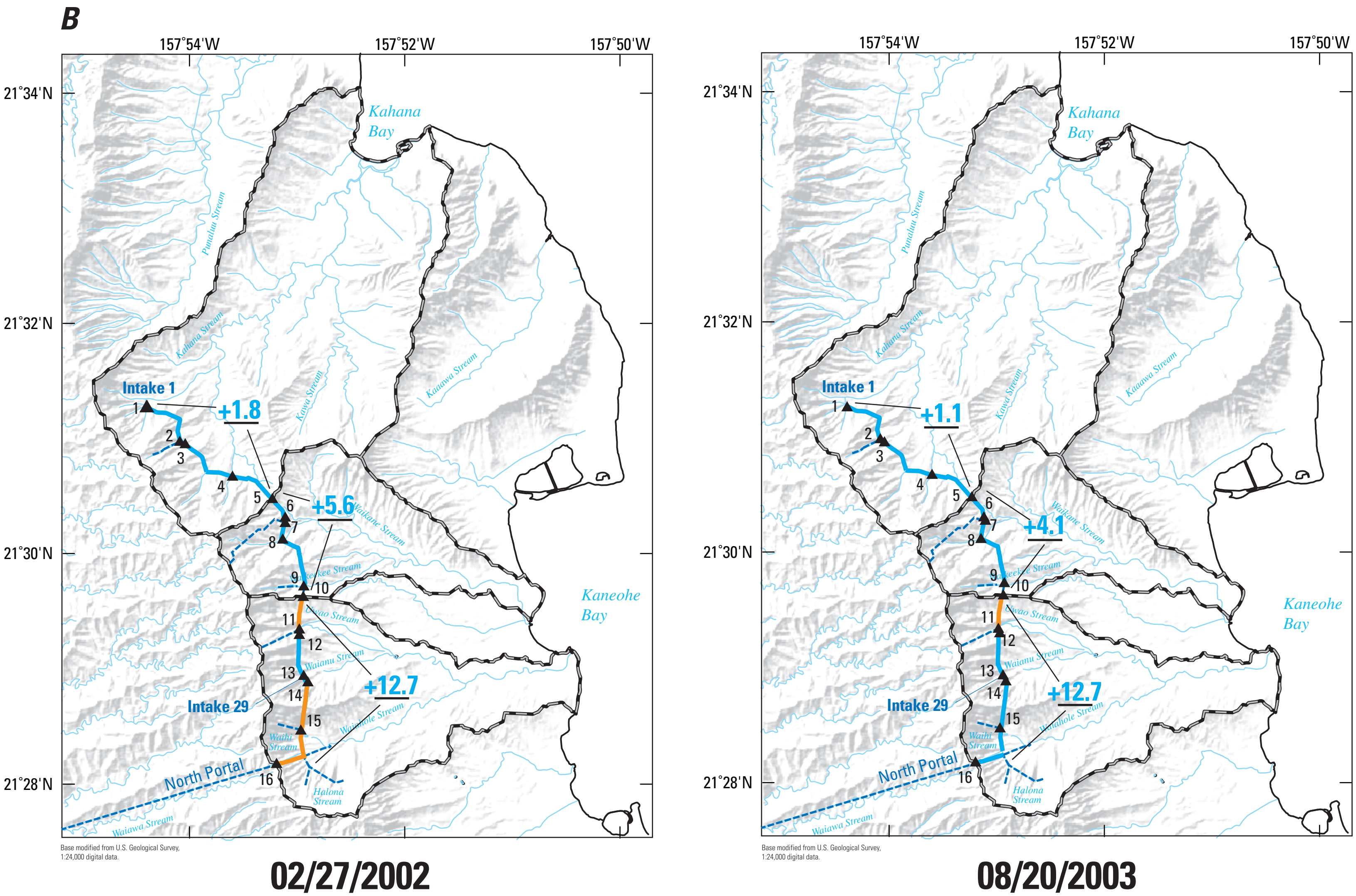


Figure 6.—Continued.

Waiāhole and Waianu Streams

Seepage runs on Waiāhole Stream and its tributary, Waianu Stream, have been made during three different hydrologic settings: (1) post-release, (2) post-ditch and pre-release, and (3) pre-ditch. To evaluate the effects of flow releases from Waiāhole Ditch at Gate 31 into Waiāhole Stream and at Gate 30 into Waianu Stream, seepage runs were conducted on Waiāhole Stream on March 14, June 26, and September 27, 1995 (fig. 7, table 4), and on Waianu Stream on May 10, June 21, and September 26, 1995 (fig. 8, table 5). These seepage runs were conducted to identify natural gains or losses of water during post-release base-flow conditions. All of the seepage runs on the Waiāhole and Waianu Streams were made after the flow releases began on December 19, 1994, and May 23, 1995, respectively, except for the May 10, 1995, seepage run on Waianu Stream. During the March 14, June 26, and September 27, 1995 seepage runs on Waiāhole Stream, measured flow releases at Gate 31 were 14.4, 11.8, and 11.1 Mgal/d, respectively. Flow release at Gate 31 was reduced over time to account for the subsequent initiation of flow release at Gate 30. During the June 21 and September 26, 1995, seepage runs on Waianu Stream, measured flow releases at Gate 30 were 1.71 and 1.07 Mgal/d, respectively.

Natural gains and losses on some Waiāhole and Waianu Stream reaches were difficult to determine because of complex patterns of inflows and flow diversions. In general, seepage runs on both streams indicate small losses of water just downstream from the two flow-release points at Gates 30 and 31. Both of the losing reaches were dry during base-flow periods before the release of water. In general, Waiāhole Stream gains water over the remaining reach down to the confluence with Waianu Stream. The three seepage runs on Waianu Stream also indicate a predominant pattern of gains between the Gate 30 release point and the confluence with Waiāhole Stream. A short losing reach exists on Waiāhole Stream, just downstream of the confluence with Waianu Stream.

Seepage runs made before the flow release on these two streams in 1959 and 1960 also indicate similar patterns. Discharge measurements for seepage runs in 1959 and 1960 (tables 6, 7) were made as part of a water resources study of windward Oʻahu (Takasaki and others, 1969). These seepage runs were not as extensive as those done in 1995, and discharge measurements were only made on parts of the two streams over relatively short reaches. Seepage runs on Waiāhole Stream were made on July 20, 1959, and July 19, 1960, and seepage runs on Waianu Stream were made on July 21, 1959, July 19, 1960, and March 28, 1961. The results of these seepage runs during pre-release flow conditions indicate mostly gaining reaches (figs. 9, 10). This also indicates that although the Waiāhole Ditch System has reduced base flow in Waiāhole Stream, ground-water discharge from the lower part of the dike complex is sufficient to sustain perennial flow.

Before the ditch construction, two seepage runs were made on Waiāhole and Waianu Streams over a period of two days from September 9 to 10, 1911 (Martin and Pierce, 1913). On Waiāhole Stream, discharge measurements were made between altitudes 160 and 20 ft. On Waianu Stream, discharge

Table 4. Discharge measurements made during seepage runs in the Waiāhole Stream, windward Oʻahu, Hawaiʻi, 1995.

[n.a., not available; Mgal/d, million gallons per day; --, not measured]

Site number (fig. 7)	Altitude (feet)	March 14, 1995 Mgal/d	June 26,1995 Mgal/d	September 27, 1995 Mgal/d	Site description
1	n.a.	14.4	11.8	11.1	Gate 31 release
1A	400	--	11.1	9.50	Near pumping station
2	320	16.5	--	12.0	Near Waiāhole Camp
3	250	18.2	--	13.4	Downstream from old USGS gage (16291000)
3A	110	--	14.1	--	Upstream from chicken farm diversion
3C	105	--	14.2	14.3	Downstream from chicken farm diversion
4A	70	16.5	15.1	13.8	Upstream from confluence, Waianu Stream
4B	75	0.67	0.60	0.81	Diversion upstream form site 4A
4C	75	0.71	3.01	2.35	Waianu Stream at mouth
5	65	17.1	16.9	14.7	Downstream from confluence, Waianu Stream
5A	40	--	--	17.5	Downstream from diversion at site 5B
5B	40	--	1.07	0.32	Diversion upstream form site 5A
5C	14	--	0.87	0.08	Return flow downstream from site 6
6	20	18.1	16.5	15.8	Upstream from Kamehameha Highway

Table 5. Discharge measurements made during seepage runs in the Waianu Stream, windward O‘ahu, Hawai‘i, 1995.

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

Site number (fig. 8)	May 10, 1995 Mgal/d	June 21, 1995 Mgal/d	September 26, 1995 Mgal/d	Site description
1	--	1.71	1.07	Gate 30 release
1A	0.02	1.44	1.07	Upstream from McCandless Pipeline inflow
2	0.40	1.72	1.34	Downstream from McCandless Pipeline inflow
3A	0.52	2.00	1.25	Upstream from McCandless diversion
4	0.08	0.11	0.12	Tributary inflow (Gate 29) at mouth
å	0.41	0.14	0.63	McCandless diversion
6	0.32	1.63	1.25	Downstream from McCandless diversion
7	0.74	2.35	1.37	Upstream from confluence, Uwao[a] Stream
8	0.37	0.13	0.19	Uwao[a] Stream at mouth
9	1.01	--	--	Downstream from confluence, Uwao[a] Stream and near diversion pond
9A	--	2.42	1.68	Downstream from diversion pond
10	0.08	0.29	0.18	Diversion upstream from site 11
11	1.22	2.38	1.56	Downstream from diversion at site 10
12	1.33	2.26	1.78	Downstream from field inflow
13	0.37	0.36	0.19	Diversion upstream from site 14
14	1.16	2.10	1.75	Downstream from diversion at site 13
14A	--	2.42	1.89	Downstream from stream ford
15	1.64	2.55	2.06	Waianu Stream at mouth

[a]Uwao was formerly spelled Uwau.

measurements were made between altitudes of about 310 and 75 ft. Because of the complex patterns of flow diversions and the difficulty in determining the exact locations of the measurements, natural gains and losses under pre-diversion conditions along the lower part of Waiāhole and Waianu streams are difficult to determine with certainty.

Other same-day discharge measurements made during the pre-ditch period also provide estimates of the magnitude of ground-water gains representative of natural (undiverted) flow conditions on certain reaches of Waiāhole and Waianu Streams. On August 11, 1911, discharge measurements were made (Lippencott, 1911) near an altitude of 750 ft (near ditch level) on Hālona and Waihī Streams and at 225 ft altitude (site 4) just downstream of station 16291000 and upstream of all irrigation diversions (fig. 9). The combined flow of the upstream discharge measurements was 7.9 Mgal/d at 750 ft altitude (table 6), and the downstream measurement indicated a total flow of 16.5 Mgal/d at 225 ft altitude under natural flow conditions (table 6). Because the measurements were made upstream from all irrigation diversions, the gains in flow represented ground-water discharge to the stream, assuming base-flow conditions with no surface runoff. The measurements indicate the stream reach between altitudes 750 ft (near ditch level) and 225 ft gained about 8.6 Mgal/d of ground water (fig. 9). Based on 19 concurrent low-flow days (September 25 to October 15, 1911) (Martin and Pierce, 1913), the differences between the combined daily discharges at Hālona and Waihī stations (16288000 and 16289000) and daily discharges at station 16292000 indicate an average gain of about 8 Mgal/d between altitudes 750 and 160 ft.

During dry-weather post-ditch periods, all of the upper tributaries of Waiāhole Stream upstream from the 750 ft altitude were dry. The net post-diversion ground-water gain within about the same reach of Waiāhole Stream, between altitudes of 750 and 250 ft (sites 1 and 3 on fig. 7), was reduced to 3.8 Mgal/d on March 14, 1995, and to 2.3 Mgal/d on September 27, 1995 (table 4).

Discharge measurements were made in Uwao and upper Waianu Streams on October 11, 1911 (Martin and Pierce, 1913). Flow measured on the north, middle, and south forks of upper Waianu Stream at about 650 ft altitude were 1.5 Mgal/d, 2.7 Mgal/d, and 1.2 Mgal/d, respectively, with a combined flow of 5.4 Mgal/d. On the same day, flow measured in Uwao Stream just upstream of the confluence with Waianu Stream was 1.4 Mgal/d and the daily flow recorded at station 16293000 just downstream of the confluence was 7.8 Mgal/d.

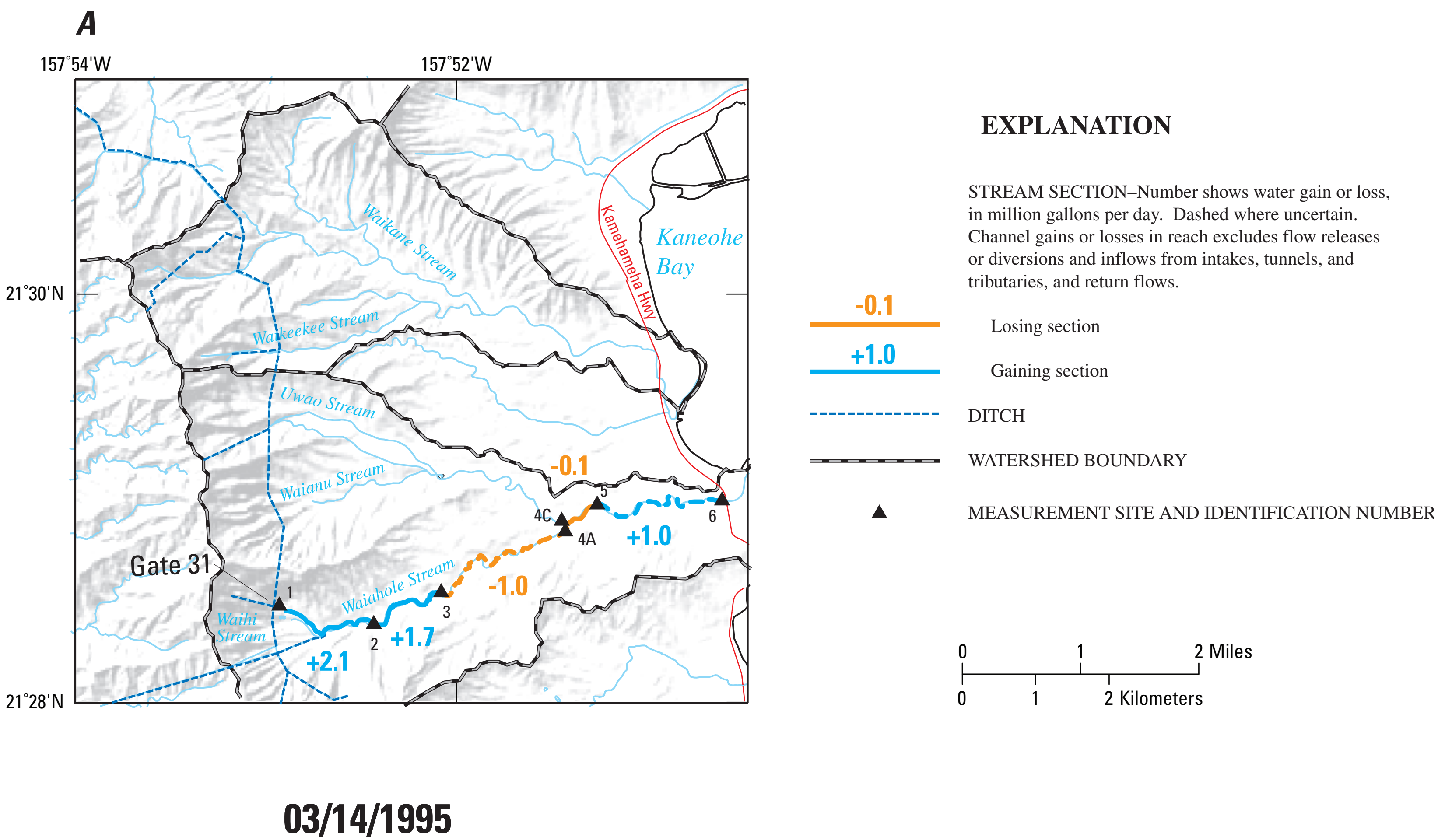
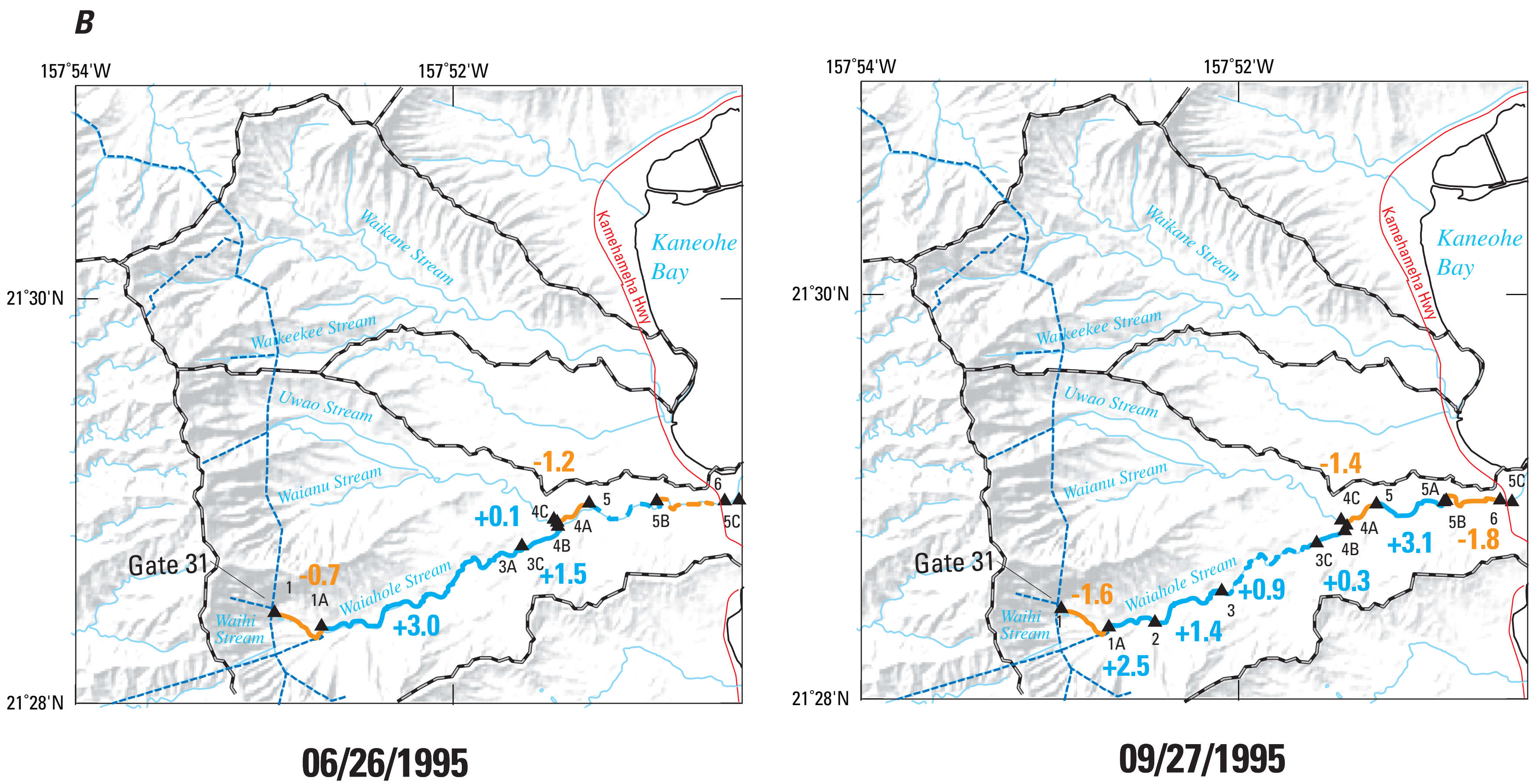


Figure 7. Results of seepage runs on Waiāhole Stream, windward O‘ahu, Hawai‘i, March 1995 (*A*) and June and September 1995 (*B*). Uwao was formerly spelled Uwau.



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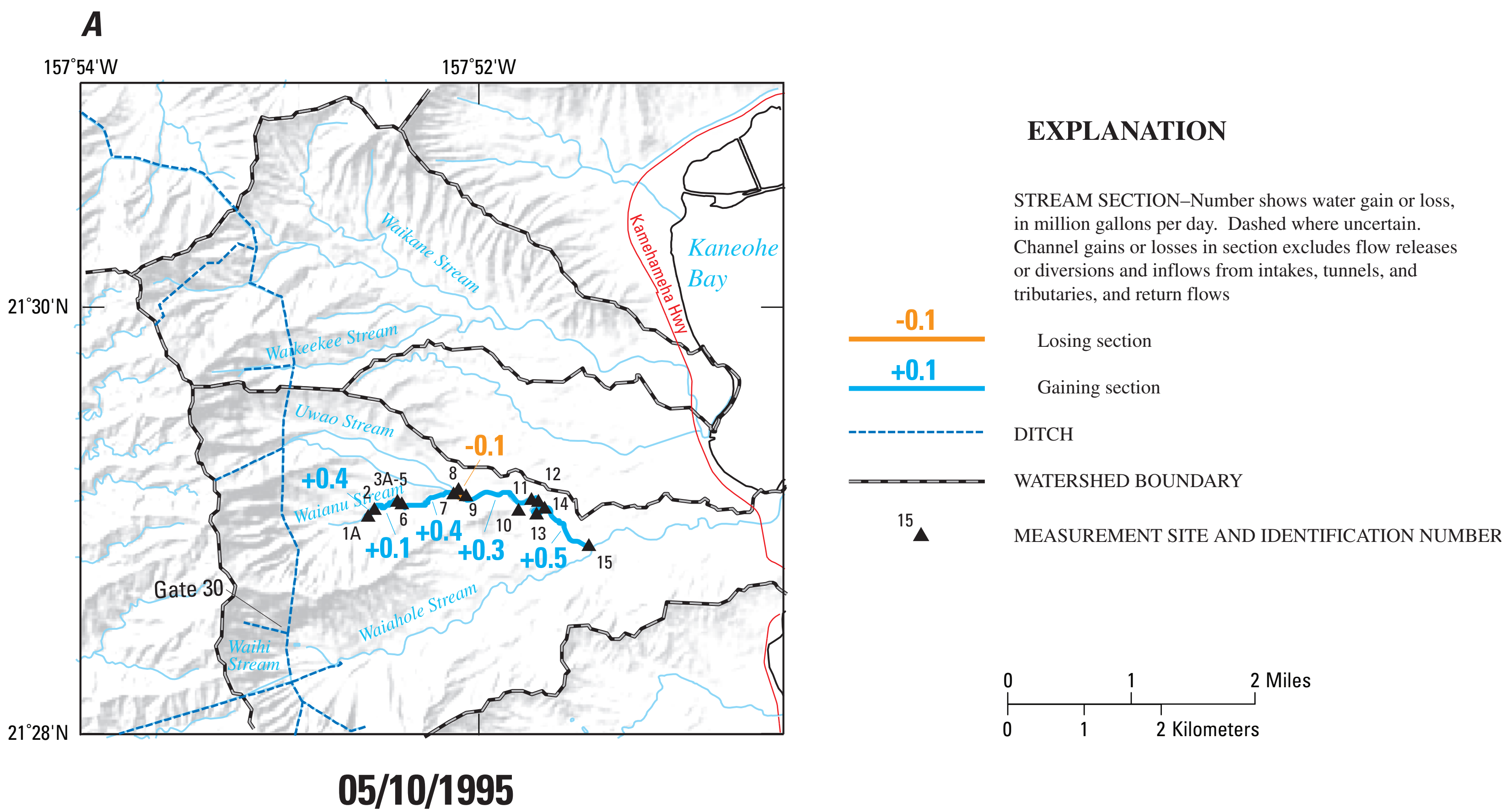
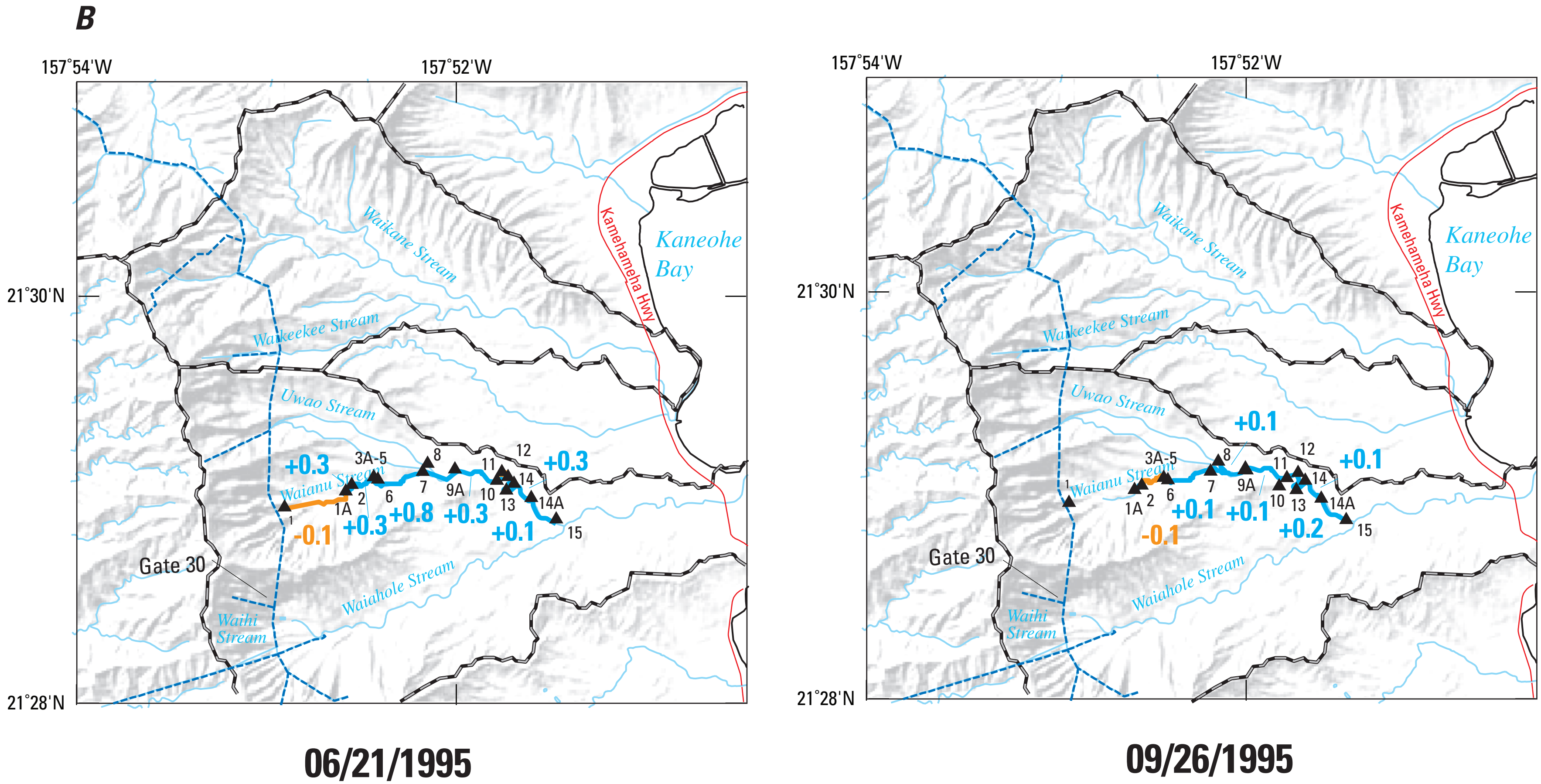


Figure 8. Results of seepage runs on Waianu Stream, windward O‘ahu, Hawai‘i, May 1995 (*A*) and June and September 1995 (*B*). Uwao was formerly spelled Uwau.



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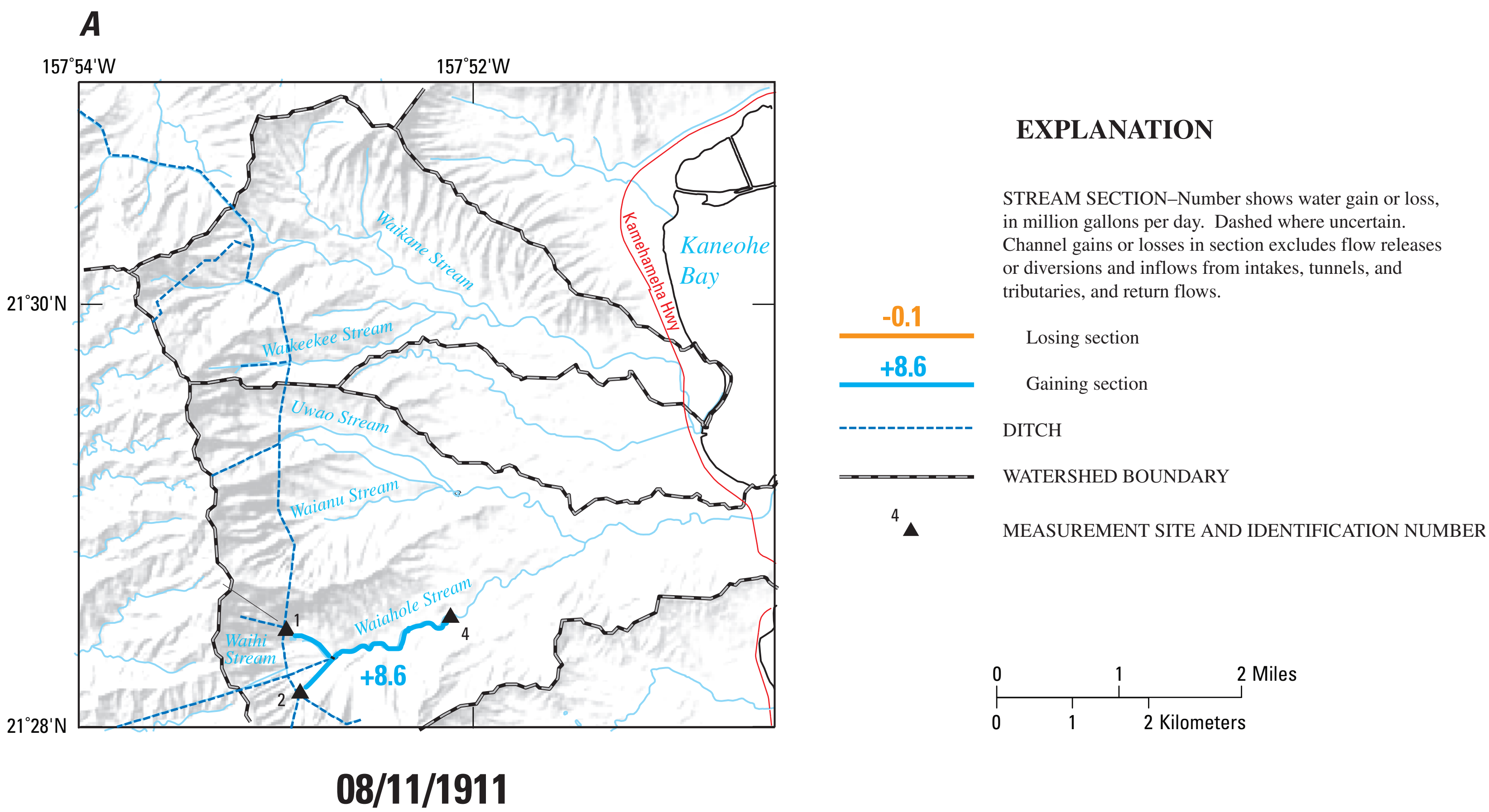


Figure 9. Results of seepage runs on Waiāhole Stream, windward O‘ahu, Hawai‘i, 1911 (*A*) and 1959-60 (*B*). Uwao was formerly spelled Uwau.

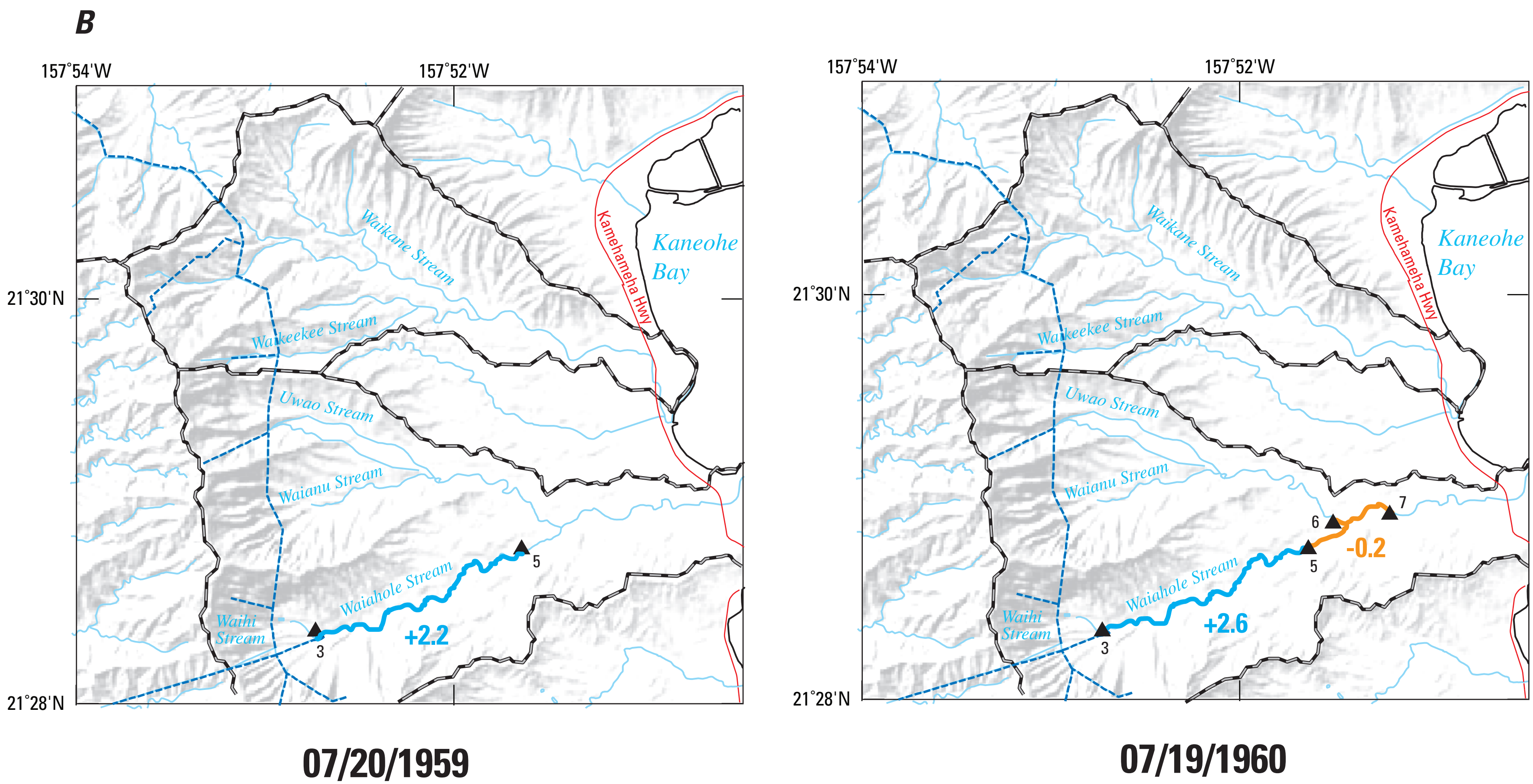


Figure 9.—Continued.

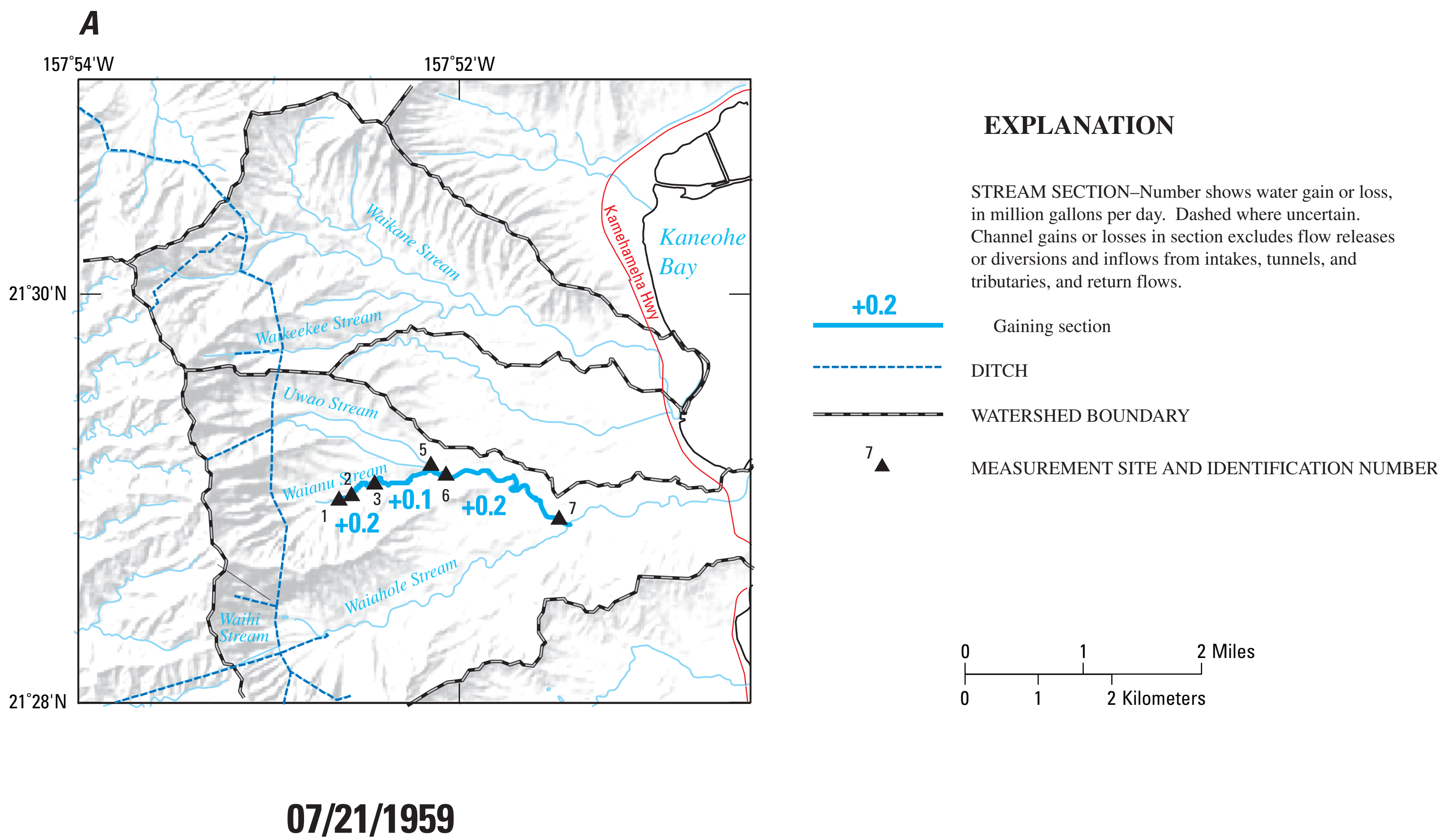


Figure 10. Results of seepage runs on Waianu Stream, windward O‘ahu, Hawai‘i, 1959 (*A*) and 1960-61 (*B*). Uwao was formerly spelled Uwau.

B

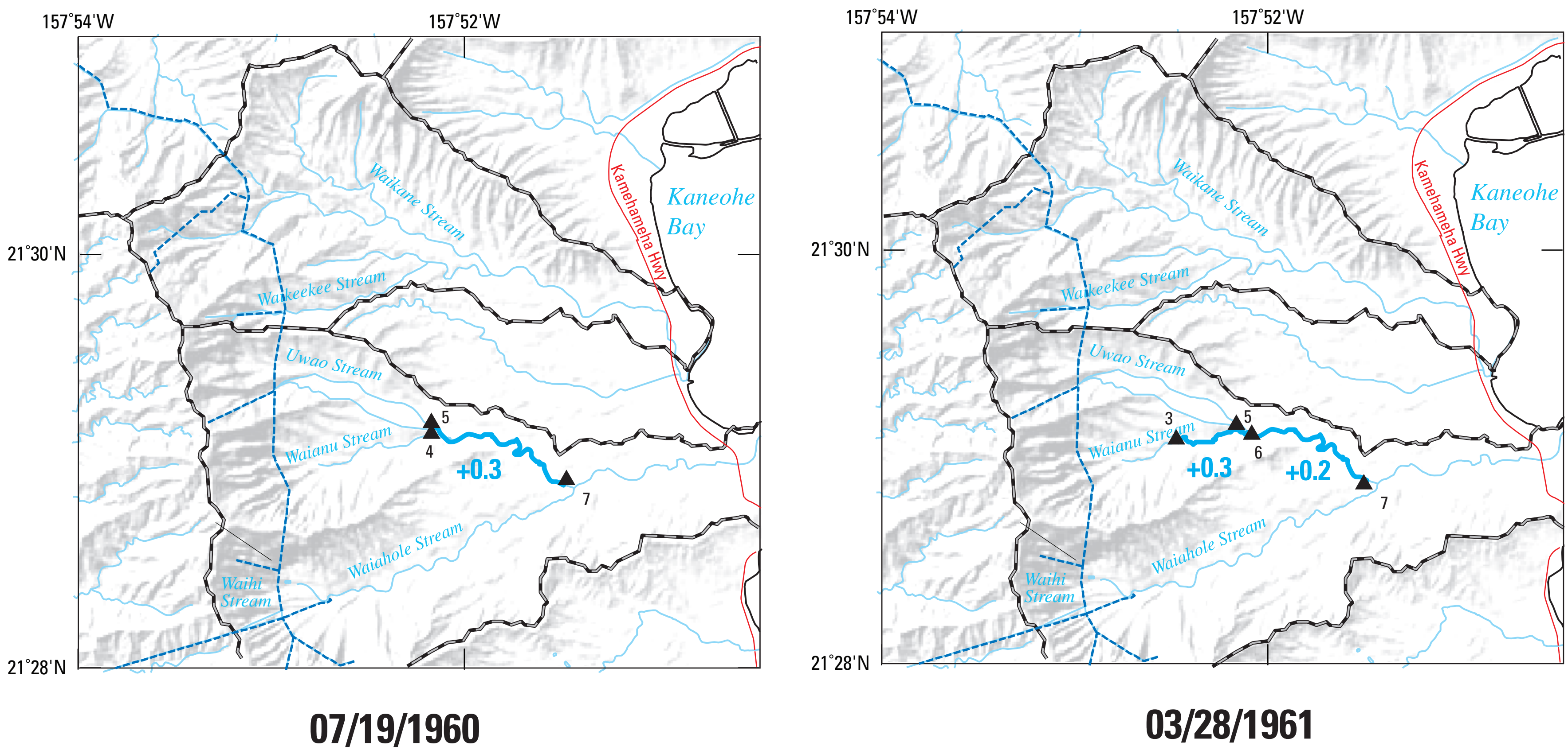


Figure 10.—Continued.

Table 6. Discharge measurements made during seepage runs in the Waiāhole Stream, windward Oʻahu, Hawaiʻi, 1911 (Lippencott, 1911) and 1959-60 (Takasaki and others, 1969).

[ft, feet; Mgal/d, million gallons per day; --, not measured]

Site number (fig. 9)	Takasaki number[a]	August 11, 1911 Mgal/d	July 20, 1959 Mgal/d	July 19, 1960 Mgal/d	Site description (Takasaki and others, 1969)
1	--	2.40	--	--	Waihī Stream at altitude 723 ft
2	--	5.50	--	--	Hālona Stream at altitude 672 ft
3	176	--	0.13	0.41	Downstream of pumping station and confluence of two streams; most of this water spills over weir at pump house--excess over pump capacity
4	--	16.5	--	--	Old USGS station 16291000; upstream of all diversions
5	178	--	2.34	2.96	Upstream of confluence with Waianu Stream
6	185	--	--	1.06	Downstream of Waiāhole road crossing on Waianu Stream
7	186	--	--	3.90	Downstream of Waianu confluence; possibly some water being diverted to taro patches on right bank

[a]Station numbers used by Takasaki and others (1969).

Table 7. Discharge measurements made during seepage runs in the Waianu Stream, windward Oʻahu, Hawaiʻi, 1959-61 (data and site descriptions from Takasaki and others, 1969).

[ft, feet; Mgal/d, million gallons per day; --, not measured]

Site number (fig. 10)	Takasaki number[a]	July 21, 1959 Mgal/d	July 19, 1960 Mgal/d	March 28, 1961 Mgal/d	Site description (Takasaki and others, 1969)
1	179	0.22	--	--	Diversion by McCandless Pipeline
2	180	0.03	--	--	100 ft downstream from confluence of right and left branches; water left in stream after diversion by pipeline
3	181	0.20	--	0.26	At first ford; at trail crossing at altitude 320 ft
4	182	--	0.51	--	Upstream of Uwao[b] confluence
5	183	0.08	0.24	0.15	80 ft upstream of road crossing - Uwao[b] Stream
6	184	0.38	--	0.72	10 ft downstream of Uwao[b] confluence
7	185	0.62	1.06	0.92	Downstream of Waiāhole road crossing on Waianu Stream

[a]Station numbers used by Takasaki and others (1969).

[b]Uwao was formerly spelled Uwau.

These measurements indicate a gain of about 1.0 Mgal/d of ground water in the 4,500-ft reach of Waianu Stream between altitudes 650 and 190 ft. This gain is much less than the gain of about 8.6 Mgal/d in the 4,000-ft reach between about the same altitudes in Waiāhole Stream on August 11, 1911 (fig. 9). Takasaki and Mink (1985, p. 35) provided an explanation for this larger gain in Waiāhole Stream: Between altitudes of 400 and 250 ft, “Waiāhole Stream cuts deeper into saturated rock in this reach than streams in the other valleys, resulting in more leakage. The gains in the other valleys are steady in the downstream direction and seem to indicate slow and uniform drainage by the streams cutting into saturated rock.”

Waikāne Stream

As part of this study, seepage runs along Waikāne Stream were made on September 18, 2002, and May 12, 2003 (fig. 11, table 8). These seepage runs document how base flow varies along the stream before and after flow releases from the ditch system began on October 11, 2002, at Intake 23. The reach on south fork of Waikāne Stream upstream of altitude 260 ft was observed to be dry during a USGS reconnaissance on August 23, 2002. It also was observed that a high percentage of streamflow at altitudes 410 and 500 ft on north fork of Waikāne Stream was ground-water discharge from dike-fed springs. In general, both seepage runs (before and after flow was released at Intake 23) indicate a pattern of gaining flow at upper altitudes. Both seepage runs indicate Waikāne Stream loses water downstream from about 35 ft altitude. Similar patterns also are evident in results from three separate seepage runs conducted in 1959-60 (fig. 12, table 9).

Kahana Stream

Kahana Stream differs from both Waiāhole and Waikāne Streams because it is not affected by the recent flow releases from the Waiāhole Ditch. The only seepage runs done on this stream were made on three occasions in 1960-62 as part of the water resources study of windward Oʻahu (Takasaki and others, 1969) (fig. 13, table 10). Discharge measurements made on August 23, 1960, indicate a pattern of gaining flow between altitudes of about 620 and 290 ft. Seepage runs on September 6, 1961, and February 13, 1962, both indicate a pattern of gaining flow extending from an altitude of about 280 ft downstream to an altitude of about 120 ft.

Continuous-Record Stations

Numerous continuous-record stations have been operated by the USGS in the Waiāhole, Waikāne, and Kahana watersheds of windward Oʻahu (table 11). Most of the stations measured streamflow, while others measured ditch flows. Only a few of the stations were operated before the construction of the Waiāhole Ditch System.

Pre-ditch

A total of six continuous-record stations were operated in the Waiāhole and Waikāne watersheds before the ditch construction. Four of the six stations were operated concurrently for several months. No continuous-record stations were operated in the Kahana watershed before the ditch-system construction; stations 16296000 and 16297000 were operated mostly during the construction period (table 11). Records collected at these pre-ditch stations are based on one gage reading per day, except for station 16292000, where records are based on two gage readings per day.

Continuous streamflow data are available for station 16292000 on Waiāhole Stream from September 25, 1911, to June 30, 1916. This station was located at an altitude of 160 ft, above the confluence of Waiāhole and Waianu Streams, and measured streamflow upstream of all irrigation diversions (fig. 14). Discharge data for the period before the construction of the ditch system are limited to those recorded from 1911 through August 1, 1913. The average flow for this period is 15.4 Mgal/d. A sharp increase in daily discharge (fig. 15) indicates that after August 1, 1913, additional water that was developed during the boring of the main tunnel was being discharged into the stream upstream from the station. Data collected subsequent to this date were therefore not used to estimate natural flow-duration discharges in Waiāhole Stream.

Station 16294000 on Waiāhole Stream at altitude 14 ft was operated for much of the same time period as station 16292000 and measured streamflow going into Kāneʻohe Bay downstream from most irrigation diversions. Because of the numerous water diversions from the stream for irrigation of rice lands in the lower part of the valley, measurements made at this station are not representative of natural flow conditions and were not used in this study.

Table 8. Discharge measurements made during seepage runs in the Waikāne Stream, windward Oʻahu, Hawaiʻi, 2002-03.

[ft, feet; Mgal/d, million gallons per day; --, not measured]

Site number (fig. 11)	USGS station number	September 18, 2002 Mgal/d	May 12, 2003 Mgal/d	Site description
1	213033157530801	0.19	0.19	North fork at altitude 500 ft
2	213030157525801	0.20	0.22	North fork at altitude 410 ft
3	16294400	0.36	0.49	North fork at altitude 220 ft, at mouth
4	213012157532601	--	3.01	Intake 23 at altitude 760 ft
5	213015157524601	0.14	--	South fork at altitude 240 ft
6	16294500	0.16	3.36	South fork at altitude 220 ft, at mouth
7	16294800	0.93	4.24	At altitude 90 ft
8	16294700	0.03	0.22	Waikeʻekeʻe Stream at altitude 90 ft, at mouth
9	16294900	1.37	4.46[a]	At altitude 75 ft
10	212950157514101	1.32	4.96	At altitude 35 ft
11	16295195	1.05	4.49	At altitude 10 ft, at Kamehameha Highway

[a] Discharge from stage-discharge relationship.

Table 9. Discharge measurements made during seepage runs in the Waikāne Stream, windward O‘ahu, Hawai‘i, 1959-60.

[ft, feet; ft^3/s, cubic feet per second; Mgal/d, million gallons per day; --, not measured]

Site number (fig. 12)	Takasaki number[a]	July 15, 1959 Mgal/d	October 19, 1959 Mgal/d	February 9, 1960 Mgal/d	Site description (Takasaki and others, 1969)
1	188	0.39	--	0.48	At altitude 240 ft, downstream of confluence of north and south forks
2	189	0.42	--	--	At altitude 220 ft
3	190	0.72	--	--	Waikāne Stream upstream of confluence with Waike‘eke‘e Stream
4	191	0.06	--	0.09	Waike‘eke‘e Stream at altitude 100 ft, upstream of confluence with Waikāne Stream
5	192	--	0.87	1.01	At altitude about 90 ft, downstream of confluence with Waike‘eke‘e Stream
6	193	--	--	1.23[b]	USGS gaging station 16294900 at altitude 75 ft
7	194	--	1.23	--	At altitude about 60 ft, downstream of ditch diversion and intake
8	195	1.38	--	--	At altitude about 35 ft, downstream of ditch diversion
9	196	--	1.18	--	At altitude about 30 ft, downstream of ditch diversion
10	198	0.70	--	--	About 20 ft downstream of Kamehameha highway

[a]Station numbers used by Takasaki and others (1969).

[b]Daily mean discharge computed at gaging station.

Table 10. Discharge measurements made during seepage runs in the Kahana Stream, windward O‘ahu, Hawai‘i, 1960-62.

[ft, feet; Mgal/d, million gallons per day; --, not measured]

Site number (fig. 13)	Takasaki number[a]	August 23, 1960 Mgal/d	September 6, 1961 Mgal/d	February 13, 1962 Mgal/d	Site description
1	210	0.08	--	--	Altitude 620 ft on eastern tributary
2	211	0.13	--	--	Altitude approximately 590 ft on eastern tributary
3	212	0.20	--	--	Altitude 560 ft on eastern tributary
4	213	0.81	--	--	Altitude 515 ft on eastern tributary
5	214	0.22	--	--	Altitude 500 ft on western tributary just above confluence
6	215	2.11	--	--	Altitude 380 ft on east branch
7	216	--	2.57	1.95	East branch of Kahana Stream 100 ft upstream of confluence at altitude 280 ft
8	217	1.95	1.42	0.92	West branch of Kahana Strearm, 20 ft upstream of confluence at 280 ft altitude
9	218	5.55	--	3.55	Kahana Stream about 30 ft downstream of confluence at altitude 280 ft
10	220	--	--	3.83	Altitude 225 ft about 50 ft downstream of confluence with western tributary
11	221	--	6.92	--	Below spring inflow about 1.0 mile (straight distance) upstream of USGS gaging station 16296500.
12	224	--	9.31	--	At 120 ft altitude

[a]Station numbers used by Takasaki and others (1969).

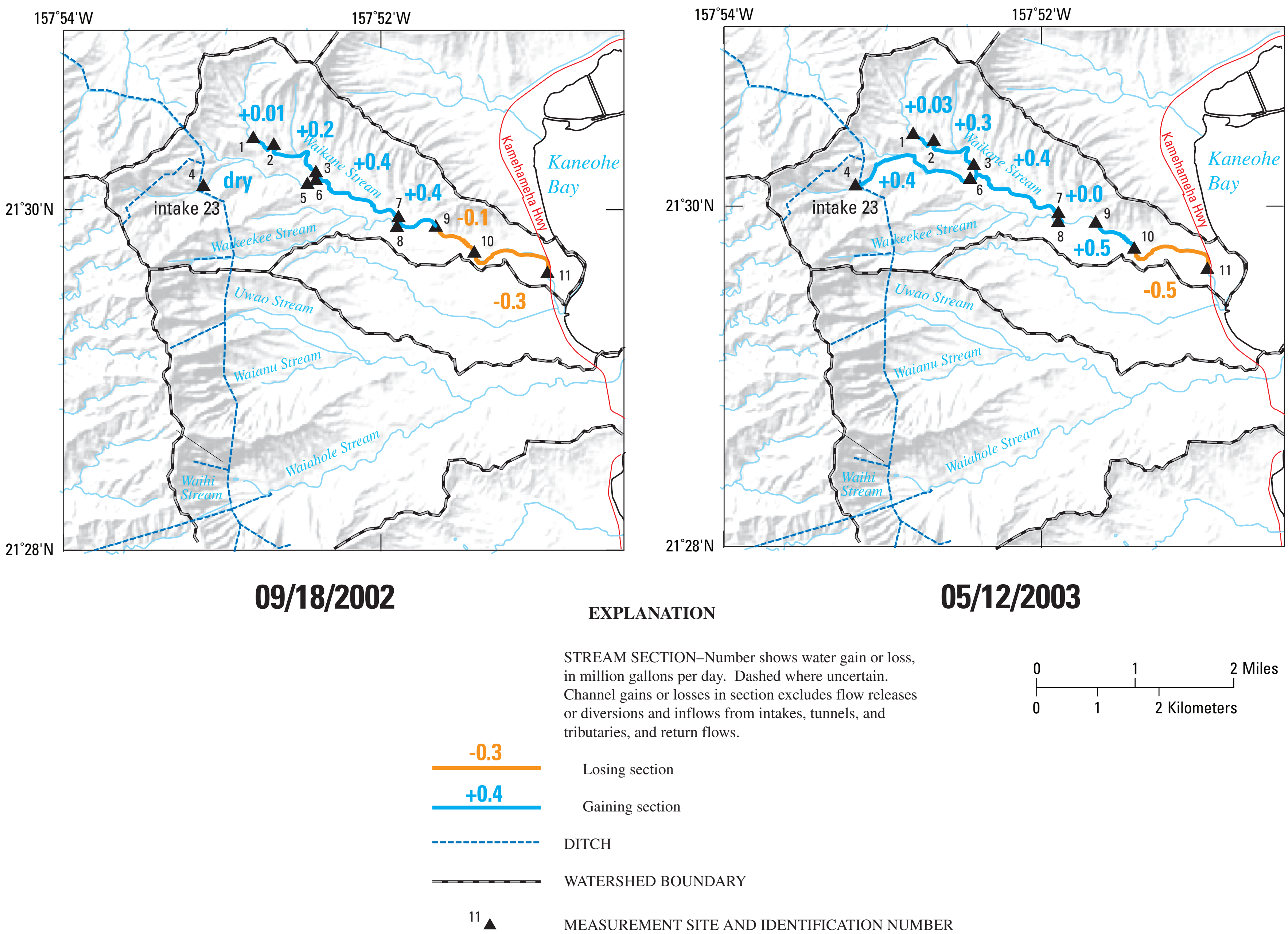


Figure 11. Results of seepage runs on Waikāne Stream, windward O‘ahu, Hawai‘i, 2002-03. Uwao was formerly spelled Uwau.

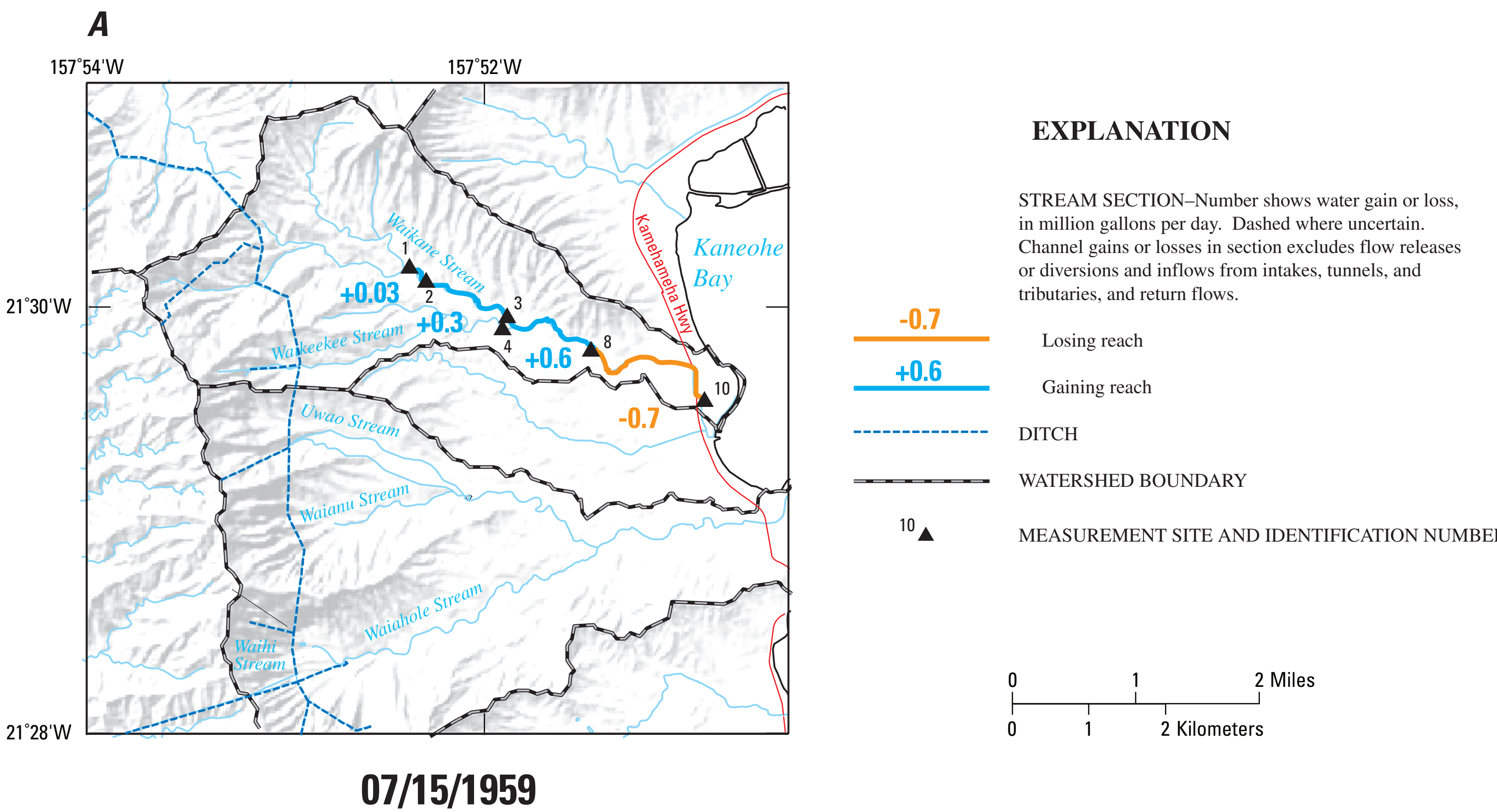
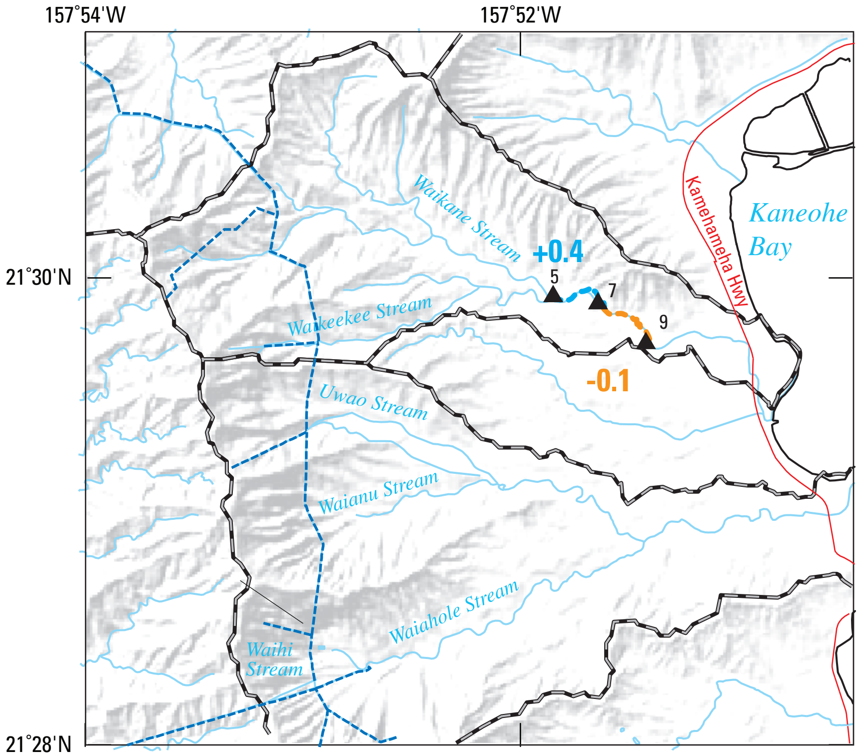
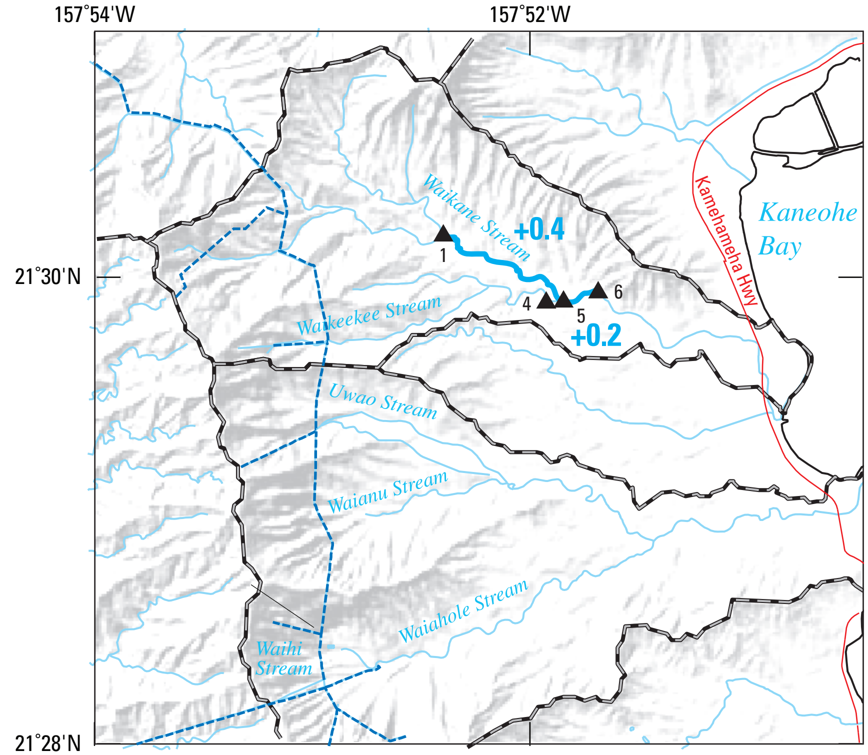


Figure 12. Results of seepage runs on Waikāne Stream, windward O‘ahu, Hawai‘i, July 1959 (*A*) and October 1959 and February 1960 (*B*). Uwao was formerly spelled Uwau.

B



10/19/1959



02/09/1960

Figure 12.—Continued.

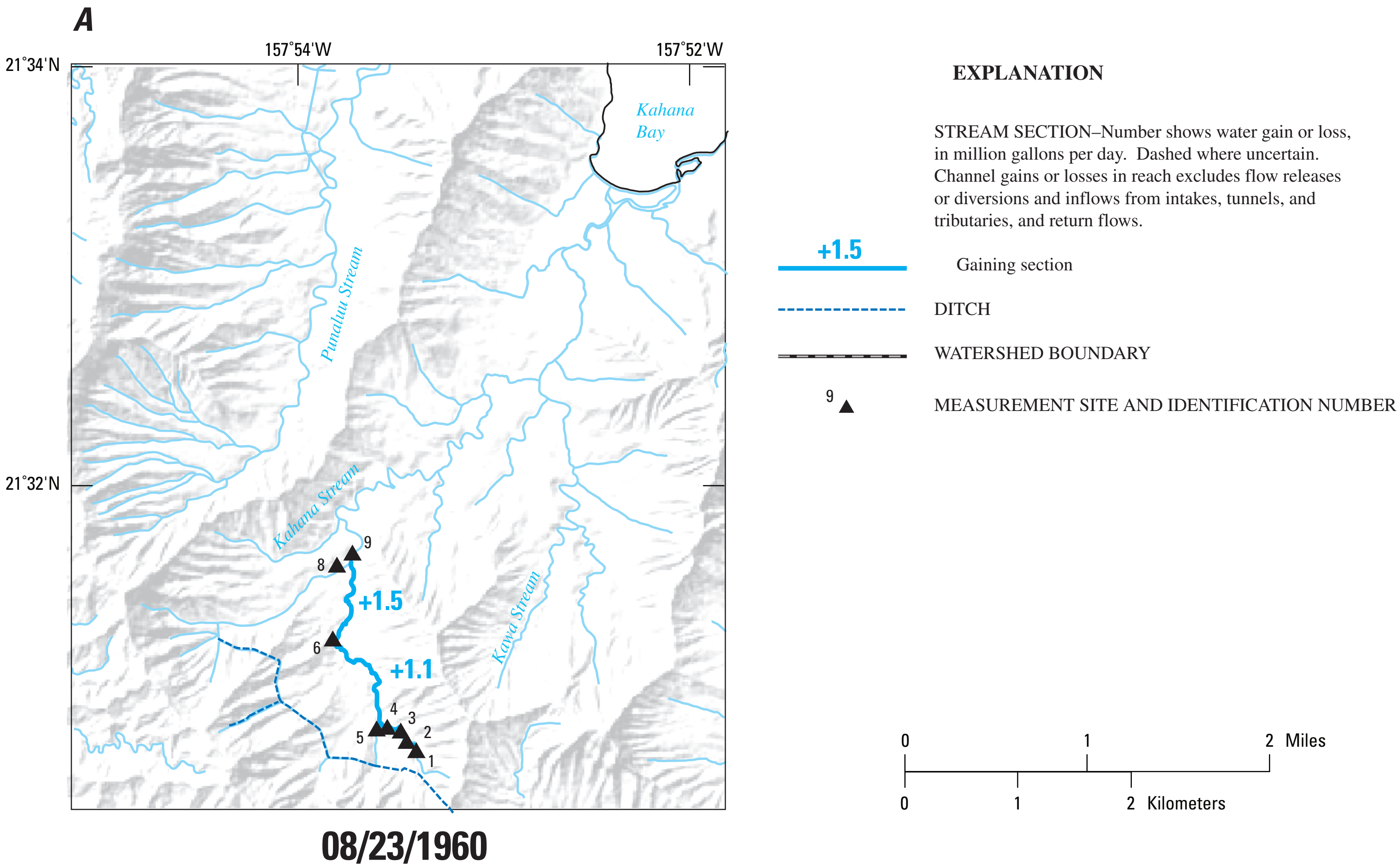


Figure 13. Results of seepage runs on Kahana Stream, windward O‘ahu, Hawai‘i, 1960 (*A*) and 1961-62 (*B*).

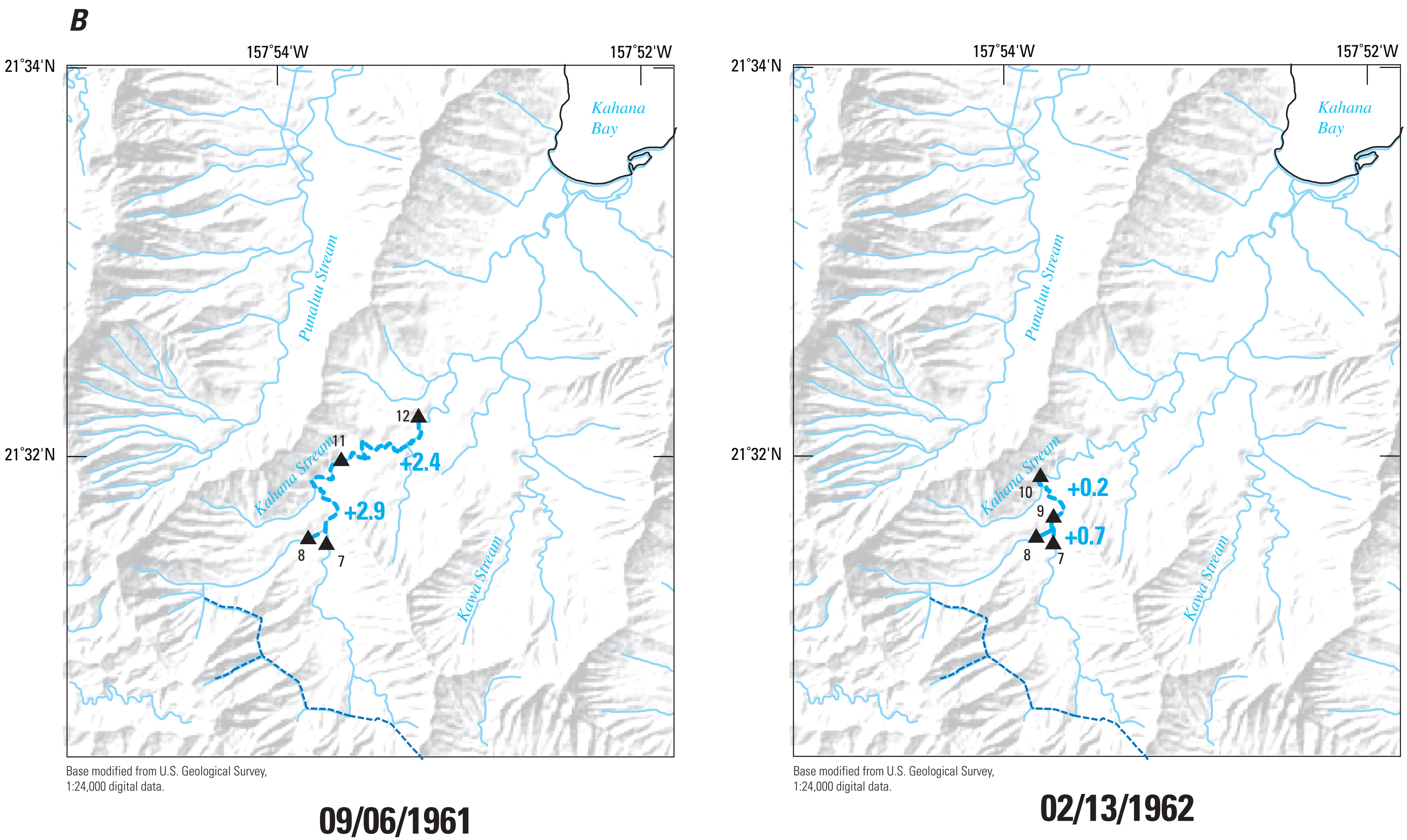
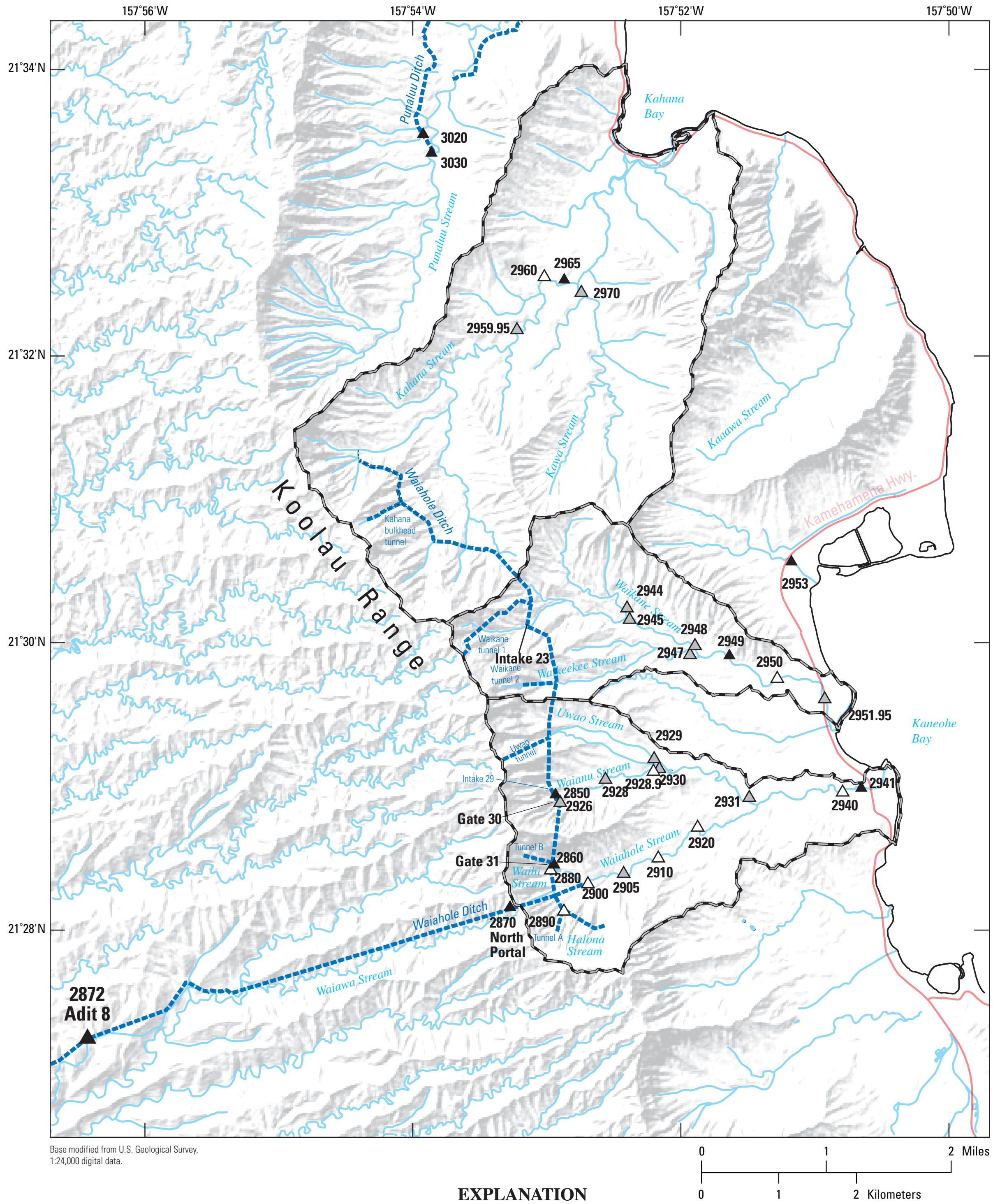


Figure 13.—Continued.

Table 11. Continuous-record streamflow stations in the Waiāhole, Waikāne, and Kahana watersheds, windward Oʻahu, Hawaiʻi.

[WWC, Waiāhole Water Company; ADC, Agribusiness Development Corporation (took over the management of Waiāhole Ditch System since 1999); stations operated before and during construction of the Waiāhole Ditch System are shown in **bold**; n.a., not available; P, present; LFPR low-flow partial-record]

Gaging-station number	Station location	Station altitude (feet)	Period of record operated by USGS	Remarks
		Waiāhole		
16285000	Waiāhole tunnel at Waianu near Gate 30	n.a.	1950-69	Established by WWC in 1916; 1916-50 and 1969-99 operated by WWC; 1999-P operated by ADC
16286000	Waiāhole tunnel wasteway at Intake 31 near Waiāhole	n.a.	1951-69 and 2000-03	Established by USGS in 1951; 1969-99 operated by WWC; 2003-P operated by ADC
16287000	Waiāhole tunnel at North portal near Waiāhole	n.a.	1951-69 and 2000-03	Established by WWC in 1916; 1916-51 and 1969-99 operated by WWC, and 2003-P operated by ADC
16287200	Waiāhole tunnel at Adit 8 near Waipahu	n.a.	1956-69 and 2000-03	Established by WWC in 1916; 1916-56 and 1969-99 operated by WWC, and 2003-P operated by ADC
16288000	**Hālona Stream near Waikāne**	**750**	**8/9/1911 - 9/30/1911**	**Fragmentary record, only 27 measurements available**
16289000	**Waihī Stream near Waikāne**	**750**	**8/11/1911 - 10/19/1911**	**Fragmentary record, only 31 measurements available**
16290000	**Waiāhole Stream downstream of powerhouse near Waiāhole**	**420**	**1915**	
16291000	Waiāhole Stream at altitude 250 feet near Waiāhole	250	1955-68	Established as LFPR station in 1970-72 and 1988-90
16292000	**Waiāhole Stream at Manianiaula, near Waikāne**	**160**	**10/1/1911 - 6/30/1916**	**Upstream of all diversions; streamflow increased in 8/1913 due to start of tunneling; read twice daily**
16293000	**Waiānu Stream near Waikāne**	**190**	**9/9/1911 - 11/22/1911**	**Fragmentary record; only 22 measurements available; upstream of all irrigation diversions**
16294000	**Waiāhole Stream at Waiāhole, near Waikāne**	**20**	**9/25/1911 - 12/31/1912**	**Downstream of irrigation diversions**
16294100	Waiāhole Stream upstream of Kamehameha Hwy	14	8/2001-Present	Currently active; affected by flow releases at Gates 30 and 31
		Waikāne		
16294900	Waikāne Stream at altitude 75 ft at Waikāne	75	12/1959-Present	Affected by flow release at Gate 23 from 10/2002
16295000	**Waikāne Stream near Waikāne**	**30**	**1/27/1912 - 09/30/1912**	**No rating obtained; read once daily; downstream of irrigation diversions**
		Kahana		
16296000	**Kahana Stream near Kahana**	**40**	**1914-17**	**Upstream of all irrigation diversions**
16296500	Kahana Stream at altitude 30 ft near Kahana	30	12/1958-Present	Currently active
16297000	**Kāwā Stream near Kahana**	**30**	**4/30/1914 - 3/8/1917**	**Upstream of all irrigation diversions; operated as LFPR station since 10/6/1960**



EXPLANATION

- ROADS
- DITCH SYSTEM
- WATERSHED BOUNDARY
- STATIONS AND ABBREVIATED NUMBER—Complete number for 2949 is 16294900.
  - 2949 ▲ Active continuous-record gaging station
  - 2890 △ Inactive continuous-record gaging station
  - 176-5 △ Low-flow partial-record station

Figure 14. Continuous-record and low-flow partial-record streamflow stations in the study area, windward O‘ahu, Hawai‘i. Uwao was formerly spelled Uwau.

A total of 22 daily flows were measured at station 16293000 on Waianu Stream at an altitude of 190 ft from September to November of 1911. This station was upstream from all irrigation diversions and measured natural streamflow. The average of the 22 daily flow values is 8.1 Mgal/d.

Streamflow records covering 31 and 27 days, during the period August through October 1911, are available for station 16289000 on Waihī Stream and station 16288000 on Hālona Stream, respectively. These records indicate that base flows of these two streams at about 750 ft altitude were fairly steady before construction of the Waiāhole Ditch System. The highest and lowest flows recorded in Waihī Stream were 2.9 and 2.4 Mgal/d, respectively. The highest and lowest flows in Hālona Stream were 7.1 and 5.8 Mgal/d, respectively.

The earliest continuous streamflow data collected in the Kahana watershed were at stations 16296000 and 16297000 between 1914 and 1917 (table 11), mainly during the period of ditch construction. Discharges measured during construction but before the opening of the ditch system may provide reasonable estimates of natural streamflow. The two bores of the main tunnel through the Koʻolau Range from the south and north portals met on December 13, 1915 (Stearns and Vaksvik, 1935). The ditch system was officially opened on May 27, 1916 (Wilcox, 1996). It is likely that the opening of the main tunnel coincided with the start of surface-water diversions by the Waiāhole Ditch from the headwaters of Kahana Stream, which would reduce base flows in the stream. Flow data at station 16296000 indeed indicate that the median streamflow in 1915 and 1916 before the opening of the ditch was about 24 Mgal/d; median streamflow after the ditch opened through 1917 was 16 Mgal/d, a drop of about 8 Mgal/d.

Post-ditch

Since completion of the Waiāhole Ditch System on May 27, 1916 (Wilcox, 1996), numerous continuous-record stations have been operated for various periods of time (table 11) on each of the diverted streams (fig. 14). These stations

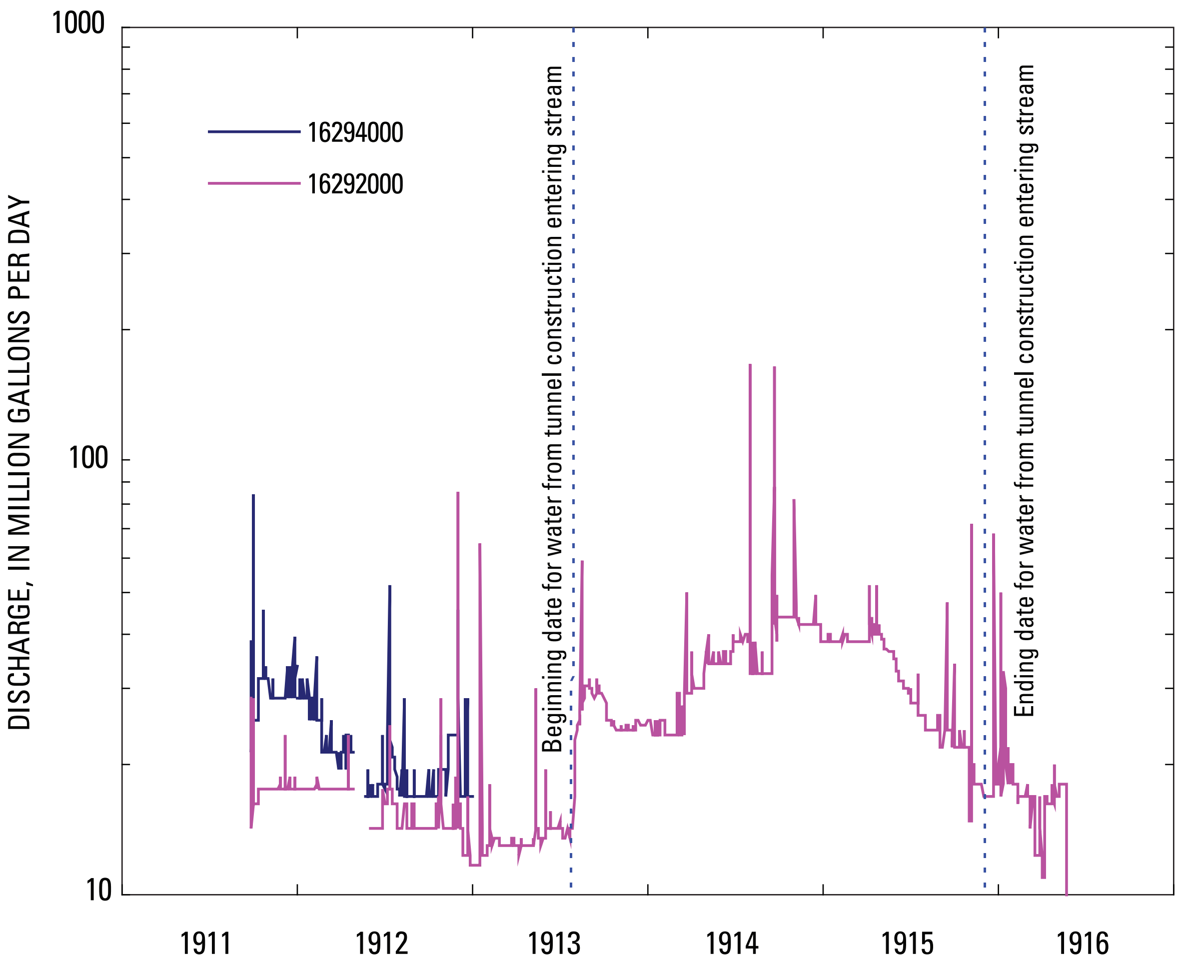


Figure 15. Logarithmic plot of daily discharge at continuous-record streamflow stations 16292000 (altitude 160 ft) and 16294000 (altitude 14 ft), Waiāhole Stream, windward Oʻahu, Hawaiʻi, September 25, 1911 to June 30, 1916.

provide streamflow records representative of post-ditch (diverted) flow conditions in the Waiāhole, Waikāne, and Kahana Streams. Three of the stations are currently active and useful for interpreting hydrologic conditions in the three diverted streams: station 16294100 on Waiāhole Stream (altitude 14 ft), station 16294900 on Waikāne Stream (altitude 75 ft), and station 16296500 on Kahana Stream (altitude 30 ft).

During the post-ditch period, two stations have been operated on Waiāhole Stream. The currently active station 16294100 has been operated from August 2001 to present, and is at an altitude of 14 ft, about 300 ft upstream from Kamehameha Highway (fig. 14). This station measures the combined flow from the Waiāhole Stream and its principal tributary, Waianu Stream. Through 2004, the average discharge for station 16294100 was 28.3 Mgal/d. The highest annual mean discharge was 35.6 Mgal/d in 2004, and the lowest annual mean discharge was 18.7 Mgal/d in 2003. Station 16291000 was operated from 1955 to 1968 on Waiāhole Stream at an altitude of 250 ft and upstream from the confluence with Waianu Stream. Flow measured at this station was affected by upstream pumping to the Waiāhole Ditch System and occasional flow releases from the ditch system through Gate 31.

Station 16294900 on Waikāne Stream has been operated from December 1959 to present and is at an altitude of 75 ft, about 0.3 mi downstream from the confluence with Waikeʻekeʻe Stream (fig. 14). Through 2004, the average discharge for station 16294900 was 5.7 Mgal/d. The highest annual mean discharge was 12.3 Mgal/d in 2004, and the lowest annual mean discharge was 2.2 Mgal/d in 1984.

Station 16296500 on Kahana Stream has been operated from December 1958 to present and is at 30 ft altitude, just upstream from the confluence with Kāwā Stream (fig. 14). Through 2004, the average discharge for station 16296500 was 23.6 Mgal/d. The highest annual mean discharge was 43.4 Mgal/d in 1982, and the lowest annual mean discharge was 13.0 Mgal/d in 1984.

Four continuous-record stations (16285000, 16286000, 16287000, and 16287200) have been operated to monitor Waiāhole Ditch flows at Gate 30, Gate 31, North Portal, and Adit 8, respectively. Responsibility for the operations of these stations has switched between the USGS, Waiāhole Water Company, and ADC from time to time. Currently, these stations are operated by the ADC (fig. 14 and table 11). Station 16285000, located near Gate 30, measures total ditch flow leaving the Uwao area. Station 16286000, located at Waiāhole Tunnel wasteway at Gate 31, monitors flow releases to Waiāhole Stream. Station 16287000, commonly referred to as the North Portal gage, is in the main tunnel directly underneath the Koʻolau crest to measure the amount of water passing from the windward to the leeward side at the topographic divide. Station 16287200, commonly referred to as Adit 8, is at the southwest (leeward) portal of the main tunnel, about 2.8 mi downstream of the North Portal. This station was established to measure the ground-water inflow in the reach between the North Portal and the end of the Waiāhole main tunnel at Adit 8.

Low-Flow Partial-Record Stations

An individual continuous-recording station can be used to characterize flow conditions with time, but only at a single location on a stream. Streamflow data for a single location cannot be used to characterize an entire stream because flow conditions vary, both with time and location along a stream, as interactions between the surface and ground water vary. Some stream reaches may gain water from the adjacent ground-water body, whereas other reaches may lose water. Low-flow estimates at different locations on each stream are useful for describing the availability and distribution of base flow along the stream. Because continuous-recording stations cannot be operated at all locations where data are desired, low-flow partial-record (LFPR) stations were established as part of this study to provide low-flow estimates at ungaged sites. A series of discharge measurements were made at each LFPR station during periods of independent flow recessions and under various base-flow conditions.

A total of 12 low-flow measurements representative of post-ditch conditions were made at each of 12 LFPR stations on Kahana, Waikāne, and Waiāhole Streams and their significant tributaries (fig. 14, table 12) in 2002-03. In addition to data collected in 2002-03, low-flow measurements made in 1988-90 and during earlier periods at these LFPR stations were compiled for analysis. The range of discharge measured at a LFPR station varies depending on the objectives of the LFPR station. Historical streamflow measurements were checked, and only those measurements made during a period when no direct runoff was taking place were used. This was determined by checking the streamflow hydrographs at nearby continuous-record stations for rapid changes in discharge, which are indicative of periods of direct runoff. Fontaine and others (1992) used this screening approach to prevent potential bias that could be introduced by including high-flow measurements in the record-extension analysis discussed in the subsequent section “Low-flow duration discharges in streams.” All of the measurements made at the LFPR stations used in this study are stored in the USGS National Water Information System database.

Miscellaneous Measurement Sites

Numerous discharge measurements were made at selected sites on each of the diverted streams before the construction of the Waiāhole Ditch System. Because exact locations of most of these miscellaneous discharge measurement sites are difficult to determine and irrigation diversion activities downstream of the Waiāhole Ditch are not fully known, only measurements made upstream of all irrigation diversions were considered for use in estimating natural streamflow prior to the construction of the Waiāhole Ditch System as part of this study.

For Waikāne Stream, four pre-ditch discharge measurements were made in the lower reach of the stream below an

Table 12. Low-flow partial-record streamflow stations on Waiāhole, Waikāne, and Kahana Streams, windward O‘ahu, Hawai‘i.

[n.a., not applicable; --, not available; mi², square mile]

USGS station number	Takasaki number[a]	Station location	Altitude (feet)	Latitude[b]	Longitude[b]	Drainage area (mi²)	Period of record
		Waiāhole Stream					
19292600	--	Waianu Stream at Gate 30 release	820	21° 28’ 59”	157° 53’ 11”	n.a	1995, 2002-03
19292800	180	Waianu Stream	380	21° 29’ 08”	157° 52’ 51”	0.55	1959-61, 1995, 2002-03
19292890	182	Waianu Stream above confluence with Uwao[c] Stream	200	21° 29’ 13”	157° 52’ 26”	0.67	1960, 1995, 2002-03
16292900	183	Uwao[c] Stream at mouth	200	21° 29’ 16”	157° 52’ 26”	0.56	1911, 1959-61, 1995, 2002-03
16293100	185	Waianu Stream at mouth	75	21° 29’ 01”	157° 51’ 47”	1.65	1959-63, 1965-66, 1988-90, 1995, 2002-03
16290500	176_5	Waiāhole Stream	320	21° 28’ 29”	157° 52’ 39”	0.92	1988-90
		Waikāne Stream					
16294400	187_5	North Fork Waikāne Stream	220	21° 30’ 01”	157° 52’ 41”	0.58	1988-90, 2002-03
16294500	187_8	South Fork Waikāne Stream	220	21° 30’ 17”	157° 52’ 40”	0.67	1988-90, 2002-03
16294700	191	Waike‘eke‘e Stream at mouth	90	21° 30’ 01”	157° 52’ 12”	0.43	1959-61, 1988-90, 2002-03
16294800	190	Waikāne Stream above confluence with Waike‘eke‘e Stream	90	21° 30’ 04”	157° 52’ 10”	1.57	1959-61, 1988-90, 2002-03
16295195	198	Waikāne Stream at Kamehameha Highway	10	21° 29’ 41”	157° 51’ 12”	2.5	1988-90, 2002-03
		Kahana Stream					
16295995	224	Kahana Stream at mauka trail crossing	80	21° 32’ 17”	157° 53’ 29”	3.18	1960-62, 1966, 1971-72, 1974-81, 1983-85, 1988-90, 2002-03
16297000	226	Kāwā Stream at mouth	30	21° 32’ 33”	157° 53’ 00”	2.09	1914-17, 1958, 1961-62, 1966, 1971-72, 1974-81, 1983-85, 1988-90, 2002-03

[a]Station numbers used by Takasaki and others (1969), and Fontaine and others (1992).

[b]Coordinates are referenced to Old Hawaiian Datum.

[c]Uwao was formerly spelled Uwau.

altitude of about 75 ft on October 9, 1911. The measurement made farthest upstream, about two miles from the mouth of the stream and near altitude 75 ft, was 6.0 Mgal/d (Martin and Pierce, 1913). This measurement represented natural streamflow upstream of all irrigation diversions. Because locations of other pre-ditch measurements for Waikāne Stream are difficult to determine, those measurements were not used in this study.

Miscellaneous measurements were made on Kahana Stream and irrigation ditches on October 27, 1911 (Martin and Pierce, 1913). One measurement indicated a streamflow of 20.8 Mgal/d downstream of an irrigation ditch intake, and another measurement indicated a ditch flow of 3.0 Mgal/d. However, it is not clear if this is from the intake upstream of the stream measurement, and the exact location of the irrigation ditch is not known.

As part of a feasibility study of bringing surface waters of the Waiāhole, Waikāne, and Kahana Streams to a sugar-cane plantation in central Oʻahu (Lippencott, 1911), weirs were constructed to measure practically all of the spring flows at approximately 750 ft altitude from Kahana to Waiāhole. During June and July 1911, W.A. Wall (Lippencott, 1911) made daily measurements at these weirs (table 13). These measurements will subsequently be referred to as the Wall measurements in this report. The total average flow measured by Wall for all the streams during June and July 1911 was 23.1 Mgal/d (Lippencott, 1911).

Wall's Waiāhole Stream measurements compared closely with the limited and fragmentary daily flow data recorded at two currently inactive USGS continuous-record stations on Waihī (station 16289000) and Hālona (station 16288000) Streams. The USGS recorded daily flows in Waihī and Hālona Streams were 2.4 and 5.8 Mgal/d, respectively, and Wall's corresponding measurements of average spring flows were about 2.4 and 5.7 Mgal/d.

Approach and Methods for Estimating Natural Low-Flow Duration Discharges

The Waiāhole Ditch System intercepted large amounts of dike-impounded ground water, above an altitude of about 750 ft, that previously fed Waiāhole (and its tributaries Waianu and Uwao), Waikāne, and Kahana Streams through seeps and springs. Diversion of the dike-impounded ground water by Waiāhole Ditch has significantly diminished base flows in

Table 13. Average flows from weir observations in Waiāhole, Waianu, Waikāne, and Kahana Streams, windward Oʻahu, Hawaiʻi, for June and July, 1911, by W.A. Wall (modified from Lippencott, 1911).

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

Stream	Weir number	Average Flow (Mgal/d)	Total for stream (Mgal/d)	Percentage of total flow[a] (percent)	Total for watershed (Mgal/d)
Waiāhole			8.14	38.9	12.98
Hālona	1	4.7			
Hālona	2	1.04			
Waihī	3	2.4			
Waianu			4.2	20.1	
South Fork	1	0.53			
Middle Fork	2	2.47			
North Fork	3	1.2			
Uwao[b]	--	0.64	0.64	3.1	
Waikāne					2.57
Waikeʻekeʻe	12	0.92	0.92	4.4	
South Fork	13	0.53			
North Fork	14	1.12	1.65	7.9	
Kahana	--	7.5	5.4[a]	25.8	5.4[a]
			Total	100.0	20.95

[a]Original average flow of 7.5 Mgal/d is reduced by 2.1 Mgal/d to account for Kahana surface water not diverted by Waiāhole Ditch.

[b]Uwao was formerly spelled Uwau.

these streams. This section describes the overall approach used to estimate natural (undiverted) low-flow duration discharges for these streams during the common period of 1960-2004 (called the base period). A combination of pre-ditch and post-ditch streamflow data, ditch-flow data, seepage runs in the ditch system, and low-flow estimates at data collection stations was used.

Natural (undiverted) low flows were estimated using the following four-step approach:

1. Low-flow duration discharges representative of post-ditch (diverted) conditions were estimated for the LFPR and continuous-record stations located downstream from Waiāhole Ditch.
2. Low-flow duration discharges of flow diverted by Waiāhole Ditch were computed.
3. The relative distributions of flow diverted by Waiāhole Ditch among Waiāhole, Waikāne, and Kahana watersheds were estimated.
4. Low-flow duration discharges for post-ditch (diverted) conditions (step 1) were combined with estimates of diversions from each watershed (step 3) to derive estimates of natural low-flow duration discharges.

Low-Flow Duration Discharges in Streams

Discharge measurements made at LFPR stations were used to develop statistical relations with concurrent daily mean discharges at continuous-record index stations. These relations were then used to obtain estimates of various flow-duration discharges at LFPR stations corresponding to flow-duration discharges at the long-term index stations for the base period. The selection of the index stations will be discussed in the next section. To avoid bias associated with estimating low-flow duration discharges using ordinary least-squares regression statistical relations (Stedinger and Thomas, 1985), record-extension methods such as graphical correlation (Searcy, 1959, p.14) and the Maintenance Of Variance Extension, Type I (MOVE.1) (Hirsch, 1982) were used. The two methods assume that the relation between discharges at the LFPR station and the index station remains constant with time (Ries, 1993). The resulting low-flow estimates at LFPR stations therefore are representative of long-term conditions during the selected base period. Adjustment of short records to a common base period allows flow comparisons that reflect spatial differences in climate and drainage-basin characteristics rather than temporal differences in rainfall (Searcy, 1959). Because the majority of the potential index stations for this study (table 14) have been operated concurrently from water year 1960 to 2004, the period 1960 -2004 was therefore selected as the common base period for the record extension analyses for this study. Hydrologic conditions during the base period were assumed to be representative of long-term conditions.

The following guidelines for the MOVE.1 and graphical record-extension methods are provided (USGS Office of Surface Water, in Technical Memorandum no. 86.02, December 16, 1985): (1) approximately 10 base-flow measurements should be available to use the MOVE.1 method, and (2) the graphical correlation technique should be used when there are fewer than 10 base-flow measurements or when there is a nonlinear relation between base-flow measurements and concurrent daily mean discharges at the index station.

To summarize the application of the two record-extension methods, the initial procedure for both methods is to check for linearity in the relation between the concurrent discharges by the use of log-log plots (fig. 16). The use of logarithm (base 10) transformation normalizes the streamflow data and transforms the common curvilinear relation between continuous-record station records to straight lines (Searcy, 1959). The correlation coefficient was used as a measure of the strength of the linear relation between the index and LFPR stations. For stations with nonlinear relations and stations with less than 10 measurements, the graphical method was used. For sites with linear relations and 10 or more low-flow measurements, the MOVE.1 method was used.

In the MOVE.1 method, estimates of the low-flow statistics for the LFPR station are obtained by entering the logarithms of low-flow statistics 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 low-flow duration discharge at the low-flow partial-record stations,
- X_i is the logarithm of the computed low-flow duration discharge at the index station,
- $\overline{Y}$ is the mean of the logarithms of the discharge measurements at the low-flow 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, and
- s_x is the standard deviation of the logarithms of the concurrent daily mean discharges at the index station.

Both the MOVE.1 and graphical methods are thoroughly explained in the references cited, and a detailed example showing the application of the MOVE.1 method is provided by Ries (1993, p.28).

The same record-extension techniques were used to extend records for short-term stations that were not in opera-

Table 14. Continuous-record streamflow stations considered as potential index stations in the study.

[n.a., not applicable; mi², square mile]

USGS station number	Station name	Latitude[a]	Longitude[a]	Drainage area (mi^2)	Period of record
16200000	NF Kaukonahua Str abv RB, nr Wahiawa, O‘ahu, HI	21° 31’ 09”	157° 56’ 53”	1.38	1913-53, 1960-Present
16229000	Kalihi Str nr Honolulu, O‘ahu, HI	21° 22’ 00”	157° 50’ 49”	2.61	1914-Present
16240500	Waiakeakua Str at Honolulu, O‘ahu, HI	21° 19’ 52”	157° 48’ 08”	1.06	1913-21, 1925-Present
16254000	Makawao Str nr Kailua, O‘ahu, HI	21° 21’ 49”	157° 46’ 02”	2.04	1912-16, 1958-Present
16294100	Waiāhole Stream above Kamehameha Hwy, O‘ahu, HI	21° 29’ 05”	157° 50’ 57”	3.76	1988-1990[b], 1995[b], 2001-Present
16294900	Waikāne Str at alt 75 ft at Waikāne, O‘ahu, HI	21° 30’ 00”	157° 51’ 54”	2.22	1959-Present
16296500	Kahana Str at alt 30 ft nr Kahana, O‘ahu, HI	21° 32’ 37”	157° 53’ 07”	3.74	1958-Present
16302000[c]	Punalu‘u Ditch nr Punalu‘u, O‘ahu, HI	21° 33’ 41”	157° 54’ 10”	n.a.	1953-Present
16303000[c]	Punalu‘u Str nr Punalu‘u, O‘ahu, HI	21° 33’ 33”	157° 54’ 06”	2.78	1953-Present
16304200	Kaluanui Str nr Punalu‘u, O‘ahu, HI	21° 35’ 22”	157° 54’ 38”	1.11	1967-Present

[a]Latitude and longitude are in Old Hawaiian Datum.

[b]Established as miscellaneous measurements.

[c]Combined records of stations 16302000 and 16303000 to reflect natural streamflow conditions.

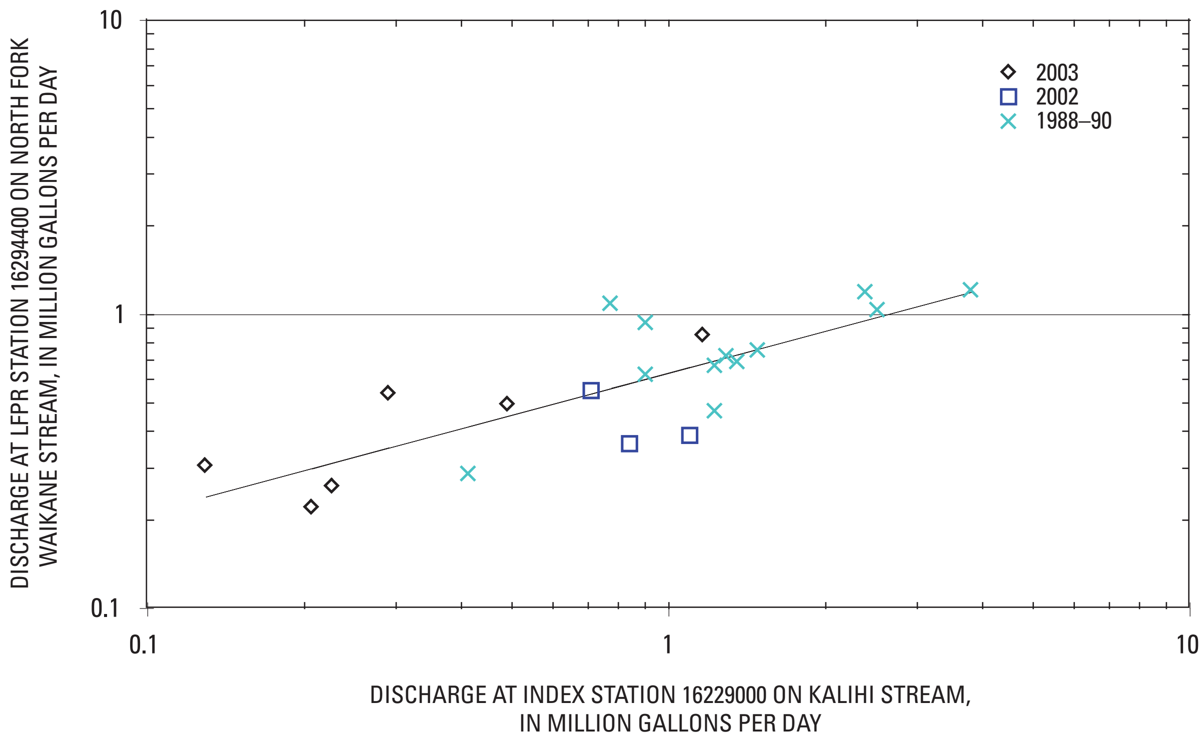


Figure 16. Graphical relation between flows at index station on Kalihi Stream and low-flow partial-record (LFPR) station on Waikāne Stream, O‘ahu, Hawai‘i.

tion through the entire base period. Application of the techniques varied slightly from the procedures used to extend records for LFPR stations. Instead of relating measured discharges at the station to concurrent daily discharges recorded at the index station, estimates for short-term continuous-record stations were obtained by relating computed duration discharges for the concurrent period of record between a short-term continuous-record station and an index station.

For the long-term continuous-record stations, flow-duration statistics were determined directly using standard USGS methods described in Searcy (1959). A flow-duration curve is a cumulative-frequency curve, which shows the percentage of time that a daily mean flow is equaled or exceeded (Searcy, 1959). The median flow (Q_{50}) and the 90th-percentile flow (Q_{90}) are the daily mean flows equaled or exceeded 50 and 90 percent of the time, respectively.

Flow-duration curves for the three currently active continuous-record stations on Waiāhole, Waikāne, and Kahana Streams were computed (figs. 17-19). The flow-duration curve for station 16294100 on Waiāhole Stream, based on data for water years 2002 through 2004, is shown in figure 17. Streamflow at this station during this period was affected by flow releases through Waiāhole Ditch System Gates 30 and 31. Flow conditions in Waikāne Stream also changed significantly after the flow release through Intake 23 started on October 11, 2002; therefore data from station 16294900 are divided into pre-release and post-release periods. Flow-duration curves of daily mean discharge were constructed for water years 1960 through 2002, representative of pre-release conditions (fig. 18*A*), and water years 2003 and 2004, representative of post-release conditions (fig. 18*B*). Post-release unadjusted flow-duration curves for both stations 16294100 (fig. 17) and 16294900 (fig. 18*B*) exhibit sharp breaks or bends at the high ends, which may primarily be a reflection of the limited period of record. The flow-duration curve for station 16296500 on Kahana Stream (fig. 19), based on data for water years 1960 through 2004, indicates that flows greater than or equal to 8 Mgal/d occurred 99 percent of the days. The long-term average discharge at this station, 23.6 Mgal/d, represents a flow rate that is equaled or exceeded about 20 percent of the time.

Flow-duration curves provide a convenient means for making comparison of the hydrologic conditions between watersheds. The low-flow end of a flow-duration curve also reflects the effect of geology on base flow. The sustained discharge of dike-impounded ground water to Waiāhole, Waikāne, and Kahana Streams is reflected in the way the curves nearly flatten out at the higher percentile flows. In addition, a flow-duration curve is a summary of the flow characteristics of streams only for the period for which they are computed because climatic conditions and resulting streamflows during different periods may not be the same (Ries, 1993, p. 20). The similarities between flow-duration curves at index station 16200000 on North Fork Kaukonahua Stream (table 14) for both the entire period of record and the base period indicate that hydrologic conditions during the selected base period of 1960-2004 were representative of long-term conditions (fig. 20).

Selection of Index Stations

An index station is a nearby, hydrologically similar, continuous-record station with long-term data available that can be used to accurately compute streamflow statistics. Selection of index stations for establishing relations with LFPR and short-term stations was based on two criteria: (1) distance between the stations and (2) a minimum correlation coefficient of 0.80 between the discharge measurements (log-transformed) for the LFPR station and the concurrent daily discharges (log-transformed) at the index station. Nearby stations on the same stream as the LFPR station are obvious candidates for index stations because these stations generally are in hydrologically similar settings and provide better relations with the LFPR station than stations from distant watersheds (Searcy, 1959). The one currently active long-term continuous-record gage on Waikāne Stream (station 16294900) therefore was considered as the primary index station for the five LFPR stations on Waikāne Stream because of its proximity to the LFPR stations (table 12). Although station 16296500 on Kahana Stream operated during the entire base period, this station was not used as an index station because flow conditions during this period may not have been uniform. The closure of surface-water intakes during the mid-1980s and the construction of a bulkhead in Kahana development tunnel in 1992 may have increased flow in the downgradient streams.

Because the currently active station 16294100 on Waiāhole Stream only has been operated since 2001, the selection of an index station for LFPR stations on Waianu Stream largely was based on the second criterion. As a result, long-term continuous-record stations outside of the study area were considered for use as index stations. High correlation coefficients for concurrent flows at the LFPR and index stations were assumed to reflect similar hydrogeological settings between the two watersheds.

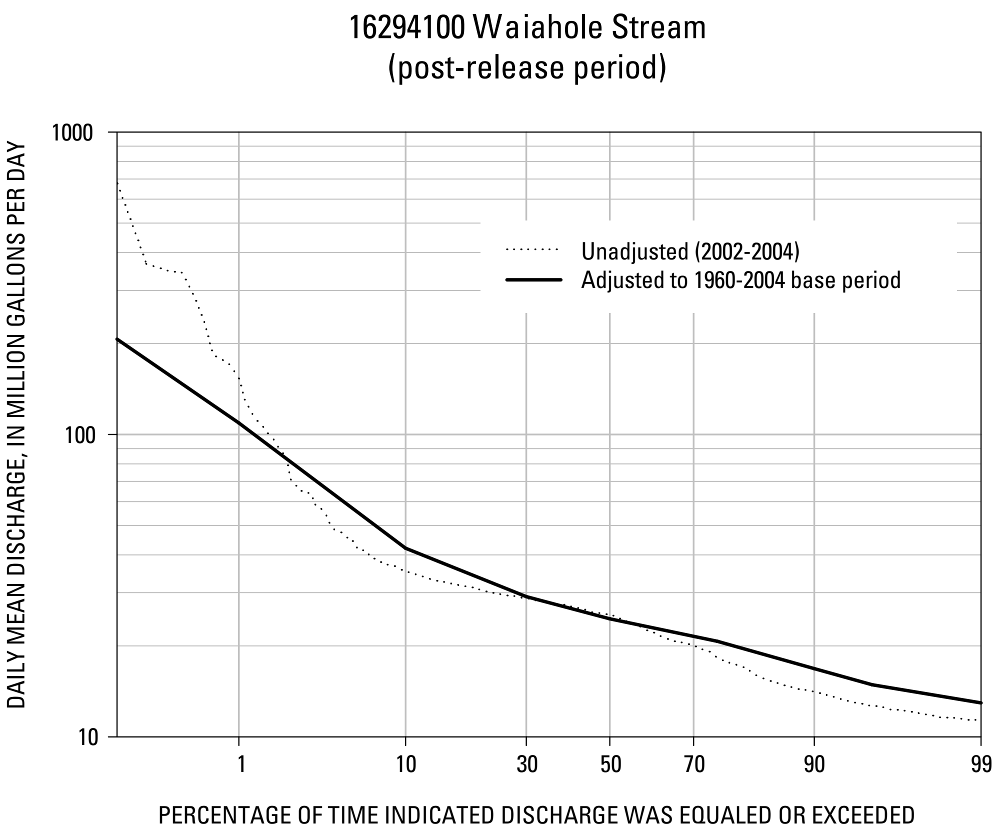


Figure 17. Unadjusted and adjusted flow-duration curves of daily mean discharge at continuous-record streamflow station 16294100 on Waiāhole Stream, windward O‘ahu, Hawai‘i, for post-release period 2002-2004.

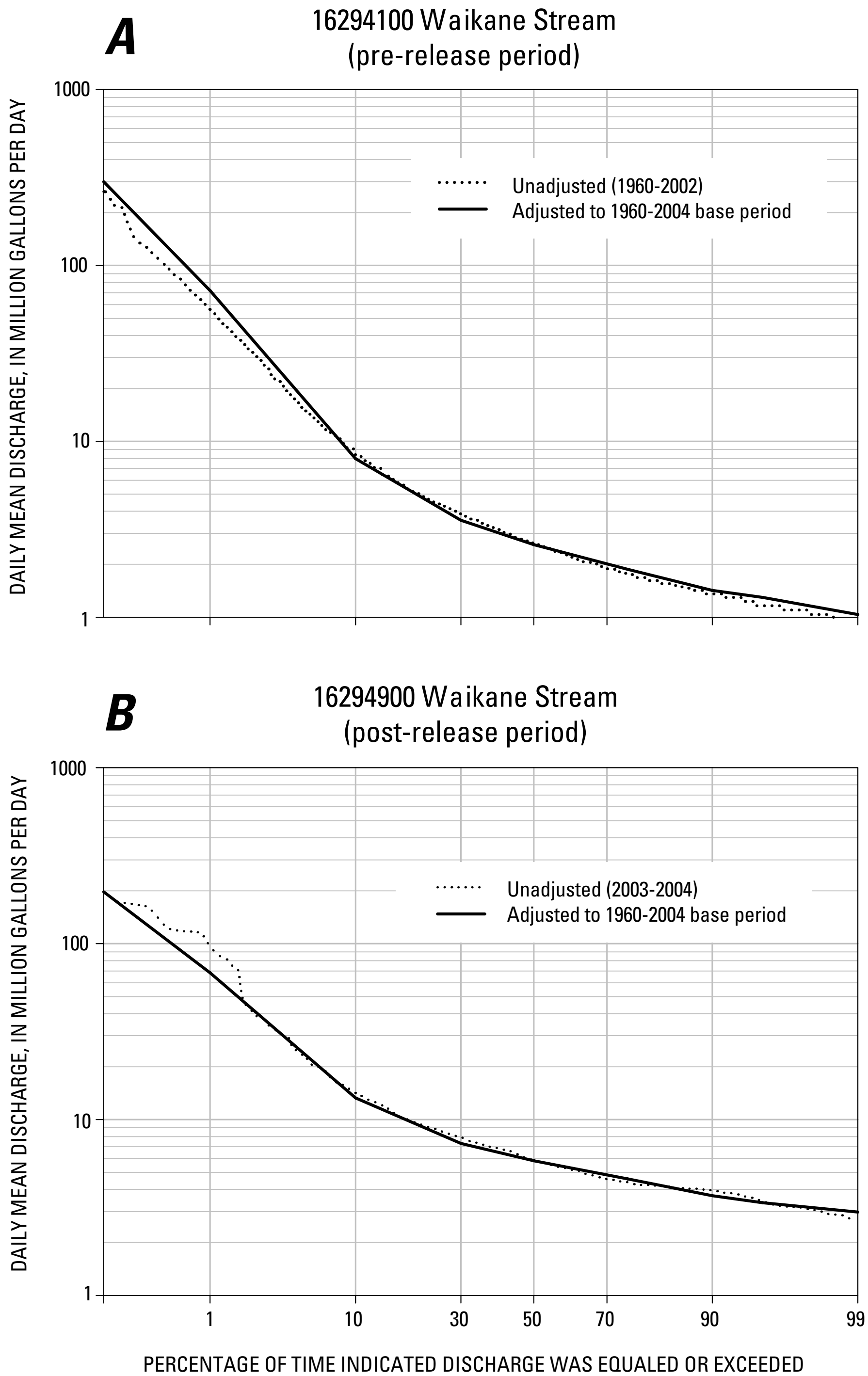


Figure 18. Unadjusted and adjusted flow-duration curves of daily mean discharge at continuous-record streamflow station 16294900 on Waikāne Stream, windward O‘ahu, Hawai‘i, for pre-release period 1960-2002 (*A*) and post-release period 2003-04 (*B*).

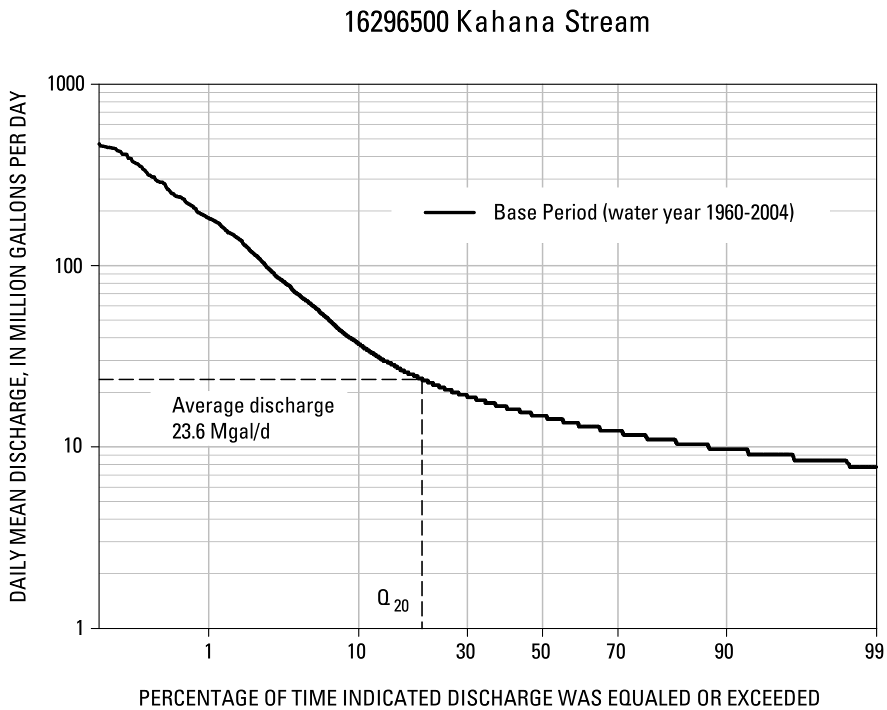


Figure 19. Flow-duration curve of daily mean discharge at continuous-record streamflow station 16296500 on Kahana Stream, windward O‘ahu, Hawai‘i, for period 1960-2004.

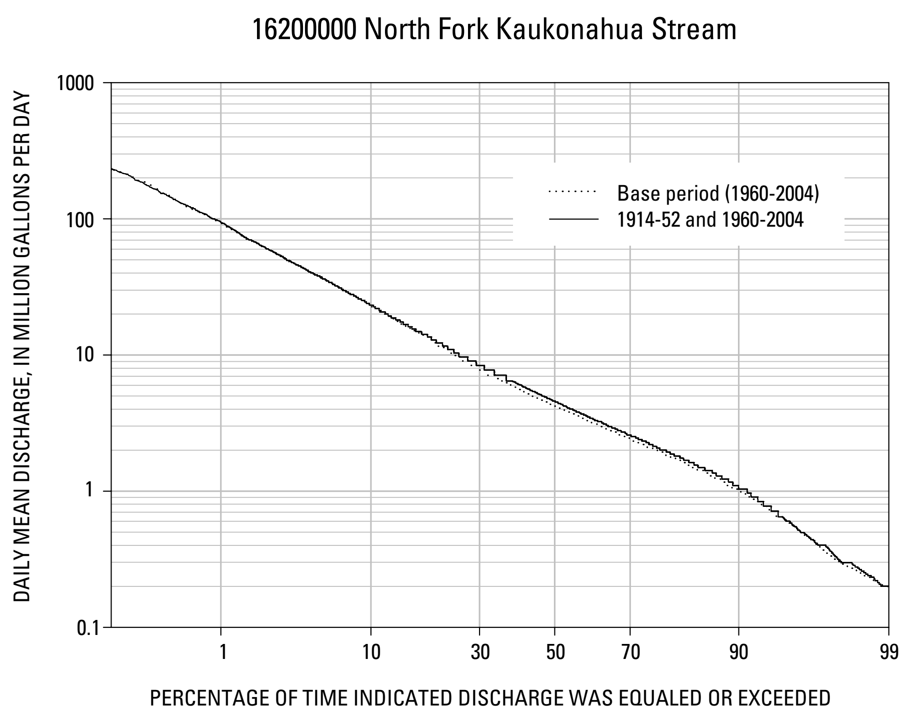


Figure 20. Flow-duration curves for base period and period of record of daily mean discharge at continuous-record streamflow station 16200000 on North Fork Kaukonahua Stream, O‘ahu, Hawai‘i.

Potential windward Oʻahu index stations (table 14) considered were station 16254000 on Makawao Stream, station 16304200 on Kaluanui Stream, and station 16303000 on Punaluʻu Stream (fig. 21). Streamflow data from station 16303000 on Punaluʻu Stream, however, do not reflect natural flow conditions because of the Punaluʻu Ditch diversions immediately upstream of the station. Daily flow data for the Punaluʻu Ditch diversions at station 16302000 were therefore combined with daily flow measured at station 16303000 on Punaluʻu Stream to provide a measure of natural flow for Punaluʻu Stream. Potential leeward Oʻahu index stations considered were station 16200000 on North Fork Kaukonahua Stream, station 16240500 on Waiakeakua Stream and station 16229000 on Kalihi Stream. These stations were selected because they were used as index stations for windward Oʻahu sites in a median streamflow study in Hawaiʻi (Fontaine and others, 1992).

Ideally, flows at index stations should reflect entirely natural flow conditions. However, a few of the potential index stations considered for this study were affected to some extent by regulations, diversions, or both (table 14). Because regulations or diversions affecting flows at the potential index stations generally were consistent throughout the base period, the daily mean discharges and low-flow statistics computed for the potential index stations could be used for the analysis at LFPR stations (Ries, 1999).

For cases in which correlation coefficients using the primary index stations were slightly less than 0.80, as for the LFPR station 16294400 on North Fork Waikāne Stream and station 16297000 on Kāwā Stream (table 15), other potential index stations were incorporated in the analysis to increase the confidence in the low-flow estimates. For LFPR station 16294400, the correlation coefficient using the primary index station is 0.78. Index continuous-record station 16229000 on Kalihi Stream, located outside of the study area, was used as a second index station for LFPR station 16294400. For LFPR station 16297000, none of the index stations produced a correlation coefficient greater than 0.80, and therefore all index stations with correlation coefficients greater than 0.74 were used.

Multiple low-flow estimates were available for some of the LFPR and short-term stations that used more than one index station (tables 15 and 16). Estimates obtained from each of the index stations were averaged to obtain a single estimate of the selected duration discharge at the LFPR station. As suggested by Tasker (1975), a weighted average was computed for each of the low-flow estimates by weighting each individual estimate by its variance and averaging the weighted estimates. This procedure results in increased confidence in the final estimates because the variance of the final weighted estimate is less than or equal to the variances of each of the individual estimates (Ries, 1999). Standard errors (in percent) for low-flow estimates also were computed based on the equation developed by Stedinger and Thomas (1985, p.18). A detailed description of the computation procedures modified from Hardison and Moss (1972) was provided by Ries and Friesz (2000).

Low-Flow Duration Discharges in Waiāhole Ditch

A daily time series of total flow diverted by the Waiāhole Ditch from windward Oʻahu was generated to estimate low-flow duration discharges of diverted water. Ditch flow recorded at the North Portal continuous-record station 16287000 beneath the Koʻolau crest (fig. 14) measures (after adjustments described below) the amount of ground water diverted by the Waiāhole Tunnel. Data in digital format for this station were available for the time periods 1951-69 and 1999-2004 (table 11).

Data for the period 1951-69 were not used in this analysis because (1) records for surface water that was pumped into the Waiāhole Ditch System from Waiāhole Stream during this period are not available, (2) occasional flow releases at Gate 31 to Waiāhole Stream also occurred, and (3) data collected during this period do not reflect current ditch-flow conditions following the extension of the Uwao development tunnel in 1964, closure of surface-water intakes during the mid-1980s, and the construction of the Kahana development tunnel bulkhead in 1992.

During the period 1999-2004, ditch flow was heavily regulated, primarily by flow releases at Intake 23 and Gates 30 and 31. ADC measured the flow releases at Intake 23 and Gates 30 and 31 for all or parts of the period, and USGS measured flow at Gate 31 from 2000-2003 (table 11). Although flow releases at Gate 30 to Waianu Stream began in May 1995, data were recorded only since November 2002. In addition, water also was released at Intake 29 (a pipe extended to the stream) and through the McCandless Pipeline to Waianu Stream. The only available measurements made at the Intake 29 release were during the three seepage runs in 1995. The measurements ranged from 0.08 to 0.12 Mgal/d and averaged 0.10 Mgal/d (table 5). Flow released through the McCandless Pipeline has been fairly steady and estimated to be about 0.5 Mgal/d (Hawaiʻi Commission on Water Resource Management, 2001).

Because information on flow releases through Gate 30 is available since November 2002, only flow data at the North Portal continuous-record station for the period 2003-2004 were used to estimate water diverted from the Kahana, Waikāne, and Waiāhole watersheds. The 2003-2004 time series of daily flows at North Portal was reconstructed to include flow releases at Intake 23, Gates 30 and 31, and the McCandless Pipeline. Because the pipe at Intake 29 was destroyed during a May 2002 flood, no flow releases at Intake 29 occurred during the period of analysis. Although the period 2003-2004 is of short duration, daily flow-release data are available to accurately reconstruct flow at North Portal station to reflect total ditch flow for the entire 2-year period. Also, ditch flow during this period is representative of homogeneous hydrologic conditions after the extension of Uwao tunnel, the installation of the Kahana bulkhead, and the closing of major surface-water intakes in Kahana Valley.

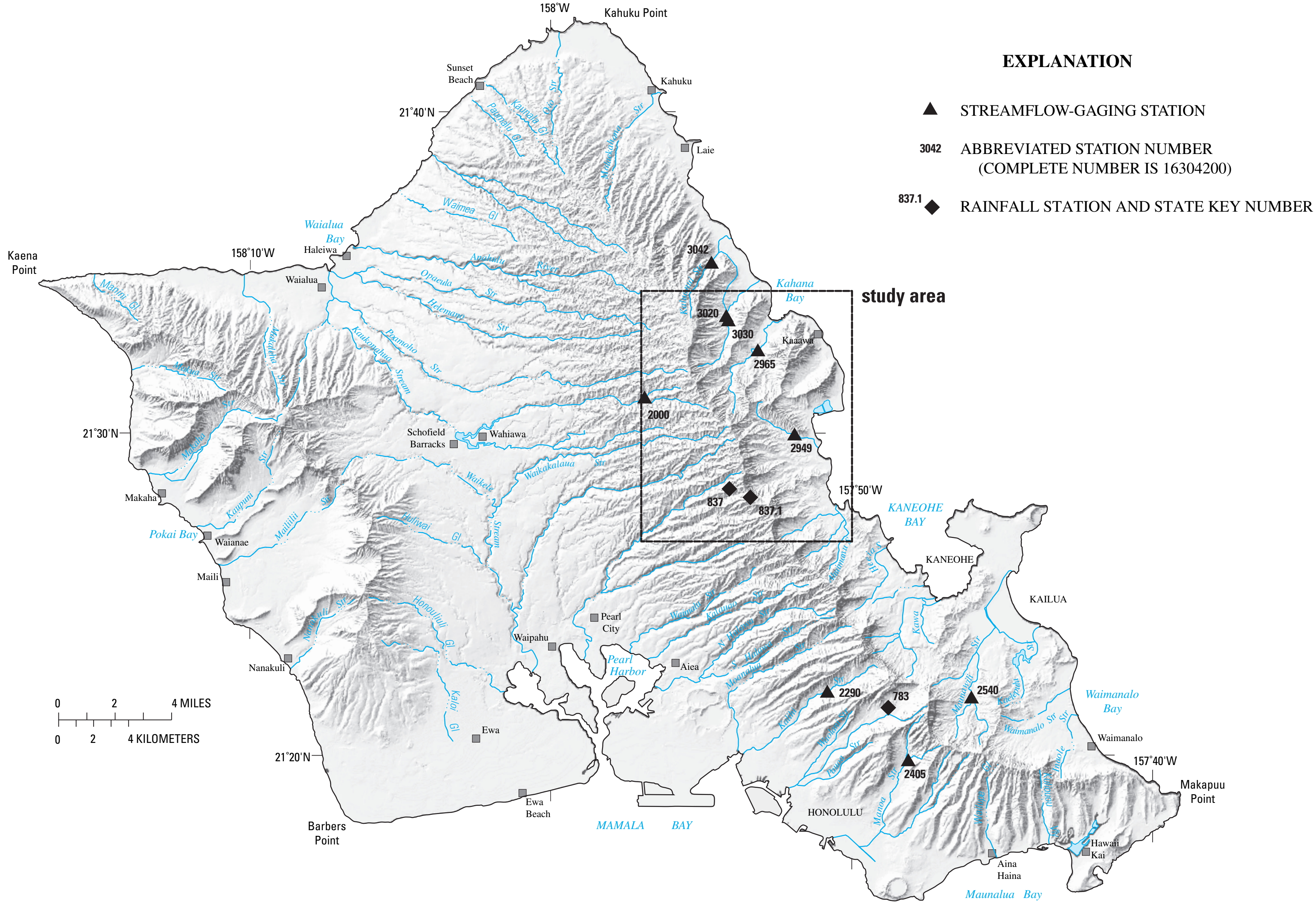


Figure 21. Locations of index streamflow stations and selected rainfall stations on O‘ahu, Hawai‘i.

Table 15. Low-flow statistics, variances, and standard errors adjusted to the base period of 1960-2004 for the low-flow partial-record stations using record-extension methods, windward O‘ahu, Hawai‘i.

[mi^2, square mile; duration discharge is in million gallons per day; variance is in units of base-10 logarithms; standard error is in percent; results shown in **red** represent a fairly significant extension or extrapolation of the data; n.a, not applicable]

Site	Drainage Area (mi^2)	Index station	Number of concurrent data points	Record extension method	Correlation coefficient	Statistic	Flow-duration percentile				
							99	95	90	75	50
Waiāhole Stream											
							Pre-release (Gate 31)				
16290500 Waiāhole Stream at altitude 320 ft	0.92	16291000	10	MOVE.1	0.87	Streamflow	**1.5**	**1.6**	**1.7**	2.0	2.3
		16294900	10	MOVE.1	0.87	Streamflow	**1.7**	**1.8**	**1.9**	2.2	2.5
						Weighted average streamflow	**1.6**	**1.7**	**1.8**	2.1	2.4
						Variance	0.001	0.001	0.001	0.000	0.000
						Standard error	7.0	6.1	5.1	3.4	2.1
Waianu Stream											
							Post-release (Gate 30)				
16292600 Waianu Stream at Gate 30	n.a.	16254000	11	MOVE.1	0.83	Streamflow	2.5	2.6	2.7	2.9	3.2
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	4.2	3.2	2.9	2.0	2.8
							Post-release (Gate 30)				
16292800 Waianu Stream at altitude 330 ft near Waiāhole	0.55	16254000	11	MOVE.1	0.88	Streamflow	2.1	2.3	2.3	2.7	3.0
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	4.6	3.4	3.1	2.1	3.3
							Post-release (Gate 30)				
16292890 Waianu Stream upstream from confluence	0.67	16254000	11	MOVE.1	0.90	Streamflow	2.0	2.2	2.3	2.7	3.4
						Variance	0.001	0.000	0.000	0.000	0.000
						Standard error	6.0	4.5	4.0	2.7	4.3
							Post-ditch				
16292900 Uwao[a] Stream at mouth[b]	0.56	16254000	16	MOVE.1	0.90	Streamflow	0.04	0.06	0.08	0.14	0.32
						Variance	0.009	0.006	0.005	0.002	0.003
						Standard error	22	18	16	11	13
							Post-release (gate 30)				
16293100 Waianu Stream at Waiāhole	1.65	16254000	9	Graphical	0.74	Streamflow	2.7	2.9	3.0	3.3	3.8
						Variance	0.000	0.000	0.000	0.000	0.001
						Standard error	7.1	4.6	3.7	3.0	7.5
							Pre-release (1955-66 and 1995)				
		16229000	13	MOVE.1	0.88	Streamflow	**0.21**	**0.36**	0.53	0.85	1.5
		16294900	13	MOVE.1	0.95	Streamflow	**0.57**	**0.68**	0.79	1.1	1.5
						Weighted average streamflow	**0.53**	**0.63**	0.74	1.0	1.5
						Variance	0.002	0.001	0.001	0.000	0.000
						Standard error	10	8.3	7.0	4.9	3.7

Table 15. Low-flow statistics, variances, and standard errors adjusted to the base period of 1960-2004 for the low-flow partial-record stations using record-extension methods, windward O‘ahu, Hawai‘i—Continued.

Site	Drainage Area (mi²)	Index station	Number of concurrent data points	Record extension method	Correlation coefficient	Statistic	Flow-duration percentile				
							99	95	90	75	50
Waikāne Stream											
							Natural flow				
16294400 North Fork Waikāne Stream[b]	0.58	16229000	21	MOVE.1	0.80	Streamflow	0.25	0.34	0.44	0.58	0.84
		16294900	14	MOVE.1	0.78	Streamflow	0.25	0.31	0.37	0.52	0.78
						Weighted average streamflow[c]	0.24	0.33	0.42	0.56	0.81
						Variance	0.003	0.002	0.001	0.001	0.001
						Standard error	12	9.3	7.4	5.9	6.7
							Post-release (Gate 23)				
16294500 South Fork Waikāne Stream	0.67	16294900	6	Graphical	0.94	Streamflow	**2.2**	**2.5**	2.7	3.2	3.9
		16200000	6	Graphical	0.80	Streamflow	**2.1**	**2.4**	2.6	2.9	3.3
						Weighted average streamflow	**2.2**	**2.5**	2.7	3.2	3.5
						Variance	0.001	0.001	0.000	0.000	0.000
						Standard error	7.4	5.2	3.7	1.8	3.2
							Pre-release (Intake 23)				
		16294900	14	MOVE.1	0.97	Streamflow	0.10	0.14	0.17	0.27	0.43
						Variance	0.002	0.001	0.001	0.000	0.000
						Standard error	9.0	7.3	5.9	3.9	3.9
							Post-ditch				
16294700 Waike‘eke‘e Stream[b]	0.43	16294900	26	MOVE.1	0.84	Streamflow	0.03	0.04	0.06	0.12	0.25
						Variance	0.012	0.008	0.006	0.002	0.002
						Standard error	26	21	17	11	9.2
							Post-release (Intake 23)				
16294800 Waikāne Stream 10 ft upstream from confluence with Waike‘eke‘e Stream	1.57	16294900	8	Graphical	0.94	Streamflow	**2.7**	**3.0**	3.2	4.0	4.9
		16254000	7	Graphical	0.85	Streamflow	**2.9**	**3.2**	3.4	4.0	4.9
						Weighted average streamflow	**2.7**	**3.1**	3.3	4.0	4.9
						Variance	0.001	0.000	0.000	0.000	0.000
						Standard error	6.4	4.8	3.9	2.4	4.0
							Pre-release (Intake 23)				
		16294900	24	MOVE.1	0.92	Streamflow	0.65	0.78	0.90	1.2	1.6
						Variance	0.001	0.001	0.001	0.000	0.000
						Standard error	7.7	6.4	5.3	3.5	2.7
							Post-release (Intake 23)				
16295195 Waikāne Stream at Kamehameha Highway	2.5	16294900	8	Graphical	0.93	Streamflow	2.6	3.0	3.4	4.4	5.9
		16254000	7	Graphical	0.82	Streamflow	2.9	3.4	3.6	4.4	5.8
						Weighted average streamflow	2.7	3.1	3.4	4.4	5.9
						Variance	0.002	0.001	0.001	0.000	0.001
						Standard error	9.2	7.0	5.7	3.5	5.7
							Pre-release (Intake 23)				
		16294900	23	MOVE.1	0.96	Streamflow	0.90	1.1	1.3	1.7	2.5
						Variance	0.001	0.001	0.000	0.000	0.000
						Standard error	6.4	5.3	4.4	2.9	2.3

Table 15. Low-flow statistics, variances, and standard errors adjusted to the base period of 1960-2004 for the low-flow partial-record stations using record-extension methods, windward O‘ahu, Hawai‘i—Continued.

Site	Drainage Area (mi^2)	Index station	Number of concurrent data points	Record extension method	Correlation coefficient	Statistic	Flow-duration percentile 99	95	90	75	50
Kahana Stream											
							Post-bulkhead				
16295995 Kahana Stream at mauka trail crossing[b]	3.18	16303000	9	Graphical	0.89	Streamflow	6.2	7.2	8.2	11	15
						Variance	0.005	0.004	0.002	0.001	0.001
						Standard error	17	14	12	7.0	7.8
							Natural flow				
16297000 Kāwā Stream (East Branch Kahana Str)[b]	2.09	16229000	48	MOVE.1	0.78	Streamflow	0.50	0.71	1.0	1.4	2.1
		16254000	50	MOVE.1	0.74	Streamflow	0.47	0.58	0.71	1.0	1.8
						Weighted average streamflow[c]	0.48	0.68	0.87	1.2	2.0
						Variance	0.002	0.001	0.001	0.001	0.001
						Standard error	9.7	7.6	6.4	5.0	5.0

[a]Uwao was formerly spelled Uwau.

[b]This stream reach is not affected by flow releases.

[c]Low-flow duration estimates are representative of natural flow conditions.

Table 16. Low-flow statistics, variances, and standard errors adjusted to the base period of 1960-2004 for the continuous-record streamflow stations using record-extension methods, windward O‘ahu, Hawai‘i.

[mi², square mile; duration discharge is in million gallons per day; variance is in units of base-10 logarithms; standard error is in percent; n.c., not computed because results represent a fairly significant extension or extrapolation of the data and have high estimation errors; n.a., not applicable]

Site	Drainage Area (mi²)	Index station	Concurrent data period	Record extension method	Correlation coefficient	Statistic	Flow-duration percentile 99	95	90	75	50
Waiāhole Ditch											
							Total ditch flow				
16287000 Waiāhole tunnel at North Portal[a]	n.a.	16303000[b]	2003-04	MOVE.1	0.83	Streamflow	18	19	20	21	24
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	0.85	0.66	0.60	0.50	0.39
Waiāhole Stream											
							Pre-release (Gate 31)				
16291000 Waiāhole Stream at altitude 250 ft[c]	0.99	16303000	1960-68	Graphical	0.99	Streamflow	2.4	2.5	2.7	3.2	3.6
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	1.5	1.2	1.0	0.6	0.7
							Pre-ditch				
16292000 Waiāhole Stream near Waiāhole	1.22	16254000	11/12/12 - 7/13/13	MOVE.1	0.42[d]	Streamflow	11	11	12	13	14
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	2.2	1.9	1.7	1.4	1.2
							Post-release (Gate 31)				
16294100 Waiāhole Stream at Waiāhole	3.76	16303000	2002-04	MOVE.1	0.99	Streamflow	13	14	16	19	22
		16229000	2002-04	MOVE.1	0.99	Streamflow	11	14	16	20	25
		16240500	2002-04	MOVE.1	1.0	Streamflow	14	16	19	23	27
						Weighted average streamflow	13	15	17	20	25
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	0.81	0.70	0.61	0.51	0.47
Waikāne Stream											
							Post-release (Gate 31)				
16294900 Waikāne Stream	2.22	16303000	2003-04	MOVE.1	0.92[d]	Streamflow	2.9	3.2	3.6	4.7	5.9
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	1.4	1.2	1.1	0.97	0.94
							Pre-release (Gate 31)				
		16303000	1961-2002	MOVE.1	0.99	Streamflow	1.0	1.2	1.4	1.9	2.6
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	0.62	0.57	0.52	0.42	0.38

Table 16. Low-flow statistics, variances, and standard errors adjusted to the base period of 1960-2004 for the continuous-record streamflow stations using record-extension methods, windward O‘ahu, Hawai‘i—Continued.

Site	Drainage Area (mi²)	Index station	Concurrent data period	Record extension method	Correlation coefficient	Statistic	Flow-duration percentile 99	95	90	75	50
Kahana Stream											
							Pre-ditch				
16296000 Kahana Stream near Kahana	3.2	16200000	12/16/14 to 5/27/16	MOVE.1	0.68[d]	Streamflow	8.7	12	15	19	24
		16240500	12/16/14 to 5/27/16	MOVE.1	0.75[d]	Streamflow	8.7	11	13	17	21
						Weighted average streamflow	n.c	n.c	n.c	18	23
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	2.8	2.2	1.8	1.4	1.1
							Pre-bulkhead				
16296500 Kahana Stream	3.74	n.a.	1960-2002	n.a.	n.a.	Streamflow	7.8	9.1	9.7	12	15
							Post-bulkhead				
		16229000	2002-2004	Graphical	0.99	Streamflow	9.2	11	12	13	15
		16303000	2002-2004	MOVE.1	0.94[d]	Streamflow	7.4	8.3	9.3	12	16
						Weighted average streamflow	8.2	9.7	11	13	16
						Variance	0.000	0.000	0.000	0.000	0.000
						Standard error	0.90	0.67	0.59	0.64	0.67

[a]Reconstructed to include flow releases at Gates 23, 30, 31, McCandless Pipeline inflow, and 55 percent of flow gained between North Portal and Adit 8 continuous-record stations.

[b]Base-flow component.

[c]To reflect natural flow conditions, records were reconstructed to include upstream pumping and releases (recorded by station 16286000). Because pumping records were not available, an estimated average rate of 1.0 Mgal/d was used (Takasaki and Mink, 1985).

[d]Correlation coefficient computed based on concurrent daily discharges between two gaging stations.

The reconstructed time series was extended (using the record extension technique discussed previously) to estimate total ditch-flow duration statistics during the base period of 1960-2004. The reconstructed time series was best correlated (correlation coefficient = 0.80) with the base-flow component of Punaluʻu Stream (combined records of stations 16302000 and 16303000) (table 16). The base-flow component was estimated using an automated hydrograph separation method developed by Wahl and Wahl (1995). The method divides the daily streamflow record into non-overlapping N-day periods and determines the minimum flow within each N-day window. Parameter values for N (number of days) and f (turning-point test factor) required for application of the method to the Punaluʻu station were 4 days and 0.9, respectively (Oki, 2003).

Ground Water Beyond the Koʻolau Crest Developed by the Waiāhole Ditch System

The reconstructed time series of ditch flow at North Portal also included a portion of the ground water gained beyond the Koʻolau crest to account for flow that was assumed to have discharged naturally to the windward streams. It is commonly thought that erosion of reentrant features at the head of windward Oʻahu valleys has resulted in diversion of ground water from the leeward side of the Koʻolau Range to the windward side. The Russ Smith Corporation (1980) suggested that the trend and strike of dikes in Waiāhole Valley could naturally direct ground water from the leeward side to flow parallel to the dike structures and emerge as springs in Waiāhole Valley. Stearns and Vaksvik (1935, p.28) indicated that the valleys of windward Oʻahu are deeper than leeward valleys; windward Oʻahu valleys captured ground water that naturally would have been tributary to leeward valleys. Takasaki and Mink (1985, p.35) stated that valleys leeward of the topographic crest of the Koʻolau Range have much lower gradients and are not cut deep enough to drain the dike-impounded reservoirs. It is therefore likely that the ground-water divide is leeward of the crest. The boring of the Waiāhole Ditch System development tunnels provided lower outlets for the dike-impounded ground water to be discharged to windward Oʻahu streams. The lowered discharge outlets in the Waiāhole Ditch System development tunnels may have shifted the ground-water divide even further leeward of the crest (Takasaki and others, 1969, p.65). However, data are not available to precisely locate the ground-water divide under natural (undiverted) conditions and to determine the effects of the development tunnels on the ground-water divide. Because of this uncertainty, the amount of ground water intercepted leeward of the Koʻolau crest in the main tunnel and Uwao development tunnel that naturally would have discharged to windward Oʻahu streams also is poorly known.

Using available historical observations and recorded flows in the main tunnel, it is possible to estimate the percentage of ground water intercepted between the Adit 8 station 16287200 (at the South Portal) and the North Portal station 16287000 (beneath the topographic crest of the Koʻolau Range) that naturally would have discharged to windward Oʻahu. According to flow records collected by the Waiāhole Water Company, the average ground-water gain leeward of the Koʻolau crest between the two stations during the period 1916-32 was about 5.8 Mgal/d (Stearns and Vaksvik, 1935, p. 403). The average ground-water gain in the main tunnel windward of the Koʻolau crest was estimated to be 1.5 Mgal/d during dry weather and 3.0 Mgal/d during wet weather (Stearns and Vaksvik, 1935, p. 403). An average ground-water gain of 2.3 Mgal/d was used in this study. Ground water gained in the entire length of Waiāhole main tunnel was about 8.0 Mgal/d (Stearns and Vaksvik, 1935). Springs that flowed at a rate of 5.7 Mgal/d in Waiāhole Valley went dry following construction of the main tunnel (Stearns and Vaksvik, 1935). Thus, 3.4 Mgal/d (5.7-2.3) of the flow at the springs was derived from the leeward part of the main tunnel. It is therefore estimated that about 59 percent (100x(5.7-2.3)/5.8) of ground water gained between the Adit 8 and North Portal continuous-record stations previously discharged naturally at the Waiāhole springs. A similar calculation using flow measurements (figure 16 in Takasaki and Mink, 1985) made at various locations along the main tunnel also indicates that about 55 percent of ground water gained between the Adit 8 and North Portal continuous-record stations previously discharged at the Waiāhole springs. Takasaki and others (1969, p.74) estimated that half of the ground water gained between the south portal and the crest previously flowed to windward Oʻahu. An average of these three estimates (55 percent) will be used in this study to apportion ground-water gains in the main tunnel leeward of the Koʻolau crest to the windward streams.

In addition to the main tunnel, Uwao development tunnel also was bored beyond the Koʻolau crest. The original Uwao tunnel was driven to the crest and was subsequently extended about 228 ft beyond the Koʻolau crest in 1963-64. The actual amount of water intercepted from the extension that naturally would have discharged to the windward side is uncertain. According to flow measurements in the main Waiāhole tunnel (figure 16 in Takasaki and Mink, 1985), ground water gained well beyond 500 ft leeward of the Koʻolau crest is needed to fully account for flow (5.7 Mgal/d) that previously discharged at the Waiāhole springs. This could imply that the natural ground-water divide in the Uwao tunnel area is possibly well over 500 ft leeward of the Koʻolau crest. Assuming similar conditions near the Uwao development tunnel, all the ground water intercepted in the 228-ft Uwao tunnel extension may have naturally discharged to the windward side. This also is consistent with the assertion by Takasaki and Mink (1985, p. 29) that "the final equilibrium of base flow of the tunnel system is not appreciably different from the sum of the base flows of streams on the windward side before the tunnels were constructed." The time series of North Portal daily ditch flows for 2003-04 was adjusted to include 55 percent of the main tunnel gain between the North Portal and Adit 8 continuous-record stations and also includes gain from the Uwao tunnel extension. The reconstructed time series of ditch flow at North Portal is summarized in appendix 1.

Distribution of Waiāhole Ditch Flows Among Watersheds

At least two methods are available to estimate the relative distribution of water being diverted by Waiāhole Ditch as natural streamflow in Waiāhole, Waikāne, and Kahana Streams at the altitude of the connecting tunnel of the Waiāhole Ditch System: (1) using historical (pre-ditch) Wall measurements (table 13) made at 750 ft altitude in each of the upper tributaries from Waiāhole to Kahana Streams and (2) using measured changes in flow in the Waiāhole Ditch between basin topographic divides obtained during tunnel seepage runs (table 2). The Wall measurements provide the best estimate because the measurements do not require the assumption that the ground-water divides are the same as the topographic divides. Use of a distribution based on tunnel seepage-runs assumes that ground-water divides coincide with topographic divides and is used only as a comparative estimate in this report.

Wall Measurements

On the basis of the Wall measurements (reduced to reflect 2.1 Mgal/d of Kahana surface water not currently diverted by the Waiāhole Ditch), Waiāhole, Waikāne, and Kahana Streams contributed, respectively, 61.9, 12.3, and 25.8 percent of the total flow diverted by Waiāhole Ditch at an altitude of 750 ft (table 17). Table 13 summarizes a further breakdown of these percentages among subwatersheds in Kahana, Waikāne, and Waiāhole Streams. A set of weir measurements on August 10-12, 1911, during a period of clear weather when normal flow of springs was observed indicated a similar distribution of flow (Lippencott, 1911). This indicates that the Wall measurements can reasonably be assumed to reflect natural base-flow conditions at 750 ft altitude on the three streams during the pre-ditch period.

It should be noted that the distribution of flow computed using the Wall measurements represents base-flow conditions over a short, two-month period during June and July 1911. No long-term streamflow data with concurrent record is available to evaluate hydrologic conditions when the Wall measurements were made. Because of the lack of data, the distribution of flows from the Wall measurements is assumed to apply over the range of flow-duration percentiles ranging from 50 to 99 percent. However, the distribution of flows diverted by the Waiāhole Ditch System must reflect flow in Kahana Stream that is currently not diverted. The average flow in Kahana Stream that is not diverted at the level of the ditch is 2.1 Mgal/d based on data collected from 1989-1993 (Hawai‘i Commission on Water Resource Management, 2001, table 1 on p. 143). The Wall measurement of 7.5 Mgal/d in Kahana Stream was therefore reduced by 2.1 Mgal/d to account for this flow, and the distribution of diverted flow from each watershed also is adjusted accordingly (table 17).

Ditch Tunnel Seepage Runs

On the basis of ditch seepage runs in 2002-2003 (table 2), adjusted to include 55 percent of the gain between North Portal and Adit 8, Waiāhole, Waikāne, and Kahana Streams contributed, respectively, 70.7, 22.5, and 6.8 percent of the total flow diverted by Waiāhole Ditch at an altitude of 750 ft (table 17). Within the connecting tunnel, discharge measurements were made beneath the topographic divides separating adjacent watersheds. These measurements made it possible to determine the ground-water contributions to the ditch system, after accounting for surface-water inflows and diversions, within each watershed (fig. 6). Flow-duration percentiles associated with daily-mean discharges at three nearby continuous-record stations (16287000 at North Portal, 16296500 on Kahana Stream, and 16303000 on Punalu‘u Stream; see fig. 14) on the days of the seepage runs provide an estimate of

Table 17. Distribution percentages of total Waiāhole Ditch flow contributed by Waiāhole, Waikāne, and Kahana Streams, windward O‘ahu, Hawai‘i.

Stream	Relative distributions of ditch flow using different methods, in percent			
	Seepage runs	Seepage runs (adjusted)[a]	Wall measurements	Wall measurements (adjusted)[b]
Waiāhole	67	70.7	56.3	61.9
Waikāne	25.3	22.5	11.2	12.3
Kahana	7.7	6.8	32.5	25.8
Total	100	100	100	100

[a]Included Uwao extension tunnel flow and 55 percent of gain between North Portal and Adit 8 gaging stations; Uwao was formerly spelled Uwau.

[b]Reduced by 2.1 Mgal/d to account for Kahana surface water not diverted by Waiāhole Ditch and selected as the relative distribution of streamflow in the natural flow computations.

ditch-flow conditions on these days (table 18). The February 2002 seepage run was made under near-median flow conditions, when discharges recorded at the three nearby stations had duration percentiles ranging from 56 to 63 percent. The August 2003 seepage run was conducted at lower flow conditions, when flow at nearby stations had duration percentiles ranging from 83 to 91 percent. Although flow conditions during the two seepage runs were different, the relative distributions of flow are reasonably close. It is therefore reasonable to assume that similar distributions of ditch flow would exist over the range of flow durations from 56 to 91 percent and that the arithmetic average of the distributions based on the two seepage runs is representative over this range of flow conditions.

Addition of Flow-Duration Discharges

Low-flow duration discharges based on the reconstructed time series of total ditch flow at North Portal are apportioned to each stream using the distribution percentages developed in the previous section (table 13). These apportioned low flows represent an estimate of the amount of dike-impounded ground water that would have naturally discharged to each stream at the level of the ditch system. To estimate natural low-flow duration discharges at downstream continuous-record and LFPR stations, the appropriate apportioned low-flow duration discharges from the ditch system are added to the corresponding low-flow duration discharges for pre-release conditions at the stations. Pre-release low-flow estimates are used because apportioned ditch flows reflect pre-release conditions.

However, a limitation associated with adding flow-duration discharges directly is that the combination of individual flow statistics does not always exactly equal the corresponding flow statistic computed from the combined record of daily flows (Fontaine, 2003). In some cases, daily flows are available from two continuous-record stations, one monitoring flow diverted from a stream and the other monitoring streamflow downstream of the diversion. Flow-duration discharges for the natural, undiverted flow in the stream can be computed from the combined record of the two stations. Because a continuous record of daily flows is not available at LFPR stations, flow-duration discharges cannot be computed from the combined record of daily flows from two stations if one of the stations is a LFPR station. In these cases, flow-duration discharges are sometimes added. Gingerich (2005) estimated possible errors associated with adding flow-duration discharges using data from two stations in northeast Maui, where flow is diverted from streams. Flow-duration discharges computed by adding individual flow-duration discharge were within about 10 percent of the corresponding flow-duration discharges computed using combined daily flows from the two stations.

To evaluate if adding computed flow statistics directly is appropriate for this study, undiverted low-flow duration discharges in 2003-2004 for two stations (16269500 on Kahana Stream and 16294900 on Waikāne Stream) downstream of the Waiāhole Ditch diversion were generated in two ways. First, low-flow duration discharges representing undiverted conditions at each station were computed based on the combined record of daily flows from the station and the appropriate

Table 18. Recorded discharge and associated flow-duration percentiles for selected continuous-record streamflow stations in windward O‘ahu, Hawai‘i, February 2002 and August 2003.

[Mgal/d, million gallons per day]

Date	Punalu‘u Stream Station 16303000[a]		North Portal Station 16287000		Kahana Stream Station 16296500	
	Discharge[b] (Mgal/d)	(1960-2004) Flow-duration percentile	Discharge[c] (Mgal/d)	(1960-2004) Flow-duration percentile[d]	Discharge[b] (Mgal/d)	(1960-2004) Flow-duration percentile
2/26/2002	12	58			14	58
2/27/2002	12	58	20	56	13	63
2/28/2002	12	58			13	63
8/19/2003	9.1	85			10	90
8/20/2003	8.4	91	18	83	10	90
8/21/2003	8.4	91			10	90

[a]Combined records with station 16302000 at Punalu‘u Ditch to reflect natural streamflow conditions.

[b]Daily mean discharge.

[c]Discharge measurement adjusted to include measured flow releases at Gates 23, 30, and 31.

[d]Computed using daily time series reconstructed to include flow releases at Gates 23, 30, and 31.

daily ditch flows apportioned to the watershed. Daily ditch flows apportioned to a particular watershed were generated by multiplying the daily total ditch flows by the appropriate distribution percentage (table 17). Second, low-flow duration discharges were computed by combining the statistics from a station and the statistics based on apportioned ditch flows (table 19). The results of the two methods compare favorably, with a maximum relative error of 13 percent and average errors of 5 percent for Waikāne Stream and 2 percent for Kahana Stream (table 19). Natural flow statistics for stations on gaining streams downstream of the Waiāhole Ditch System can be estimated reasonably well by adding flow statistics from two stations.

Estimates of Low-Flow Duration Discharges for Diverted and Natural Flow Conditions

Diverted Flow Conditions

Major flow releases to the Waiāhole, Waianu, and Waikāne Streams from the Waiāhole Ditch System started between December 1994 and October 2002 in response to court rulings and have significantly changed the diverted-flow conditions in these streams. Streamflow in Kahana Stream is not affected by flow releases from the Waiāhole Ditch System. For Waiāhole, Waianu, and Waikāne Streams, diverted-flow conditions can be divided into pre-release and post-release periods. Log-log plots of the concurrent discharges between the LFPR and index stations were used to identify changes in low-flow conditions at the LFPR stations along these streams. Pre-release and post-release low-flow estimates representative of base period conditions were computed using record-extension methods discussed in the previous section for the data collection stations where a sufficient number of low-flow measurements are available (tables 15 and 16).

Six to eight low-flow measurements were made at the five LFPR stations on Waikāne Stream after the beginning of the flow release on October 11, 2002. Earlier discharge measurements at the LFPR stations provided information that was used to determine pre-release low-flow characteristics. The change in flow conditions associated with flow releases is clearly illustrated by two different groupings of the data points, as shown in the log-log plot of concurrent flows at the LFPR station 16294500 on South Fork Waikāne Stream and index station 16254000 on Makawao Stream (fig. 22). One group of data points describes the relation associated with post-release flow conditions and the second group describes the relation associated with pre-release flow conditions. Assuming flow conditions at the index station remain constant

Table 19. Comparison of flow statistics computed for stream sites where natural flows are estimated, using data from multiple time series of daily flow, windward O‘ahu, Hawai‘i.

[All flows are in million gallons per day; relative error is (column 4 - column 5)/column 5 x 100]

Flow-duration percentile	Downstream gaging station	Upstream ditch flow time series	Sum of upstream and downstream flow statistics	Flow statistics based on combined upstream and downstream daily flows	Relative error, in percent
16296500 Kahana Stream near Kahana					
99	8.6	4.6	13.2	13.7	-4
95	9.8	4.9	14.7	15.3	-3
90	10.4	5.1	15.5	15.9	-2
75	11.8	5.5	17.3	17.3	0
50	15.6	6.1	21.7	22.2	-2
				average	-2
16294900 Waikāne Stream at altitude 75 ft at Waikāne					
99	0.4	2.2	2.6	2.9	-13
95	0.8	2.3	3.1	3.2	-4
90	0.9	2.5	3.4	3.4	-2
75	1.4	2.7	4.0	3.9	3
50	2.7	2.9	5.6	6.1	-7
				average	-5

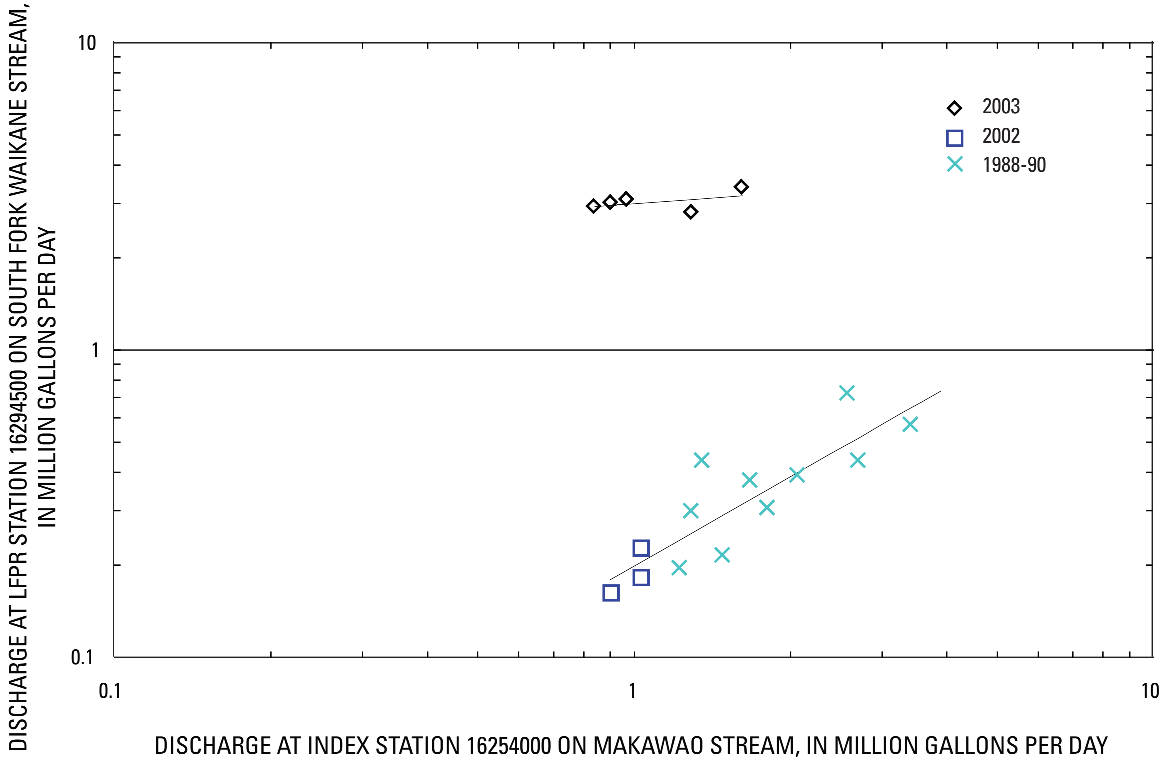


Figure 22. Graphical relation between flows at index station on Makawao Stream and low-flow partial-record (LFPR) streamflow station on Waikāne Stream, O‘ahu, Hawai‘i.

through time, a change in the relation between the concurrent discharges measured at the two stations is most likely due to flow releases that significantly increased low flows in Waikāne Stream. At LFPR stations where low flow was significantly affected by flow releases, statistical relations associated with the post- and pre-release flow conditions were developed. At LFPR stations where base flow was unaffected by the flow releases, only one grouping of data points was evident (see station 16294400 on North Fork Waikāne Stream in figure 16).

Of the five available LFPR stations on Waianu and Uwao Stream, only stations 16292900 and 16293100 had sufficient low-flow measurements, made before the start of flow releases (May 1995), available to estimate pre-release low-flow statistics. However, conflicting trends are evident in the log-log plot of concurrent discharges between the LFPR station 16293100 and index station 16229000 on Kalihi Stream (fig. 23). More than one relation could be drawn from data collected during pre-release periods. For a particular flow at the index station, concurrent flows measured during 1988-90 were consistently higher than flows measured during the other two pre-release periods (1959-66 and 1995). These two relations represent different low-flow conditions, possibly associated with differences in water diversions or manipulations upstream of the LFPR station. In addition to flow releases through Gate 30, upstream diversions (for example, the McCandless diversion) or other water manipulations also may affect streamflow. The relation associated with discharges measured in 1995 and 1959-66 was selected to estimate pre-release low-flow characteristics because this relation represents longer-term pre-release flow conditions in the stream extending over two different periods. This relation also reflects more current flow conditions, which include the 1995 pre-release discharge measurements.

Streamflow in Kahana Stream is not affected by flow releases from the Waiāhole Ditch System but the close-off of the surface-water intakes during the mid-1980s and the construction of a bulkhead in Kahana development tunnel in 1992 may have gradually increased flow in the lower part of Kahana Stream. The installation of the bulkhead was an attempt to restore ground-water storage in the dike compartments. Installation of the bulkhead reduced flow from the Kahana development tunnel into Waiāhole Ditch by about 1.5 Mgal/d. According to the latest data, water pressure behind the bulkhead has stabilized, which indicates that ground-water outflow from the dike compartments behind the bulkhead seems to have stabilized (Edwin Sakoda, CWRM, written commun., 2005). It is assumed that the majority of the outflow discharges downgradient to Kahana Stream, but the exact effects of the bulkhead

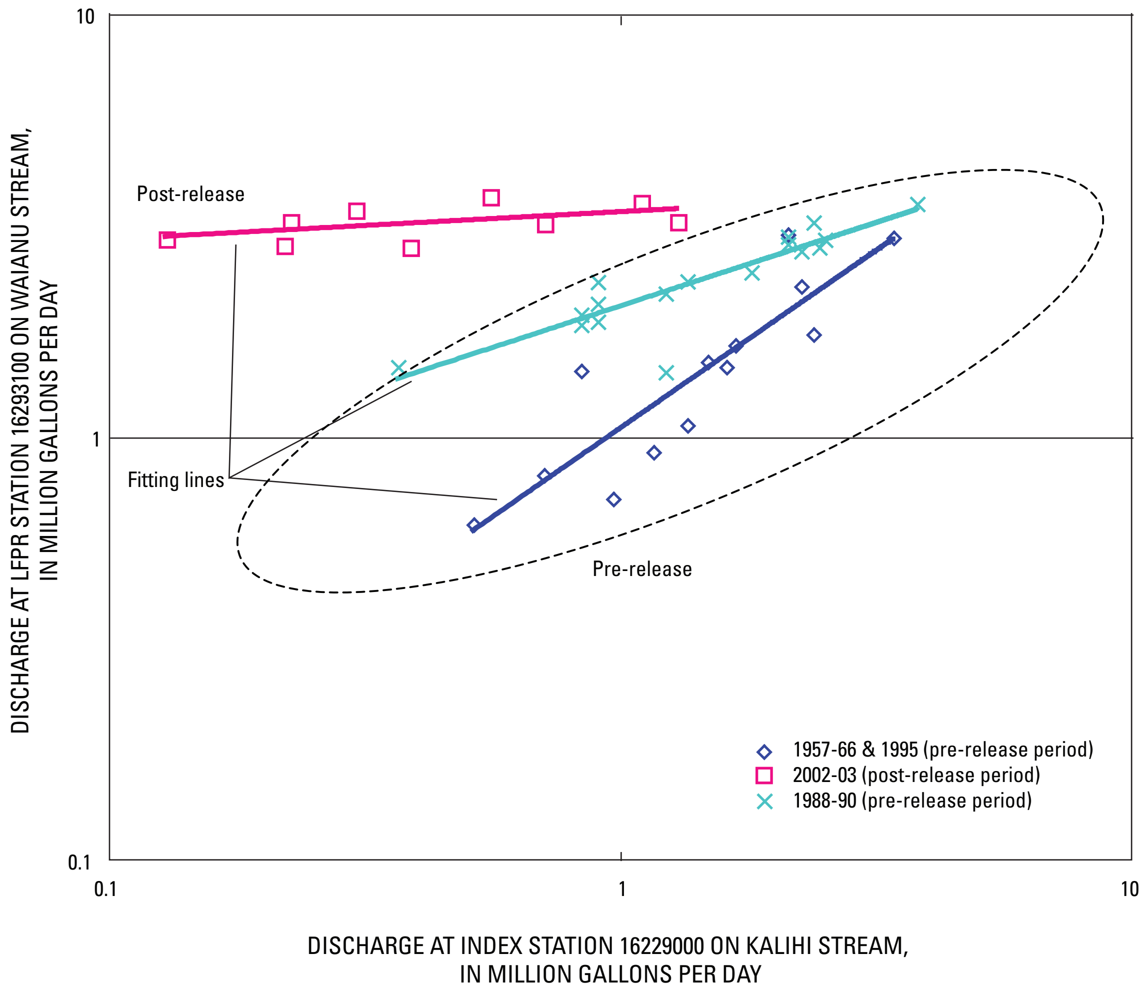


Figure 23. Graphical relations between flows at index station on Kalihi Stream and low-flow partial-record (LFPR) streamflow station on Waianu Stream, Oʻahu, Hawaiʻi.

on low flows in Kahana Stream are uncertain. Because the pressure behind the bulkhead probably increased gradually, the increase in outflow from the dike compartments also probably increased gradually.

A log-log plot of the concurrent discharges between the LFPR station 16295995 on Kahana Stream and index station 16229000 on Kalihi Stream was used to identify changes in low-flow conditions in Kahana Stream (fig. 24). The change in low-flow conditions is illustrated by three different groupings of the data points. The 1960-1984 data points describe the relation associated with pre-bulkhead flow conditions before the close-off of surface water intakes, the 1985-1990 data points associate with pre-bulkhead flow conditions after the close-off of surface water intakes, and the 2002-2003 data points are used to estimate low-flow statistics representative of post-bulkhead flow conditions. Because data are not available to determine exactly when the pressure behind the bulkhead reached the approximate steady state, it will be assumed that the use of 2002 to 2004 data for computing current low-flow duration statistics at station 16296500 on Kahana Stream captures the effects of the bulkhead on low flows in Kahana Stream (table 16).

Natural Flow Conditions

The Waiāhole Ditch System intercepts dike-impounded ground water that would otherwise contribute to base flows of Waiāhole, Waikāne, and Kahana Streams. Low flows measured at the downstream stations in the diverted streams are measures of ground water gained downstream of the Waiāhole Ditch diversions. Natural low-flow duration discharges at the data collection stations were estimated by combining ditch and stream low-flow duration discharges. Natural low-flow estimates are limited to locations where pre-release low-flow estimates have been computed. Estimates of pre-release low-flow statistics could not be made at a number of LFPR stations. This is primarily attributed to the lack of pre-release

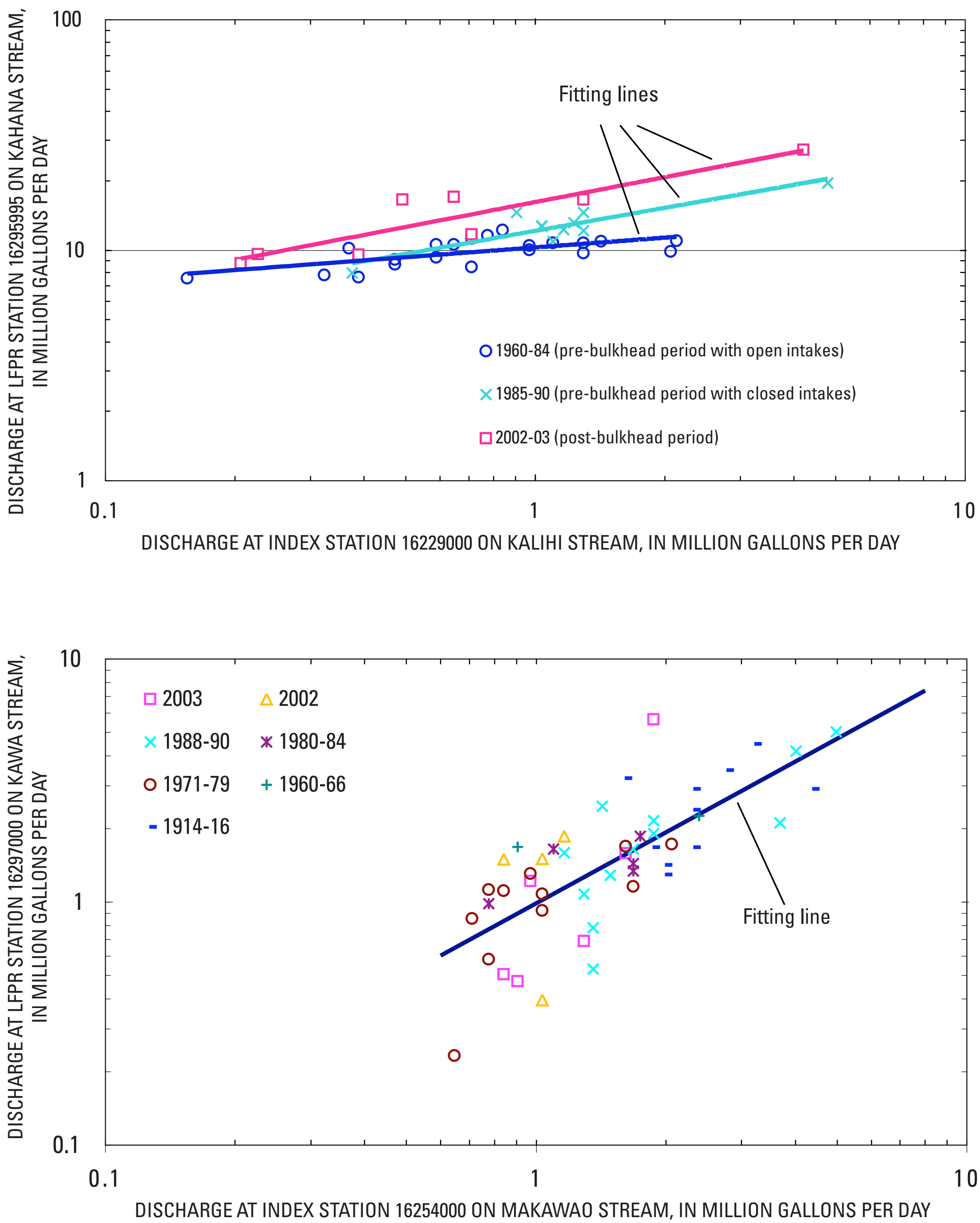


Figure 24. Graphical relations between flows at index stations on Kalihi and Makawao Streams and low-flow partial-record (LFPR) streamflow stations on Kahana and Kāwā Streams, Oʻahu, Hawaiʻi.

low-flow measurements available at those stations, which are mainly on Waianu Stream (table 15). Natural low-flow duration discharges also were estimated at selected locations where pre-ditch stream measurements were available. Comparisons of natural low-flow duration discharge estimates based on addition of ditch and stream data and estimates based on pre-ditch stream flow measurements were made.

Estimates Based on Addition of Ditch and Stream Data

Natural (undiverted) low-flow duration discharges for 50 to 99 percentiles were estimated for two stations on Waiāhole Stream, one on Waianu Stream and one on its tributary Uwao Stream, five on Waikāne Stream and one on its tributary Waikeʻekeʻe Stream, and two on Kahana Stream and one on its tributary Kāwā Stream (tables 20-22). To illustrate the computations, the apportioned Q_{50} ditch flow to station 16294700 in Waikeʻekeʻe Stream (Waikāne watershed) is computed by multiplying the Q_{50} ditch flow of 24 Mgal/d (table 16) by the distribution percentage of 4.4 percent (table 13) for Waikeʻekeʻe Stream. Then, the apportioned ditch flow of 1.1 Mgal/d (24 Mgal/d x 4.4 percent) is added to the low-flow Q_{50} estimate of 0.25 Mgal/d (table 15) at station 16294700 to estimate 50th-percentile natural flow-duration discharge of 1.3 Mgal/d at station 16294700 (altitude 90 ft). For Waiāhole Stream, natural Q_{50} (median) flows at altitudes of 320 and 250 ft were estimated to be 12 and 13 Mgal/d, respectively. For Waianu Stream and its tributary Uwao Stream, natural Q_{50} flows at altitudes of 200 and 75 ft were estimated to be 1.0 and 7.0 Mgal/d, respectively. For Waikāne Stream and its tributary Waikeʻekeʻe Stream, natural Q_{50} flows between altitudes of 220 and 10 ft range from 0.81 to 5.5 Mgal/d. Natural Q_{50} flows for Kahana Stream at altitudes of 80 and 30 ft were estimated to be 21 and 22 Mgal/d, respectively.

Low-flow duration discharge estimates under post-ditch conditions for North Fork Waikāne and Kāwā Streams are also representative of natural (undiverted) flow conditions. Natural Q_{50} flow for Kāwā Stream at an altitude of 30 ft is 2.0 Mgal/d, and natural Q_{50} flow for North Fork Waikāne Stream at an altitude of 220 ft is 0.81 Mgal/d. North Fork Waikāne and Kāwā Streams are tributaries of the diverted streams, and both originate below tunnel level and receive negligible groundwater discharge from upper dike compartments. Streamflow in these two reaches is not affected by flow releases from Waiāhole Ditch and not significantly affected by Waiāhole Ditch diversions. A log-log plot of concurrent discharges between the LFPR station 16297000 on Kāwā Stream and the index station 16254000 on Makawao Stream indicates that low flows in Kāwā Stream were not likely to be affected by the construction of the Waiāhole Ditch System (fig. 24). A single relation was developed for concurrent discharges covering a time period from 1914 to 2003 that spanned periods before and after the completion of Waiāhole Ditch.

In addition, the unit-area duration discharges (adjusted to base period) are similar and mostly under one for continuous-record station 16295300 on Hakipuʻu Stream and both LFPR station 16297000 on Kāwā Stream and station 16294400 on North Fork Waikāne Stream (table 23) which support the assumption that low-flow estimates under post-ditch conditions for these stream reaches are representative of natural (undiverted) flow conditions. Streamflow in Hakipuʻu Stream is assumed to be representative of natural streamflow for streams originating in the marginal dike zone of windward Oʻahu. Construction and operation of station 16295300 on Hakipuʻu Stream was initiated in 2002. This station provides streamflow data for a windward Oʻahu stream in the study area that is not diverted into the Waiāhole Ditch System. Contrasting to streams that drain upper dike compartments, unit-area duration discharges for station 16296500 on Kahana Stream are much greater than one (table 23).

Estimates Based on Pre-ditch Data

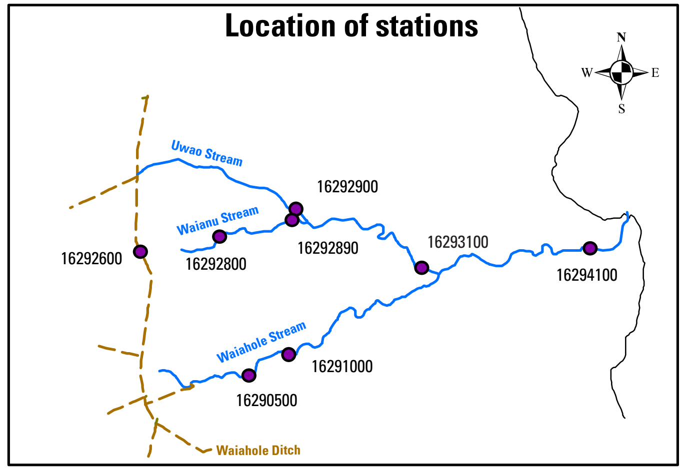
The limited streamflow data collected before ditch construction cannot be used directly to estimate natural low flows for the common base period because of temporal differences in climatic and hydrologic conditions. For example, the Q_{90} flow during an extremely dry year could be much lower than Q_{90} flow during a longer period like the base period used in this study. It is therefore critical to adjust the available pre-ditch flow record to represent the base period so that estimates of natural flows can be compared to other flow duration statistics computed for this same base period.

The only continuous records of natural streamflows before the construction of Waiāhole Ditch for the Waiāhole and Kahana Streams were collected at stations 16292000 and 16296000. These pre-ditch flow data were adjusted to the base period of 1960–2004 by using record-extension techniques described in a previous section (table 16). For station 16292000 on Waiāhole Stream, selection of an index station was limited to Makawao Stream station 16254000, the only active long-term streamflow station on the windward side of the island that has concurrent data. Concurrent pre-ditch flows for record extension are available on Waiāhole and Makawao Streams from November 12, 1912, to July 31, 1913. For station 16296000 on Kahana Stream, there are uncertainties associated with the decline of flow in the later part of 1914 (fig. 25). The 90th-percentile streamflow during 1914 was substantially higher than Q_{90} flow during subsequent years, and rainfall during 1914 was not significantly higher than during subsequent years (fig. 26). There is no written record of any event that was associated with this significant reduction in flow near the end of 1914. Flows recorded during 1914 therefore were not considered natural low flows and only concurrent records with index stations between December 16, 1914, and May 27, 1916, were used in the record extension analysis.

Although correlation coefficients computed for the logarithms of the selected duration discharges from each pre-ditch

Table 20. Estimates of natural, pre-release, and post-release low-flow duration discharges for continuous-record and low-flow partial-record (LFPR) streamflow stations in Waianu and Waiāhole Streams, windward O‘ahu, Hawai‘i.

[Mgal/d, million gallons per day; --, not available; n.a., not applicable; estimates shown in **red** represent significant extension or extrapolation of the data and therefore have higher estimation errors]



Station	Station altitude (feet)	Duration Percentile	Estimated natural flow at station (Mgal/d)	Estimated pre-release flow at station (Mgal/d)	Estimated post-release flow at station (Mgal/d)
Waianu Stream					
16292600	820	99	--	--	2.5
		95	--	--	2.6
		90	--	--	2.7
		75	--	--	2.9
		50	--	--	3.2
16292800	380	99	--	--	2.1
		95	--	--	2.3
		90	--	--	2.3
		75	--	--	2.7
		50	--	--	3.0
16292890	200	99	--	--	2.0
		95	--	--	2.2
		90	--	--	2.3
		75	--	--	2.7
		50	--	--	3.4
16292900[a]	200	99	0.57	0.04	n.a
		95	0.64	0.06	n.a
		90	0.67	0.08	n.a
		75	0.75	0.14	n.a
		50	1.0	0.32	n.a
16293100	75	99	**4.6**	**0.53**	2.7
		95	**5.1**	**0.63**	2.9
		90	5.4	0.74	3.0
		75	5.9	1.0	3.3
		50	7.0	1.5	3.8
Waiāhole Stream					
16290500	320	99	**8.4**	**1.6**	--
		95	**9.3**	**1.7**	--
		90	**9.6**	**1.8**	--
		75	10	2.1	--
		50	12	2.4	--
16291000	250	99	9.2	2.4	--
		95	10	2.5	--
		90	11	2.7	--
		75	12	3.2	--
		50	13	3.6	--
16294100	20	99	--	--	13
		95	--	--	15
		90	--	--	17
		75	--	--	20
		50	--	--	25

[a]Stream reach is not affected by flow releases

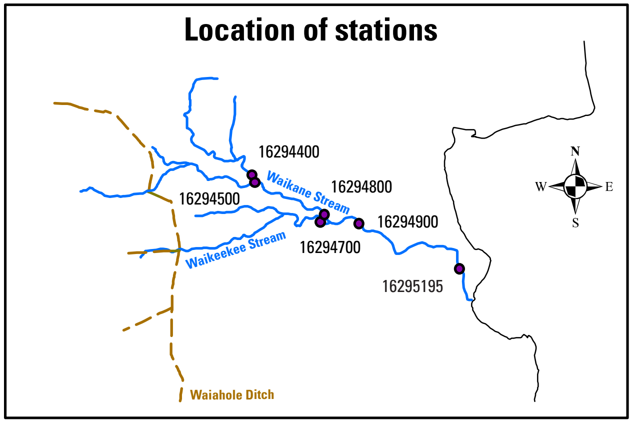


Table 21. Estimates of natural, pre-release, and post-release low-flow duration discharges for continuous-record and low-flow partial-record (LFPR) streamflow stations in Waikāne Stream, windward Oʻahu, Hawaiʻi.

[Mgal/d, million gallons per day; --, not available; n.a., not applicable; estimates shown in **red** represent significant extension or extrapolation of the data and therefore have higher estimation errors]

Station	Station altitude (feet)	Duration Percentile	Estimated natural flow at station (Mgal/d)	Estimated pre-release flow at station (Mgal/d)	Estimated post-release flow at station (Mgal/d)
Waikāne Stream					
16294400[a]	220	99	0.24	--	--
		95	0.33	--	--
		90	0.42	--	--
		75	0.56	--	--
		50	0.81	--	--
16294500	220	99	1.5	0.10	**2.2**
		95	1.7	0.14	**2.5**
		90	1.8	0.17	2.7
		75	2.0	0.27	3.2
		50	2.3	0.43	3.5
16294700[b]	90	99	0.80	--	0.03
		95	0.90	--	0.04
		90	0.94	--	0.06
		75	1.1	--	0.12
		50	1.3	--	0.25
16294800	90	99	2.0	0.65	**2.7**
		95	2.3	0.78	**3.1**
		90	2.5	0.90	3.3
		75	2.8	1.2	4.0
		50	3.5	1.6	4.9
16294900	75	99	3.2	1.0	2.9
		95	3.7	1.2	3.2
		90	3.9	1.4	3.6
		75	4.5	1.9	4.7
		50	5.5	2.6	5.9
16295195	10	99	3.1	0.90	2.7
		95	3.5	1.1	3.1
		90	3.8	1.3	3.4
		75	4.4	1.7	4.4
		50	5.5	2.5	5.9

[a]Stream reach is not affected by the Waiāhole Ditch System diversion

[b]Stream reach is not affected by flow releases

Table 22. Estimates of natural and diverted low-flow duration discharges for continuous-record and low-flow partial-record (LFPR) streamflow stations in Kahana Stream, windward O‘ahu, Hawai‘i.

[Mgal/d, million gallons per day; --, not available; n.a., not applicable; estimates shown in **red** represent significant extension or extrapolation of the data and therefore have higher estimation errors]

Station	Station altitude (feet)	Duration Percentile	Estimated natural flow at station (Mgal/d)	Estimated diverted flow at station (Mgal/d)
Kahana Stream				
16295995[a]	80	99	**11**	**6.2**
		95	**12**	**7.2**
		90	13	8.2
		75	17	11
		50	21	15
16296500[a]	30	99	13	8.2
		95	15	9.7
		90	16	11
		75	18	13
		50	22	16
16297000[b]	30	99	0.48	n.a.
		95	0.68	n.a.
		90	0.87	n.a.
		75	1.2	n.a.
		50	2.0	n.a.

[a]Stream reach is not affected by flow releases

[b]Stream reach is not affected by the Waiāhole Ditch System diversion

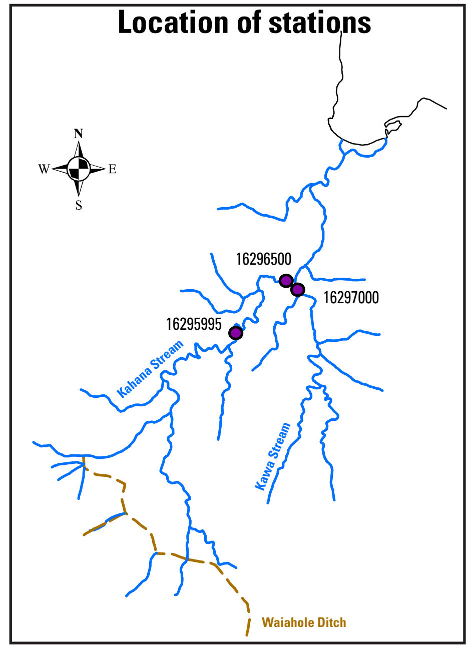


Table 23. Unit-area duration discharges representative of natural streamflow originating in the marginal dike zone of windward O‘ahu, Hawai‘i.

[mi², square mile; duration discharge is in million gallons per day; unit-area duration discharge = duration discharge / drainage area]

USGS Station	Stream	Drainage area (mi²)	Adjusted duration discharges to base period (1960-2004) at selected duration percentiles					Unit-area duration discharges at selected duration percentiles				
			99	95	90	75	50	99	95	90	75	50
16297000	Kāwā	2.09	0.48	0.68	0.87	1.24	1.95	0.23	0.33	0.42	0.59	0.93
16294400	North Fork Waikāne	0.58	0.24	0.33	0.42	0.56	0.81	0.42	0.57	0.72	0.96	1.40
16295300	Hakipu‘u	0.85	0.22	0.26	0.30	0.44	0.60	0.26	0.30	0.35	0.52	0.71
16296500	Kahana Stream[a]	3.74	13	15	16	18	22	3.48	4.01	4.28	4.81	5.88

[a] Kahana Stream data are representative of natural streamflow originating in the upper dike zone

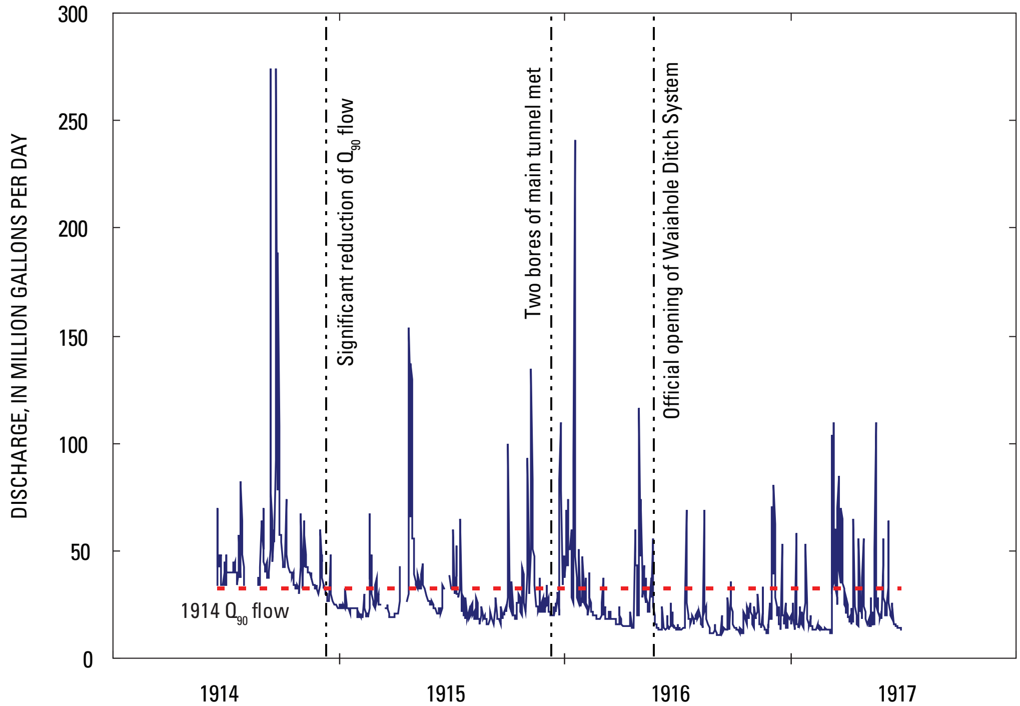


Figure 25. Daily discharge at continuous-record streamflow station 16296000, Kahana Stream, windward O‘ahu, Hawai‘i, June 19, 1914, to June 30, 1917. The 1914 Q_{90} flow is the flow that was equaled or exceeded 90 percent of the time during 1914.

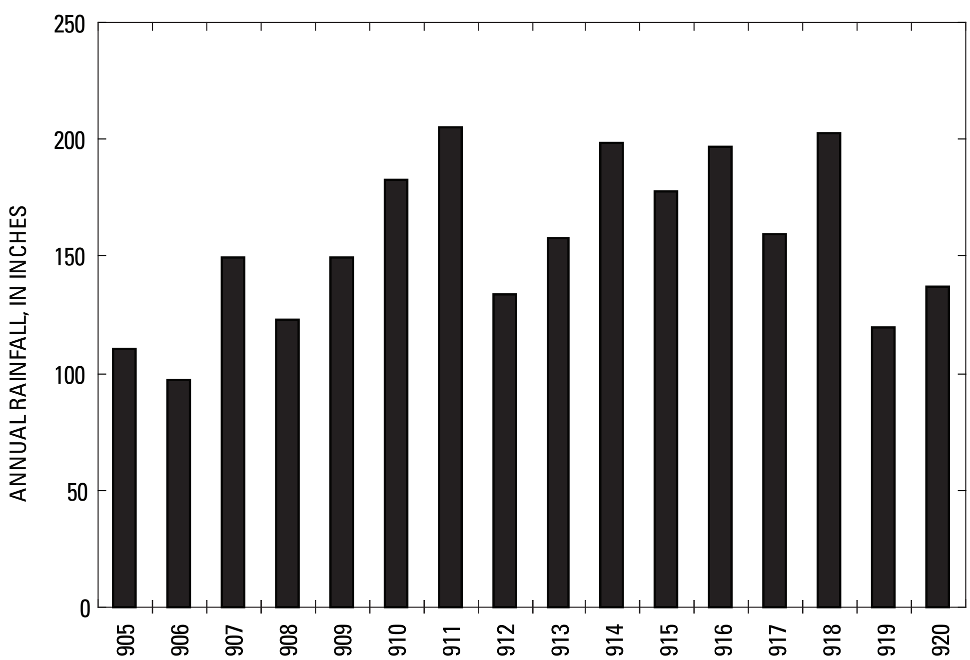


Figure 26. Annual rainfall at station 783 at Nu‘uanu Reservoir 4, O‘ahu, Hawai‘i, 1905-1920 (digital data from Hawai‘i Commission on Water Resource Management).

station and its corresponding index station are above 0.80, complete years of record are recommended to compute flow-duration statistics (Searcy, 1959). When plotting concurrent daily discharges to confirm a linear relation, the computed correlation coefficients for both stations are below 0.80. In addition to the poor correlation, it also is uncertain whether diversions that existed upstream of the index station on Makawao Stream remained consistent throughout all years.

Long-term rainfall data collected at station 783 at Nuʻuanu Reservoir 4 (fig. 21) were used to determine whether streamflow data from the pre-ditch period were collected during dry or wet conditions. Station 783 is close to the study area and has long-term data extending from the pre-ditch period (1905) to present. Rainfall collected at this station in Nuʻuanu are reasonably correlated with concurrent rainfall collected at stations 837.1 and 837 in Waiāhole (figs. 27 and 28), indicating similar rainfall conditions in the two areas. Station 837.1 in Waiāhole, at about 2,150 ft altitude, was operated during 1911–14 and recorded the only pre-ditch rainfall data available in Waiāhole near the topographic divide of Waiawa and Waiāhole watersheds; station 837 in Waiāhole at about 745 ft altitude was in operation during 1916–2004 (fig. 21). Exceedance probabilities (similar to flow-duration percentiles) for the annual rainfall values from station 783 indicate that annual rainfall values during 1911–16 have low percentiles and therefore that these are years of high rainfall. Although it is not possible to determine definitive flow-duration percentiles from these rainfall measurements, the percentiles associated with rainfall at least indicate that conditions were relatively wet when the pre-ditch flow data were collected, and flows measured during these periods may be higher than median flows. Oki (2004) also suggested that statistically significant downward trends in annual base flow as well as rainfall during 1913–2002 were detected at seven long-term stations throughout the State.

Comparison of Estimates

Estimates of natural low-flow statistics based on the adjusted pre-ditch streamflow data collected at station 16292000 on Waiāhole Stream and station 16296000 on Kahana Stream are compared with estimates computed at

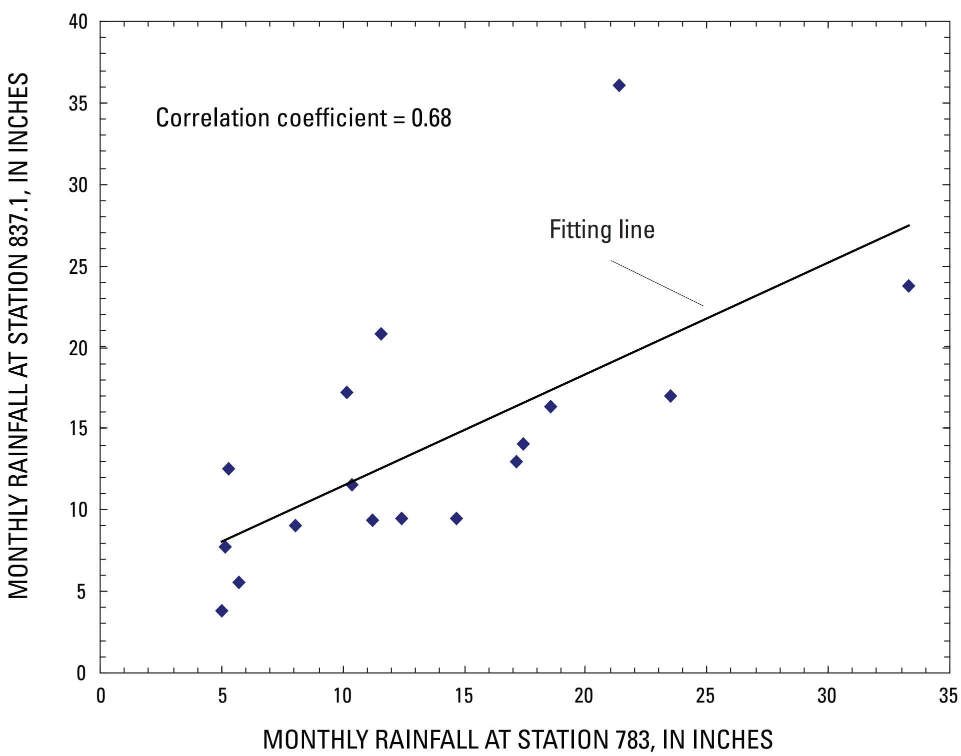


Figure 27. Correlation between monthly rainfall at stations 783 (Nuʻuanu Reservoir 4) and 837.1 (Waiawa-Waiāhole divide) for concurrent period January 1913 to May 1914 (digital data from Hawaiʻi Commission on Water Resource Management).

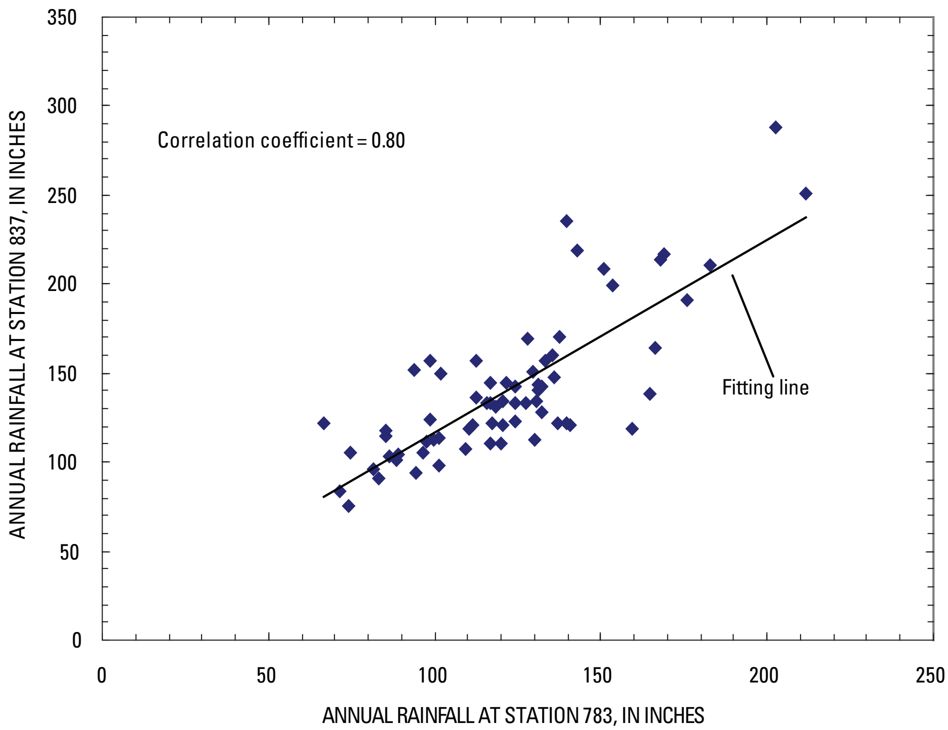


Figure 28. Correlation between annual rainfall at stations 783 (Nu‘uanu Reservoir 4) and 837 (Waiāhole) for concurrent period 1917-1986 (digital data from Hawai‘i Commission on Water Resource Management).

nearby station 16291000 on Waiāhole Stream and station 16296500 on Kahana Stream (fig. 29). For Waiāhole Stream, natural low-flow estimates at station 16291000 based on the two distribution methods are reasonably similar to each other and to estimates based on pre-ditch flow data at station 16292000, which provides some measure of confidence in the estimates for this stream. Natural Q_{50} flows at station 16291000 based on Wall measurement and ditch seepage run distribution methods are 13 and 14 Mgal/d, respectively, and natural Q_{50} flow at station 16292000 is 14 Mgal/d. Because Waiāhole Stream is a gaining stream, natural low-flow estimates at downstream pre-ditch station 16292000 at 160-ft altitude are expected to be slightly higher than those at upstream station 16291000 at 250-ft altitude. Results based on the Wall measurement distribution, when compared with the pre-ditch flow data, are consistent with this pattern. Using the Wall measurement distribution, flow estimates for station 16291000 are on average about 1.1 Mgal/d lower than estimates made from station 16292000 (fig. 29). This 1.1 Mgal/d average difference also agrees with the gain in base flow in the 1-mi reach of Waiāhole Stream between altitudes of 160 and 250 ft measured during the September 27, 1995 seepage run (table 4).

For Kahana Stream, estimates at station 16296500 are expected to be similar to estimates at station 16296000 because of their proximity (fig. 14). Estimates of natural low-flow durations based on the Wall measurement distribution are again in agreement with the pre-ditch flow data (fig. 29). Natural Q_{50} flows at station 16296500 based on Wall measurement and ditch seepage run distribution methods are 22 and 18 Mgal/d, respectively, and natural Q_{50} flows at station 16296000 is 23 Mgal/d. It should be noted that estimates of higher duration percentiles (90, 95, and 99) based on pre-ditch flow at station 16296000 are not computed because the results represent a significant extrapolation of the data and therefore have higher estimation errors (table 16).

Effects of Diversions on Low-Flow Duration Discharges

Flow-duration discharges for natural and diverted (pre-release) conditions at the continuous-record and LFPR stations indicate significant effects of the diversion by Waiāhole Ditch on the low-flow characteristics of streams. Diverted (pre-release) flows at the continuous-record and LFPR stations at

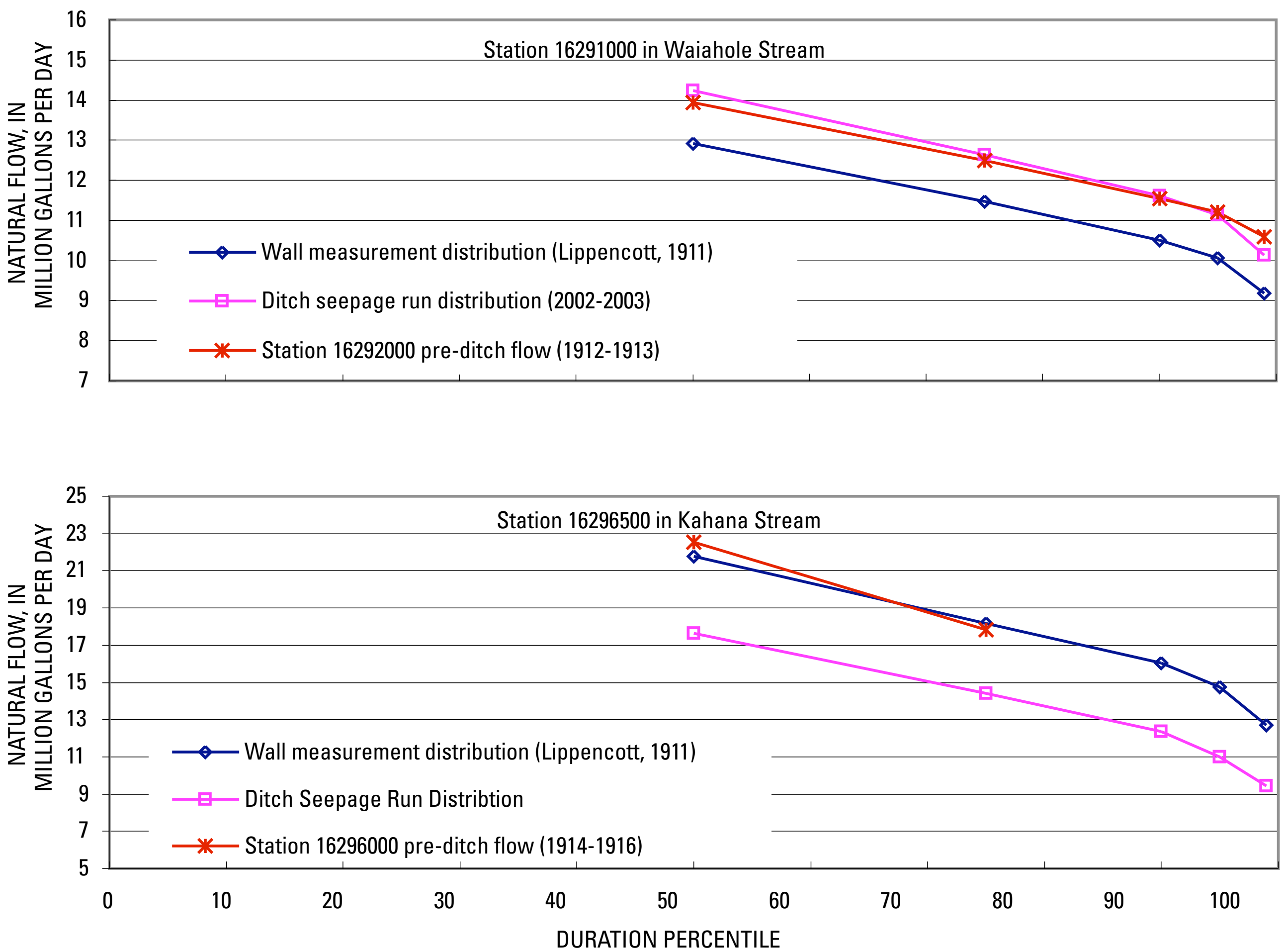


Figure 29. Estimated low-flow duration discharges of natural streamflow using various methods at Waiāhole and Kahana Streams, windward O‘ahu, Hawai‘i.

altitudes of 250 to 320 ft on Waiāhole Stream, 10 to 220 ft on Waikāne Stream, and 30 to 80 ft on Kahana Stream were compared to natural flows to illustrate the effects of the diversions on streamflow. The diverted-flow values were expressed as percentages of the corresponding natural flows (figs. 30-32). Small percentages of diverted to natural flows indicate a relatively large effect of diversion on streamflow; higher percentages indicate a relatively smaller effect of diversion on streamflow. For Waiāhole Stream, diverted (pre-release) flows for the selected duration percentiles at an altitude of 250 ft range from 25 to 28 percent of natural flows, whereas at an altitude of 320 ft they range from 19 to 20 percent of natural flows (fig. 30). For Waikāne Stream, diverted (pre-release) flows associated with the lower altitudes are consistently higher percentages of natural flows than at higher altitudes because the reduction in flow is less significant as the stream gains ground water at lower altitudes (fig. 31). Diverted (pre-release) flows for the selected duration percentiles at an altitude of 10 ft range from 30 to 46 percent of natural flows, whereas percentages at an altitude of 220 ft range from 7 to 19 percent. For Kahana Stream, the percentages for the selected duration percentiles at an altitude of 30 ft range from 65 to 72 percent, whereas percentages at an altitude of 80 ft range from 58 to 71 percent (fig. 32). At similar altitudes, therefore, diversion of water by the Waiāhole Ditch System has caused a greater percentage reduction in streamflow in Waikāne Stream compared to Kahana Stream.

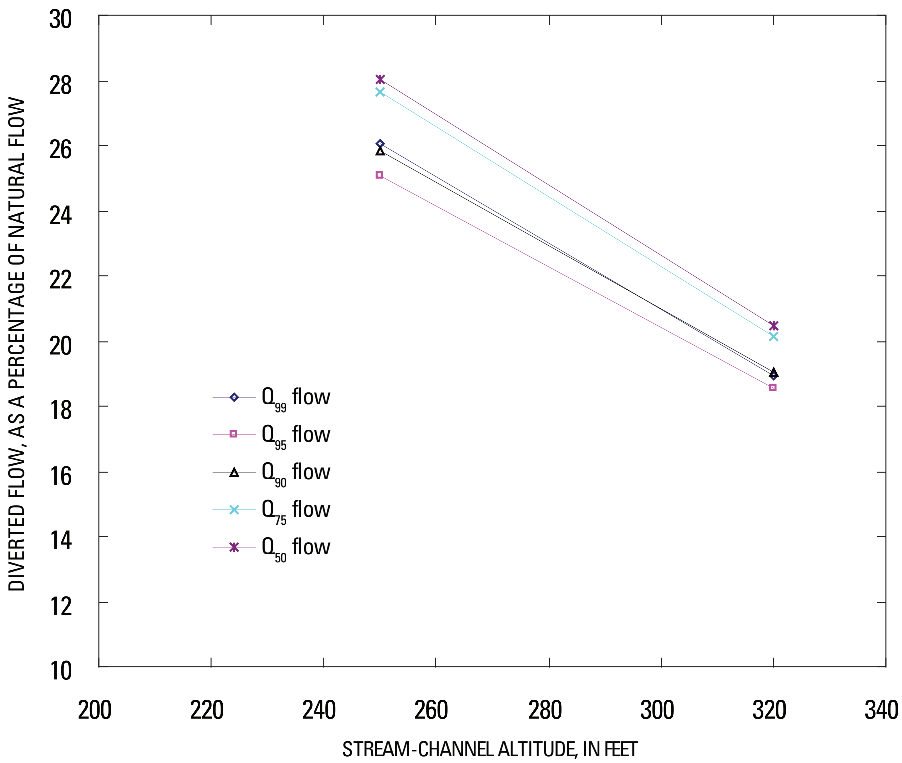


Figure 30. Diverted (pre-release) flows compared to natural flows (Q_{50} to Q_{99}) at stream-channel altitudes of 250 to 320 feet, Waiāhole Stream, windward O‘ahu, Hawai‘i.

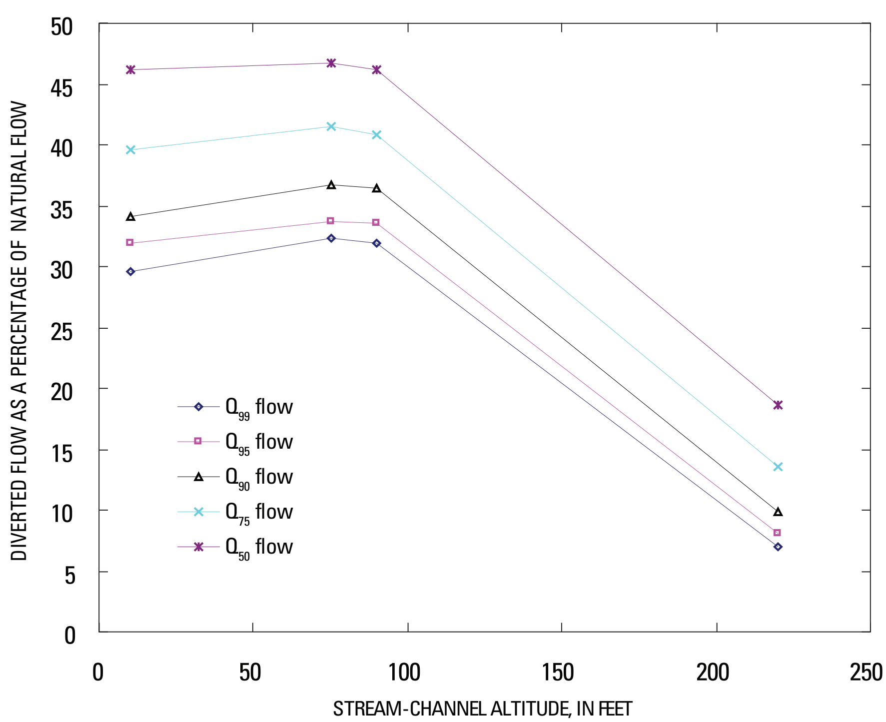


Figure 31. Diverted (pre-release) flows compared to natural flows (Q_{50} to Q_{99}) at stream-channel altitudes of 10 to 220 feet, Waikāne Stream, windward O‘ahu, Hawai‘i.

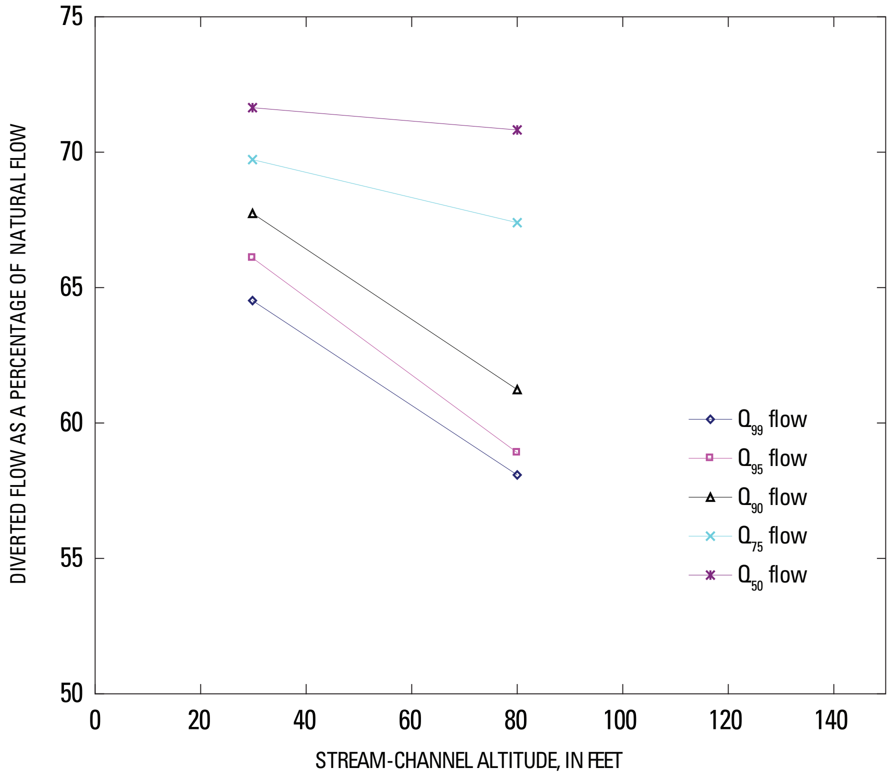


Figure 32. Diverted (pre-release) flows compared to natural flows (Q_{50} to Q_{99}) at stream-channel altitudes of 30 to 80 feet, Kahana Stream, windward O‘ahu, Hawai‘i.

Effects of Flow Releases on Low-Flow Duration Discharges

Currently, flow releases from the Waiāhole Ditch System are affecting streamflow in Waiāhole, Waianu, and Waikāne Streams. This section compares estimates of post-release flows to estimates of natural flows and pre-release flows.

Comparison of Post-release to Natural Flows

Differences between the post-release and natural flow estimates were compared for continuous-record and LFPR stations along Waikāne and Waianu Streams to assess how current streamflows compare to natural conditions (table 24). Currently, flow is being released to one of the two tributaries to Waikāne Stream through Intake 23 (fig. 14). For the upper reach of Waikāne Stream at an altitude of 220 ft (at station 16294500), above the confluence with Waike‘eke‘e Stream, the current post-release flows for selected flow-duration percentiles are from 48 to 62 percent higher than natural flows. At an altitude of 90 ft (at station 16294800), just above the confluence with Waike‘eke‘e Stream, current post-release flows are 32 to 40 percent higher than natural flows. For the stream reach below the confluence with Waike‘eke‘e Stream, the current post-release flows at altitudes of 75 and 10 ft (at stations 16294900 and 16295195, respectively) are within 12 percent of natural flows. The results indicate that the current post-release flows are higher than natural flow along the upper reach of Waikāne Stream, but along the lower reach they are relatively close to natural flows. The post-release low-flow estimates for Waikāne Stream are mainly representative of flow-release conditions in 2003 because the estimates were made by correlating mostly 2003 low-flow discharge measurements and the concurrent daily discharges at index stations.

For Waiāhole Stream, the only station with available post-release and natural flow estimates is station 16293100 on Waianu Stream (table 20). Post-release flows for selected flow-duration percentiles at an altitude of 75 ft (station 16293100) are 41 to 46 percent lower than natural flows, which indicate that a higher flow release would be needed to restore flow at an altitude of 75 ft on Waianu Stream to natural flow conditions.

Table 24. Percent difference between estimates of natural and post-release low-flow duration discharges for continuous-record and low-flow partial-record (LFPR) streamflow stations, windward Oʻahu, Hawaiʻi.

[Mgal/d, million gallons per day; percentage of difference = 100 x (post-release flow - natural flow) / natural flow]

Station	Station altitude (feet)	Duration percentile	Estimated natural flow at station (Mgal/d)	Estimated post-release flow at station (Mgal/d)	Percentage of difference
Waianu Stream					
16293100	75	99	4.6	2.7	-41
		95	5.1	2.9	-43
		90	5.4	3.0	-45
		75	5.9	3.3	-44
		50	7.0	3.8	-46
Waikāne Stream					
16294500	220	99	1.5	2.2	49
		95	1.7	2.5	48
		90	1.8	2.7	52
		75	2.0	3.2	62
		50	2.3	3.5	51
16294700	90	99	0.80	0.03	-97
		95	0.90	0.04	-95
		90	0.94	0.06	-94
		75	1.1	0.12	-89
		50	1.3	0.25	-81
16294800	90	99	2.0	2.7	35
		95	2.3	3.1	33
		90	2.5	3.3	32
		75	2.8	4.0	39
		50	3.5	4.9	40
16294900	75	99	3.2	2.9	-10
		95	3.7	3.2	-12
		90	3.9	3.6	-7
		75	4.5	4.7	4
		50	5.5	5.9	7
16295195	10	99	3.1	2.7	-12
		95	3.5	3.1	-11
		90	3.8	3.4	-9
		75	4.4	4.4	1
		50	5.5	5.9	8

Comparison of Pre-release to Post-release Flows

Flow-duration discharge estimates at different locations make it possible to characterize the spatial distribution of low flows in the lower parts of the streams affected by upstream diversions and water releases. Effects of the flow releases can be assessed by comparing low-flow duration discharges between the pre-release and post-release periods. The comparison is limited to Waikāne Stream because insufficient pre-release discharge measurements are available for Waianu Stream and insufficient post-release discharge measurements are available for Waiāhole Stream.

Pre-release flows at the continuous-record and LFPR stations along Waikāne Stream at altitudes of 10 to 220 ft were compared to post-release flows in order to assess downstream changes in flow along the streams where releases were made (fig. 33). Pre-release flows for the selected duration percentiles at an altitude of 10 ft range from 35 to 43 percent of post-release flows, whereas percentages at a higher altitude of 220 ft range from 5 to 11 percent. At a particular stream altitude, Q_{50} (median) pre-release flows are consistently greater percentages of post-release flows than pre-release flows at higher duration percentiles because the relative effect of the added flow is smaller at higher flow conditions. Similarly, for a particular flow-duration percentile, pre-release flows associated with lower stream-channel altitudes are consistently greater percentages of post-release flows than those at higher stream-channel altitudes because the relative effect of the flow release is smaller as the stream gains ground water at lower altitudes.

Limitations of Approach

The computation of natural low flows in streams using apportioned ditch flows assumes a one-to-one relation between water diverted by the Waiāhole Ditch System and loss of flows from the streams. Takasaki and Mink (1985, p. 29) suggested that the final equilibrium base flow of the ditch system is not appreciably different from the total base flow of the diverted streams before the diversion system was constructed. The intercepted ground water was once discharged at springs above the level of the current ditch system; construction of the Waiāhole Ditch System created new and lower points of discharge (Takasaki and others, 1969). The effect of tunneling is similar to an extension of a valley floor. If a tunnel is long enough, it may partly or completely replace a stream as the location where ground water will drain (Takasaki and others, 1969, p.102).

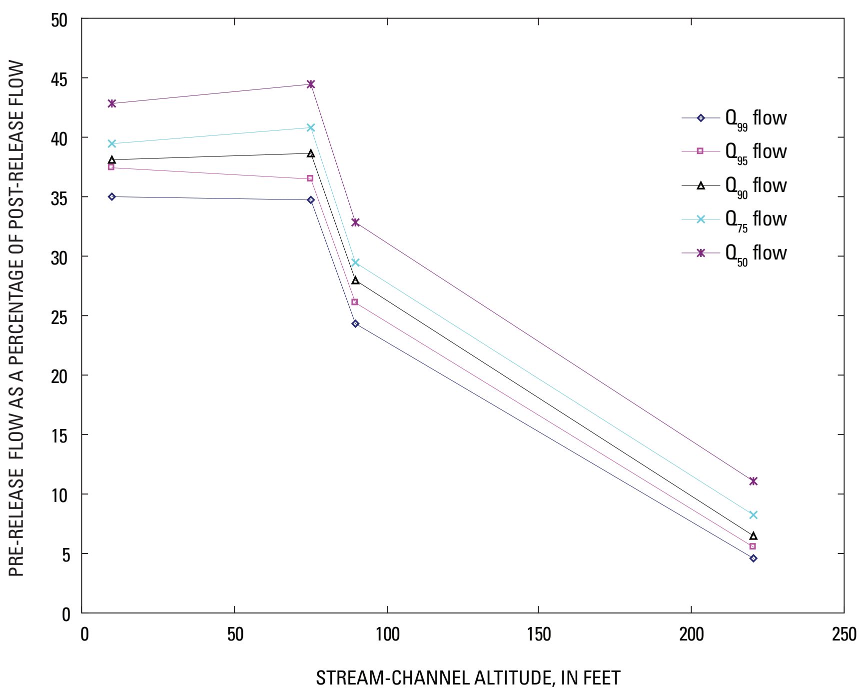


Figure 33. Pre-release flows compared to post-release flows (Q_{50} to Q_{99}) at stream-channel altitudes of 10 to 220 feet, Waikāne Stream, windward O‘ahu, Hawai‘i. The Q_{50} flow is the median flow, and the Q_{99} flow is the flow that is equaled or exceeded 99 percent of the time.

The computation of natural low flows in streams downstream from the Waiāhole Ditch System assumes that intercepted base flows would have flowed naturally in streams above the level of the ditch system. As discussed in a previous section, the effect of tunneling largely affected ground-water discharge to stream reaches at higher altitudes, and effects at lower altitude reaches may be small. The uppermost LFPR station in the study area is station 16292800 at 380 ft altitude in Waianu Stream, well below the ditch altitude of approximately 750 ft. Thus, for this study, it is reasonable to assume that all ground water intercepted by the Waiāhole Ditch System would have discharged naturally to the stream reaches above the uppermost LFPR station. Low-flow estimates at the LFPR and continuous-record stations account for the current spatial distributions of gains and losses of water in the streams, and these distributions are assumed to be similar for both natural and diverted flow conditions.

Accuracy of Low-Flow Duration Estimates

The ranges of standard errors for the selected low-flow duration discharges at the LFPR stations on Waiāhole, Waikāne, and Kahana Streams are 2.0 to 22, 1.8 to 26, and 5.0 to 17 percent, respectively (table 15). The ranges of standard errors at the continuous-record stations on Waiāhole, Waikāne, and Kahana Streams are 0.47 to 2.2, 0.38 to 1.4, and 0.59 to 2.8 percent, respectively (table 16). The natural, pre-release, and post-release low-flow statistics at various locations on the diverted streams were computed using flow-duration analysis at continuous-record stations with long-term records and record extension techniques at stations with records shorter than the base period and at LFPR stations. Streamflow statistics for the long-term continuous-record stations were determined directly using the flow-duration analysis, and the computed daily flow statistics accurately represent flow conditions for the period of record over which they have been computed (Fontaine, 2003). Because low-flow estimates computed for short-term continuous-record stations and LFPR stations are not based on long-term data, they contain error. Accuracies associated with these low-flow estimates are largely related to the strength of the correlation between the discharges at the continuous-record and LFPR stations and the number of concurrent discharges available for the record-extension analysis. Accuracies associated with the pre-release low-flow estimates for station 16294900 are expected to be high because the available record from 1960 to 2002, representative of pre-release conditions, is only two years short of the base period (1960-2004). The standard errors should be considered minimum errors because the methods used do not take into consideration the potential errors inherent in the discharge measurements made at the LFPR stations or the daily mean discharges at the index station (Fontaine, 2003). In addition, flow estimates at higher duration percentiles for some of the continuous-record and LFPR stations represent a significant extension or extrapolation of the data.

In general, accuracies associated with the pre-release flow estimates on Waikāne Stream are higher than accuracies associated with the post-release estimates. Flow releases at Intake 23 and Gates 30 and 31 were inconsistent and frequently higher than the targeted restoration flows (Hawai‘i Commission on Water Resource Management, 2001) (fig. 34). The variability of flow releases in time reduces the reliability of the post-release flow estimates for this stream. In addition, because a small number of post-release discharge measurements at LFPR stations in Waikāne Stream were made during a relatively short period of time, the range of flows represented by these measurements was limited.

For the natural flow estimates, the addition of flow statistics introduced additional errors. As discussed in an earlier section, the relative errors associated with adding flow statistics for stations on gaining streams downstream of the Waiāhole Ditch System were estimated to average less than 5 percent.

Summary and Conclusions

Since 1916, the Waiāhole Ditch System intercepted large amounts of dike-impounded ground water at high altitudes (above approximately 700 to 800 ft altitude) that previously discharged to Waiāhole (and its tributaries Waianu and Uwao), Waikāne, and Kahana Streams through seeps and springs. Diversion of this ground water has significantly diminished low flows in these streams. Between December 1994 and October 2002, flow releases were initiated to Waikāne, Waianu, and Waiāhole Streams from the Waiāhole Ditch System. Natural (undiverted), pre-release, and post-release low-flow duration discharges for percentiles ranging from 50 to 99 percent were estimated for continuous-record streamflow and LFPR stations along the affected streams. The computations involved the use of historical pre-ditch streamflow data and post-ditch streamflow data from USGS continuous-record stations, low-flow discharge measurements at LFPR stations, and seepage runs in the connecting tunnels and diverted streams. All flow estimates were adjusted to the base period of 1960-2004, so that differences in flow reflect spatial differences in climate and drainage-basin characteristics rather than temporal differences in rainfall.

Natural low-flow duration discharges were estimated for four sites at altitudes of 75 to 320 ft in Waiāhole Stream (and its tributaries Waianu and Uwao Streams), for six sites at altitudes of 10 to 220 ft in Waikāne Stream, and for three sites at altitudes of 30 to 80 ft in Kahana Stream. Among the available low-flow estimates along each affected stream, the highest natural Q_{50} (median) flows on Waiāhole (altitude 250 ft), Waianu (altitude 75 ft), Waikāne (altitude 75 ft), and Kahana (altitude 30 ft) Streams are 13, 7.0, 5.5, and 22 million gallons per day, respectively. The natural low-flow duration estimates compared favorably with limited pre-ditch streamflow data available for Waiāhole and Kahana Streams.

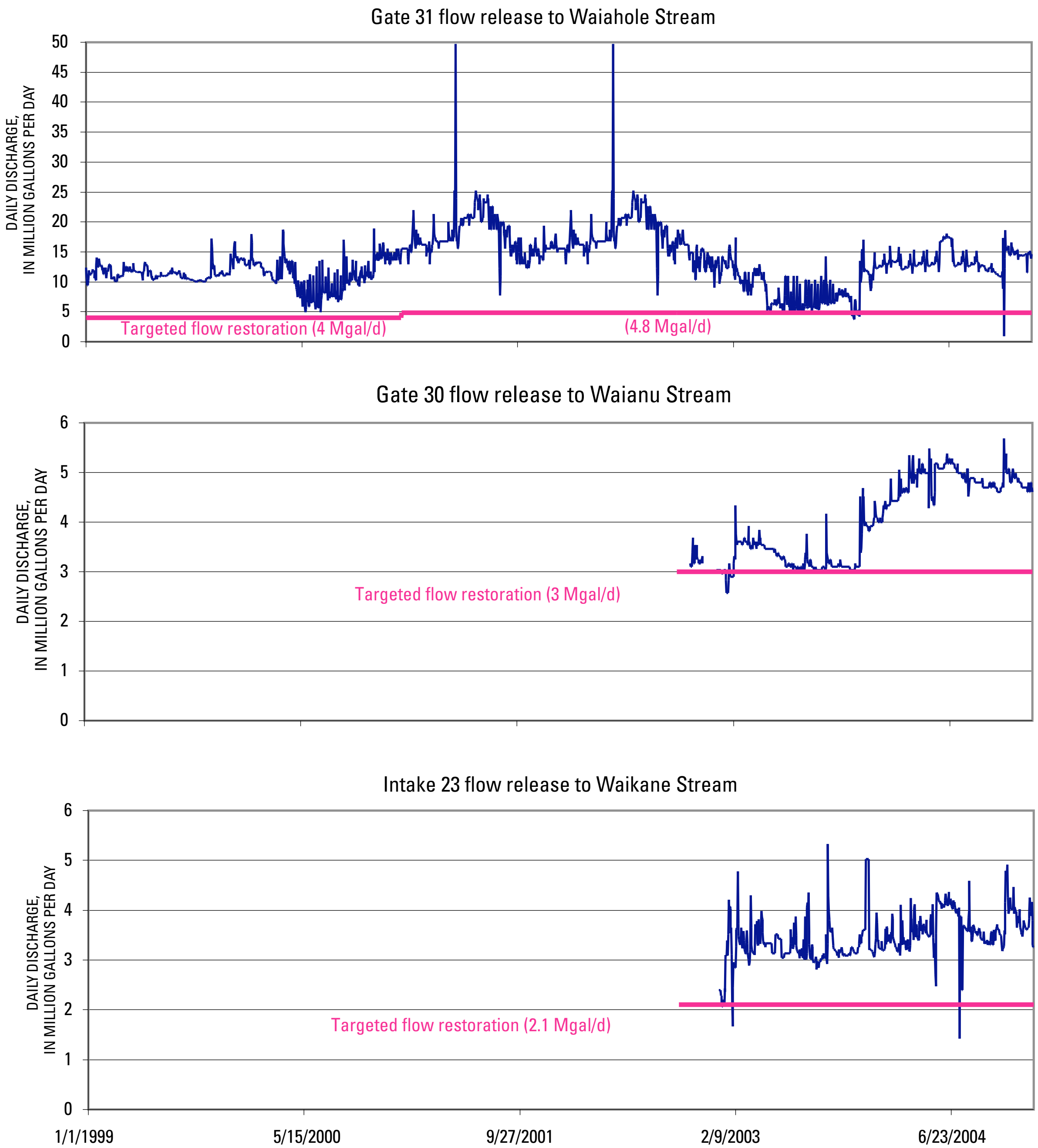


Figure 34. Daily flow releases at Gate 30, Gate 31, and Intake 23 on Waiāhole Ditch System, windward O‘ahu, Hawai‘i (daily flow data collected by Agribusiness Development Corporation and targeted flow restoration values issued by Hawai‘i Commission on Water Resource Management (2001)).

Natural low-flow duration discharge estimates were compared with available current post-release flow duration discharge estimates at selected sites to assess how close current streamflows are to natural conditions. For Waianu Stream, current post-release flows at an altitude of 75 ft are 41 to 46 percent lower than corresponding natural flows which indicate higher flow release would be needed to restore flow to natural conditions. For the upper reach of Waikāne Stream above the confluence with Waikeʻekeʻe Stream, current post-release low flows, at altitudes of 220 and 90 ft, are 32 to 62 percent higher than corresponding natural flows. For the stream reach below the confluence with Waikeʻekeʻe Stream, current post-release flows, at altitudes of 75 and 10 ft, are within 12 percent of corresponding natural flows. The results indicate that the current post-release flows are greater than natural flows along the upper reach of Waikāne Stream, but the current post-release flows along the lower reach are relatively close to natural flows.

Pre-release flows and natural flows were compared at selected sites along the diverted streams from altitudes of 250 to 320 ft in Waiāhole Stream, 10 to 220 ft in Waikāne Stream, and 30 to 80 ft in Kahana Stream. The results indicate that the effects of the Waiāhole Ditch System diversion are consistently greater at lower low-flow conditions (Q_{99} to Q_{90}) than at higher low-flow conditions (Q_{75} to Q_{50}). Results also indicate that the effects of the diversion become less significant as the streams gain additional ground water at lower altitudes. For Waiāhole Stream, pre-release flows at an altitude of 250 ft range from 25 to 28 percent of natural flows, whereas at an altitude of 320 ft they range from 19 to 20 percent of natural flows. For Waikāne Stream, pre-release flows for selected flow-duration percentiles at an altitude of 10 ft range from 30 to 46 percent of natural flows, whereas at an altitude of 220 ft they range from 7 to 19 percent of natural flows. For Kahana Stream, pre-release flows at an altitude of 30 ft range from 65 to 72 percent of natural flows, whereas at an altitude of 80 ft they range from 58 to 71 percent of natural flows.

Comparisons of pre-release and post-release flows at stations along Waikāne Stream at altitudes of 10 to 220 ft were used to assess downstream changes in flow along the stream reach where flow releases were made. At a particular stream altitude, pre-release flows associated with median flows are consistently greater percentages of median post-release flows than those associated with lower low flows are of corresponding post-release flows because the relative effect of the added flow is smaller at higher low-flow conditions. Similarly, for a particular flow-duration percentile, pre-release flows associated with lower altitudes are consistently greater percentages of post-release flows than those at higher altitude because the relative effect of the flow release is smaller as the stream gains ground water at lower altitudes. Pre-release flows for selected duration percentiles at an altitude of 10 ft range from 35 to 43 percent of post-release flows, whereas at a higher altitude of 220 ft they range from 5 to 11 percent of post-release flows.

References Cited

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

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

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

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

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

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

Hardison, C.H., and Moss, M.E., 1972, Accuracy of low-flow characteristics estimated by correlation of base-flow measurements, *in* Manual of hydrology—Part 2. Low-flow techniques: U.S. Geological Survey Water-Supply Paper 1542-B, p. 35-55.

Hawaii Commission on Water Resource Management, 2001, Proposed legal framework, findings of fact, and decision and order (August 1, 2001), *for* the Waiahole Ditch combined contested case hearing (CCH-OA95-1), 153 p.

Hirashima, G.T., 1971, Tunnels and dikes of the Koolau Range, Oahu, Hawaii, and their effect on storage depletion and movement of ground water: U.S. Geological Survey Water-Supply Paper 1999-M, 21 p.

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

Klasner, F.L., and Mikami, C.D., 2003, Land use on the Island of Oahu, Hawaii, 1998: U.S. Geological Survey Water-Resources Investigations Report 02-4301, 20 p.

Kluegel, C.H., 1916, Engineering features of the Waiahole Water Project of the Waiahole Water Company: Hawaiian Gazette Co. Ltd., 24 p.

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

Lippencott, J.B., 1911, Report on the feasibility of bringing the waters of the Waiahole, Waikane, and Kahana Streams through the Koolau Range to the lands of the Oahu Sugar Company, Limited: Hawaiian Gazette Co., Ltd., 1918, Report to the Honorable Mayor and Board of supervisors of the City and County of Honolulu on the available water supply for the City of Honolulu, volume IV, p. 4-33.

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

Nullet, D., and Sanderson, M., 1993, Radiation and energy balances and air temperature, chap. 3 *of* Sanderson, M., ed., Prevailing trade winds, weather and climate in Hawaii: Honolulu, University of Hawaii Press, p. 37–55.

Oki, D.S., 2003, Surface water in Hawaii: U.S. Geological Survey Fact Sheet 045-03, 6 p.

Oki, D.S., 2004, Trends in streamflow characteristics in Hawaii, 1913-2002: U.S. Geological Survey Fact Sheet 2004-3104, 4 p.

Oki, D.S., and Brasher, M.D., 2003, Environmental setting and the effects of natural and human-related factors on water quality and aquatic biota, Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 03-4156, 98 p.

Presley, T.K., Sinton, J.M., and Pringle, Malcolm, 1997, Postshield volcanism and catastrophic mass wasting of the Waianae Volcano, Oahu, Hawaii: Bulletin of Volcanology, v. 58, p. 597–616.

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

Ries, K.G., 1999, Streamflow measurements, basin characteristics, and streamflow statistics for low-flow partial-record stations operated in Massachusetts from 1989 through 1996: U.S. Geological Survey Water-Resources Investigations Report 99-4006, 162 p.

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

Russ Smith Corporation, 1980, Preliminary engineering report covering water resources in Waiahole Valley: Russ Smith Corporations, 33 p.

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

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

Stearns, H.T., 1939, Geologic map and guide of the island of Oahu, Hawaii: Hawaii Division of Hydrography, Bulletin 2, 75 p., map scale 1:62,500.

Stearns, H.T., and Vaksvik, K.N., 1935, Geology and ground-water resources of the island of Oahu, Hawaii: Hawaii Division of Hydrography, Bulletin 1, p. 399-409.

Stedinger, J.R., and Thomas, W.O., 1985, Low-flow frequency estimation using base-flow measurements: U.S. Geological Survey Open-File Report 85-95, 22 p.

Takasaki, K.J., and Mink, J.F., 1985, Evaluation of major dike-impounded ground-water reservoirs, island of Oahu: U.S. Geological Survey Water-Supply Paper 2217, 77 p.

Takasaki, K.J., Hirashima, G.T., and Lubke, E.R., 1969, Water resources of windward Oahu, Hawaii: U.S. Geological Survey Water-Supply Paper 1894, 119 p.

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

Visher, F.N., and Mink, J.F., 1964, Ground-water resources in Southern Oahu, Hawaii: U.S. Geological Survey Water-Supply Paper 1778, 133 p.

Wahl, K.L., and Wahl, T.L., 1995, Determining the flow of Comal Springs at New Braunfels, Texas: American Society of Civil Engineers, Proceedings of Texas Water ’95, component conference of the First International Conference on Water Resources Engineering, August 16-17, 1995, San Antonio, Texas, p. 77-86.

Water Resource Associates, 2003, Agricultural water use and development plan, prepared for the Department of Agriculture, State of Hawaii, 145 p.

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

Appendix 1. Reconstructed daily time series of ditch flow at North Portal station 16287000 near Waiāhole, windward O‘ahu, 2003-04.

[Streamflow is in million gallons per day; --, not available]

2003												
Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	24	25	22	23	22	21	21	21	21	19	19	21
2	24	24	23	23	22	21	21	22	20	19	17	22
3	24	24	22	22	22	21	20	22	20	19	18	23
4	24	24	22	24	22	21	21	21	20	19	19	27
5	24	23	22	23	21	22	21	22	20	19	19	28
6	24	23	23	24	21	21	22	21	22	20	18	24
7	23	23	24	23	23	21	21	22	22	19	19	29
8	23	23	23	23	22	22	21	22	20	20	19	25
9	23	23	23	24	22	22	21	22	20	20	19	25
10	23	23	22	26	22	22	21	20	21	20	18	25
11	23	23	23	24	22	21	21	21	31	20	17	25
12	23	23	22	23	22	21	21	20	24	20	18	25
13	23	22	22	23	22	20	21	20	23	19	18	25
14	24	31	22	23	22	21	21	21	22	20	18	25
15	24	25	22	22	22	22	20	20	21	20	17	25
16	23	23	27	22	22	22	21	21	21	19	17	23
17	24	23	24	22	22	21	21	22	20	20	18	23
18	24	23	22	22	22	21	21	20	21	19	19	23
19	24	23	22	22	22	21	21	20	21	20	18	23
20	25	23	22	23	21	21	22	20	21	19	18	23
21	24	23	22	22	22	21	21	20	22	19	18	23
22	24	24	22	22	22	21	20	20	20	19	18	23
23	23	23	22	22	22	21	21	21	20	19	18	23
24	23	23	22	22	22	21	21	21	20	19	18	23
25	23	22	22	22	22	22	23	20	20	19	18	23
26	23	23	22	22	22	21	26	20	20	19	18	23
27	23	23	24	21	21	21	23	20	20	19	18	23
28	23	23	23	21	21	22	25	20	20	19	18	23
29	23	--	24	21	21	22	22	20	20	19	28	23
30	26	--	24	21	21	21	21	21	20	19	25	24
31	28	--	24	--	21	--	21	21	--	19	--	25
MEAN	24	23	23	23	22	21	21	21	21	19	19	24

Appendix 1. Reconstructed daily time series of ditch flow at North Portal station 16287000 near Waiāhole, windward O‘ahu, 2003-04—Continued.

[Streamflow is in million gallons per day; --, not available]

						2004						
Day	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	26	27	27	28	29	33	30	29	27	26	31	29
2	29	27	30	31	31	33	32	31	27	27	30	28
3	27	27	28	30	29	33	30	30	27	26	30	28
4	25	27	27	28	28	33	29	30	27	27	30	28
5	25	28	27	28	28	33	29	28	27	26	31	28
6	25	27	27	28	28	33	29	27	28	26	31	28
7	25	31	27	27	29	33	30	28	27	26	31	28
8	25	30	27	27	28	33	30	27	27	26	30	29
9	25	26	27	28	28	34	30	27	27	26	29	29
10	25	27	27	28	28	35	30	27	27	26	29	28
11	25	27	27	28	29	35	30	27	27	26	29	28
12	25	27	27	28	28	34	26	27	27	25	29	28
13	25	27	27	29	28	34	29	28	27	25	29	28
14	26	27	28	29	28	34	30	28	27	25	32	28
15	25	27	27	28	28	34	30	28	26	25	30	30
16	25	27	27	29	28	34	29	28	26	25	30	30
17	25	27	27	28	27	35	28	28	26	25	30	29
18	25	27	27	28	27	34	27	28	26	25	30	29
19	26	27	27	28	28	34	27	28	26	25	29	29
20	26	27	27	29	30	34	29	28	26	25	29	25
21	26	27	30	29	30	34	30	28	26	25	29	26
22	28	27	30	30	31	35	33	29	26	25	28	30
23	28	28	29	29	30	34	32	28	27	25	29	29
24	27	27	29	29	30	34	32	28	27	26	29	29
25	29	27	30	31	32	34	31	30	27	23	29	29
26	28	28	28	30	30	34	30	29	26	33	29	29
27	27	33	28	29	30	34	30	28	26	32	28	30
28	26	29	28	29	30	34	32	28	27	16	30	29
29	26	28	29	27	30	33	30	28	27	28	30	28
30	26	--	30	31	28	34	28	26	27	29	28	28
31	27	--	29	--	30	--	30	30	--	35	--	28
MEAN	26	28	28	29	29	34	30	28	27	26	30	28

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